We regret that some of the pages in the microfiche copy of this report may not be up to the proper legibility standards, even though the best possible copy was used for preparing the master fiche

Missing pages: pg. 11

28 NOV. 1994

LAPP-EXP-94.22

NOVEMBRE 1994

NEUTRAL CURRENTS

Contribution to the International Conference
on the History of original ideas and basic discoveries on Particle Physics
ERICE - August 1994

Bernard AUBERT
CNRS-IN2P3 - LAPP Annecy-Le-Vieux, France

L.A.P.P. B.P. 110 F-74941 ANNECY-LE-VIEUX CEDEX • TÉLÉPHONE 50.09.16.00+ • TÉLÉCOPIE 50 27 94 95

The evidence for the existence of weak neutral current has been a very controversed topics in the early 1970's, as well as the muon did in the 1930's. It is a very interesting aspect of the relationships between the theory and the experiment. The history is also very rich considering the evolution of the experimental technics in high energy particle physics.

I. Weak interactions theory and experiment.

Experimentation in weak interaction covers a very broad field from β decay to cosmic ray studies of hyperon. The parity violation experiment of Mrs. Wu and the solution of the $\tau-\theta$ puzzle are a good illustration of the strong correlation between question arising from the theory side and the program of experimenters. The accelerators Era in the late 1950's offer the tools of K beam and bubble chamber detectors.

All weak interactions were well represented by the Universal Fermi Interaction. This interaction was local, which means a priori, it does not need any propagator. All interactions were adequately described by a phenomenological current Lagrangien completed with some selection rules, as the absence of neutral current. All experimental studies with the decay of hyperon and K meson satisfy the Fermi model.

But the weak interaction theory develops with the arise of gauge theory. In the same time theorists underline the difficulties of the Fermi interaction, radiative corrections, divergences and no renormalization. A theory built on the model of electromagnetic interaction needs the existence of an heavy propagator. The presence of an intermediate Vector Boson become one of the main interest of the community of particle physicists as well as theorists than experimenters. This interest turn into a really burning question when in 1971, Gerard Hooft allowed the gauge theory to be renormalizable. The presence of neutral current became one of the tool of experimenters to check the theory.

Later the quest of the intermediate vector boson continues with the decision of the community to build a large proton antiproton collider.

II. Neutral current before 1970's.

As test of selection rule, the absence of neutral current was a usual topic for experimenters, and slowly, the allowed level for decay violating such rule lowered with time. The precise test came with K decaying with two leptons in the forbidden channel. Level as low as 10^{-6} for charged K meson and 10^{-9} for neutral kaons were fixed.

An other tool for weak interaction is the beam of neutrino particles. The discovery of two kinds of neutrino has been possible with a heavy target to compensate for the low cross section. The heavy target forbids to see the interaction point and to study the kinematic of the interaction. Bubble chamber as target , suffers of the low statistic.

The comunity of neutrino physicists sets its priority by looking for intermediate Vector Boson through the deviation of the linear rise of the cross section with the incident energy. This leads to trigger neutrino interaction by the charged outgoing lepton and then to blind the presence of neutral current.

Then came a big step forward in the building of neutrino beam. The use of magnetic horn, to focus charged particle parent of neutrino, increase by several order of magnitude the flux of neutrino . A bubble chamber experiment became possible.

The CERN heavy liquid bubble chamber group took data using different liquid, propane and freon, in order to study the interaction. Several interactions compatible with the presence of neutral current were recorded. But due to the limited size of the chamber, the background analysis was not possible on reliable bases. The prediction of Weinberg for the effect to be detected set the neutral current at the level of 15% to 25%. The uncertainty of the measurement was of the same order.

The motivation of the search of the W was strong enough to motivate A.Lagarrigue and his team to fight to be allowed to construct a giant heavy liquid bubble chamber. In December 2nd, 1965, F.Perrin, "Haut Commissaire" at the French atomic energy commission, and V.Weiskopf, CERN Director, signed the document to give the green light for the construction of Gargamelle (a 3.5 meter long heavy liquid bubble chamber).

Later, in the early 1970's, the new accelerator of Batavia (Illinois) allowed to consider new neutrino experiments with high statistic due to the increase of cross section with energy. Two experiments were designed, one mainly oriented on heavy lepton search and one on W search. Neutral currents were not the main focus of any of the scheduled experiments.

