EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN/EP 84-104
17 August 1984

MASSIVE NEUTRINOS IN ACCELERATOR EXPERIMENTS

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Xth International Conference - Particles and Nuclei (PANIC 84)
30 July - 3 August 1984, Heidelberg, Germany

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EP/2118P/FV/ed

When Pauli invented the neutrino he gave it a mass, small compared to the one of the electron. After the discovery of maximum parity violation in weak interactions a zero mass was assumed for simplicity and lack of contrary evidence. Today theories trying to unify electroweak and strong interactions prefer massive neutrinos, even if predictions vary over large ranges. A mass strictly equal to zero is difficult to understand, and this legitimates the searches which actively look for an effect of mass. Today, we know three neutrinos, even if the ν_τ has never been seen, and limits exist on their masses which are the following:

$$m(\nu_e) \leq 35 \text{ eV}$$

$$m(\nu_\mu) \leq 500 \text{ keV}$$

$$m(\nu_\tau) \leq 160 \text{ MeV}$$

The first limit comes from an ITEP experiment [1] which in fact claims a non-zero mass of 30 eV for $m(\nu_e)$. The experiment is extremely difficult and a confirmation is eagerly awaited. The limit on $m(\nu_\mu)$ comes from an extremely precise measurement [2] of the decay $\pi \rightarrow \mu\nu$. Although extracted with a lot of effort the limit is still at the level of the electron mass. Finally, the latest limit on $m(\nu_\tau)$ [3] obtained in τ decays is larger than the π mass and leaves plenty of room for searches of rather heavy neutrinos. Possible effects of heavy neutrinos are numerous, and I will only summarize the situation obtained in experiments done at accelerators, even if, for completeness some results coming from lower energies will be mentioned. The topics not covered include tritium decays and electron captures, both processes trying to improve on $m(\nu_e)$ and double β decays with no emission of neutrinos, which should be a proof of a non-zero mass.

Actually the most exciting consequences of massive neutrinos may concern astrophysics, but this would be the subject of a completely different presentation.

1. WHAT ARE MASSIVE NEUTRINOS?

The three known neutrinos ν_e , ν_μ , ν_τ , which are produced in weak processes are not necessarily eigenstates of mass. The neutrinos with definite mass and consequently definite time evolution will be called ν_1 , ν_2 , ν_3 . The most general relationship between these two sets of neutrinos is

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

The matrix so defined resembles the Kobayashi-Maskawa matrix which links the strong interacting quarks with the weak interacting ones. In the case of quarks the matrix is not diagonal and we have no reason to expect the one among neutrinos to be diagonal. The weak neutrinos are then linear combinations of ν_i and every weak process has to be interpreted as an incoherent sum over independent channels.

For instance the tritium experiment should be analyzed as:

$${}^3\text{H} \rightarrow \sum {}^3\text{He}^+ + e^- + \bar{\nu}_i$$

The sum runs over all ν_i for which there is available phase-space, this means all ν_i of mass smaller than 18 keV. As a consequence the weak combination " ν_e " produced in ${}^3\text{H}$ decays is not necessarily identical to the " ν_e " coming from π or K decays where the kinematics allow ν_i of mass up to 400 MeV. The limits quoted before should then apply to the mass eigenstates. The mixing matrix being almost diagonal this means:

$$m(\nu_1) \leq 35 \text{ eV}$$

$$m(\nu_2) \leq 500 \text{ keV}$$

$$m(\nu_3) \leq 160 \text{ MeV}$$

2. PRODUCTION OF HEAVY NEUTRINOS

As a consequence of what has been said in any physical beam (ν_μ) there can be a component of a neutrino having a mass well above the limit applying to the dominant component, and if fourth and fifth generation neutrinos exist some contribution of ν_4 and ν_5 may already be present in existing beams. A heavy mass eigenstate ν_H will be present in a ν_μ beam at the level of $|U_{H\mu}|^2$. In fact an extra helicity factor [4] favours the production of ν_H when the mass is not negligible with respect to the phase space available at production.

Production of massive neutrinos via mixing is not the only way. There is also the possibility of direct production. For instance ν_τ which is a candidate for being heavy, is directly produced in τ decays and more practically by $F \rightarrow \tau \nu_\tau$. More generally heavy neutrinos can be pair produced: whilst $\pi^0 \rightarrow \nu\bar{\nu}$ is forbidden for massless neutrinos, it is possible for massive ones [5]. The branching ratio is of order 10^{-9} for neutrinos of mass 20-100 MeV. The same decay modes exist for $K^0_{\eta\eta'}$. Finally the Z^0 is a powerful source of ν_H since it gives equal contributions (some 1000 events per day at LEP) for the different channels $Z^0 \rightarrow \nu_H \bar{\nu}_H$ up to neutrino masses of ~ 40 GeV. As a conclusion massive neutrinos may exist at any neutrino source and the problem is to detect their presence. There are several ways to achieve this aim. We will discuss first the phenomenon of oscillations, then the search for neutrino decays, and we will finish with the technique of time-of-flight which can be envisaged in the future.

