Ref.TH.3708-CERN

THE FIRST MIRROR LEPTONS

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ABSTRACT

Recent analyses of tritium β decay can be interpreted as indicating the existence of a heavy electron neutrino N_E of mass about 100 eV. Assuming that the N_E is a mirror neutrino forming a doublet with a heavy mirror electron L_E , this paper studies the consequences for neutrino oscillations, double β decay, astrophysics, cosmology, low energy leptonic CC and NC reactions, beam dump experiments, and Z^0 and $W^\pm$ decay.

Ref.TH.3708-CERN
August 1983

1. TRITIUM β DECAY

In 1980 measurements at ITEP (Moscow) of the high energy part of the β -spectrum of tritium in the valine molecule were published ¹⁾. When the spectrum was analyzed under the assumption of only one species of electron-like neutrino, ν_e , the mass limits

$$14 \text{ eV} < m(\nu_e) < 46 \text{ eV} \quad (99\% \text{ C.L.})$$

were obtained.

In 1983, the results of new measurements at ITEP with an improved detector have been reported ²⁾. A single-neutrino analysis, similar to the previous one, gave

$$m(\nu_e) > 20 \text{ eV.} \quad (95\% \text{ C.L.})$$

If the neutrinos ν_e , ν_μ and ν_τ are massive, it would be natural to have them mix. In this spirit, numerous neutrino oscillation experiments have been carried out, with the result of no detected oscillations. Another possibility is that of right-handed massive neutrinos mixing with the ordinary left-handed ones. Many models with parity restored at high energy have such neutrinos: extensions of the standard model having massive, right-handed neutrinos, or models with a complete right-handed replica of the left-handed fermions (mirror fermions). A third possibility is a plain repetition of the first three lepton families (excited fermions).

Any such massive electron neutrino N_e with the same conserved leptonic number as the ν_e would cause ν_e - N_e oscillations, and would show up in a multitude of experiments involving ν_e . In particular, if it were allowed by kinematics, the presence of an N_e would be signalled by the shape of the β -spectrum of tritium ^{*)}.

With this idea in mind, I have reanalyzed ⁴⁾ the 1980 ITEP tritium β -spectrum to search for an N_e . Making use of the published data points ¹⁾ I first reproduced the ITEP single-neutrino fit, with the result

$$m(\nu_e) = 37 \text{ eV}$$

$$\chi^2 = 13.0 \text{ for 14 data points.}$$

^{*)} Some sample β -spectra with various assumptions on the neutrino species have been published by Mc Kellar ³⁾.

Subsequently I made a two-neutrino fit to the same data points, adding the constraint

$$R \equiv \frac{N_e \text{ intensity}}{\nu_e \text{ intensity}} = \tan^2 \phi_e < 0.035 \quad (68\% \text{ C.L.}) \quad (1)$$

from neutrino oscillation experiments (to be discussed below). This fit then has 3 free parameters and 12 degrees of freedom. The result was

$$\begin{aligned} m(\nu_e) &= 34 \pm 3 \text{ eV} \\ m(N_e) &= 102 \pm 20 \text{ eV} \\ R &= 0.031 \end{aligned} \quad (2)$$

$$\chi^2 = 9.2$$

Note that the spectrum end point is determined by the mass of the lightest neutrino, no matter how many neutrino species are present, whereas the shape of the spectrum is determined by all the neutrino species ³⁾. Thus the two-neutrino fit has made the ν_e lighter, but within errors it still agrees with the one-neutrino fit.

Of greater interest is the observation that the best fit wants an N_e of about 100 eV mass, and that this fit in terms of χ^2 is an improvement over the one-neutrino fit.

Preliminary two-neutrino analyses of the 1983 ITEP experiment ²⁾ confirm these results, both qualitatively and quantitatively.

An upper limit to the N_e mass has been obtained ⁵⁾ from a search for kinks in the β spectrum of tritium implanted in a Si X-ray detector. At a value of the mixing angle corresponding to the limit (1) one has

$$m(N_e) \lesssim 500 \text{ eV.} \quad (95\% \text{ C.L.})$$

The purpose of this paper is to further study the consequences of the existence of two electron-like neutrinos, the heavier one, N_e , having a mass of about 100 eV. To work within a specific model I assume that N_e is a dominantly right-handed mirror neutrino. Properties of models with mirror leptons have been discussed in detail elsewhere ^{6, 7, 8)}. In particular, the mirror neutrino must have a charged companion with which it forms an $SU(2)_W$ doublet.

