NEUTRINO'82
III.

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ABSTRACT

We present here preliminary results on a recent experiment on $\nu_\mu + e^- \to \nu_\mu + e^-$ elastic scattering. A brief review of the Glashow-Salam-Weinberg theory is given, indicating how the measurement of the total cross section gives rise to an ambiguous solution for $\sin^2 \theta_W$, and showing how the differential cross section can be used to resolve the ambiguity. The experimental configuration and the extraction of the signal are described. The data are compared with those from our previous experiment, and relevant distributions from the combined data sample are presented. The differential cross section is examined in an attempt to resolve the ambiguity in $\sin^2 \theta_W$, the lower value of $\sin^2 \theta_W = 0.20$ being favored.
The differential cross section for $\nu - e^-$ elastic scattering is given by:

$$
\frac{d\sigma}{dE_e} = \frac{G^2 M_e}{2\pi} \left[ (g_V + g_A)^2 + (g_V - g_A)^2 \left( (1 - \frac{E}{E_V})^2 - (\frac{M_e}{E_V})^2 \right) \right]
$$

where $E$ = incident neutrino energy; $E_e$, $M_e$ = Energy, Mass of the scattered electron; $g_V$, $g_A$ are the vector, axial-vector couplings of the neutral current to the electron. At FNAL/SPS energies, $E_V \gg M_e$ and the third term above can be neglected.

The total cross section is given by

$$
\sigma = \frac{G^2 M_e E_v}{2\pi} \left[ (g_V + g_A)^2 + (g_V - g_A)^2 / 3 \right]
$$

The kinematics of this reaction impose a further constraint on the scattered electrons:

$$
E_e \Theta_e^2 \leq 2 M_e
$$

where $\Theta_e$ is the scattering angle (with respect to the incident neutrino) of the electron; e.g. for electrons of energy 2 GeV (the lower limit for electrons in this experiment), the scattering angle $\Theta_e \approx 22.6 \text{ mrad}$. Hence interactions due to $\nu - e^-$ elastic scattering are characterised by the observation of a single electron at a very small angle to the incident neutrino beam direction.

In the standard model of Glashow-Salam-Weinberg, the couplings $g_V$, $g_A$ are parameterized by

$$
g_V = 2 \sin^2 \theta_W - \frac{1}{2}, \quad g_A = -\frac{1}{2},
$$

such that the cross sections become

$$
\frac{d\sigma}{dE_e} = \frac{G^2 M_e}{2\pi} \left[ (2 \sin^2 \theta_W - 1)^2 + (2 \sin^2 \theta_W)^2 \left( 1 - \frac{E}{E_V} \right)^2 \right]
$$

$$
\sigma = \frac{G^2 M_e E_v}{2\pi} \left[ \frac{16}{3} \sin^4 \theta_W - 4 \sin^2 \theta_W + 1 \right]
$$
Fig. 1 displays the slope \( (\sigma/E_{\nu}) \) for neutrinos and antineutrinos as a function of \( \sin^2 \theta \), together with the result from our previous experiment \( (\sigma/E_{\nu} = (1.8 \pm 0.8) \times 10^{-42} \text{ cm}^2 \text{ GeV}^{-1}) \). As can be seen an ambiguous value for \( \sin^2 \theta \) is obtained; \( \sin^2 \theta = 0.20 \pm 0.08 \) or \( 0.57 \pm 0.07 \). Fig. 2 displays the electron energy spectra which would be observed in the FNAL wideband neutrino beam corresponding to the two values of \( \sin^2 \theta \).

The experiment was conducted at FNAL using the 15' bubble chamber filled with a heavy (64% atomic) Neon/Hydrogen mixture, operating a 30 kG magnetic field. The radiation length of 40 cm. affords excellent electron identification. The angular resolution on electron tracks is typically 4 mrad, while the energy resolution is 10% at 2 GeV, and 15% at 20 GeV. The beam used in this experiment was the single horn focussed wideband neutrino beam producing a neutrino energy spectrum which extends from a few GeV to over 200 GeV, peaking at 25 GeV. In our previous experiment a two horn focussed beam was employed.

The data was selected via a two step process; firstly a dedicated scan to collect all unassociated electromagnetic showers in the forward direction; and secondly the separation of the showers into electrons, positrons and photons \( (\gamma \rightarrow e^+ e^-) \). In the dedicated scan, the following event types were recorded:

1) All unassociated single electrons/positrons/photon within 30° of the beam direction (This large angle was selected, to avoid any losses caused by apparent distortions due to the optics).

2) Any low multiplicity interactions, in which there were any electron/positron and no more than two hadrons (excluding proton stubs due to nuclear breakup). These events are used in determining the background due to the reaction \( v_e n \rightarrow e^- p \), in which the proton has too low an energy to be observed.

For a track to be considered as an electron/positron, it had to be identified by two or more of the usual signatures; converted bremsstrahlung; annihilation; spiralization; large trident; or sudden curvature change. All events with an electron/positron having an energy greater than 2 GeV and within 52 mrad (3°) of the beam direction were considered by physicists in the second step.
The aim of the second step was to select single electrons/positrons while rejecting photons. An event was defined to be a single electron/positron, if there was no visible radiation on a negative/positive track, before there was observable curvature, so that the event clearly had a single track at the origin. If there was visible radiation on the track before curvature, the track was still considered as a single electron if (a) the fastest track coming from the confused region was negative, (b) the energy of the fastest positron was less than one quarter of the energy of the fastest electron and (c) the energy of the second fastest electron was greater than one tenth of the energy of the fastest positron. Condition (b) removes fast symmetric pairs and condition (c) removes asymmetric pairs with a delta near the origin. The losses caused by these conditions (an electron radiating more than one quarter of its energy into a highly asymmetric pair before the original electron had observable curvature) is calculated to be 3%.

The data, from a single scan, is shown in Table 1, together with the data from the previous experiment and the combined total. The data are directly comparable, since each experiment had approximately the same flux of neutrinos, and from an initial estimate of the scanning efficiency, the single scan efficiency in the new experiment is equal to the overall scanning efficiency in the previous experiment. Clearly the new data are very consistent with the previous results. Fig. 3 displays the scatter plot of the electron energy $E_e$ vs. the scattering angle $\theta$ for all the single electron events. All the events are consistent with the kinematics of $\nu_e - e^-$ elastic scattering. Fig. 4 displays the variable $E\theta^2$ for (a) the single electrons, (b) the single positrons; and (c) the isolated photons. The single electrons peak sharply, while the single positrons and isolated photons are more uniformly distributed.

The major background to the single electron signal arises from the reaction $\nu_e n \rightarrow e^- p$, in which the proton has such low energy that it is unobserved. The background due to this process is estimated at 6%. A further 1% background arises from asymmetric photons whose kinematics are consistent with $\nu_\mu - e^-$ elastic scattering.
The observed electron energy spectrum is shown in Fig. 5, together with the predicted spectrum corresponding to the two values of \( \sin^2 \theta_w \) determined in our previous experiment. The data appears to be in better agreement with the lower value for \( \sin^2 \theta_w \). In general the measurement of electrons in heavy liquid tends to underestimate the true electron energy. A mismeasurement of the electron energy would soften the energy spectrum, causing the higher value for \( \sin^2 \theta_w \) to be favored. This effect is not observed in our data.

In conclusion, we have approximately doubled the size of our previous data sample, the new data being very consistent with previous data. The observed electron energy spectrum from the combined data sample appears to favor the value of \( \sin^2 \theta_w = 0.20 \) over \( \sin^2 \theta_w = 0.57 \).

The determination of the scanning efficiency from a rescan of the film and a complete calculation of the background and losses will allow a precise measurement of the total cross section and \( \sin^2 \theta_w \). This research supported in part by the U. S. Department of Energy under Contract No. DE-AC02-76CH00016 and by the National Science Foundation.

<table>
<thead>
<tr>
<th>Event Type</th>
<th>This Experiment</th>
<th>Previous Experiment</th>
<th>Combined Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single electron</td>
<td>9</td>
<td>11</td>
<td>20</td>
</tr>
<tr>
<td>Single positron</td>
<td>5</td>
<td>4</td>
<td>9</td>
</tr>
<tr>
<td>Isolated photon</td>
<td>27</td>
<td>22</td>
<td>49</td>
</tr>
<tr>
<td>( \nu_e ) Quasi-elastic ( e^- p (+ stubs) )</td>
<td>17</td>
<td>22</td>
<td>39</td>
</tr>
<tr>
<td>Overall Scanning Efficiency</td>
<td>((78 \pm 15))</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

TABLE 1
Number of Observed Events
Figure 1. The slope \((\sigma/E)\) of the total cross sections for neutrino and
anti-neutrino elastic scattering on electrons, as a function of \(\sin^2 \theta_w\).
The dashed line is the result obtained from our previous experiment.

Figure 2. The predicted electron energy spectrum, corresponding to \(\sin^2 \theta_w = 0.20\) and \(\sin^2 \theta_w = 0.57\) from F.N.A.L. wideband beam.

Figure 3. The scatter plot of electron energy \(E_e\) vs. scattering angle \(\theta_e\) for
the 20 observed single electrons.

Figure 4. The variable \(E_\theta^2\) for (a) single electrons (b) single positrons and
(c) isolated photons.

Figure 5. The observed electron energy spectrum. Overlaid on this plot are
the predicted spectra from Figure 2.

REFERENCES

   Salam, A., in 'Elementary Particle Theory' edited by N. Svartholm (Alm-
PROGRESS REPORT ON AN EXPERIMENT TO STUDY
WEAK NEUTRAL CURRENT ELASTIC SCATTERING OF NEUTRINOS

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A. Thorndike, P. Wanderer, H. White, H. Williams, T. York.
(Presented by R.E. Lanou)

In this paper we present progress to date in an experiment (E-734) to
measure neutral current phenomena at low neutrino energy (200 ≤ Eν ≤ 3GeV).
The principal goals center upon the elastic reactions:

1. (ν̄μ)p → (νμ)p
2. (ν̄μ)e → (νμ)e

In addition, for purposes of normalization and determination of background
we also measure the reactions:

3. νμ+n → νμ+p + e− + p
4. νμ+N → νμ+p + N' + π
5. νe+n → νe+p + e− + p

The kinematic regime and the dynamics of the reactions involved dictate
that the detector be an almost (85%) fully active, neutrino target with
fine segmentation. This permits good angular resolution, total energy measure-
ments of hadrons and showers as well as pion and proton identification.

The detector is constructed in a modular fashion. One module consists of
one plane (Y) of liquid scintillator calorimeter and two planes (X and Y) of
proportional drift tubes (PDT's). The details of one module are given in Table I.

The main detector is followed by a "gamma catcher" consisting of 10
calorimeter modules each separated by one radiation length of lead. This allows
energy determination of electron and photon events occurring in the down-stream
portion of the detector. Following the "gamma catcher" is a magnetic spectrometer which aids in measuring $\nu_\mu (\bar{\nu}_\mu)$ contamination by $\nu_e (\bar{\nu}_e)$. The entire detector is under microprocessor control (Figure 1).

An important feature in limiting certain types of background is the time structure utilized in data taking. The primary beam from the Alternating Gradient Synchrotron of the Brookhaven National Laboratory is extracted in twelve, radio-frequency "buckets" each separated by 220 nanoseconds. Target associated background with $\nu \neq e$ then arrives out-of-time between the buckets. Figure 2 shows a portion of this bucket structure for triggers recorded in the detector; the out-of-time background is negligible.

The accelerator operates with an approximately 1.4 second repetition rate with an intensity approaching $1 \times 10^{13}$ protons-on-target (POT) per pulse into a horn-focussed wide band beam.

To date approximately $1.5 \times 10^{19}$ POT have been accumulated for $\nu_\mu$ and $\bar{\nu}_\mu$, about $1 \times 10^{19}$ POT for $\nu_e$. In an attempt to verify the existence of the rare $\nu_\mu + e \rightarrow \nu_\mu + e$ signal and to check upon its predicted rate, we have performed a preliminary analysis on the first $0.9 \times 10^5$ machine pulses with a $\nu_\mu$ beam. These data are taken from the first half of the completed detector only; the last portion not yet having been brought into operation. In this preliminary analysis we have used very simple algorithms and further development of them is underway; however, as can be seen from what follows they adequately serve the present purpose.

As a guide to the magnitude of the quantities entering into the extraction of the $\nu_\mu e \rightarrow \nu_\mu e$ signal we quote the relevant, relative fluxes ($\phi$) and cross sections ($\sigma$):

$$\phi(\nu_\mu) : \phi(\nu_e) : \phi(\bar{\nu}_\mu) : \phi(\bar{\nu}_e) = 1 : 5 \times 10^{-3} : 1 \times 10^{-3} : 2 \times 10^{-4}$$

$$\sigma(\nu_\mu n \rightarrow \mu^- p) : \sigma(\nu_\mu e + \nu_\mu e) : \sigma(\nu_\mu n + \nu n n^0) : \sigma(\nu_\mu n + e^- p)$$

$$= 1 : 2 \times 10^{-4} : 0.1 : 1$$

The principal background to the $\nu_\mu e \rightarrow \nu_\mu e$ signal comes from $\nu_\mu n + e^- p$ where the proton missed detection and from $\nu_\mu n \rightarrow \nu_\mu n n^0$ where the neutron and one of the photons from the $n^0$ were missed. Other reactions involving charged currents and/or charged hadrons are easily suppressed via energy deposition in the calorimeters. (See Figure 3).
We have used a two step technique for background suppression in the present analysis. The first step is via an "anti-hadron and muon filter" algorithm based primarily on calorimeter information -- this removes most of the charged current and charged hadron background while passing (according to Monte Carlo calculation) 96% of the electron signal. In the data sample under consideration here this filter passes 290 events with an energy ≥ 200 MeV and in an angular interval with respect to the mean beam direction of approximately ±15°.

This sample of 290 events should then consist primarily of signal and electron and photon fragments of the reactions $\nu_e n \to e^- p$ and $\nu_\mu n \to \nu_\mu n^0$ mentioned above. Thus the second step in our preliminary analysis is to try to suppress these fragments by passing them through a second algorithm which separates singly ionizing (favors $\nu_\mu e \to \nu_\mu e$) from doubly ionizing particles emerging from the vertex. This selection is guided by Monte Carlo studies (75% of single electrons but only 5-10% of photons should pass) and measurements with singly ionizing cosmic rays passing through the detector. The resulting algorithm is based upon use of the average energy deposited in the first two calorimeters after the vertex being less than 15 MeV and a similar cut using the PDT's. The PDT cut is made by selecting from the first six PDT's (X + Y) the average of the lowest two $\frac{dE}{dx}$ measurements (to minimize Landau fluctuations). A value of < 9 keV is used as is illustrated in Figure 4. A distinct separation can be seen between singly and doubly ionizing particles. We are thus confident that a low background contamination can be achieved via this separation.

Evidence for the signal can be seen by selecting those events which pass the above cut (80 events) and plotting them so as to take advantage of the $\nu_\mu e \to \nu_\mu e$ kinematics. A scatter plot of $E_e$ versus $\theta^2$ (since $E_e \theta^2 \leq 2m_e$) would be most appropriate, however, until we have established our angular resolution and energy calibration in a tagged electron beam (this run is currently in progress at the A.G.S.) it is not useful to make such a plot. A more appropriate variable is an $E_e^2 \theta^2$ histogram and this is shown in Figure 5a. Also shown is the histogram of the same variable for those (210 events) which fail the cut. As can be seen from the two plots, there is a clean signal on a low background at small $E_e^2 \theta^2$ and that the background at least as represented by Figure 5b has a very different shape.
Until we have completed our electron beam calibrations and extracted from the neutrino data samples of the background reactions, we are not in a position to make a reliable background subtraction. This work, as well as refinement of our algorithms, is already underway. If, however, we provisionally take the subtractions as normalized, then from this analysis we have a rate of $\nu_\mu \rightarrow \nu_e$ into the fiducial volume of the full detector of $2.5^{+1}_{-1}$ event per day in agreement with our design expectations.

Using this number we would then expect to find in our presently accumulated data $\sim 65 \nu_\mu \rightarrow \nu_e$ and $\sim 24 \bar{\nu}_e \rightarrow \bar{\nu}_e$ events. Our future program includes the extraction and analysis of these events, additional approved running in 1983, identification and extraction of the $\nu_\mu p \rightarrow \nu_p$ signals several thousand of these should be in our present data), followed by a program in neutrino oscillation studies (these experiments are discussed in this conference in the talk of C. Baltay).
### TABLE I
#### PROPERTIES OF A SINGLE MODULE

**Calorimeter (liquid scintillator):**
- **Active area**: 4.2 x 4.1 (meter)
- **Thickness per module**: 7.9 cm
- **No. of cells per module**: 16 (vertical segment)
- **Weight (liquid plus acrylic)**: 1.35 metric tons
- **Phototubes**: two, Amperex 2212A/cell
- **1 pulse height per phototube**
- **2 timing hits per tube**

**Proportional Drift Tubes:**
- **Active area**: 4.1 x 4.1 (meter)
- **Thickness per module**: 7.9 cm
- **No. of cells per module**: 54(X) and 54 (Y)
- **Cell size**: 4.1m x 7.7 cm x 3.8 cm
- **1 pulse height per cell**
- **2 timing hits per cell**

**Total Assembly:**
1. 118 modules (172 tons)
2. Gamma catcher (30 tons)
3. Magnetic spectrometer
4. Phototubes (total of 4096)
5. PDT (total of 13,824 cells)
6. Volume (4 meters x 4 meters x 24 meters)
7. Control (Logic in four parts under microprocessor (LSI-11/03) and PDP-11/34 control).
List of Figures

Fig. 1  Logical and physical organization of the F-734 detector

Fig. 2  A portion of the time distribution of events seen in the detector. The beam is extracted from the A.G.S. with 220 nsec separation between buckets.

Fig. 3  The energy deposited per cell \(\frac{dE}{dx}\) for some of the particles in an inelastic event \(\nu \mu + p - \pi^0\). The upper trace clearly shows the low energy proton plus muon in the first two cells while the minimum ionizing muon continues on into the remaining cells. The lower trace shows the drastically different shower development of one of the photons.

Fig. 4  a) Raw \(\frac{dE}{dx}\) in first PDT after vertex.
        b) Variable used for cut in PDT's. (solid = data; dashed = Monte Carlo; dotted = cosmic rays).

Fig. 5  a) Distribution of those events passing the single-double ionizing cut
        b) Distribution for those failing the cut (normalized beyond bin 4). (Note that these events are likely to be dominated by \(\pi^0\) fragments).
E-734 DATA COLLECTION

Fig. 1
ENERGY DEPOSIT IN CALORIMETERS

Fig. 3
Fig. 4
Fig. 5

NU-MU BEAM

DATA AFTER SINGLE MINIMUM ION. CUT

PASS CUT

FAIL CUT (norm)

\(e^2 \text{ (mev-rad)} \times 10^3\)
MEASUREMENT OF THE RATIO $\sigma(\nu_\mu e + \nu_\mu e)/\sigma(\bar{\nu}_\mu e + \bar{\nu}_\mu e)$

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(Presented by C. Santoni)

ABSTRACT

Results of the measurement of the ratio of muon neutrino-electron to
antineutrino-electron cross-sections are presented. The measured ratio,
based on a sample of $46 \pm 12$ neutrino events and $77 \pm 19$ antineutrino events,
is $1.37 \pm 0.44$. It corresponds to a value of $\sin^2 \theta_W = 0.215 \pm 0.040$. The
systematic error in $\sin^2 \theta_W$ is estimated to be 7%.

* * *

The main goal of pursuing the study of muon neutrino and antineutrino
scattering on electrons is to determine the coupling constants of the
leptonic weak neutral current and to compare them with the predictions of
the gauge models, avoiding the uncertainties inherent in the use of hadronic
targets.

The neutrino and antineutrino electron cross-sections were measured
with the same detector. The ratio

$$ R = \frac{\sigma(\nu_\mu e)}{\sigma(\bar{\nu}_\mu e)} $$

allows a determination of the coupling constants that is less affected by
systematic uncertainties than that from a single cross-section.

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Within the framework of the $SU(2)_L \times U(1)$ theory the two cross-sections can be expressed in terms of the electroweak mixing angle ($\sin^2 \theta_W$) and a multiplying factor ($\rho^2$) equal to the ratio of the overall strengths of neutral-current (NC) and charged-current (CC) couplings; $\rho^2$ can be related to the isospin of the Higgs bosons\(^1\). It follows that the cross-section ratio $K$ provides the most direct determination of the parameter $\sin^2 \theta_W$ without any hypothesis on the value of $\rho^2$. Moreover, the value of $\rho$ (expected to be one in the standard model) can be derived from the measured values of the two cross-sections, once $\sin^2 \theta_W$ is known from the ratio.

The relation between $R$ and $\sin^2 \theta_W$ is given by

$$R = \frac{\sigma(\nu_\mu e)}{\sigma(\bar{\nu}_e \mu)} = 3 \frac{1 - 4 \sin^2 \theta_W + (16/3) \sin^6 \theta_W}{1 - 4 \sin^2 \theta_W + 16 \sin^6 \theta_W}.$$  

$R$ varies rapidly for values of $\sin^2 \theta_W$ in the range 0.1-0.3. In particular, $\Delta \sin^2 \theta_W = \frac{1}{6}(\Delta R/R)$ for $\sin^2 \theta_W \approx 0.25$. This fact allows an accurate measurement of $\sin^2 \theta_W$ in purely leptonic processes, even for modest precision on $\Delta R/R$.

The main features of the muon neutrino-electron scattering processes are: i) small cross-section $\sigma(\nu_\mu e) = 10^{-3} \sigma(\nu_\mu N)$; ii) appearance of a single electron in the final state; iii) very small angle of the recoil electron $[\theta < \sqrt{(2m_eE)/E}] = 7 \text{ mrad}$.

The CHARM detector\(^2\) is a fine-grain calorimeter followed by a muon spectrometer. The target calorimeter consists of 78 subunits. A subunit comprises a marble plate of $3 \times 3 \text{ m}^2$ surface area and 8 cm thickness followed by two planes of sensitive elements: i) 128 proportional drift tubes, each tube having the dimensions $3 \times 3 \times 400 \text{ cm}^3$; ii) 20 plastic scintillators, of the dimensions $15 \times 3 \times 300 \text{ cm}^3$, oriented at $90^\circ$ with respect to the tubes. The fiducial mass of the detector is 80 t. The separation between electromagnetic and hadronic events is based on the different width of the transverse profile of electromagnetic and hadronic showers as measured by the scintillators and the proportional tubes\(^3\), the electron-induced showers being narrower. A further distinction between electron- and pion-induced showers is based on the difference in the development of the showers close to the vertex. The shower angle, measured by the proportional tubes, is determined in each projection by the line
joining the shower vertex to the shower centre). The energy of the showers is measured by ionization in the scintillators.

The experiment was performed in the horn-focused wide-band neutrino and antineutrino beams of the CERN 400 GeV SPS. In two exposures of $1.4 \times 10^{18}$ and $5.7 \times 10^{18}$ protons on target, respectively $1.3 \times 10^{6}$ neutrino interactions and $1.4 \times 10^{6}$ antineutrino interactions were observed in the fiducial mass of the detector.

The analysis has been carried out using the same selection criteria for the neutrino and antineutrino data. This implies that the systematic error in the efficiency of detecting electron-induced showers cancels out in the ratio of the two cross-sections. The criteria are those developed previously for the measurement of the muon antineutrino-electron cross-section.

The candidate events for neutrino and antineutrino scattering on electrons are searched for among those events which: i) are muonless; ii) contain electromagnetic showers; iii) have a shower angle $\theta$ with respect to the neutrino beam axis which is smaller than 100 mrad; iv) have an energy $E$ deposited in the calorimeter between 7.5 and 30 GeV. The $E^2\theta^2$ distributions for events with $E^2\theta^2 < 0.54$ GeV are shown in Figs. 1a and b. We chose the variable $E^2\theta^2$ to emphasize the difference of the signal and the background. The measured energy and angular resolutions imply that 90% of the $\nu_e$ events have $E^2\theta^2$ less than 0.12 GeV, corresponding to the first two bins in Figs. 1a and b.

The number of genuine $\nu_e$ events in the region $E^2\theta^2 < 0.12$ GeV (forward region) was obtained by extrapolating the background from the region $0.12 < E^2\theta^2 < 0.54$ GeV (reference region). We assumed that the background is due to two sources:

a) Elastic and quasi-elastic CC events induced by the $\nu_e$ and $\bar{\nu}_e$ contamination of the beams.

b) Neutral-current events with $\gamma$ and/or $\pi^0$ in the final state produced by coherent scattering of muon neutrinos on nuclei.

The normalization of background (a) and (b) was obtained, as in the published analysis, by a study of the energy deposition $E_p$ in the first scintillator plane following the shower vertex. As shown in Fig. 2, electromagnetic showers initiated by one or more photons tend to deposit in this
Fig. 1 Distributions of the selected events versus the variable $E^2 \theta^2$. (a) and (b) show the neutrino and antineutrino events satisfying the selection criteria discussed in the text; (c) and (d) show neutrino and antineutrino events satisfying the additional criterion $E_F < 8$ MeV. The background subtractions are discussed in the text.

Fig. 2 Measured distributions of the energy deposition in the first scintillator plane following the shower vertex: a) electron-induced showers in a 15 GeV test beam traversing on an average a marble plate of 4 cm thickness; b) photon-induced showers produced by neutrino and antineutrino beams in an energy-angle range where coherent processes dominate. ($7.5 < E < 17.5$ GeV, $E^2 \theta^2 > 0.56$ GeV$^2$). The contamination due to electron-induced showers is estimated to be 15%.
scintillator plane an energy larger than one minimum ionizing particle (6 MeV), whilst a large fraction of the showers due to single electrons give an energy deposition corresponding to one minimum ionizing particle. For electron-induced showers the efficiency for $E_\gamma < 8$ MeV is $(0.32 \pm 0.05)^5$.

The number of events attributed to background (a) is obtained from the events with $E_\gamma < 8$ MeV in the reference region, and from the efficiency of this cut for elastic and quasi-elastic $^{\nu_e}$-induced events. The remainder is attributed to background (b). The efficiency of the cut $E_\gamma < 8$ MeV for showers initiated by background (a) was obtained using the events with visible energy between 30 and 50 GeV and $0.12 < E_\gamma^2 < 0.54$ GeV$^2$. We found it to be $(0.26 \pm 0.06)$, equal within the errors, for neutrino- and antineutrino-induced events. Since in a fraction of the quasi-elastic $^{\nu_e}_-$-induced events the electron is expected to be accompanied by other charged particles, we used this number, which is compatible with the efficiency for single electrons $(0.32 \pm 0.05)$, in the analysis.

The $E_\gamma^2$ distribution of background (a), known to be energy independent, has been determined by folding the measured $E_\gamma^2$ distributions of elastic and quasi-elastic CC reactions induced by muon neutrinos and antineutrinos$^6$) with the measured electron energy and angular resolutions. The $E_\gamma^2$ distribution of background (b) was calculated following Lackner's model$^7$. Since the ratio (forward rate)/(reference rate) is not very different for the two backgrounds, 0.49 for processes (a) and 0.39 for processes (b), a possible error in the composition of the total background has little effect on the final result.

The results of this analysis are summarized in Table 1 and the shapes of the two backgrounds are shown in Figs. 1a and b.

The amount of background (a) found in the $\nu$ and $\bar{\nu}$ beam exposures agrees with that expected from the computed $v_e$ and $\bar{v}_e$ contamination of the two beams$^8$). The number of neutrino and antineutrino events attributed to background (b) corresponds to a cross-section ratio compatible with one. This supports the hypothesis that these events are due to coherent scattering of muon neutrinos on nuclei.
The variable $E_f$ allows the selection of a clear "electron" sample through the requirement $E_f < 8$ MeV. The $E^{2\theta^2}$ distributions for the selected 32 neutrino and 123 antineutrino events with $E^{2\theta^2} < 1.08$ GeV$^2$ are shown in Figs. 1c and d. By fitting the shape of background (a) to the events having $E^{2\theta^2} > 0.12$ GeV$^2$, $(10 \pm 4)$ events are attributed to the neutrino electron scattering in the $\nu$ beam and $(25 \pm 8)$ events to the antineutrino electron scattering in the $\bar{\nu}$ beam, in good agreement with the two signals derived from the full samples of events and the efficiency for detecting electrons: $(0.32 \pm 0.05)^5$. This agreement confirms that the signal is in both cases due to events with a single electron in the final state.

The background analysis was repeated for different energy windows and gave the energy distributions for the signals and for the two backgrounds which are shown in Fig. 3 together with their expected behaviour, based on a simulation of the beams and the energy dependence of the reactions. The energy distribution of backgrounds (a) and (b) is in agreement, within the large errors, with what is expected for CC $(\bar{\nu}_{\mu})$- and NC $(\nu_{\mu})$-induced events, confirming once more the validity of the assumptions made in the procedure for subtracting the backgrounds.

Owing to the experimental requirement imposed on the recoil electron energy, $7.5 < E < 30$ GeV in the analysis, the observed events correspond to a fraction of the total cross-section $(\sigma^{\text{vis}})$. In the framework of the standard model the inelasticity distribution is a function of $\sin^2 \theta_W$, therefore the relation between $\sigma^{\text{vis}}$ and the total cross-section depends on $\sin^2 \theta_W$. 

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### Table 1

Summary of selected events

<table>
<thead>
<tr>
<th>Beam</th>
<th>Forward region</th>
<th>Reference region</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Signal</td>
<td>Background (a)</td>
</tr>
<tr>
<td>$\nu$</td>
<td>$46 \pm 12$</td>
<td>$20 \pm 7$</td>
</tr>
<tr>
<td>$\bar{\nu}$</td>
<td>$77 \pm 19$</td>
<td>$95 \pm 14$</td>
</tr>
</tbody>
</table>
Fig. 3 Distribution of the shower energy $E$ deposited in the calorimeter for the events attributed to the signal and to background (a) [CC] and to background (b) [NC]. The curves show the expected distributions.

Fig. 4 Ratio of muon neutrino-electron to antineutrino-electron cross-sections versus $\sin^2 \theta_W$. The full curve represents the expectation for the energy range 7.5 to 30 GeV. The dashed curve represents the expectation in the case of full energy acceptance. The measured value of $R$ and its statistical error is shown together with the corresponding values for $\sin^2 \theta_W$. 

$$R = \frac{\sigma (\nu_e \mu)}{\sigma (\bar{\nu}_e \mu)}$$
In Fig. 4 the full line represents the expected behaviour of the quantity

$$R_{\text{vis}}(\sin^2 \theta_W) = \frac{\sigma_{\text{vis}}(\nu_e)}{\sigma_{\text{vis}}(\overline{\nu}_e)}$$

as a function of $\sin^2 \theta_W$. The integration of $\sigma_{\text{vis}}$ over the energy spectra of the beams takes into account the folding of the electron-energy cuts by the energy resolution of the calorimeter. The dashed curve represents the expectation in the case of full energy acceptance. Here again one can appreciate the advantage of the ratio method: the difference between the two curves is very small around $\sin^2 \theta_W = 0.25$, implying that uncertainties of the spectra and of the energy cuts have little influence on the final result.

The ratio of the normalized number of $\nu_e$ and $\overline{\nu}_e$ events is

$$R_{\text{exp}} = \frac{N(\nu_e)}{N(\overline{\nu}_e)}$$

where $N(\nu_e)$ and $N(\overline{\nu}_e)$ are the number of events induced by muon neutrino- and antineutrino-electron scattering, and $F$ is the ratio of $\overline{\nu}_\mu$ and $\nu_\mu$ energy-weighted fluxes. The flux of the various types of neutrinos in the two beams has to be known. The ratios $\overline{\nu}_\mu/\nu_\mu$ in the neutrino beam and $\nu_\mu/\overline{\nu}_\mu$ in the antineutrino beam were experimentally determined from the observed $\mu^+/\mu^-$ ($\mu^-/\mu^+$) ratios in elastic and quasi-elastic reactions$^6$, while the $\nu_e$($\overline{\nu}_e$) contaminations were computed using the wide-band beam simulation program$^8$.

We attribute $(42 \pm 11)$ events of the total $(46 \pm 12)$ to muon neutrino-electron scattering and $(64 \pm 16)$ of the total $(77 \pm 19)$ to muon antineutrino-electron scattering.

The neutrino fluxes were monitored in two ways:

i) by measuring the ratio of the neutrino and antineutrino interactions on nucleons induced by each beam in the same fiducial volume of the calorimeter, making use of the known neutrino-nucleon and antineutrino-nucleon total cross-sections$^9$;
ii) by measuring the number of single $\mu^-$ ($\mu^+$) events induced by quasi-elastic $\nu_\mu$ ($\bar{\nu}_\mu$)-nucleon interactions in the fiducial volume of the calorimeter, making use of the equality of the cross-sections for exclusive neutrino- and antineutrino-nucleon interactions on an isoscalar target.

The average of the results of the two methods gives a value of $F = 2.09 \pm 0.15$ (syst.).

The experimental result is

$$R^{\text{exp}} = 1.37^{+0.65}_{-0.44} \text{ (stat.)} .$$

The measured quantity $R^{\text{exp}}$ agrees with the predicted $R^{\text{vis}}(\sin^2 \theta_W)$ for

$$\sin^2 \theta_W = 0.215 \pm 0.040 \text{ (stat.)} ,$$

as is shown in Fig. 4.

The main sources of systematic uncertainty on $R$ are due to the background subtraction ($\pm 10\%$) and to the normalization ($\pm 7\%$).

The error in the background subtraction has been evaluated by varying the shapes and the amounts of backgrounds (a) and (b) in a correlated way for the neutrino and antineutrino cases. The error in the normalization factor was estimated from the difference of the results of the two methods.

The systematic error on $R$, obtained by adding these two components quadratically, leads to the final result:

$$\sin^2 \theta_W = 0.215 \pm 0.040 \text{ (stat.)} \pm 0.015 \text{ (syst.)} .$$

By using the procedure outlined in Ref. 4, we obtain the cross-sections:

$$\frac{\sigma(\nu_\mu)}{E_\nu} = [2.1 \pm 0.55 \text{ (stat.)} \pm 0.49 \text{ (syst.)}] \times 10^{-42} \text{ cm}^2/\text{GeV} ,$$

$$\frac{\sigma(\bar{\nu}_\mu)}{E_{\bar{\nu}}} = [1.6 \pm 0.35 \text{ (stat.)} \pm 0.36 \text{ (syst.)}] \times 10^{-42} \text{ cm}^2/\text{GeV} .$$

The second value agrees with that obtained by analysing 80% of the total statistics. 4)
The simultaneous measurements of $R$ and $\sigma(e^+e^-)$ allow a determination of $\rho$. The experimental result is

$$\rho = 1.12 \pm 0.12 \text{ (stat.)} \pm 0.11 \text{ (syst.)},$$

in good agreement with the expectations of the standard model.

The new determination of the value of the weak mixing angle, derived from the ratio of the measured cross-sections of two purely leptonic NC processes, is less affected by systematic errors than the one obtained from the value of a single leptonic cross-section alone and is not subject to the theoretical uncertainty due to the value of $\rho^2$. It agrees within statistical errors with the values previously found in leptonic$^4$ and semi-leptonic$^5,^6$ reactions, thus favouring a universal coupling of leptons and quarks to the weak neutral current.

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ELECTRON NEUTRINO-ELECTRON ELASTIC SCATTERING AT LAMPF

(Univ. of California at Irvine)

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Presented by T. J. Bowles

ABSTRACT

An experiment (LAMPF No. 225) to measure electron neutrino-electron elastic scattering will begin data acquisition shortly. This experiment will also provide information on $\bar{\nu}_e \rightarrow \bar{\nu}_e$ oscillations, $\mu^+ \rightarrow e^+ \bar{\nu}_e \nu_\mu$ as a test of the multiplicative law, $\nu_e 12C \rightarrow e^- 12N$, and lifetimes of $\nu_\mu$ and $\bar{\nu}_\mu$.

Electron neutrino-electron elastic scattering is a process of fundamental interest and is the primary physics being investigated by a UCI/LANL collaboration at LAMPF (Experiment 225). This scattering process involves both the neutral and charged currents as shown in figure 1.

![Feynman diagrams for neutral and charged current contributions to $\nu_e - e$ elastic scattering.](image)

Figure 1. Feynman diagrams for neutral and charged current contributions to $\nu_e - e$ elastic scattering.

The neutral and charged currents can interfere with each other and various models make specific predictions for the sign and amplitude of the interference. Figure 2 shows the predictions of the Weinberg-Salam model for $\nu_e - e$ scattering cross sections. For $\sin^2 \theta_W = .23$, one expects a destructive interference of about 25%. The goal of E225 is to measure $\nu_e - e$ scattering to sufficient accuracy to determine the sign of this interference.

Several other processes can be studied simultaneously with the E225 detector. Oscillations of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ can be searched for at LAMPF.
by the reaction $\bar{v}_e p \rightarrow e^+ n$ using the hydrogen in the scintillators of the detector. Since $\bar{v}_e$ can normally be produced by $\pi^- \rightarrow \mu^- \bar{\nu}_\mu$ followed by $\mu^- + e^- \rightarrow \nu_e$ and since only $10^{-4}$ to $10^{-3}$ of the $\pi^-$ produced at the beam stop decay before they are absorbed, there is only a small contamination of $\nu_e$ in the beam. The presence of a rate appreciably in excess of that expected would indicate neutrino oscillations. (Neutrino oscillations could also affect the results of $\nu_e - e$ scattering, but current limits on oscillations set a limit on such an effect well below our accuracy in measuring $\nu_e - e$ scattering. ) Alternately, such an excess rate could also be attributed to the decay of $\mu^- + e^- \nu_e \bar{\nu}_e$ which is allowed by the multiplicative law of lepton number conservation but is forbidden by the additive law of lepton number conservation.

The reaction $\nu_e \rightarrow^{12} C + e^- \rightarrow^{12} N$ can be observed using the $^{12} C$ present in the detector scintillators. We will measure the rate of this reaction to bound levels of $^{12} C$ by looking for a delayed coincidence with the $e^-$ emitted from the beta decay of $^{12} N$. Finally, we will also be able to substantially improve the limits on the lifetime of $\nu_\mu$ and $\bar{\nu}_\mu$ for any decay mode of the neutrinos in which a photon is emitted. A positive result would imply that the neutrino has a nonzero rest mass, that lepton number conservation is violated, and that there is an odd half-integer spin particle with a mass less than that of the neutrino.

The neutrino facility at LAMPF is shown in figure 3. 800 MeV protons from the LAMPF linac impinge on several production targets after which the beam is stopped in a 20 cm thick water degrader and a water cooled copper beam dump. Typically the beam striking the degrader and beam stop is 550 $\mu$A of 730 MeV protons with pulses 600 $\mu$sec long at a repetition rate of 120 Hz. The water degrader is immediately in front of the copper beam stop and increases the neutrino flux by about 40% over that of the copper beam stop alone due to the increased cross section section of pion production off oxygen.

The neutrino spectrum at the LAMPF beam stop is shown in figure 4. It consists of equal numbers of $\nu_\mu$, $\bar{\nu}_\mu$, and $\nu_e$ originating from the decay of $\pi^+ \rightarrow \mu^+ \bar{\nu}_\mu$ followed by $\mu^- + e^- \rightarrow \nu_e \bar{\nu}_e$. The neutrino flux was originally determined in an experiment which measured the muon flux from a mockup beam stop at Berkeley (1). The flux uncertainty from that measurement was about 7%. However, due to modifications of the LAMPF beam stop (primarily the addition
of the water degrader), the present uncertainty in the flux is about 15%. We plan to remeasure muon fluxes from a mockup degrader and beam stop to reduce the neutrino flux uncertainty to about 7%. The neutrino flux and estimated event rates are given on Table 1.

The neutrino cave is located at $90^\circ$ from the beam stop (as shown in Figure 3) in order to minimize the thickness of shielding required to attenuate high energy neutrons which are peaked in the forward direction. A prototype study at LAMPF (Experiment 148) showed that 6.3m of iron shielding is sufficient to attenuate beam associated charged particle, gamma, and neutron backgrounds to less than 10% of the expected $\nu_e$ scattering rate. The cave is enclosed by the equivalent of 1.2m of iron on the sides and top which serves to eliminate most of the hadronic component of cosmic rays.

The detector is shown in Fig. 5. It consists of alternate layers of 1" thick plastic scintillator and layers of flash chambers to provide tracking information of the electrons. Each layer of flash chamber consists of 5x and 5y layers with tubes 5.8mm wide and 5.1mm high. The entire detector consists of 40 layers of scintillator and flash chambers and measures 3m x 3m x 3.7m deep and has a mass of about 14 tons. Each 3m x 3m x 2.5cm scintillator plane consists of 4 3m x .75m x 2.5cm scintillator slab each of which is viewed by a 5" photomultiplier. The flash chambers are constructed of extruded polypropylene sheets and use 90% Ne - 10% He gas. The flash chambers are read out by a very compact capacitive pickup system which was specifically designed to fit in the severely limited space available in the neutrino cave.

The detector is surrounded by an active anticoincidence shield to provide suppression of cosmic ray backgrounds. This shield consists of 600 counters in 4 layers of drift tubes on the sides and over the detector and a single layer under the detector. Each drift tube is constructed of extruded aluminum with 8 triangular shaped tubes which provide very high geometric coverage. Inside the layers of drift tubes is a layer of iron 13cm thick with an additional 2.5cm thick layer of lead on the front and back walls and on the roof. This additional shielding acts to reduce neutral backgrounds (eg. muon bremsstrahlung) in which the associated charged particle does not pass through the anticoincidence shield.
The electronics of the detector and anticoincidence system is designed to provide very high on-line rejection of cosmic ray background. A strong constraint on the electronics design is to keep the pulse rate of the thyratrons which pulse the flash chambers to less than 1 trigger/sec which is the maximum recharge rate of the capacitor banks of the thyratron circuits. This requires a sophisticated recognition system since cosmic muon rates are \( \lesssim 100 \text{ Hz} \) in the detector. To achieve this, a fast signal from the anticoincidence counters and a check of floor and roof counters to identify through muons is used to prevent the flash chambers from being pulsed on background events and to reduce the dead-time of the detector. In order to identify backgrounds due to delayed betas from muons which have stopped in the detector, the output from the scintillators and anticoincidence counters is put into an 80 bit FIFO registers which stores a 32 usec history. Thus, when a valid scintillator trigger from the central detector occurs, the history of the antis and scintillators can be examined off-line to check for a muon which passed through the antis and stopped in the central detector without triggering the central detector. The 32 usec period (about 15 muon half-lives) provides for detection of all but about \( 10^{-6} \) of muons which decay.

The electronics is also designed to store the output from the scintillators for 80msec following valid trigger. This allows recognition of the beam associated background \( ^{12}\text{C} \to ^{12}\text{N} \) followed by the beta decay of \( ^{12}\text{N} \) which has a 11.0msec half-life with a 16.3 MeV endpoint energy.

A typical background event for a muon stopping in the detector is shown in Fig. 6. In this event, the muon was detected by the anticoincidence counters and the detector was triggered by the beta from the subsequent muon decay. The memory time of the flash chambers is several microseconds, so one sees the muon track entering the detector as well as the track from the subsequent beta decay.

The expected electron scattering event rate and expected background rates are given on Table I. These rates are based on extrapolations from a prototype detector used in the LAMPF Experiment 148. During the LAMPF running cycle in November of 1981, we took preliminary data with part of the central detector and most of the anticoincidence counters in operation to measure beam associated backgrounds. During that run, because the rejection of cosmic ray backgrounds by the anticoincidence system was only about \( 10^3 \)
we were not able to look directly at electron backgrounds. Instead, we searched for proton triggers in the counter which occur due to the scattering of high energy neutrons from the beam stop off protons in the scintillator of the detector. We then used the measured ratio from Experiment 148 of electron background from high energy neutrons to proton triggers from high energy neutrons in order to determine the rate of beam associated electron backgrounds. That data confirmed the extrapolations of Experiment 148 and set a limit on beam associated electron backgrounds at less than that of the expected V-A rate on Table I. With the anticoincidence counters fully operational, the expected signal to background rate should ultimately be 10 to 1.

The current status of this experiment is that 60% of the central detector is fully operational with the remaining 40% expected to be fully operational about the beginning of August, 1982. More than 95% of the anticoincidence counters are fully operational. The computer readin system for the anticoincidence counters is also undergoing final debugging and checkout. Thus, we anticipate that the entire detector and anticoincidence systems will be fully operational this summer. Complete checkout of detector performance should be finished by the end of the summer at which point final data acquisition will begin. We plan to run for one to two calendar years (150-200 days of beam time) in order to measure approximately 300 electron scattering events.

The primary physics goal of the experiment is to measure 300 electron scattering events with a signal to background of 10 to 1. Coupled with a flux uncertainty of 7%, this will provide a 10% measurement of the total neutrino-electron scattering rate. This will be sufficient to determine the sign of the interference between the charged and neutral currents as well as to provide a crude measurement of the amplitude of the interference.

As secondary physics goals, we expect to

1. set limits on the oscillation $\nu_{\mu} \rightarrow \nu_e$ of $\Delta m^2 = 0.35 \text{ eV}^2$ (90\% C.L.) at maximal mixing and of $\sin^2 2\theta = 9 \times 10^{-3}$ (90\% C.L.) at large $\Delta m^2$. These results should be achieved within the first 2-3 months of running at which point our sensitivity will be limited by beam associated backgrounds.
(2) set a limit of about 2% (90% C.L.) on the possible existence of a multiplicative law of lepton number conservation.

(3) measure a rate for $\nu_{e}^{12} + e^{-12} \rightarrow N$ to bound levels of $^{12}N$

(4) to improve the limit on the lifetime of $\nu_{\mu}$ or $\bar{\nu}_{\mu}$ by two orders of magnitude above the current limit of $1.1 \times 10^{5}$ $\nu_{\nu}$ (s/MeV)\(^{(5)}\).

References


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7) H. H. Chen et al., Proceedings of Neutrinos 81 Conference, p. 182
Table 1
LAMPF Neutrino Fluxes and 7-3 Reaction Event Rates (per day)

<table>
<thead>
<tr>
<th>Full Beam</th>
<th>1σ</th>
<th>2σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Problem</td>
<td>1000</td>
<td>770</td>
</tr>
<tr>
<td>proton energy (MeV)</td>
<td>600</td>
<td>770</td>
</tr>
<tr>
<td>proton intensity (10^8)</td>
<td>740</td>
<td>770</td>
</tr>
<tr>
<td>stopped e^- decay/proton</td>
<td>0.076</td>
<td>0.067</td>
</tr>
<tr>
<td>stopped e^- decay/sec</td>
<td>0.067</td>
<td>0.059</td>
</tr>
<tr>
<td>νe flux at 1σ (nm^-2 sec^-1 MeV^-1)</td>
<td>3.2 x 10^6</td>
<td>3.2 x 10^6</td>
</tr>
<tr>
<td>νe flux at 2σ (nm^-2 sec^-1 MeV^-1)</td>
<td>2.1 x 10^7</td>
<td>3.1 x 10^7</td>
</tr>
<tr>
<td>ρp (90°)</td>
<td>12.8</td>
<td>9.9</td>
</tr>
<tr>
<td>Ar-18 &amp; 20 MeV threshold</td>
<td>2.8</td>
<td>3.6</td>
</tr>
<tr>
<td>R10</td>
<td>0.8</td>
<td>0.9</td>
</tr>
<tr>
<td>R20</td>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>

Notes:
(a) Additive angular momentum conservation law is assumed.
(b) Absolute energy uncertainty is ±25%.
(c) The νe and νμ fluxes are equal to the νμ fluxes.
(d) 12.8 m long, 30 Kt plastic scintillator target/detector.
Figure 6. On-line readout of stopped muon event in detector (See text for description.)
ABSTRACT

The BCDMS Collaboration (CERN NA4 experiment) has taken data to measure the asymmetry in the deep inelastic scattering of $\mu^+$ and $\mu^-$ beams incident on a carbon target. This measurement can check the structure of the neutral weak current and set a limit on the weak isospin of the right-handed muon. The analysis of over 3 million events taken at 120 and 200 GeV is in progress. At the present level of understanding the data are in agreement with the standard WS-CDM model.
I. INTRODUCTION

The discovery of weak neutral currents in $\nu N$ interactions [1] in 1973 triggered both experimental and theoretical efforts to study their structure in detail. The experiments done since then on $\nu N$, $\nu e$, $eN$ scattering and $e^+e^-$ annihilation are in good agreement with the predictions of the standard WS-GIM model [2] of electroweak interactions. Still, it is considered important [3,4] to test the model in new kinematical regions and reaction channels.