One other channel was allowed for investigating neutral current. It is the purely leptonic channel. One, apparently, good place for that, could be the use of intense flux of electron neutrino in nuclear reactor. F.Reines tried this method but found difficult to cope with background. The observed rate of candidate is very similar reactor on and reactor off. This purely leptonic channel is also accessible with bubble chamber but the rates are even lower than the classical semi leptonic channel.

The general belief, as stated by D.Perkins in the International Conference on High Energy Particle Physics (1972-Chicago Batavia), is that the semi leptonic interactions on nuclei, are too much complex to be interpreted. Useful data on purely leptonic must be precise enough, better than 20% , to demolish Weinberg theory. So it was more or less a no hope message to be vehiculed to the Community.

III. Characteristics of neutrino experiments.

The first bubble chamber neutrino experiment in the 1960's used the Ecole Polytechnique 300 liters,BP3, and the neutrino flux were obtained just by looking a target hit by the proton beam. No event was found.

The source of neutrino is the decay of pions and kaons. A target on a proton beam produces secondary particles. A decay path allows to a good portion of those, to decay and produce neutrino. A shielding kills the remaining charged component as well as the neutrons. Finally only neutrinos goes through.

Thanks to Simon Van Der Meer, a focusing device based on a "Horn" , a toroïdal magnetic field surrounding the target, increase by several order of magnitude the flux of secondary beam in the detector direction. The neutrino flux and spectra were known by measurement of the shape and of the penetration of the muons inside the shielding.

In the same time, the size of the bubble chamber increase drastically. Gargamelle is fifty time bigger than BP3. Several technical problems like pressure or illumination have to be solved. The volume of a cylinder of 4.8 meter long and 1.8 meter of diameter is filled with propane or even better for weight, freon. Such a volume provides a reasonable target for neutrino interaction, but also, provides good possibilities to study background, interaction length , secondary reaction...

Finally as the cross section increases with the energy, an increase of the energy of the proton beam will induce an increase of the spectra of the different kind of neutrinos and antineutrinos. Basically the average neutrino energy is about one tenth of the proton energy. The start of the accelerator of NAL at Batavia allows to get neutrinos of the order of 20 GeV (compared to an average of 2 Gev at CERN). One possibility to get a better defined energy of the neutrino is to use instead of the horn focussed beam, a "classical" momentum selected pions and kaons beam. Thanks to the increase of the accelerator energy, experiments with a so-called monochromatic beam were possible.

The tools available for study of weak interaction with neutrino beam were then shared by the two main centers, CERN and NAL. NAL has the higher flux and electronics detector, CERN has the giant bubble chamber detector which allows to visualize the interaction vertex and to follow the secondaries. Worth also to mention that the bubble chamber community, thanks to precedent experiments, was built with physicists well aware of the weak interaction theory and of the neutrino beam. This community was also the first large collaboration in high energy particle physics with all sociological scheme of group meeting, conveners, memoranda and ...

IV. Discovery of neutral current.

In order to prove the existence of neutral current with neutrino interaction several channels had to be studied and show the same behaviour. As mentioned by Perkins in Chicago a very clean signal but with low cross section is the elastic scattering of neutrino electron on electron. Experimentally the signature is a single electron recoil aligned on the neutrino direction. Other more important channels are all reactions involving no charged lepton in the final product. The question here is the visibility of very low energy leptons.

IV.1. The purely leptonic interaction.

The search concerned here, is for single electron with an angle below 5º with the direction of the neutrino beam. In order to know the efficiency of the experimental process, pair e^+e^- were also recorded. The threshold of 300 MeV was requested. Only two events gamma materialization, were found.

Background analysis was possible with the study of standard elastic neutrino electron interaction which provided the spectrum of the electron. A neutral current candidate was found in February 1973 in an antineutrino beam. The main background in anti neutrino is from the contamination of neutrino producing electron, since the elastic anti neutrino interaction give birth to positron.

Flux of $1.8\ 10^{15}\ \nu/m^2$ (375000 pictures) and of $1.2\ 10^{15}\ \bar{\nu}/m^2$ (360000 pictures) were used. No event in ν and only one in $\bar{\nu}$ channels were seen. The expectation , following the Weinberg model, was between 0.6 and 6 events for neutrino and 0.4 to 8 events in anti neutrino. The background figures were 0.3 ± 0.2 for neutrino and 0.03 ± 0.02 for antineutrino.