2. NEUTRINO OSCILLATION

Consider a GUT with fermion and mirror fermion representations. In the weak $SU(2)_L \otimes U(1)$ subgroup one then has ⁶⁾ the following leptonic weak eigenstates:

$$\begin{pmatrix} \nu'_e \\ e' \end{pmatrix}_L, \begin{pmatrix} N'_e \\ L'_e \end{pmatrix}_R, \nu'_{eR}, e'_{eR}, N'_{eL}, L'_{eL}, \quad (3)$$

where $\ell = e, \mu, \tau$ is the family index, capital letters N, L stand for neutral and charged mirror leptons, respectively, and the subscripts L, R denote left- and right-handed components, respectively. Primes denote weak interaction eigenstates.

Fermions and mirror fermions of the same charge and family will mix, in spite of having opposite helicities, to form the mass eigenstates

$$\begin{aligned} \psi_\ell &\equiv \begin{pmatrix} \ell \\ L_\ell \end{pmatrix} = R(\theta_\ell) \begin{pmatrix} \ell' \\ L'_\ell \end{pmatrix}, \\ \psi_{\nu_\ell} &\equiv \begin{pmatrix} \nu_\ell \\ N_\ell \end{pmatrix} = R(\phi_\ell) \begin{pmatrix} \nu'_\ell \\ N'_\ell \end{pmatrix}, \end{aligned} \quad (4)$$

where R is the orthogonal mass mixing matrix

$$R(\alpha) = \begin{pmatrix} \cos \alpha & -\sin \alpha \\ \sin \alpha & \cos \alpha \end{pmatrix}, \quad \alpha = \theta_\ell, \phi_\ell. \quad (5)$$

The weak Lagrangian in the mass eigenstate basis can be written ⁶⁾

$$\mathcal{L}^{CC} = -\frac{g}{2\sqrt{2}} W_\alpha^\dagger \sum_\ell \left\{ \bar{\psi}_{\nu_\ell} \gamma^\alpha [R(\phi_\ell - \theta_\ell) - R(\phi_\ell + \theta_\ell) \gamma_5 \tau_3] \psi_\ell \right\} + h.c. \quad (6)$$

$$\begin{aligned} \mathcal{L}^{NC} = & -\frac{g}{4\cos\theta_w} Z_\alpha \sum_\ell \left\{ \bar{\psi}_{\nu_\ell} \gamma^\alpha [1 - R(2\phi_\ell) \gamma_5 \tau_3] \psi_{\nu_\ell} + \right. \\ & \left. + \bar{\psi}_\ell \gamma^\alpha [4\sin^2\theta_w - 1 + R(2\theta_\ell) \gamma_5 \tau_3] \psi_\ell \right\}, \end{aligned} \quad (7)$$

where W and Z are the standard model vector boson fields.

Restricting ourselves to the e-family, the Lagrangian depends on the electron-mirror electron mixing angle θ_e and the neutrino-mirror neutrino mixing angle ϕ_e .

Consider the case for which $\theta_e = 0$ (I shall motivate this choice in Sec. 4 with astrophysical arguments). In the tritium decay experiment the observed ν_e neutrinos are produced at the decay vertex with relative intensity $\cos^2 \phi_e$, and the N_e neutrinos with $\sin^2 \phi_e$.

Let us now turn to neutrino oscillation experiments of the type ν_e disappearance. A small loss of neutrino intensity at the production vertex, of the order of $\sin^2 \phi_e$, may go unnoticed because of uncertainties in the absolute intensity. However, the dominant ν_e component will oscillate into the inert N_e component along the path of flight, so that oscillation experiments are in fact sensitive to ϕ_e .

In the present case,

$$\Delta m^2 = m(N_e)^2 - m(\nu_e)^2 \approx 10^3 - 10^4 \text{ eV}^2, \quad (8)$$

so that the oscillations develop rapidly and one observes an effectively incoherent sum of ν_e and N_e , with averaged ν_e intensity ⁸⁾

$$\langle I(\nu_e) \rangle = 1 - \frac{1}{2} \sin^2 2\phi_e. \quad (9)$$

The most precise ν_e disappearance experiments are those of the reactors in Gösigen ⁹⁾ and at ILL Grenoble ¹⁰⁾, and an experiment ¹¹⁾ using accelerator neutrinos from K^+ decay. In the limit of large Δm^2 (larger than 5 eV^2) the reactor experiments give

$$\sin^2 2\phi_e \leq 0.17 \quad (90\% \text{ C.L.}). \quad (10)$$

From this one obtains

$$\phi_e \leq 12.3^\circ, \quad \tan^2 \phi_e \leq 0.0475. \quad (90\% \text{ C.L.}) \quad (11)$$

In Eq. (1) I already made use of this limit.

