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ABSTRACT

We discuss the value, in the light of recent "two neutrino" experiments, of giving meaning to the neutrino charge or lepton number independent of helicity; i.e., of giving up two-component neutrino theory and reverting to a single four-component neutrino whose left- and right-helicity states are coupled to e^- and μ^+, respectively. It is shown that, in fact, only by such experiments, involving muons and electrons or their neutrinos, can a non-trivial meaning be given to lepton conservation. This Dirac neutrino theory is compared with the conventional theory of two two-component neutrinos from the conceptual and experimental points of view. Some remarks are made about the possibility of explaining the μ-e mass difference.

TWO NEUTRINOS OR ONE?*

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I. INTRODUCTION

Polarization measurements show that in the Fermi interactions

$$n \to p + e^- + \overline{\nu}, \qquad (1a)$$

$$\mu^- + p \to \nu' + n, \qquad (1b)$$

and

$$\mu^- \to \nu' + e^- + \overline{\nu}, \qquad (1c)$$

the particles p, n, μ^-, and e^- are preferentially produced left handed in association with $\overline{\nu}$ or $\overline{\nu}'$, which are always right handed. Along with measurements of nuclear recoil, the μ-decay spectrum, and the $\pi_{e2}/\pi_{\mu2}$ ratio, these experiments favor, for the basic Fermi interaction,

$$H_{weak} = G(J^{\alpha} j_{\alpha} + J^{\alpha} j'_{\alpha} + j^{\alpha} j'_{\alpha}) + \text{h.c.} \qquad (2)$$

$$= H_a + H_b + H_c ,$$

where

$j_{\alpha} = i\overline{e}\,\gamma_{\alpha}^{+}\nu$, $j'_{\alpha} = i\overline{\mu}\,\gamma_{\alpha}^{+}\nu'$, $\gamma_{\alpha}^{+} = \frac{1}{2}(1 + \gamma_5)$, and where J_{α} is a strangeness-preserving current having the quantum numbers of $\overline{P}\gamma_{\alpha}^{+}N$. (The field operators for negative muons and electrons are denoted by μ and e.) The field charge conjugate to ν is denoted by $\nu^c = C^{-1}\overline{\nu}^T$, where $C\,\gamma_{\mu}\,C^{-1} = -\gamma_{\mu}^T$; its particle is conventionally denoted by $\overline{\nu}$.)

A. Neutrino-Chirality Conservation

That e^- and μ^- transmute into left-handed neutrinos is expressed by the conservation of neutrino chirality[2]

$$S = \int i\,(\bar{e}\,\gamma_\alpha\, e + \bar{\mu}\,\gamma_\alpha\,\mu + \bar{\nu}\,\gamma_\alpha^+\,\nu + \bar{\nu}'\,\gamma_\alpha^+\,\nu')\,d\sigma^\alpha\,, \qquad (3)$$

where $S = +1$ for e^-, μ^-, ν_L, and ν'_L; and where $S = -1$ for e^+, μ^+, $\bar{\nu}_L$, and $\bar{\nu}'_L$. The S-conservation is exact if $m_\nu = m_{\nu'} = 0$. (If S is extended to include n and p and is modified by the replacement $\gamma_\alpha \rightarrow \gamma_\alpha^+$ everywhere, then

$$\begin{aligned} S' = \int i\,(\bar{N}\,\gamma_\alpha^+\,N + \bar{P}\,\gamma_\alpha^+\,P + \bar{e}\,\gamma_\alpha^+\,e + \bar{\mu}\,\gamma_\alpha^+\,\mu \\ + \bar{\nu}\,\gamma_\alpha^+\,\nu + \bar{\nu}'\,\gamma_\alpha^+\,\nu'). \end{aligned} \qquad (4)$$

The V-A form of interactions (1) can then be derived by requiring the invariance of H_{weak} under S' transformations. The chirality S' is, of course, only partially conserved because of the mass terms and strong interactions.)

In the two-component neutrino formulation,[3] neutrino chirality is identified with neutrino lepton number: ν (and ν') is assumed to be a Weyl or Majorana field specified completely by its momentum and helicity, and the neutrino lepton number is <u>defined</u> to be the negative of its helicity. In this paper, we discuss the value of giving meaning to the neutrino charge or lepton number independent of its helicity, in other words, of giving up the two-component neutrino formulation.