Later with increase of data taking two more events were found. The three events proved without ambiguity the presence of leptonic neutral current.

IV.2. Neutral current in semi leptonic processes.

The reaction here is :

$$\nu_\mu + \text{Nucleon} \rightarrow \nu_\mu + \text{hadrons}$$

The large size of the chamber, the density (1.5 g/cm^3) of the freon, the short radiation length (11 cm) and interaction length (70 cm) permitted the unambiguous identification of the secondary particles in most cases by interactions, by stopping or decay. 83000 pictures in ν beam and 207000 in $\bar{\nu}$ beam were scanned. To be considered, events should originate in a restricted fiducial volume of 3 m^3 within a 7 m^3 visible volume.

Three categories of events are defined :

*NC all outgoing tracks are identified as hadrons, by interaction or by stopping with a range momentum criterion : 102 in ν and 63 in $\bar{\nu}$

*CC typical neutrino events with an identified μ leaving the chamber without interaction or stopping : 428 in ν and 148 in $\bar{\nu}$

*AS candidate for the reaction ν+N $\rightarrow$ μ+n+X
$\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad$ |
$\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad$ $\rightarrow$ neutron star

where both vertices are visible in the chamber : 15 in ν and 12 in $\bar{\nu}$.

A cutoff of 1 GeV on the hadronic part (totality of the event in NC, all tracks but the muons in CC), was applied. The background could come from several sources :

1- Neutral particles produced at the target. The comparison of rate of NC per incident proton in neutrino and antineutrino beam must be identical if the origin comes from protons on the target.

2- Neutral particles produced by pions or kaons. The same ratio must be one half, ratio of negative to positive particles.

3- K^o produced by neutrino. Neutrinos must also produce strange particles Λ^o.

4- Cosmic rays. No UP/DOWN asymmetry was observed, nor in position or in momentum.

5- Low energy muons escaping identification. This is not compatible with the extrapolation of the muons spectrum.

6- The only main remaining source of background is the neutron star coming from neutrino interaction in the surroundings of the visible volume.

To study such background we used several methods :

1- Study of the spatial distribution.

2- Topology of NC event compared to hadrons part of CC event (number of π^o in both cases).

3- Study by the Bartlett method of the mean free path of the neutral particle giving the star. This provides a length of the order of 2 meters, as for CC, and not 70 cm, as for neutral star in AS events.

4- If the neutrons are produced by neutrino in the vicinity of the visible volume, the neutron flux must be in equilibrium with the neutrino flux. So a simple method could be used to deduce the ratio of background neutron star coming from non visible neutrino interaction to the associated neutron star coming from visible interaction.

5- To be complete, a simulation of the flux of neutrons produced by neutrino interactions in the surrounding of the visible volume must be calculated. The data going into the Monte Carlo take into account the flux of charged particles produced at the target and follow them in the beam. The kinematical hypothesis for the neutron produced by neutrino in the shielding is checked by the associate event AS. The "rich man's" Monte Carlo including several effects like the cascade, and input from a special proton beam exposure in Gargamelle, would only be available in 1974.

Finally, the ratio : background to associate star is 0.8 ± 0.4 event.

Like in a puzzle, all those internal and external pieces of evidence built a complete representation, where, even if you don't have all the pieces in hand, you can easily see the image. Finally we found that the neutron flux could account for only 10 % of the NC events after correction and in a CERN seminar of July 19th 1973, P.Musset announced the result :

ν beam	$R = NC/CC = 0.217 \pm 0.026$
$\bar{\nu}$ beam	$\bar{R} = NC/CC = 0.43 \pm 0.12$

These two values are compatible with the value $0.3 < \sin^2\theta_w < 0.4$. After correction to account for the cut in energy on the hadronic part (1 GeV), the corresponding value for

$$\sin^2 \theta_W = 0.39 \pm 0.05.$$

IV.3. NAL-E1A.

The group from Harvard, Pennsylvania and Wisconsin led by Carlo Rubbia, Al Mann and Dave Cline built for *National Laboratory in Chicago* one of the two neutrino experiments. Priority, like everywhere, was to identify a possible signature of W boson by measuring the total cross section of neutrino. But the Laboratory was just starting the neutrino complex. The status was such that the first data taking were with a bare target.