In order to measure the effect of the $Z^*$ exchange interfering with the dominant one photon exchange and check the prediction of the WS-GIM model, the Bologna-CERN-Dubna-Munich-Saclay collaboration (CERN NA4 experiment) has measured the deep inelastic scattering of positive and negative muons on nucleons in an isoscalar carbon target

\[ \mu^+ N + \mu^- N \rightarrow \cdots \]

at two incident energies 120 GeV and 200 GeV. This experiment differs from the SLAC $e^- D$ experiment [5] in that both the helicity and the charge of the muon are simultaneously reversed (by reversing the polarities of all magnets in the experiment), i.e. we measure the asymmetry $B(u,v,\lambda)$ defined as

\[
B(u,v,\lambda) = \frac{\frac{d^2\sigma^+}{dudv}(-\lambda) - \frac{d^2\sigma^-}{dudv}(\lambda)}{\frac{d^2\sigma^+}{dudv}(-\lambda) + \frac{d^2\sigma^-}{dudv}(\lambda)}
\]

where $\frac{d^2\sigma^\pm}{dudv}$ are the doubly differential cross sections of positively and negatively charged muons with respect to any two convenient kinematical variables $u$ and $v$ characterising the scattered muon, while $\lambda$ is the average longitudinal polarization of the negative muon beam. In order to present data of limited statistics, it is convenient to integrate the doubly differential cross sections with respect to one or even both kinematical variables, thus arriving at the asymmetries $B(u,\lambda)$ and $B_{\text{tot}}(\lambda)$ defined in complete analogy to expression (1). The domain of integration is determined by the acceptance of the apparatus and the kinematical cuts applied to the data.
If one takes into account only the one photon and the one single $Z^*$ exchange graph, the asymmetry $B(u,v,\lambda)$ is equal to [6]

$$B(u,v,\lambda) = -K (\alpha - \lambda \nu) A_\mu w$$

(2)

The quantity $K = \frac{G}{\sqrt{2}} \frac{1}{2\pi a}$ (where $G$ = Fermi constant, $\alpha$ = fine structure constant) $= 1.80 \times 10^{-8}$ GeV$^{-2}$ characterizes the strength of the $\gamma Z^*$ interference. In principle, the asymmetry $B$ contains terms higher than linear in $K$ which have been neglected in expression (2). $A_\mu$ is defined as the ratio of structure functions $G_1$ and $F_2$, i.e.

$$A_\mu = \frac{xG_1(x,Q^2)}{F_2(x,Q^2)}$$

The definition of $G_1$ and $F_2$ is given in ref. 6. $Q^2$ is the four momentum transfer and $x$ is the Bjorken scaling variable

$$x = \frac{Q^2}{2M(E_\mu - p)}$$

where $E_\mu$ is the incident muon energy, $p$ is the scattered muon energy and $M$ is the proton mass. In the parton model, for an isoscalar target, $A_\mu$ reduces to a constant, namely

$$A_\mu = \frac{6}{5}(a_d - 2a_u),$$

the quantities $a_d$ and $a_u$ being the axial coupling constants of the $Z^*$ to the d and u quark, respectively. Similarly, $\alpha_{\mu}$ and $\nu_\mu$ in expression (2) are the axial and vector coupling constants of the $Z^*$ to the negative muon. Without restricting the muon to any specific weak isospin $I_s$, we can write

$$\alpha_{\mu} - \nu_\mu = \frac{1}{2}(1-\lambda) - \frac{1}{2}(1+\lambda) = 2\sin^2\theta_W$$

$L$ and $R$ labelling the left- and right-handed muon, respectively, and $\theta_W$ being the Weinberg angle. The asymmetry $B(u,v,\lambda)$ is thus proportional to a single kinematical variable $w$ defined as

$$w = g(y)Q^2 = \frac{1 - (1-y)^2}{1 + (1-y)^2} Q^2$$

where $1-y = p/E_\mu$. 
Notice that the asymmetry $B$ contains both a parity violating term $v^\mu A^\mu$, and a parity conserving term $a^\mu A^\mu$. In the standard model with $\sin^2 \theta_W = 0.23$, the vector coupling constant $v^\mu$ is small and the parity conserving term dominates. In this case, the asymmetry $B$ is negative for any value of $\lambda$.

It has been shown [7,8] that higher order electroweak terms ("radiative effects") make an important positive contribution to the asymmetry $B$ and thus tend to decrease it in absolute value (e.g. by $\sim 40\%$ at an incident energy of 200 GeV and by $\sim 80\%$ at 120 GeV.)

2. APPARATUS

The NA4 spectrometer is situated in the CERN SPS muon beam behind the apparatus of the European Muon Collaboration [9]. The muon beam is operated with the average muon energy 20 GeV lower than the average energy of the parent pions and kaons. At 200 GeV this yields maximum intensity and leads to a calculated [10] absolute value of average polarization $|\lambda| = 0.81 \pm 0.04$. The measured [11] polarization at 200 GeV agrees with the calculated value within experimental and computational errors. At 120 GeV the calculated average polarization is $|\lambda| = 0.66 \pm 0.05$.

![Fig. 1 - Schematic view of the NA4 spectrometer](image-url)
The general layout of the NA4 spectrometer is shown in fig. 1. It consists of a ca. 50 m long torus of iron magnetized to saturation (ca. 2 T) with targets located in the central bore. Muons of the same charge as the incident beam are focused by the magnetic field and perform periodical oscillations inside the iron with amplitudes proportional to $Q^2/Q^2_{\text{max}} = Q^2/(2HE_r)$. The spectrometer is subdivided into ten identical supermodules. Each supermodule consists of:

(a) a separate carbon target 5 m long and 12 cm in diameter (except in the last two supermodules);
(b) 32 iron disks (each 11 cm thick) magnetized by a common coil;
(c) two trigger counter planes, each consisting of seven concentric rings with constant radial width and separation which make $Q^2$-selective triggering possible;
(d) eight planes of multiwire proportional chambers (MWPC) to determine the muon trajectory. Alternating planes measure the x and y coordinates of the track with a channel width of 4 mm (the spectrometer axis is defined as the z-axis).

For the asymmetry measurement the spectrometer possesses the important advantages of high luminosity, large redundancy, and high degree of azimuthal symmetry.

About 130 m upstream of our apparatus and not shown in fig. 1, a beam momentum station (BMS) consisting of beam deflecting magnets and hodoscopes measures the energy of each incident muon with a resolution of 0.5%. Hits in the BMS hodoscopes can be correlated in time (to about 1 ns) with hits in the three beam hodoscopes (each consisting of 72 scintillators in five concentric rings) shown in fig. 1, as well as with the trigger counter planes (to about 10 ns). The first of the beam hodoscopes monitors the beam flux and is also used in the trigger logic. The apparatus is shielded against the beam halo muons by a veto system of scintillation counters. A detailed description of the spectrometer is being published elsewhere [12].
3. DATA TAKING, ANALYSIS, AND RESULTS WITH STATISTICAL ERRORS

Data for the B asymmetry were taken at two incident energies 200 GeV and 120 GeV at approximately constant beam intensity of $2 \times 10^7 \mu$/spill in eight periods of 12 days each. The polarities of all magnets were reversed typically twice during a period; substantially more frequent reversals were not feasible considering that each took several hours and necessitated a resharing of the SPS proton beam.

The standard trigger condition for data taking required the coincidence of four consecutive trigger planes (ca. 11 m long track) and the beam-halo signal. This trigger detects interactions wherever they occur along the effective target length of ca. 36 m. Part of the 120 GeV data (one period) were taken with full planes (rings 1-7) in the trigger, corresponding to $Q_1/Q_{\text{max}}^2 \approx 0.05$, while the remaining 120 GeV data (two periods) and all 200 GeV data (five periods) were taken with ring 1 excluded from the trigger. The latter condition reduces the triggering rate due to showers and leads to $Q_1/Q_{\text{max}}^2 \approx 0.1$.

The data were processed with a standard program [13] using automatic selection of deep inelastic events which represent typically 10% of all triggers. A few percent of dubious candidates for deep inelastic events were visually scanned and about half of these were rejected as being mainly halo feed-through muons. Crude stability checks were applied to consecutive samples of data containing several thousands deep inelastic events each. These checks concerned beam energy, detector efficiencies, number of events per incoming flux, average values of kinematical quantities such as scattered momentum and $Q^2$, etc. About 15% of the samples did not pass these checks. Finally, the following cuts were applied to the data in order to avoid regions of rapidly varying acceptance and poor resolution:

<table>
<thead>
<tr>
<th>$Q_1^2$</th>
<th>$Q_2^2$</th>
<th>$Q_{\text{max}}^2$</th>
<th>$x_{\text{min}}$</th>
<th>$x_{\text{max}}$</th>
<th>$y_{\text{min}}$</th>
<th>$y_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 GeV$^2$</td>
<td>180 GeV$^2$</td>
<td>120 GeV$^2$</td>
<td>25 GeV$^2$</td>
<td>120 GeV$^2$</td>
<td>120 GeV$^2$</td>
<td>120 GeV$^2$</td>
</tr>
<tr>
<td>12.5 GeV$^2$</td>
<td>.2</td>
<td>.8</td>
<td>.2</td>
<td>.9</td>
<td>.8</td>
<td>.8</td>
</tr>
</tbody>
</table>
These and similar cuts tried for test purposes do not change the resulting \( B \) by more than one standard deviation [14].

The remaining data contain the following number of deep inelastic events (in millions):

<table>
<thead>
<tr>
<th>200 GeV</th>
<th>120 GeV (rings 2-7)</th>
<th>120 GeV (rings 1-7)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu^+ )</td>
<td>0.67</td>
<td>0.31</td>
</tr>
<tr>
<td>( \mu^- )</td>
<td>0.88</td>
<td>0.30</td>
</tr>
</tbody>
</table>

We have investigated the dependence of \( B_{\text{tot}} \) on geometrical variables such as the vertex coordinate \( z \) and the azimuthal angle \( \phi \) of the scattered muon and found it constant within statistical errors. The distribution of events at 200 GeV as function of the variable \( w = g(y)Q^2 \) and the resulting asymmetry are presented in fig. 2. The asymmetries \( B \) are presented in fig. 3 as function of \( w \), the scattered muon energy \( p \), the Bjorken \( x \) and the momentum transfer \( Q^2 \), both for 200 GeV and 120 GeV (rings 2-7) data corrected for radiative effects. The solid lines in both figures are predictions of the standard model with \( \sin^2 \theta_W = 0.23 \) and, in the case of raw \( B \), with radiative corrections from ref. 7. The experimental acceptance and resolution have been taken into account in the calculations. The errors (vertical bars) in figs. 2 and 3 are only statistical.

The relative +/- normalization reflects itself best in the total asymmetry \( B_{\text{tot}} \). In all three cases (220 GeV, 120 GeV rings 2-7, and 120 GeV rings 1-7) the experimental \( B_{\text{tot}} \) agrees within the statistical error of about 0.1% with the theoretical \( B_{\text{tot}} \) as predicted by the standard model with \( \sin^2 \theta_W = 0.23 \) and radiative corrections.
Fig. 2 Distribution of $\mu^+\mu^-$ events (upper part) and the asymmetry (lower part) as a function of $w = g(y)Q^2$ at 200 GeV. The raw asymmetry data and data corrected for radiative effects are compared to corresponding predictions of the standard model (solid lines).
Fig. 3 The asymmetry $B$ as a function of $w = g(y)q^2$, $P$, $X$ and $Q^2$ at 200 GeV and 120 GeV (rings 2–7). Data have been corrected for radiative effects and are compared to predictions of the standard model with $\sin^2\theta_W = 0.23$ (solid lines).
4. SYSTEMATIC ERRORS

Systematic errors can arise because of imperfect time stability of the apparatus, imperfect polarity reversal of magnets, side effects of this reversal (e.g. change in beam phase space, change of detector efficiencies), and natural asymmetries other than $B$ (due to the fact that matter consists predominantly of electrons, $u$-quarks and $d$-quarks rather than their antiparticles). The study of systematic errors and the application of the corresponding corrections to raw data is in progress and only a brief preliminary discussion and estimates can be given here.

An objective way of determining the stochastic part of the systematic error is to repeatedly measure $B$ and calculate the $\chi^2$ of the results. Data as presented in fig. 3 were fitted with the two-parametric form $B(\omega, \lambda) = a(\lambda) + b(\lambda)\omega$. The slope parameter $b(0.81)$ was obtained separately for the five 200 GeV data taking periods. From the spread of results a total stochastic error was determined with the result:

$$b(0.81) = (-1.6 \pm 0.5) \cdot 10^{-6} \text{ GeV}^{-1}.$$  

The statistical error alone amounts to $\Delta b_{\text{stat}} = 0.3 \cdot 10^{-6} \text{ GeV}^{-1}$. The two 120 GeV (rings 2-7) periods yield values of $b(0.66)$ differing from each other only by a fraction of the statistical error with the result

$$b(0.66) = (-2.4 \pm 0.9) \cdot 10^{-6} \text{ GeV}^{-1}.$$  

Finally, the single 120 GeV (rings 1-7) period yields

$$b(0.66) = (-1.7 \pm 1.1) \cdot 10^{-6} \text{ GeV}^{-1}.$$  

These three $b$-values are clearly all mutually compatible and also compatible with the standard model prediction for $\sin^2 \theta_W = 0.23$

$$b(\lambda) = (-1.61 + 0.13 \lambda) \cdot 10^{-6} \text{ GeV}^{-1}.$$  

An analogous variation of results beyond statistical errors is observed in $B_{\text{tot}}$ for the five periods at 200 GeV, leading to a fluctuating systematic error of 0.2% in $B_{\text{tot}}$. For this reason we have not yet exploited $B_{\text{tot}}$ to reduce the error on $b(\lambda)$ by effectively determining it from a one-parameter fit.

Another indication of comparable time fluctuating systematic error in the 200 GeV data is obtained by calculating the apparent asymmetry between any two sets of data with equal sign muons, separated by data taken at opposite polarity (i.e. also by a large time interval).
Efforts are in progress to reduce or eliminate the sources of fluctuating systematic errors. At present, not even the straightforward corrections for varying trigger counter, MWPC and electronic efficiencies (which are determinable from data owing to high detection redundancy) have been applied to the data.

Compared to the stochastic errors, the systematic errors arising from imperfect polarity reversal and its side effects and from natural asymmetries are estimated to be small. The spectrometer magnetic field was reversed on a constant computer controlled hysteresis curve with a relative uncertainty of $2 \times 10^{-4}$ determined from the analysis of induction loop and Hall probe measurements as well as iron temperature monitoring. The relative uncertainty on the equality of $\mu^+$ and $\mu^-$ incident energies is at present $6 \times 10^{-5}$, as derived from the time stability of the spatial position and electronic performance of the BMS hodoscopes and the monitoring of BMS magnetic fields by Hall probes. The phase space regions of the muon beams with opposite polarity differed imperceptibly from each other. These three sources of error together cause a systematic error $\Delta \theta_{\text{rev.1}} < 0.05 \times 10^{-4}$ GeV$^{-1}$.

We have indications that the detection efficiencies (trigger counters, MWPC, and electronics) shift slightly when the polarity is reversed. Until the corresponding corrections are applied the additional systematic error on the slope parameter is estimated at $\Delta \theta_{\text{rev.2}} < 0.13 \times 10^{-4}$ GeV$^{-1}$.

The natural asymmetries considered and studied comprise the charge asymmetry of halo contaminating the deep inelastic events, the charge asymmetry of hadronic and electromagnetic showers produced both in the carbon target and the iron of the spectrometer, the resulting asymmetry of muons produced in the decay of the hadronic shower component, and the asymmetry of stopping power of muons in matter. The best present estimate of systematic error due to these asymmetries is $\Delta \theta_{\text{nature}} < 0.13 \times 10^{-4}$ GeV$^{-1}$.
5. CONCLUSIONS

The observed asymmetry in deep inelastic scattering of oppositely polarized positive and negative muons on a carbon target is within experimental errors correctly described by:

1. the standard WS-GIM model with \( \sin^2 \theta_W = 0.23 \),
2. the radiative corrections of Bardin and Shumeiko,
3. the quark parton model used in part of the radiative correction calculations and in the evaluation of the nucleon structure function ratio \( A_e \).

Specifically, fitting an arbitrary weak isospin \( I_R(\mu) \) to the data under the latter two assumptions and with \( \sin^2 \theta_W = 0.23 \) yields \( I_R(\mu) = 0.04 \pm 0.07 \pm 0.03 \) as the weighted average of the results obtained at 200 GeV, 120 GeV (rings 2-7), and 120 GeV (rings 1-7). The first error is stochastic, the second is due to uncertainties about polarity reversal and natural asymmetries.

On the other hand, with the latter two assumptions and \( I_R(\mu) = 0 \), the best fits to \( \sin^2 \theta_W \) yield as the weighted average \( \sin^2 \theta_W = 0.28 \pm 0.08 \pm 0.04 \).

Finally, assuming the correctness of the standard model with \( \sin^2 \theta_W = 0.23 \) and of the \( A_e \)-value, the radiative corrections of Bardin and Shumeiko are experimentally confirmed within a factor of about 1.5.

Of course, an accidental cancellation of potential deviations from the above assumptions is always possible. We consider the results of our experiment as a consistency check on these assumptions to be viewed in connection with all other experimental information on the subject.
REFERENCES


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[7] D.Yu. Bardin, N.M. Shumeiko, Yad. Fiz. 29 (1979) 969; see also:


[12] D. Bollini et al., submitted to NIM.


[14] For more details on analysis see: A. Argento et al.,
    Report at the XVII Rencontre de Moriond 1982, presented by J. Cvach.
ABSTRACT: In an exposure of the bubble chamber BEBC, filled with deuterium, to the CERN SPS wideband neutrino beam we have measured the neutral to charged current cross section ratios on proton, neutron and deuterium. The values found are:

\[ R^p = 0.478 \pm 0.033 \text{ (stat)} \pm 0.030 \text{ (syst)} \]
\[ R^n = 0.262 \pm 0.017 \text{ (stat)} \pm 0.020 \text{ (syst)} \]
\[ R^N = 0.335 \pm 0.016 \text{ (stat)} \pm 0.020 \text{ (syst)} \]

The resulting values for the neutral current chiral coupling constants are: \( u^2 = 0.14 \pm 0.04 \) and \( d^2 = 0.18 \pm 0.05 \).

In the Weinberg-Salam model this corresponds to \( \sin^2 \theta_W = 0.21 \pm 0.03 \).

In the framework of the quark parton model the neutral to charged current cross section ratios on proton and neutron can be written as:

\[ R^k = f_1^k u^2_L + f_2^k d^2_L + f_3^k u^2_R + f_4^k d^2_R \quad \text{where } k = p, n \]

The neutral current chiral coupling constants \( u^2_L, d^2_L, u^2_R \) and \( d^2_R \) were introduced by Zahali. The coefficients \( f \) are ratios of integrals of quark density distributions inside the proton.

From previous experiments it is known that:

a) the contribution of the right-handed coupling constants is small compared to the one of the left-handed coupling constants.

\[ (u^2_R + d^2_R)/(u^2_L + d^2_L) = 0.1 \quad \text{[2,3,4]} \]

b) for neutrino induced interactions the coefficients \( f_3 \) and \( f_4 \) are small compared to \( f_1 \) and \( f_2 \). \( f_3/f_1 = f_4/f_2 = 1/3 \) [5,6].

Therefore, measurement of the ratios for neutrino induced events on proton and neutron separately allows the determination of \( u^2_L \) and \( d^2_L \).
Previous measurements in hydrogen\textsuperscript{7} and deuterium\textsuperscript{8} have yielded results on the values of $u_L^2$ and $d_L^2$ which, although not in disagreement with each other due to the large errors, require further verification.

In this experiment the bubble chamber BEBC filled with deuterium was exposed to the CERN SPS wideband neutrino beam, obtained from 400 GeV protons. This analysis is based on a sample of 38,000 pictures, which were double scanned for all topologies, except one-prongs without $\nu^0$ or gamma. All events with at least four charged tracks were measured. Events with two or three charged tracks were measured only if at least one of the tracks has a momentum larger than 4 GeV/c or if there is an associated $\nu^0$ or gamma. One-prongs were measured only if the momentum of the track is larger than 4 GeV/c and if there is an associated $\nu^0$ or gamma. All two-prongs were processed through kinematics in order to identify the decay of gammas, neutral kaons and (anti)lambdas. Decays without visible origin were removed from the sample.

An event is classified as a charged current interaction (CC) if it contains at least one particle with momentum larger than 4 GeV/c, identified as a muon by hits in both planes of the external muon identifier (EMI)\textsuperscript{9}. Otherwise it is classified as a neutral current candidate (NC). For further analysis only events with total visible hadronic energy $E_h$ larger than 5 GeV are used. An event is classified initially as occurring on neutron (proton) if its charged multiplicity, excluding backward spectator protons, is even (odd). To correct for forward spectators and deuteron rescattering effects, event weights are used as in ref. 8. The rescattering probability is taken to be $0.12 \pm 0.03$ (see ref. 10). After correction for scanning efficiencies and passing rates as a function of topology the sample consists of 3421 CC interactions on neutron, 1899 CC interactions on proton, 3455 NC candidates on neutron and 2554 NC candidates on proton.

Important corrections have to be applied to the raw number of events. They come from two different sources:

a) the limited geometrical acceptance of the EMI and its electronic inefficiency lead to a loss of CC events and a contamination of the NC sample.

b) neutrino interactions in the material in front of the bubble chamber produce neutral hadrons (neutrons and $K^0_L$) which may interact inside the chamber and contaminate the NC sample.
The geometrical acceptance of the EMI as a function of the muon momentum, its angle with the beam direction and its charge, is determined with a Monte Carlo program which uses the spatial distribution of the neutrino interactions as input.

The "electronic" efficiency of the EMI is estimated from a sample of throughgoing muons to be $97 \pm 1\%$. Using the geometrical acceptance table and the electronic efficiency the CC- and the NC-sample are corrected starting from the observed CC events.

Since the EMI-acceptance drops sharply for muons with momentum smaller than 4 GeV/c, a different method of correction is needed there. This correction is calculated using a Monte Carlo program which properly reproduces the observed features of the CC events with muon momentum larger than 4 GeV/c. It gives the extrapolation to lower muon momenta and results in weight factors to be applied to the observed CC events.

The correction of the NC sample for hadron induced events is performed using the B/AS method\textsuperscript{11).} This method starts by attempting to associate NC candidates to primary interactions visible in the bubble chamber. If the line of flight joining the primary interaction and the NC candidate makes a small angle with the beam direction (smaller than 10 degrees) and the total transverse momentum of the NC candidate with respect to the line of flight is small (smaller than 1.4 GeV/c) the NC candidate is considered to be an interaction of a neutral hadron (an associated event). The number of events associated to an invisible origin (in front of the bubble chamber) is obtained by multiplying the number of associated events with a factor B/AS. This factor is calculated with a Monte Carlo program. Its value depends primarily on the density of matter in front of the bubble chamber (including its wall) and the density of the liquid. It also depends on the energy spectrum of the beam, on its spatial distribution, and on the energy spectrum and the angular distribution of the neutral hadrons produced in the neutrino interactions. These quantities can be determined from the observed events and are used as input to the Monte Carlo program.

The corrections for unidentified muons and hadron induced events are large with respect to the number of observed events and produce considerable systematic uncertainties. As pointed out earlier\textsuperscript{7) their effect can be strongly reduced by taking advantage of the following facts, observed in CC events:

a) in a neutrino interaction the total transverse momentum with respect to the beam direction is smaller than the transverse momentum of the hadronic
system alone.

b) the transverse momentum of an individual hadron is smaller than the transverse momentum of the total hadronic system ($P^t_h$).

Consequently, by considering only events with $P^t_h$ larger than some cut-off value the influence of the background can be drastically reduced. From the observed NC to CC ratio as a function of the cut-off value it was decided to use only events with $P^t_h$ larger than 1.5 GeV/c.

Further corrections have to be applied for:

a) hadrons being incorrectly identified as muon due to background hits in the EMI or decay in flight. The probability for this to occur is determined by extrapolating the hadrons in the CC events to the EMI. Then the loss of NC events and the contamination in the CC sample is calculated from the observed NC candidates (about 3% and 1% respectively).

b) antineutrino background in the neutrino beam. This contamination of the NC sample is determined from the observed CC events with a positively charged muon. (2% of the CC events with negatively charged muon).

c) electron-neutrino background in the muon-neutrino beam. Since the outgoing electrons are usually not identifiable in deuterium these interactions contaminate the NC sample. According to the beam simulation program [2] this contamination of the beam is 1.7%. The correction is applied starting from the observed CC events and assuming $\mu-e$ universality.

d) scanning losses. Events with less than four charged tracks have to satisfy certain criteria which suppress NC events more strongly than CC events. The correction for this is determined from the hadron showers of the CC events to be $(5 \pm 2)$% for the events on proton.

All these corrections are summarized in table 1 together with the raw and corrected number of events.
Table 1: Raw event numbers and corrections for events with $E_h > 5$ GeV and $p_h^t > 1.5$ GeV/c.

<table>
<thead>
<tr>
<th>Raw event numbers</th>
<th>CC on proton</th>
<th>CC on neutron</th>
<th>NC on proton</th>
<th>NC on neutron</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unidentified muons with $p_\mu &gt; 4$ GeV/c</td>
<td>813</td>
<td>1587</td>
<td>488</td>
<td>611</td>
</tr>
<tr>
<td>Unidentified muons with $p_\mu &lt; 4$ GeV/c</td>
<td>+44</td>
<td>+105</td>
<td>-21</td>
<td>-48</td>
</tr>
<tr>
<td>Hadron induced events</td>
<td>+21</td>
<td>+54</td>
<td>-10</td>
<td>-25</td>
</tr>
<tr>
<td>Hadrons identified as muon</td>
<td>-6</td>
<td>-13</td>
<td>+13</td>
<td>+19</td>
</tr>
<tr>
<td>Antineutrino events</td>
<td>-10</td>
<td>-9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electron-neutrino events</td>
<td>-17</td>
<td>-28</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scanning losses</td>
<td>+20</td>
<td>0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The resulting values for the neutral to charged current cross section ratios on proton ($R^p$), on neutron ($R^n$) and on deuterium ($R^d$) are:

- $R^p = 0.473 \pm 0.033 \pm 0.030$
- $R^n = 0.262 \pm 0.017 \pm 0.020$ with $E_h > 5$ GeV and $p_h^t > 1.5$ GeV/c
- $R^d = 0.335 \pm 0.016 \pm 0.020$

The first error is the statistical one; the second error represents an estimate of the systematic uncertainties.

The ratio on proton agrees well with previous results in hydrogen $(0.51 \pm 0.04)^7)$ and deuterium $(0.49 \pm 0.06)^8)$. The ratios on neutron and deuterium are different by one standard deviation from the ones obtained recently in another deuterium experiment $((0.22 \pm 0.03$ and $0.30 \pm 0.03)^8)$. The ratio on deuterium is in good agreement with a previous result of a high precision experiment on a heavy isoscalar target $(0.320 \pm 0.010)^2)$ although the cuts applied there are very different (only $E_h > 2$ GeV).
To obtain from $R_P$ and $R_N$ the values of the chiral coupling constants $u_L^2$ and $d_L^2$, equation (1) has to be solved.

For the integrals of the quark density distributions which enter into the coefficients $f_j$, the values determined previously in this experiment are used. The effect of the cuts in $E_R$ and $P_R$ is determined with the previously mentioned Monte Carlo program which properly reproduces the features of the observed CC events. For the dependence of the quark density distributions on the Bjorken scaling variable $x$ the parametrization of Buras and Gaemers is taken. The resulting values of the coefficients are:

\[
\begin{align*}
&f_1^R = 0.46 \pm 0.06 & f_2^R = 1.01 \pm 0.02 & f_3^R = 0.19 \pm 0.02 & f_4^R = 0.32 \pm 0.03 \\
&f_1^P = 2.10 \pm 0.26 & f_2^P = 0.96 \pm 0.02 & f_3^P = 0.78 \pm 0.09 & f_4^P = 0.40 \pm 0.06
\end{align*}
\]

From a previous experiment it is known that $u_R^2 + d_R^2 = 0.036 \pm 0.013$. Using this value together with the computed values of $f_3$ and $f_4$ we estimate the contribution of the right-handed coupling constants as $0.02 \pm 0.01$ for interactions on proton and $0.01 \pm 0.005$ for interactions on neutron. It then follows that $u_L^2 = 0.14 \pm 0.04$ and $d_L^2 = 0.18 \pm 0.05$, where the errors include the statistical and systematic uncertainties in $R_P$ and $R_N$ as well as the uncertainties in the coefficients $f_j$.

The values found for $u_L^2$ and $d_L^2$ are in good agreement with the ones obtained by combining $R_P$ measured in hydrogen with $R_N$ measured in neon ($u_L^2 = 0.15 \pm 0.05$ and $d_L^2 = 0.17 \pm 0.07$). They also agree within the errors with the values obtained in deuterium ($u_L^2 = 0.19 \pm 0.06$ and $d_L^2 = 0.13 \pm 0.04$).

In the Weinberg-Salam model the coupling constants depend on one common parameter, according to:

\[
\begin{align*}
u_L^2 &= (1/2 - 2/3 \sin^2 \theta_W)^2 & d_L^2 &= (1/2 - 1/3 \sin^2 \theta_W)^2
\end{align*}
\]

which implies that $u_L^2$ should not be larger than $d_L^2$.

As can be seen in figure 1 our result is in good agreement with this prediction. When the Weinberg-Salam constraint is imposed to our values of $u_L^2$ and $d_L^2$ we obtain $\sin^2 \theta_W = 0.21 \pm 0.03$. 

- 56 -
Figure 1. Relations between the coupling constants $u_L^2$ and $d_L^2$ from this experiment. Also shown is the prediction of the Weinberg-Salam model.

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NONDIAGONAL Z-DECAY - Z → \bar{\nu} + \nu + \mu

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Poster presented by T. Riemann

Using the Weinberg-Salam theory with a nondiagonal neutrino mass matrix à la Kobayashi and Maskawa we calculate the decay rate of the heavy neutral gauge boson Z into two light leptons of different flavors: Z → \bar{\nu} + \nu + \mu. This is of interest for two reasons. With a large e^+e^-storage ring like LEP one has a Z-factory at hand and it is of value to know all allowed branchings of the Z-decay. At the other hand, every new place to search for lepton number violation is welcome - and the process Z → \bar{\nu} + \nu + \mu is a new measure of the pure Z\nu\nu-vertex at high energy.

We define the branching ratio of interest as

$$B_Z = \frac{\sigma(Z → \bar{\nu} + \nu + \mu)}{\sigma(Z → \bar{\nu} + \nu + \mu)}$$

The process is allowed in one-loop approximation by the following diagrams:

The counter term is completely defined by wave function renormalization of charged fermions /1/. In the approximation of vanishing masses of charged fermions we get the following branching ratio:

$$B_Z = \left(\frac{\alpha}{\pi}\right)^2 \left|\sum_{i=1}^{N} P_{ii} \frac{M_W}{M_Z} V(D_i, \beta)\right|^2$$

Here we use the abbreviations $\beta = M_Z^2/M_W^2 \approx 1.25$, $s^2 = 1 - \frac{1}{\beta} \approx 0.2$ and $A_i = m(\nu_i)^2/M_W^2$. The $P_{ii}$ are elements of the neutrino Koba-
The vertex function $V(\Delta, y)$ may be expressed by the two- and three point functions of 't Hooft and Veltman (C(4A) = 0 and C(4A) = 5);

$$V(\Delta) = (p + \frac{1}{2} A^2) C_0 + p (2 C_{24} + C_{23}) + 2 C_{24} + 2 A^{-\frac{3}{2}} \Delta \tilde{C}_o - 4 \tilde{C}_{24}$$

$$- 2 \tilde{C}_{23} - \frac{1}{2} A^{-\frac{3}{2}} \Delta \tilde{C}_o + \frac{1}{2} A^{-\frac{3}{2}} [2 + A B_1 - 1]$$

$V(\Delta, y)$ is divergent by the contributions from $C_{24}$, $B_{24}$ and $B_1$, but the combination $\sum p^+ p^- V(\Delta)$ is finite since the divergent pole parts in $V$ are independent of $\Delta$ and cancel for nondiagonal transitions as a result of the unitary sum.

Numerical results for very small neutrino masses - all $\Delta_1 \ll 1$

In this case the vertex function may be approximated as follows $(0 \leq y < 2)$:

$$V(\Delta, y) = V_0 + V_1 \Delta + \ldots$$

$$\text{Re} V_0 = \frac{-2}{3} (p + 1) \text{Re} C_0 (100) + \frac{2}{3} \frac{(4p^2 - 3p - 6)}{2p} C_{101} (101) \frac{p}{p} \sin \phi$$

$$+ \frac{2}{3} (2 \sin^2 \theta - 2 \sin \theta) \frac{1 + 2 \sin \theta}{2p} + \frac{2}{3} (p^2 + 2p + 6) \text{arccosh} (2y)$$

$$+ \frac{2}{3p} (3p + 2) \text{arccosh} \left( \frac{p - 1}{2p} 2y \right)$$

$$\text{Im} V_0 = \frac{2}{3} (y + 1) \text{Im} C_0 (100) + \frac{2}{3} \frac{p}{p}$$

Here we used $\gamma = \frac{2}{3} \sqrt{p^2 - p^2}$. Numerically, we get

$$V(\Delta, 1.25) = (1.25 + 1.031) + (2.53 - 2.311) \Delta + \ldots$$

which yields

$$B_2(\Delta, 1.24) = 0.99 \times 10^{-4} \left| \sum_{i=1}^{N} P_{ni} P^i + \Delta_i \right|^2$$

This is of approximately the same order of magnitude like results for the decay $\mu \to e \gamma / 3$. The prospects to detect a decay $Z \to e e$ following this formula are rather bad.
Numerical results for mediate neutrino masses - $0 \leq \Delta_i \leq 1$

<table>
<thead>
<tr>
<th>$m_i$</th>
<th>$\Delta^2$</th>
<th>$B_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>~100 eV</td>
<td>$\sim 2 \times 10^{-36}$</td>
<td>$\leq 2 \times 10^{-40}$</td>
</tr>
<tr>
<td>~20 GeV</td>
<td>$\sim 3.2 \times 10^{-3}$</td>
<td>$\leq 3 \times 10^{-7}$</td>
</tr>
</tbody>
</table>

The existence of heavy, unstable neutrinos with masses of several GeV is not excluded experimentally /4/. Their existence would prevent the GIM-cancellation of the (finite) constant contributions in $V(A, \gamma)$ and allow larger rates. Let us assume $(N-3)$ heavier neutrinos besides the 3 known types $\nu_e, \nu_\mu, \nu_\tau$. Then the branching ratio is

$$B_2 = 0.84 \times 10^{-5} \left| \sum_{i=+}^{N} (V(A_i) - V(\phi)) P_{\mu i} P_{i e}^* \right|^2$$

Comparing with fig. 1 which shows the function $V(A, 1.25)$ one may obtain an upper limit for $B_2$ (assuming $0 < \Delta \leq 1$) using that $|V(A_i) - V(\phi)| \leq |V(A_{HR}) - V(\phi)|$.

The $\Delta_{HR} = 4$ is the threshold value where $V(A, \gamma)$ gets an imaginary part from diagrams with two neutrino propagators. We get

$$B_2 < 1.14 \times 10^{-5} \left| \sum_{i=+}^{N} P_{\mu i} P_{i e}^* \right|^2$$

This prediction is also smaller than necessary for the detection of possible leptonic non-diagonal Z-decays based on the conventional Kobayashi-Maskawa mixing in the WS theory. There remains only the hope that more sophisticated theoretical schemes allow for larger rates.
To summarize, we have calculated the branching ratio
\[ B_Z = \frac{\Gamma(\mu\mu\nu\nu)\Gamma(\tau\tau\nu\nu)}{\Gamma(\mu\mu\nu\nu)} \] using the simplest theoretical framework. A non-zero \( B_Z \) would indicate lepton number violation at the \( Z \)-vertex. Unfortunately, assuming the use of a storage ring like LEP with \( \leq 10^6 \) \( Z \)-decays per experiment we got negligible rates for \( 0 < m(\nu) < M_W \).

References

/1/ For details of our calculations see:
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/2/ G. 't Hooft and M. Veltman, Nucl. Phys. B153 (1979) 365; for slight modifications of the normalization see ref. /1/.


---

\[ V(\Delta) \]

**Fig. 1.**
Form factor \( V \) for the flavor non-diagonal \( Z \)-decay as function of \( \Delta = m(\mu)^2/M_W^2 \). \( \varphi = 4.25 \).
INTRODUCTION

All experimental data on electroweak processes are in agreement with the standard gauge model of Glashow, Salam and Weinberg. It is therefore customary to use this model as a guideline for discussing experimental results.

The basic features of the model may be briefly recalled. The underlying gauge group is $SU(2)_L \times U(1)$. Fermions are grouped in left-handed isospin doublets and right-handed isospin singlets as

$$\begin{align*}
\left( \nu_e \right)_L, \left( \nu_{\mu} \right)_L, \left( \nu_{\tau} \right)_L, \left( u^c \right)_L, \left( d^c \right)_L, \left( s^c \right)_L, \left( b^c \right)_L
\end{align*}$$

and

$$e_R, u_R, s_R, d_R, \ldots$$

The energy scale is set by the mass of the intermediate vector bosons $m_Z$ and $m_W$, which means that with present accelerators we are still exploring the low-energy domain:

$$Q^2 \ll \frac{m_Z^2}{m_W^2}$$

Interactions can therefore be described by an effective Lagrangian of current x current coupling,

$$L_{\text{eff}} = \frac{G_F}{\sqrt{2}} \left[ J^+ \lambda J^- \lambda + \rho J^0 \lambda J^0 \lambda \right],$$

where $J^+ \lambda J^- \lambda$ describes the charged-current (CC) coupling, and the neutral-current (NC)

$$J^0 \lambda = J^+ \lambda - \sin^2 \theta_W J^{\text{em}} \lambda$$

is composed of the third component of the weak isospin and the electromagnetic piece.
Gauge interactions conserve helicity, so that only vector (V) and axial-vector (A) couplings occur. In particular, CC couplings should be purely left-handed, V - A.

In the simplest form of the model, NC and CC couplings have the same strength: \( \rho = 1 \).

The structure of the Lagrangian is completely determined up to one free parameter \( \sin^2 \theta_w \), and the masses of the vector bosons are fixed by the low-energy Lagrangian as

\[
m_W = m_Z \cos \theta_w = 37.3 \text{ GeV}/\sin \theta_w.
\]

This last year has seen essential progress in the investigation of electroweak interactions, where the main achievements have been the opening up of a new field by the discovery of electroweak interference effects in deep-inelastic muon scattering, and the advances made in the investigation of purely leptonic weak interactions, not only in the scattering of neutrinos by electrons but also especially in \( e^+e^- \) annihilation.

In my talk I will concentrate on recent results, mainly contributions to this conference, and will refer to review articles for a survey of the whole field.

1. TEST OF V, A COUPLING AND TIME REVERSAL INVARIANCE IN ANTINEUTRINO-NUCLEON SCATTERING

Vector and axial-vector interactions conserve helicity. Scalar (S), pseudoscalar (P), and tensor (T) interactions are accompanied by a spin flip for the lepton. Since the helicity state of neutrinos is known from beta-decay experiments, the measurement of the longitudinal polarization of \( \mu^+ \) in the reaction

\[
\overline{\nu}_e + \mu^+ \rightarrow X
\]

constitutes a very direct test of possible S, P, T contributions to the interaction. Such an experiment has been performed jointly by the CDHS* and CHARM** Collaborations.

The kinematical variables of reaction (1) are reconstructed from data recorded in the CDHS detector, whereas the CHARM detector, situated just downstream of the CDHS detector, is used as a polarimeter. The forward-backward asymmetry of the decay positrons from muons stopping in the CHARM

* CERN-Dortmund-Heidelberg-Saclay.
** CERN-Hamburg-Amsterdam-Rome-Moscow.
calorimeter is measured as a function of the muon decay time. This asymmetry

\[ R(t) = \frac{N_B(t) - N_F(t)}{N_B(t) + N_F(t)} = R_0 \cos(\omega t + \phi) + \text{const.} \]  

shows the characteristic cosine shape as shown in Fig. 1, since the muon is precessing in a low magnetic dipole field perpendicular to the neutrino beam.

Fig. 1 Decay time of \( \mu^+ \) (a) and time-dependent backward-forward asymmetry of decay \( e^+ \) (b).
Based on \( \sim 17,000 \) events at \((Q^2) = 4 \text{ (GeV/c)}^2\), a fit of Eq. (2) to the data points yields a phase of \( \phi = -3.02 \pm 0.08 \) compatible with \(-\pi\) as expected for positive helicity. The results for \( R_\alpha \), which is the product of polarization and analysing power, are shown in Fig. 2a as a function of the inelasticity \( y = (E_0 - E_\mu^+)/E_0 \). An increased sensitivity to \( S\) and \( P \) contributions is obtained in analysing the asymmetry in terms of \( y \). This is illustrated in Fig. 2b, which shows the expected polarization as a function of \( S \) and \( P \) contributions for various bins in \( y \). From the ratio \( R_\alpha (y < 0.2) \) to \( R_\alpha (y > 0.5) \), which does not depend on the analysing power, one can deduce

\[
\frac{\sigma_{S,P}}{\sigma_{tot}} \leq 7\% \quad (95\% \text{ CL}).
\]

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig2}
\caption{a) Asymmetry \( R_\alpha \) as a function of the inelasticity \( y \). b) Expected polarization for different regions of \( y \) as a function of \( S \) and \( P \) contributions.}
\end{figure}

In a previous experiment\(^7\), where the absolute polarization was determined, also \( T \) contributions, which do not vanish at \( y = 0 \), were constrained as

\[
\frac{\sigma_{S,P,T}}{\sigma_{tot}} \leq 18\% \quad (95\% \text{ CL}).
\]

This experiment has shown that the coupling is mainly \( V \) and \( A \), and, together with results from investigations of inverse muon decay\(^8\), which can distinguish \( V + A \) from \( V - A \), leads to the conclusion that the CC is coupling predominantly with left-handed quarks.

The same experiment has also set limits on contributions to the coupling that violate time-reversal invariance. For this purpose the polarization component perpendicular to the lepton plane, i.e. proportional to
\[ \mathcal{P}_\mu (p_\nu \times \bar{p}_\mu), \] was measured. No such term was found in accordance with T-invariance. Quantitatively,

\[ \sigma_{T, \text{violating}} / \sigma_{\text{tot}} < 11 \% \quad (95\% \text{ CL}). \]

2. LIMIT ON RIGHT-HANDED COUPLINGS IN INELASTIC NEUTRINO-NUCLEON INTERACTIONS

Based on an analysis of differential cross-sections, the CDHS Collaboration has obtained a limit to the coupling of right-handed quarks for the CC reactions

\[ \nu_F e + \bar{\nu}_F e \rightarrow \mu X, \]

If the current couples only to left-handed quarks, then the cross-section of \( \nu \) scattering on quarks \( q \) (\( \bar{\nu} \) on antiquarks \( \bar{q} \)) is independent of \( y \), and of \( \nu \) scattering on \( \bar{q} \) (\( \bar{\nu} \) on \( q \)) is proportional to \( (1-y)^2 \). With the quark and antiquark structure functions \( q(x) \) and \( \bar{q}(x) \),

\[ \frac{d^2 \sigma^\nu}{dx dy} \sim q(x) + (1-y)^2 \bar{q}(x), \]

\[ \frac{d^2 \sigma^{\bar{\nu}}}{dx dy} \sim (1-y)^2 q(x) + \bar{q}(x). \]

The presence of coupling to right-handed quarks can be parametrized by

\[ \rho = \left| c_R / c_L \right|, \]

so that

\[ \frac{d^2 \sigma^\nu}{dx dy} \sim q(x) + \rho^2 \bar{q}(x) + (1-y)^2 \left[ q(x) + \rho^2 q(x) \right] \]

\[ = q_L(x) + (1-y)^2 q_R(x), \]

\[ \frac{d^2 \sigma^{\bar{\nu}}}{dx dy} \sim (1-y)^2 \left[ q(x) + \rho^2 \bar{q}(x) \right] + \bar{q}(x) + \rho^2 q(x) \]

\[ = (1-y)^2 q_L(x) + q_R(x). \]

The different dependence on \( y \) for \( \nu \) and \( \bar{\nu} \) reactions can be used to determine the \( x \) dependence of the structure functions for left-handed and right-handed quarks. A result of this analysis for a particular bin in \( Q^2 \) is
shown in Fig. 3. There are no right-handed quarks at large $x$. The quantitative result

$$|p^2| = \frac{q_R}{q_L} < 0.009 \quad (90\% \, \text{CL})$$

obtained for $<q^2> = 33 \, (\text{GeV}/c)^2$ can be used to set limits on the mass mixing of a second charged vector boson which is predicted in left-right symmetric theories based on $\text{SU}(2)_L \times \text{SU}(2)_R \times U(1)$. The mixing of the two masses $M_1$ and $M_2$ is determined by an angle $\theta$ and

$$C_L = \frac{\cos^2 \theta + \sin^2 \theta}{M_1^2}; \quad C_R = \sin \theta \cos \theta \left( \frac{1}{M_2^2} - \frac{1}{M_1^2} \right).$$

In Fig. 4 the result is compared with limits obtained from muon decay$^{10}$.)

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Fig. 3 Left-handed and right-handed structure functions in a particular $Q^2$ range.

Fig. 4 Experimental limits on the mixing angle $\theta$ as a function of the mass ratio.
It is important to note that the CDHS result is obtained at high $Q^2$ and is valid also for massive right-handed neutrinos.

3. ELECTROWEAK EFFECTS IN DEEP-INELASTIC SCATTERING OF MUONS

The discovery of a $C$-invariance violating asymmetry in deep-inelastic scattering of polarized negative and positive muons,\[ \mu^- C + \mu^- X \]
\[ \mu^+ C + \mu^+ X \] \hspace{1cm} (3)
by the BCDMS\(^a\) Collaboration at CERN\(^{11}\) opens up a new branch of the Sakurai tetragon (Fig. 5) for the investigation of electroweak interactions. It provides an essential possibility for testing $e - \mu$ universality of NC coupling. It is also important to note that the experiment was performed at high $Q^2$.

Fig. 5 Sakurai tetragon of NC couplings

The asymmetry in reaction (3) is predominantly due to parity-conserving $A$-lepton $^A$quark interactions, whereas the famous SLAC experiment on scattering of polarized electrons on deuterons\(^{12}\) measures parity-violating terms of the form $V_{lepton}^A$quark'.

The experiment measures the asymmetry,\[ B = \frac{d\sigma^+(-\lambda) - d\sigma^- (+\lambda)}{d\sigma^+(-\lambda) + d\sigma^- (+\lambda)} \]

\(^a\) Bologna-CERN-Dubna-Munich-Saclay
where $\lambda$ is the longitudinal polarization of the muon beam. An asymmetry arises if the helicity and charge of the incident $\mu$ are simultaneously inverted.

In the framework of gauge models\textsuperscript{11),}

$$B(z,\lambda) = k(\lambda v_\mu - a_\mu)A_0 z,$$

with

$$k = \frac{G}{\sqrt{2}} \frac{1}{2m_G} = 1.8 \times 10^{-4} \text{ GeV}^{-2},$$

and the kinematical variable

$$z = \frac{g(y)Q^2}{1 + (1-y)^2} Q^2$$

[$y = \text{inelasticity}; y = (E_\mu^\text{in} - E_\mu^\text{out})/E_\mu^\text{in}$].

Vector and axial-vector coupling of the muon to $Z^0$ are written as $v_\mu$ and $a_\mu$, and $A_0$ describes the couplings of the quarks to the $Z_0$:

$$A_0 = \frac{xG(x,Q^2)}{F_2(x,Q^2)} = \frac{6}{5} (a_d - 2a_u),$$

given in terms of the structure functions $G_1$ and $F_2$ or, for isoscalar targets, in terms of axial-vector couplings of u and d quarks, $a_u$ and $a_d$ ($A_0$ is assumed to be known from other measurements).

The experiment was performed at two different energies, 120 GeV and 200 GeV. Data were taken for two different polarities of the beam corresponding to $\mu^-_R$ and $\mu^+_L$, with longitudinal polarization $|\lambda| = 80\%$. The analysis is based on about $3 \times 10^6$ events. Figure 6 shows the distribution of events at 200 GeV as a function of $z$, as well as the asymmetry $B$ which, after radiative corrections, is shown in Fig. 6b; $B$ is a linear function of $z$.

The general gauge-theory couplings of the muon, allowing for left- and right-handed isospin multiplets, can be expressed as:

$$v_\mu = I_1^L + I_3^R + 2 \sin^2 \theta_W,$$

$$a_\mu = I_1^L - I_3^R,$$

and these couplings are related to the slope $b$ of the asymmetry by

$$\frac{b}{kA_0} = \lambda v_\mu - a_\mu = I_1^L(\lambda-1) + I_3^R(\lambda+1) + 2\lambda \sin^2 \theta_W. \quad (4)$$
Fig. 6  a) Distribution of events as a function of $z$.  b) Charge conjugation asymmetry after corrections.