B. Muon-Number Conservation

Recent experiments show that the neutrinos ν' produced in

$$\pi^+ \rightarrow \mu^+ + \nu' \qquad (1b')$$

reproduce muons by inverse μ capture but are incapable of producing electrons by inverse electron capture.[1] The transmutation $\mu^- \rightarrow e^-$ is also apparently forbidden.[4] We have accordingly written the μ decay interaction H_c with two different neutrinos, hypothesizing that there are only two kinds of neutrinos and that in μ decay they are each coupled to μ and e as in β^- and π^- decay.

This second conservation law, the conservation of muon number

$$L = \int i(\bar{e}\,\gamma_\alpha e - \bar{\mu}\,\gamma_\alpha \mu + \bar{\nu}\,\gamma_\alpha^+ \nu - \bar{\nu}'\,\gamma_\alpha^+ \nu')\, d\sigma^\alpha , \tag{5}$$

where $L = +1$ for e^-, ν, $\bar{\nu}'$ and μ^+, and where $L = -1$ for e^+, $\bar{\nu}$, ν', and μ^-, is independent of the conservation of neutrino chirality S, and the occurrence of this second neutrino ν' is unexplained in the two-component neutrino or V-A theories. In this paper, we will discuss the identification of lepton number with muon number so as to make (for neutral as for charged leptons) lepton number independent of helicity, and to give meaning to the suppressed neutrino-charge degree of freedom.

II. CONVENTIONAL TESTS OF LEPTON CONSERVATION

In a theory conserving neutrino chirality (i.e., knowing that $\overline{\nu}$ and $\overline{\nu}'$ in reactions (1a) and (1b) are definitely right-handed, and that ν and ν' are left-handed), how <u>could</u> the neutrino-charge degree of freedom reveal itself? So long as $m_\nu = m_{\nu'} = 0$, the three interaction Hamiltonian terms in Eq. (2) are each transformed into an equivalent (physically indistinguishable) interaction Hamiltonian by each of the independent Pauli transformations[5]

$$\begin{aligned} \nu_L &\to \tilde{\nu}_L = \alpha \nu_L + \beta \nu^c_L , \\ \nu^c_L &\to \tilde{\nu}^c_L = -\beta^* \nu_L + \alpha^* \nu^c_L , \end{aligned} \tag{6}$$

$$\begin{aligned} \nu'_L &\to \tilde{\nu}'_L = \alpha' \nu'_L + \beta' \nu'^c_L , \\ \text{and} \quad \nu'^c_L &\to \nu'^c_L = -\beta'^* \nu'_L + \alpha'^* \nu'^c_L , \end{aligned} \tag{7}$$

where $|\alpha|^2 + |\beta|^2 = 1$, and $|\alpha'|^2 + |\beta'|^2 = 1$.

This equivalence expresses the fact that if neutrino states are specified completely by momentum and helicity, there can be no observable distinction between a neutrino of definite helicity and any linear unitary combination of "neutrino" and "antineutrino" of the same helicity and momentum. The substitutions (6) and (7) amount only to a redefinition of the neutral leptons involved in reactions (1).

A. <u>Second-Order β-Decay Processes</u>

To be specific, the null results of the Davis experiment[6] and the search for neutrinoless double β decay[7] are, for $m_\nu = m_{\nu'} = 0$, already consequences of neutrino-chirality conservation and cannot test lepton conservation. The definite right-handedness of the neutrinos $\overline{\nu}$ emitted in reaction (1a) prevents their absorption in the reaction $\overline{\nu} + n \to p + e^-$ irrespective of whether any other neutrino-antineutrino distinction is possible or whether lepton number is conserved. The same remarks apply to scattering experiments such as $2e^- \rightarrow 2\pi^-$ which proceed by iteration of the basic β-decay interaction.

