THE N-\bar{N} OSCILLATION EXPERIMENT AT THE TRIGA MARK II REACTOR OF THE UNIVERSITY OF PAVIA

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(Presented by A. Piazzoli)

- Abstracts -

The detection of the proton decay and of the neutron-antineutron (n\bar{n}) oscillations are the two crucial experiments to check the validity of the Grand Unified Theories.

An experiment on the n\bar{n} oscillations to be performed at the Triga Mark II Reactor at the LENA Laboratory of the University of Pavia is presented.

A neutron beam extracted from the Reactor hits a thin target through a vacuum pipe shielded to strongly reduce the earth magnetic field. The detector of the charged and neutral pions produced in the annihilation reactions of the antineutrons, arising in the neutron beam, consists of four quadrants of fine grain calorimeters capable to provide the reconstruction of the annihilation point and an estimate of the momentum-energy balance of the reaction.

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For an exposure of $10^7$ s (≈100 days) the experiment can
provide an estimated "sensitivity time" $\tau_{_{\text{SN}}} = 5.10^7 s$. More
technical problems related to the use of the Reactor facility
in the experiment will be presented by Prof. M. Terrani in
his talk.

1 - Theoretical introduction and motivations of the experiment

The great goal of the present particle physics is a uni­
fied theory of the four fundamental interactions. A partial
success was obtained in the past decade with the Weinberg–
Salam electroweak theory (WST) on the basis of the group
SU(2)xU(1).

In order to unify the strong interactions also, one can
add the color group SU^C(3) representing the quark–gluon inte­
raction and look for the smallest group of which SU^C(3)xSU(2)_L
xU(1) is the maximal subgroup. This approach leads to the mini­
mal SU(5) grand unified group (mGUT). In mGUT the violation
of barionic (B) and leptonic (L) number conservation, that is
transitions with $\Delta(B-L) = 0$ are expected, in particular proton
decays as $P \rightarrow e^+\pi^0$. The expected value for the unification mass
is $\geq 10^{14}$ GeV and leads to a proton lifetime $\geq 10^{30}$ y.

Another possible elegant approach is to start with a left–
right symmetric electroweak group SU(2)_LxSU(2)_R xU(1) and get

$$SU(2)_L x SU(2)_R x U(1)_{B-L} x SU^C(3) = SU(2)_L x SU(2)_R x SU^C(4)$$

where B-L is the fourth color in the simple group SU^C(4).
This is the Partial Unified Theory (PUT) and leads to the
basic equation

$$\Delta I_{3R} = - \frac{\Delta(B-L)}{2}$$
where $I_{3R}$ is the thirh component of the right electroweak isospin.

If the spontaneous symmetry breaking is achieved via fermion condensates, one gets $\Delta I_{3R} = 1$ and this gives the following selection rules:

$$\Delta B = 0, \, \Delta L = 2 : \nu \bar{\nu} \, \text{transitions}$$

$$\Delta B = 2, \, \Delta L = 0 : n \bar{n} \, \text{transitions}$$

(and no proton decay)

Only Extended Unified Theories (EUT), for example $SO(10)$, can provide both $n\bar{n}$ transitions and proton decay. The most plausible value of partial unification mass is $10^5 \div 10^6$ GeV falling into the great desert between WST mass ($\sim 10^2$ GeV) and GUT mass ($\sim 10^{14}$ GeV) giving a transition time

$$\tau_{n\bar{n}} \sim 10^6 \div 10^7 \, \text{sec.}$$

2 - Phenomenology of the $n\bar{n}$ transitions

If the $\Delta B = 2$ $n\bar{n}$ transitions are possible, two new eigenstates $|n_1>, |n_2>$ must be introduced, in analogy with $\Delta s = 2$ $k_\circ \bar{k}_\circ$ transitions:

$$|n_1> = \frac{|n> + |\bar{n}>}{\sqrt{2}}$$

$$|n_2> = \frac{|n> - |\bar{n}>}{\sqrt{2}}$$

For IDEAL FREE (NON-INTERACTING) NEUTRONS, the CP invariant mass matrix is

$$E_\circ \quad \Delta m$$

$$\Delta m \quad E_\circ$$

where:

5-3
$E_0$ is the $n$ and $\bar{n}$ mass

$m_{1,2} = E_0 \pm \Delta m$

A pure neutron beam is described by the state $|n\rangle$ given by

$$|n\rangle = \frac{|n_1\rangle + |n_2\rangle}{\sqrt{2}}$$

On account of the terms $e^{-iE_1t}$ and $e^{-iE_2t}$ hidden in $|n_1\rangle$ and $|n_2\rangle$, the $nn$ transitions give up an "$nn$ oscillation" with a transition time given by

$$\tau_{nn} = \frac{1}{\Delta m}$$

Numerical example

$$\tau_{nn} \approx 5 \times 10^6 \text{ sec if } \Delta m < 10^{-22} \text{ ev}$$