The experimental result is

$$b = [-1.56 \pm 0.40 \text{ (stat.)} \pm 0.16 \text{ (syst.)}] \times 10^{-4} \text{ GeV}^{-2},$$

to be compared with the standard model prediction of $b = -1.51 \times 10^{-4} \text{ GeV}^{-2}$.

This result can be used either to determine the mixing angle in the framework of the standard model (i.e. assuming $I_3^L = -\frac{1}{2}$, $I_3^R = 0$), giving

$$\sin^2 \theta_w = 0.24 \pm 0.08 \text{ (stat.)} \pm 0.03 \text{ (syst.)},$$

or to determine the weak isospin of the right-handed muon assuming universality and $\sin^2 \theta_w = 0.23$, $I_3^L = -\frac{1}{2}$, and one finds

$$I_3^R = 0 \pm 0.07 \text{ (stat.)} \pm 0.03 \text{ (syst.)},$$

which is about 5 standard deviations away from the next possible values $|I_3^R| = \frac{1}{2}$.

It should be mentioned that if the experiment could be performed at different values of the polarization $\lambda$, the quantities $\sin^2 \theta_w$, $\rho$, and $I_3^R$ could be simultaneously determined [see Eq. (4) and Ref. 13].
Table 1 shows a comparison of the muon results with those from other reactions. One can conclude that in agreement with the standard model the muon couples according to universality, and that right-handed fermions are isospin singlets. Isospin doublets of the form

\[
\left( \begin{array}{c} N^0 \\ e^- \end{array} \right)_R, \left( \begin{array}{c} N^0 \\ \nu^- \end{array} \right)_R
\]

are excluded for any mass of the neutral leptons \( N^0 \) and \( M^0 \).

**Table 1**

Results of inelastic muon scattering (Ref. 11) compared with those for other couplings (Ref. 2). Values in brackets constitute inputs to the analysis.

<table>
<thead>
<tr>
<th>Coupling</th>
<th>( \sin^2 \theta_w )</th>
<th>( R^H )</th>
<th>( \rho )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu q )</td>
<td>0.24 ± 0.08 ± 0.03</td>
<td>[0]</td>
<td>[1]</td>
</tr>
<tr>
<td></td>
<td>[0.23]</td>
<td>( R^H(\mu) = 0.233 ± 0.009 )</td>
<td>[1]</td>
</tr>
<tr>
<td>( \nu q )</td>
<td>0.233 ± 0.009</td>
<td>[0]</td>
<td>[1]</td>
</tr>
<tr>
<td>( \nu e )</td>
<td>0.249 ± 0.031</td>
<td>( R^H(\mu) = 0.249 ± 0.031 )</td>
<td>( \rho = 0.101 ± 0.058 )</td>
</tr>
<tr>
<td>( \nu e )</td>
<td>0.249 ± 0.031</td>
<td>( R^H(\nu) = -0.010 ± 0.040 )</td>
<td>( \rho = 0.101 ± 0.058 )</td>
</tr>
</tbody>
</table>

4. **PURELY LEPTONIC INTERACTIONS**

4.1 **Scattering of muon-neutrino and muon antineutrinos off electrons**

The CHARM Collaboration has measured the cross-section of \( \nu_e \) and \( \bar{\nu}_e \) scattering in the same detector; the same criteria are used for the selection of events and the same cuts are applied. Moreover, since the cross-section ratio \( R \) is considered to determine the mixing angle, systematic errors tend to cancel.

Background is the main problem of this experiment, as can be seen from Fig. 7. A careful investigation was performed in order to understand the shape and magnitude of the two main background sources: quasi-elastic (\( \nu_e \)) scattering, and coherent \( \pi^0 \) and \( \gamma \) production by (\( \nu_\mu \)). The lower part of Fig. 7 shows, as an example, the selection of signal and quasi-elastic...
Fig. 7 Events as a function of $E^2 \theta^2$ for (a) neutrinos and (b) antineutrinos, and, after selection of one minimum-ionizing particle close to the vertex, for (c) neutrinos and (d) antineutrinos.

($\nu_e$) background at reduced efficiency by selecting events which are consistent with one minimum-ionizing particle emerging from the interaction vertex.

After background subtraction and correction for the composition of the beam of different neutrino types, the following events are found:

$\nu_e$ scattering: $42 \pm 11$ events,

$\bar{\nu}_e$ scattering: $64 \pm 16$ events.
The cross-section is determined by normalization to the total number of charged-current $\nu_\mu$ interactions. Figure 8 shows the relation of $R$ to $\sin^2 \theta_W$:

$$R = \frac{\sigma_\nu}{\sigma_0} = \frac{1 - 4 \sin^2 \theta_W + 16/3 \sin^4 \theta_W}{1 - 4 \sin^2 \theta_W + 16 \sin^4 \theta_W}.$$ 

From this, one can extract

$$\sin^2 \theta_W = 0.215 \pm 0.040 \text{ (stat.)} \pm 0.015 \text{ (syst.)}.$$ 

Since $R$ is independent of $\rho^2$, the relative strength of NC to CC coupling, one can use the relation

$$\sigma = \rho^2 \sigma_{\text{standard model}}$$

**Fig. 8** Cross-section ratio $R$ as a function of $\sin^2 \theta_W$ compared to expectation for acceptance-corrected energy range (full line) and uncorrected energy interval (dashed line).
in order to determine \( \rho \) simultaneously:

\[
\rho = 1.12 \pm 0.12 \text{ (stat.)} \pm 0.11 \text{ (syst.)}.
\]

The result is consistent with \( \rho = 1 \) as required by gauge models with minimal Higgs sector, where all Higgs particles occur in isospin doublets.

The status of checks on the universality of the weak neutral current coupling is summarized in Table 2, which compares the result from purely leptonic reactions with results from semileptonic reactions\(^1\).

**Table 2**

<table>
<thead>
<tr>
<th>Coupling</th>
<th>( \rho )</th>
<th>( \sin^2 \theta_W )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \nu_\mu q )</td>
<td>0.999 ( \pm 0.025 )</td>
<td>0.232 ( \pm 0.027 )</td>
</tr>
<tr>
<td>( \nu_\mu \bar{e} )</td>
<td>1.12 ( \pm 0.16 )</td>
<td>0.215 ( \pm 0.043 )</td>
</tr>
</tbody>
</table>

\(^4.2\) Annihilation of \( e^+e^- \) into lepton pairs\(^1\)

These purely leptonic interactions explore the highest \( Q^2 \) range at present accessible at accelerators. The magnitude of the electroweak interference effect can be estimated using electromagnetic and weak scattering amplitudes:

\[
\frac{|A_{\text{em}}|^2 |A_{\text{weak}}|}{|A_{\text{em}}|^2 + |A_{\text{weak}}|^2} = \frac{|A_{\text{weak}}|}{|A_{\text{em}}|} = \frac{G}{e^2/q^2} = \frac{10^{-\gamma q^2}}{\frac{e^2}{m^2}}.
\]

where the SLAC eD experiment\(^{12}\) found effects in the \( 10^{-3} \) range, the CERN muon scattering experiment\(^{11}\) in the \( 10^{-2} \) range; at PETRA and PEP, effects of \( \sim 10\% \) are expected.

Assuming universality, one needs three coupling constants, \( h_{VV} \), \( h_{AA} \), and \( h_{VA} \), to describe each of the three reactions

\[
e^+e^- \to e^+e^- \quad \text{(time-like and space-like } q^2) ,
\]
\[
e^+e^- \to \mu^+\mu^- \quad \text{(time-like } q^2) ,
\]
\[
e^+e^- \to \tau^+\tau^- \quad \text{(time-like } q^2) .
\]
The measurable quantities are the deviations of the cross-section from the QED predictions

\[
\frac{\sigma - \sigma_{\text{QED}}}{\sigma_{\text{QED}}} = 4s \frac{G}{\sqrt{2} e^2} h_{VV},
\]

and the angular distribution (\(\theta = \) angle between incoming and outgoing lepton of the same charge)

\[
\frac{d\sigma}{d \cos \theta} = \frac{\alpha e^2}{2s} [A(1-\cos^2 \theta) + B \cos \theta],
\]

with the symmetric term

\[
A = 1 - 4s \frac{G}{\sqrt{2} e^2} h_{VV}
\]

and the asymmetric term

\[
B = -8s \frac{G}{\sqrt{2} e^2} h_{AA}.
\]

From Eq. (6) one gets the forward-backward asymmetry,

\[
A_{FB} = \frac{F - B}{F + B} = 3s \frac{G}{\sqrt{2} e^2} h_{AA}.
\]

To determine the third coupling constant involved, \(h_{VA}\), polarized beams or the measurement of the polarization of outgoing leptons would be needed. For simplicity, the above equations are given assuming \(s \ll m^2\). At the highest PETRA energies, mass propagator effects are however important (e.g. \(\sim 20\%\) increase of \(A_{FB}\)) and are taken into account in the analysis of the data.

The standard model predicts for the coupling constants:

\[
h_{VV} = \frac{1}{4} \left(1 - 4 \sin^2 \theta_W\right)^2,
\]

\[
h_{AA} = \frac{1}{4},
\]

\[
h_{VA} = \frac{1}{4} \left(1 - 4 \sin^2 \theta_W\right).
\]

Examples of asymmetry and cross-section measurements are shown in Figs. 9 and 10. The \(\mu\)-pair asymmetries are in agreement with the standard model prediction of \(A_{FB} \approx -9\%\) for \(\sin^2 \theta_W = 0.23\). This is also
Fig. 9 Angular distribution of $\mu$ pair production. Dashed line shows QED prediction (Ref. 16).

Fig. 10 Cross-section for $\mu$-pair and $\tau$-pair production (Ref. 17).
true for the most recent average value for \( \tau \) pairs obtained at PETRA\(^{(15)} \)

\[
A_{\text{FB}}^{\tau\tau} = (-6.8 \pm 3.2)\% .
\]

Table 3 shows results for the coupling constants obtained from fitting cross-sections and angular distributions simultaneously. The average is again in agreement with the standard model predictions using \( \sin^2 \theta_W = 0.23 \).

**Table 3**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>( h_{\text{AA}} )</th>
<th>( h_{\nu\nu} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>CELLO (^{(18)} )</td>
<td>0.17 ± 0.17</td>
<td>-</td>
</tr>
<tr>
<td>JADE (^{(19)} )</td>
<td>0.36 ± 0.11</td>
<td>0.05 ± 0.08</td>
</tr>
<tr>
<td>MARK J (^{(16)} )</td>
<td>0.28 ± 0.06</td>
<td>0.01 ± 0.05</td>
</tr>
<tr>
<td>TASSO (^{(17)} )</td>
<td>0.44 ± 0.09</td>
<td>-0.11 ± 0.13</td>
</tr>
<tr>
<td>Average</td>
<td>0.324 ± 0.044</td>
<td>0.009 ± 0.040</td>
</tr>
<tr>
<td>Standard model</td>
<td>0.25</td>
<td>0.0016</td>
</tr>
</tbody>
</table>

Results of determinations of \( \sin^2 \theta_W \) at PETRA and PEP are given in Table 4: the average agrees well with the most accurate determination of \( \sin^2 \theta_W \) from \( \nu \bar{\nu} N \) scattering.

The couplings for \( e^+ e^- \) and \( (\nu)^{\mu} e \) are related in models with only one \( Z^0 \) by factorization relations,

\[
h_{\nu\nu} = \frac{g_\nu^2}{c_\nu^2} ; \quad h_{\text{AA}} = \frac{g_A^2}{c_\nu^2},
\]

where \( c_\nu^2 \) determines the strength of \( \nu \bar{\nu} N \) coupling, and \( c_\nu^2 \approx 1 \) in the standard model. This relation can be used to resolve the ambiguity of \( \nu \mu e \) coupling constants\(^*\)

\[
S_A = -0.52 \pm 0.06 \quad \text{OR} \quad S_A = 0.06 \pm 0.08 \\
S_\nu = 0.06 \pm 0.08 \quad \text{OR} \quad S_\nu = -0.52 \pm 0.06
\]

\(^*\) Latest CHARM results not yet included.
Table 4
Results from PETRA and PEP on $\sin^2 \theta_W$ (Ref. 5)

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\sin^2 \theta_W$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CELLO</td>
<td>0.22 ± 0.15</td>
</tr>
<tr>
<td>JADE</td>
<td>0.25 ± 0.15</td>
</tr>
<tr>
<td>MARK J</td>
<td>0.25 ± 0.11</td>
</tr>
<tr>
<td>PLUTO</td>
<td>0.23 ± 0.17</td>
</tr>
<tr>
<td>TASSO 17)</td>
<td>0.29 ± 0.09</td>
</tr>
<tr>
<td>MAC</td>
<td>0.24 ± 0.16</td>
</tr>
<tr>
<td>MARK II</td>
<td>0.36 ± 0.09</td>
</tr>
<tr>
<td>Average</td>
<td>0.259 ± 0.051</td>
</tr>
</tbody>
</table>

without reference to semi-leptonic reactions. Clearly $h_{VV} \approx 0$ and $h_{AA} \approx 0.34$ single out the predominantly axial-vector solution, again in agreement with the standard model which predicts

$$g_A = -\frac{1}{2}; \quad g_V = -\frac{1}{2} + 2 \sin^2 \theta_W.$$

Combining the results from purely leptonic reactions, one obtains

$$\sin^2 \theta_W = 0.233 \pm 0.033$$

which, compared with the $\nu\nu$ result

$$\sin^2 \theta_W = 0.229 \pm 0.009 \pm 0.005,$$

again strongly supports the universality of electroweak interactions.

The PETRA results can also be used to search for an extra term in the effective Lagrangian due to the exchange of a second, higher mass $Z_2^0$

$$J^3 - \sin^2 \theta_W J^{em}_\lambda + C(J^{em}_\lambda)^2.$$

This extra term with the coefficient $C$ is not visible in $\nu$ interactions; nor is it visible in the experiment of polarized electron scattering, since it is parity conserving.
The PETRA results as summarized in Table 5 are ruling out such an extra term with fairly good precision.

**Table 5**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Limit on $C$ (95% CL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CELLO</td>
<td>&lt; 0.032</td>
</tr>
<tr>
<td>JADE</td>
<td>&lt; 0.039</td>
</tr>
<tr>
<td>MARK J</td>
<td>&lt; 0.027</td>
</tr>
<tr>
<td>PLUTO</td>
<td>&lt; 0.060</td>
</tr>
<tr>
<td>TASSO</td>
<td>&lt; 0.020</td>
</tr>
<tr>
<td>TASSO$^{15}$</td>
<td>&lt; 0.010</td>
</tr>
</tbody>
</table>

### 4.3 Search for trident production

Coherent lepton pair production by neutrinos in the Coulomb field of nuclei (Fig. 11) is one of the few sources that allow the study of NC and CC interference. The CHARM Collaboration has searched for such events. Out of $\approx 3 \times 10^6$ CC events from wide-band beam $\nu_\mu$ and $\bar{\nu}_\mu$ interactions, candidates were selected with two muons with $p_\mu > 7$ GeV/c and without visible hadronic recoil ($E_h < 200$ MeV). From $1.7 \pm 1.7$ events found, an upper limit on the diagonal leptonic coupling constant can be given:

$$G_D < 1.5 \, G_F \quad (90\% \, \text{CL}),$$

in agreement with a CDHS result $^3$ of

$$G_D < 1.6 \, G_F \quad (90\% \, \text{CL}),$$

and in agreement with the prediction of the standard model $G_D = 0.77 \, G_F$.

![Fig. 11 Coherent production of lepton pairs.](image)
5. NEUTRINO QUARK SCATTERING

According to Hung and Sakurai\(^1\) the strength and isospin structure of weak neutral currents can be described by four coupling constants, \(\alpha, \beta, \gamma,\) and \(\delta,\) as

\[
J_q = aV^3 + bA^3 + \gamma V^0 + \delta A^0 .
\]

The chiral coupling constants \(u_L, d_L, u_R,\) and \(d_R,\) as introduced by Sehgal\(^2\),

\[
J_q = \tilde{u}_L [u_L (1 + \gamma s) + u_R (1 - \gamma s)] u
+ \tilde{d}_L [d_L (1 + \gamma s) + u_L (1 - \gamma s)] d
\]

are sometimes more directly related to experimentally measurable quantities. The two sets of constants are related by

\[
\begin{align*}
  u_L &= \frac{1}{4}(\alpha + \beta + \gamma + \delta) ; \\
  u_R &= \frac{1}{4}(\alpha - \beta + \gamma - \delta) , \\
  d_L &= \frac{1}{4}(\alpha + \beta + \gamma + \delta) ; \\
  d_R &= \frac{1}{4}(\alpha - \beta + \gamma - \delta) .
\end{align*}
\]

To determine the strength and the isospin structure of the coupling, one assumes, in general, V, A structure and the validity of the quark-parton model, and applies the following strategy:

a) High-precision cross-section ratios on isoscalar targets

\[
\frac{\sigma(\nu_N + \nu^+X)}{\sigma(\nu_X)}
\]

are used to measure

\[
g_L^2 = (u_L^2 + d_L^2) ; \\
g_R^2 = (u_R^2 + d_R^2) .
\]

b) Semi-inclusive \(\pi\) production (\(\nu_N + \nu\pi X\)) or inclusive \(\nu p\) and \(\nu n\) scattering can be used to separate especially \(u_L^2\) and \(d_L^2,\) since

\[
\begin{align*}
  R^p &= \frac{\sigma(\nu p + \nu\pi X)}{\sigma(\nu p + \nu^+X)} = 2u_L^2 + d_L^2 + \text{corrections} , \\
  R^n &= \frac{\sigma(\nu n + \nu\pi X)}{\sigma(\nu n + \nu^-X)} = \frac{1}{2}(2u_L^2 + 2d_L^2) + \text{corrections} .
\end{align*}
\]
c) Elastic scattering \( (\gamma)p \rightarrow (\gamma)p \), exclusive \( \pi \) production \( \nu p \rightarrow \nu n \pi^+ \), etc.,
deuteron break-up \( (\gamma)D \rightarrow (\gamma)np \), and coherent production of \( \pi^0 \) in
\( (\gamma)N \rightarrow \pi^0(\gamma)N \) yield information on the sign of the chiral couplings and
thereby the isospin character.

5.1 Inclusive reactions of neutrinos with
neutrons and protons

There are two contributions to the conference with respect to this
subject which have not been presented by other speakers. Both experiments
are performed using BEBC at CERN.

The Bari-Birmingham-Brussels-London (UC)-E.P. Palaiseau-Rutherford-
Saclay Collaboration \(^{21} \) uses an \( H_2 \) track-sensitive target (TST) to measure
the NC-to-CC ratio on protons

\[
R_p = \frac{\sigma(\nu p \rightarrow uX)}{\sigma(\nu p \rightarrow u'X)}
\]  

(7)

The Ne-\( H_2 \) filling of BEBC surrounding the \( H_2 \) target allows a good measure-
ment of the neutral shower components. Combined with a novel method of
classification, called by the authors a multidimensional discriminant analy-
sis, events can be reliably separated into the three main classes: charged
current, neutral current, and hadron-induced neutral showers. This is
illustrated in Fig. 12, which shows the raw \( R^p \) values as a function of the

![Graph](image-url)

Fig. 12 Cross-section ratio \( R^p \) as a function of the transverse momentum
of the shower: \( a \) for the \( H_2 \) bubble chamber, \( b \) for the \( H_2-NC \) bubble
chamber, with TST.
shower transverse momentum $p_T^h$ for a normal $H_2$ bubble chamber (Fig. 12a) and the new TST method (Fig. 12b). Clearly, the cut which had to be applied to eliminate hadronic background in Fig. 12a requiring $p_T^h > 1.5$ GeV/c is no longer necessary in this experiment.

After all corrections, $911 \pm 52$ CC events and $446 \pm 37$ NC events are found, from which one obtains the result

$$R^P = 0.49 \pm 0.05 .$$

The Amsterdam-Bergen-Bologna-Padua-Pisa-Saclay-Turin Collaboration\textsuperscript{22)} uses BEBC filled with deuterium to derive NC-to-CC ratios on protons and neutrons. To obtain a clean event classification, the cuts $E_h > 5$ GeV and $p_T^h > 1.5$ GeV/c have to be applied for this experiment. After corrections the following results are obtained:

$$R^P = 0.48 \pm 0.05 ,$$
$$R^n = 0.26 \pm 0.03 ,$$
$$R^D = 0.33 \pm 0.03 .$$

As illustrated in Fig. 13, these results can be used to derive values for the coupling constants and the mixing angle:

$$u_L^* = 0.14 \pm 0.04$$
$$d_L^2 = 0.18 \pm 0.05$$
$$\sin^2 \theta_W = 0.210 \pm 0.030 .$$

![Fig. 13 Relation between coupling constants $d_L^2$ and $u_L^*$, and limits obtained by the BEBC experiment (Ref. 20).](image.png)
5.2 Neutrino-induced coherent π° production

In a contribution to this conference, the Aachen-Padua Collaboration describes the measurement, in a spark chamber experiment at the CERN Proton Synchrotron (PS), of coherent production of π° from Al nuclei by neutrinos and antineutrinos. The analysis is based on fully reconstructed 2γ events with no visible recoil. A resolution of ≈ 32% is achieved for the 2γ invariant mass, and Fig. 14 shows the angular distribution of selected π°. The forward peak for θ < 16° is attributed to coherent π° production. The

![Graph showing angular distribution of π° compared with a prediction for resonant production and a control sample with visible proton recoil.]

Fig. 14 Angular distribution of π° compared with a prediction for resonant production (Ref. 22) and a control sample with visible proton recoil.

*) The values quoted are those of an updated analysis received after the conference.
background can be explained assuming resonance production as illustrated in the figure, by comparison with a model prediction of Rein and Sehgal\textsuperscript{2a}) as well as with the experimentally determined dashed histogram, which contains events with a visible proton recoil.

The signal of 106 ± 33 events is used to derive the cross-section for coherent $\pi^0$ production:

$$\sigma_{\gamma} = (15.7 \pm 5.1) \times 10^{-46} \text{ cm}^2/\text{Al nucleus}.$$  

The reaction constitutes a test of the axial-vector part of weak neutral currents since, in the extreme forward direction, vector couplings do not contribute (CVC theorem). In the weak coherent interaction of neutral current,

$$j_{\mu}^{\text{coherent}} = \beta A_3^\mu + \delta A_0^\mu,$$

the isovector coupling $\beta$ describes coherent $\pi^0$ and the isoscalar coupling $\delta$ describes coherent $\eta^0$ production. Figure 15 shows the invariant mass of forward $2\gamma$ events. The $\pi^0$ signal is clearly visible, whereas no $\eta^0$ are produced. Coherent $\eta^0$ production is reduced also because of the low average neutrino energy. The cross-section for $\pi^0$ and the limit on $\eta^0$ production can be used to derive values for the coupling constants. Table 6 compares the results with previous measurements\textsuperscript{2b}). The axial-vector part of NC coupling is predominantly isovector, in agreement with the standard model prediction.

![Fig. 15 Invariant mass of forward-going $2\gamma$ events.](image-url)
6. **SUMMARY**

All new experimental results are consistent with the predictions of the standard model. They confirm the predominance of V and A coupling and especially of V-A coupling for charged current interactions. They show that fermions couple as left-handed doublets and right-handed singlets and that the relative strength of neutral to charged current couplings is consistent with being equal also for purely leptonic interactions. The coupling of all leptons and quarks to the Z° is of universal strength, as illustrated in Fig. 16 which shows the results of measuring the electroweak mixing angle in a wide variety of reactions over a large range of Q².

![Fig. 16](image)

Fig. 16 The $\sin^2 \theta$ determined in various reactions as a function of the average $Q^2$ used in the experiments.
These agreements between experiment and theory are quantitatively verified to a level of 90% or better. The crucial test of the relation

$$m_{\nu} = 37.3 \text{ GeV} / (\cos \theta_W \sin \theta_W) + \text{corrections}$$

will certainly be made in the near future. With the next increase in energy, experiments at PETRA will permit the measurement of the mass of the $Z^0$ through propagator effects and with the $p\bar{p}$ collider experiments at CERN, some $W^\pm$ and $Z^0$ bosons may soon be identified. Even if these experiments confirm the standard model predictions, there remains the challenge to determine $\sin^2 \theta_W$ with high precision as a fundamental constant of nature and as a possible discriminator for grand unified theories.

Acknowledgements

I thank all my colleagues from the CHARM Collaboration for their support, especially K. Winter and G. Barbiellini for many discussions and their critical reading of the manuscript. I am grateful to the members of the BEBC and Aachen-Padua Collaborations for providing me with their recent results, especially to W. van Doninck, H. Faissner and H. de Witt who discussed these results with me.
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PARITY NON-CONSERVATION IN ATOMS

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For the first time the parity non-conservation (PNC) effects in atoms due to neutral currents were discussed by Ja. Zel'dovich /1/ in 1959. The important step was made by M. Bouchiat and C. Bouchiat /2/ who pointed out that these effects are enhanced in heavy atoms (Z low) and proposed to measure a circular polarization in strongly forbidden MI transitions.

The circular polarization of radiation arises due to PNC interaction because of the opposite parity states admixture to the wave functions of electrons in atoms. As a consequence, a small admixture of an E1 amplitude A(E1) to the amplitude of an MI transition A(MI) appears. In this case, the radiation is circular polarized with a degree of polarization

\[ P \sim \frac{A_{\text{PNC}}(E1)}{A(MI)}. \]

The PNC amplitude \( A_{\text{PNC}}(E1) \) can be calculated for atoms if the constants of weak interaction of electron with nucleons, which violates spatial parity, are known:

\[
H = \frac{g}{\sqrt{2}} \left\{ -\bar{u}_e \gamma_5 u_e [c_1 \bar{u}_N \gamma^\mu u_N + \frac{C_3}{2m_p} \partial_\nu (\bar{u}_N \sigma_{\nu \mu} u_N)] + 
+ [c_2 \bar{u}_e \gamma_5 u_e + \frac{C_4}{2m_e} \partial_\nu (\bar{u}_e \sigma_{\nu \mu} u_e)] \bar{u}_N \gamma^\mu u_N \right\}.
\]

The terms with the derivatives can be omitted because they are very small: term with \( C_3 \sim m^{-1}_p \), term with \( C_4 \) corresponds to "anomalous weak moment" and is smaller in \( \sim \alpha/2\pi \) times. Therefore the weak interaction in atoms can be expressed only through four parameters \( C_{1p}, C_{1n}, C_{2p}, \) and \( C_{2n} \):

\[
H = -\frac{g}{\sqrt{2}} \delta(\vec{r}) (\vec{a}_q \gamma_5 - \vec{A} \gamma_5),
\]

\[
z_q = 2c_{1p} + (\Lambda - 2) c_{1n}, \quad \vec{A} = c_{2p} \vec{e}_{\rho i} + c_{2n} \frac{1}{j} \vec{e}_{\rho j}.
\]
In the Weinberg-Salam-Glashow (W-S-G) model

\[ c_{1P} = \frac{1}{2} (1 - 4 \sin^2 \theta), \quad c_{1m} = -1/2, \]

\[ c_{2P} = c_{2m} = -1/2 (1 - 4 \sin^2 \theta) \cdot 1.25 \]

and \( P \sim 10^{-7} \) for usual MI transition in bismuth \((Z = 83)\), \( P \sim 10^{-4} \) for strongly forbidden MI transition in Cs \((Z = 55)\), \( P \sim 10^{-3} \) for strongly forbidden MI transition in Tl \((Z = 81)\).

Another possibility to measure the PNC effects was proposed by Khriplovich /3/, Sandars /4/, Soreide and Portson /5/ who suggested to measure the optical activity of heavy metal vapour. The rotation of the plane of polarization of light appeared due to the difference of refractive indices \( n_+ \) and \( n_- \) for right and left polarized quanta. The rotation angle over a length \( l \) is

\[ \psi^{\text{PNC}} = \frac{2\pi}{\lambda} \frac{\ast}{\Re} \frac{n_+ - n_-}{2} \frac{4\pi l(n-1)R}{\lambda}, \]

where \( \lambda \) is wave length of light, \( R = -P/2 \) and for MI transitions \( R = \text{Im} A^\text{PNC}(E_1)/A(\text{MI}) \). For the bismuth vapour in optimal experimental conditions \( \psi^{\text{PNC}} \sim 10^{-7} \) in the frame of W-S-G model.

**Parity nonconservation in hydrogen atoms**

For hydrogen atoms, in spite of low \( Z \), the PNC effects are not quite near zero because the closeness of the 2P and 2S levels. Without external fields admixture of 2P in 2S state is about \( 10^{-11} \). Additional enlargement of PNC effects is possible due to the 2S - 2P level crossing in magnetic field. For example, in 575 Gs magnetic field the \( e^- \beta \) states crossing takes place (see Fig.1) and PNC effects in microwave transition \( \Delta \nu = 1600 \text{ MHz} \) will be sufficiently enlarged. The microwave experiments in hydrogen are now underway in Michigan /6/, Seattle /7/, Yale /8/ and Zurich /9/. In Fig.2 the microwave parity experiment in Michigan is shown. In this experiment the interference between Stark and weak induced terms can be measured, as it is clear from Fig.3.
Fig. 1. Zeeman diagram for hydrogen at low fields.

Fig. 2. Schematic diagram of the microwave parity experiment.
The first results of the experiment, recently published /10/, give very rough estimation of the $C_{2p}$ parameter: $C_{2p} \leq 620$. Thus the present sensitivity is several orders of magnitude from providing a test of electroweak theory. The main limitation of the experiment arose from modulation of the direction of the magnetic field.

Cesium experiment in Paris

In this experiment /11/ the circular polarization of 1.36 micron fluorescent photons, induced by 540 nm laser light beam, is measured (see Fig.4). The PNC effects arise due to the interference of Stark and weak interaction induced amplitudes. The scheme of the experiment is presented in Fig.5. The electric field is perpendicular to the laser light beam direction $\mathbf{E}_l \perp \mathbf{k}_l$. The field induces the electric dipole in cesium atom $D_{\text{ind}} = -\mu E + i A (\mathbf{E} \cdot \mathbf{k})$. The neutral current weak interaction also gives the electric dipole moment $D_{\text{PNC}} = E \cdot \mathbf{E}_{\text{PNC}} \mathbf{E}$. In this case (see Fig.6), the polarization of the upper 7S 1/2 state in electric field has two components one of which $\mathbf{P} = \mathbf{P}_{\text{ind}} + \mathbf{P}_{\text{PNC}}$ consists of the interference terms of Stark amplitude with MI and PNC amplitudes. Latter term is proportional to degree of circular polarization of incident photons $\gamma_i$. In the experiment the circular polarization of fluorescent photons in the $\mathbf{k}_s$ direction perpendicular to $\mathbf{E}$ and $\mathbf{k}_s$ is measured. This corresponds to the measurement of the first component $\mathbf{P}_i^s$. In 1979 after 15 hours of measurements the value compatible both with zero and WS model prediction was found with statistical uncertainty about $\pm 1$ WS. The control experiment with $\gamma_i = 0$ had un-
Fig. 4. First energy level of Cs.

Fig. 5. The scheme of the experiment.

Fig. 6. Two components of polarization.
certainty ±2WS and no definite conclusion about PNC effect has been done. After this many efforts to avoid false signals due to the spurious electric field were undertaken.

**Thallium experiment in Berkeley**

In this experiment the interference of Stark amplitude with MI strongly forbidden transition amplitude and PNC EI amplitude was measured. The polarization of 7^2P_{1/2} F = 1 state (see Fig. 7) caused by 293 nm ±1 helicity photons was analyzed by selective excitation of 7^2P_{1/2} m_F = ±1 substates to the 8^2S_{1/2} state with circularly polarized 2.18 μm light and observation of 8^2S_{1/2} → 6^2P_{3/2} fluorescence at 323 nm. The difference in polarization for left and right 293 nm photons

\[ \Delta = \frac{2A(M1)}{A_{Stark}(E1)} (1 \pm \delta/2) \]

defines the value of circular dichroism \( \delta = 2 \text{Im}[A^\text{PNC}(E1)/A(M1)] \), which in the frame of W-S-G model was calculated /12,13/

\[ \delta_{\text{theor}} = (2.1 \pm 0.7) \cdot 10^{-3} \]

The first result of the experiment /14/ \( \delta_{\text{exp}} = (5.2 \pm 2.4) \cdot 10^{-3} \)

didn't contradict the W-S-G model, the last one /15/

\[ \delta_{\text{exp}} = (2.8 \pm 0.7 \pm 0.3) \cdot 10^{-3} \]

is consistent with \( \delta_{\text{theor}} \) quite well.

![Fig. 7. First energy levels of Tl.](image)
Optical rotation in bismuth vapour

The scheme of low energy levels of atomic bismuth is shown in Fig. 8. The optical activity of bismuth vapour was investigated in region of the allowed MI transitions at $\lambda = 648$ nm (Oxford, Novosibirsk and Moscow) and at $\lambda = 876$ nm (Seattle). For these lines the theoretical calculations fulfilled by different methods agree now quite well with may be one exception /20/. In /20/ the Hartree-Fock method was used, which underestimates the result.

Table 1

<table>
<thead>
<tr>
<th>Line</th>
<th>Novosibirsk</th>
<th>Seattle</th>
<th>Oxford</th>
<th>Moscow</th>
</tr>
</thead>
<tbody>
<tr>
<td>648 nm</td>
<td>$-19^{16}$</td>
<td>$-11^{20}$</td>
<td>$-14^{19}$</td>
<td>$-15.5^{21}$</td>
</tr>
<tr>
<td>876 nm</td>
<td>$-14^{16}$</td>
<td>$-18^{17}$</td>
<td>$-12^{19}$</td>
<td>$-12.8^{21}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$-12^{18}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$-8.3^{20}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The Novosibirsk group used semiempirical approach and the accuracy of their calculations can be estimated as 15%. Therefore, in comparison with experiments their $R_{\text{theor}}$ values were used.

Fig. 8 First energy levels of Bi.
Bismuth experiment in Oxford

The measurements of PNC optical rotation have been done only in the vicinity of the most intense \( F = 6 \rightarrow F = 7 \) hyperfine component of the MI transition \( 6P^{3/2}S_{3/2} \rightarrow 6P^{3/2}D_{5/2} \). The scheme of the experiment is shown in Fig.9. The optical system consists of a pair of crossed polarizers with a bismuth oven between them. The optical rotation of bismuth vapour is measured by standard method with the help of the Faraday cell. The bismuth oven has no magnetic shield and therefore the measurements were done at the laser wavelengths, at which Faraday effect is near zero and PNC effect has maximum. As a control the measurements with dummy tube without bismuth vapour have been done.

The old result of the experiment /22/

\[ R_{\text{exp}} = (2.7 \pm 4.7) \times 10^{-8} \]

is consistent with zero. The new result /23/

\[ R_{\text{exp}} = (-3 \pm 2) \times 10^{-8} \]

is definitely above zero. The Oxford group searches also now

Fig.9. Schematic diagram of apparatus. A, P-crossed Glan-Thompson polarizers, F-Faraday cell, I-interference filter, PSD-phase sensitive detectors, PD-pin detectors.
PHC optical rotation at 876 nm. The preliminary result for this line $|R| < 15 \times 10^{-8}$ was reported at the Vavilov Conference (Novosibirsk, 1981).

Bismuth experiment in Seattle

The experiment was done on the $6p^3^{4}S_{3/2} \rightarrow 6p^3^{2}D_{3/2}$ absorption line at 876 nm where there are no $\text{H}_2$ molecular bands. The scheme of the experiment (see Fig. 10) is similar to that of Oxford.

Fig. 10. Schematic view of the apparatus.

The old results of the experiment /24,25/ are close to zero:

$$R_{\text{exp}} = (-0.7 \pm 3.2) \times 10^{-8} \quad (1977),$$

$$R_{\text{exp}} = (-1.1 \pm 1.2) \times 10^{-8} \quad (1978)$$

and the new result /26/
\[ R_{\text{exp}} = (-10.4 \pm 1.7) \times 10^{-8} \]

is definitely above zero and in agreement with W-S-G model prediction.

**Bismuth experiment in Novosibirsk**

The measurements of optical activity on 648 nm bismuth line were made with the help of wavelength modulation method shown in Fig.11. In this method the wavelength modulation generates the signal from PMT2

\[ V_2 \sim \text{Isin}^2(\theta + \psi_{\text{PNC}}(t)) = I \theta^2 \left( 1 + 2 \psi_{\text{PNC}}(t)/\theta \right), \]

in which 1 kHz harmonic appears only through \( \psi_{\text{PNC}}(t) \), if the wavelength modulation is done exactly at the centre of absorption line. The signal from PMT1 is equal to

\[ V_1 \sim \text{Icos}^2(\theta + \psi_{\text{PNC}}(t)) = I \theta^2 \]

and it is possible to subtract \( V_1 \) and \( V_2 \) signals, so that

![Fig.11. The scheme of the experiment. P-polarizer, A-prism analyzer, PMT1 and PMT2-photomultipliers, PSD-phase sensitive detectors, ADC- analog-digital converter, PD- pin detector.](image-url)
In the experiment the subtraction is better than $10^{-3}$ so that
\[ V_{\text{subtr}}(2 \text{kHz})/V_{\text{E}}(2\text{kHz}) < 10^{-3}. \]
The suppression of 1 kHz signal in I is also better than $10^{-3}$. During the experiment the pressure of helium buffer gas (bismuth vapour pressure) was
\[ \sim 16 \text{ Torr}, \quad l_{\text{eff}} \approx 50 \text{ cm}, \quad H_{\text{appr}} \leq 2 \cdot 10^{-5} \text{ Gs}, \quad \theta = 4 \cdot 10^{-3} \text{ rad.} \]
During one measurement $\theta$ changes 20 times $\theta \leftrightarrow -\theta$.

At the first stage of the experiment the measurements have been done on five MI transitions (1,3,7,12 and 18 lines, see Fig.12) and three E2 transitions (2,10,17 lines) of the hyperfine structure of the atomic bismuth lines, and on four molecular lines (A,B,C,D).

Fig.12. Observed absorption spectrum of bismuth vapor and Faraday rotation curve in the vicinity of the 648 nm atomic bismuth line.
In these measurements the PNC effect due to neutral current weak interaction was observed /27,28/:

\[ R_{\text{exp}} = (-19.5 \pm 5) \times 10^{-8}. \]

At the next stage of the experiment /29/ the measurements were done on 1, 2, 3 and A lines (see Figs. 12 and 13). The results are presented in Fig. 13 and in Table 2.

Fig. 13. a) Dashed line - the theoretical prediction for PNC optical rotation of bismuth vapor, solid line - the calculated Faraday rotation; b) - observed absorption spectrum; c) - the calculated curve \( d\psi^{\text{PNC}}/d\lambda \) and the results of the measurements.
Table 2

The $\psi_{\text{exp}}$ and $R$ values in $10^{-8}$ rad and $10^{-8}$ units, correspondingly.

<table>
<thead>
<tr>
<th>Line</th>
<th>$F-F'$</th>
<th>$\psi_{\text{exp}}$</th>
<th>$R$</th>
<th>$\psi_{\text{exp}}/\psi_{\text{theor}}$</th>
<th>Time of meas., h</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6-7</td>
<td>-12.9±2.0</td>
<td>-20.9±3.4</td>
<td>1.11±0.18</td>
<td>26 x 1/2</td>
</tr>
<tr>
<td>2</td>
<td>5-7</td>
<td>-0.7±1.3</td>
<td>-</td>
<td>-</td>
<td>26 x 1/2</td>
</tr>
<tr>
<td>3</td>
<td>6-6</td>
<td>-2.9±1.8</td>
<td>-17±11</td>
<td>0.9±0.6</td>
<td>13 x 1/2</td>
</tr>
<tr>
<td>A</td>
<td>-</td>
<td>-0.3±1.4</td>
<td>-</td>
<td>-</td>
<td>26 x 1/2</td>
</tr>
</tbody>
</table>

From these measurements

$$R_{\text{exp}} = (-20.6±3.2) \cdot 10^{-8}$$

and the average over all measurements

$$\langle R_{\text{exp}} \rangle = (-20.2±2.7) \cdot 10^{-8}.$$  

Bismuth experiment in Moscow

The outset of the experiment is shown in Fig. 14 and is very similar to that of Oxford.

For stabilization of laser beam position the optical fiber was used and for a control the measurements were done at low bismuth pressure. The results of measurements [30,31] on $F = 6 \rightarrow F = 7$ hyperfine component of 648 bismuth line are shown in Fig. 15 and in Table 3.

As it is seen from Fig. 15 and Table 3, the measurements during the third run point out that at low pressure the effect is not equal to zero. It means that the scheme is not free from spurious effects.

Table 3

<table>
<thead>
<tr>
<th>Run</th>
<th>$\Delta \psi_{\text{exp}}^{\text{PNC}} \cdot 10^8$</th>
<th>$\Delta \psi_{\text{exp}} \cdot 10^8$</th>
<th>$R_{\text{exp}}/R_{\text{theor}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>-0.23±1.0</td>
<td>-1.2±1.0</td>
<td>-0.02±0.1</td>
</tr>
<tr>
<td>II</td>
<td>-</td>
<td>-</td>
<td>0.22±0.08</td>
</tr>
<tr>
<td>III</td>
<td>3.6±1.3</td>
<td>-3.2±1.2</td>
<td>0.23±0.08</td>
</tr>
<tr>
<td>Average</td>
<td>3.6±1.3</td>
<td>-3.2±1.2</td>
<td>0.13±0.07</td>
</tr>
</tbody>
</table>
Fig. 14. Setup of the experiment.

Fig. 15. $\Delta \psi$ measurement on $F=6 \rightarrow F=7$ bismuth line.
- - for full pressure, o - for low pressure.
Summary of the results and conclusion

The last results of the Michigan hydrogen experiment give no hope to have significant information about an electroweak interaction of electrons with nucleons in the nearest future. As before, bismuth experiments have the highest sensitivity. Table 4 lists the results of R experiments performed by different groups. It is seen that the experimental results obtained by Novosibirsk, Oxford and Moscow groups still contradict each other.

Fig.16 presents, in chronological sequence, the results of PNC electron-nucleon interaction experiments. New thallium experiments in Berkeley and bismuth ones in Seattle give additional evidence in favour of the validity of W-S-G model.

<table>
<thead>
<tr>
<th>Table 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>The $R_{\text{exp}}$ values in $10^{-8}$ units and $R_{\text{exp}}/R_{\text{theor}}$ ratio for Bi</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>Seattle, 1977</td>
</tr>
<tr>
<td>876 nm 1978</td>
</tr>
<tr>
<td>1980</td>
</tr>
<tr>
<td>Oxford, 1977</td>
</tr>
<tr>
<td>648 nm 1980</td>
</tr>
<tr>
<td>Novosibirsk 1979</td>
</tr>
<tr>
<td>Moscow 1980, I</td>
</tr>
<tr>
<td>648 nm 1980, II</td>
</tr>
</tbody>
</table>
Fig. 16. The ratio of experimental PNC parameter to that predict in W-S-G model with \( \sin^2 \theta = 0.25. \)

- Seattle /24-26/, o - Oxford /22,23/,  
\( \Delta \) - Novosibirsk /27-29/, x - Berkeley /14,15/,  
\( \Delta \) - Moscow /30,31/, n - Stanford /32,33/. 

References

A SEARCH FOR THE ELECTRIC DIPOLE MOMENT OF THE NEUTRON

V.M. Lobashev

Report at the International conference "Neutrino-82"

After discovery of CP-violation in K\(^0\)-decay a search for CP-violating phenomena outside the K\(^0\)-system became one of the most important problems of elementary particle physics. CP-violation phenomena are expected to be displayed at low energy processes as tiny effects. May be in the Higgs particle world those effects are big enough, but in spite of the smallness of its manifestations in the common hadron–lepton world, CP-violation probably played a determinant part for the production of a baryon excess at the earliest stage of development of Universe.

A search for the electric dipole moment of neutron and other elementary particles as a measure of P-parity violation was first discussed by N. Ramsey and E. Pursell in 1949, later it was understood as a mean to test both parity and time-reversal invariance.

From the first experiment by N. Ramsey et al./1/ to the latest result reported below the limit on the existence of the EDM of the neutron was reduced from \(\sim 5 \times 10^{-20}\, \text{e.cm}\) to \(4 \times 10^{-25}\, \text{e.cm}\): that is, by more than five orders of magnitude.

The most sensitive approach for measuring the EDM to date is the magnetic resonance method for neutrons with an electric field applied within the region of a permanent magnetic field. Interaction of the EDM with the electric field produces a neutron spin precession frequency shift in the magnetic field. The experi-
ment should involve measurements of the resonance frequency shift as the direction of the electric field is reversed with respect to the magnetic field. The magnitude of this shift is very small. As an example, for an electrical field strength of ± 25 kV/cm and EDM = 10^{-25} e.cm, the frequency shift is ≈ 2.5 \times 10^{-6} Hz. It is evident that the task of observing such a shift is extremely complex and calls for both high intensity of the neutron beam and high sensitivity of the spectrometer to the resonance frequency shift.

This indicates that the width of the magnetic resonance line should be reduced, which in turn is restricted by the neutron residence time in the spectrometer; that is, by the relation \( \Delta E \Delta t \approx \frac{\hbar}{E} \).

In the earlier experiments in the search for the neutron EDM, use was made of a thermal or cold neutron beam and hence the interaction time was limited by the neutron time-of-flight through the spectrometer, which amounted at best to \( \approx 10^{-2} \) s.

This report presents the latest results of long study of use of ultracold neutrons for measurements of EDM of the neutron.


The experiment described below was conducted on the WWR-M reactor of the INI using the maximum neutron flux density of \( \approx 2.10^{14} \) neutron/cm².s, which is one order of magnitude less than that on the ILL reactor at Grenoble.

Preparation for the experiment started in 1968 involved overcoming the problems connected with the production, channeling and storage of UCN, developing the method of UCN polarization and for polarization analysis as well as with the methods for increasing the ef-
efficiency of the UCN detectors\(^2\). Setting up a highly stable and uniform magnetic field in the spectrometer turned out to be an important problem. The problems related to high-voltage equipment and to an insulator coating with a high boundary velocity of neutron reflection proved to be bigger than originally anticipated.

In place of a single-chamber spectrometer, use was made of a differential double-chamber version incorporating an electric field of opposite sign in the two chambers but featuring a common magnetic field and a common system of oscillating fields. In this case, the influence of fluctuations of the common magnetic field and various spurious effects caused by the reversal of the high voltage were reduced to a negligible quantity. This circumstance is critical in experiments in the search for the EDM because it is impossible to conduct a full-scale check experiment.

The first result of this study published in 1979 was:

\[
d_n = (4 \pm 7.5) \times 10^{-25} \text{e.cm};
\]

or at 90% confidence limit

\[
|d_n| < 1.6 \times 10^{-24} \text{e.cm}
\]

At this stage a source of UCN comprised a 300K helium cooled Berillium convertor placed in thermal neutron flux \(\sim 10^{14} \text{n/cm}^2 \cdot \text{s}\) providing \(\sim 1.2 \times 10^4 \text{UCN/s}\) on the output of neutron quide of 7x6 cm\(^2\) cross section. At present measurements a more intensive source of UCN based on a 150 cm\(^3\) liquid hydrogen moderator was developed providing an UCN flux of \(\sim 5 \times 10^4 \text{UCN/s}\).

A simplified sketch of the spectrometer used in the experiment is shown in fig.1.

The spectrometer incorporates two equivalent channels, each channel being connected to its appropriate trap for storage of UCN
(upper and lower chambers). The electrical field strength in the upper and lower chambers is opposite in direction, and hence parallel electric and magnetic fields are set up in one chamber and anti-parallel in the other. If the polarity of the voltage supply to the spectrometer is reversed, the resonance frequency shift (with \( B_{DI} \neq 0 \)) in the upper and lower channels will be opposite in sign. This will make it possible to distinguish the true "EDM effect" from the spurious one related, for instance, to changes in the spectrometer resonance conditions due to the influence on the electronic instrumentation when changing high voltage. A spurious resonance shift in the upper and lower channels will be of the same sign because use is made of common systems furnishing resonance conditions in the upper and lower chambers. Such an experimental system enables one to reduce the effect of the magnetic field instability on the accuracy of the experimental results and, in addition, solves the problem related to the check experiment. The advantages specified above give the experimental results a better reliability and a doubled or trebled gain in the final accuracy.

Secondly, a double analysis of the neutron beam polarization is made at the spectrometer output. Such a system for the analysis of polarization makes it possible to register both spin components of the neutron beam and hence results in a two-fold increase of the intensity recorded.

The system incorporates two analyzers made of thin ferromagnetic film placed in the magnetic field, with the first one used to replace the side wall of the neutron guide. One component of the neutron beam, whose spin is opposite to the field, passes through the film and strikes a double detector \( D_1 \) while the other one is reflected from the film and travels further to the double detector \( D_2 \) and thus the spin components of the neutron beam are separated.
For improving the efficiency of the polarization analysis, another film analyzer is provided ahead of detector $D_2$ and a flipper placed between the films is used for passing the "proper" spin component through the analyzer.