For the same reasons, the cross section[8] for $\bar{\nu} + p \rightarrow e^- + n$ is independent of the kinds of neutral leptons emitted in reaction (1a).[9]

B. The μ Decay

From the helicities observed in the $\pi - \mu - e$ chain it is known that the two neutrinos are in opposite spin states, as suggested by the "particle-antiparticle" designations in reaction (1c). If the two neutrinos were identical particles in the same helicity state, then the exclusion principle would inhibit the emission of energetic electrons and lead to a spectrum characterized by $\rho = 0$. That the two neutrinos actually appear in opposite helicity states was interpreted in the single two-component neutrino theory[3] as evidence that, if lepton number is conserved, μ^- and e^- must bear the same lepton number. If the two neutrinos in μ decay are not identical or if one gives up the connection between neutrino helicity and lepton number, this historic argument does not apply and the alternative assignment,[10] that e^- and μ^+ are both leptons, is consistent with lepton conservation.

Clearly lepton conservation cannot be tested in second order β processes (so long as $m_\nu = 0$) because of neutrino chirality, and cannot be tested in μ decay because of the occurrence of two neutrinos.[9]

III. ONE FOUR-COMPONENT NEUTRINO

Under those circumstances, what meaning can be attached to the distinction between neutrino and antineutrino and to the principle of lepton conservation? Is there a process, allowed by chirality conservation, which becomes forbidden only by an assignment of quantum numbers to the leptons? If so, this quantum number is entitled to be called lepton number.

A test of lepton-number assignments is possible only by considering two-step processes where different interactions H_b and H_a (or H_b and H_c, or H_c and H_a) are involved. This is precisely the experiment performed[1] where neutrinos issuing from reaction (1b') induced the inverse of reaction (1b) but not (1a). If there is a lepton-conservation law and lepton number means anything, it can only mean what was called muon number above: $L = +1$ for e^-, ν, $\overline{\nu}'$, and μ^+; $L = -1$ for e^+, $\overline{\nu}$, ν', and μ^-.

Now ν' has the same quantum numbers as $\overline{\nu}$, so that the most economical description of all the conservation laws is to identify $\nu' \equiv \overline{\nu}$; i.e., to recognize ν and $\overline{\nu}'$ as left- and right-helicity states of a four-component neutrino coupled to e^- and and μ^+, respectively. In the interaction (2) j'_a is replaced by $j''_a = i\overline{\mu}\gamma_a^+\nu^c$, and the basic reactions (1) involving muons can be re-written by placing on each ν, a prime superscript (designating the associated muon) and a c or overhead bar (designating the charge conjugate):

$$n \to p + e^- + \overline{\nu}_R \,, \tag{8a}$$

$$\mu^- + p \to \overline{\nu}_L + n \,, \tag{8b}$$

$$\pi^+ \to \mu^+ + \overline{\nu}_L \,, \tag{8b'}$$

and

$$\mu^- \to \overline{\nu}_L + e^- + \overline{\nu}_R \,. \tag{8c}$$

For clarity we have now inserted the neutrino chiralities which were heretofore implicit in the neutrino-antineutrino distinction; e^- and μ^- are produced in association with right-helicity neutrinos and transmute into left-helicity neutrinos. The new feature is that the neutrino is now a four-component Dirac field whose two charge states, particle and antiparticle, are realized by their coupling to e^- and μ^- respectively. The Pauli transformations (6) and (7) are incompatible with the condition $\nu' \equiv \overline{\nu}$ and are now not admitted; the degeneracy with respect to neutrino charge which existed in the two-component neutrino theory, which made meaningless the distinction between neutrino and antineutrino, is lifted by the coupling to the μ^-, e^- fields.

Because of the anticommutation relations, which the fermion operators satisfy, it follows that $\overline{\nu}' \gamma_\alpha^{+} \nu' = \overline{\nu}\, \gamma_\alpha \frac{1}{2} (-1 + \gamma_5) \nu$. The chirality and lepton current densitites in Eqs. (3) and (5) take the forms $i(\overline{e}\, \gamma_\alpha\, e + \overline{\mu} \gamma_\alpha \mu + \overline{\nu}\, \gamma_\alpha \gamma_5 \nu)$ and $i(\overline{e}\, \gamma_\alpha e - \overline{\mu}\, \gamma_\alpha \mu + \overline{\nu}\, \gamma_\alpha \nu)$, respectively. The condition $m_\nu = 0$ as the condition for neutrino-chirality conservation is apparent. The V-A interaction form follows, as before, from the parenthetical remarks about Eq. (4).