3. OSCILLATIONS OF NEUTRINOS

In a world with two kinds of neutrinos (ν_e and ν_μ), the mixing matrix reduces to a rotation matrix

$$\begin{aligned}\nu_e &= \nu_1 \cos\theta + \nu_2 \sin\theta \\ \nu_\mu &= -\nu_1 \sin\theta + \nu_2 \cos\theta\end{aligned}$$

If ν_μ is produced at time $t = 0$, because the wave functions associated to ν_1 and ν_2 propagate with different speeds the admixture of ν_1 and ν_2 will be different downstream of the point of birth: the beam is no longer purely ν_μ but contains a ν_e component, and the composition will vary with distance.

To have this phenomenon one has to fulfil two conditions: the different neutrinos must have different masses, at least one should be massive; then there must be a mixing between neutrino generations which implies a violation of lepton number. In a world with three neutrinos there is always a pair oscillating first, and the phenomenon starts with the oscillation between two neutrinos.

The probability of oscillations between two "weak" neutrinos ν and ν' is given by:

$$P = \sin^2 2\theta \sin^2 \pi \frac{R}{L}$$

R is the distance over which one measures the oscillation, and L is the oscillation length:

$$L = 2.5 \frac{E(\text{GeV})}{\Delta m^2(\text{eV}^2)} \text{ (km)}$$

where E is the energy of the beam and $\Delta m^2 = |m_1^2 - m_2^2|$ with m_1 and m_2 referring to the neutrino mass eigenstates.

The oscillation probability varies like $(R/E)^2$. The sensitivity of an experiment can be increased in augmenting the distance R or lowering the energy E .

There are two experimental ways to search for oscillations:

- (a) The disappearance method tries to detect a decrease in the flux of the original beam, faster than the geometrical decrease $1/R^2$. This is best achieved with two detectors in the beam line positioned at a close and a far distance from the source. This program has been undertaken by the CERN experiments [6] CDHS (1500 t of iron) and CHARM (300 t of marble) over a distance ~ 1 km for a ν_μ beam of energy ~ 1 GeV. The disappearance method is also used at reactors which are powerful sources of $\bar{\nu}_e$. Here experiments have been done with only one detector which can be moved to two different positions or the analysis has relied on calculated fluxes.
- (b) The appearance method searches a new kind of neutrino in a source of known composition. The limitation comes here from the contamination in the original beam. The Big European Bubble Chamber BEBC [7] measures the amount of ν_e in a ν_μ beam, again at a distance ~ 1 km and for an energy ~ 1 GeV.

Today all experiments, but one, claim negative results. This allows to set limits in the plot $\sin^2 2\theta$ vs. Δm^2 in the a priori three different channels existing among the three known neutrinos. The situation is summarized in fig. 1 and already the masses probed in oscillation searches reach below 1 eV for mixings not too small.

Fig. 1

But one experiment claims an indication of oscillations. It took data at the French Bugey reactor [8]. Comparing the fluxes at 13 and 18 m from the core, the experimenters see a decrease of 5% with an uncertainty of 2%. This allows them to retain the region shown in fig. 2 with a probable solution: $\sin^2 2\theta = 0.25$, $\Delta m^2 = 0.2 \text{ eV}^2$ applying to either $\nu_e \rightarrow \nu_\mu$ or $\nu_e \rightarrow \nu_\tau$. This sets the goal for future experiments looking in this field.

4. NEUTRINO DECAYS

Heavy neutrinos are likely to decay. But the scale of masses discussed here is different from the one concerning oscillations. Oscillation experiments probe very small neutrino masses 0 (1 eV) but mixings generally not very small 0 (1%). Decays offer a complementary search, where masses must be large but mixings can be very small [9].

Fig. 2

If the mass is greater than 1 MeV the decay channel $e^+e^- \nu_e$ is open, corresponding to the graph shown in fig. 3. The same type of diagram is responsible for μ decay. The evaluation of the lifetime is similar, except for a coupling strength U_{He} which measures the mixing between ν_H and ν_e . The partial lifetime is

$$\tau = 2.8 \cdot 10^4 \frac{1}{m_\nu^5} \frac{2}{|U_{He}|^2} \text{ (s)}$$

Fig. 3

If neutrinos with even heavier masses exist, other channels, leptonic but also hadronic, will open up. With increasing mass we find the modes: $\mu^- e^+ \nu_e$, $e^- \pi^+$, $\mu^- \mu^+ \nu_\mu$, $\mu^- \pi^+$... In fact the hadronic channels become predominant as soon as they are kinematically allowed.