Note that with this system of polarization analysis the resonance frequency shift leads to an increase in the counting rate for one double detector and a decrease of the rate for the other. This fact makes it possible to mark out the change in the resonance conditions against the background of variations in the neutron beam intensity brought about by other causes.

In general, features of such an experimental system are based on the principles of correlation analysis. The experimental system in hand incorporates four detectors. The presence of a true EDM effect causes a specific correlation in changes of the counting rate for the four detectors which makes the system adequately protected against most of the spurious effects possible.

The experimental equipment is shown in more details in fig.2. Ultra-cold neutrons are produced from thermal neutrons in inelastic scattering on the converter (17). The cooled converter and a mirror type neutron guide section made of stainless steel are placed in a water cavity in the centre of the reactor active zone (16) where the flux of thermal neutrons is $1 \times 10^{14} \text{n/cm}^2\text{s}$.

The UCN flux thus obtained is fed into a magnetic resonance spectrometer. The polarizer (13) is made from a 1 $\mu$m thick Fe-Co film placed in a 600 Oe magnetic field set up by permanent magnets. The polarizer lets neutrons with one spin component pass through and reflects those with the other. Polarized neutrons go further through a neutron guide made of plate glass coated with a layer of $58\text{Ni}, \text{Mo}$ - alloy and get into the spectrometer surrounded by a system of magnetic screens (10).
Two coils (6) in the central part of the screens set up a uniform static magnetic field whose strength is 0.020 Oe, which corresponds to a neutron spin precession frequency of 83 Hz. The solenoid (12) producing the oscillating field is found on the input neutron guide and the magnetic field gradient is set up by the coils (4). Once through the solenoid, the neutrons are delivered into two chambers. The side walls of the chambers are made from fused quartz coated by beryllium oxide. Neutrons are fed into the chambers through the central electrode charged at zero potential. The electrical field strength in the chambers is ~25 kV/cm.

On wandering inside the chambers (the UCN mean storage time is 5 s), the neutrons traverse the double neutron guide through an output solenoid setting up the oscillating field and get into the double polarization analysis system.

The neutrons come to one of the detectors depending upon the sign of the spin projection onto the magnetic field. It will be recalled that each detector is of a double type.

Ahead of the detectors there is a downward-bent neutron guide section for accelerating the neutrons in a gravitational field so as to let them pass through the aluminium windows of the detectors which are proportional counters filled with a $^3$He-Ar mixture. The overall efficiency of the neutron detection in such a system is close to 100%.

Each cycle of measurements comprises four exposures with alternating polarity of the electric voltage, that is + - - + or - + + -, so as to eliminate the influence of the linear drift of the magnetic field and of the neutron intensity. The cycles of measurements with the phase shift between the input and output oscillating fields of 90° and 270° followed one after another.
For each detector, the resonance frequency shift and the neutron EDM are calculated from the changes in the neutron counting rate caused by the high voltage polarity reversal using the formula

\[ d_i^k = \left( \alpha_i^k / E \right) \Delta f_i^k = \alpha_i^k (N^+ - N^-)^i_k / E (\partial N / \partial f)^i_k, \quad (1) \]

where \( \alpha_i^k = (-1)^1(A) \) (with \( A \) constant), \( E \) is the electric field strength, \( \Delta f \) is the change in the resonance frequency caused by the electric field reversal, \( N^+, N^- \) are the detector counting rates for positive and negative polarity of the electric voltage, respectively. Subscripts \( i = 1, 2 \) refer to the upper and lower chambers and \( k = 1, 2 \) to detectors 1 or 2, respectively.

Such a spectrometer scheme offers a check on possible systematic errors. For the purpose, linearly independent combinations are formed from the four quantities \( d_1^1, d_1^2, d_2^1, d_2^2 \):

\[ d = \frac{1}{4} \left[ (d_1^1 + d_1^2) + (d_2^1 + d_2^2) \right], \]

\[ J = \frac{1}{4} \left[ (d_1^1 + d_1^2) - (d_2^1 + d_2^2) \right], \]

\[ J = \frac{1}{4} \left[ (d_1^1 - d_1^2) - (d_2^1 - d_2^2) \right], \]

\[ z = \frac{1}{4} \left[ (d_1^1 - d_1^2) + (d_2^1 - d_2^2) \right]. \quad (2) \]

The first of these combinations is specific for the magnitude of the effect sought. The second permits the possible influence of the electric voltage reversal on the resonance to be revealed (such as changes of the magnetic field, of the frequency of the oscillating magnetic field, the phase difference between the oscillating magnetic fields at the spectrometer input and output, etc.). The
third combination contains information relating to the possible influence of the voltage reversal on the detectors. Finally, the fourth combination takes into account the extent to which the above effects are compensated for. The difference likely to occur in the sensitivity of the counting channels of different detectors to spurious effects due to high-voltage breakdowns is eliminated by periodic sign reversals of the derivatives $\Delta N/\Delta t$ for all detectors using a switch for changing the phase of the oscillatory field (from a particular $\Delta \Psi$ to $\Delta \Psi + 180^\circ$). These spurious effects can be eliminated by combining the results of such measurements. Conversely, to reveal these effects, the difference $J^- = J(\Delta \Psi) - J(\Delta \Psi + 180^\circ)$ should be set up, when analyzing the results for $J$.

It should also be noted that the spectrometer scheme referred to makes it possible not only to compensate for the main systematic errors, but also to suppress instabilities. The level of instability both of the resonance conditions and of the intensity can be found from the data analysis making use of the difference between the r.m.s. errors of the values obtained for $J$ and $J^-$ and the statistical errors.

The results of measurements of EDM of the neutron are presented in Table 1. The results for $\Delta \Psi$ and $\Delta \Psi + 180^\circ$ are averaged.

<table>
<thead>
<tr>
<th></th>
<th>I run</th>
<th>II run</th>
<th>III run</th>
<th>The weighted average</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d$</td>
<td>$+2,1 \pm 2,4$</td>
<td>$-1,0 \pm 2,8$</td>
<td>$-3,5 \pm 1,3$</td>
<td>$-2,0 \pm 1,0$</td>
</tr>
<tr>
<td>$J$</td>
<td>$16,6 \pm 4,8$</td>
<td>$+1,5 \pm 5,8$</td>
<td>$1,1 \pm 2,8$</td>
<td>$4,5 \pm 2,2$</td>
</tr>
<tr>
<td>$z$</td>
<td>$4,8 \pm 2,4$</td>
<td>$-2,6 \pm 2,7$</td>
<td>$-3,7 \pm 1,3$</td>
<td>$-1,9 \pm 1,0$</td>
</tr>
<tr>
<td>$J^-$</td>
<td>$-5,3 \pm 3,5$</td>
<td>$-5,0 \pm 4,1$</td>
<td>$-0,6 \pm 2,2$</td>
<td>$-2,4 \pm 1,7$</td>
</tr>
</tbody>
</table>
The first run was carried out keeping the average level of leakage current in high voltage system about 1 \( \mu \)A. The other two were carried out at the leakage current not more then 0.2 \( \mu \)A.

This difference of leakage current conditions was probably the reason why we could not completely eliminate the effect of the high-voltage reversals upon the spectrometer, which is obvious from the value of \( \delta \) different from zero by 3,5 standard deviations. An analysis carried out for the cases featuring large deviations showed that the influence of this effect on the EDM is compensated for by the two chamber system by a factor of about 20. The contribution of the possible effect due to nonparallelism of the electric and magnetic fields were checked by measuring a magnetic field inclination with respect to the electric one. The additional magnetic field perpendicular to the electric one was produced by special coils and a shift of resonance frequency for different current value in the coils was measured. An angle between magnetic and electric field directions proved to be \( \approx 0.1 \) mrad, that is the simulated EDM value may be less than \( 10^{-26} \) e.cm.

Run III showed a significant deviation from zero both \( d \) (EDM) and \( Z \) (zero effect) value. The same correlation of \( d \) and \( Z \) values but statistically less significant was observed also in Run I result. At this moment we do not have an explanation of this correlation, if it would exist.

The EDM value averaged over three runs is:

\[
d_n = -(2 \pm 1) \times 10^{-25} \text{ e.cm.}
\]

This value should be interpreted at present understanding of accuracy level only as:

\[
|d_n| < 4 \times 10^{-25} \text{ e.cm}
\]

at 90% confidence limit.
Some further improvements of the experiment sensitivity are now under preparation, so we anticipate to achieve the level of statistical accuracy of about \((0.3-0.5) \times 10^{-25}\) in the next year.

At this stage the overall accuracy probably would be dominated by systematical errors, especially those ones caused by leakage currents.

Two-chamber system of spectrometer will allow to control the appearance of such effects, but they should be at last carefully eliminated.

The calculation of EDM of the neutron are made on the base of two models.

In the first one a CP-violation is introduced into Higgs particles interactions (Weinberg S. /4/). The calculation on the base of this model give

\[
\begin{align*}
\delta_n &= 2.3 \times 10^{-24} \text{ e.cm} /4/; \\
\delta_n &= -(1+3) \times 10^{-25} \text{ e.cm} /5/; \\
\delta_n &= -(3+9) \times 10^{-25} \text{ e.cm} /6/;
\end{align*}
\]

(the later corrected for sign).

The first value is convincingly ruled out by our limit for the EDM. The two other are still within the experimental uncertainty limits.

The second class of models of CP-violation is a Kobayashi-Maskawa model, where CP-violation is introduced in lepton and quark mixing angles. The predictions of this model for EDM of the neutron are lower than \(10^{-26}\) e.cm.

The next two years probably will give us information about EDM of the neutron, which will allow to choose between these models.
FIGURE CAPTIONS

FIG. 1 1- magnetic shield; 2- coils; 3- chambers of storage of UCN; P- polarizer; A₁, A₂ - analyzers; D¹₁, D¹₂, D²₁, D²₂ - detectors; H₀ is the constant magnetic field; H₁ is the oscillating magnetic field; E is the electric field.

FIG. 2 Experimental setup.
  1- double detectors; 2- flipper of double polarization analysis system; 3- analyzers; 4- coils setting up magnetic field gradient; 5- demagnetizing coils; 6- coils setting up constant magnetic field; 7- UCN storage chambers; 8- flux-gate external magnetic field stabilization system; 9- quantum magnetometer transducer; 10- magnetic screens; 11- cryogenic piping; 12- solenoid for field H₁; 13- polarizer; 14- neutron guide; 15- lead screen; 16- reactor core; 17- converter.
REFERENCES


source of UCN from liquid \( \text{H}_2 \)

\( \rho \approx 2.5 \, \text{cm}^{-2} \)

Fig. 1
DEEP INELASTIC SCATTERING STRUCTURE FUNCTION
RECENT RESULTS FROM THE CHARM COLLABORATION

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(Presented by A. CAPONE)

ABSTRACT

Recent results of the neutrino counter experiment carried out by the
CHARM Collaboration are presented. They cover the following topics:

i) Measurement of the polarization of positive muons produced in high-
energy antineutrino interactions (in collaboration with the CDHS
group).

ii) Study of \(x\) distributions in semileptonic neutral-current neutrino-
and antineutrino interactions.

iii) Search for coherent muon pair production by muon neutrino and anti-
neutrino scattering on nuclei.

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1. **STUDY OF THE POLARIZATION OF POSITIVE MUONS BY $\bar{\nu}_\mu$**

This experiment was performed in the wide-band antineutrino beam of the 400 GeV Super Proton Synchrotron (SPS) at CERN, using the massive CDHS (CERN-Dortmund-Heidelberg-Saclay Collaboration) neutrino detector$^1$ as the target for $\bar{\nu}_\mu$ interactions.

The CHARM apparatus$^2$ was used as a muon polarimeter. Positive muons focused by the toroidal field of the CDHS detector entered the CHARM apparatus, where about 3% of them stopped (Fig. 1). The experimental arrangement as well as earlier results have been described elsewhere$^3$.

A magnetic field of 58 G perpendicular to the beam direction, produced by magnetizing the calorimeter frame as a dipole, induced the spin of the stopped muons to precess with a period of 1.3 $\mu$s. This precession causes a time-dependent backward-forward asymmetry of the outgoing positron from muon decay at rest, with a phase and amplitude related to the longitudinal polarization of the muon. The study of the $\mu^+$ polarization is a test of the structure of weak charged-current interactions at high centre-of-mass energy.

Vector and axial-vector currents preserve lepton helicity, whereas possible $S$, $P$, $T$ terms in the Lagrangian of the charged-current $\nu$ interaction would flip the helicity and produce positive muons with negative helicity (Fig. 2).

A total of 195,473 muons were produced in the target and stopped in the polarimeter, where 27,812 decay positrons were detected. After fiducial volume cuts in the CDHS and CHARM analysis, 17,484 events were left. The observed time dependence of the backward-forward asymmetry

$$R(t) = \frac{N_B(t) - N_F(t)}{N_B(t) + N_F(t)}$$

is shown in Fig. 3.

---

**Fig. 1**  
**Fig. 2**
We parametrized the time-dependent backward-forward asymmetry as
\[ R(t) = R_0 \cos(\omega t + \phi) + R_1, \]
where \( R_0 = \alpha \cdot P \) is given by the polarization value \( P \) of the \( \mu^+ \) and the polarimeter analysis power \( \alpha \); \( \phi \) is related to the sign of the helicity, and we expect \( \phi = 0 \) for negative helicity and \( \phi = -\pi \) for positive helicity. The best fit of the measured asymmetry (continuous line in Fig. 3) gives \( R_0 = 0.116 \pm 0.010, \phi = -3.02 \pm 0.08, \) and \( R_1 = 0.364 \pm 0.007. \) The value of \( \phi \) is in excellent agreement with the value of \( -\pi \) predicted for muons of positive helicity.

The S and P terms do not contribute to the interaction at \( y \ll 0; \) therefore, neglecting T contributions, the value of the polarization at small \( y \) (\( y \leq 0.2 \)) can be used as normalization for the polarization at large \( y \) to derive a limit on S and P contributions which is unaffected by the systematic errors on the knowledge of the analysis power of the polarimeter \( \alpha. \)

Figure 4 shows the value of \( R_0 \) as a function of the inelasticity \( y. \) Using the value of \( R_0 \) for \( y \leq 0.2 \) as normalization, we get from \( 0.5 \leq y \leq 1.0 \) a limit of
\[ \frac{\sigma_{S,P}}{\sigma_{\text{tot}}} \leq 0.07 \quad (95\% \text{ CL}). \]

We can test time-reversal invariance at large \( Q^2 \) by looking for a component of the polarization outside the \( \mu^+ \) production plane. Such a term would be proportional to
\[ \vec{\sigma}_\mu (\vec{p}_\mu \times \vec{p}_\mu). \]
where $\hat{O}$ is the spin of the $\mu^+$, and $p_\mu^+$, $p_\mu^-$ are the momentum vectors of the incoming antineutrino and outgoing muon. Since the CHARM polarimeter can only measure the polarization component in the horizontal plane (perpendicular to the magnetic field which is vertical), we have performed the study of time-reversal invariance by comparing the results of fits to the backward-forward asymmetry for events in which the positrons from $\mu^+$ decays appear in two different azimuthal regions of the polarimeter. Two samples of events were analysed determined by a cut in the azimuthal muon production angle $\phi$. The results of the fits are summarized in Table 1.

Indicating by $O^T$ the contribution to the charged-current cross-section from time-reversal violating and by $O^N$ the time-reversal non-violating terms, we can write

\[
\begin{align*}
\left(\sigma_{\text{tot}}^O\right)_{|\phi| \leq 60^\circ} &= \sigma_{\text{NT}}^O - \frac{\sigma_{\text{NT}}^O}{2}, \\
\left(\sigma_{\text{tot}}^O\right)_{|\phi| \geq 120^\circ} &= \sigma_{\text{NT}}^O + \frac{\sigma_{\text{NT}}^O}{2}.
\end{align*}
\]

From the results of Table 1 we find $O^T/\sigma_{\text{tot}} < 11\%$ at the 95\% confidence level.

<table>
<thead>
<tr>
<th>R$_0$</th>
<th>$\phi$</th>
<th>R$_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>All data</td>
<td>0.116 ± 0.010</td>
<td>-3.02 ± 0.08</td>
</tr>
<tr>
<td>$</td>
<td>\phi</td>
<td>\leq 60^\circ$</td>
</tr>
<tr>
<td>$</td>
<td>\phi</td>
<td>\geq 120^\circ$</td>
</tr>
</tbody>
</table>

2. **SEARCH FOR COHERENT MUON PAIR PRODUCTION BY $\nu_\mu$ AND $\bar{\nu}_\mu$ INTERACTIONS ON NUCLEI**

A study of the reactions (see Fig. 5):

\[
\begin{align*}
\nu_\mu + (A,Z) &\rightarrow \nu_\mu^+\mu^- + (A,Z) \\
\bar{\nu}_\mu + (A,Z) &\rightarrow \bar{\nu}_\mu^+\mu^- + (A,Z)
\end{align*}
\]

provides information about the diagonal four-fermion interaction$^b)$. These reactions can be mediated both by neutral and charged currents, and in the standard model the diagonal coupling constant $G_D$ should be of the order of the Fermi coupling constant $G_F$. 

---

$^a)$

$^b)$
Assuming the Glashow-Salam-Weinberg model, the interference between the charged and neutral current terms should be negative. We then expect: $G_D = 0.77 G_F$, assuming $\sin^2 \theta_\mu = 0.23$.

A search for events described by reactions (1) and (2) has been performed using data collected during an exposure of the CHARM detector to $\nu_\mu$ and $\bar{\nu}_\mu$ wide-band beams at the CERN 400 GeV SPS. During these exposures, corresponding respectively to $1.3 \times 10^{18}$ and $5.2 \times 10^{18}$ protons on target, we collected $1.5 \times 10^6$ and $1.8 \times 10^6$ neutrino- and antineutrino-induced charged-current events in a fiducial volume corresponding to a target mass of 129 tons, with the following trigger requirements:

i) detected energy larger than 1 GeV;
ii) at least four scintillator planes hit;
iii) at least one track penetrating at least three magnets of the muon spectrometer.

We selected recoilless events ($E_h \leq 3$ GeV) in which both muons had penetrated the muon spectrometer (this implies an effective momentum cut $p_\mu \geq 7 \pm 2$ GeV).

After these cuts we are left with 27 events induced by neutrinos and by antineutrinos: we will analyse them together because events due to reactions (1) and (2) are symmetric with respect to $\mu^+$ and $\mu^-$. Figure 6 shows the distribution of the total energy deposited in 10 scintillator planes $E_{10}^{\text{meas}}$ following the vertex: the expected energy deposition for two muons is $E_{10}^{\text{meas}} = 150$ MeV. We select recoilless events
with less than 200 MeV deposited energy in the first 10 planes after the vertex. The efficiency of this cut is (89.5 ± 1.0)%. After this cut we are left with eight candidates. The other signature for events due to reactions (1) and (2) is a low invariant \(\mu^+\mu^-\) mass. The invariant mass distribution for the eight candidates is shown in Fig. 7. The dashed line in the figure is a Monte Carlo prediction for trident events assuming the standard model and using our knowledge of the beam spectra and of the experimental resolutions. Applying a cut at \(W_{\mu^+\mu^-} < 0.8\) GeV (corresponding to an efficiency of 60% for trident events), two events survived. The possible background is due to semileptonic hadron (pion, charmed meson, etc.) decays and can still contribute to the candidate sample. Assuming that there is no difference in the background dimuon invariant mass distribution for low hadron-energy and recoilless events, we estimated the number of background events below \(W_{\mu^+\mu^-} = 0.8\) GeV using the dimuon invariant mass distribution for 19 events with \(E_{\text{miss}} > 200\) MeV (Fig. 8). The estimated background is 0.3 ± 0.5 events. The signal which can be attributed to reactions (1) and (2) is finally 1.7 ± 1.7 events, corresponding to

\[ G_D = (0.75 \pm 0.40)G_F, \]

in agreement, within the very large error, in the context of gauge theories, with negative interference between the \(W^+\) and \(Z^0\) exchange diagrams as predicted in the case of the Glashow-Salam-Weinberg model. A limit can be set on the diagonal four-fermion coupling constant corresponding to

\[ G_D < 1.5 G_F \quad (90\% \text{ CL}) . \]
3. STUDY OF THE \( x \)-DISTRIBUTION IN SEMILEPTONIC NEUTRAL-CURRENT \( \nu \mu \) AND \( \bar{\nu} \mu \) INTERACTIONS

Several studies of the \( x \)-distribution and the structure function \( F_2 \) and \( xF_3 \) for charged-current neutrino interactions have been published\(^3-8\) but, up to now, only a bubble chamber experiment\(^9\) has reported a measurement of the neutral-current \( x \)-distribution in a low-energy (10 GeV) neutrino beam, based on 23 events.

As the energy of the outgoing \( \nu \) cannot be measured, the kinematics of neutral-current events cannot be determined on an event-by-event basis.

The \( x \)-variable can be expressed, in the small-angle approximation, as a function of the hadronic energy (\( E_h \)) and hadronic angle (\( \theta_h \)), as

\[
x = \left( \frac{E_\nu (E_h - m)}{2m (E_\nu - E_h + m)} \right) \theta_h.
\]

In neutral-current events the initial neutrino energy cannot be evaluated from the final state of the interaction.

We have analysed events collected by exposing the CHARM detector to the 200 GeV narrow-band beam, which allows a relation to be established between the neutrino energy and the distance \( r \) of the interaction vertex from the beam axis. The spread in the beam momentum, limitations in experimental resolution, and the ambiguity between the neutrinos from pion and kaon decay do not allow us to reconstruct the event kinematics on an event-by-event basis.

Therefore we expressed the measurable quantities (e.g. \( E_h, \theta_h, r \)) as functions of \( x \), and performed a fit to the distribution in these measured quantities to determine the \( x \)-distribution.

Denoting by \( G(E_h, \theta_h, r) \) this measured distribution, and by \( R(E_h, \theta_h, r;x) \) an expression that takes into account our knowledge of the beam flux and the experimental resolutions, the structure functions can be determined from the following relation\(^8\):

\[
\frac{d^2 \sigma}{dx dy} = G^2 m E_\nu \left\{ \left[ 1 + (1-y)^2 \right] (u^2 L + u^2 R + d^2 L + d^2 R)^2 \right\} F_{\pm}^{NC}(x, Q^2) \\
= \left[ 1 - (1-y)^2 \right] [u^2 L + d^2 L - (u^2 R + d^2 R)] xF_3^{NC}(x, Q^2).
\]

*) In our analysis we have assumed the validity of the Callan-Gross relation\(^1\) and neglected the strange and charmed quark contribution. The differential cross-section for NC can be expressed as
where \( G^b(E_h, \theta_h, r) \) is the background contribution, and where the + sign refers to neutrino interactions and the - sign to antineutrino ones. The evaluation of the background and the event selection criteria have been described in a previous paper\(^{11}\) on the total \( \nu \) cross-section; in Table 2

<table>
<thead>
<tr>
<th>Raw events</th>
<th>K background</th>
<th>WBB background</th>
<th>CC - NC</th>
<th>Corrected events</th>
<th>NC</th>
<th>CC</th>
<th>NC</th>
<th>CC</th>
</tr>
</thead>
<tbody>
<tr>
<td>2352</td>
<td>-191</td>
<td>-60</td>
<td>-134</td>
<td>1967</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6496</td>
<td>-81</td>
<td>+134</td>
<td>6543</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1021</td>
<td>-42</td>
<td>-92</td>
<td>-24</td>
<td>863</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2689</td>
<td>-197</td>
<td>+24</td>
<td>2516</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

we summarize the event numbers and the various backgrounds. In Eq. (3) \( F_{\pm}^{NC}(x) \) is a linear combination of the chiral coupling constant \( u_L, u_R, d_L, d_R \) and of the structure functions \( F_2(x) \) and \( xF_3(x) \):

\[
F_{\pm}^{NC}(x) = \frac{4}{3}(u_L^2d_L^2 + u_R^2d_R^2) \left[ F_2^{NC}(x) \pm \frac{2}{3} \left( u_L^2 + d_R^2 \right) - \left( u_R^2 + d_L^2 \right) \right] xF_3^{NC}(x) .
\]

To fit the measured distributions we parametrized \( F_{\pm}(x) \) as a linear superposition of bell-shaped functions \( b_i(x) \):

\[
F_{\pm}(x) = \sum_{i=1}^{N} a_i b_i(x) ,
\]

where \( b_i(x) \) are quartic B-splines defined between the knots (bin edges) shown in Figs. 9 and 10. The parametrization of Eq. (5) involves no \textit{a priori} assumption concerning the shape of \( F_{\pm}(x) \), merely that it varies smoothly over a bin in \( x \), chosen to be of the order of the experimental resolution.

A maximum likelihood fit to the experimental distribution \( \text{[unfolding of the integral in Eq. (3)]} \) determined the coefficients \( a_i \), and by integrating Eq. (5) for each bin of \( x \) we can calculate the average value of \( F_{\pm}(x) \).
In reality the fit was performed using the variables \( h = \sqrt{E_h} \), \( u = \sqrt{E_h/2m_e} \), and \( x \), because for \( h \) and \( u \) the variation of the resolution with hadronic energy is much weaker than for \( E_h \) and \( \theta_h \). We included corrections for scaling violations, assuming that they are the same for neutral-current interactions as those found previously in charged-current reactions\(^8\).

To check the validity of the method, we analysed, using the above unfolding procedure, the charged-current data sample of Ref. 8 without using the information from the measurement of the muon momentum vector.

We expressed \( F_3(x) = 4/3 F_2 \pm 2/3 xF_1 \), using \( F_2(x) = q_{\text{sea}}(x) + q_{\text{val}}(x) \) and \( xF_1(x) = q_{\text{val}}(x) \) and the parametrizations

\[
q_{\text{val}}(x) = \frac{\int F_3(x) \, dx}{\beta(a, b + 1)} \, x^a (1-x)^b
\]

\( q_{\text{sea}}(x) = C(c+1)(1-x)^c \).

Assuming, as predicted by the Gross and Llewellyn Smith sum rule, that \( \int_0^1 F_3(x) \, dx = 3 \), and fixing the exponent \( c \) to be 4.55 as found in the charged-current analysis\(^8\), we obtained the results in column (b) of Table 3 by fitting the \( v_\mu \) and \( \bar{v}_\mu \) data simultaneously.

For comparison, the results of the fit performed on charged-current data using the \( \mu \) information are given in column (a). Comparing the results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>(a) CC with ( \mu ) measurement</th>
<th>(b) CC unfolding method</th>
<th>(c) NC unfolding method</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \int_0^1 F_3(x) , dx ) (fixed)</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>( a )</td>
<td>0.52 ± 0.03</td>
<td>0.61 ± 0.09</td>
<td>0.36 ± 0.12</td>
</tr>
<tr>
<td>( b )</td>
<td>3.08 ± 0.16</td>
<td>4.37 ± 0.65</td>
<td>2.03 ± 0.70</td>
</tr>
<tr>
<td>( C )</td>
<td>0.11 ± 0.01</td>
<td>0.13 ± 0.02</td>
<td>0.10 ± 0.03</td>
</tr>
<tr>
<td>( c )</td>
<td>4.55 ± 0.49</td>
<td>4.55 (fixed)</td>
<td>4.55 (fixed)</td>
</tr>
<tr>
<td>( \chi^2/DF )</td>
<td>6.9/9</td>
<td>7.8/9</td>
<td></td>
</tr>
</tbody>
</table>
in columns (a) and (b), we conclude that reliable $x$-distributions can be obtained by the unfolding methods described above. Column (c) shows the results of the fit performed on the neutral-current samples using the unfolding procedure. The fitted parameter values agree within the errors with the values from the charged-current reactions. In particular, we note close agreement for the amount of sea quark as seen by the neutral and charged currents. To observe the expected small differences between neutral-current and charged-current $x$-distributions caused by the different strange- and charmed-quark contributions, higher statistics and improved resolutions will be needed. Comparing the sea content ($C$) with that estimated from our previous analysis of the shape of neutral-current distribution$^{12}$, we find $\alpha = 0.22 \pm 0.22$ for the $y$-shape parameter, in good agreement with $\alpha = 0.22 \pm 0.07$, deduced from the value of $C$.

Figures 9 and 10 show the structure functions $F_+(x)$ obtained for charged-current and neutral-current reactions, respectively; the full lines represent the fit performed using the unfolding method, and the dashed line in Fig. 9 that performed using the information from the measurement of the
muon momentum vector. Since the unfolding of the distributions $u, h, r$ produces negative correlations between bin contents, the errors in Figs. 9 and 10 take into account the full covariance matrix errors. In Figs. 11, 12, and 13 we show the measured distributions compared with the continuous lines which represent the fitted curves.
4. CONCLUSIONS

From a study of the $\mu^+$ polarization we can conclude that $V$ and $A$ terms are dominant in charged-current neutrino reactions at high energy, and using the value of the polarization at low $y$ as normalization we establish a limit on $S$ and $P$ contributions of $\sigma_{S,P}/\sigma_{tot} < 7\%$ at the 95\% CL. Moreover, we put a limit to the contribution of time-reversal violating terms in high-energy charged-current neutrino interactions of $\sigma_{T}/\sigma_{tot} < 11\%$ at the 95\% CL.

In a search for coherent $\mu^+\mu^-$ pair production induced by $\nu_\mu$ and $\bar{\nu}_\mu$ events, we have found $1.7 \pm 1.7$ events that can be attributed to trident production and thus set a limit on the diagonal coupling constant for the four-fermion interaction of $G_d < 1.5 G_F$ at the 90\% CL.

The analysis of neutral-current $x$-distributions, performed with a novel unfolding method, shows no significant difference in the structure of the nucleon as seen by the neutral and the charged current, as expected from the quark model of the nucleon.

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NEW RESULTS ON CHARGED CURRENT REACTIONS
FROM THE CDHS - GROUP†

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Abstract
An analysis of the $\bar{\nu}$ differential cross-section at
large $x$ and large $y$ yields upper limits on $R = q_e/q_\mu$ and
on the presence of right handed currents. Results of the
CDHS hydrogen experiment on the $\nu$-p and $\bar{\nu}$-p total cross-
sections, the valence quark distribution ratio $d_\nu(x)/u_\nu(x)$,
and the sea quark ratio $u(x)/d(x)$ are presented.

Invited talk at the 10th International Conference on Neutrino

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1. Analysis of $d^2\sigma^{\bar{\nu}N}/dx dy$ at large $x$ and large $y$

The analysis of the differential antineutrino cross-section is based on a total of 175,000 $\bar{\nu}$ events and 90,000 $\nu$ events, obtained in both wide and narrow band beams, in the CDHS-detector at the CERN SPS.

In the presence of right handed quark currents, the differential antineutrino-nucleon cross-section can be expressed in terms of the right- and left-handed structure functions $q_{\text{right}}$ and $q_{\text{left}}$ and the longitudinal structure function $q_{L}:

$$
\frac{1}{2} \frac{d^2\sigma^{\bar{\nu}N}}{dx dy} = q_{\text{right}}(x) + q_{\text{left}}(x)(1-y)^2 + q_{L}(x)(1-y)
$$

$q_{\text{right}}$ is dominated by the antiquark contribution; the quark contribution is suppressed by $C_{R}^2/C_{L}^2$, where $C_{R}$ and $C_{L}$ are the right- and left-handed coupling constants:

$$
q_{\text{right}}(x) = \bar{q}(x) + C_{R}^2/C_{L}^2 q(x).
$$

The contribution of $q_{\text{left}}$ can be eliminated by subtracting the differential $\nu$ cross-section, weighted with $(1-y)^2$. The quantity which is used in the following is:

$$
\left[\frac{d^2\sigma^{\nu N}}{dx dy} - (1-y)^2 \frac{d^2\sigma^{\nu N}}{dx dy}\right] \left[\frac{d^2\sigma^{\bar{\nu}N}}{dx dy} - (1-y)^2 \frac{d^2\sigma^{\bar{\nu}N}}{dx dy}\right]
$$

$$
= \frac{C_{R}^2}{C_{L}^2} \left[\frac{\bar{q}}{q} + \frac{q_{L}}{q} \right] \left[\frac{1}{(1-y)} - (1-y)^3\right] (\text{at large } x \text{ and } y) \quad (1)
$$

This quantity is experimentally found to be zero to good approximation at large $x$ and at large $y$, a result, which is used to deduce upper limits on $C_{R}^2/C_{L}^2$ and on $R = q_{L}/q_{T}$.

1.1 Limit on $R = q_{L}/q_{T}$

We find: $R = q_{L}/q_{T} < 0.006 \pm 0.012 \pm 0.025$ for $0.4 < x < 0.7$ with $\langle Q^2 \rangle = 38 \text{ GeV}^2/c^2$, where the errors given are the statistical and systematic error in terms.
This upper limit depends only on the absence of the cross-section at large x and is therefore rather reliable.

Fig. 1 shows the upper limit on R for 3 x-bins, compared to the QCD prediction. The result is also compared to previous measurements, based on an analysis of the y-distributions of electron scattering [1] and ν + ν̄ scattering data [2]. The new method is much more sensitive at large x. Thus at high values of Q², the Callan-Gross violation is near zero at large x. The large positive value of the SLAC-MIT experiment - if confirmed - would require a large nonperturbative contribution which vanishes rapidly with Q². Substantial progress on the measurement of R(x) also at small x will be possible in the future using expression (1).

Fig. 1
1.2 Limit on right-handed currents [6]

The upper limit \( C_R^2/C_L^2 < 0.009 \) (90% confidence) is obtained for \( <Q^2> = 33 \) \( \text{GeV}^2/c^2 \). This limit can be used to constrain the mixing angle \( \theta \) and the squared mass ratio \( M_1^2/M_2^2 \) of the right- and left-handed vector bosons, which appear as parameters in left-right symmetric models [4] with right-handed currents (fig. 2). The restriction on \( \theta \) is \( |\theta| < 0.1 \), nearly independent of \( M_1^2/M_2^2 \). This limit is slightly worse than the results based on precision measurements of the parameters in muon decay [3], however it applies also to models in which the right-handed neutrino is heavy, where the muon decay results are inapplicable.

![Diagram](image)
2. Results of the CDHS hydrogen experiment

The experimental layout of the CDHS hydrogen experiment is shown in Fig. 3. The two main parts are a hydrogen target (32 m$^3$) upstream to the iron core magnets, and a vertex localizer, consisting of 5 multiwire proportional chambers with a total of 15 planes, in between the target and the first iron core magnet.Muon momentum and hadron energy of hydrogen events are measured by the CDHS u-spectrometer and hadron calorimeter respectively. The proportional chamber hits of penetrating charged particles are used to reconstruct the event vertex to separate $\text{H}_2$ interactions from tankwall interactions. Fig. 4 indicates the performance of the vertex reconstruction: each point represents one vertex, plotted versus the distance from the first MWPC and the symmetry axis of the target. The two iron tankwalls of the dewar are clearly resolved.
This analysis is based on 4453 $\nu$ events and 3959 $\bar{\nu}$ events with $E_\nu \geq 20$ GeV and $E_H \geq 5$ GeV, registered during the 1979 and 1980 400 GeV wide band beam periods of the CERN SPS. To normalize the total cross-sections in hydrogen to the total cross-sections in iron, we use 2280 $\nu$ events and 1168 $\bar{\nu}$ events in the iron tankwalls, as indicated in fig.4, which are registered simultaneously with the hydrogen events in the same beam, under identical trigger conditions, and with similar systematical problems as the hydrogen events.

2.1 Total cross-section ratio

Using the iron tankwall events, we obtain the following results for the total cross-section ratios $H_\nu/Fe$, valid for $<E_\nu> = 63$ GeV and $<E_{\bar{\nu}>} = 55$ GeV:

$$\frac{\sigma_{\nu}}{\sigma_{\bar{\nu}}} = 0.63 \pm 0.02 \pm 0.04$$

$$\frac{\sigma_{\bar{\nu}}}{\sigma_{Fe}} = 1.31 \pm 0.05 \pm 0.10$$

where the statistical and systematic errors are given in
terms. Since \( \sigma^{\nu p}/\sigma^{\nu Fe} = 56\sigma^{\nu p}/(26\sigma^{\nu p} + 30\sigma^{\nu n}) \), we can also obtain the n/p cross-section ratios from the \( H_2/Fe \) ratios. The results are given in tab.1 and in fig.5 for 3 values of \( E_\nu \), in comparison to previously published results. There is good overall agreement. It should be noted that our measurement is at significantly higher energies compared to other experiments, and (in the case of neutrino) is rather accurate.

\[
\begin{array}{|c|c|c|c|c|}
\hline
& E_\nu [\text{GeV}] & \sigma^{\nu n}/\sigma^{\nu p} & \sigma^{\bar{\nu} n}/\sigma^{\bar{\nu} p} & \text{Ref} \\
\hline
\nu H_2 Ne 7'BNL & 1-10 & 1.80\pm0.19 & & 7 \\
\bar{\nu} H_2 Ne 15'FNAL & 10-200 & & 0.57\pm0.05 & 8 \\
\nu D_2 & > 10 & 2.18\pm0.13\pm0.28 & 0.51\pm0.15\pm0.07 & 9 \\
\bar{\nu} D_2 BEBC & > 10 & 2.22\pm0.12\pm0.25 & 0.51\pm0.01\pm0.03 & 10 \\
\nu H_2 Ne BEBC-TST & \sim 30 & 1.98\pm0.19 & & 11 \\
\nu H_2, \nu Fe CDHS & 20-160 & 2.05\pm0.09\pm0.17 & 0.56\pm0.05\pm0.10 & \\
\hline
\end{array}
\]

Tab. 1

![Fig. 5](image-url)
### 2.2 Determination of $d_v(x)/u_v(x)$

Hydrogen experiments are of interest mainly for two reasons: i) to determine the ratio $d_v(x)/u_v(x)$ of the valence quark distributions and ii) to determine the ratio $\bar{u}(x)/\bar{d}(x)$ of the sea quark distributions, which can only be measured in neutrino scattering.

At large $x$ (i.e. $x \geq 0.3$), the contribution of the sea quarks to the differential cross-sections is small, i.e.:

$$d_v(x)/u_v(x) = 1/2\sigma_0 [d\sigma^{VP}/d\chi]/[d\sigma^{\bar{VP}}/d\chi] \cdot (1-y)^2$$

for $x \geq 0.3$.

This quantity as measured$^1$ is shown in fig. 6. It is com-

---

$^1$ Diff. cross-sections are evaluated using the cross-section ratios of section 2.1. The data have been corrected for acceptance and smearing with the help of extensive MC-simulations. The corrections are large at small hadron energies and low muon momentum, they become less important at high neutrino energies. Most results are based on cross-section ratios, for which these effects cancel to good approximation. Radiative corrections have been applied according to de Rújula et al. [5].
pared to a parametrisation, assuming $d_v(x)/u_v(x) = (1-x)$ and accounting for the sea quark contribution at small $x$. At large $x$, $u_v(x)$ is clearly dominating. Fig. 6 also shows the same quantity for iron, which is expected to be 1 in the valence region. The observed deviation from 1 at small $x$ indicates the contribution of sea quarks. The clear difference between hydrogen and iron data shows that the observed $x$-dependence of $d_v(x)/u_v(x)$ is not instrumental.

2.3 Determination of $(\bar{U} + \bar{S})/(\bar{D} + \bar{S})$

The contribution of sea quarks is most easily measured in $\bar{v}$-scattering at large $y$. To determine the sea quark ratio $\bar{U}/\bar{D}$, we compare the $y$-distributions for $\bar{v}$-scattering on proton and iron targets, using the quantity

$$\left[1/2\sigma_{\bar{v}p}dy\right]/\left[1/\sigma_{\bar{v}N}dy\right] =$$

$$\left[U(1-y)^2 + \bar{D} + \bar{S} + Q^P_L(1-y)\right]/\left[(U+D)(1-y)^2 + \bar{U} + \bar{D} + 2\bar{S} + Q^P_L(1-y)\right].$$

Our result for this ratio is shown in fig. 7, compared to expectations for different assumptions on $\bar{U}/\bar{D}$. There are two sources of information about $\bar{U}/\bar{D}$: i) the value at $y = 1$ (should be 0.5 for $\bar{U} = \bar{D}$) and ii) the shape of the $y$-distribution. A fit to this observed ratio yields for an average hadron energy of 40 GeV:

$$(\bar{U} + \bar{S})/(\bar{D} + \bar{S}) = 1.29 \pm 0.3,$$

where the error contains the statistical and the systematic error due to the error on the total cross-section ratio. It should be noted that this result is based on the analysis of a cross-section ratio, which is unaffected by scaling violations and insensitive to assumptions about the Callan-Gross violation. Thus within the given errors, our result is consistent with a symmetric sea. This is further supported by a comparison of the shape of the $\bar{v}$-p and $\bar{v}$-N

$\dag$ The present analysis uses high statistic wide band beam iron data, registered in the CDHS-detector, which are passed through the same analysis programs as the hydrogen data.
Fig. 7

\[ \frac{1}{2} \frac{d\sigma^{p}/dy}{d\sigma^{N}/dy} \]

- 0.5
- 0.615 (d = \frac{1}{2} d)
- 1
- Best fit: \[ \frac{u + s}{d + s} = 1.29 \pm 0.3 \]

\( y > 0.5 \), (\( v \)) = 50 GeV

Fig. 8a  

Valence contr. subtr.
x-distributions at large y, which are dominated by scattering off sea quarks. The differential cross-sections are compared in fig. 8a. Indicated are also the expected valence quark contributions. Fig. 8b gives the cross-sections after subtraction of the valence contributions, indicating that the sea is also symmetric in shape.

2.4 Determination of $d_v(x)/u_v(x)$ in the sea region

To determine $d_v(x)/u_v(x)$ also in the sea region, we use the $\nu\bar{\nu}$ cross-section ratios for hydrogen and iron. From an experimental point of view, these ratios are the best measured quantities, as uncertainties due to acceptance, smearing, etc. cancel. Also Fermi motion effects for the iron cross-section cancel.

The cross-section ratios can be expressed by the two parameters $d_v(x)/u_v(x)$ and $\text{sea}(x)/u_v(x)$:

$$\frac{[d\nu^P/dx]}{[d\bar{\nu}^P/dx]}(1-y)^2 = \frac{[d_v/u_v + \text{sea}/u_v]}{[1+ \text{sea}/(1-y)^2]}$$

$$\frac{[d\nu^H/dx]}{[d\bar{\nu}^H/dx]}(1-y)^2 = \frac{[1+d_v/u_v+2\text{sea}/u_v]}{[1+d_v/u_v+2\text{sea}/u_v]}$$

where the SU2-symmetry of the sea has been used. This system of linear equations can be solved for $d_v/u_v$ for each value of $x$ at fixed $y$. The result is plotted in fig. 9, which shows our measurement of $d_v(x)/u_v(x)$ for all $x$ for $<\nu> = 35$ GeV.

This procedure automatically corrects for effects of a Callan-Gross violation and is independent of scaling violations, since it can be applied for fixed $<\nu>$. It should be noted that this analysis has been restricted to a limited $y$-range $0.2 < y < 0.8$, where the experimental acceptance is large and uniform.
2.5 Valence structure functions $xu_v(x)$ and $xd_v(x)$

In a last step we can determine the $x$-dependence of sea and valence quarks; there are two different possibilities: the first method is based on the $y$-dependence of the differential cross-sections and has been used by previous experiments, the second method is based on a direct comparison of hydrogen and iron differential cross-sections.

Since the relative contribution of quarks and antiquarks to the differential cross-sections is $y$-dependent (fig. 10), an analysis of the shape of the $v$-p and $\bar{v}$-p...
y-distributions leads to a separation of the quark and antiquark momentum distributions $x(d(x) + s(x))$, $x(u(x) + c(x))$, and $x(\bar{d}(x) + \bar{s}(x))$. This method, however, is very sensitive to assumptions about $q_L(x)$, and, as the mean four momentum squared $<Q^2>$ at low $y$ is different from $<Q^2>$ at large $y$, large corrections for scaling violating effects have to be applied. Fig.11 shows the quark and antiquark momentum distributions extracted from the shape of the $\nu$-p and $\bar{\nu}$-p y-distributions for $<\nu> = 20$ GeV. For this determination we used the QCD-prediction for $q_L(x)$ and corrected for scaling violations as measured in iron.

The antiquark momentum distribution $x(\bar{d}(x) + \bar{s}(x))$ is compared to a parametrisation for $q(x)/2 = 0.5x(\bar{u}(x) + \bar{d}(x) + 2\bar{s}(x))$ as measured in iron for the same value of $<\nu>$. The agreement
of data and parametrisation shows again that the \( x(x) + s(x) \) and \( x(d(x) + s(x)) \) are compared to a modified parametrisation determined in iron \(^+\), assuming \( d(y)/u(x) = 1 - x \).

A combined analysis of the \( \nu \) and \( \bar{\nu} \)-hydrogen differential cross-sections and the \( \nu/\bar{\nu} \)-iron cross-section ratio allows a separation of the valence and sea contributions. These are related to the three variables \( x_d(x), x_u(x) \), and \( \text{sea}(x,y) \) by

\[
\frac{1}{2} (d^2\sigma/dx/\nu - d^2\sigma/dx/\bar{\nu}) = x_d(x) + \text{sea}(x,y)
\]

\[
\frac{1}{2} (d^2\sigma/dx/\bar{\nu} - d^2\sigma/dx/\nu) = x_u(x)(1-y) + \text{sea}(x,y)
\]

\[
\left[ (d^2\sigma/dx/\nu) - (d^2\sigma/dx/\bar{\nu}) \right] = \frac{1}{x_d(x) + x_u(x)} \left[ (x_u(x) + x_d(x) + 2\text{sea}(x,y)) \right]
\]

This system of equations can be solved for \( x_d(x) \) and \( x_u(x) \) for each value of \( x \) at fixed \( y \). Since this method does not use the shape of the \( y \)-distributions, it is independent of scaling violations and insensitive to assumptions about \( q_L(x) \). Fig. 12 shows the result for \( x_d(x) \) and \( x_u(x) \), determined for 3 bins in \( \langle \nu \rangle \). The results are compared to the modified iron parametrisation (including scaling violations), which give a satisfactory description of the data. The valence distributions \( x_d(x) \) and \( x_u(x) \) are consistent with expected scaling violations. The average values \( \langle x \rangle \) decrease with increasing \( \langle \nu \rangle \), as expected. The integrals of the valence distributions are summarized in tab.2.

\(^+\) At \( \langle Q^2 \rangle = 5 \text{ GeV}^2/\alpha^2 \), the valence parametrisations shown are:

\[
q_v(x) = \frac{3}{B_q} x^{0.3543} (1-x)^{4.083} (1 + 11.734 x^{1.576})
\]

\[
x_u(x) = \frac{2}{B_u} x^{0.3543} (1-x)^{3.333} (1 + 11.734 x^{1.576})
\]

\[
x_d(x) = \frac{1}{B_d} x^{0.3543} (1-x)^{4.333} (1 + 11.734 x^{1.576})
\]

where: \( B_q, B_u, B_d \) are normalisation factors which give the expected number of valence quarks. These distributions are then propagated to different \( Q^2 \)-values using the measured scaling violations for \( q_v(x,Q^2) \).
3. Conclusions

The analysis of $\bar{\nu}$-scattering at large $x$ and $y$ has provided for the first time a stringent limit on $R = \sigma_L/\sigma_T$ at large $x$ and a tight bound on the presence of right-handed currents. The H2-experiment has high statistics for both $\nu$- and $\bar{\nu}$-scattering. A combined analysis of this data and measurements in iron allows for the first time a measurement of $u_\nu(x)/d_\nu(x)$ in the whole $x$-range and a reliable measurement of $\bar{u}/\bar{d}$. 

<table>
<thead>
<tr>
<th>$&lt;\nu&gt;$</th>
<th>$&lt;\nu&gt; = 16$ GeV</th>
<th>$&lt;\nu&gt; = 50$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_\nu = \int xu_\nu(x)dx$</td>
<td>0.233±0.019±0.020</td>
<td></td>
</tr>
<tr>
<td>$D_\nu = \int xd_\nu(x)dx$</td>
<td>0.093±0.007±0.007</td>
<td>0.076±0.008±0.008</td>
</tr>
</tbody>
</table>
References

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NEUTRINO CHARGED CURRENT STRUCTURE FUNCTIONS

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ABSTRACT

Charged current total cross sections and structure functions were extracted from neutrino and antineutrino data taken with the Fermilab narrow band beam. The cross section results are $\sigma^{\nu}/E = 0.701 \pm 0.004 \pm 0.025 \times 10^{-38}$ cm$^2$/GeV and $\sigma^{\bar{\nu}}/E = 0.350 \pm 0.04 \pm 0.022 \times 10^{-38}$ cm$^2$/GeV. The structure functions exhibit scaling violations. A comparison with structure functions obtained in muon scattering experiments indicates a ratio consistent with $18/5$ within the systematic errors of both experiments. The structure function function $xF_3$ is used to test the Gross-Llewellyn Smith sum rule. The data is in agreement with the prediction of 3 for the number of valence quarks on the nucleon.