The theory we have been led to, characterized by one Dirac neutrino and the Konopinski-Mahmoud assignment of lepton numbers, is that discussed by Schwinger and by others in connection with a now obsolete VT-theory of β decay.[11]

A. Tests for this Theory

The identification $\nu' \equiv \overline{\nu}$ is possible only if muon and electron neutrinos differ solely in charge; i.e., if $m_\nu = m_{\nu'}$, and all other quantum numbers are the same. The β-decay neutrino mass is known to be very small ($m_\nu < 0.004\, m_e$); but for the muon neutrino the present upper limit, derived[12] from the range of $\pi_{\mu 2}$ muons in emulsion, together with independent determinations of the π and μ masses, is $m_{\nu'} < 8\, m_e$. If, since the muon mass is now better known than in 1955, the pion-mass and muon-momentum determinations can be refined, this limit on $m_{\nu'}$ can be improved.

The kinematics of $K_{\mu 2}$ decay or of μ-capture is, of course, the same as that of π-decay. In $K_{\mu 2}$ decay, the muon range is much longer than in $\pi_{\mu 2}$ decay, but the quoted K mass is three times more uncertain than the π mass from which it is at present derived. An upper limit of $m_{\nu'} < 8$ MeV has already been set[13] from μ capture in H_e^3.

If the association of ν' with μ, and ν with e, found in the interaction with unstrange particles, is reversed when dealing with strange particles[14] ("neutrino flip"[15]), then either lepton number is not conserved in such strange-particle processes, or ν and ν' differ in some other quantum number besides lepton number. The preliminary data suggest this is not so.

As the neutrino mass, $m_{\nu'}$, and neutrino-flip experiments are refined, one may observe ν-ν' differences which invalidate the association of ν and ν' into one Dirac neutrino. If a third neutrino ν'' were discovered, the formulation given in this paper would probably lose its attractiveness.

B. Comparison With Two-Neutrino Theory

If ν and $\bar{\nu}'$ are identical, except for their association with e^- and μ^-, and if $m_\nu = 0$, the present four-component formulation differs from the theory of two two-component neutrinos only in a trivial way, since it divorces neutrino lepton number from chirality and identifies it with neutrino charge. Nevertheless the Dirac formulation would appear to enjoy certain conceptual advantages:

(1) The absence of $\mu \rightarrow e$ conversion processes and the results of the high-energy neutrino experiments are interpreted in terms of a single neutrino which has the same number of internal degrees of freedom as do all other fermions, and no new conservation law (muon number) needs to be invoked. The minimum number of fields necessary to describe dynamically the conservation of electric charge, lepton number, and chirality, is three; thus, the muon is almost logically necessary, instead of being an unexpected guest.

(2) The economy in description obtained may also suggest a unification of the description of all elementary particles.[16] The three lepton fields are suggestive of the three baryon fields needed to realize charge, baryon number and hypercharge conservation. The e^-, ν, μ^+ triple, differing formally from the two doublets (e^-, ν) and (μ^-, ν'), also suggests different weak-interaction symmetries. For example, although the numerical equalities in the Puppi triangle still obtain, the "universal" Fermi interaction looks different in form when expressed as an interaction between the (np) doublet and the e^-, ν, μ^+ triplet. This change in form may suggest a numerical change in coupling strength when going to strange particles.

(3) The mystery why the neutrino should have only two components--which explained nothing until supplemented by the additional assumption of neutrino chirality conservation[17]--disappears. The neutrinos missing two components, ν_R, are connected to μ^+! (This situation is similar to that in electrodynamics: while e^- and e^+ could be described by two two-component spinors, we find it more convenient to recognize a single Dirac electron field whose two charge states are distinguished by their coupling to the electromagnetic field.) In this sense, the muon and its neutrino are given a natural role they otherwise do not enjoy. In the last section we discuss the μ-e mass difference in this light.