For REAL INTERACTING NEUTRONS, the mass matrix is

$$\begin{pmatrix} E_0 + \Delta E & \Delta m \\ \Delta m & E_0 - \Delta E \end{pmatrix}$$

and the new eigenstates $|n'_1\rangle$, $|n'_2\rangle$ are:

$$|n'_1\rangle = \cos \theta |n\rangle + \sin \theta |\bar{n}\rangle$$

$$|n'_2\rangle = \sin \theta |n\rangle - \cos \theta |\bar{n}\rangle$$

with $\tan \theta = \frac{\Delta m}{\Delta E + \sqrt{\Delta E^2 + \Delta m^2}}$ and $m'_{1,2} = E_0 \pm \sqrt{\Delta E^2 + \Delta m^2}$

The probability of finding $\bar{n}$ in a FREE NEUTRON beam during an observation time $t$ is

$$P(\bar{n}, t) \sim \left( \frac{t}{\tau_{nn}} \right)^2 \text{ if } \Delta m t << 1$$

The same probability for INTERACTING NEUTRONS goes to zero as

$$5 - 4$$
\[(\Delta m/\Delta E)^2\] and one gets (for \(\Delta m = 10^{-22}\) eV):

\[P_{\text{max}} \sim 10^{-58}\] for Nuclear Potential \((\Delta E \sim 10\) MeV)\n
\[P_{\text{max}} \sim 10^{-20}\] for Earth Magnetic Field \((\Delta E \sim 10^{-12}\) eV)\n
It follows:
- the detection of \(\Delta B = 2\) transitions in nuclei is unreliable
- the earth magnetic field must be strongly reduced if one wishes to get quasi free neutron condition

\[P_B(n,t) = \alpha_B \left(\frac{t}{nn}\right)^2\]

where \(\alpha_B\) is a reduction factor due to the magnetic field.

3 - NADIR experiment

The general idea of the Pavia-Rome experiment (NADIR) is very simple.

A neutron beam is extracted from the Reactor Triga Mark II of the LENA Laboratory of Pavia. The beam reaches a target where the antineutrons, produced during the flight of the neutrons, annihilate with protons or neutrons inside the target through the reactions:

\[\bar{n} + p \rightarrow n^{+} \pi^{+} + m_{-}\pi^{-} + m_{0}\pi^{0}\]

\[\bar{n} + n \rightarrow m\pi^{+} + m\pi^{-} + m_{0}\pi^{0}\]

\(m_{+} - m_{-} = 1\)

The mean expected pion multiplicity is \(\sim 5\). The cross section of these reactions is very high \((\sigma \sim 3000\) A\(^{2/3}\) barn) and then the annihilation probability is \(\sim 1\) in any reliable target.

A large fine grain detector, surrounding the target, reveals the pattern of charged and neutrals pions allowing the reconstruction of annihilation point. An estimate of pion
energies will allow a rough energy-momentum balance.

The signature of the true events is very good, owing to the release of ~2 GeV against the very low energy of the neutrons. On the other hand the experimental constraints in order to obtain a good sensitivity (maximum detectable value for $\tau_{nn}$) are rather strong:
- high intensity and low energy for the neutron beam
- long free neutron path between source and target
- neutron beam must be inside a vacuum pipe with a strongly weakened earth magnetic field
- low background in the detector, either from the neutron channel or produced in the target itself
- low cosmic background simulating annihilation events

The experimental layout is sketched in Fig. 1 and the "NADIR numbers" are the following:

"NADIR NUMBERS"

**Neutron beam**
- cross sectional area : \(\sim 1 \text{ m}^2\)
- length (Reactor core-target) : 23 m
- energy distribution : Maxw. with \(T_0 = 300 \text{ K}\)
  \[V_0 = 2,200 \text{ m/s}\]
- mean time of flight : \(7.3 \times 10^{-3} \text{ s}\)
- intensity on the target : \(3 \times 10^{11} \text{ n/s}\)

**Pipe**
- material : anticorodal 12 mm thick
- size : diameter 1.15 m in the first 16 meters and 2 m around the target
- vacuum : \(10^{-4} \text{ mm Hg}\)
- shielding factor : \(\sim 100\) (\(B_{\text{in}} = 4.1 \pm 1.5 \text{ mG}\))
- \(a_B = P_B(\vec{n},t)/P(\vec{n},t) = 0.98 \pm 0.92\) (Fig. 2)

Magnetic shield : compensating coils + \(\mu\) metal strips
Target: disk with 1.2 m diameter and 5 interaction length thick

Background: $10^5$ to $10^6$ Hz per scintillator unit

Detector: - four 3m x 3m quadrants around the target and outside the neutron beam
- fine grain calorimeters containing: plastic scintillators, FC's, RPC's, metal layers

Observation time: $\Delta t = 10^7$ s (~100 days)

Sensitivity time: $\tau_{nn} = 5 \times 10^7$ s

4 - The detector

A cross-section view of the detector is sketched in Fig. 3. It consists of four quadrants placed as shown in figure. Each quadrant is a fine grain calorimeter containing:

- Scintillator plates
- Flash Chambers (F.C.) of plastic material (extruded polypropylene)
- Resistive Plates Counters (RPC)
- Metal plates (Pb and Fe)

Each scintillator unit has an area 270x27 cm, is 4 cm thick and is viewed by two P.M.'s.