1. Introduction

This report reviews measurements of total charged current cross sections and presents preliminary results on the structure functions $F_2$ and $xF_3$. The data were obtained using the Fermilab narrow band beam and the Laboratory E neutrino detector.$^{1,2,3}$ The structure function $xF_3$ is used to test the Gross-Llewellyn Smith sum rule$^4$ which states that within the quark parton model the integral $\int F_3(x)dx$ should equal the number of valence quarks in the nucleon. The structure function $F_2$ when compared to the $F_2$ structure function extracted in muon scattering experiments tests the mean square charge of the nucleon constituents. The $Q^2$ dependence of the structure functions test for scaling violations which are predicted by QCD.
The structure functions are extracted from the neutrino and antineutrino event samples by investigating the distributions in the variables $x$, $y$ and $Q^2$ where:

$$Q^2 = 4EE_\mu \sin^2 \theta/2, \quad x = Q^2/2ME_H, \quad y = E_H/E = E_H/(E_\mu + E_H)$$

Here $\theta$ and $E_\mu$ are the outgoing muon angle and energy, $E$ is the incident neutrino energy, $E_H$ is the energy of the final state hadrons and $M$ is the nucleon mass.

Within the quark parton model we define the structure function $2xF_1 = x(q+\bar{q})$, and $xF_3 = x(q-\bar{q})$ where $q(x)$ and $\bar{q}(x)$ are the quark and antiquark distributions in the nucleon. The structure function $F_2$ is related to $2xF_1$ by the relation

$$\frac{2xF_1}{F_2} = \frac{1 + \frac{2m^2}{4M^2} Q^2}{1 + R}.$$

For the data reported here, $R$ is assumed to be equal to 0.1. Extraction of $R$ from the data will be done at a later stage in the analysis. The neutrino and antineutrino differential cross sections for iron are then related to the structure functions $F_2$ and $xF_3$ as follows:

$$\frac{d^2\sigma^\nu}{dx dy} = \frac{G^2ME}{\pi} \left\{ \left[ 1 - y + \frac{x^2}{2} \left( 1 + 2M^2x^2/Q^2 \right) \right] F_2 + \frac{1 - (1-y)^2}{2} xF_3 + C^\nu \right\}$$

$$\frac{d^2\bar{\sigma}^\nu}{dx dy} = \frac{G^2ME}{\pi} \left\{ \left[ 1 - y + \frac{x^2}{2} \left( 1 + 2M^2x^2/Q^2 \right) \right] F_2 - \frac{1 - (1-y)^2}{2} xF_3 + C^\nu \right\}$$

where $C^\nu$ and $C^\bar{\nu}$ are small corrections due to the non-isoscalar nature of the target and the strange sea. $C^\nu = (1-2Z/A)(u_y-d_y)(1-y^2)+(1-(1-y)^2)xs$ and $C^\bar{\nu} = -(1-2Z/A)(u_y-d_y)(1-y^2)+(1-(1-y)^2)xs$ where $u_y$ and $d_y$ are the valence up and down quark distributions, $s$ is the strange quark distribution and $Z$ and $A$ are the atomic number and weight of the iron nucleus. The data were also radiatively corrected using the method of DeRujula et al.\textsuperscript{5} The corrections $C^\nu$ and $C^\bar{\nu}$ are small ($\leq 5\%$) and were calculated assuming a half SU(3) symmetry sea, i.e. $s + \bar{s} = \frac{1}{2}(\bar{u} + \bar{d})$.

The structure functions $F_2$ and $xF_3$ are extracted from the sum and difference of the neutrino and antineutrino cross sections.
2. Apparatus

The CCFRR detector at Laboratory E consists of a non-magnetic 640 ton target calorimeter composed of 3m x 3m x 5cm steel plates sandwiched with liquid scintillation counters (every 10cm of steel) and spark chambers with magnetostrictive readout (every 20cm of steel). The position accuracy of the spark chambers is 0.5mm which results in a muon angular resolution of 68 mr/p (GeV). The excellent angular resolutions allows a good determination of x, especially near x = 0. The hadron energy is obtained by summing (without weighting) the pulse height in the scintillation counters downstream of the interaction point. The hadron energy calibration and resolution were determined by using the N5 hadron beam to laboratory E. The rms hadron energy resolution is 0.89/√E_H (GeV).

The target calorimeter is followed by a solid steel toroidal muon spectrometer consisting of 24 magnetized iron disks, each 20cm thick and 1.8m in radius (with a 12cm hole). The spectrometer is instrumented with scintillation counters every 20cm of steel (to monitor muon energy loss, and for triggering) and with spark chambers every 80cm of steel. The muon energy resolution was measured to be ±11% using beams of momentum tagged muons.

There were two independent triggers which utilized (a) the presence of a penetrating muon into the magnet downstream of the target (E_μ > 10 GeV and 0 < θ < 100 mrad); and (b) the presence of a minimum hadron energy deposition in the target (E_H > 10 GeV) and a penetrating muon (E_μ > 2.9 GeV, 0 < θ < 370 mrad), respectively. The first trigger was used for structure function analysis, and both triggers were used for the total cross section analysis.

3. Neutrino and Antineutrino total cross sections

The cross sections were extracted from the events using both triggers mentioned in the previous section. Data were taken with a 1 msec spill extraction and a 1 second spill extraction. The cross sections for both extractions agreed on average to ±1%. We report here on the measurements using 55,000 ν and 17,000 ¯ν events for the 1 msec extraction data.

The two triggers were completely independent in both the counters used and the logical circuitry to complete the triggers. Typical events lay in a kinematic regime of trigger overlap: about 75% of the observed events
were recognized by both triggers. For cross section analysis, the only corrections for losses involve simple geometric rotation in azimuth on an event-by-event basis, since individual trigger efficiencies were essentially 100%. These corrections for azimuthal loss averaged less than 6% in magnitude. Over the kinematic range ($0 < 100 \mathrm{mrad}, P > 10 \mathrm{GeV}$), trigger (a) was $(99.5 \pm 0.5)\%$ efficient; over the range ($0 < 370 \mathrm{mrad}, P > 10 \mathrm{GeV}$), trigger (b) was $(100.0 \pm 0.1)\%$ efficient. These overlapping domains cover essentially all kinematic possibilities in this neutrino energy region in an unbiased fashion, for $\theta_{\mu} < 370 \mathrm{mrad}$. Corrections for larger angles were made by calculation; they were generally small (<6%), decreasing at higher energies.

Deadtime occurs due to the inability of the apparatus to respond while recording data. The data presented here were taken during fast resonant extraction (1 machine cycle). The experiment could record only one event per machine cycle. The fraction of the beam to which the experiment was sensitive averaged 70% during neutrino running and 90% during antineutrino running. This live beam fraction was measured in two ways: by recording the flux transmitted during the triggerable and non-triggerable times, and by counting the triggers during the two times. The measurements of the fraction of sensitive beam as obtained from the two methods typically agreed to 1%. Data were also taken during 1 sec extraction of the beam during neutrino running. The experiment was sensitive for 85% of the flux for this data. The cross section obtained with this data agreed to $\sim 1\%$ with that from the fast extraction data.

The experiment was performed using the NO dichromatic beam. The secondary beam of $\pi, K, \rho$ was sign and momentum selected ($\Delta p/p = \pm 9.4\%$) before it traversed the 350 m decay region. The relative populations of the particle types was measured utilizing a focusing Cerenkov counter to obtain particle fractions with typical rms errors of $(1-4)\%$ for pions and $(4-7)\%$ for kaons. The magnitude of hadron flux was monitored during data taking by ion chambers at two separated locations along the decay region.

The ion chambers' linearity and stability were demonstrated over a much wider range of intensities than actually used for the cross section data taking. Their stability was monitored throughout data accumulation.
The ion chambers were calibrated using three independent techniques: Cu foil irradiation and subsequent counting of Na\(^{24}\) (the cross section for the transition having been measured in two experiments using beam current transformers), an rf cavity of known resonant frequency and quality factor placed in situ to count beam particles by exploiting the 18.6 ns time structure of the Fermilab beam, and a calibration performed in a low intensity secondary beam line in which the number of particles traversing the ion chamber was counted directly. The methods and results of these calibrations has been reported elsewhere.\(^1,2,3\) The agreement among all techniques was well within the known limitations, which were \(<5\%\). We estimate the calibration of ion chamber response versus hadron flux is accurate to 2.5%.

In accumulating neutrino data, the magnetic elements were energized under ten separate operating conditions to transmit and focus 120, 140, 165, 200, and 250 GeV secondary hadrons with both signs of electric charge. This permitted collection of both neutrino and antineutrino interaction events over the energy range 30 to 250 GeV. In the dichromatic beam, neutrinos from \(K \rightarrow \mu \nu\) decay populate energies near the hadron beam energy and neutrinos from \(\pi \rightarrow \mu \nu\) decay cover a range below 0.43 of the beam setting.

Figure 1 shows \(\sigma/E\) for both neutrinos and antineutrinos. The inner error bars are statistical and the outer error bars are systematic. Also shown are cross sections from an earlier neutrino run\(^3\) at a secondary beam setting of 300 GeV. That data extends the range of the cross section measurements to higher energy.

4. \(F_2\) and \(xF_3\) Structure Functions

The structure functions \(F_2\) and \(xF_3\) were extracted from data where the muon traversed the magnet. Data for both 1 msec and 1 sec extraction were used. The event sample consisted of 116,000 \(\nu\) and 17,000 \(\bar{\nu}\) events. After cuts the final event sample consisted of 60,000 \(\nu\) and 7,000 \(\bar{\nu}\) events. The most important cut was the requirement that the hadron energy be greater than 10 GeV. Although this requirement eliminated a large number of events, it was imposed because the resolutions for \(E_H < 10\) GeV were
poor. The fiducial cut on the neutrino events from pion decays consisted of a 60" diameter circle. The fiducial cut on the neutrinos from kaon decays consisted of a 100" square.

The extracted structure functions $F_2$ and $xF_3$ are shown in figures 2 and 3, respectively.

5. $xF_3$ and the Gross-Llewellyn Smith Sum Rule

The Gross-Llewellyn Smith sum rule is related to the number of valence quarks in the nucleon

$$ \int_0^1 F_3(x) dx = 3\left(1 - \frac{\alpha_s}{\pi}\right) $$

where we included the first order correction from perturbative QCD. Experimentally, this integral is difficult to evaluate because it is sensitive to the behavior of $xF_3$ at small $x$ since the extracted structure function must be divided by $x$. About 50% of the integral is from the region $x < 0.06$. Previous extractions of $\int F_3(x) dx$ relied heavily on a theoretical form for $xF_3$ in the region $x < 0.1$. This experiment, because of the excellent $x$ resolution, can measure $xF_3$ at very small $x$ and therefore is less sensitive to model assumption. Figure 4 shows $xF_3$ versus $x$ for $0 < x < 1$. For region II ($x > 0.06$) the integral is evaluated directly from the data points. Figure 5 shows the values of $xF_3$ for $x < 0.06$. The $x$ resolution is shown on the figure. We have fit the data with the function $xF_3 = x^\alpha$. We find that for $x < 0.06$, $\alpha = 0.53 \pm 0.16$. The value $\alpha = 0.5$, expected from Regge theory, has been assumed by previous experiments. This experiment indicates that such assumption is correct. The contribution of region I ($x < 0.06$) to the integral has been evaluated from the fit. The error due to the uncertainty in $\alpha$ has been included in the statistical error. The data yield the following values for three different fixed $Q^2$ regions:

<table>
<thead>
<tr>
<th>$Q^2$ (GeV/c)$^2$</th>
<th>$\alpha$</th>
<th>$\int F_3 dx$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.49 ± 0.20</td>
<td>2.89 ± 0.40 ± 0.15</td>
</tr>
<tr>
<td>3</td>
<td>0.53 ± 0.16</td>
<td>2.95 ± 0.33 ± 0.15</td>
</tr>
<tr>
<td>5</td>
<td>0.49 ± 0.13</td>
<td>3.22 ± 0.46 ± 0.16</td>
</tr>
</tbody>
</table>
where the first error is statistical (mainly from the uncertainty in $u$) and the second error assumes a 5% normalization uncertainty. Within QCD models the integral is expected to be smaller than 3. Therefore, the data indicates small values of $A$. A similar conclusion can be drawn from the previous determinations of $\int F_3 dx$ which obtain values close to 3.

6. $F_2$ and Comparison to Muon Scattering Experiments

A comparison of muon and neutrino data provides a direct test of fractional quark charges.

$$F_2^\mu = \left[ \frac{4}{9} (u + \bar{u}) + \frac{1}{9} (d + \bar{d}) + \frac{1}{9} (s + \bar{s}) + \frac{4}{9} (c + \bar{c}) \right] x$$

$$F_2^\nu = [q + \bar{q}] x \quad \text{where} \quad q = u + d + s + c \quad \text{and} \quad \bar{q} = \bar{u} + \bar{d} + \bar{s} + \bar{c}$$

Therefore if $c$ and $\bar{c}$ are neglected we obtain

$$F_2^\nu = \frac{18}{5} \frac{F_2^\mu}{1 - \frac{3}{5} \frac{s + \bar{s}}{q + \bar{q}}}$$

The strange sea correction is only important at small $x$. We have assumed a $\frac{1}{4}$ SU(3) symmetric sea which yields a 5% correction at $x = 0.1$. The ratio of the CCFRR data to the EMC data and the ratio of the CDHS data to the EMC data are shown in figure 6. (The strange sea correction has been applied to the EMC data.) The quark model prediction assuming fractional charges is satisfied to $\sim 10\%$. The major difference between CDHS, CCFRR and EMC appears to be normalization differences of order $\pm 10\%$. Note that when the EMC hydrogen and deuterium data are compared to SLAC and CHIO data the EMC data are 10% lower than SLAC and 8% lower than CHIO.

Despite the $\pm 10\%$ normalization differences between experiments, all experiments yield similar results for the scaling violation at fixed $x$ versus $Q^2$. These are shown in figure 7.
References

2. R. Blair, A Total Cross Section and v-1Distribution Measurement for Muon-Type Neutrinos and Antineutrinos in Iron; Ph.D. Thesis (1982), California Institute of Technology, Pasadena, Calif.

Figure Captions

1. Neutrino and antineutrino total cross sections divided by the incident neutrino energy.
2. The structure function F2 extracted from the CCFRR data (preliminary).
3. The structure function xF3 extracted from the CCFRR data (preliminary).
4. The structure function xF3 versus x for 0 < x < 1 and Q2 = 3 (GeV/c)2.
5. The structure function xF3 for x < 0.06 and Q2 = 3 (GeV/c)2. The fit is xF3 = Axα.
6. The ratio of CCFRR and CDHS F2 structure function to 18 5 F1ν from EMC. The EMC data has been corrected using a 5 SU(3) symmetric sea. Most of the difference is due to difference in normalization.
7. Scaling violation extracted from various experiments.
Figure 1

Figure 2

Figure 3
Figure 4. 

$Q^2 = 3 \text{ GeV}^2$

Region I 
$x < 0.06$

Region II 
$x > 0.06$

Figure 5.

Region I 
$\alpha + 1\sigma$
$\alpha - 1\sigma$
$\alpha = 0.53 \pm 0.16$

$x$-Resolution

Figure 6. 

$Q^2 = 10 \text{ GeV}^2$

$F^2_2/F_2^\mu$

$+13\%$ CCFRR
$-10\%$ CDHS

$F_2 = A(x)[1 + b \log Q^2/10]$

Figure 7.

ALL
$E_{\text{HAD}} > 10 \text{ GeV}$

EXPT DEAM
CCFRR
CDHS
EMC

Figure 7.
Q C D THEORY OF POWER CORRECTIONS TO DEEP INELASTIC SCATTERING

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This talk is devoted to the theoretical study of power (in $1/Q^2$) corrections to deep inelastic scattering. These corrections show up as the deviations from Bjorken scaling in the region of relatively low $Q^2 \sim 1 - 10 \text{ GeV}^2$. The talk is based mainly on our works /1/. Some of our results coincide with those obtained independently by R.L. Jaffe and M. Soldate /2/.

1. Previously the theory has been concentrated mainly on the calculations of logarithmic effects /3/. In order to ascribe the observed scaling violation for $Q^2 = 1 - 10 \text{ GeV}^2$ to these effects one needs a large value of fundamental QCD parameter $\Lambda = 0.5 \pm 0.7 \text{ GeV}$. This value was in contrast with other determination of $\Lambda$ from $J/\psi$ width /4/ and $e^+e^-$-annihilation /5/, and now we know it for sure that $\Lambda = 100 \pm 150 \text{ MeV}$ due to new generation of muon data at large $Q^2$ /6/. So, the dominance of power effects at moderate values of $Q^2$ becomes evident.

2. The methodical tool used is the operator expansion (OPE) for the product of two currents

$$i \int d^4x e^{ix} T[j_1(x)j_2(x)] = \sum_c c_i(x) O_i$$

where summation is made over all types of local operator $O_i$, Lorentz indices are suppressed here but it is well known that the contribution of operators with a given Lorentz spin into nucleon matrix element of eq. (1) is connected with corresponding Nachtmann moments of measured structure functions. Also it is known the physical meaning of OPE. All effects of the interaction on short distances $X < \sqrt[4]{k}$, where $k$ is some arbitrary normalization point, are accounted by coefficients $C_i$ and the distances $X > \sqrt[4]{k}$ enter into matrix elements of operators $O_i$. In such general definition the OPE is always valid. But re-
al advantages of the OPE in QCD are due to possibility to calculate the operator coefficients perturbatively since \( \alpha_s (\mu) \ll 1 \). Generally speaking, nonperturbative effects enter both matrix elements of \( O_1 \) and coefficients \( C_1 \). However in the coefficients such effects show up as a very high power \( 1/Q^4 \). So hopefully for not too small \( Q^2 \) it is possible to disregard nonperturbative effects for \( C_1(q) \) and connect power corrections under the study with matrix elements of higher twist operators.

There interesting attempts \(^{7/} \) to develop a parton-like technique for power corrections. We only note that some arising distribution functions do not have the meaning of probability but the interference of the scattering of the current on the different number of partons.

3. What we calculated really is the coefficients for next-to-leading twist operators with spin 1 and 2. As an example let us consider the corrections to Gross-Llewellyn-Smith sum rule

\[
\int_0^\infty \frac{Q^2}{[1 + \sqrt{1 + (4m_n^2 x^2 Q^2)^2}]} \left( \frac{\alpha_s}{\beta_0} \right)^2 \frac{1}{\beta_0^2} \frac{\Lambda^2}{(n^2 + m_n^2)} \frac{1}{Q^4} (x, Q^2) \left( \frac{\alpha_s}{\beta_0} \right)^2 \frac{1}{\beta_0^2} \frac{\Lambda^2}{(n^2 + m_n^2)} \frac{1}{Q^4} (x, Q^2) \left( \frac{\alpha_s}{\beta_0} \right)^2 \frac{1}{\beta_0^2} \frac{\Lambda^2}{(n^2 + m_n^2)} \frac{1}{Q^4} (x, Q^2)
\]

Here first term in r.h.s. is just the sum rule mentioned (matrix element of baryon current), the second one is the perturbative correction \( O(\alpha_s) \), \( (\beta = 11 - \frac{2}{3} N_f) \) and the last term is the power correction. The magnitude of this term is fixed by averaging over nucleon state of the operator \( O_\alpha \).

\[
O_d = g \bar{d} \gamma^\alpha (\bar{u} \gamma^\beta d) \gamma^\beta (\bar{u} \gamma^\alpha d), \quad \bar{O}_d = \frac{1}{2} \epsilon_{\alpha \beta \gamma} G_{\alpha \beta}, \quad \langle N(p) | O_\alpha | N(p) \rangle = 2 \rho_d \langle 0 \rangle
\]
The experimental data for this moment is too poor to extract the value of the matrix element \( \langle \langle 0 \rangle \rangle \).

We also have found the expressions for \( 1/Q^4 \) corrections (twist 6) to spin 1.

4. As an example for the spin 2 write down the second moment of structure function \( F_{2eV}^{eS}(x, Q^2) \) describing electroproduction on a singlet target:\cite{1,2}

\[
M_{2eS}^{sS}(2) = \int \frac{dx}{x} \left( \frac{2}{x+1+4m_N^2/x^2} \right) \left[ \frac{11}{20} + \frac{9}{20} \sqrt{1+4m_N^2/x^2} + \right.
\]

\[
+ \left. \frac{3}{5} \cdot \frac{4m_N^2/x^2}{Q^2} \right] e_2^s(x, Q^2) = \frac{5}{18} \ll L_{S}^{S} + \frac{5}{32Q^2} B_{S}^{S} - \frac{1}{10} B_{S}^{S} + \frac{1}{4Q^2} C e_2^s \right]>.
\]

\[
L_{S}^{S} = i \bar{u} \gamma_{\mu} D_{\mu} u + (u \leftrightarrow d) \quad <\langle N|L_{S}^{S}|N\rangle = 2\langle N|B_{S}^{S}|N\rangle = (4)
\]

\[
- \frac{1}{4} g_{S}^{SS} \rho_{S}^2). \ll L \gg, B_{S}^{S} = g^{2} \bar{u} \gamma_{\mu} \gamma_{5} \gamma_{\mu} \left[ \bar{u} \gamma_{\mu} \gamma_{5} \gamma_{\mu} + \bar{u} \gamma_{\mu} \gamma_{5} \gamma_{\mu} \right] + (u \leftrightarrow d)
\]

\[
L_{S}^{SS} = g^{2} \bar{u} \gamma_{\mu} \gamma_{5} \gamma_{\mu} \left[ \bar{u} \gamma_{\mu} \gamma_{5} \gamma_{\mu} + \bar{u} \gamma_{\mu} \gamma_{5} \gamma_{\mu} \right] + (u \leftrightarrow d)
\]

The normalization point \( \mu = 0 \) is implied above, but we have checked that logarithmic dependence on \( Q \) matrix elements of \( A_{S}B_{S}C \) is really weak.

Numerically four-fermion operators \( A, C \) enter with the coefficients four times larger than the quark-gluon operator \( B \) and we disregard the latter in the following (some other arguments also show that \( B \) is not the dominant operator).

The scaling violation for second moments is not large experimentally so to extract from the data the magnitude of \( 1/Q^2 \) term with some accuracy we have used the extrapolation from the
data the magnitude of $1/Q^2$ term with some accuracy we have used the extrapolation from the higher moments. The fitted result has the form

$$\frac{1}{2} M^2 (m) = \langle L^{(m)} > + \frac{\mu}{2 Q^2} \cdot 0.15 \text{GeV}^2 \cdot \frac{\mu^2}{Q^4} \cdot 0.06 \text{GeV}$$

(5)

It seems very interesting that theoretical estimates of $1/Q^2$ effect based on a picture of nucleon as a state of three valence quarks lead to the drastic disagreement with the data. It turns out [1,2] that a bag-like averaging of four-fermion operators over nucleon gives the number $\approx -0.01$ instead of 0.15 (see eq. (5)). The negative sign follows immediately from the antisymmetry of color wave function of three valence quarks, it is common for such kind of models.

5. The positive contribution may arise due to the presence of two quarks of the same color inside a nucleon. One can reproduce the experimental number 0.15 if quark-antiquark pairs are correlated in the space with valence quark at the distances of the order $R \sim 1/(0.5 \times 1) \text{ GeV}$, approximately $1/3$ of the nucleon size. Another possibility which seems to us less probable is numerous but uncorrelated quark-antiquark pairs inside the nucleon.

To our mind this result seems to be relevant to the structure of constituent quark and to the basis of the additive quark model [3] , i.e. for hadronic physics in general. Note the coincidence of $R$ mentioned above and the known estimates of the size of constituent quark.

That is why we are calling for more accurate experimental study of the parameters of scaling violation in the region $Q^2 = 1 \times 10 \text{ GeV}^2$. It is a proper time to come from the question "Whether QCD is right?" to "How the nucleon is made in QCD?" and the study of deep inelastic scattering gives a very subtle information on this point.

It is worth mentioning that in general power corrections are different for neutrino and electron scattering. But the picture of a nucleon described above implies the validity of the well known relation between the moments
\[ M_{2}^{Y,S_{2}}(2) = \frac{\delta}{5} M_{2}^{S_{2}}(2), \quad M_{2}^{Y,N_{S}}(2) = 6 M_{2}^{e,N_{S}}(2) \]

not only for the leading twist 2 but for the next twist 4 as well. It is interesting to check these relations.

References


3. For recent review see: A. Buras, Rev. Mod. Phys. 52 (1980) 199.


DEEP INELASTIC SCATTERING
FINAL STATE
HADRON FINAL STATE RESULTS FROM BEBC

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This talk reports new 1982 results from three of the BEBC experiments on the reactions

\[ \nu N + \mu^+ \pi^- \rightarrow \text{Ne-H}_2 \text{ mix (WA59)} \]

\[ \nu, \nu p + \mu^+ \pi^- \rightarrow \text{H}_2 \text{ (WA21)} \]

\[ \nu p + \mu^+ \pi^- \rightarrow \text{H}_2 \text{ track sensitive target surrounded by Ne-H}_2 \text{ mix (WA24).} \]

The situation in 1981 is well reviewed by Schmitz at Bari (1). The usual kinematic variables are defined with respect to Figure 1 as

\[ Q = - (\frac{p_\nu}{M} - \frac{p_\mu}{M})^2 \text{ momentum transfer squared} \]

\[ q = p_\nu - p_\mu \]

\[ v = \frac{p_\nu + p_\mu}{M} = E_\nu - E_\mu = \text{lab energy of exchanged vector boson}, W^2 \]

where \( M \) = stationary target mass

\[ x = \frac{Q}{Q} \frac{1}{2p_\nu q} \quad y = \frac{v}{v} \frac{p_\mu}{p_\nu} \quad \text{Bjorken} \ x \text{ and} \ y \]

\[ W = Q (\frac{1}{x} - 1) + M^2, \text{ effective mass of all final state hadrons.} \]

\[ p_t = \text{transverse momentum of particle with respect to} \quad \vec{q} \quad \text{vector}. \]

\[ x_f = \frac{p_{th}^\pi}{p_{th}^\mu}, \text{ Feynman} \ x, \text{ where} \ p_{th}^\pi \text{ is the longitudinal momentum of the} \]

individual particle in the final state hadron c.m. system with respect to the lab \( \vec{q} \) vector.
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\[ \gamma_R = \frac{E_h + p_{th}}{\sqrt{m^2 + p_T^2}} \]

rapidity, where \( m \) is the individual particle mass.

A fragmentation function is defined as \( D^h(x,z,Q^2) = \frac{1}{N_{ev}(x,Q^2)} \frac{dN^h}{dz} \), where

\( N_{ev}(x,Q^2) \) is the number of events in the \( x,Q^2 \) region of interest and \( dN^h \) is the number of hadrons of type \( h \) having \( z \) values, \( z + dz \).

It is useful to use a simple quark parton picture (Fig 2) to discuss the data.

Most simply, the observed final state hadrons are the fragmentation products of the quark struck by the \( W \) boson, called current fragments, or of the spectator diquark (or multiquark systems if sea quarks are allowed as actors or spectators), called target fragments. The fragmentation of the quarks is assumed independent of their previous history, so that \( D^h(x,z,Q^2) = D^h(z) \).

The separation of the target and current fragments experimentally is non-trivial. Usually we assume that hadrons for which \( x_F > 0 \) (\( < 0 \)) i.e. forward (backward) in the hadron c.m. are current (target) fragments. This separation does not make sense when the rapidity distribution is narrow, as it is for low \( W \) events. \( W > 4 \) GeV is necessary before any forward/backward separation is visible in the data.

This year, however, a more serious experimental problem has occupied our attention. In a bubble chamber it is not often possible to identify protons of \( p > 1 \) GeV/c in the lab. Misidentifying them as pions can shift their rapidity right into the forward direction - if the rapidity distribution is narrow - and distort the forward \( \pi^+ z \) spectra, right up to high values of \( z \). It seems necessary to restrict \( W > 4 \) GeV to obtain a sufficiently large rapidity space to confine such misidentified protons to low \( z \) values.

Particle identification in \((u,e)N\) experiments\(^{(2)}\) points to the conclusion that misidentified protons can fake interesting physics effects like: (i) scale and factorization breaking: (ii) distortion of forward and backward charge (quark charge) analysis: (iii) seeming disagreement of \( v \) and \( \bar{v} \) fragmentation functions.

Historically \( vp^{(3)} \) and \( WHe^{(4)} \) experiments from BEBC have shown scale breaking \((D(z) + D(z,Q^2))\) and factorization breaking \((D(z,Q^2) + D(x,z,Q^2))\).
only if events at all W values are included. For $W > 4$ GeV there was no effect\(^{(3,22)}\). One can argue for the inclusion of the low W region theoretically\(^{(4,5)}\) (making no separation of forward and backward regions, but weighting higher $z$ values preferentially) and interpret these observations as the dependence of the fragmentation of a quark on its production characteristics due to gluon radiation\(^{(6)}\) (Fig. 3).

However, if no correction is made for the effects of proton misidentification at low $W$, the results are likely to be systematically distorted. This becomes evident when we consider $\bar{v}$ data\(^{(7)}\), where this problem becomes catastrophic. The non singlet difference, $D^{NS}(m,Q^2) = D^+(m,Q^2) - D^+(m,Q^2)$, (where $D(m,Q^2) = \frac{1}{z} \int D(z,Q^2) \, dz$) becomes negative within errors for $1 < Q^2 < 5$ GeV/c\(^2\), and then rises with $Q^2$, contrary to QCD expectations (see fig 4a).

Considering $D^-$, $D^+$ separately (Fig 4c,d) for all $W$, and for $W > 4$ GeV, we see that this is due to the striking excess of $D^+$ at low $Q^2$, when low $W$ events are included. This excess can be fitted (dashed lines on Fig 4d) by an LPS Monte Carlo with backward baryon production and misidentification of protons for which $p > 1$ GeV/c. The misidentification introduces spurious scale breaking since such protons are assigned to incorrect rapidity. Note how a similar effect in $\nu$ reactions would enhance any genuine QCD-like trend in the difference $D^+ - D^-$. After making the cut $W > 4$ GeV new high statistics $\bar{v}$ data from WA59 do exhibit behaviour qualitatively consistent with leading twist QCD expectations for $m > 2$ (see full line on fig 4b), showing evidence for modest scale and factorisation breaking in agreement with higher $W$ muon data\(^{(8)}\).

If we wish to look at fragmentation functions over all $x_F$, i.e. for low as well as high $x_F$ values, then even after making a W cut, we must correct for the effects of particle misidentification carefully. Preliminary work from the WA21 collaboration\(^{(9)}\) has used the Lund Monte Carlo to make these corrections and to correct for smearing in the observed values of $z$, due to the need to estimate, rather than measure, total hadron energy in any event with undetected neutral hadrons. Referring to Fig 2 for the flavour preferences of the currents in $\nu$ and $\bar{v}$ interactions, we see that one can measure...
all restricted $x > 0.1$ to minimize sea quark contributions. The expectations $D^{-} = D^{-}, D^{+} = D^{+}, D^{-} = D^{-}, D_{ud} = D_{ud}$, are all well verified (see Fig 5). Previous data without correction for proton misidentification has always found $D^{-} > D^{+}$.

The investigation of higher twist terms is also very sensitive to proton misidentification. K L Berger (11) has calculated an additional term to the semi-inclusive differential cross sections for the processes, $\sqrt{s} N \rightarrow \mu^{+} \pi^{-} x$.

$$\frac{d^{4} \sigma}{dx dy dz dp_{t}} = \frac{x u(x)}{z p_{t}} \frac{x (1-y)^{2} (1-z)^{2} + \frac{4}{9} (1-z) p_{t}^{2}}{Q^{2}}$$

and $\sqrt{s} N \rightarrow \mu^{-} x$

$$\frac{d^{4} \sigma}{dx dy dz dp_{t}} = \frac{x d(x)}{z p_{t}} \frac{x (1-y)^{2} + \frac{4}{9} (1-y) p_{t}^{2}}{Q^{2}}$$

applicable for large $z$ values, $p_{t}^{2} << Q^{2}$. The second term in these expressions is the higher twist (HT) contribution to the production of the leading pion, and the first term is the usual quark parton model (QPM) scaling contribution (no leading twist is considered here). $x d(x), x u(x)$ give the momentum distributions of the struck valence quarks.

An HT term of this form would give rise to $y/z$ correlations at low $q^{2}$ (provided $Q^{2} > 1$ GeV/c$^{2}$ to make sense of the higher twist calculation) since it has a harder $z$ dependence and a softer (harder) $y$ dependence than the scaling term for $\sqrt{s} N$ interactions. In 1980 strong correlations of this sort were observed in the $y$ and $z$ distributions of the interaction $\sqrt{s} N \rightarrow \mu^{-} x$ at Cargamelle (12). All of scale breaking was attributed to the HT term.

However, Mazzanti (13) has noted that for $\nu$ production a similar $y/z$ correlation is expected from LPS restrictions, since low $y$ means low $W$ and low $W$ means low multiplicities and thus larger $z$ per particle.

Misidentification of protons can also produce the correlations (2) since fast protons can appear as $\pi^{\pm}$ at high $z$ for low $W$, and thus for low $y$, events.

In support of these criticisms we note that no effect is seen in $\sqrt{s} N$ by WA47 (4) using a narrow band beam which yields few events at low $W$.

To clarify the situation $\sqrt{s} N \rightarrow \nu^{+} \pi^{-} x$ interactions were studied, since the leading pion is a $\pi^{-}$ unaffected by proton misidentification and Mazzanti's effect will act oppositely to the HT term. In 1981 (1) no effect was seen in
the z distributions of $\tau^-$ in $\overline{\nu}d$ or $\overline{\nu}n$ in BEBC, and a small effect was seen in $\overline{\nu}n$ in the 15' at FNAL. However, these experiments are not statistically incompatible. The null/small effect may be interpreted as cancellation of the HT term and Mazzanti's effect, but more significantly, we should note that Berger's prediction involves production of quarks, and in $\overline{\nu}$ interactions the antiquark contribution is very important, becoming dominant at high $y$, since the antiquark cross section

$$d\sigma \approx \frac{zq(x)}{zp_t^2} \left[ (1-z)^2 + \frac{4}{9} \left( 1 - \frac{1}{y} \right) Q^2_p \right]$$

has a flat $y$ distribution for the scaling term. Thus the antiquark contribution has opposite $y/z$ correlations to the scaling term. We must therefore make an $x$ cut to minimize this contribution before we can interpret data on $y$ and $z$ distributions simply. A further caution is that $z$ distributions are very sensitive to smearing for high $z$ values, where the HT term is important.

In 1982 an extensive analysis has been done on $\overline{\nu}n$ interactions by the WA59 collaboration, accounting for the above mentioned pitfalls. Comparison of the $y$ distributions for events with $\pi^-, \pi^+$ produced at high $z$ is less sensitive to smearing than consideration of the $z$ distributions. Fig 7a shows the ratio of the $y$ distributions in $\overline{\nu}n + \mu^+\pi^+\pi^- x$ for $\pi^-$ and $\pi^+$ of $z > 0.5$, for events of all $x$, all $W$ values and $1 < Q^2 < 8$ GeV/c$^2$. This figure shows a striking rise, but this cannot be attributed to the HT term, since although the quark contribution would give a rise (dotted line) the presence of the antiquark contribution turns this into a slight fall (dashed line). A fall is also expected from Mazzanti's effect, so the only remaining plausible explanation for the observed rise is the presence of misidentified protons in the $\pi^+$ background sample at low $y$ but not at high $y$. The full line in Fig. 7(a) shows LPS Monte Carlo with misidentification included. Fig 7b gives the same ratio of $y$ distributions under the cuts, $x > 0.15$, to reduce the antiquark contribution, and $W > 4$ GeV, to remove misidentification effects and to escape the region of trivial LPS correlations. A moderate rise is seen, compatible with a small HT term, but not incompatible with the LPS Monte Carlo (full line).

In fact, $y$ is not the optimal variable to consider, since in $\overline{\nu}n$ interactions off quarks, although the HT effect increases with $y$ (relative to the scaling term), higher $y$ means higher $Q^2$ and the HT effect decreases as $Q^2$ increases.

A more quantitative investigation (14) generalizes the formalism to include the antiquark contribution and defines a more optimal variable. We write

$$\frac{d\sigma}{dx dy dz dp_t^2} = \frac{x}{zp_t^4} \left[ (q(x)(1-y)^2 + \overline{q}(x))(1-z)^2 + \frac{4}{9} \left( 1 - \frac{1}{y} \right) Q^2_p (q(x) + \overline{q}(x))p_t^2 \right]$$

which yields fragmentation functions for $z > s$
where \( <K^2> \) is a weighted average over \( p_t^2 \), giving the magnitude of the
higher twist effect, including complications due to mass effects(11), and

\[
R = \frac{4}{9} \frac{(q(x) + \bar{q}(x))}{(1-y)} \frac{(1-y)}{Q^2} = \frac{1}{(1-y)Q^2}
\]

\( R \) includes the dependence of the HT effect on \( x, y \) and \( Q^2 \), and is the most optimal variable to consider.

It is calculated by parametrizing the \( x \) distribution of the data by appropriate combinations of \( x_q(x), \bar{x}_q(x) \). If the HT term accounts for all scale breaking then a plot of \( D^-(z>a) \) versus \( R \) yields a straight line the slope/intercept of which gives \( <K^2> \). The value of \( <K^2> \) should depend
neither on the \( z \) cut, for high \( z \), nor on cuts on the event variables
\( x, y, Q^2, W \) etc.

Fig. 8 shows \( D^-(\pi^-)(z>a) \) for \( Q^2 > 1 \text{ GeV}/c^2, W > 5 \text{ GeV}, a = 0.5, 0.6, 0.7 \).
The linear dependence is well verified with \( <K^2> = 0.25 \text{ GeV}/c^2 \) for \( \pi^- \) and
\( <K^2> = 0 \) for \( \pi^+ \) (no HT contribution). There is no dependence on the \( z \) cut
for \( z > 0.5 \), or on the \( W \) cut for \( W > 4 \text{ GeV} \). There is also no dependence on the
\( x \) cut even though the formalism has very different \( y \) dependences for the
quark and antiquark contributions, and should be very sensitive to the \( x \)
region under investigation. The exact \( y, Q^2 \) dependence has been investigated
by maximum likelihood generalising the HT term to

\[
\frac{4}{9} \frac{(1-y)}{Q^2} <K^2>
\]

obtaining \( d = 1.2 \pm 0.4, b = 0.8 \pm 0.2, <K^2> = 0.25 \pm 0.10 \text{ GeV}/c^2 \). Full
accounting for smearing yields \( 0.15 < K^2 < 0.45 \text{ GeV}/c^2 \).

Thus the observed scale and factorization breaking takes the \( y, Q^2 \) behaviour
predicted by Berger. However, investigation of the \( p_t^2 \) dependence of the
data does not support the HT prediction. Fig. 9 shows that \( <p_t^2> \) decreases
as \( R \) increases, for high \( z \) tracks \((z>0.7)\), whereas the HT term would give
the opposite behaviour. Thus the data may still admit of leading twist
interpretation (\( y, z \) correlations imply \( x, z \) correlations, for limited \( Q^2 \)
ranges).

The WA24 collaboration have been investigating the possibility of
identifying protons in up interactions from \( E-p_x \) balance(15). In a perfect
event \( E-p_x \) for the final state (hadrons and muon) is equal to the target
mass. This is far from true when the final state baryon is not identified
even when all final state hadrons, including neutrals, are found and well
measured. The use of a hydrogen track sensitive target (TST), surrounded by
Neon, provides a control sample of well measured events without the
complications of Fermi motion and nuclear products. For an event to be
classed as well measured, the conditions
\[ p_{T,U} + p_{\text{had}} < 200 \text{ MeV}/c \text{ and } 0.85 \frac{p_{T,\text{in}}}{p_{T,U}} < 1.05, \]

where \( p_{T,\text{in}} \) is the total hadron \( p_T \) in the lepton plane, must be met. Then the final state proton is identified as the positive hadron which gives \( |E - p_T - M| < 200 \text{ MeV} \), when assigned the proton mass. The event is supposed to have a final state neutron if this condition cannot be satisfied. Complete events have an energy correction applied according to their \( p_T \) imbalance before the method can be used. Ambiguities and backgrounds are investigated by applying the method to negative hadrons, and by applying it to events where the final state baryon was already identified. The method is most reliable for \( p < 2.5 \text{ GeV}/c \) protons — a substantial improvement on \( p < 1 \text{ GeV}/c \).

Preliminary results which seem insensitive to backgrounds and ambiguity of choice are:

1) On average more positively charged hadrons are produced in the backward than in the forward direction, and from this it follows that backward and forward charge are roughly equal (at least at low \( W \) values). This contradicts previous years' conclusions\(^{(1)}\), and the difference lies in the proton identification. The conditions for previous hydrogen target results have been simulated by dropping all the seen neutrals and not identifying protons of \( p > 1 \text{ GeV}/c \). Fig. 10 shows a comparison of those conditions and the TST results, where one clearly sees the reversal in forward and backward positive charge.

2) Quark charge (or leakage) evaluation by extrapolation of the net forward charge against \( 1/W \)\(^{(16,17)}\), is systematically shifted. Fig. 11 shows a comparison of TST results to previous results.

3) \( \sim 75\% \) of events have final state protons.

4) The proton fragmentation function, shows that protons are more often backward produced than \( A \). Fig. 12 shows proton and \( A \) fragmentation functions as a function of \( x_F \). Thus using \( A \) spectra to correct for proton misidentification in \( v \) interactions may be unreliable.

The WA21 collaboration have been doing more detailed work on quark charge evaluation\(^{(17)}\) accounting for the problems of particle misidentification and ambiguity more carefully. Considering Fig. 2, one might try to measure quark charge by the average charge of the current fragments, \( <Q_{\text{jet}}> \). This will work provided one can make a meaningful separation of the target and current fragments. Even theoretically this may be difficult, since many models\(^{(18)}\)
of quark hadronization involve recursive cascading of quark-antiquark pairs and separation of current fragments involves cutting a quark line, such that,

\[ \langle Q \rangle = e - \sum_q q \text{ struck quark charge - leakage term} \]

\[ \text{Jet} \]

\[ \text{where } e_u \text{ is the u quark charge and } \gamma_u \text{ is the probability to create a } u \bar{u} \text{ pair. This gives } \langle Q_{\text{jet}} \rangle^y = 1 - \gamma, \langle Q_{\text{jet}} \rangle^u = -\gamma, \text{ for } u,d,s \text{ quark types where } \gamma_u = \gamma_d = \gamma \text{ and } e_u - e_d = e_s - e_s = 1. \text{ Thus } \langle Q_{\text{jet}} \rangle \text{ measures } \gamma \text{ rather than quark charge. Only } \langle Q_{\text{jet}} \rangle^y = e_u - e_d, \text{ is independent of hadronization assumptions.} \]

Usually \( \langle Q_{\text{jet}} \rangle \) is measured as a function of \( 1/W \) and an extrapolation \( 1/W \rightarrow 0 \), is made to ensure the separation of current and target fragments, experimentally. 1982 results (17) using this method are

\[ \langle Q_{\text{jet}} \rangle^y = 0.61 \pm 0.1, \quad \langle Q_{\text{jet}} \rangle^u = -0.50 \pm 0.17 \]

where a cut \( x > 0.1 \) is made to exclude sea quarks. However this method is sensitive to the extrapolation procedure. An extrapolation in \( 1/W \) may be just as valid(19) and yields systematically different results. Also extrapolation is sensitive to the starting point, usually taken as \( W > 2.5 \text{ GeV} \), which, as we saw in the last section, is insufficient to exclude bias from misidentified protons wrongly boosted to the forward direction.

Finally extrapolation is sensitive to smearing effects, which affect the definition of the c.m. frame and the value of \( W \).

Ochs, Shimada and Stodolsky(20) have suggested an alternative method to measure quark charge which does not require extrapolation, is less dependent on misidentification and smearing biases, and is independent of the details of hadronization models. They derive that the ratio of the average net charge, \( \Delta Q \), to the average fractional energy, \( \Delta \varepsilon \), emitted in an angular interval \( d \lambda \), measures the jet charge, where \( \varepsilon = E_h \lambda/(W/2) \) and \( \lambda = \cos \theta_h \lambda/(W/2) \). \( \Delta \varepsilon / d \lambda \) and \( \Delta Q / d \lambda \) are scaling, energy independent quantities dependant on the same function of \( \lambda \), so that \( \Delta \varepsilon / d \lambda = \frac{1}{\langle Q_{\text{jet}} \rangle} \Delta Q / d \lambda \) holds, and
follows independent of hadronisation model. \( \lambda \) has the further advantage that it is a "clustering invariant" quantity, (unlike \( x_{\perp} \)) so that charge is distributed in \( \lambda \) roughly the same before and after resonance decay. Extrapolation is avoided by observing angular intervals close to the current direction (jet axis). The data verifies scaling for \( W > 4 \text{ GeV} \).

Insensitivity of the results to smearing and misidentification biases above this \( W \) cut, has been checked by Monte Carlo (21).

Fig. 14 shows \( \frac{\Delta Q}{\Delta \lambda} \) and \( \frac{\Delta Q}{\Delta Q} \) versus \( \lambda \), for \( W > 4 \text{ GeV}, \lambda > 0.1 \). \( \frac{\Delta Q}{\Delta \lambda} \) is independent of \( \lambda \) for \( \lambda > 0.5 \text{ GeV}^{-1} \) as predicted by recursive models for hadronisation (20). The jet charge is taken from the most forward angular intervals (\( \lambda > 2 \text{ GeV}^{-1} \)) as \( \langle Q_{\text{jet}} \rangle^V = 0.8 \pm 0.11 \) \( \langle Q_{\text{jet}} \rangle^\nu = -0.33 \pm 0.15 \). \( \frac{\Delta Q}{\Delta Q} \) is independent of \( \lambda \) for \( \lambda > 0.5 \text{ GeV}^{-1} \) both in forward and backward directions and yields values close to QPM charges, with or without leakage accounting.

To summarise our conclusions

Beware proton misidentification and smearing. When they are accounted for we have,

i) \( D_u^+ - D_d^+ \), \( D_u^- - D_d^- \), \( n_{ud}^+ - n_{ud}^- \), and \( v,\bar{v} \) fragmentation functions are compatible.

ii) Backward positive charge > forward positive charge, in \( \nu \bar{p} \).

iii) \( \langle Q_{\text{jet}} \rangle^{\nu \bar{p}} - \langle Q_{\text{jet}} \rangle^{\nu \bar{p}} = 1.13 \pm 0.19 \), QPM charges verified.

iv) Evidence for small scale and factorization, breaking effects in \( \nu \bar{p} \) interactions, which can be parametrized by the form

\[
\frac{4}{9} \frac{(1-y)}{Q^2} <K^2 > , \langle K^2 > = 0.25 \text{ GeV}^2/c^2
\]

as predicted by higher twist calculations.
References


   W. Borkus, Phys. Lett. 85B, 67 (1979)
   R. Baler and K. Fawcett, Z. Physik C2, 339 (1979)

   WA47: Reference 4.


10. See Reference 2.


Fig. 4

$D_{NS}(m, Q^2)$: a) for all $W$; b) for $W > 4$ GeV; c) $D_{h^-(m, Q^2)}$ for all $W (+, x, B)$ and $W > 4$ GeV ($0, \Delta, \gamma$); d) as for c) for $D_{h^+(m, Q^2)}$: \( \gamma \)N WAS9 data.
Fig. 5: Corrected normalized $x_F$-distributions $D^{\pi^\pm}(x_F) = \frac{1}{N_{ev}} \frac{d^2 N}{dx_F} \left[ \pi^+ \text{ (full circles)} \right.$ and $\pi^- \text{ (open circles)} \left. \right]$ in the forward ($x_F > 0$) and backward ($x_F < 0$) cms hemispheres from $\nu p$ and $\bar{\nu} p$ events with $N > 3$ GeV, $x_B > 0.1$, $\nu$, $\bar{\nu}$ WA21 data.
Fig. 7: a) ratio of $\pi^-/\pi^+$ y distributions for all x, all W, $1 < Q^2 < 8$ GeV/c$^2$
dotted line, HT prediction for quarks; dashed line, HT prediction for
quarks and antiquarks; full line, LPS Monte Carlo including proton
misidentification.
b) as for a) for $x > 0.15$, W > 4 GeV: $\rightarrow$ WA59 data.

Fig. 8: a) $D^m(z > a)$ versus R for $a = 0.5$, 0.6, 0.7; W > 5 GeV, $Q^2 > 1$ GeV/c$^2$.
b) as for a) for $D^m(z > a)$ for $a = 0.5$, 0.6: $\rightarrow$ WA59 data.

Fig. 9: $<p_t^2>$ versus R for W > 4 GeV, $Q^2 > 1$ GeV/c$^2$, $z > 0.7$: $\rightarrow$ WA59 data.
Fig. 10: mean charged multiplicities for, +, - tracks in forward and backward directions versus log W^2

a) for \( vp \) WA24 data with proton identification.

b) for \( vp \) WA24 data, without proton identification and without neutral hadrons.