This experiment was built in order to operate in the broad band beam with a sensitive target of 16 tanks of scintillating mineral oil (20 tons) followed by a μ spectrometer, built with optical spark chambers and iron toroids. The early design required a signal in the trigger counter and so could accept only muon events. But with the growing interest in neutral current both from theorist and from Gargamelle activity, the trigger was redesigned so that the detector would fire if either the hadron energy was above a threshold or a muon passed into the spectrometer. A signal above 6 GeV (for 300 GeV primary proton beam) in the calorimeter triggered the spark chambers . 1116 triggers were recorded at 300 GeV and 368 at 400 GeV. The beam was unfocused. The sensitive target covered 9 interaction lengths. A veto counter in front of the calorimeter, provided protection from neutron background. Events originating in tanks 7-12 and 50 cm away from the edges of the target, were selected for both 300 and 400 GeV protons runs. One "out-of-spill" trigger allowed for comparison with events of cosmic ray origin.

In such an experiment, the only correction is the μ detection which comes from angular measurement (muons missing the spectrometer in direction) and from low energy muons which do not go to the first identification chamber. The correction here is large (estimated by Monte Carlo) and depends on the neutrino energy. It suffered from the fact that the knowledge of the beam was only rudimentary at the beginning. The particle production would only be measured in early 1974. The number of events recorded was 93 with muon and 76 with no visible muon. The estimation of the purity of the sample was 50%.

The conclusion at this stage was an excess of muonless event coming from several possible origins : neutral current, contamination from ν_e, kinematic effects at the neutrino interaction and a new type of lepton.

In order to be less dependent on unknown quantities, a second run was performed with layout modification to improve the flux and the muon identification. The 300 GeV proton beam was steered on to an aluminium target included in a horn device and the detection was modified such:

a) to get an earlier μ identification, by adding 35 cm of iron in front of the spectrometer

b) to double the size of the original μ identifier counter system.

This new design needed a new evaluation of the muon identification as well as punchthrough correction. Those two corrections ε_μ and ε_p are function of the positions x,y,z of the vertex and of the energies E_μ and E_h. They can be evaluated from the data itself. The comparison of two different beams, one from a bare target and one with secondary hadrons focussed in such a manner as to get a beam enriched in neutrinos, would increase the redundancy of this search. In the fall of 1973, 535 trigger were recorded. The data were corrected for μ identification (of the order of .7-.9) and for hadron punchthrough (of the order of .1-.5). The corrected ratio R (NC/CC) is deduced from the measured number R_m by the formula :

$$R = \frac{[\varepsilon_\mu + \varepsilon_p - \varepsilon_\mu \varepsilon_\mu](1+R_m) - 1}{1-\varepsilon_p(1+R_m)}$$

Finally, $R = 0.20 \pm 0.05$.

This result cannot be compared directly to the CERN result because at high energy the separation between ν and $\bar{\nu}$ cannot be achieved. We talk here of enriched beam. It is worth underlining here the virtue of the original HPW set up which had been modified in only a few weeks in order to produce an experiment with more internal consistency. Later in early 1974, with several different beam conditions and after the target production measurement, R_ν and $R_{\bar{\nu}}$ will be separated. The agreement between Gargamelle and HPW was considered as fair.

IV.4 Search of neutral current elsewhere.

Gargamelle and Experiment IA were not the only place to look for the possible existence of neutral current. National Laboratory in Chicago supports two experiments, E21 from Caltech make several choice which preclude such discovery. The aim was to look for heavy lepton, the "other" model. The signature of such model is the identification of a wrong sign lepton. To reduce the background, experimenters choice to use the properties of a sign selected beam and, as the flux is low, to build a very heavy iron target . The signature would be on muon identification. Such choices obviously forbid to record any neutral current candidate.

Two other accelerators at Brookhaven and Argonne were conducting neutrino experiments. Brookhaven with spark chamber detector and a beam of the same energy range as CERN, looked specifically on the production of one pion. The low flux and the lack of details at the vertex did not allow any positive answer. The same happened in Argonne for reason of kinematical check. The first large 12ft bubble chamber took 800000 pictures in hydrogen and deuterium. Looking only for the one pion channel, experimenters found 13 events for 3 background estimates and did not conclude on the possible existence of neutral current.