The accelerator experiment ¹¹⁾ also sees no oscillations, the average ν_e intensity being quoted as

$$\langle I(\nu_e) \rangle = 1.04 \pm 0.15. \quad (12)$$

From this one deduces the weaker bound

$$\phi_e < 14^\circ \quad (68\% \text{ C.L.}), \quad (13)$$

in agreement with Eqs. (11).

3. DOUBLE β DECAY

Neutrinoless double β decay can, in the standard picture, be generated by massive Majorana neutrinos. If one extends the standard model by V + A interactions, the Majorana neutrinos need not be massless¹²⁾. In certain models also Dirac neutrinos will do, and mirror neutrinos as well¹³⁾.

So far, no such decay has been observed. This puts a limit on the weighted average of neutrino masses. Assuming that only two species participate, one has

$$\langle m \rangle = m(\nu_e) \cos^2 \phi_e + m(N_e) \sin^2 \phi_e, \quad (14)$$

or

$$\langle m \rangle = |m(\nu_e) \cos^2 \phi_e - m(N_e) \sin^2 \phi_e|, \quad (15)$$

depending on the CP-eigenvalues of ν_e and N_e ^{14, 13)}. Taking $m(N_e) = 100$ eV, $\phi_e = 12.3^\circ$, and

$$\langle m \rangle < 7 \text{ eV} \quad (90\% \text{ C.L.}) \quad (16)$$

from the Mont Blanc laboratory measurements¹⁵⁾, one obtains

$$m(\nu_e) < 2.6 \text{ eV} \quad (90\% \text{ C.L.}) \quad (17)$$

from Eq. (14), and

$$m(\nu_e) < 12.1 \text{ eV} \quad (90\% \text{ C.L.}) \quad (18)$$

from Eq. (15).

Further limits on $m(\nu_e)$ from other types of experiments are much less restrictive. Let me note here that if the ν_e has a Majorana mass, an upper limit of 5.6 eV can be established¹⁵⁾.

4. ASTROPHYSICS AND COSMOLOGY

The N_e decays leptonically via

$$N_e \rightarrow \nu_e \bar{\nu}_e \nu_e, \quad (19)$$

and radiatively via

$$N_e \rightarrow \nu_e \gamma. \quad (20)$$

The leptonic decay rate can be estimated to an order of magnitude by scaling the muon decay rate. Thus one finds

$$\Gamma_{\text{lept}} \approx 10^{-24} \text{ s}^{-1} \quad (21)$$

The radiative decay rate has been estimated ⁷⁾ to be

$$\Gamma_{\text{rad}} \approx (10^{-9} - 10^{-10}) \sin^2 2\theta_e \text{ s}^{-1}, \quad (22)$$

where θ_e is the mixing angle defined in Eq. (4).

However, there exist severe astrophysical constraints on the lifetime of unstable neutrinos which can undergo radiative decay. These come from the observed cosmic photon spectrum and the 3°K background radiation. In particular, the limits on the photon flux from supernova explosions, applicable to any kind of neutrino of mass less than 10 MeV, is ¹⁷⁾

$$\Gamma_{\text{rad}} < 0.3 \cdot 10^{-23} \text{ s}^{-1}. \quad (23)$$

To meet this condition the mixing of the charged leptons e and L_e must be severely suppressed,

$$\sin 2\theta_e \lesssim \mathcal{O}(10^{-7}). \quad (24)$$

From a phenomenological point of view ϕ_e and θ_e are completely independent, so they can well be of quite different orders of magnitude. Whether this can be achieved naturally *) in a gauge theory with mirror fermions is, however, not yet known.

The reactions (19) and (20) may thus proceed at similar rates. If the ν_μ and ν_τ masses are lighter than 40 - 50 eV, the N_e will have corresponding leptonic decays into these channels.

*) I am indebted to A. de Rújula for raising this question.

From a cosmological point of view the N_e is then stable. Together with ν_e , ν_μ and ν_τ it then saturates the somewhat model-dependent cosmological bound of at most 4 stable neutrino species ^{17, 18)}.

What about the mirror muon neutrino N_μ , then? Much less can be said about its mass and lifetime, and thus it is not clear whether it would have to be counted as a fifth stable neutrino or whether it would decay rapidly enough not to challenge the cosmological models. Recent experiments ¹⁹⁾ seem to exclude the mass range

$$10 \text{ MeV} < m(N_\mu) < 1750 \text{ MeV}.$$

Various people have argued ²⁰⁾ that most of the energy of the universe may reside in galactic halos composed of slowly moving massive neutrinos. From standard big bang cosmology arguments one then concludes that these neutrinos must weigh at least 24 eV, perhaps 100 eV.