For masses below 1 MeV radiative decays are possible with 1γ emission or better 2γ emission. But the decay probabilities are very small and this kind of search is more suited, up to now, to astrophysics endeavour.

How to search for neutrino decays? Because of Lorentz boost and to avoid neutrino interactions which will generate background a decay experiment is best done at low energy.

A dedicated experiment [10] is taking data in the PS beam at CERN at an energy ~ 1 GeV. The detector is composed of a decay volume followed by a fine grain calorimeter. In order to suppress interactions the decay volume consists of helium bags separated by planes of chambers. Fig. 4 shows a charged track through the 12 m of decay volume and showering in the calorimeter. It could be an electron produced by a ν_e in the shielding preceding the detector.

Results from older experiments exist in the search for neutrino decays. All limits are again expressed in terms of the mass and the mixing parameter U^2 between ν_H and the connected lepton. Fig. 5 gives the limits obtained so far in mixings with e or μ . In particular very good

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Fig. 4

Fig. 5

limits exist on mixings of ν_3 obtained by CHARM and BEBC [11] at high energy. Here the production of ν_τ is computed as originating from the production of F and subsequent decay into $\tau\nu_\tau$.

Fig. 5 also shows the results obtained from searches of massive neutrinos in leptonic π and K decay. This method is based on the fact that a heavy enough mass eigenstate will give, for example in the decay at rest $K \rightarrow \mu + \nu$ a monochromatic line in the μ momentum spectrum [12]. Results exist in this channel and also in $\pi \rightarrow \mu\nu$, $K \rightarrow e\nu$. The two methods, search for lines in lepton spectra and direct decay of neutrinos, set limits in the same mass range. The second method allows to probe smaller mixings because of the very large fluxes available in neutrino beams. Also the experiment is simpler since it is only necessary to detect a signal very characteristic, and high precisions are not required.

5. FUTURE PROJECTS

The subject of heavy neutrinos is not closed. Some indications of mass effects may already exist but we are still far from a clear picture. This explains the continued interest in this line of research.

New oscillation experiments are due to come, specially at Brookhaven and Lampf. To push the limits one needs to increase the statistics with a maximum sensitivity parameter distance/energy. This explains an experiment proposed at CERN in the high energy SPS beam [13]. The advantage of high energies is to be above the threshold for ν_τ interactions. This experiment then is optimized for the channel $\nu_\mu \rightarrow \nu_\tau$. But there is a price to pay namely the distance must be increased together with the energy. Fortunately the SPS beam points upward, it crosses the Jura mountain and reemerges 17 km farther away. This is shown on fig. 6(a). This proposal, to be presented soon, will improve by at least an order of magnitude the present limits in the channel $\nu_\mu \rightarrow \nu_\tau$, and in particular it will be able to probe parameters like the ones found in the Bugey experiment.

Along this line it is not difficult to go bolder: as shown in fig. 6(b) one can send from CERN a neutrino beam towards the Frejus or the GranSasso large proton lifetime detectors, respectively at 100 and 1000 km

distances [14]. One still improves on the limits and this kind of search could be envisaged in a more distant future.

Fig. 6

Concerning the search for decays, LEP will open the range of very heavy neutrinos having masses up to 40 GeV. Such neutrinos are likely to decay with rather short lifetimes and the LEP experiments should be able to set limits in U^2 down to 10^{-15} rather easily. This method will again give limits in the distribution mass vs mixing. A new method which gives an absolute limit, independent of any coupling, becomes feasible with the SPS oscillation experiment: time-of-flight over large distances. The present SPS extracted beam has a time structure of 0.5 ns every 5 ns. The flight time for 17 km is 50 μ s, with a 0.5 ns accuracy on the arrival time, neutrinos of mass larger than 50 MeV will give out-of-time events. The present limit on $m(\nu_\tau)$ is 160 MeV. The SPS experiment could expect about 10 ν_τ interactions, and so improve the limit by a factor 3.

The topic of massive neutrinos is fundamental to our knowledge of particle physics. Finding a non-zero mass would give the first hint of the physics existing beyond the Glashow-Weinberg-Salam electroweak theory

which had its climax with the discovery of W and Z bosons. Two indications exist: the ITEP tritium decay measurement, and the Bugey reactor oscillation result. It is of utmost importance to confirm these results and, if so, to study systematically all the experimental consequences resulting from the exciting possibility that neutrinos after all, have a non-zero mass.

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