V. Study of neutral current.

As soon as the neutral current existence shows up, experimenters modify their detector and their method in order to cross check and measure the rate in different type of channel with different environment. Like experiment 1A, they were able to do it quickly .

V.1 The Caltech experiment.

We have seen above that the choice of this team drive to the use of an heavy target layout followed by a muon magnetic spectrometer to identify the sign of the outgoing muon. They adapted their target scheme by measuring the energy deposit behind each of the seventy iron plates and trigger not only in the muon spectrometer but also with a threshold of the energy deposit.

The method to identify neutral current and also to measure their rate is very clean and powerful. Since 1974 such method has been used in every counters experiments as CDMS or Charm at CERN. The path, for the more penetrating particle, is recorded, in unit of iron plate. In normal event, the curve just reflects the spectrum of the incoming neutrino which is known, in a sign selected "monochromatic" beam. The presence of neutral current events will add the characteristic contribution of hadronic interaction hadron shower. The events recorded are classified in 3 categories. The first are events with a muon in the spectrometer where angle and momentum of the muon as well as energy deposit are recorded. The second are events with a large angle muons identified by range where only angle of the muons and energy are measured. The last category includes neutral current and large angle muons charged current where only energy is recorded.From the beam construction and analysis, this contains only a very small contribution coming from neutrino electron, cosmic ray or neutron event. The first two categories allow to extrapolate the contribution of charged current in the third.

The final results of Caltech with this very clean method give $R_{\nu} = 0.22$ and $R_{\bar{\nu}} = 0.33$ for neutrino energy below 6 GeV. The high statistic as well as the cleanliness of the method close the controversy on the neutral current existence.

V.2 Other exclusive channels.

With the information coming from other experiments several teams improved their analyses, and so, was able to contribute significantly by providing good data on specific channels.

V.2.1. Neutrino elastic scattering.

This channel is in principle easy to detect : a single recoil proton with the angular distribution measured in the charged current elastic event. But this channel is also the more sensitive to the low energy neutron background. The Brookhaven Columbia experiment (CIRB Collaboration) uses the time of flight between proton beam and event, to tag neutrino from neutron. The use of penetration curve "à la Caltech" allows to identify proton from pion. Finally 38 neutral current candidates and 77 charged currents allow W.Lee to present a ratio NC/CC of 0.23 ± 0.09.

V.2.2. One pion production by neutral current.

Bubble chamber experiments suffer from statistics but while is needed, are able to perform a kinematic analysis. It was the case for the CERN heavy liquid bubble chamber filled with propane, for the Argonne 12 ft bubble chamber, for the 7 ft Brookhaven bubble chamber, for the 15 ft in Fermilab and for BEBC.

A good example of a dedicated experiment comes from Argonne. We have seen above that the team was unable to give convincing evidence due to the neutron background. Then they study a dedicated channel $n+p \rightarrow pp\pi^-$, perfectly identified. This channel provides a measurement of the neutron background in the bubble chamber. Showing that the level of the contamination of their 13 events is of the order of two , then allowing a good signal for neutral current in one pion production channel.

Using the same analysis, A.Rousset reanalysed in 1974 the data recorded by the CERN teams in 1967 and showed that the propane data left room for discovery. But the neutron analyses were missing at this time.

V.3 The purely leptonic channel.

Two kinds of experimentation are possible with neutrino electron or neutrino muon.

V.3.1 Electron neutrino scattering.

The most natural way is to use the very high flux produced by nuclear reaction. F.Reines shows how it was difficult at the Savannah River reactor, where the recorded signal reactor off is 80% of the signal reactor on, underlining the background. Same conclusions come from experiments at Kurchatof Institut, in Russia.

A possibility to use enriched ν_e beam by the suppression of negative π and by tagging in time the event has been used at Los Alamos. But the interpretation of the measurement, due to the presence of V-A allowed channel, is more difficult than in the ν_μ elastic channel.

V.3.2 Muon neutrino scattering.

Since the few events recorded by Gargamelle in 1973-1974, several experiments have tried to measure this difficult channel. In the late 80's the CHARM-II experiments have recorded few thousand such events.