(4) One does not pretend to attribute parity non-conservation to an intrinsic property of neutrinos. After all, maximal parity violations are found in some processes in which neutrinos are not apparently involved, and parity manages to be conserved in other (electrodynamic and gravitational) processes in which the masslessness of the relevant quanta might also have suggested a reduced number of components for the quanta involved.[18]

C. Neutrino Mass and Broken Chirality Invariance

The possibility $m_\nu = 0$ expressing exact neutrino chirality conservation is certainly most attractive theoretically. Nevertheless, in the case of $m_\nu \neq 0$, the present Dirac formulation is, in principle, distinguishable from the theory of two two-component neutrinos. Double β decay, the Davis reaction, and an anomalous neutrino-proton absorption cross section are then no longer forbidden by chirality conservation. (The cross sections for these second-order Fermi processes, depressed by an additional factor proportional to m_ν^2, are, needless to say, ridiculously small.) If found, these effects imply that neutrino chirality and lepton number are both not conserved; such a positive result may be interpreted as due to a small neutrino mass of perhaps weak interaction origin.

If no $\mu^- \to e^-$ processes are seen but $\mu^+ \to e^-$ observed, then neutrino chirality is not conserved, but lepton conservation may be presumed, with the Konopinski-Mahmoud assignments.[19] On the other hand, if neither $\mu^- \to e^-$ nor $\mu^+ \to e^-$ is observed, and if the neutrino mass, m_ν, is nonzero, then lepton conservation (with the conventional assignments) and a separate muon-number conservation law are called for.

IV. COMMENTS ON THE MUON-ELECTRON DIFFERENCE

Heretofore, μ^- and e^- have appeared as identical particles except for their mass difference. To explain this large, apparently nonelectromagnetic mass difference, anomalous muon interactions have been hypothesized. Such dynamics, nonsymmetric between muon and electron has so far not revealed itself.

The present theory, however, builds on a triplet that is symmetric under the weak interactions: μ^- and e^- are, besides their mass, distinguished only by lepton charge. Can this symmetry be extended to the electromagnetic interactions and still explain, qualitatively at least, the μ-e mass difference? Suppose e^-, ν, and μ^+ to be originally massless ($m_0 = 0$) and therefore degenerate in the absence of electromagnetic interactions. The minimal electromagnetic interaction

$$H_{em} = i\, e\, [\bar{e}\, \gamma_\alpha\, e + \bar{\mu}\, \gamma_\alpha\, \mu]\, A^\alpha$$

leads after a self-consistent calculation, to the electromagnetic self-energy

$$\delta m = m - m_0 = m(3\alpha/2\pi)\, \ln\, \Lambda/m. \qquad (9)$$

Because it is determined by weak interaction unitarity or gravitational considerations, the cutoff Λ is expected to be rather large here (as compared with any cutoff in the strong interactions).

For $m_0 = 0$, Eq. (9) has the unequal mass solutions

$$m = 0,$$

and

$$m = \Lambda \exp(-2\pi/3\alpha). \qquad (10)$$

It seems possible that these two solutions realize the difference between L = +1 and L = -1 charged leptons. This solution for $m_0 = 0$ is, of course, not yet to be taken seriously quantitatively (a value $m_0 \neq 0$, or a breakdown of minimal electrodynamics, is necessary for the lighter lepton to acquire an $m \neq 0$, and for other reasons. A mass will, incidentally, allow the Dirac neutrino to have a small magnetic moment.) We mean only to suggest that the assignment of opposite lepton number to e^- and μ^- leaves room, within the framework of known interactions, for a difference between μ^- and e^- that becomes manifest in their masses.

Our main purpose, however, was to show that while ν and ν' can be described by different two-component fields, the most economical description consistent with the known facts is that they are particle and antiparticle states of a Dirac field, distinguished by their coupling to e^- and μ^+, respectively. While this idea originates with Konopinski and Mahmoud,[10] Touschek, Schwinger and other authors,[11] we wish to emphasize that, in a chirality-conserving theory, what has been called muon number is also the only independent meaning that we can attach to lepton number.

FOOTNOTES AND REFERENCES

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If, since there is no intervening neutrino interaction or mass difference, the two steps are treated coherently, then the cross-section twice the parity-conserving result must be obtained. The μ-decay calculation referred to by Konopinski deals with the emission of neutrinos that are not of definite chirality.

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