Fig. 11: mean charged multiplicity in the forward direction versus \( 1/W \) for \( vp \) WA24 data

a) and b) as for Fig. 10. Lines (1) and (2) are from References (16).
Fig. 12: $x_F$ normalised distributions for protons (up WA24 data) and lambda's (WA21 data, Bossetti et al, Nucl. Phys. B194, 1 (1982)).

Fig. 14: a) $\frac{\Delta Q}{\Delta \lambda}$ versus $\lambda$ for up and $\bar{u}p$ WA21 data, b) $\frac{\Delta Q_{\bar{u}p}}{\Delta Q_{up}}$ versus $\lambda$ for the same data.
In many different investigations it was shown that the properties of the hadronic system produced in both neutrino and antineutrino collisions with nucleons or nuclei for incoming energies $E_\nu \sim 10 \text{GeV}$ can be explained in the framework of the quark parton model (QPM) \(^1\). Whereas at large $Q^2$ corrections of quantum chromodynamics (QCD) to the model become important \(^2\), the question arises about the validity limit of the QPM at low $E_\nu$.

We report here about new data on inclusive charged hadron production in neutrino and antineutrino interactions in the energy range $3 - 30 \text{ GeV} \ (/3,4/$. Furthermore, preliminary results on strange particle production in this energy range will be given \(^5\).

The following reactions have been studied:

\[
\begin{align*}
\bar{\nu} A &\rightarrow \mu^- h^{-} X (1) \\
\bar{\nu} A &\rightarrow \mu^+ h^{+} X (2) \\
\nu A &\rightarrow \mu^- K^-(\Lambda) X (3)
\end{align*}
\]

The experiment has been carried out with the heavy liquid bubble chamber SKAT exposed to wide band neutrino and antineutrino beams of the IHEP Serpukhov. The average beam energy was about 6 GeV. The chamber was filled with freon CF$_3$Br which properties provide a reliable detection of neutral particles and a good muon selection.

The total volume of the chamber is 6.5 $\text{m}^3$, the fiducial volume was chosen to 1.7 $\text{m}^3$. The analysis is based on 100 000 $\nu$ and 176 000 $\bar{\nu}$ pictures corresponding to $\sim 5$ 000 $\nu A$ and $1$ 500 $\bar{\nu} A$ interactions in the fiducial volume. After all cuts for the clean selection of reactions (1) and (2) we find 2 153 $\nu A$ and 528 $\bar{\nu} A$ charged current interactions with the hadronic mass squared $W^2 > 1 \text{ GeV}^2$. For reactions (3) we chose $E_\nu > 2 \text{ GeV}$ and $W > 1.5 \text{ GeV}$ which results in $1$ 549 events.

The final state particles considered have been classified as follows:

- all negative tracks were signed $h^-$, they are dominantly $\pi^-$
- positive tracks beside identified protons were signed $h^+$ and got the pion mass; the ratio of positive pions to unidentified protons was estimated to be about 2;
- $K^-$'s and $\Lambda$'s are identified by 3 constrained kinematical fits.

Our data sample is concentrated at very low values of $W^2 < 25 \text{ GeV}^2$ and at the four momentum transfer squared $Q^2 < 70 \text{ (GeV/c)}^2$. In this region one expects yet a strong overlap between quark and diquark fragmentation processes at Feynman $x_s = 0$ in the current nucleon cms. Furthermore, our data will be influenced by quasi-elastic $\Delta$-production at low $W^2$.

1) $X^0$ means $X^0$ or $\bar{X}^0$
For the average multiplicity of charged particles as function of \( W^2 \) we observe the well known dependence <\( n > = a + b \cdot \ln W^2 \). For negative particles of reactions (1) and (2), the slopes are given in table 1. They are similar to each other and to results at higher \( E^*/2 \), 6, 7.

In pp-scattering a multiplicity correlation

\[ <n_p> = a + b \cdot n_B \]  

(4)

for forward and backward going charged particles was observed at ISR energies. The slope \( b \) was found to be greater than zero but seems to decrease with the energy \( /2 \). We present in fig. 1 our results for reaction (1). One observes a good description of the data by eq. (4) with \( b < 0 \) and slightly increasing with \( W^2 \).

For independent particle production the multiplicity is distributed Poisson-like. Therefore, one gets for the dispersion

\[ D = \sqrt{<n>} \]  

(5)

For charged particle production in hadronic interactions, however, the empirical relation 8/9

\[ D = a + b <n> \]  

(6)

was found to be true.

Our results are shown for 'leading' fragments 1) of reaction (1) and (2) in fig. 2a, for 'non-leading' fragments in fig. 2b, respectively. As one can see the leading fragments are well described by the linear relation (6) whereas non-leading fragments seem to be produced more independently (the dashed curves in fig.2) correspond to eq. (5)).

A different behaviour of both types of fragments was also found studying the correlation parameter \( f^* \) as a function of \( <n> \). Leading fragments behave similar to pp-annihilation data as observed for \( f^* \) also at higher \( E^* /2 \). In contrast, non-leading fragments follow more closely pp-scattering results.

The difference of the average forward charges in x and \( \gamma \) interactions

\[ D(Q_F) = <Q_F^x > - <Q_F^\gamma > = e_q - e'_q = 1 \]  

(7)

can be exactly predicted by the QPM. To measure this quantity has also the advantage that the overlap of quark and diquark fragmentation may not strongly influence the result. In fig. 3 we show \( D(Q_F) \) as a function of \( W^2 \). One observes that already for \( W^2 \approx 10 \text{ GeV}^2 \) the QPM prediction is reached by the data.

To study the event structure of our data we compare in fig. 4a,b the average transverse momentum \( <p_T> \) and the average longitudinal momentum \( <p_Z> \) for charged hadrons of reactions (1) and (2) as a function of \( W^2 \). Both quantities increase slightly with \( W^2 \). For \( W^2 < 10 \text{ GeV}^2 \) \( <p_T> \) is even smaller than \( <p_Z> \) and up to \( W^2 = 25 \text{ GeV}^2 \) it does not exceed \( <p_Z> \) significantly. This means

1) 'Leading' fragments we call those particles which contain the struck quark from the primary interaction.
that we have in the whole $W^2$-range considered dominantly isotropic events and no clear two jet structure has developed.

The average transverse momentum as a function of $x$ is given in figs. 5a,b for charged hadrons for two $W^2$-intervals of our $\nu$ and $\bar{\nu}$ data. A behaviour well known as sea gull effect is observed for all distributions. The significance of the effect increases with $W^2$.

Studying the invariant structure function $F(x_F)$ for different intervals of $W^2$ we found a strong dependence on this variable at lower $W^2$. For a quantitative analysis we fitted our data with the ansatz

$$F(x_F) \sim (1 - |x_F|)^n$$

The calculated parameters $n$ are given in table 2 for negative particles with $x_F > 0$. They are compared to $\gamma^*\nu$-scattering results at different targets at large $W^2$ /2,6,9/. The comparison of low and high energy data shows that only for $W^2 \geq 10$ GeV $^2$ Feynman scaling seems to be reached.

In fig. 6 we show for different intervals of $W^2$ the distributions in the jet variable $z = E_J/E_\nu$ for leading (a.) and non-leading (b.) fragments of reactions (2) and (1). Also given are the QPM predictions of Feynman and Field /1/ for the production of leading and non-leading pions on an isoscalar target. The reactions studied show a slight $W^2$-dependence. The data are described by the model already at $W^2 > 4$ GeV $^2$. A $Q^2$-dependence of $dN/dz$ as predicted by QCD has not been found for our data.

For charged current neutrino freon interactions at energies below 30 GeV, $\pi^-$ and $\Lambda$ multiplicities are given in table 3. We find a visible strange particle production rate of $R_{\pi^-} = 2.8^{+1.4}_{-1.1} \%$. The $W^2$-dependence of this quantity is given in fig. 7 and compared to other neutrino experiments /10/. Reasonable agreement between lower and higher $E_\nu$-data is visible. Correcting for the efficiency of the experiment and unseen decay modes the corrected neutral strange particle production rate is $R_{corr} = 7.6^{+1.4}_{-1.1} \%$.

Summarizing our results on inclusive hadron production in charged current neutrino and antineutrino interaction we conclude that the predictions of the quark parton model describe our data well already above $W^2 = 10$ GeV $^2$ although no clear two jet structure has developed at this energy.

References:


/2/ see e.g. N. Schmitz in Proceedings of the international Symposium on Lepton and Photon Interactions at High Energies, Bonn 1981.

/3/ D.S. Baranov et. al. 'Inclusive charged hadron production in $\nu A$ and $\bar{\nu} A$ interactions at $E_\nu \leq 30$ GeV - Part I: Multiplici-
     ty properties'; Contribution to the conferences 'O-82' Balatonfüred and Paris (1982).
/4/ D.S. Baranov et al., 'Inclusive charged hadron production in ∆A and ∆A interactions at E<sub>γ</sub> ≲ 30 GeV - Part II: Transverse and longitudinal momentum spectra', Contribution to the conferences '∆-82' Balatonfüred and Paris (1982).

/5/ D.S. Baranov et al., 'Results on neutral strange particle production in charged current ∆A - interactions at E<sub>γ</sub> ≲ 30 GeV'; Contribution to the conferences '∆-82' Balatonfüred and Paris (1982).


/10/ N.J. Baker et al., BNL-preprint 29794 (1980).
Table 1

\[ \langle n_c \rangle = a + b \ln W^2, W^2 > 3 \]

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<th>( a )</th>
<th>( b )</th>
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<tr>
<td>( \phi )</td>
<td>(0.39 \pm 0.31)</td>
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Table 2

\[ F(x_F) \sim (1 - |x_F|)^\nu, \Omega(x_F) > 0 \]

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<th>( \nu )</th>
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<td>( n )</td>
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<td>( \Delta n )</td>
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</table>

Table 3

\[ V^* \text{- production} \]

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<th>part. observed number</th>
<th>corrected number</th>
<th>( \langle n &gt; )</th>
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</thead>
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<tr>
<td>( K^* ) 24</td>
<td>93 ± 20</td>
<td>0.06 ± 0.01</td>
</tr>
<tr>
<td>( \Lambda ) 25</td>
<td>57 ± 13</td>
<td>0.04 ± 0.01</td>
</tr>
<tr>
<td>( V^* ) 49</td>
<td>150 ± 24</td>
<td>0.10 ± 0.02</td>
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Fig 1

Fig 2

Fig 3
Abstract

Recent results on various aspects of hadronic final states in deep inelastic muon-nucleon scattering as obtained by the European Muon Collaboration (EMC) are presented and compared with QCD: the scaled energy distributions of charged hadrons, the average $P_T^2$ of neutral mesons and the azimuthal dependence of charged hadrons. The size of the primordial transverse momentum is being discussed in connection with the inclusion of soft gluons. Preliminary results for hadron production on nuclei are given. Finally the new experiment (NA9) of the EMC is shortly described.
Introduction

In the first phase of experiments carried out by the EMC the object was to study the scaling violation of the structure functions and, related to this talk, the production of hadrons in the fragmentation region of the electromagnetic current. For these experiments a forward spectrometer /1/ was used with an open dipolmagnet, with some identification of charged particles by a Cerenkov counter and in the late part of data taking with the inclusion of a lead glass detector to measure photons. High statistic results on $F_2(x, Q^2)$ /2,3,4/ have lead to a rather low QCD-scale breaking parameter $\Lambda$ of around 150 MeV. Already the early results of the EMC on charged hadronic final states /5, 6, 7/, covering a kinematic range up to $W^2 = 450$ GeV$^2$ and $Q^2 = 100$ GeV$^2$, showed for the transverse momentum behaviour and the production of forward jets good agreement with predictions by QCD including nonperturbative effects. These results were complemented by the measurement of the yield of fast protons and antiprotons /8/, for which models are developed /9, 10, 11/. More recent results presented here add considerably to the understanding of the production of hadrons in the current fragmentation region.

For the second phase of experiments of the EMC a vertex detector, covering the target fragmentation region, and more particle identification were added to the forward spectrometer. Data taking commenced in fall 1981, and first results can be expected soon.

Scaled Energy Distributions of charged Hadrons

The distribution of the sum of positive and negative hadrons over the scaled energy $z = E_h/v$ ($v$ the energy of the virtual photon), normalized to $N$, the number of events, has been studied /12/ as a function of $Q^2$, the square of the four momentum transfer by the virtual photon, of Bjorken $x = Q^2/2vv$ and of $W^2$, the square of the mass of the final hadronic system. In the quark parton model (QPM) this distribution is given for hadrons of type $h$ by

$$\frac{1}{N_u} \left( \frac{dN^h_+}{dz} + \frac{dN^h_-}{dz} \right) = \sum_i e_i(x) \left( D_i^{h+}(z) + D_i^{h-}(z) \right)$$

(1)

with $e_i = e_i^2 \cdot q_i(x) / \sum_j e_j^2 q_j(x)$, where the $q_i(x)$ are the quark distributions and $i, j$ run over quarks and antiquarks of all flavours. $D_i^{h}(z)$ is the probability for a quark of type $i$ to fragment into a hadron of type $h$. In the QPM (1) is independent of $Q^2$ and the factorisation structure of (1) leads, neglecting strange and charm quarks, to a complete independence of $x$ for pions:

$$\frac{1}{N_u} \left( \frac{dN^\pi_+}{dz} + \frac{dN^\pi_-}{dz} \right) = D_u^{\pi+}(z) + D_u^{\pi-}(z)$$
Without any particle identification this is then equivalent to the distribution of all charged hadrons $(\frac{dN^+}{dz} + \frac{dN^-}{dz})/N_\mu$, if one neglects differences for the fragmentation into strange mesons and baryons. In the leading logarithm approximation of QCD the $\epsilon_1$ and $D_1^h$ become $Q^2$ dependant, but the factorization structure remains. However in 1. order of QCD, with the emission of gluons and their fragmentation into hadrons also, with the gluon vertex correction and with the $q, \bar{q}$ production coupled to the nucleon via a gluon,

the expression $(\frac{dN^+}{dz} + \frac{dN^-}{dz})/N_\mu$ becomes also $x$ dependant /13/.

The data used for this analysis were taken with a primary energy of 280 (120) GeV on a 6 m long $H_2$ target, however interactions in the downstream 3m (2 m) part were selected only. Cuts were applied to the data to keep the systematic error on $(\frac{dN^+}{dz} + \frac{dN^-}{dz})/N_\mu$ in all bins of $z$, $Q^2$ and $x$ below 10 %. The remaining number of events are 35 K (25 K).

The $Q^2$ dependence of the resulting multiplicity is shown for two intervals of $x$ and for different $z$ bins in Fig. 1 a. Especially at the higher values of $z$ a small but definite decrease of the multiplicity with $Q^2$ is seen. The dashed curves are the result of a QPM calculation, based on standard quark distribution functions /14/, and fragmentation functions /15/, and show no $Q^2$ dependance. The full lines however, resulting from a 1. order QCD calculation /16/ with quark and gluon distributions from /17/, fragmentation functions from /18/ with $A = 500$ MeV, show a decrease with $Q^2$ in qualitative agreement with the data.

The $x$ dependance, now for two fixed intervals of $Q^2$, is given in Fig. 1 b, again together with the QPM and QCD calculations. The data show an increase of the multiplicity with increasing $x$. This behaviour is also represented by the QCD calculation.

A more quantitative picture of the amount of scaling violation and factorization breakdown is obtained by looking at the derivatives of $\ln((\frac{dN^+}{dz} + \frac{dN^-}{dz})/N_\mu)$ with respect to $\ln Q^2$ and $\ln x$. These quantities are shown in Fig. 2 as a function of $z$ for all available bins of $x$ respectively $Q^2$ /19/. The full lines are the QCD calculation. Especially from these figures it is clear, that this QCD calculation represents the main trend of the data, but does not agree with them quantitatively. It should be noted however, that no attempt was made to vary the input: the quark and gluon distribution and fragmentation
functions. For the scale breaking parameter \( \Lambda \) one would expect it to be the same as for structure functions. It had been pointed out, that this QCD calculation does not treat the parton distributions in 1. order QCD, which should be done to obtain a more reliable result /20/.

Instead of choosing the variable \( Q^2 \) or \( x \), one can use also \( W^2 \), the square of the total energy of the final hadrons in their center-of-mass system. At fixed values of \( W^2 \) the data do neither show a \( Q^2 \)- nor a \( x \)-dependance. The data therefore were combined and Fig. 3 shows their \( W^2 \) dependence for the different \( z \) bins. A clear decrease of the multiplicity with increasing \( W^2 \) is observed for all values of \( z \) shown (\( z > 0.15 \)), which is also present in the QCD calculation for \( z > 0.25 \). This result may indicate, that only the amount of energy being transfered to the struck quark is important for the amount of gluon radiation, leading to less and less particles of high momenta with increasing \( W^2 \). This effect has at least to be compensated at small values of \( z \), apparently only below \( z = 0.15 \), by an increase of the multiplicity with increasing \( W^2 \). Because of the independance of \( x \) at fixed energy \( W \) the gluon radiation and the quark and gluon fragmentations seem to be roughly independant of the quark content of the nucleon.

Transverse Momentum of neutral Pions

Neutral pions have been measured using a leadglass detector, which was placed symmetrically around the beam in the forward spectrometer in front of the hadron absorber (see Fig. 13). It consisted of a preshower section with 5.5 radiation length of leadglass and two MPWC's, having ADC readout on cathode strips, and a back array of 450 leadglass blocks 8 x 8 x 40 cm\(^3\) adding another 13.5 radiation length. This detector covers an area of 2.4 m vertically times 1.2 m horizontally.

Data were taken with 200 GeV primary muons on 6 m of \( H_2 \)-target, but only events in the downstream 3 m were used. Showers were selected giving at least 5 GeV of total energy in the leadglass and at least 0.5 GeV in the back array. Neutral pions were separated from single photons by requiring two separated showers in the back array in the \( \pi^0 \) - energy range of 5 - 20 GeV, thus giving the energies of the two photons separately and their opening angle. In the range 20 - 80 GeV again either two separated showers were required (very \( \pi \)-symmetric decays) or two separated clusters in the MPWC, thus giving the opening angle of the two photons in the almost symmetric decay and the combined energy. Above 80 GeV no \( \pi^0 \) are used. A Monte Carlo program was developped, which simulated production and detection of \( \pi^0 \)'s leading to a full agreement of the mass spectrum between data and Monte Carlo. At present 8500 \( \pi^0 \)'s are in the results. At least a factor of two more can be expected from more data being analysed.

In Fig. 4 the scaled energy distribution of \( \pi^0 \)'s is compared with those for hadrons of positive and negative charge, as measured by the EMC at 280 GeV. The neutral pions
are lying nearer to the negative hadrons than to the positive ones, which can be understood, as protons and kaons are not subtracted. For a quantitative comparison a large sample of identified \( \pi^\pm \) is necessary which is not yet available at these energies.

The overall \( p_T^2 \) distribution of \( \pi^0 \)'s \( (0^2 > 3 \text{ GeV}^2, 50 < W^2 < 350 \text{ GeV}^2) \), where the \( p_T \) is measured with respect to the direction of the virtual photon, is shown in Fig. 5 and compared with a QCD calculation using the Lund model /21/. The main input parameters for the model are \( \Lambda = 500 \text{ MeV} \), fragmentation \( p_T \) of the primary quarks \( \alpha_q = 310 \text{ MeV} \) and the primordial transverse momentum with \( \langle k_T^2 \rangle = 0.65 \text{ GeV}^2 \). The agreement of the model with the data is good. Excluding QCD effects and primordial \( k_T \) the high transverse momenta are clearly not reproduced.

Searching for the kinematic variation of the average \( p_T^2 \) of neutral pions Fig. 6 a shows the \( z^2 \), Fig. 6 b the \( Q^2 \) and Fig. 6 c and 6 d the \( W^2 \) dependance. In Figs. 6 a and 6 d the \( \langle p_T^2 \rangle \) for charged hadrons is also shown and the agreement with the neutral pions is very good. Also given are the results from the Lund model using the same parameters as before. The agreement with the data as it had been for the \( \langle p_T^2 \rangle \) of charged hadrons /5, 7/ is indeed good. The large amount of what is called primordial \( k_T \) needed is demonstrated in the \( z^2 \) distribution (Fig. 6 a), where \( \langle k_T^2 \rangle = 0 \) in the model is also shown (dashed line). Eliminating in addition QCD (dashed dotted line) one sees only the transverse momentum resulting from fragmentation with a maximum of \( \langle p_T^2 \rangle = 0.25 \text{ GeV}^2 \) at \( z^2 = 0.3 \).

**Azimuthal Distribution of charged Hadrons**

To get more information about the primordial transverse momentum of the quarks inside the nucleon, the azimuthal distribution of charged hadrons has been studied. The azimuthal angle \( \phi \) is measured between the scattering plane and the plane defined by the observed hadron and the virtual photon (Fig. 7). In general the dependance on \( \phi \) can be written as follows, assuming single photon exchange:

\[
\frac{1}{N_p} \frac{dN}{d\phi} = A + B f_1(y) \cos \phi + C f_2(y) \cos 2\phi + D \cdot P \cdot f_3(y) \sin \phi \tag{2}
\]

The \( f_i \) are known functions of the variable \( y = v/E \) (E the energy of the primary muon), which is directly related to the polarisation of the virtual photon. \( P \) is the polarisation of the initial muon. The \( \cos \phi \) term corresponds to the interference between longitudinal and transverse photons, the \( \cos 2\phi \) term to transversely polarised photons and \( \sin \phi \) to the polarisation of the initial lepton. In the QPM rather clean predictions were made /22/, relating the \( \cos \phi \) and \( \cos 2\phi \) term to the initial transverse momentum \( k_T \) of the struck quark:
\[ \langle \cos \phi \rangle = -2 \cdot \frac{\langle k_T \rangle}{Q^2} f_1(y) \]

\[ \langle \cos^2 \phi \rangle = +2 \cdot \frac{\langle k_T^2 \rangle}{Q^2} f_2(y) \]

It was already pointed out /22/, that this is to be expected for the quarks after scattering, that for the final hadrons however the \( \phi \)-distribution will be smeared out by the fragmentation. Also from QCD a small azimuthal dependance of the hadrons is expected /23/.

To study the azimuthal dependance the same 280 and 120 GeV data have been used as for the scaled energy distributions. Fig. 8 shows the angular distributions for four different bins of \( Q^2 \) in the total range from 5 to 100 GeV\(^2\). It is clearly seen, that the distributions are not constant, a \( \cos^\phi \) term seems to dominate. The distributions have been fitted with equation (2) and the results are given in Fig. 9. The \( \cos^\phi \) term is indeed dominant and negative as expected. At small \( Q^2 \) also the \( \cos^2\phi \) term is different from zero and positive, again as expected. A QCD calculation including the effect of the primordial \( k_T \) has been carried out by Kroll and König /24/. The result for \( \langle \cos \phi \rangle \) and \( \langle \cos^2 \phi \rangle \) is also shown in Fig. 9. The main input parameters for the calculation are \( \alpha_s (Q^2 = 20 \text{ GeV}^2) = 0.34 \), \( \langle k_T \rangle = 0.6 \text{ GeV}^2 \) and \( \alpha_q = 0.31 \text{ GeV} \). The main trend of the data with respect to \( \langle \cos \phi \rangle \) is reproduced, the \( 1/Q^2 \) behaviour as expected from the above simple equation is suppressed by phase space effects at low \( Q^2 /24/ \). If the \( \langle k_T \rangle \) is set to zero in the calculation (dashed line), the \( \langle \cos \phi \rangle \) is practically zero, indicating that the QCD effect on the level of the hadrons is very small. It was also possible to show with the model calculation, that the fragmentation reduces the size of \( \langle \cos \phi \rangle \) by roughly a factor two at all \( Q^2 \), when going from the parton level to the level of the observed hadrons.

**Soft Gluons**

In all the present and previous /5, 7/ comparisons of transverse momentum phenomena on single particle distributions with models the primordial \( k_T \) has to be rather high \( (\langle k_T^2 \rangle = .6 - .8 \text{ GeV}^2) \) to get agreement with data. This goes together with a rather high value of the QCD parameter \( \Lambda \) of 500 MeV. When however selecting events with at least four charged forward hadrons (\( p_{\text{Lab}} > 6 \text{ GeV} \) /6, 7/ the \( \langle k_T^2 \rangle \) was only around 0.4 GeV\(^2\). This large and inconsistent value of \( \langle k_T^2 \rangle \) has led Andersson et al. /25/ to a modification of their model. They have explicitly introduced soft gluons, which are emitted and reabsorbed by the quarks during the scattering process and which in this way give some additional transverse momentum to the struck quark. The energy of
these gluons is too low to create extra q̅q pairs. They essentially may correspond to those soft gluons which in the usual treatment in QCD are cut away because of the infrared singularities. The amount of soft gluons is also controlled by α₆ and the authors have chosen it to be the same as for hard gluons. They have made a new comparison with the <p₂ > of charged hadrons from the 280 GeV EMC data. This is shown in Fig. 10, where <p₂ > is given as function of z². For the result of the new Lund model, somewhat arbitrarily <k₂ > was chosen to be 0.2 GeV² and λ = 300 MeV. The agreement with the data is indeed rather good.

As this new Lund model can describe data using reasonably small values of <k₂ > the question arises, is there any difference between the primordial k₂ of the quarks and the p₂ introduced by soft gluons? The authors claim, that the part of transverse momentum of the struck quark, arising from soft gluons and being transferred to the leading hadron, should be compensated by hadrons produced in the central region of rapidity. In the case of primordial k₂ however the compensation should take place in the target (backward) region. To be able to do a full test on this picture data with target fragments are needed. As however the forward spectrometer data include part of the central region the test has been made and the result is shown in Fig. 11. In the upper half the p₂ of the charged trigger particle (p₁ > 6 GeV), defined by z > 0.5, for all events with q₂ > 5 GeV² and 100 < W² < 340 GeV, normalised to the number of events, is shown as a function of the rapidity Y^CM. Also preliminary data taken on a D target at 280 GeV are used. In the lower part the transverse momentum component of all other charged particles (p₂ > 6 GeV) opposite to the transverse momentum of the trigger particle is plotted as function of Y^CM. The solid line is the QCD calculation with soft gluons, λ = 300 MeV and <k₂ > = 0.2 GeV², whereas the dashed line is for no soft gluons and <k₂ > = 0.74 GeV². Although the agreement between the solid curve and the data is convincing the complete test including the target fragmentation has still to be seen. For the trigger particle there is practically no difference in the rapidity distributions of the two cases.

Hadron Production on Nuclear Targets

There are speculations in the literature that the study of hadron production on nuclear targets would give information about the space-time development of the quark fragmentation and possibly about the quark-nucleon scattering cross section. If one scatters on a large enough nucleus and if the fragmentation process of the struck quark starts only after a time τ = E_q / m² (E_q and m are energy and mass of the quark), then an interaction of the quark with a nucleon could take place first. This could lead to a suppression of high energy hadrons (z > 0.5 or large rapidity) in heavy nuclei compared to light ones, to an increase of the multiplicity in the central region of rapidity and to an increase of the <p₂ >. These ideas are supported in lepton scat-
tering by some measurements done at SLAC /27/ with a 20.5 GeV electron beam on $D_2$, Be, C, Cu and Sn targets, where indeed up to 40% lower multiplicity was found on Cu compared to C at $z > 0.5$ and $q^2 > 1$ GeV$^2$. Even at $z = 0.3$ the difference is more than 20%.

Although this type of experiment is still foreseen by the EMC using also the vertex system, a feasibility study was made with the forward spectrometer which has led to some preliminary results. Carbon (8.1 g/cm$^3$) and Copper (30.9 g/cm$^3$) were used as targets. The thickness was chosen such to be comparable in radiation length with 6 m of $H_2$ for reasons of electromagnetic background in the spectrometer. Also the absorption length was not too different from 3 m of $H_2$. The nuclear targets were split into 6 thin ones, being spread out over the place of the downstream 3 m of $H_2 (D_2)$ target, to have similar acceptances. The primary energy of the muons was 200 GeV. The following cuts were applied to the data: $q^2 > 4$ GeV$^2$, $x_{BJ} > 0.02$, $25 < W^2 < 290$ GeV$^2$, $0.07 < y < 0.85$, $p_{Had} > 6$ GeV, $e_y > 25$ mrad. At present 6300 events are in the Cu sample (70% of the data) and 3400 in the C one (30%). The differential hadron multiplicities are compared with those as obtained on hydrogen in Fig. 12 a, b in terms of the rapidity $Y_{CMS}$ and in Fig. 12 c, d in terms of $p_T^2$. The data are divided into two different regions of the energy $v$ of the virtual photon. From these preliminary data one can conclude that there are no large differences between the three different targets in the $Y_{CMS}$, $p_T^2$ and also in the $z$ (not shown) distributions. For a more detailed comparison more statistics is needed, also comparison with $D_2$ and extension of the data to cover the full rapidity range.

The new EMC experimental Program with a Vertex Detector

The forward spectrometer has been complemented by a large vertex detector (Fig. 13) consisting of a superconducting magnet, a streamer chamber around the target and large angle track chambers. This will allow the track measurement of charged hadrons over almost 4π solid angle and close to the primary vertex with a good possibility to reconstruct also complicated events and secondary vertices in the streamer chamber. Furthermore many detectors for particle identification have been added to the EMC apparatus (Cerenkov and time-of-flight counters), to cover as much in momentum space as possible. Data taking and analysis has started in the fall of 1981.

The main physics aims are the study of
- Target (diquark) fragmentation,
- Fragmentation into identified hadrons,
- Correlations among identified particles, for example among baryons,
- Transverse momentum balance,
Complete three jet events with its particle content,
- Production of charm and strangeness,
- Fragmentation in heavy nuclei,
- Shadowing.

The new detector system is a powerful tool to carry out these studies, and important results can be expected, if sufficient beam time and general support will be made available for these experiments.

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Figure Captions

Fig. 1 a  $Q^2$ dependence of $(dN^+/dz + dN^-/dz)/N_u$
Fig. 1 b  $x$ dependence of $(dN^+/dz + dN^-/dz)/N_u$
Fig. 2  Derivatives of $\ln((dN^+/dz + dN^-/dz)/N_u)$ with respect to $\ln Q^2$
Fig. 3  $W^2$ dependence of $(dN^+/dz + dN^-/dz)/N_u$
Fig. 4  $dN/dz$ for $\pi^0$ compared with charged hadrons
Fig. 5  $dN/dp_T^2$ for $\pi^0$ compared with QCD ($\Lambda = 500$ MeV, $<k_T^2> = 0.65$ GeV$^2$, $\sigma_q = 310$ MeV)
Fig. 6 a-d  $z^2$, $Q^2$ and $W^2$ dependence of $<p_T^2>$ for $\pi^0$ compared with charged hadrons and QCD ($\Lambda = 500$ MeV, $<k_T^2> = 0.65$ GeV$^2$, $\sigma_q = 310$ MeV)
Fig. 7  Definition of the azimuthal angle $\phi$
Fig. 8  Azimuthal angular distributions of charged hadrons
Fig. 9  $<\cos\phi>$, $<\cos2\phi>$ and $<\sin\phi>$ of charged hadrons compared with a QCD Model
Fig. 10  $<p_T^2>$ vs. $z^2$ for charged hadrons compared with QCD including soft gluons (V); The different contribution are (I) from fragmentation, (II) QCD 1. order, (III) primordial $k_T$, (IV) soft gluons
Fig. 11  The rapidity distribution of the $p_T$ per event of a charged trigger hadron ($z > 0.5$) (upper half) and of the balancing $p_T$ of the other charged hadrons (lower half) compared with QCD with (---) and without (- -) soft gluons, but large $k_T$
Fig. 12 a,b  Rapidity distribution of charged hadrons on $H_2$, $C$, $Cu$
Fig. 12 c,d  $p_T^2$ distribution of charged hadrons on $H_2$, $C$, $Cu$
Fig. 13  The EMC (NA9) detector.
Fig. 2
Fig. 6a

Fig. 6b

Fig. 6c

Fig. 6d
\frac{1}{N_{ev}} \frac{d}{dY} \int p_{T}^{\text{tri}} \frac{dN}{dp_{T}} [\text{GeV}]

100 \leq W^{2} \leq 340 \text{GeV}^{2}
\quad Q^{2} \geq 5 \text{GeV}^{2}
\quad Z_{\text{tri}} > 0.5
\quad P_{\text{Lab}} \geq 6 \text{GeV}

○ H_{2}
○ D_{2}

Fig. 11
Fig. 12a

Fig. 12b
Fig. 12c

Fig. 12d
EMC (NA 9) - DETECTOR

NA 2 - Detector after Target

VSM = Vertex Magnet; FSM = Forward Magnet; SC = Streamer Chamber; PV1-3, PL-3, POA-C = Prop. Chambers; 'Il-7 = Driftchambers; H1-5, F1-4, BHA-B = Hodoscopes; V2-3 = Vetocounters; CO-2, CA = Cerenkovcounters

Fig. 13
$e^+e^-$ AND $\bar{p}p$

COLLISIONS
RECENT RESULTS FROM CESR

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Abstract

Recent experiments on the decay of the upsilon states carried out by the CLEO and CUSB groups at the Cornell Electron Storage Ring are described, with emphasis on spectroscopic transitions observed through decay of \( \Upsilon(3S) \).

I. Introduction

For the past several years the Cornell Electron Storage Ring has operated exclusively in the region of the upsilon resonances near 10 GeV center of mass energy (fig. 1). The upsilon properties entirely support the hypothesis that the resonances are bound states of \( \bar{b}b \) quark pairs with \( m_b \sim 4.5 \) GeV and \( q_b = -1/3 \). CESR has two interaction regions, with a large solenoidal detector, CLEO(1) in the south area and the CUSB(2) non-magnetic NaI-Lead Glass array in the north area (figs. 2 and 3).

Several changes were made last summer. A superconducting coil permitting operation at 1.0 Tesla was installed in the CLEO detector - performance has been exemplary. NaI endcaps and muon steel were installed in the CUSB detector to improve solid angle coverage and muon identification. The

![Graph](image.png)

**Fig. 1:** Total cross sections for \( e^+e^- \rightarrow \) hadrons (CLEO).
The data contains about 60,000 hadron events and an integrated luminosity of 16000 nb\(^{-1}\).
storage ring was modified with a mini-beta focussing scheme in which the CLEO solenoidal field is compensated by rotated quadrupoles. This has resulted in an increase in peak luminosity from $2.5 \times 10^{30}$ to $1.2 \times 10^{31}$ (cm$^{-2}$-sec)$^{-1}$. Luminosity is now accumulated at a rate of $\pm 400$ nb$^{-1}$/day. Cross-sections for the upsilon resonances range from $\sim 18$ nb for $\Upsilon(1S)$ to $1$ nb for $\Upsilon(4S)$, so it is now possible to collect samples of $\sim 10^6$ for all resonances.

The first physics run with mini-beta, from Nov-Feb '82, was at $\Upsilon(3S)$, motivated by the interest of the CUSB group in observing photonic transitions. I am presenting preliminary results from CUSB and CLEO for this data. Subsequent running has been at $\Upsilon(4S)$, the "B meson factory". The sample of B meson decays has now been increased by a factor of two over the previous sample, but analysis is still underway. I will make several remarks on plans for study of the B mesons.

The detectors were shut down for the month of April to permit the test of a superconducting RF cavity structure in the storage ring. The main purpose was to study the interaction of the electron bunches with the high order mode RF generated by the short bunches in a high frequency (1500 MHz) and high Q structure, and to study the ability to extract this unwanted energy from the cavity using auxiliary waveguides.

Results were encouraging - currents of $>10$ ma were stored and stable operation was achieved with a wide range of bunch lengths. The 5 cell "muffin-tin" cavities used in the test had lower Q and maximum accelerating voltage than has been achieved with 2 cell test cavities, and the immediate goal is to raise the accelerating voltage in the large assemblies to the 3 MV/meter required for the CESR II 50 GeV e$^+e^-$ storage ring.
II. Axion Search

A byproduct of recent Υ(3S) and Υ(1S) running is a limit on axion production from Υ. Both CLEO and CUSB have searched for Υ→φπ+ "nothing", with E_y~beam energy. The "standard" axion interacts weakly and should leave the detector before decaying if mₐ ≤ 10 MeV. Coupling of the standard axion to vector mesons depends on the quark charge through a factor X:

\[ \frac{\Gamma(Υ→γπ^0)}{\Gamma(Υ→μ^+μ^-)} = \begin{cases} \frac{G_F m_π^2 X}{\sqrt{2} \pi} & \text{for } e_q = 2/3 \\ \frac{G_F m_μ^2 X}{\sqrt{2} \pi} & \text{for } e_q = -1/3 \end{cases} \]

The product of branching ratios for Υ and Υ is therefore independent of X and can be calculated:

\[ B(Υ→γπ^0)B(Υ→μ^+μ^-) = B(Υ→μ^+μ^-) \frac{G_F^2 m_π^2 m_π^2}{2 \pi^4} = 1.6 \times 10^{-8} \]

The Crystal Ball has measured B(Υ→πa) < 1.4x10⁻⁵ (90% C.L.), which implies that B(Υ→πa) ≥ 10⁻³. CLEO sees one candidate in ~20k Υ(1S) decays and CUSB sees no candidates in 20k Υ(1S) and ~60k Υ(3S). Scaling the Υ(3S) result by the ratio of leptonic branching fractions, B(Υ→μ^+μ^-)/B(Υ→μ^+μ^-)~2/3, gives a combined result, B(Υ→πa) < 5x10⁻⁵ (90% C.L.) So the standard axion is dead.

III. Spectroscopy (Υ(3S) decays)

The spectroscopy of the upsilon system doesn't have much to do with weak interactions but like neutrino physics it has a great deal to do with strong interactions. For example there are many theoretical results from perturbative QCD for level splittings and decay widths so it should be possible from precise experimental measurements to make several independent determinations of \( \Lambda_{ms} \). The recent Υ(3S) data gives the first real experimental overview of the spectroscopy, letting us check the rough consistency with theoretical expectations and also the experimental accessibility of the rather complicated upsilon level structure.

I will start by reminding you of the spectroscopy of a simpler system, charmonium (fig. 4). Decays of ψ(2S) are almost equally divided between direct decays (annihilation of the cc pair, 30%), hadronic transitions (mostly ψ→ππψ, 50%), and electric dipole transitions (ψ→X_c, ~20%).
The large photonic transition rate means that the $^3P$ charmonium levels, which do not couple to $e^+e^-$, are easily observed in $\psi'$ decays. The upsilon level structure is shown in fig. 5. The most important question is whether the photonic transitions have substantial branching fractions, since that is a prerequisite for detailed study of the system and observation of the more suppressed transitions, for example to the spin singlet states.

a) **Hadronic Transitions**

$\Upsilon(3S)$ can decay by 2 pion emission to either $\Upsilon(2S)$ or $\Upsilon(1S)$. These decays are experimentally very different; $m(3S) - m(1S) = 890$ MeV, so that the pions are relativistic, but $m(3S) - m(2S) = 328$ MeV, which leaves only 50 MeV for kinetic energy of the pions. The slow pions are not easily observed. CLEO has observed the $\Upsilon(3S) \rightarrow \Upsilon(1S)$ transition using the missing mass spectrum for $\pi^+\pi^-$ pairs (fig. 6) and also in the exclusive mode $\pi^+\pi^-e^+e^-$ (or $\mu^+\mu^-$) (fig. 7). The statistics for the exclusive mode are reduced by the leptonic branching fraction, $B_{\mu^+\mu^-}(1S) = 0.033 \pm 0.005$, but the signal is very clean. The CUSB detector is sensitive in the exclusive mode to both transitions since there is no magnetic field to curl up the soft pions. Fig. 8 shows the electron pair mass vs. the energy deposited in the NaI by the two pions (which is only approximately the kinetic energy of the pions). There is a cluster of events at $m_{ee} \sim 10$ GeV$\cdot$m(2S) and track energy less than 100 MeV. The efficiency for the $3S \rightarrow 2S$ transitions is lower than for $3S \rightarrow 1S$ because higher cuts must be made to eliminate background. The branching ratios are:
CLEO missing mass $B(\Upsilon(3S) \rightarrow \pi^+\pi^- \Upsilon(1S)) = 5.6 \pm 1.1 \pm 0.6 \%$
exclusive $ee, \mu\mu$ $= 4.5 \pm 1.2 \pm 0.5 \%$
CUSB exclusive $ee$ $= 3.5 \pm 1.0 \pm 1.0 \%$
exclusive $ee$ $B(\Upsilon(3S) \rightarrow \pi^+\pi^- \Upsilon(2S)) = 2.5 \pm 1.6 \pm 1.3 \%$
CUSB also observes 5 events for $\Upsilon(3S) \rightarrow \rho^0 \rho^0 \Upsilon(1S)$ and 5 events for $\Upsilon(3S) \rightarrow \rho^0 \rho^0 \Upsilon(2S)$. This is consistent with $B_{\rho^0\rho^0} = 1/2 B_{\pi^+\pi^-}$.
The approximate equality of the transitions to $1S$ and $2S$ is surprising since the latter has almost no phase space. This result was predicted by Kuang and Yan\(^{(5)}\) in their QCD multipole expansion treatment of the hadronic transitions, and is due to delicate cancellations in the matrix element for $3S \rightarrow \pi^+\pi^- \Upsilon$. The predicted branching ratios are 1-3\% for $3S \rightarrow \pi^+\pi^- 1S$ and 1-2\% for $3S \rightarrow \pi^+\pi^- 2S$. The calculations work well.

The first evidence for a large photonic branching fraction came from a short run at $\Upsilon(3S)$ more than a year ago in which $\Upsilon(3S)$ data were observed to contain a larger fraction of jet-like events than the $\Upsilon(1S)$ data. Hadronic annihilation of the $3S$ states proceeds through relatively isotropic 3 gluon→3 jet decays, but the $3P_0$ and $3P_2$ states are expected to decay by 2 gluons→2 jets. By

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig6}
\caption{Missing Mass for $\pi^+\pi^-$ Pairs from CLEO Detector.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig7}
\caption{M(T) vs. deposited track energy for exclusive $ee\pi^+\pi^-$ events from CUSB detector.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig8}
\caption{Missing Mass for $\pi^+\pi^-$ pairs in exclusive decay modes.}
\end{figure}
comparing the thrust distribution for \( \Upsilon(3S) \) to those for \( \Upsilon(1S) \) and con-

continuum an excess 2 jet fraction of approximately 20% was derived for \( \Upsilon(3S) \). A similar analysis for \( \Upsilon(2S) \) gave a 7% excess; the decision to take further data at \( \Upsilon(3S) \) was largely motivated by this result.

The present data sample consists of 14 pb\(^{-1} \) at \( \Upsilon(3S) \) with 60k \( \Upsilon(3S) \) produced, 5 pb\(^{-1} \) of continuum near \( \Upsilon(3S) \), with 20k events, and 1 pb\(^{-1} \) at \( \Upsilon(1S) \) with 20k events. The event samples used in the analysis are somewhat smaller due to trigger inefficiency and hadronic event selection criteria. The \( \Upsilon(1S) \) and continuum data were taken expressly for modelling the back-

ground for the inclusive photon spectrum at \( \Upsilon(3S) \). CUSB has results both for the inclusive photon spectrum and also for exclusive double electric dipole transitions to \( \Upsilon(1S) \) and \( \Upsilon(2S) \).

Fig. 9 shows the inclusive photon spectrum at \( \Upsilon(3S) \). The background line is not a fit to the \( \Upsilon(3S) \) data but is an absolutely normalized prediction using a fit to a sum of the \( \Upsilon(1S) \) and continuum inclusive spectra, with the contributions weighted to give the average thrust observed at \( \Upsilon(3S) \) (this essentially duplicates the 2 jet and 3 jet decay fractions for \( \Upsilon(3S) \)). A predicted contribution from \( \Upsilon(3S) \rightarrow \pi^0 \pi^0 \Upsilon(2S) \) and \( \Upsilon(3S) \rightarrow \eta \eta \Upsilon(1S) \) is also added. There is a large excess of events near 100 MeV which is the expected energy range for the \( 3S \rightarrow 2P_j \) transitions. We expect three lines for \( j=0,1,2 \); obviously they are not resolved. The apparatus resolution and efficiency has been studied by generating showers from 100 MeV photons in the apparatus using the EGS Monte Carlo and then throwing these photons into real hadronic events and per-

forming the standard reconstruction and analysis. The result is an efficiency of 18.5% and a re-

![](image)
olution function with $\sigma \sim 8\%$ and non-Gaussian tails. The subtracted photon spectrum is then fit with this function. A one peak fit to the excess gives $\chi^2$/DOF = 54/18 and is ruled out. A two peak fit gives $\chi^2$/DOF = 23/16 and a three peak fit gives $\chi^2$/DOF = 12/14. The three peak fit is shown in fig. 10. Peaks are observed at 84$^{+2}_{-3}$, 99$^{+3}_{-4}$, and 118$^{+4}_{-4}$ MeV, with a total excess of 226$^{+200}_{-100}$ photons, giving a branching ratio for $3S \rightarrow 2P$ of 33$^{+4}_{-4} \%$ and an observed average energy of 98 MeV for the excess. These results are preliminary; the errors are statistical and do not include uncertainty in the background modelling. Also, the errors for the positions of the three peaks are only the diagonal error matrix elements and do not include the substantial couplings between the positions and areas.

The CUSB group has also looked for the exclusive final states:

$3S \rightarrow \pi^0 2P \rightarrow \pi^0 1S \rightarrow \pi^0 \pi^0 e^+ e^-$ (\mu\mu)
$3S \rightarrow \pi^0 2P \rightarrow \pi^0 2S \rightarrow \pi^0 \pi^0 e^+ e^-$ (\mu\mu)
$3S \rightarrow \pi^0 1P \rightarrow \pi^0 1S \rightarrow \pi^0 \pi^0 e^+ e^-$ (\mu\mu)

These are rare, since the rate is a product of three branching ratios, but they can be completely reconstructed and have little background. Fig. 12 shows the 16 $\gamma\gamma\mu\mu$ events observed with the two photon energies plotted as $E_{\text{low}}$ vs. $E_{\text{high}}$. The diagonal lines are the $T(3S)-T(2S)$ and the $T(3S)-T(1S)$ mass differences, corrected for recoil energy, and the dotted lines give $2\sigma$ bands in the photon energy resolution. There is an obvious clustering of events near 100 MeV in both the $T(2S)$ and $T(3S)$ bands. Fig. 13 is the corresponding plot for $\pi^0 \pi^0 e^+ e^-$ events. Here there is a background from doubly radiative Bhabha scatter. The background is estimated by counting events outside of the $+2\sigma$ bands, and is checked using experimental measurements of singly radiative Bhabhas. The estimated branching ratios from the $2\sigma$ bands are:

<table>
<thead>
<tr>
<th>Process</th>
<th>ee - bkgd</th>
<th>$\mu\mu$</th>
<th>total</th>
<th>BR</th>
</tr>
</thead>
<tbody>
<tr>
<td>$3S \rightarrow \pi^0 2P \rightarrow \pi^0 1S$</td>
<td>12 - 2</td>
<td>4</td>
<td>14</td>
<td>4.2$^{+1.5}_{-1.5}$%</td>
</tr>
<tr>
<td>$3S \rightarrow \pi^0 2P \rightarrow \pi^0 2S$</td>
<td>10 - 3</td>
<td>5</td>
<td>12</td>
<td>5.8$^{+2.6}_{-2.6}$%</td>
</tr>
<tr>
<td>$3S \rightarrow \pi^0 1P \rightarrow \pi^0 1S$</td>
<td>5 - 4</td>
<td>1</td>
<td>2</td>
<td>2.7% (90% CL)</td>
</tr>
</tbody>
</table>
The present results from the inclusive and exclusive spectra are consistent with predictions of many potential models, but more data and better momentum resolution will be needed to distinguish between, for example, the "QCD motivated" and the simply phenomenological models.

We can now summarize the decays for \( \Upsilon(3S) \). Hadronic transitions have branching ratio \( \pm 12\% \), photonic transitions \( \pm 33\% \), and direct decays therefore \( \pm 55\% \). The total width of \( \Upsilon(3S) \) can be estimated to be about 20 keV, compared to 215 keV for \( \Psi(6) \). So even though the absolute rate for photonic transitions is much reduced from \( \Psi' \), the hadronic transitions are reduced even more and the photonic transitions are a large fraction of the total width, so that it should be possible, as for charmonium, to study the spectroscopy in great detail.

c) B Mesons (present running)

The basic features of the B mesons, studied through \( B\bar{B} \) production at the \( \Upsilon(4S) \) resonance, were reported at the Bonn Conference in 1981 and results from the recent running are not yet available. Briefly, the semileptonic branching ratio is \( B\rightarrow \ell^{-}e^{+} \pm \pm 1.5\% \), enhanced kaon production is observed, consistent with a dominant \( b\to c \) coupling, and there is no evidence for neutral current decays, \( B\rightarrow l^{+}l^{-}X \). All features are consistent with weak charged current decay of the b quark, with standard coupling
of the W. More precise interpretation of the data is complicated by several things, for example that the mass of the $B^+$ and $B^0$ mesons is not precisely known. This means that the endpoint of the lepton spectrum is smeared by an unknown doppler shift, and that the relative production of $B^+B^-$ and $B^0\bar{B}^0$ at $\Upsilon(4S)$ is not known.