Each F.C. is made of four 3x3 m$^2$ plastic sheets, has a tubular cells structure with 4x4 mm$^2$ cross-sectional area and is filled with a He-Ne gas mixture. Plane electrodes sensitize FC with triggered HV pulses and the cells traverses by charged particles provide electrical signals through capacitive pickup strips.

RPC's are fast, d.c. operated, parallel plates counter, filled with a Ar-Butane-Freon gas mixture.

The electrodes are made of high resistivity material in order to prevent the development into a spark of the avalanche due to particle traversals.
The electrical signals are provided by inductive pick-up aluminium strips.
The build-up of each quadrant, sketched in Fig. 4, shows five different regions:

I - Charged Track Definer, containing FC's
II - Trigger Element, containing Pb, scintillators, FC's, and RPC's
III - Gross Calorimeter, containing Pb and FC's
IV - Range Calorimeter, containing Fe and FC's
V - Veto System, against cosmic background, containing RPC only

5 - Trigger Logic

Several possible trigger logics were analyzed by means of a M.C. calculation simulating \( \bar{n}n \) and \( \bar{n}p \) annihilation events:
- 2-track, 3-layer
- 2-track, 4-layer
- 3-track, 3-layer
- 3-track, 4-layer

If we want the spurious trigger rate lower than \( 10^{-1} \) Hz, we must use the 3-track logic. The 3-layer logic will be possible only if the \( \gamma \)-background will be lower than \( 10^5 \) Hz per scintillator unit and the efficiency for true events will be about .45. Otherwise, we shall be forced to use the 4-layer logic with an efficiency about .3.

6 - Other \( nn \) Experiments

The comparison of our experiment with other on the same subject is shown in Table 1.
### TABLE I - Status of n⁻ oscillations experiments - September 1982

<table>
<thead>
<tr>
<th>Collaboration</th>
<th>Facility</th>
<th>Neutrons</th>
<th>Flight time (path)</th>
<th>Target current</th>
<th>Detector</th>
<th>Claimed sensitivity</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>CERN/Ill/Padua/ Ruth/Sussex</td>
<td>Ill 53 MW</td>
<td>Cold</td>
<td>30 ms (4.5 m)</td>
<td>$10^9$ n/s</td>
<td>Energy calorimeter</td>
<td>$4 \times 10^6$ s</td>
<td>D.T.</td>
</tr>
<tr>
<td>Harvard/Oak Ridge/Tennessee</td>
<td>ORNL 30 MW</td>
<td>Thermal</td>
<td>9 ms (20 m)</td>
<td>$2 \times 10^{13}$ n/s</td>
<td>Lead glass-lead scintillator (energy+multiplicity)</td>
<td>$10^8$ s</td>
<td>Prop.</td>
</tr>
<tr>
<td>Los Alamos</td>
<td>LASL 8 MW</td>
<td>Thermal</td>
<td>5 ms (10 m)</td>
<td>$10^{12}$ n/s</td>
<td>Lead-scintillator calorimeter (rough event reconstruction)</td>
<td>$10^7$ s</td>
<td>Prop.</td>
</tr>
<tr>
<td>Los Alamos/Texas/William &amp; Mary</td>
<td>LAMPF Pulsed</td>
<td>Beam dump</td>
<td>18 ms (35 m)</td>
<td>$3 \times 10^{12}$ n/s</td>
<td>Wire chamber scintillator (event reconstruction)</td>
<td>$6 \times 10^7$ s</td>
<td>Prop.</td>
</tr>
<tr>
<td>Pavia/Rome</td>
<td>LENA 1/4</td>
<td>Thermal</td>
<td>9 ms (20 m)</td>
<td>$3 \times 10^{11}$ n/s</td>
<td>Flash chamber scintillator resistive plane (event reconstruction)</td>
<td>$5 \times 10^7$ s</td>
<td>Constr.</td>
</tr>
</tbody>
</table>
Figure Captions

Fig. 1 - A general layout of NADIR experiment

Fig. 2 - $\alpha_B$ (magnetic attenuation factor) vs Bxl

Fig. 3 - A cross-section view of the detection apparatus

Fig. 4 - The array of each quadrant of the detector
Fig. 2
Fig. 3
Fig. 4

Q.5 cm thick Pb plates
3.5 cm thick Fe plates