In 1976 the team of Padova and Aachen built an experiment with light aluminium plate and optical spark chamber. This produced 11 neutrino and 8 antineutrino candidates. Technical difficulties of the optic for a very large layout give difficulties in the interpretation of the result.

By far the cleanest experiment here is CHARM-II. Using low density glass target with streamer tube for direction measurement and scintillators for energy measurement, this team has developed a method similar to Caltech E21 for the semi leptonic channel. Here the sensible parameter is the produce of energy by angle, $E\theta$ of the identified outgoing electron as was the path range of the more penetrating particle in the Caltech case.

As we see for the Gargamelle experiment, the scattered electron is aligned with the neutrino beam. Neutral current must produce a peak at zero value of the parameter $E\theta^2$. Background from charged current are coming from contamination of the ν_μ beam by ν_e. Background also could come from neutral current with π^0 production.

Extrapolation of the $E\theta^2$ curve at zero value, produces the best identification and rate measurement of the purely leptonic neutral current. About twenty years later after the D.Perkins request at the Chicago conference, this experiment give a measurement of the Weinberg angle

$$\sin^2 \theta_{\nu e} = 0.237 \pm 0.007 \pm 0.007$$

This was the final point of the study of neutral current.

VI. Conclusions.

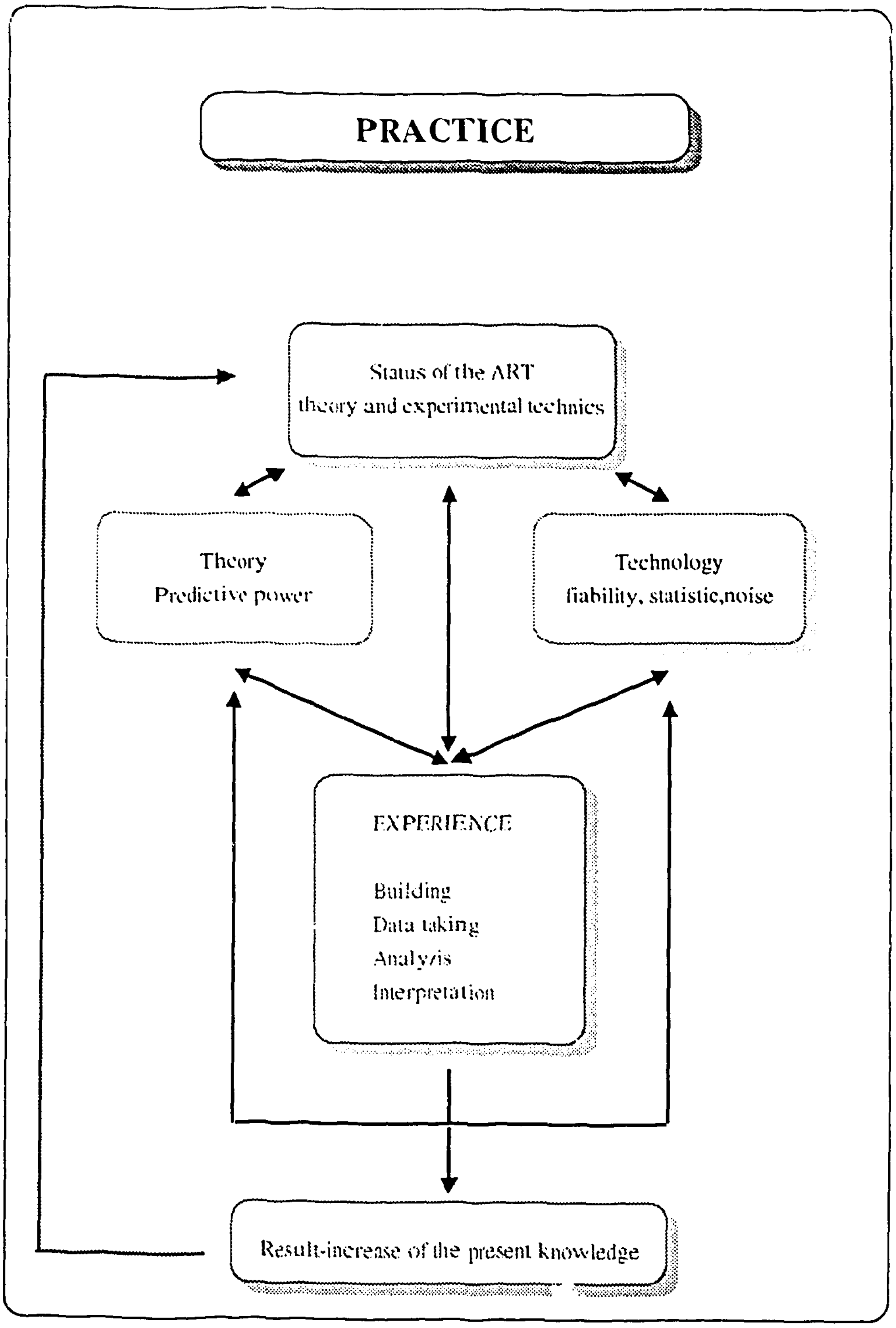
As a contribution to the history of Science, the " twenty year" neutral current chapter of the history of particle physics is very reach on several aspects.