The present plan is to run at the peak of the $4S$ for a year or so, collecting $\sim 50$ pb$^{-1}$ of luminosity with $\sim 50k$ $B\bar{B}$ events. This will provide a factor of $>10$ increase in statistics for the lepton and kaon spectra. It may also permit reconstruction of $B^+$ or $B^0$ mesons, giving values for $m(B)$ which will help in interpreting the spectra. The best chance for reconstructed $B$'s is decays including $\psi$, for example, $B^+\rightarrow \psi K^+$. The rate $B \rightarrow \psi X$ could be as high as $3\psi(10)$ or much lower. An experimental result for $B \rightarrow \psi X$ should be available soon.

d) Future Plans. Several possibilities for increasing CESR luminosity are now being pursued, including a high current electron gun for improved injection, multibunch operation, and a "micro-beta" lattice. We expect a factor of two within the next year. The CLEO group is now planning for an improved detector, CLEO II. The CUSC group is hoping to install a high resolution quadrant built of Bismuth Germanate (BGO) and is making plans for a completely new north area detector. We foresee a long and productive association with the upsilon family.

REFERENCES

1. CLEO Collaboration: Cornell University, Harvard University, Ithaca College, University of Rochester, Rutgers University, Syracuse University, Vanderbilt University.
2. CUSB Collaboration: Columbia University, SUNY at Stony Brook, Max Planck Institute, Munich, Louisiana State University, Cornell University.
1. Introduction

At the 1976 Neutrino Conference in Aachen C. Rubbia suggested converting the CERN SPS into a proton-antiproton collider. The centre-of-mass energy of 540 GeV (an order of magnitude higher than at existing accelerators) together with a luminosity of $10^{29} - 10^{30} \text{ cm}^{-2}\text{s}^{-1}$ would enable the search for the intermediate vector bosons $W^\pm, Z^0$ predicted by the standard Weinberg - Salam model to be carried out. Apart from this main motivation for the new storage ring the possibility of studying strong interactions at very small distances below $10^{-15}$ cm is also very exciting. High transverse momentum jets arising from the hadronisation of scattered quarks and gluons should stick much clearer out of the underlying background once their transverse momenta are above 20 - 30 GeV/c. The study of these high transverse momentum phenomena may lead to a confirmation of a possible theory of strong interactions. Furthermore new phenomena, some of which have already been suggested by cosmic ray experiments, may show up when entering this new energy domain.

The realisation of the proton-antiproton collider would not have been possible without the invention of the beam-cooling technique which allows sufficiently dense beams of antiprotons to be prepared. Electron cooling was first suggested by G. Budker at Novosibirsk in 1966 and stochastic cooling by S. van der Meer in 1968 at CERN. After the successful demonstration of stochastic cooling in the "Initial Cooling Experiment" (ICE) the construction
Tab. 1: Important machine parameters for the Antiproton Accumulator and the SPS - Collider.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>design</th>
<th>normal</th>
<th>best</th>
<th>hope for end 1982</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Antiproton Accumulator</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \bar{p} ) yield = ( \frac{\bar{p} \text{ injected}}{\bar{p} \text{ on target}} )</td>
<td>( 2 \times 10^{-6} )</td>
<td>( 6 \times 10^{-7} )</td>
<td>( 8 \times 10^{-7} )</td>
<td>( 10^{-6} )</td>
</tr>
<tr>
<td>accumulation efficiency</td>
<td>0.67</td>
<td>0.4</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>accumulation rate ( \bar{p}/\text{hour} )</td>
<td>( 2 \times 10^{10} )</td>
<td>( 4 \times 10^{9} )</td>
<td>( 5 \times 10^{9} )</td>
<td>( 10^{10} )</td>
</tr>
<tr>
<td>cooled emittances ( \varepsilon )</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>horiz. (( \equiv ) mm mrad)</td>
<td>1.4</td>
<td>1.2</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>vert. (( \equiv ) mm mrad)</td>
<td>1.6</td>
<td>1.0</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>( \Delta p/p )</td>
<td>( 3 \times 10^{-3} )</td>
<td>( 3 \times 10^{-3} )</td>
<td>( 3 \times 10^{-3} )</td>
<td></td>
</tr>
<tr>
<td>Transfer AA + PS ( \rightarrow ) SPS</td>
<td>100%</td>
<td>25%</td>
<td>75%</td>
<td>75%</td>
</tr>
<tr>
<td><strong>SPS Collider</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \bar{p}/\text{bunch} )</td>
<td>( 10^{11} )</td>
<td>( 1.6 \times 10^{9} )</td>
<td>( 10^{10} )</td>
<td>( 2 \times 10^{10} )</td>
</tr>
<tr>
<td>( p/\text{bunch} )</td>
<td>( 10^{11} )</td>
<td>( 6.1 \times 10^{10} )</td>
<td>( 10^{11} )</td>
<td>( 10^{11} )</td>
</tr>
<tr>
<td>Bunches ( \frac{p}{\bar{p}} )</td>
<td>6</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Beam lifetime (hour)</td>
<td>24</td>
<td>20</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>low ( \beta ) ( \beta ) horiz. (m)</td>
<td>2</td>
<td>7.0</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>( \beta ) vert. (m)</td>
<td>1</td>
<td>3.5</td>
<td>0.75</td>
<td>0.75</td>
</tr>
<tr>
<td>Luminosity (( \text{cm}^{-2}\text{sec}^{-1} ))</td>
<td>( 10^{30} )</td>
<td>( 3 \times 10^{26} )</td>
<td>( 5 \times 10^{27} )</td>
<td>( 5 \times 10^{28} )</td>
</tr>
<tr>
<td>Estimated integrated luminosity (( \text{cm}^{-2} ))</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>for the running period in autumn 1982</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>( 5 \times 10^{34} )</td>
</tr>
</tbody>
</table>
of the Antiproton Accumulator (AA) started at CERN in 1978. In July 1981 proton-antiproton collisions in the SPS at a centre-of-mass energy of 540 GeV were observed for the first time. A run with an average luminosity of $3 \times 10^{26}$ cm$^{-2}$sec$^{-1}$ took place in December 1981 resulting in an integrated luminosity of $\sim 10^{32}$ cm$^{-2}$ available for use by the different experiments. The first physics results from this running period will be reported here.

To demonstrate the influence of the different machine parameters on the luminosity the most important parameters of the Antiproton Accumulator and the SPS collider are listed in table 1. The design values are compared with the average values obtained during the run in 1981 and the best values achieved up to the present. In addition an estimate is given for the coming run, which may yield an integrated luminosity of some $10^{34}$ cm$^{-2}$, provided the collider runs reliably.

2. The UA experiments

Five experiments (UA1 - UAS) were approved at the start of the pp collider experimental programme.

The general-purpose detector of experiment UA1 was designed for an almost complete coverage of the whole solid angle down to polar angles of less than 1°. Its central part, shown in fig. 1, is a 6 m long by 2.4 m diameter drift chamber configuration with large drift distances (= 18 cm). The two-dimensional image read-out yields space points at centimetre intervals along the tracks. These central chambers are surrounded along their length by 48 semicylindrical electromagnetic calorimeters and at each end by 32 radial sectors of electromagnetic calorimeter. All of the above detectors are situated inside a dipole magnet (7 m * 3.5 m * 3.5 m) which produces a uniform field of 0.7 T. The laminated return yoke of the magnet, equipped with scintillation counters, also serves as the hadron calorimeter. The outer shell of the detector is a large-area muon detector composed of 8 layers of drift tubes (2 chambers each with 4 layers). In addition calorimetrized compensator magnets, small-angle calorimeters and charged particle detectors extend the forward region to production angles of less than 1°.

The UA2-detector (fig.2), well-matched for the W$^\pm$ and Z$^0$ search, is composed of fine segmented calorimeter cells, 240 in the central region and
Fig. 1 View of the central part of the UA1-experiment

Fig. 2 View of the UA2-experiment from above
240 in the forward-backward cones. They are arranged in a tower structure pointing to the intersection region. An inner detector, using drift and proportional chambers, determines the vertex position. The forward-backward detectors include magnetic spectrometers (toroidal magnets and drift chambers) to measure the charge asymmetry of the electrons from the $W^\pm$ decays. For the 1981 and 1982 runs a wedge of the central calorimeter is replaced by a magnetic spectrometer with particle identification by time-of-flight and a lead-glass array to identify neutral pions by their decays.

Experiment UA3 is a search for magnetic monopoles by looking for their expected high ionization in Kaptan foils, which are placed both inside and outside the vacuum tube in the intersection region and around the outside of the UA1 central drift chambers.

Experiment UA4\(^6\) measures the elastic scattering and (using the optical theorem) the $p\bar{p}$ total cross-section. Small drift- and proportional chambers can be placed very near to the beams inside "Roman pots" situated 40 metres from the intersection point in both directions.

The main part of the UA5 detector\(^7\) consists of two large streamer chambers surrounding the intersection region, lead-glass plates in the chambers allowing photon identification. This experiment concentrates on measuring particle densities and correlations.

3. Elastic scattering

The elastic scattering of protons on antiprotons was measured by UA4 and UA1 in two ranges of squared four-momentum transfer near $t = 0.1 \text{ GeV/c}^2$ (UA4) and near $t = 0.2 \text{ GeV/c}^2$ (UA1) with a slight overlap of the two measurement regions. Fig. 3 shows both results, which are well fitted by an exponential form, but with different slope parameters in the two $t$-ranges. Both results are in agreement with extrapolations from lower energy data for the appropriate $t$-ranges.

By extrapolating their data to $t = 0$ and using the optical theorem the UA4 group has determined the total cross-section. The preliminary value of $\sigma_{\text{tot}} = 66 \pm 7 \text{ mbarn}$ is in good agreement with the extrapolation from ISR data and shows the continuing rise of the total cross-section with energy.
Fig. 3 Differential cross-section for elastic scattering

Fig. 4 A typical event seen by the UA1 central detector
4. Minimum bias physics

The experiments UA1, UA2 and UA5 have each presented results on minimum bias physics. A typical event, as seen by the UA1 central drift chambers (fig. 4), is characterized by a large number of particles. The pseudo-rapidity distributions\(^9\) of charged particles and photons are compared in fig. 5 with the charged particle distribution from the ISR, and a clear increase of the particle multiplicity in the central region is seen. Whereas a cylindrical phase space description with a mean transverse momentum \(<p_T> = 350\text{ MeV/c}\) describes the ISR data well (solid line) it completely fails for the pp collider data. This indicates that either the width of the pseudo-rapidity distribution has not grown as much as was possible on kinematical grounds or that the mean transverse momentum has increased.

To obtain an almost clean pion distribution, kaon and proton contributions (~16%) and photons from \(K_0^*\) decays are globally subtracted. If all photons come from \(s^0\) decays the average number of photons should equal that of charged pions. Since \(<n_{\gamma}> = 37.5 \pm 2\), which is much higher than \(<n_\pi> = 22.5 \pm 1\) the UA5 group concluded that there is a 32% contribution from \(\gamma^*\) decays. With this assumption the photon distribution can be well described (solid line).

The particle density in the central region \(|\eta| < 1.3\) is shown in fig. 6 together with data from the ISR and from cosmic ray experiments\(^{10}\). These data have not been corrected for \(K_0^*\) and \(\Lambda^0\) charged decays but in order to compare with the ISR data at least one particle in the central region was
Fig. 6 Mean multiplicity per unit of $\Delta \eta$ in the central plateau as a function of c.m. energy required. The mean charged multiplicity per unit of pseudorapidity is $3.6 \pm 0.3$, the inclusion of events with no tracks in the central region reduces this number to $3.6 \pm 0.3$. The rise of the central particle density - a substantial violation of Feynman scaling - persists up to the collider energy.

Fig. 7 Multiplicity distribution in the scaling variable $z$
The distribution of the multiplicity in the central rapidity plateau \(|\eta|<1.3\) is plotted in fig. 7 together with ISR data from roughly the same rapidity interval. It is surprising that all multiplicity distributions from \(\sqrt{s} = 5\) to 500 GeV coincide, once they are expressed in terms of the variable \(z = n/\langle n\rangle\), suggested by the idea of KNO-scaling\(^{11}\). The distribution is much wider than a Poisson distribution indicating the existence of multiparticle correlations. It is assumed that clusters are first produced, which then decay on average into 2 to 3 charged particles. Fig. 8 shows the multiplicity distribution for \(|\eta|<3.5\) which is in excellent agreement with the independent cluster emission model\(^{12}\).

The transverse momentum spectrum for unidentified charged hadrons is given in fig. 9 for three different bands of multiplicity, averaged over the interval \(|\eta|<2.5\)\(^{13}\). The three spectra have been normalized to the full inclusive cross-section at \(p_T = 0\). Even at rather low \(p_T\) values the spectrum becomes flatter with increasing multiplicity, as has been suggested by cosmic ray experiments\(^{14}\). The mean transverse momentum \(\langle p_T \rangle\) increases with the mean multiplicity (fig. 10) and flattens off at very high multiplicities. This may be due to the saturation of the available centre-of-mass energy. The points without error bars give the global \(p_T\) average at FNAL, ISR and \(\bar{p}p\) collider energies. The fact that \(\langle p_T \rangle\) increases with energy may thus be an effect of the increasing multiplicity.

The UA2 group has measured the \(p_T\)-spectrum of pions, the charged ones being identified by their time-of-flight and the neutrals by their decay into two photons\(^{15}\). The two spectra fit well together (fig. 11). With tighter cuts on the mass reconstruction they observe an \(\eta\)-signal,
Fig. 9 Transverse momentum distributions for various multiplicity bands

Fig. 10 \(<p_\perp> as a function of the central multiplicity

Fig. 11 The inclusive transverse momentum distribution for identified pions

Fig. 12 The transverse momentum distributions for K^0 and Λ^0
consistent with an $n/\pi$ ratio of 0.55 as measured at the ISR. For transverse momenta below 1.2 GeV/c kaons and protons were identified and the particle ratios $K/\pi$ and $p/\pi$ are independent of the transverse mass $m_T$ (fig. 12).

The UA5 group has also identified kaons and lambdas from their charged decays. Their transverse momentum distributions (fig. 13) are less steep than that for pions, with mean transverse momenta of $0.70 \pm 0.12$ and $0.67 \pm 0.2$ GeV/c for kaons and lambdas respectively. The multiplicity of neutral kaons ($K^0 + \bar{K}^0$) per inelastic event is $2.0 \pm 0.4$ (for $\Lambda^0 + \bar{K}^0$ it is $0.35 \pm 0.1$) corresponding to a ratio of neutral kaons to charged pions of $11 \pm 2\%$. This ratio is higher than at lower energies, perhaps an indication of the existence of new thresholds involving heavy flavour production (fig. 14).

**Fig. 12**
The particle ratios $K/\pi$, $p/\pi$ as a function of transverse mass $m_T = \sqrt{p_T^2 + m^2}$.

**Fig. 14**
The $K/\pi$ ratio as a function of c.m. energy.
5. Physics at large transverse momentum

Large transverse momentum phenomena were one of the exciting phenomena when a new energy range was entered by the ISR\textsuperscript{17)}. The increasing yield of large transverse momentum particles with energy makes the study of hadronic interactions at small distances below $10^{-15}\text{cm}$ even more promising at the $\bar{p}p$ collider.

The invariant cross-section for unidentified charged hadrons as a function of transverse momentum is given in fig. 15\textsuperscript{13)}. The comparison with the ISR results shows that the $p_T$-spectrum is much flatter at the $\bar{p}p$ collider and this already at rather low values of $p_T$. At $p_T = 10 \text{ GeV/c}$ the cross-section is three orders of magnitude larger than at the ISR. This difference can be well understood in terms of a recent QCD model\textsuperscript{18)} which includes in addition to hard scattering and parton fragmentation processes gluon radiation off initial and final state partons. The $p_T$-spectrum can be described by the following empirical form:

$$E \frac{d^3\sigma}{dp^3} = \frac{A_{p_T^0}}{(p_T + p_{T0})^n}$$

$$n = 9.44 \pm 0.9$$

$$A = (0.47 \pm 0.1) \times 10^{-24} \text{ cm}^2 \text{ GeV}^{-2}$$

$$p_{T0} = 1.30 \pm 0.2 \text{ GeV/c}$$

The measurements from the electromagnetic calorimeters which are sensitive to neutral pions, etas and photons are also displayed in fig. 15. Given that the two spectra are for different particle mixtures, the agreement is good.

The UA1 group has also studied correlations among large $p_T$ charged particles to look for indications of jets arising from the fragmentation of scattered partons\textsuperscript{19). A trigger particle was defined by having the largest $p_T$ in the event and at least 4 GeV/c. Relative to this trigger particle the distributions of rapidity and azimuth for all other particles in each event are plotted in fig. 16. The rapidity distributions are given separately for the azimuthal hemispheres "towards" (centred on) and "away" (opposite to) the trigger."
Fig. 15 The invariant cross-sections as a function of transverse momentum at ISR energies and at the pp collider ($\sqrt{s} = 540$ GeV)
Fig. 16 Rapidity difference between secondaries and the trigger particle of $p_T > 4$ GeV/c in the towards (a) and away (c) hemispheres, together with the azimuthal difference (b): upper row: all secondaries, middle row: secondaries with $p_T > 1$ GeV/c, lower row: secondaries with $p_T > 2$ GeV/c.
Fig. 17
Two-dimensional plot of the difference in rapidity and azimuth with respect to the trigger particle for all secondaries (a), those with $p_t > 1$ GeV/c (b) and those with $p_t > 2$ GeV/c (c).

Fig. 18
$p_t$-spectrum of towards secondaries within $\Delta y = \pm 0.5$ and $\Delta \phi = \pm 30^\circ$ of the trigger particle, compared to the minimum bias inclusive $p_t$-spectrum.
A clear correlation in azimuth and rapidity with respect to the trigger particle is observed, increasing strongly with the $p_T$ of the secondary particles. The two-dimensional plot in fig. 17 illustrates that the secondaries cluster both in rapidity and azimuth around the trigger particle. The secondaries which are near to the trigger particle ($Δy = ± 0.5, Δφ = ± 30^\circ$) have a much flatter $p_T$-distribution than the ones from minimum bias events (fig. 18). The above features can be well understood in terms of jets arising from parton fragmentation. The trigger particle defines reasonably well the direction of the scattered parton due to the steep fall of the $p_T$-spectrum. Additional large $p_T$ secondaries then tend to cluster around the trigger particle because of their limited transverse momentum with respect to the parton axis in the fragmentation process.

On the away side the direction of the scattered parton is unknown. Therefore the large $p_T$ particles are smeared over a wide range of rapidity (figs. 16 and 17). However an azimuthal correlation emerges around $180^\circ$ with respect to the trigger particle. This coplanarity, increasing with $p_T$, favours the picture of two scattered partons, whereas narrow rapidity correlations on the same side could also be explained by the decay of low mass resonances.

6. Future expectations

For the running period in autumn 1982 we can hope for an integrated luminosity of some $10^{34}$ cm$^{-2}$. The following expectations may then be realized:

The large $p_T$ inclusive spectrum will be measured up to transverse momenta of $30 - 40$ GeV/c. At these high transverse momenta jets can clearly be separated from the low transverse momentum background. A calorimeter trigger on large transverse energy will probably efficiently pick-up unbiased high $p_T$ jets, provided the transverse energy threshold is large enough to cut-off high multiplicity events from the tail of the multiplicity distribution. Since the jet cross-section is 2 - 3 orders of magnitude higher than the single particle cross-section a few hundred unbiased jets with transverse momenta around 50 GeV/c can be expected. Hopefully many of these events will show a two-jet structure.

An integrated luminosity of $5 - 10^{34}$ will make the search for $W^\pm$ and $Z^0$ decays very promising. According to new QCD calculations about 3 - 5 leptonic $Z^0$-decays and 50 leptonic $W^\pm$ decays will be expected, resulting in
a charge asymmetry of 7:2 for polar angles of 25° to 40°. Fig. 19 shows the $p_T$ distribution of muons from $W$-decays. The curves a-c give the different background for the UA1 experiment based on the hadron $p_T$ spectrum from QCD calculations, normalized to the data at 10 GeV/c. Curve c is the $\pi - \mu$ decay in the central detector, a and b the hadron punch through the absorber for polar angles of 90° (a) and 45° (b). The transverse energy balance in the central region of the event, shown as an insert, may help to identity the missing energy from $W$-decays.

**Fig. 19** $p_T$-distributions of muons from $W$-decays and different background sources

**Acknowledgments**

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DETECTORS
NEW TRENDS IN DETECTOR CONSTRUCTION

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ABSTRACT

New developments in the techniques of measuring position, energy and momentum of particles and identifying them are described. Most of the material presented can be found in Physics Reports 84 (1982) p.85 - 161.
NEUTRINO AND PROTON DECAY DETECTOR WITH STREAMER OR GEIGER PLASTIC TUBES

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ABSTRACT.

The use of plastic streamer tubes, with both digital and charge readout, is discussed in connection with digital tracking calorimeters for neutrino detectors. A new development of plastic tubes, based on limited Geiger operation and Geiger propagation time measurement, is described, and its possible application for p-decay and low energy neutrino detectors is discussed.

1. INTRODUCTION.

Neutrino and proton decay detectors require particle identification and energy measurements in a dense medium. A standard approach is based on the use of tracking calorimeters, that is detectors which provide together shower energy measurement and the detailed pattern of the charged secondaries sampled through the dense medium. Event identification relies on the recognition of characteristic patterns (non showering tracks, hadron showers, e.m. showers) and on the measurement of vertices and directions.

The natural trend of neutrino and proton decay detectors is to be large (massive), which in practice imposes the use of simple and cheap devices. Presently digital tracking calorimeters look to be the most favoured detectors, because they can be based on the use of simple saturated mode devices, such as limited streamer or Geiger tubes or flash chambers.
In this paper, after a brief description of Plastic Streamer Tubes (PLA.S.Tubes), and a discussion of the performance of streamer tube calorimeters, I will sketch out a high energy neutrino detector based on their use. I will also report on a recent development of Plastic Tubes, now operated in a limited Geiger mode, and with a time projection readout based on Geiger propagation time measurement; this device is being developed in Frascati in view of a large p-decay calorimeter in the Gran Sasso laboratory.

2. PLASTIC STREAMER TUBES.

Multitube devices, with respect to wire chambers, have two distinctive modularity features: i) large "chambers" can be built by simple addition of several tube modules; ii) a single wire failure can be reduced to a single wire loss, by simply cutting the wire connection to the anode voltage, supposed accessible. These practical features are of crucial importance concerning design and operation of very large calorimetric detectors.

The use of plastic tubes with resistive cathode, allows a simple way reading out the second coordinate of a multitube chamber, by using external pick-up electrodes, such as strips. These are passive elements which can be given the desired modularity, so that large tube chambers with two coordinate readout may be obtained by simple assembly of multitube and pick-up electrode modular units.

Limited streamer is a saturated mode localized in a few millimeters, favoured by the use of thick sense wires (100μm typically), featuring big signals (~1mA peak current), and exhibiting noiseless operation in a wide H.V. range.
The big streamer signals make possible to use very large aerea pick-ups, such as very long strips, which can be operated as terminated transmission lines. That operation mode combined with the plastic tube device, makes possible to envisage detection planes of very large dimensions. Actually the limit (~10x10 m$^2$) is given by practical problems, such as handling and transportation of the modular elements. By the way, very long wire lengths (~10 m) are made possible by the use of thick anode wires, which are supported every 50 cm (for 1 cm$^2$ tubes): in this way tubes can be operated without strict planarity requirements.

The plastic streamer tube device has found a large scale application in the proton decay detector now in operation in the Mont Blanc tunnel$^2$. This detector makes use of ~50 000 tubes, equipped with ~100 000 x-y pick-up strips, for a total pick-up aerea of 3400 m$^2$. One of the first events detected in the Mont Blanc is shown in Fig.1: a cosmic ray muon producing a hadron shower via a virtual photon.

The large mass production for this detector has evidenced a further attractive feature of plastic tubes: both the modularity of the device components, which consist of essentially unidimensional elements, and the use of thermoplastic materials (PVC) and technologies, allow the development of automatic assembly equipments.

The modular components of the Mont Blanc detector are three: i) a 16-tube module, ii) a 16-x-strip pick-up unit, iii) a 16-y-strip pick-up unit. Tube and strip granularity is ~1cm, the length 3.5 m.

It is straightforward to use different pick-up electrodes, such as pads, as it has been made for calorimetric test modules for LEP$^3$. 
Fig. 1. A cosmic ray event in the Mont Blanc detector.

Fig. 2. Response to electrons of the Mont Blanc calorimeter.

Fig. 3. Response to electrons of the C.H.A.R.M. streamer tubes (preliminary).
3. DIGITAL CALORIMETERS.

The basic idea of digital calorimetry is to count some discrete quantity instead of measuring an analog quantity such as the total $\Delta E/\Delta x$ measurement of standard sampling calorimeters.

In the simplest version, a digital calorimeter uses a multitube device with a simple digital (YES/NO) readout of the individual elements. Shower energy is measured by counting the hit tubes, which is equivalent to an approximate measurement of the total track length (tracks at an angle will hit more elements). At low shower energy (low track density) where negligible track obscuration takes place (more than one track in a single tube element), the energy response is linear and energy resolution varies as $1/\sqrt{E}$, being comparable to that obtained with scintillation counters.

The attractive features of such a calorimeter are the following: i) simple saturated mode devices can be used, such as streamer, Geiger, or flash tubes; ii) the YES/NO readout usually implies stable energy response (i.e. no calibration and monitoring problems); iii) the full tracking is available. In Fig. 2 the response to electrons of the Mont Blanc calorimeter is shown (4), which exhibits the typical features of digital calorimeter response: linear behaviour at low energy, then a smooth deviation from the linear response (10% non linearity at ~500 MeV); while the energy response deviates from linearity, the energy resolution deviates from the $1/\sqrt{E}$ behaviour, saturating at a constant value.

At a given energy, for a given absorber material, and for small non linearity, the latter may be assumed proportional to the tube width, and the average detector density; in fact two track separation is proportionally improved either by decreasing the tube dimensions or by diluting the detector,
Fig. 4. Response to pions of the C.H.A.R.M. streamer tubes (preliminary).

Fig. 5. Charge response to electrons of the PLA.S.Tube test module with pad readout. The signal is in units of orthogonal track signal. The solid line comes from the experimental points, corrected for shower losses on the back.
which makes tracks drift apart.

The effect of density is shown in the response to electrons \( \text{of the streamer tube calorimeter of the C.H.A.R.M. neutrino detector} \) \( \text{of Fig.3) of the streamer tube calorimeter of the C.H.A.R.M. neutrino detector} \) \( \text{This consists of 8 cm thick marble absorbers interleaved with scintillation counters, proportional drift tubes, and 1 cm}^2 \text{ aluminium streamer tubes. The average r.l. of the detector is } \bar{X}_o=20 \text{ cm, to be compared with the } \bar{X}_o=4.5 \text{ cm of the Mont Blanc calorimeter. Although low energy points are not available, a wider linear energy range in a ratio of the order of the density ratio can be inferred from the available points.}

The response to pions of the C.H.A.R.M. streamer tube calorimeter \( \text{of Fig.4. Due to the much lower track density in hadron showers, the linear range is comparably wider: 10% non linearity at 50 GeV. The energy resolution, shown up to 30 GeV in the same figure, results to be } \sim 64\%/\sqrt{E}, \text{ which is only 15% worse than that simultaneously measured with the scintillation counters} \) \( \text{The streamer tubes give this result with much less effort (no gain monitoring problems), and while giving a fine tracking of the events.}

A wider linear range and improved energy resolution at high shower energy can be obtained with streamer tubes, if total streamer charge is readout, which is equivalent to count streamers, which in turn is a measure of the total sampled track length. Track obscuration is much reduced, since the saturated element now is not the tube, but only the few millimeter long dead region due to a single streamer.

In view of possible use in a LEP detector, a preliminary test \( \text{has been performed with electrons at the CERN-PS, using a PLA.S.Tube test module, with charge readout by external pads.} \)
With an average $X_0=3.3$ cm a much wider linear range was found (6% non linearity at 10 GeV). The energy resolution with 1 r.l. thick lead sampling, is $27\%/\sqrt{E}$ (see Fig.5).

Further testing is being made or prepared with both hadron and e.m. test calorimeters.

4. A NEUTRINO DETECTOR WITH PLASTIC STREAMER TUBES.

Taking the C.H.A.R.M. detector as a model, considering the performance of its streamer tube system as tracking calorimeter, and taking into account the possibility of improving the high energy response by the total streamer charge readout, one can envisage a very simple detector based only on the use of PLA.S.Tubes.

A sensitive plane is shown in Fig.6, made of PLA.S. Tube modules of the Mont Blanc detector type, likewise equipped with x and y strips as the digital tracking system. The wires of one tube plane are connected together to an ADC, to measure the total streamer charge, to improve high energy shower measurement. Here the same device performs both the calorimetric and tracking functions, separately performed by scintillation counters and proportional tubes in the original C.H.A.R.M. detector. Combining the results shown before, for a detector density about that of the C.H.A.R.M. detector, one can infer a linear response up to ~50 GeV for e.m. showers, and $>$100 GeV for hadron showers.

The full detector is sketched out in Fig.7, with a visualization of the tracking and calorimetric output.

An improved readout is suggested by C.Rubbia\(^{(8)}\), based on the use of the BBD device. In the simple Mont Blanc detector readout scheme, based on parallel loading and serial data transmission, the (digital) shift register is substituted by an analog "shift register". This readout
Fig. 6. Multi-tube layer with x-y strips.

Fig. 7. Sketch of a PLAS. Tube neutrino detector, with x-y tracking strips and total streamer charge readout on wires.
would greatly improve detector performance, providing local linear track counting (high energy showers) and high space accuracy (charge centroid method).

5. A GEIGER PROJECTION CALORIMETER.

5.1. Plastic Geiger Tubes.

The next generation of proton decay calorimeters demands for masses in the several kiloton range, with improved granularity when compared with the Mont Blanc detector.

A Geiger device is being studied in Frascati (9,10) which is an evolution of the Mont Blanc detector device toward economicity and simplicity, which are needed in view of the much larger detector dimensions. The basic idea is shown in Fig.8. Plastic tubes with 100 μm wires are operated in the Geiger mode, with the Geiger propagation limited by the wire supports which are about 50 cm apart. The wire signals are big enough to be read out by direct connection to a CMOS Shift Register. To readout the second coordinate, external strips are placed across the wires in correspondence of the Geiger limitation devices, to pick-up the front of the propagating Geiger discharge at the limitation point. Measurement of the Geiger propagation time provides the second coordinate, with a conversion constant (Geiger propagation velocity) of ~300 ns/cm. From preliminary tests a space accuracy better than 1 cm, and two track separation of ~1 cm, appear feasible. The cost/m² for the Geiger projection readout is of the same order of the Shift Register readout of wires, for equal lengths of wires and strips.

Two features of this Geiger device are worth of mention, concerning reliability and operation simplicity: the non flammable gas mixture (Argon + 4% Ethyl Bromide), and the very low operation voltage (~1500 V).
Fig. 8. The Plastic Geiger Tube device, with strips to pick-up Geiger front.

Fig. 9. Sketch of the Geiger Projection Calorimeter module.
5.2. Modularity of the GPC.

Existing or proposed proton decay calorimeters, in the very large scale perspective, show two problems. The first one concerns the use of iron, which is expensive and difficult to assemble in the form of thin and large plates. The second one, actually the major one, concerns the lack of the proper kind of modularity: they all consist of alternate layers of crossed elements (tube-tube, tube-strip, drift wire-strip). Due to the very large detector cross-section, that implies the very individual components (sensitive elements, iron slabs, readout cards) to be put together in the underground laboratory, which is expensive. The point is that these p-decay calorimeters are big and finely textured buildings, to be built-up in an unconventional place. The idea being studied in Frascati is to build-up the full detector by combining together large calorimetric modules: GPC modules (see Fig.9) consisting of plastic Geiger tubes embedded in a concrete block, with all active terminations (x-y signals, gas, H.V.) on one single face of the module. This structure is made possible by the fact that the second coordinate readout of the GPC is based on the use of a small number of passive elements (1 strip/50 cm).

The increase in readout channels due to the shortening of the cross-strips, can be compensated by grouping together far apart strips (image overlap).

Permanent embedding of tubes in concrete implies a calculated risk approach, which is based on the possibility already mentioned, of getting read of the single badly working wires, and on a supposed small probability of single wire failure (< 10^{-3}/year). The latter is consistent with the very early life of the Mont Blanc detector.
The dimensions of the GPC modules are fixed on the basis of full detector dimensions and transportation problems: the feasibility of 20 ton blocks, 10x2.5x0.4 m$^3$ is being studied.

GPC blocks would be equipped with electronics and tested in the home laboratory, and then transported to be piled-up in the underground laboratory. Various assembly configurations are possible: vertical or horizontal, crossed or parallel.

5.3. Detection Features.

The granularity can be 8x8 mm$^2$, roughly equivalent on both views. Tracking capability with respect to the Mont Blanc detector would be improved by thinning the sampling thickness: 0.2 instead of .6 r.l. In this case the average detector density is $\sim 2$ g/cm$^3$. Time resolution is $\sim 25$ ns for the single hit. That is comfortable for the ($K^+, \pi^+\mu^+\nu\rightarrow e^+$ decay identification, for which this detector actually exhibits a high efficiency ($> 50\%$). For several meters deep detectors, that resolution is sufficient to determine the direction of flight of particles throughout the detector (identification of muons from very high energy neutrinos). Taking into account the fact that the quoted resolution comes from a drift time distribution (no tails on the low edge), and that a multi-hit pattern improves it, it is worth of mention the possibility of getting the $K^+\rightarrow\mu^+$ time signature (in connection with the now popular $p\rightarrow K^+\nu$ decay), although with a limited efficiency.

For a more effective direction identification ($p-$decay, neutrino oscillations), counters with $\sim 1$ ns time resolution could be anyway inserted in the concrete blocks.
The problem is cost. Very promising in this respect is the spark counter device (Resistive Plate Counters) being developed in Rome by R.Santonico\textsuperscript{(12)}.

CONCLUSIONS.

Digital tracking calorimeters are instruments which fit the requirements of neutrino and p-decay physics.

The streamer mode makes possible to conceive sensitive surfaces unaccessible to standard wire systems, with fine calorimetric performance in a wide energy range.

Plastic Tubes give a great flexibility in designing readout topologies.

Plastic Geiger tubes look to be a promising instrument, in view of very large scale underground calorimeters, for which optimization of performance and cost is of crucial importance.

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A NEW NEUTRINO DETECTOR FOR THE SERPUKHOV ACCELERATOR


We describe the design and performance of a finegrained $\nu$-detector which will come into operation at the Serpukhov accelerator to study $\nu_e$ and $\nu_\mu$ elastic scattering in a wide band beam and to measure inclusive reactions in a dichromatic and in a $\nu_e$ enriched beam. This detector will also provide information on prompt neutrino production and on $\nu_e \rightarrow \nu_\mu$ oscillation.

1. THE DETECTOR

1.1. General setup

A general view of the detector is given in fig. 1 showing the two main components, the target calorimeter and the muon spectrometer. The target calorimeter consists of 40 modules, each module has the following structure:
- a plane of 10 horizontal $20 \text{ cm} \times 30 \text{ cm} \times 5 \text{ m}$ liquid scintillator cells
- two $(x, y)$ drift chamber planes, $4.0 \times 4.5 \text{ m}^2$ each
- a magnetized iron frame in which additional absorber plates can be placed to increase the total target mass from $120 \text{ t}$ pure scintillator up to $200 \text{ t}$.

MUON SPECTROMETER   TARGET CALORIMETER

![Diagram of detector setup](image)
The muon spectrometer designed for the momentum and charge analysis of muons consists of 16 modules, each having a magnetized iron toroid of 4.0 m in diameter and of x-y drift chamber planes of 4 m² each.

Between the target calorimeter and the μ-spectrometer a lead/plastic scintillator sampling detector is placed to identify electrons and gammas produced in the back part of the target and to measure their energy.

1.2. The Scintillation Calorimeter

A scintillation counter plane consists of 10 Al-containers, 5.0 x 0.3 x 0.2 m³ each, filled with a liquid scintillator on the base of white spirit. The inner walls of the containers are covered with a transparent Dacron film. This allows light transmission by total internal reflection on the boundary between Dacron and air since the inner Al-surface is relatively rough. Both sides of the counter are viewed by photomultipliers PMU-49 which have a photocathode of 150 mm diameter.

Fig. 2 shows the amplitudes A₁, A₂ and their sum A₁ + A₂ measured in dependence on the coordinate where minimum ionizing cosmic muons passed through the counter. An attenuation length of λ = 2.25m was obtained for distances up to ± 2m from the counter centre. The sum of both amplitudes corresponds in average to about 450 photoelectrons per minimum ionizing particle.

The ln A₁/A₂ representation in Fig. 3 shows a linear dependence and allows to estimate the particles coordinates with an accuracy of ± 11 cm. The hadron energy resolution of the target calorimeter
was estimated using Monte-Carlo calculations:
\[ \sigma(E)/E = (30-40 \%) / E_{M}(GeV) \]

The fine sampling of scintillation counter and drift chamber planes guarantees a good angular resolution:
\[ \Delta \theta [\text{mrad}] = 40 + 200/E_{M} (GeV) \]

1.3. Drift Chambers

Two types of drift chambers with signal elements of 4 signal wires for the coordinate measurement of particle trajectories have been developed and tested:

(i) for the target calorimeter, chambers with a sensitive region of \(4 \times 0.5 \text{ m}^2 \) and a drift space of \(25 \text{ cm} \) [1]

(ii) for the \( \mu \)-spectrometer, \(4 \times 2 \text{ m}^2 \) chambers and \(12 \text{ cm}\) drift space.

Fig. 4a shows a schematic diagram of chamber type (i). A more detailed view of the signal element gives fig. 4b. The small shift of the four 60 \(\mu\)m signal wires from the symmetry axis solves the problem of left-right ambiguities.

The chambers work with a secure gas mixture of \(94\% \text{ Ar and } 6\% \text{ CO}_2\). Test measurements gave the following characteristics:

- length of counting rate plateau \(\approx 150 \text{ V}\)
- space resolution \(0.4 - 0.6 \text{ mm}\)
- multitrack detection, if the distance between tracks is \(> 3 \text{ mm}\)
- good detection efficiency for tracks with angles \(< 70^\circ\)
- \(99.5\%\) efficiency for the resolution of left-right ambiguities.

\[ \text{FIG. 4} \]

\[ \text{of MEP drift chamber, side view} \]
1.4. The Muon Detection System

For a highly efficient muon detection the system consists of two parts (see fig. 1) - (i) magnetized iron frames surrounding the target calorimeter modules and (ii) an end muon spectrometer, which have the following characteristics:

(i) 40 frames with an external size of $4.5 \times 4.5$ m$^2$ and a window of $3 \times 3$ m$^2$; the detection efficiency for muons is 90%, the energy resolution is $\Delta E/E_\mu = 15 - 25\%$, the angular resolution is $\Delta \theta_\mu = (10 - 30)$ mrad /GeV/c.

(ii) 18 magnetized iron toroids with a magnet field of 1.92 T in the centre and 1.5 T at the periphery, interspersed with x, y drift chamber planes; the momentum resolution is $\Delta p/p_\mu = 10\%$.

Fig. 5 shows the acceptance of the $\mu$-detection system for the $x$ and $y$ variables at $E_\nu = 10$ GeV.

The smooth (dotted) lines indicate the limits of $x - y$ acceptance with (without) the magnetized iron frames for 50% efficiency of $\mu$-detection.

1.5. Electromagnetic Shower Detector

Electromagnetic cascades are rather long (up to 4 m) in the liquid scintillation calorimeter. An II radiation length deep detector plane at the end of the target calorimeter improves considerably the fiducial volume for e$^+$/e$^-$ scattering. It is further indispensable for the detection of gammas and electrons from $\nu_e$--N interactions. The detector is a wall of 16 horizontal cells. Each cell is 3.6 m long, 19 cm high and 20 cm deep and consists of a sandwich of 12 4mm lead and 10mm plastic scintillator sheets. It is viewed by two photomultipliers FEU-49. Calibration measurements with 90 cm and 160 cm long test modules were performed in an $e^+$/e$^-$ and hadron beam at energies between 1 and 5 GeV [2]. The energy resolution for electrons was obtained to be

$$\Delta(E)/E = 14\% / \sqrt{E_e} \ (GeV).$$
2. THE NEUTRINO BEAMS

The installation of the booster which will come into operation at the end of 1983 will yield a proton intensity of \((3 - 5) \times 10^{13}\) protons per pulse. This allows high statistics experiments with the existing \(\nu_e\) and \(\bar{\nu}_e\) wide band beams. The \(\nu_e\) beam spectrum is shown in fig. 6. There are further proposals to install a dichromatic beam [3] with a \(\nu_e(\pi)/\nu_e(\pi)\) ratio of about 100/1 and to build a \(\nu_e\) enriched beam with neutrinos from the \(K^-\) decay [4].

The corresponding spectra of the proposed neutrino beams are shown in figs. 7 and 8.

FIG. 6

FIG. 7

FIG. 8
The main features of all $\nu$ - beams are summarized in the following table.

<table>
<thead>
<tr>
<th>BEAM</th>
<th>$&lt; E_\nu &gt;$ [GeV]</th>
<th>$\Delta E/E$ [%]</th>
<th>$\nu$ -Intensity $\times 10^{-6}$/proton m$^2$·s$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>wide Band</td>
<td>$\nu_e$</td>
<td>6</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>$\bar{\nu}_e$</td>
<td>6</td>
<td>-</td>
</tr>
<tr>
<td>Dichromatic</td>
<td>$\nu_\mu (\pi)$</td>
<td>3.5</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>$\nu_\mu (K)$</td>
<td>7.5</td>
<td>7.5</td>
</tr>
<tr>
<td>8 GeV/c</td>
<td>$\nu_\mu (\pi)$</td>
<td>3.5</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>$\nu_\mu (K)$</td>
<td>7.5</td>
<td>7.5</td>
</tr>
<tr>
<td>$\nu_\tau$ + $\bar{\nu}_\tau$ from $K_L$ - decay</td>
<td>10</td>
<td>-</td>
<td>1.</td>
</tr>
</tbody>
</table>

3. PHYSICAL MOTIVATION

3.1. Introduction

The combination of liquid scintillation counters interleaved with drift chamber planes and the high muon detection efficiency forms a device best suited to study the pure leptonic process

$$\nu_\mu e \rightarrow \nu_\mu e$$

and to test the validity of the standard model. As a byproduct exclusive reactions as

$$\nu_\mu \rho \rightarrow \nu_\mu \rho$$

$$\nu_\mu n \rightarrow \mu^- \rho$$

$$\bar{\nu}_\mu \rho \rightarrow \mu^- \bar{\rho}$$

are measured in the wide band beams with rather good statistics.

For the study of inclusive processes the fiducial mass of the detector can be increased by Al-absorber plates. The excellent properties of the proposed dichromatic $\nu_\tau$ - beams allow us to perform precision measurements of the total cross sections of the processes

$$\nu_\tau N \rightarrow \mu X$$

$$\bar{\nu}_\tau N \rightarrow \bar{\nu}_\tau X$$
in the energy range $3 \leq E_\nu \leq 30$ GeV. Furthermore, a detailed study of NC and CC structure functions and a search for $\bar{\nu}_e \rightarrow \bar{\nu}_e$ oscillations is possible.

In the proposed $\bar{\nu}_e$ enriched beam inclusive $\nu_e$ interactions

$$\bar{\nu}_e N \rightarrow e X$$

(7)

$$\bar{\nu}_e N \rightarrow \nu_e N$$

(8)

can be measured for the first time with good statistics at high energies.

It is also planned to perform beam dump experiments to study the properties and the origin of prompt produced neutrinos.

3.2. Elastic Scattering in the Wide Band Beam

a) $\nu_\mu e \rightarrow \nu_\mu e$ scattering

The kinematics of elastic $\nu_\mu e$ scattering is characterized by a small angle of the recoil electron

$$\theta_e^2 = 2 m_e (1/E_e - 1/E_\nu)$$

The large fraction of sensitive material between adjacent drift chambers (16 g/cm$^2$ scintillator to 3 g/cm$^2$ Al, corresponding to about $1/3$ rad. length) and the space resolution of the drift chambers guarantee a good measurement of the electron trajectory. Monte-Carlo simulation predicts the following accuracy for the electron angle

$$\Delta \theta_e = (2 + 10/E(\text{GeV})) \text{ mrad}$$

and shows, that the $e^-/f$ and $e^-/$hadrons discrimination properties of the proposed target calorimeter suppress drastically background reactions of the type $\nu_\mu \rho \rightarrow \nu_\mu n^\rho X$ and $\nu_\mu p \rightarrow \nu_\mu n^\rho p$.

The influence of remaining background processes shows the distribution in fig. 9. The expected background-to-signal ratio is better than 10%. With a fiducial mass of 40 t and an intensity of $3 \cdot 10^{13}$ ppp it will be possible to detect $\tau \nu_\mu e$ and $3 \nu_\mu e$ events per day.

![Monte-Carlo Results Graph](image-url)
b) elastic $\nu_\mu p$- and quasielastic scattering

In the same exposure elastic neutrino scattering (2) and quasielastic reactions (3) and (4) can be measured with high statistics. The result of a Monte-Carlo simulation of the proton angular distribution from $\nu_\mu p$ scattering and from the main background reaction is shown in fig. 10. For angles $\theta_p > 60^\circ$ the expected contribution from background reactions is less than 3%. The sensitivity of the detector for elastic scattering amounts to about 80 $\nu_\mu p$ and 30 $\bar{\nu}_\mu p$ events per day.

3.3. Deep inelastic Scattering in the Dichromatic Beam

The increase of the target mass by adding a 8 cm Al-absorber plate to each module provides a nearly complete energy deposition of hadronic and electromagnetic components of the shower. Apart from energy measurements, the angles of hadronic and electromagnetic showers are defined by the drift chamber planes. A measurement of the inclusive $3\gamma$ reaction (5) in a beam with very good $\nu$-energy resolution allows a detailed analysis of nucleon structure functions $F_2^{\gamma\gamma}(x, Q^2)$ and $x \cdot F_3^{\gamma\gamma}(x, Q^2)$ and of the relation

$$ R(x, Q^2) = \frac{F_2^{\gamma\gamma}(x, Q^2) - x \cdot F_3^{\gamma\gamma}(x, Q^2)}{F_2^{\gamma\gamma}(x, Q^2)} $$

in the region $1 \leq Q^2 \leq 10$ (GeV/c)$^2$. The advantages of the detector capability and of the dichromatic beam lie in the possibility to measure the x and y variables for neutral current events (6) and to determine the structure functions $F_2^{NC}(x)$ and $x F_3^{NC}(x)$. The expected statistics for a one month exposure ($10^{19}$ protons on target) and a fiducial mass of 80 t is given in the following table for the parent beam momenta:
The number of NC-events is approximately 1/3 of the CC-statistics given in the table.

3.4. Search for $\nu_\mu \rightarrow \nu_e$ Oscillations in the Dichromatic Beam

It is suggested to use the dichromatic neutrino beam at a meson momentum of 8 GeV/c to study $\nu_\mu \rightarrow \nu_e$ transitions.

The special advantage at this energy is a very low flux of neutrinos from kaon decay ($\nu_\mu (K) / \nu_\mu (n) \approx 0.04$ and $\nu_e (K) / \nu_e (n) \approx 0.004$ in the energy region $2.5 \leq E_{\text{kin}} \leq 4.0$ GeV). This small admixture of $\nu_e$ allows to set the following limits, on the $\nu_\mu \rightarrow \nu_e$ oscillation parameters: $\sin^2 2\theta = 5 \times 10^{-4}$ (90% C.L.) at large $\Delta m^2$ and of $\Delta m^2 = 0.34$ eV$^2$ (90% C.L.) at maximal mixing. The results should be achieved within one month of running with 80 t fiducial mass.

3.5. Beam-Dump Experiment

The study of charmed particle production in pN-interactions near the production threshold is planned in a beam-dump experiment at 70 GeV proton energy. The same beam geometry will be used as in the beam-dump experiment from 1977 [5]. At that time the ITEP spark-chamber detector has measured a charm production cross section of $\sigma_{\text{charm}} = 5^{+4}_{-4}$ mb. In the proposed experiment the search for prompt neutrinos can be performed at a qualitatively new level, since the fiducial mass of the detector will be about ten times higher and also the intensity of the proton beam will increase considerably.
Fig. 11 shows the calculated energy spectrum of $\nu_e N$-interactions with $\nu_e$ from two different sources: (i) from the decay of DD-pairs, (we have assumed cross sections of 1/ub and 5/ub and a branching ratio for semileptonic decays of $B = 0.1$) and (ii) from the decay of $K^-$ and $K^0$ mesons giving the main background contribution. For $10^{19}$ protons hitting the beam-dump target about 320 $\nu_e$ from DD decay (if $\sigma = 5/ub$) are expected. The experiment will be sensitive for $\nu_e$ from charmed particle decay if $\sigma_{CHARM} > 1/\mu b$. 