From the requirement that the neutrino energy density does not exceed the upper limit of the present universe, one deduces ²¹⁾ that the sum of the masses of light, non-degenerate stable neutrinos cannot exceed 400 eV.

5. Low energy CC and NC reactions.

In previous publications ^{6), 7)} the Helsinki group has explored the totality of low energy CC and NC reactions to limit the parameters characteristic of mirror leptons: the four mixing angles $\theta_e, \phi_e, \theta_\mu, \phi_\mu$ of Eq. (4) for the first two families. The variety of models considered then can now be reduced considerably by making use of the astrophysical constraint

$$\theta_e \approx 0$$

and the tritium spectrum information

$$m(N_e) \approx 100 \text{ eV} \ll m(e).$$

The remaining models were denoted "a incoherent" and "b incoherent", with the only difference:

- a) $m(N_\mu) < m(e)$, $\theta_\mu = 0$
- b) $m(N_\mu) > m(K)$.

As already explained in Sec. 2, the ν_e and N_e components appear incoherent in oscillation experiments because of the large N_e mass. In Model a, we fitted the parameters $\sin^2 \Theta_w$, ϕ_e, ϕ_μ , and in Model b, Θ_μ in addition, to the following data: the muon decay parameters, the electron longitudinal polarization in muon decay and in Gamow-Teller decays, the cross section for inverse muon "decay", the ratio of $e2$ to $\mu2$ pseudoscalar decays, neutrino scattering on electrons, the forward-backward asymmetry in $e^+e^- \rightarrow \mu^+\mu^-$, inclusive neutrino scattering on isoscalar target and on protons and neutrons, and charge asymmetry in polarized electron scattering on deuterium and in muon scattering on carbon.

The published results ⁷⁾ of these fits were (at 68% C.L.) :

$$\begin{aligned} \text{a) } & \phi_e < 27.5^\circ, \quad \phi_\mu < 16.3^\circ \\ \text{b) } & \phi_e < 36.3^\circ, \quad \phi_\mu < 12.9^\circ, \quad \Theta_\mu < 9.3^\circ, \end{aligned} \quad (25)$$

and for both models

$$\sin^2 \Theta_w = 0.239 \pm 0.011.$$

This value of $\sin^2 \Theta_w$ should not be considered as a world average, since we had to select only those constraints for which a formulation in terms of mirror leptons was possible. Also, it does not contain radiative corrections. Still, it is in good agreement with independent determinations.

Recent data (mainly improved forward-backward asymmetries from PETRA and PEP) do not change the Model a parameters, but they reduce all the Model b mixing angles by $4^\circ - 5^\circ$.

Thus, the ϕ_e limits in Eq. (25) are not very restrictive, and they do in fact allow the value in Eq. (11).

Let us note here that a limit on $m(N_e)$ can be quoted from π_{e2} decays at TRIUMF²²⁾. Since no

$$\pi \rightarrow e N_e$$

decays were seen, the mass range 4 - 135 MeV is excluded.

6. BEAM DUMP EXPERIMENTS

Beam dump experiments observing the disappearance of ν_e are in principle also oscillation experiments, but we group them separately for convenience. In the past, the observed ratio of $e^\pm / \mu^\pm$ in beam dump experiments has been contradictory, surprisingly small, however, in the majority of experiments. This situation has already been analyzed in the context of mirror models ⁸⁾.

Recently the experimental situation has changed. Now three experiments see an $e^\pm / \mu^\pm$ ratio consistent with universality, whereas one experiment stands in contradiction. Averaging the results from BEBC, CDHS and Fermilab E 613 ²³⁾, one obtains

$$e^\pm / \mu^\pm = 1.12 \pm 0.12.$$

Converting this to a lower limit,

$$e^\pm / \mu^\pm > 0.92 \quad (90\% \text{ C.L.}) \quad (26)$$

On the other hand, the $e^\pm / \mu^\pm$ ratio in the case of rapidly oscillating, incoherent ν_e and N_e beams is given by the expression (9), or

$$e^\pm / \mu^\pm = 1 - \frac{1}{2} \sin^2 2\phi_e > 0.915 \quad (90\% \text{ C.L.}), \quad (27)$$

using the limit (10) from reactor experiments.

Thus, (three out of four) beam dump experiments agree with the reactor neutrino oscillation experiments, as well as with the observed N_e fraction R , Eq. (1) in tritium β decay.

7. Z^0 AND $W^\pm$ DECAY

In Sec. 1, I assumed that the N_e belongs to an $SU(2)$ doublet, with a charged right-handed electron-like partner L_e . What do we know about this particle?