We see that the first neutrino experiments were recording data with the muon signature: in order to know, what we have to look for, we need to have a comprehensive theoretical background on the physics we are working on.

The relationship between theoretical physicists and experimentalists was questionned by some Sciences's philosopher. This relationship must exist. This does not exclude the critical look on the performance of the detector and of the data. In the present work for the physic at LHC, the CERN management requests a physics group to interfere with the designer of detector. This does not forbid the experimentalists to build what they call general purpose detector.

The next lesson is that discovery does not only mean signal identification but also background analysis , cross check of the information , on the experimental aspect but also theoretical aspect. In the neutral current history, the possibility to check the neutron background and also to measure the rate in so many different channels as elastic, semi elastic, purely leptonic was a capital pieces in the process of building evidence.

Finally a very learning point was more sociological. More and more high energy particle physics calls for large collaboration. The Gargamelle experiment is the first large collaboration in modern physics. Announcing a discovery must first imply convincing evidence for the members of the collaboration. Each member has his own history and personal background . This is specially sensitive in what we calls an "evidence", for some of them more convincing is statistical analysis, for other it will be the presence of "golden platted" events. Clearly more active is the collaboration in an experiment, more solid must be the evidence, before to call for discovery.



This story of neutral current could be considered as a teach book for the present time as far as decision process, fine analysis and building a conclusion is concerned.

The final table summarize the practice of today where several loop must be accomplished between the status of our present knowledge to the next increase of this knowledge. No loop could be avoided between theory and experiment , between technics and experiment , and inside experiment himself. This is the way to progress.

VII. Bibliography.

0. Early status

- Neutrino Interactions

    Proceeding of the XVI International conference on High Energy Physics

    Chicago Batavia Vol 4 -208 . D.H. Perkins

1. Discovery

a- Search for elastic muon neutrino electron scattering.

    Phys. Lett. B46 (1973) 121-24. F.J.Hasert et al. - Sept. 1973.

b- Observation of neutrino like interaction without muon or electron in the Gargamelle neutrino experiment.

    Phys. Lett. B46 (1973) 138-40. F.J.Hasert et al. - Sept. 1973.

c- Observation of muonless neutrino induced inelastic interaction.

    Phys. Rev. Lett. 32 (1974) 800-805. A.Benvenutti et al. - 8 April 1974.

d- Further observation of muonless neutrino induced inelastic interaction.

    Phys. Rev. Lett. 1454-1457. B.Aubert et al. - 24 June 1974.

e- 1973. Discovery of neutral currents.

    Phys. Report 239 - B.Aubert - April 1994.

2. Neutral current studies

a- Semi leptonic decay

1) BC Barish et al. PRL 34 (1975) 538.

   BC Barish et al. NIM 130 (1975) 49.

2) M. Holder et al. PL 71B (1977) 222.

   M. Holder et al. PL 72B (1977) 254.

b) Pur leptonic decay

P.Vilain et al. PL 281B (1992) 247.

3. General references.

1) P.Galison. How Experiments End.

The University of Chicago Press contain an historical account on both Gargamelle and HPW experiment with an overview comparison of style and method in the two group of physicists.

2) A.Rousset. Gargamelle et la découverte des courants neutres [in French].

1994 - to be published.

3) Proceeding of the Conference : Neutral Currents twenty years later.

Paris 1993 - Edited by U.Nguyen Khac and A.M.Lutz. World Scientific.