3.6. Experiment in the Enriched $\nu^\circ_L$-Beam 

The neutrino beam from $K^0\bar{L}$-decays [4] contains $\nu_\mu, \bar{\nu}_\mu, \nu_e$, and $\bar{\nu}_e$ with 1.4 times more electron- than muon-neutrinos. For one month running with $10^{19}$ protons and 60 $t$ fiducial mass we expect to measure $4 \times 10^3$ CC $\nu_e N$-events (7) and $0.9 \times 10^3$ NC $\nu_e N$-events (8).

It has to be emphasized that there is no possibility to distinguish (i) between $\nu_e N$- and $\bar{\nu}_e N$-CC reactions in our detector and (ii) between the four NC reactions $\phi^\circ_L N$ and $\phi^\circ_R N$ in general.

But since there is very few information about $\nu_e N$ scattering, the following investigations seem to be rather interesting:

(i) to measure the sum of total CC-cross sections $\sigma(\nu_e N)$ and $\sigma(\bar{\nu}_e N)$ in the energy range $3 < E_\nu < 30$ GeV

(ii) to estimate the CC-structure function $F_2^{\nu_e N}(x, Q^2)$ and to compare it with $F_2^{\nu_e N}(x, Q^2)$

(iii) to estimate the $\nu_e N$ NC cross section by subtracting the $\phi^\circ_L N$ contribution which can be measured in the dichromatic beam

(iv) to test $\mu$-$\e$ universality; we expect to detect deviations from universality at a level of 10-15 %. 

3.6. Experiment in the Enriched $\nu^\circ_L$-Beam
REFERENCES

A proposal for a high intensity national neutrino facility which will make use of the low duty factor intense beam from the Proton Storage Ring at LAMPF is described. Intense high purity beams of $\nu_e$ and $\bar{\nu}_e$ from pion decay in flight as well as beams of $\nu_\mu$, $\bar{\nu}_\mu$, and $\nu_\tau$ from a beam stop will be provided. A broad range of neutrino physics in both nuclear and particle physics can be addressed at this facility.

In January, 1982 a proposal to build a high intensity national neutrino facility at the Los Alamos Meson Physics Facility (LAMPF) was submitted to the Department of Energy. The proposal is based on the recommendations of a neutrino workshop held at Los Alamos in June, 1981 and on a proposed experiment to search for neutrino oscillations (LAMPF Experiment 638\(^{(1)}\)).

The facility will make use of 200 $\mu$A of 800 MeV $^1$H beam from LAMPF which is deflected into Line D (see Fig 1). This beam can either be injected into the Proton Storage Ring (PSR) or can be multiplexed to provide 100 $\mu$A to a neutron production target on line D and 100 $\mu$A into a parallel neutrino beam line to a neutrino production target. LAMPF beam pulses into Line D are 500 $\mu$sec long at 24 Hz. If injected into PSR, the pulses are bunched and ejected from PSR as 270 nsec long pulses at 24 Hz at a peak current of 25 A. 100 $\mu$A of PSR beam can then be multiplexed into Line D and 100 $\mu$A into the neutrino beamline.

The beam is focused onto a 40 cm long, 3cm diameter pyrolytic graphite target. Pions produced in this target will be focused into a decay channel by either a DC split dipole magnet or a horn pulsed at 12 Hz. The decay channel is 4m across and the target can be moved to provide a
variable decay length from 0 to 30m. The decay channel is followed by 9m of iron shielding in front of a large detector building. For experiments using a beam stop production target at the end of the decay channel, there is a detector building at 90⁰ from the proton beam direction with 6.3m of iron shielding between it and the beam stop. For experiments searching for neutrino oscillations, detector buildings are situated at 200m and 3800m from the production target.

Flux calculations have been carried out by Monte Carlo using input from measurements of positive pion production off carbon and includes energy loss and absorption of the protons and pions and multiple scattering. The flux calculation results are given in Table I. The purity of these beams is also high, with a calculated contamination of $\bar{\nu}_e$ in the $\nu_\mu$ beam of 0.005 (0.09) and a contamination of $\nu_e$ in the $\nu_\mu$ beam of 0.001.

We have proposed a detector for this facility, a detector which is capable of addressing some of the proposed physics. The design of the detector is based on its capability to search for neutrino oscillations and to measure $\nu_\mu$-e and $\bar{\nu}_\mu$-e elastic scattering and has very fine granularity to match the low energies involved. The detector, as shown in Fig. 2, consists of layers of 1 cm thick aluminum plates interspersed with alternating layers of x and y proportional drift chambers (PDC) to provide tracking information. The PDC thickness is 1 cm with 1.5 cm drift distance. Every fifth layer of PDC is replaced by 2 cm thick scintillator. Each module consists of 4 + 1/2 cm thick aluminum plates, 2x and 2y PDC's, and a scintillator plane. The total detector consists of 271 modules 5m on a side and is 22m long with a total mass of 500 tons. An active anticoincidence shield surrounds the detector to provide rejection of cosmic ray backgrounds. Table II gives pertinent information about the detector.

Neutrino oscillations will be searched for by a collaboration which has already received LAMPF PAC approval. The channels to be investigated are $\nu_\mu \rightarrow$ anything and $\bar{\nu}_\mu \rightarrow \nu_e$. These experiments will use a 20 ton detector of dimensions 1m x 1m x 22m at 200m from the production target to normalize the experiment. The 500 ton detector will be at 3800m. This arrangement eliminates several systematic effects. The sensitivity of these experiments, which is shown in Fig. 3, is an order of magnitude better than...
any other proposed experiment to date. This is due to the low neutrino energy, high beam purity, and high intensities available at this facility. If oscillations of \( \nu_\mu \) are observed, oscillations of \( \bar{\nu}_\mu \) will also be searched for at somewhat reduced sensitivity as a test of CP violation.

The very fundamental process of muon neutrino - electron elastic scattering can also be studied with this detector. Event rates for \( \nu_\mu - e \) and \( \bar{\nu}_\mu - e \) scattering are calculated to be approximately 6 and 1.3 events/day respectively with a signal to noise of better than 100 to 1.

An accurate measurement of the Weinberg angle can be made from the total \( \nu_\mu - e \) and \( \bar{\nu}_\mu - e \) total cross sections \( \sigma \) and \( \bar{\sigma} \) from the relation

\[
\frac{\nu - \bar{\sigma}}{\sigma + \bar{\sigma}} = 1 + 4 \sin^2 \theta_w. \tag{1}
\]

The spectra of the \( \nu_\mu \) and \( \bar{\nu}_\mu \) flux can be adjusted to overlap one another by adjusting the focusing dipole or horn current and the use of appropriate beam plugs. Thus, only the amplitudes of the \( \nu_\mu \) and \( \bar{\nu}_\mu \) fluxes enter into the above equation. We believe that the ratio of \( \nu_\mu / \bar{\nu}_\mu \) fluxes can be accurately determined by measuring the charged current reaction \( \nu_\mu \bar{1}^2C + \mu^- \bar{1}^2N \) and \( \bar{\nu}_\mu \bar{1}^2C + \mu^+ \bar{1}^2B \) to bound final states by observing the subsequent beta decay of \( \bar{1}^2N \) and \( \bar{1}^2B \). Thus, we believe an 8% measurement of the relative cross sections is possible. This translates to a 2-3% determination of \( \sin^2 \theta_w \). Such accuracy provides a test of different grand unified field theories which make predictions for corrections to \( \sin^2 \theta_w \) which differ at the few percent level.

Furthermore, a determination of the \( y \) distribution will be possible in \( \nu_\mu - e \) and \( \bar{\nu}_\mu - e \) scattering with this detector. A measurement of the \( y \) distribution provides information about the coupling constants of the weak interaction. The differential cross section for \( \nu_\mu - e \) elastic scattering is

\[
\frac{d\sigma}{dy} = G^2 M_e^2 / 2\pi \left[ A_\mu + 2 B_\mu (1-y) + C_\mu (1-y)^2 \right] \tag{2}
\]

where

\[
A_\mu = (\nu+\bar{\nu})^2 + 1/16(S+P)^2 + 1/16(S-P-4T)^2 = (1-2\sin^2 \theta_w)^2,
B_\mu = T^2 - 1/16(S+P)^2 - 1/16(S-P)^2 = 0, \tag{3}
\]
\[ C_\mu = (V-A)^2 + \frac{1}{16}(S+P)^2 + \frac{1}{16}(S-P-4T)^2 = 4\sin^2 \theta \]

and \(A_\mu\) and \(C_\mu\) are interchanged for \(\bar{\nu}_e\) scattering. The middle column of Eqs. 3 include scalar, pseudoscalar, and tensor couplings while the right hand column gives the predictions of the Weinberg-Salam model. The average energy of 150 MeV is ideal for this experiment since it is high enough that multiple scattering does not completely wash out the angular information while the neutrino energy is also low enough that substantial showering does not occur and the recoil angles are large enough to allow a measurement with PDC's. The \(y\) distribution can be determined from measurements of the recoil angle \(\theta_e\) and electron energy from E\(_e\) the relation

\[ y = \frac{y}{\sqrt{y(1-\cos \theta)}} \]

With an energy resolution of 15% and angular measurements of 20-60 mrad, \(y\) can be determined for values above 0.5 with an accuracy of 20%.

A wide range of other experiments are possible at this facility. Some of these are \(\nu_\mu\) elastic scattering, \(\bar{\nu}_\mu\) elastic and inelastic scattering, \(\nu_\mu\) \(^4\)He coherent scattering, and inelastic scattering to specific nuclear states in \(^{12}\)C.

The proposed construction schedule calls for funding to begin in 1984 with completion of most of the facility by late 1985. The neutrino oscillation experiments would be carried out prior to PSR becoming fully operational in late 1986. Following upgrading of the PSR in early 1987, the other experiments described above can begin.

REFERENCES


2) P. Denes, B. D. Dieterle, D. M. Wolfe (University of New Mexico), T. Bowles, T. Dombeck, J. E. Simmonson (Los Alamos National Laboratory), T. S. Bhatia, G. Glass, W. B. Tippens (Texas A&M University), to be published.
TABLE I
NEUTRINO FLUX CALCULATION*

<table>
<thead>
<tr>
<th>Dipole (Current sign)</th>
<th>Decay Region</th>
<th>Flux at Close Position</th>
<th>Flux at 200 m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Diam(m) x L(m)</td>
<td>(v/cm²-s)</td>
<td>(MeV)</td>
</tr>
<tr>
<td>no dipole</td>
<td>4 x 30</td>
<td>----</td>
<td>----</td>
</tr>
<tr>
<td>positive</td>
<td>4 x 30</td>
<td>----</td>
<td>----</td>
</tr>
<tr>
<td>positive</td>
<td>4 x 12</td>
<td>4.0x10⁶</td>
<td>150</td>
</tr>
<tr>
<td>negative</td>
<td>4 x 30</td>
<td>----</td>
<td>----</td>
</tr>
<tr>
<td>negative</td>
<td>4 x 12</td>
<td>1.0x10⁶</td>
<td>130</td>
</tr>
</tbody>
</table>

*All values are calculated for a carbon target, 3-cm diameter and 40-cm long.
Assumes 100 μA-proton current on target; all fluxes are integrated for $E_\nu > 60$ MeV.

**The close position for neutrinos is at 21 m and with a pion decay channel length of 12 m. The anti-neutrino flux is quoted at 19 m for a decay channel of 10 m. These values are discussed in the text.

TABLE II
Detector Components and Parameters

1) 1084 Aluminum plates - 1/2cm x 5m x 5m
2) 271 Scintillator planes - 5m x 5m
   Each contains 4 - 2cm x 2.5m x 2.5m acrylic scintillator slabs with 1 - 5" photomultiplier
3) 271 PDC Modules - 5m x 5m
   Each module contains 4 - 1cm x 5m x 5m proportional drift chambers
   wire spacing: 1.5cm - alternating sense wires and cathode pickups
   Gas mixture: 80% Ar - 20% CO₂
   1 mm spatial resolution
   ±20 mrad angle resolution per module

Size = 5m x 5m x 22m
Avg. density = 0.91 gm/cm³
366 tons aluminum
Avg. radiation length = 38cm
Avg. dE/dx = 1.6 MeV/cm (minimum ionizing)
Avg. gamma conversion length = 49cm
% electron energy deposited in scintillator = 30% (Visible total energy)
STATUS OF THE CERN LEP PROJECT

G. Plass

CERN, Geneva/Switzerland

1. Overview

The proposal to build a large \( e^+e^- \) storage ring as Europe's next instrument for elementary particle physics was first published in 1977 and the main stages of development this project has undergone in the meantime are summarized below. The most important milestone is no doubt the approval by the CERN Council in December 1981 of an initial construction stage called LEP Phase 1. This is an \( e^+e^- \) storage ring of 26.6 km circumference to be built in the area straddling the Swiss-French border near the CERN sites (fig. 1). With a top energy near 60 GeV, the maximum luminosity of about \( 10^{34} \text{cm}^{-2} \text{s}^{-1} \) will occur at 51.5 GeV. With the nominal 4 bunches, there are 8 crossing points, but experimental caverns will be built only in four of them in Phase 1.

The existing proton synchrotrons will be used as injectors. The \( e^+e^- \) beams will first be accelerated to 600 MeV in an electron linac, transferred via an accumulator ring to the CERN PS where they are accelerated to 3.5 GeV, then accelerated to about 20 GeV in the CERN SPS, and injected into LEP (fig. 2).

<table>
<thead>
<tr>
<th>Date</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1977</td>
<td>Design concept for a 100 GeV ( e^+e^- ) Storage Ring (LEP)</td>
</tr>
<tr>
<td></td>
<td>- circumference 50 km</td>
</tr>
<tr>
<td>April 1978</td>
<td>ECFA chooses LEP and proposes CERN as site</td>
</tr>
<tr>
<td>August 1978</td>
<td>15 to 100 GeV LEP</td>
</tr>
<tr>
<td></td>
<td>- circumference 22 km</td>
</tr>
<tr>
<td>August 1979</td>
<td>25 to 130 GeV LEP</td>
</tr>
<tr>
<td></td>
<td>- circumference 30.6 km</td>
</tr>
<tr>
<td>June 1980</td>
<td>Formal proposal to the CERN Council to build LEP Phase 1</td>
</tr>
<tr>
<td>Early 1981</td>
<td>High tune lattice (90° phase advance)</td>
</tr>
<tr>
<td></td>
<td>25 to 125 GeV LEP</td>
</tr>
<tr>
<td></td>
<td>- circumference 26.6 km</td>
</tr>
<tr>
<td>End 1981</td>
<td>Choice of the final location for LEP</td>
</tr>
<tr>
<td></td>
<td>CERN Council approval of LEP Phase 1</td>
</tr>
<tr>
<td>March/April 1982</td>
<td>Environmental impact study submitted for a machine up to 100 GeV beam energy and</td>
</tr>
<tr>
<td></td>
<td>Tenders invited for - civil engineering</td>
</tr>
<tr>
<td></td>
<td>- dipoles</td>
</tr>
<tr>
<td></td>
<td>- klystrons 1MW c.w.</td>
</tr>
</tbody>
</table>
A cross section of the LEP machine tunnel is shown in fig. 3. Fig. 4 shows the lattice functions. The main parameters for Phase 1 are given in tables 1 and 2.

LEP is viewed as an evolving project. The construction permits currently requested from the Host States are for a machine designed to cover the energy range from 25 to 100 GeV with luminosities in the range $10^{30}$ to $10^{31}$ cm$^{-2}$ s$^{-1}$. Its power consumption, about 70 MW initially, shall not exceed 150 MW, and the number of experimental areas may rise to six.

2. Development potential and experimental facilities

2.1 Energy increase

It is easily seen that the size of the machine has been chosen for a top energy higher than in Phase 1. Below the energies are listed which can be attained in successive stages of increasing RF power and with two assumptions about the accelerating gradient which superconducting RF cavities may be able to sustain. Whereas a betatron phase advance per lattice cell of 60° is chosen for Phase 1, a stronger focusing with 90° phase advance, is envisaged for higher energies, (cf. table 1).

<table>
<thead>
<tr>
<th>Potential Energy Increase of LEP</th>
<th>Room Temperature RF</th>
<th>Superconducting RF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installed RF Power (MW)</td>
<td>16 24 48</td>
<td>48 48</td>
</tr>
<tr>
<td>Length of RF Structure (m)</td>
<td>271.5 407.2 814.4</td>
<td>814.4 814.4</td>
</tr>
<tr>
<td>No. of Exp. Areas with RF</td>
<td>2(partial) 2(full)</td>
<td>4(full) 4(full)</td>
</tr>
<tr>
<td>Max. Energy (zero luminosity) (GeV)</td>
<td>59.0 65.5 78.0</td>
<td>92 305</td>
</tr>
<tr>
<td>Acc. Gradient (MV/m)</td>
<td>1.47 1.47 1.47</td>
<td>3 5</td>
</tr>
</tbody>
</table>

The possibility has been discussed to install acceleration cavities in all eight intersection points, raising the energy to 93 GeV with normal RF cavities or to 125 GeV with 5 MV/m gradient in superconducting cavities. This, however, will require major modifications of the machine and all the infrastructure and is not part of the present plans.

2.2 Current and luminosity limitations

The luminosity is for flat beams given by

$$L = \frac{I \gamma \Delta \Omega_y}{2 e r_e \beta_y}$$

where
- $I$ is the current (equal in both beams)
- $\gamma$ is the usual relativistic factor
- $\Delta \Omega_y$ is the beam-beam time shift
- $\beta_y$ is the vertical lattice function at the crossing
It is at present well established that the limit of $\Delta Q_y$ is near 0.03, rather than 0.06 as hoped for some time ago. This value is the maximum achieved in existing storage rings and has, more recently, also been verified by computer simulation. The technical limit of $\beta_y$ for LEP is expected at 0.1 m or somewhat below (cf table 2). The beam current is limited by turbulent instabilities excited by the interaction of the beam with the surrounding medium, which are strongest at injection energy. The instability threshold is estimated to lie at about 3 mA. Inserting these values into equ. (1), one obtains

$$L = \frac{31}{10} \text{ barn}^{-1}$$

This luminosity value should of course not be taken as one to be achieved at start-up. As usual, it will take quite some time to understand the machine so well that it can be attained. It also corresponds to the present state-of-the-art and one sees no major luminosity development potential, except perhaps for a factor of two or so.

2.3 Experimental intersections

It is planned to provide in Phase 1 four experimental caverns in points P2, P4, P6 and P8, with the possibility for two additional ones in P1 and P5. The layout of a typical experimental cavern is shown in fig. 5, and an artist's view of it in fig. 6. It is similar to the cavern built at the SPS in CERN for the pp experiments and provides space for the assembly of an experiment in a "garage" position. Once assembled, the whole experiment is moved at once into the beam area.

The free space between the "low beta" quadrupoles nearest to the experiment is given in table 3 as ± 5 m, corresponding to a vertical beta-function of 0.1 m. Design work is currently underway in order to define the practical minima of these values which can be achieved. In order to preserve a high degree of symmetry in the machine, it is envisaged to provide the 4 experimental crossings with identical low beta insertions.

2.4 e-p option

An experimental cavern in P1 may be of particular interest: the position of LEP with respect to the SPS has been arranged in such a way that the protons from the SPS can be brought to LEP P1 through a by-pass replacing one-third of the SPS, so that e-p interactions can be observed there (fig. 7). The by-pass is so designed that protons of about 280 GeV, the maximum energy that the SPS magnet can sustain continuously, can be brought down to LEP.

2.5 Polarization

Recent theoretical and experimental work has strongly enhanced the confidence that polarized $e^\pm$ beams can be obtained in LEP at about 50 GeV. In particular, polarization in the range of 65\% to 80\% has been consistently achieved with colliding beams in PETRA at luminosities up to $4 \times 10^{30}$ cm$^{-2}$s$^{-1}$. For LEP it is expected that the polarization time can be decreased to about 2 hours with the help of wiggler magnets and it appears that the requirements on the closed orbit correction to avoid depolarizing resonances, can be met at least with a lattice of 60° phase advance. Preliminary design proposals for the spin rotators necessary to obtain longitudinal polarization in the interaction point, have been worked out.
3. Some essential technical considerations

It is impossible in a short time to justify all design choices of LEP. This brief review will deal with those issues which are most directly influenced by the large power which electrons lose due to synchrotron radiation on a curved path.

\[ P = \frac{E I}{R} \]  
where \( E \) is the beam energy  
\( R \) is the bending radius  
\( I \) is the beam current

At the energy in question, many megawatts of synchrotron radiation power are at stake, which are expensive to produce, to dissipate and to shield. In addition, the X rays are destructive where they escape the lead shield.

3.1 Size and position

As increasing the machine radius is the only possible defence against the overwhelming rise of the synchrotron radiation power, the "largest possible" machine must be built. The size chosen permits (cf. section 2.1) to attain the energy necessary for Z° and W physics according to current theory, and its realization appears possible from the engineering point of view.

The positioning of the machine is largely conditioned by its size and the constraints of the geology of the area. The underground rock which supports all existing CERN machines is a molasse which is stable, dry and makes the drilling of a tunnel easy. This molasse rock is bordered in the West by the Jura mountain range, and in the East by an underground valley under Geneva airport, where the moraine cover reaches a thickness of more than 100 m, both of which had to be avoided as far as possible. The requirement for a later implementation of e-p interactions imposes, in addition, rather stringent constraints on the geometry of the ensemble LEP-SPS. These considerations essentially lead to the compromise position shown in fig. 1 with about 85% of the circumference in molasse and 15% in jurassic limestone.

In order to keep the depths of the shafts to a minimum, it was necessary to incline the plane of the tunnel by 1.5% as indicated in fig. 8. They range now between 50 and 140 m in depth.

3.2 Dipole magnets

The dipole magnets which must be placed along the entire curved part of the circumference are amongst the most costly items of the machine. Over 3300 dipole cores of nearly 6 m in length, totalling almost 20km of magnet, are required for LEP. On the other hand, the large machine radius, imposed by consideration of the synchrotron radiation power at the top energy, leads to very low magnetic inductions: at injection energy (20 GeV) about 210 G and at 100 GeV about 1050 G.

The low carbon steel normally used for accelerator magnets does not show any saturation below 10 kg induction, and that led to the proposal to dilute the steel with some non-magnetic, cheap material. The steel laminations are being interleaved with layers of suitable thickness of the filler material, for which concrete was chosen. The dipole design is shown in fig. 9, and one of the prototype magnets in fig. 10.
3.3 Acceleration system

The RF system must make up for the synchrotron radiation loss. 16 MW of radiofrequency power are necessary in Phase 1 and the power requirement will increase as shown in Para 2.1. This large RF power demand has led CERN to stimulate industry to undertake the development of highly efficient, very high power klystrons. To date, two prototype 1MW c.w. klystrons have been received with an efficiency of about 64% (fig. 11).

In an acceleration system with room temperature copper cavities, a large fraction of the RF power is lost in the cavity wall. In a large machine like LEP where only few bunches circulate, the accelerating field is required only rather rarely and for a short time when a bunch passes. This has led to the development of a system of coupled cavities, where the energy oscillates between the accelerating cavity and a high-Q storage cavity (fig. 12), whereby the losses are reduced to 65%.

Superconducting acceleration cavities are the only way to achieve the ultimate energy level of LEP. Therefore, a long term development of such cavities has been undertaken in collaboration with other laboratories. Progress is very promising: in April 1982, a superconducting 500 MHz cavity, built at Karlsruhe has been used to store 2 mA of electrons at 5 GeV in PETRA (DESY) and a set of 1500 MHz cavities was tested in CESR (Cornell), storing 7 mA of electrons at 3.5 GeV. The CERN group is currently preparing a 500 MHz five-cell structure for testing in PETRA early in 1983.

3.4 Vacuum system

The LEP vacuum system is designed for an initial pressure of 2.10^{-9} torr. Due to the continued bombardment by synchrotron radiation the pressure is expected to drop to a value near 2.10^{-10} torr/MA beam after about 1000 hours of operation. Non-evaporable getter (NEG) pumps, located in a chamber parallel to the beam vacuum chamber (fig. 13) will be used as the magnetic induction in LEP is too low at low energies to sustain distributed ion pumping as used in other machines. The NEG pump needs an initial conditioning at 700°C. When the strip is beginning to saturate, it can be reconditioned at 400°C, whereby the absorbed molecules migrate into the bulk of the strip. Fig. 14 shows the decrease of the pressure in a prototype LEP vacuum chamber installed in PETRA for several months and which was reconditioned a few times.

The synchrotron radiation emitted by the beam must be absorbed as near as possible to the source, i.e. in the wall of the vacuum chamber, in order to protect other machine components. Lead cladding of the aluminium vacuum chamber, as shown in fig. 13, is therefore envisaged for LEP. The development of a reliable tight cladding technique proved quite difficult, but recently satisfactory test sections have been obtained by soldering pre-cast half-shells onto the chamber.

4. Status and outlook

The development of some of the key machine components which was started two years or more ago is well advanced and a number of invitations to tender have already been sent out to industry. The design work on the very considerable technical infrastructure that is necessary for this machine has been allocated and progresses well.
A final campaign of geoelectrical measurements and test borings was launched in critical places along the final tunnel position, in order to locate with precision the top molasse level. The reconnaissance gallery which was started at the end of 1980 has reached its future intersection with the LEP tunnel and was stopped there. The tunnelling machine went through the molasse/limestone interface without major problems. One local fault carrying water under 9 bar pressure caused alarm, but it could be drained and crossed quite easily.

The tendering for the civil engineering work is under way and we expect to adjudicate the first contracts before the end of the year. The sizeable documentation necessary for the environmental impact clearance in one of the Host States was submitted in March and it is hoped to obtain the construction permit in time for the tunnelling work to begin early in 1983.

The parameters of the long chain of injectors - two linacs, an accumulator and two synchrotrons - have been thoroughly scrutinized and the final scheme, taking account of intensity and density limitations at the various steps, has been designed. A contract was signed with the Laboratoire de l'Accelerateur Linéaire at Orsay (France) for the joint design and construction of the injector linacs, size and lattice of the accumulator have been chosen, and well defined projects are in hand for the necessary additions and modifications to the CERN proton synchrotrons.

In conclusion, one can say that at the present moment - June 1982 - the LEP project is gathering the necessary momentum for a speedy execution. CERN still has to solve a number of difficult problems of staff and budget reallocation, and to arrange for a healthy co-existence of this huge project with the on-going physics programme within a constant staff and budget envelope. We all hope sincerely to finish this project soon enough for physics experiments at LEP to start up early in 1988.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference (including sagitta in dipoles)</td>
<td>26650.8793 m</td>
</tr>
<tr>
<td>Average radius</td>
<td>4242.3924 m</td>
</tr>
<tr>
<td>Minimum diameter</td>
<td>0.406 km</td>
</tr>
<tr>
<td>Maximum diameter</td>
<td>0.526 km</td>
</tr>
<tr>
<td>Bending radius</td>
<td>3099.2095 m</td>
</tr>
<tr>
<td>RF frequency</td>
<td>352.2091 MHz</td>
</tr>
<tr>
<td>Revolution time</td>
<td>88.9244 μs</td>
</tr>
<tr>
<td>Harmonic number</td>
<td>31320</td>
</tr>
<tr>
<td>No. of bunches per beam</td>
<td>4</td>
</tr>
<tr>
<td>No. of interactions</td>
<td>0</td>
</tr>
<tr>
<td>Equipped Experimental Areas (P2, P4, P6, P8)</td>
<td>4</td>
</tr>
<tr>
<td>Horizontal/Vertical β values at I.P.</td>
<td>1.60/0.10 m</td>
</tr>
<tr>
<td>Installed RF power (in P2 and P6)</td>
<td>16 MW</td>
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<tr>
<td>Active RF structure length</td>
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</tr>
<tr>
<td>Injection energy</td>
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</tr>
<tr>
<td>Energy at maximum luminosity</td>
<td>51.5 GeV</td>
</tr>
<tr>
<td>Maximum energy (zero beam current)</td>
<td>-60 GeV</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Optical functions</th>
<th>60°/period</th>
<th>90°/period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal betatron wave number</td>
<td>50.35 ± 2</td>
<td>90.35 ± 2</td>
</tr>
<tr>
<td>Vertical &quot; &quot; &quot;</td>
<td>66.2 ± 2</td>
<td>94.2 ± 2</td>
</tr>
<tr>
<td>Momentum compaction factor</td>
<td>3.905×10⁻⁵</td>
<td>1.929×10⁻⁵</td>
</tr>
<tr>
<td>Uncorrected horiz. chromaticity</td>
<td>-110.04</td>
<td>-157.69</td>
</tr>
<tr>
<td>&quot; vert. &quot;</td>
<td>-176.6</td>
<td>-216.60</td>
</tr>
<tr>
<td>Energy variation of horizontal damping partition number</td>
<td>-712.5</td>
<td>-379.9</td>
</tr>
</tbody>
</table>
The minimum free space between quadrupoles and the $\beta$ functions are still under study.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Over-all insertion length</td>
<td>77.819 m</td>
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<tr>
<td>Free space between quadrupoles</td>
<td>$\pm 5$ m</td>
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<tr>
<td>Crossing angle</td>
<td>0 degree</td>
</tr>
<tr>
<td>Horiz. $\beta$-function at I.P.</td>
<td>1.60 m</td>
</tr>
<tr>
<td>Vert. $\beta$-function at I.P.</td>
<td>0.10 m</td>
</tr>
<tr>
<td>Dispersion</td>
<td>0 m</td>
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<tr>
<td>Horiz. rms beam radius at I.P. (design coupling)</td>
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</tr>
<tr>
<td>Vert. rms beam radius at I.P. (design coupling)</td>
<td>118.6 $\mu$m</td>
</tr>
<tr>
<td>Horiz. rms beam radius at I.P. (full coupling)</td>
<td>273 $\mu$m</td>
</tr>
<tr>
<td>Vert. rms beam radius at I.P. (full coupling)</td>
<td>39.4 $\mu$m</td>
</tr>
<tr>
<td>Assumed beam-beam tune shift</td>
<td>0.03</td>
</tr>
<tr>
<td>Luminosity at 51.5 GeV</td>
<td>$1 \times 10^{31}$ cm$^{-2}$ s$^{-1}$</td>
</tr>
<tr>
<td>Assumed current</td>
<td>3 mA</td>
</tr>
<tr>
<td>&quot; particles per bunch</td>
<td>$4.17 \times 10^{11}$</td>
</tr>
</tbody>
</table>
FIG 2. SCHEMA D'INJECTION POUR LEP
THE INJECTION SCHEME FOR LEP
FIG. 3. **Tunnel Cross Section**
\[ \phi 3.6 \text{m.} \]
FIG. 4: Lattice Functions
FIG. 5. **Typical Experimental Cavern (point 6)**
FIG. 8. COUPE GEOLOGIQUE SIMPLIFIEE
Simplified Geological Section

JURA
PLAINE
MOLASSE
SPS
MORAINES
FIG. 9. Steel-concrete magnet core
FIG. 11. Prototype IMW Klystron
FIG. 12. Accelerating cavity (below) & Storage cavity (above)
FIG. 13. CROSS SECTION OF THE DIPOLE VACUUM CHAMBER

SECTION DE LA CHAMBRE A VIDE DIPOLE

Beam channel
Canal faisceau

Cooling channels
Canaux de refroidissement

Lead
Plomb

Pump channel
Canal pompe

getter pump
Pompe getter
Total accumulated gas load
0.75 torr l m⁻¹

Total accumulated gas load
1.25 torr l m⁻¹

Total accumulated gas load
0.21 torr l m⁻¹

FIG. 14.
The IHEP accelerating-storage complex is a 3 TeV superconducting proton synchrotron in which the possibility to create colliding beams has been foreseen. This is a two stage accelerator. The first stage accelerates protons from 70 GeV to 400 GeV. The second stage—a superconducting accelerator—accelerates protons from 400 GeV to 3000 GeV. The total length of the accelerator is 20772 m. The maximum magnetic field strength for 3 TeV is 5 T. At present investigations are being carried out with 1 m and 6 m models. The maximum field attained in 1 m dipole is 6.23 T. A first 6 m sc magnet has been manufactured. After some training the current values coinciding with the measured current in short cables has been achieved. The measurements point to high mechanical stability of the structure.
My lecture was not supposed to be a formal summary of the conference but there are mainly some remarks, those mirror my personal response to the scientific situation presented at the conference.

At first I would like to note that the topics which were considered at the conference include almost all hot problems of elementary particle physics. Many excellent reviews, partially overlapping, illuminated these problems, so there is no need to point out all the important achievements of experiments and theory. Therefore, I will try to give some brief critical comments of the main topics.

The main subject of the conference is neutrino. According to the Prof. F.Reines is remark in the conclusion talk at the Hayaji conference the neutrino instead of being an "elusive" particle becomes a "pervasive" one. This is really so and even more. In some experiments neutrino is now also an "interfering" particle, that is the source of background. It is especially important for the first topic to which I would like to proceed - the proton decay experiments.

Proton decay

It is obvious that a search for incontrovertible proofs a existence of the specific phenomena of great unification theory is a matter of the greatest importance.
Various variants of GUT give a base of unification of isolated worlds of electro-weak and strong interactions and of barions and leptons. It is also the base of various scenarios of Origin of Universe. In spite of the undoubted success of the description of low energy phenomena, there is a lack of direct evidences of validity of the GUT approach up to now. The proton decay plays a very important part in this game. The discovery of proton decay independently of any specific theory would manifest a universality of various kind of fermions (barions and leptons) with respect to some new kind of interaction. It is obvious also that the exceptional importance of proton decay discovery makes the proof of this fact to be a very uneasy task.

There were presented three reports about the experiments on a search for the proton decay at the conference. In the report presented by Dr. Miyake the results of experiment of Kolar Gold Fields group were described, which now caused great excitement, as the authors announced the observation of at least three events ascribed to the decay of proton.

Kolar Gold Fields group is well known as a pioneering experimental group in the construction and operation of highly sophisticated deep underground detectors. They are working at a depth of 7.6 km of water equivalent at cosmic muon background of about 0.5 muon/day in the experimental set-up. The detector used by KGF group during the last few years comprises a calorimeter with layers of proportional counters (of 10x10 cm² cross section) interleaved by 1/2 steel sheets. The total weight of calorimeter is 150 ton of steel. In this device there were observed about thousand of muon tracks, a few tens of the atmospheric neutrino events and six events, which are regarded as the candidates for proton decay.
Three of them are linked to the end layers of counters, but another three seem to be isolated by a few layers of counters inside calorimeter and are considered to be the true proton decays. If taking these events, the time of experiment and a mass of fiducial volume of calorimeter of 60 ton, the proton decay time would be about $7 \times 10^{30}$ years.

However taking into account a limited amount of information about each event due to relatively rough structure of the calorimeter, one has to be very careful about the firm interpretation of these events. An energy deposition and especially the sense of direction of emitted particles and showers are strongly dependent on the hypothesis accepted by analysis. The neutral current neutrino events is the natural source of background in proton decay experiments and this background should be carefully analysed before making the final conclusion.

Another report about proton decay experiment "Nusex" which is now being carried out under Mont Blanc was presented by E.Fiorini. "Nusex" comprises much more fine-grained calorimeter (1 cm $\phi$ of counters, 160 t total weight). Some part of total set-up was irradiated on the neutrino beam by neutrino spectrum similar to atmospheric neutrino one.

Some of the events recorded in the test run proved to be alike the isolated tracks in KGF experiment. It is certainly not a proof, but an indication of possibility of misinterpretation of the experimental results.

The 10 days run of "Nusex" gave a lower limit for the proton decay corresponding to $\sim 2 \times 10^{30}$ years, so the further running may produce very important information.

The 7 kiloton water Čerenkov detector of IBM collaboration
is now under final preparation, as it was reported by P. Reines.

The other huge experiments of multikiloton size are now in progress.

Anyway the search of the proton decay in the vicinity of $\sim 10^{31}$ years has demonstrated already a necessity of use of very sophisticated detectors unlike the first steps around $\sim 10^{30}$ years.

The phenomenon, which is searched for, is too important to be recognized without strong criticism.

**Neutrino mass**

No new data on electronic neutrino mass was presented at the conference. The ITEP experiment on tritium $\beta$-spectrum measurement is still only one indicating nonzero $\nu_e$ mass. This experiment is now being continued after some modification of the experimental set-up. There is no doubt that the sensitivity corresponding to neutrino mass of about $10^{\text{eV}}$ is on the boundary of the present experimental technology, therefore besides of criticism an independent verification of this experiment and a search of new approaches is necessary.

A few new projects of tritium experiments were presented at the conference. In spite of the excellent ingenuity of the projects it is worth-while to mention that all of them do not promise a significant improvement of sensitivity but only some partial ameliorations.

Another approach, suggested by A. de Rujula, is based on the internal bremsstrahlung spectrum measurement in electron capture process. The measurement of proton spectra seems to be less vulnerable
with respect to some interfering effects in comparison with electron spectra measurements, but it is necessary to find a suitable isotope, which has low enough end-point energy of proton spectrum and could be produced in sufficient amount.

The first steps in this direction were reported here. The properties of isotope $^{163}$Ho were investigated at KEK (Japan) and CERN. $Q$-value of electron capture for this isotope proved to be $2.3 \pm 0.15$ keV.

The internal bremsstrahlung intensity is strongly dependent on $Q$, so that the change of $Q$ from 2.1 keV to 2.3 keV changes the intensity near the end-point energy by a factor of $10^4$. It means that in the worst case the experiment would be quite impossible.

So a feasibility of this approach is being determined by availability of suitable isotope. Unfortunately everybody, who tried ever to select an isotope for some particular experiment knows that in spite of availability of thousands of them there is usually lack of the necessary one.

Massive neutrino is now passionately wanted by cosmologists. As we have learned from Ja.B.Zeldovitch, the existence of our Galaxy could be under heavy danger without existence of some massive ($\sim 10^{-100} \text{ eV/c}^2$) and elusive particle. Unfortunately present situation does not provide the firm experimental basis for such ideas.

An indication of the nonzero neutrino mass in the ITEP experiment made more animated the neutrinoless double beta-decay search. A few new experimental results were presented at the conference. They shift the lower limit of lifetime for the neutrinoless double $\beta$-decay sometimes almost to $10^{22}$ years ($^{76}$Ge). Some new approaches were also discussed. The prime goal of most of this projects is to achieve the decay lifetime of about $10^{-23}$ to $10^{-24}$ years, that is predicted
by calculations based on the suggestion of Majorana neutrino with mass of order of $10 \text{ eV}/c^2$.

At the moment the only positive evidence for the existence of double $\beta$-decay (mostly two-neutrino) is known from geological investigations of abnormal isotopic abundance of the daughter nuclei of $^{82}\text{Se}$, $^{128}\text{Te}$ and $^{130}\text{Te}$ double $\beta$-decay. In early published measurements (Henneke, 1978) the ratio of $^{128}\text{Te}$ and $^{130}\text{Te}$ lifetimes ($\sim 1,5 \times 10^3$) provided some room for speculations about possibility of neutrinoless $\beta$-decay admixture compatible with neutrino mass of about $30 \text{ eV}/c^2$.

New measurement of this ratio (Heidelberg, 1982) are in disagreement with previous one and are compatible with zero neutrino mass.

Neutrino oscillations

Neutrino oscillations first pointed out by B. Pontecorvo in 1958 now became an important area of experimental activity including experiments at the reactors, accelerators and cosmic rays study. A discovery of this phenomenon would be a manifestation of lepton flavor mixing never observed earlier and an important evidence in favor of unification ideas.

The experimental results presented at the conference provide only upper limits for the phenomenological parameters of oscillations. These parameters are model dependent, but for two-neutrino mixing model one may characterize all the data by two-dimension plot, were one axis is $\Delta m^2$ and other one $\sin^22\Theta$.

For the low $\Delta m^2$ the best limit was given in the experiment of Caltech-SIN-TUM collaboration carried out at Gösgen power station. A 90% confidence limit is well below $\Delta m^2 \sim 0.1 \text{ eV}^2$ at $\sin^22\Theta > 0.1$. 
A result obtained in cosmic neutrino experiments at Baksan neutrino observatory (INR Academy Sci. USSR) (\( \Delta m^2 < 10^{-2} \text{ ev}^2 \)) is formally somewhat lower, but does not provide the good limit for \( \sin^2 2\Theta \) due to poor statistic.

The accelerator results reviewed by C. Baltay are more restrictive in the area of \( \Delta m^2 \) of about 1-10 \text{ ev}^2. In this area the plot \( \sin^2 2\Theta \) is limited by the level of about \( 0.5 \times 10^{-2} \), that is significant for some models of lepton mixing.

All the results on neutrino oscillations obtained up to now appear to be a very impressive experimental achievement, but from the point of view of present unification models it is still far from the expected \( \Delta m^2 \) values. If not to consider a large mass of electronic neutrino, the expected \( \Delta m^2 \) should be not more than \( 10^{-3} \text{ ev}^2 \). This is a real challenge for the present experimental state of art. May be solar neutrino detection experiment will be more informative for the solution of neutrino oscillation problem.

Neutron-antineutron oscillation

This phenomenon would be the manifestation of the barion quantum number violation with \( B = 2 \). The phenomenology of it is similar to neutrino, or \( K^0 \)-meson oscillation and may be described by a period of oscillation. As it was shown by V. Kuzmin at al. (INR Acad. Sci. USSR) the existing limit on proton decay lifetime gives the lower limit for the period of oscillation of order \( 2 \times 10^7 \) sec. As we have learned from the report of M. Baldo-Ceolin it is a very complicated problem to achieve this figure by direct observation of free neutron oscillation. Nevertheless there are some projects to achieve the limit of about \( 10^9 \) sec (Moscow meson factory neutron source).
Experiments are obviously very difficult.

**Deep underwater neutrino experiments**

The first attempts to estimate the light situation at the depth of about 1.5 kilometer were performed in the Pacific ocean and at the Baikal lake. A module of "muon string", which is proposed for DUMAND, was lost in the attempt to carry out the measurement at more depth. It is the first sacrifice to Ocean from DUMAND but probably not last, because the ocean situation is very far from the laboratory one. In spite of the fact, that light situation at those depth proved to be not very optimistic (very high bioluminescence light yield), it is worth-while to emphasize again the importance of the further development of this direction in view of long-term problems of construction of detectors with a mass more than $10^{12}$ ton. It seems to be the only possibility to detect very rare events of neutrino of extremely high energy, which may inform us of processes at the energy close to Plank mass (giving room for phantasy).

**Salam-Weinberg model tests**

Most of the low energy specific predictions of Salam-Weinberg model relate to neutral current phenomena. The structure of hadronic neutral current and universality of Weinberg angle were already established a few years ago. Leptonic part of neutral current was investigated with much less precision.

The interesting achievements of the last year are the measurement of $J_\mu$ and $\bar{\nu}_\mu \ell$ scattering in two counter experiments of BNL and CERN groups performed with relatively high statistics. Both the experiments have about the same statistics (but different background) and their results are in a good agreement with $\sin^2 \Theta_W$ accepted now.
In the experiment performed at CERN a charge asymmetry of muon-nucleon deep inelastic cross-section was measured. A comparison of the experimental asymmetry with theory is however a matter of radiation corrections, but there is no disagreement with the existing theoretical estimates.

The other new result is the forward-backward asymmetry of $\mu^+\mu^-$-pair production in $e^+e^-$ collisions at PETRA. The results of four groups (if averaged) are in agreement with the expected from S.-W.-model 9% asymmetry.

Unfortunately this result may only provide a limit for neutral boson mass corresponding to $M_Z > 50 \text{ GeV}/c^2$.

So inspite of the perfect agreement of all the experiments with low energy S.-W.-model predictions there is a lack of direct evidences of the validity of this excellent model. One of the nearest hope to see the production of $Z^0$-boson in $\bar{p}p$-collisions at the collider at CERN according to report of K. Eggert is still somewhat distant due to luminosity problem.

Nucleon-nucleon weak interactions

I would like to spend some time for the problem of parity nonconservation in nuclear processes.

There are now a few tens of experimental results concerning parity violation effects in complex nuclei and nucleon-nucleon collisions.

Almost all the data are in agreement (when nuclear factors might be calculated) with Salam-Weinberg model with two exclusions:

A circular polarization of $J$-quanta in $np \rightarrow dJ$, measured by
Leningrad group (1972) is $P_f = -(1.30 \pm 0.45) \cdot 10^{-6}$. Theory gives $P_f < 10^{-7}$.

A helicity dependence of total cross-section of $p(H_2O)$ at 6 GeV. The asymmetry of about $3 \cdot 10^{-6}$ was measured at Argonz ZGS in 1979. It is at least by an order more than theoretical estimates.

The circular polarization of $\gamma$-quanta in the reaction $np \rightarrow d\gamma$ has been remeasured with modified experimental set-up at Leningrad. New measurements showed that the previous result was due to penetration of $\gamma$-quanta from active zone of the reactor (bremsstrahlung radiation from $\beta$-decay of fission fragments). No circular polarization is seen at the present accuracy level. The preliminary upper limit for circular polarization at 95% confidence level is $|P_f| < 5 \cdot 10^{-7}$.

So besides the Argonz result now there is no contradiction between PNC-effects in nuclear processes and theory.

**New particles**

It would be very difficult to charachter briefly an experimential situation with hadrons and leptons carrying new flavors. The main part in production of this particles belongs to electron-positron colliders and it was a real pleasure to hear about the CERN collider as a "beauty factory" through $Y^{m}$-generation.

As a whole, however, there is an obvious lack of data about charm- and beauty particles decay that is of mixing of quark flavors. The number of well detected decays of charmed particles is too low in spite of hard experimental work.

If not considering this particular point of charm and beauty
problem there is a satisfactory agreement of almost all c, b-spectroscopy with QCD prescriptions.

Some aspects of this topic look alike the nuclear level spectroscopy turned up-side-down. It is known that the ground states and low-excited levels of nuclei are described by theory quite satisfactorily, due to Fermi-system specific properties of low-energy excitations. It is opposite to high-excitations of nuclei, where specific nuclear properties play the main part.

In hadron spectroscopy the QCD may describe heavy quark state, due to asymptotic freedom but appears to have low-predictive power for light quarks states where unsolved confinement and vacuum problem dominate.

Generally speaking, it is not quite clear whether the highest-energy experiments and superheavy particles study would help to the problem of confinement and of light hadrons. However our environment is almost totally made of light quark states.

**True new particles**

A discovery of heavy particles representing gauge fields would be a direct evidence in favor of the present theoretical ideas.

Not less significant as well would be observation of the very light or even massless partners of heavy gauge particles. As a prime pretender to this part could be an axion a pseudoscalar boson introduced by S. Weinberg to resolve CP-problem in QCD.

The search for such axion now may be considered as completed one. The experiments on a search of its two-gamma decay at the reactors, radioactive source, electronic accelerator and a search of $\psi \rightarrow aJ$ and $\gamma \rightarrow aJ$ decay mode allow to conclude very definit-
ly that "standard" axion is dead.

Nevertheless it is still a question about possible existence of light particles of another kind with more exotic properties.

According to H. Feissner a flux of some penetrating particles decaying into two gamma-quanta (but obviously not axions) is emitted by reactor, meson factory beam-stop at SIN and it is seen in high energy neutrino beam at CERN.

As to high energy events of single showers at CERN they could be probably explained as specific neutral current neutrino phenomena (S. Gerstein, Serpuckov).

As to the experiments of H. Feissner's group at SIN and at Julich reactor it is worth-while to say that they were carried out in the bad background conditions and should be repeated with much better shielding before being taken seriously.

The question about massless (non decaying) scalar and pseudoscalar particles usually has been closed on a base of astrophysics consideration of energy and lifetime of the Sun and red giants.

A factor of absorption increase, which is needed to forbid for such particles to escape the stars interior was calculated earlier to be of about $10^5$.

Recently, however, A. Anselm (Leningrad) indicated some mechanism which lowers this factor up to $10^3$ at least for one of the variants of massless axion. It is apparently not sufficiently to forbid the escape, but it is not clear to what extent could we exclude the existence of any another absorption mechanism.

Perhaps, the problem of new massless particles and their long-range interactions could be better tested in classic type experiments as was proposed by A. Anselm and V. Kuzmin et al. (Moscow).

In the lecture of J. Ellis we learned about immense world of
supersymmetric particles. The search of them seems to be a real
challenge to our experimental ability to look for unknown things.

If these particles are rare enough (by their origin) heavy
and stable, it is very uneasy to discover them, if they do not
carry some exotic mark, but only weak interaction with our World.

Nevertheless it is not excluded, that in not too distant
future we will take part, according to J.Ellis, in conference
"nuino..."
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