Its mass is at present limited to the range

$$20 \text{ GeV} \leq m(L_e) \leq 200 \text{ GeV}. \quad (28)$$

The lower limit comes from the combined PETRA experiments ²⁴⁾ on sequential leptons L produced in the reaction

$$e^+ e^- \rightarrow L^+ L^-.$$

The higher limit is based on considerations on one-loop corrections to the Higgs potential in the standard model, and on the stability of the vacuum ²⁵⁾. It is thus perfectly possible that the L_e is too heavy to be produced in Z^0 or $W^\pm$ decay. Let us, however, neglect that possibility for the moment.

The Z^0 may decay into mirror leptons as follows:

$$Z^0 \rightarrow N_e \bar{N}_e \quad (29)$$

$$Z^0 \rightarrow N_e \bar{\nu}_e, \bar{N}_e \nu_e \quad (30)$$

$$Z^0 \rightarrow L_e^+ L_e^- \quad (31)$$

$$Z^0 \rightarrow L_e^+ e^-, L_e^- e^+ \quad (32)$$

The effect of decay (29) will notably be to increase the Z^0 full width. The decays (30) are suppressed with a factor $\sin^2 2\phi_e = 0.2$ relative to (29) and will therefore hardly be detectable even when the Z^0 width is well measured.

The decay (31) may already have been seen. The mirror leptons decay leptonically

$$L_e^- \rightarrow N_e + (e^- \bar{\nu}_e, \mu^- \bar{\nu}_\mu, \tau^- \bar{\nu}_\tau, q\bar{q}) \quad (33)$$

so that an observation of

$$Z^0 \rightarrow e^+ e^- \quad (34)$$

with very unequal electrons or missing energy may be such a decay. Thus, candidates for the reaction

$$Z^0 \rightarrow l^+ l^- \gamma \quad (l = e, \mu) \quad (35)$$

with missing energy interpreted as a radiative decay, may also be candidates for the decay (31). Note that the lepton pairs $e^+ e^-$, $\mu^+ \mu^-$, $e^+ \mu^-$ and $e^- \mu^+$ are equally likely, whereas the neutral current decay

$$L_e^- \rightarrow e^- + (l^+ l^-, \nu \bar{\nu}, q\bar{q}) \quad (36)$$

is forbidden due to the condition (24).

The decays (32) are also forbidden due to the smallness of the $L_e - e$ mixing angle θ_e .

The W^- -bosons decay into mirror leptons as follows:

$$W^- \longrightarrow L_e^- N_e \quad (37)$$

$$W^- \longrightarrow L_e^- \bar{\nu}_e, \quad e^- N_e. \quad (38)$$

In the decay (37) the mirror leptons L_e^- manifest themselves just as any new heavy leptons would. Only an analysis of the Lorentz structure of the coupling would reveal their right-handedness.

The non-diagonal decays (38) will be suppressed by a factor $\tan^2 \phi_e \approx \approx 0.05$ with respect to the decays (37). Since N_e is so light, there will be no observable shift in the Jacobian peak in P_T .

If the branching ratio of $W^\pm$ into mirror leptons is important, this channel should be signalled by an increased $W^\pm$ width and a corresponding decrease in the peak cross section. Since the coupling of the mirror leptons to the W is well known, the only unknown affecting the branching ratios is in the kinematics. Thus, failure to detect the necessary broadening in $W^\pm$ merely sets limits on the $L_e^\pm$ mass

8. CONCLUSIONS

On the basis of an analysis ⁴⁾ of the first ITEP measurement of the tritium β spectrum ¹⁾, recently confirmed by the second ITEP experiment ²⁾, I conclude that the existence of an electron-like heavy neutrino N_e is plausible. Its mass would be ≈ 100 eV, the $\bar{\nu}_e$ mass would be of the order of 10 eV or less, and their mixing angle of the order of 12° . I propose that N_e be interpreted as a mirror neutrino ^{6, 7)}, forming an $SU(2)$ doublet together with a heavy, right-handed electron L_e .

The lifetime of the N_e must be of the order of 10^{24} s. The properties of the N_e are compared with various constraints from astrophysics, cosmology, neutrinoless double β decay, low-energy charged and neutral current reactions, searches for heavy neutrinos in neutrino beams, reactor neutrino oscillation experiments and beam dump experiments.

I discuss the signatures of Z^0 and $W^\pm$ decays into mirror leptons, and I suggest that such decays may already have been seen.

I have profited from useful discussions with and criticism by M. Chaichian, Helsinki, A. De Rújula, CERN and K. Mursula, Helsinki.

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