Analog of the Michel Parameter for Neutrino-Electron Scattering: A Test for Majorana Neutrinos

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It is shown that the ratio of forward to backward scattering cross sections plays the same role for neutrino-electron scattering as does the original ρ parameter for muon decay. Values of the ratio greater than 2 imply that the neutrino is a Dirac particle and that the tensor interaction is present in the effective Hamiltonian; values less than 2 do not exclude the Majorana case.

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The ρ parameter was invented by Michel[1] as a crude test of the identity of the neutrinos emitted in muon decay. Values of greater than $\frac{3}{4}$ imply that the two neutrinos must be distinguishable from one another, and that the tensor interaction is present in the decay Hamiltonian; values less than or equal to $\frac{3}{4}$ are consistent with the neutrinos being distinguishable particles, but do not exclude the possibility that they are indistinguishable. In the context of the times in which Michel was writing, the emission of two identical neutrinos in muon decay would have been taken as evidence that the neutrino is a Majorana particle, identical with its antiparticle; today the two particles are known to belong to different families[2] and so the ρ parameter for muon decay no longer provides evidence for or against the existence of Majorana neutrinos. There is, however, another purely leptonic process to which the original Michel analysis can still be applied and that is neutrino-electron scattering.[3]

If, as is generally believed to be the case, elastic neutrino-electron scattering preserves the flavor of the incident neutrino, $\nu_l e^- \to \nu_l e^-$, then the process is related by crossing symmetry to such processes as $e^+e^- \to \nu_l \bar{\nu}_l$ and $e^* \to e\nu_l\bar{\nu}_l$, where e^* denotes an electron excited by an electromagnetic field. The properties of these latter processes are obviously influenced by whether or not ν_l and $\bar{\nu}_l$ are identical particles, and so the properties of the former process must also be influenced by the issue of identical ν_l and $\bar{\nu}_l$. The problem, then, is to find a simple parameter which reflects this influence.

To do this, let us relax for the moment the standard constraints on neutrinos and antineutrinos, and let us imagine that they couple to electrons in all conceivable states of helicity. The largest range of kinematical configurations is then open to the neutrino pair in the process $e^* \to e\nu_l\bar{\nu}_l$. In particular, the neutrino and antineutrino could be travelling antiparallel to the electron with the same helicity and momentum, as shown in Fig. 1. This configuration can occur when the electron has its maximum kinematically allowed momentum, but it is forbidden by the Pauli principle if $\nu_l \equiv \bar{\nu}_l$. Therefore, to the extent that $\nu_l \equiv \bar{\nu}_l$, the probability for finding an outgoing electron with its maximum momentum will be diminished. For muon decay, this probability is nothing but the ρ parameter!

In neutrino-electron scattering, the configuration corresponding to parallel neutrino emission of Fig. 1 is one in which the neutrino scatters through 180° in the center-of-mass system and undergoes a helicity flip; that is, the neutrino reverses its momentum but not its spin. From the preceding discussion, it follows that this configuration is forbidden by Pauli statistics if $\nu_l \equiv \bar{\nu}_l$. By contrast, forward scattering, which is equivalent to antiparallel emission in $e^* \to e\nu_l\bar{\nu}_l$, is never forbidden. Therefore the analog of ρ for ν-e scattering is a parameter which compares backward scattering with forward scattering.

Having relaxed the standard constraints on neutrino helicities, in the above argument, we write the Hamiltonian for neutrino-electron scattering in its most general, Lorentz-covariant form:

$$H(\nu e) \equiv \frac{G}{\sqrt{2}} \sum_{\substack{S,T,P,\\V,A}} (\bar{\psi}_\nu \Gamma_i \psi_\nu)[\bar{\psi}_e \Gamma_i (C_i + D_i \gamma_5)\psi_e] + \text{H.c.} \qquad (1)$$

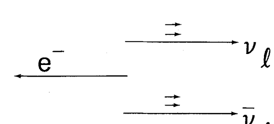

FIG. 1. Collinear configuration of muon decay which occurs when the electron has its maximum kinematically allowed momentum. The short double arrows represent the spin directions of the neutrinos.

We assume CP invariance, so that

$$D_S = D_P = D_T = 0 \tag{2}$$

while all other coupling constants are real.[4] For Dirac neutrinos, all five covariants S, P, T, V, A are allowed; but for Majorana neutrinos, the condition for self-conjugacy under charge conjugation, namely

$$\psi_\nu = \psi_{\nu c} = C\tilde{\bar{\psi}}_\nu \tag{3}$$

has the effect of eliminating V and T, and doubling all the other coefficients *(Majorana condition)*:

$$C_V = D_V = C_T = D_T = 0, \quad C_x \to 2C_x, \ D_x \to 2D_x, \ (x \neq V, T). \tag{4}$$

In most experiments, the ν_l and $\bar{\nu}_l$ are produced from π^+ (K^+) and π^- (K^-) decays, and they are therefore in left-handed and right-handed helicity states, ν_L and $\bar{\nu}_R$, respectively. The cross sections we can measure are limited to[4]

$$d\sigma(\nu_L e)/dy = (G^2 m_e/2\pi)[A + 2B(1-y) + C(1-y)^2], \tag{5}$$
$$d\sigma(\bar{\nu}_R e)/dy = (G^2 m_e/2\pi)[C + 2B(1-y) + A(1-y)^2],$$

where the variable $y = E_e/E_\nu$ in the laboratory frame, and $y = \sin^2\frac{1}{2}\theta$ in the center-of-mass frame. The coefficients A, B, C can be expressed in terms of the coupling constants appearing in Eq. (1):

$$A = (g_V + g_A)^2 + (C_+)^2 + (C_- - C_T)^2,$$
$$B = C_T^2 - (C_+)^2 - (C_-)^2, \tag{6}$$
$$C = (g_V - g_A)^2 + (C_+)^2 + (C_- + C_T)^2,$$

where

$$g_V = -\tfrac{1}{2}(C_V + D_A), \quad g_A = -\tfrac{1}{2}(C_A + D_V), \quad C_\pm = \tfrac{1}{4}(C_S + C_P). \tag{7}$$

Notice that neutrino and electron mass correction terms have been omitted under the presumption that $E_{\nu,e} \gg m_{\nu,e}$.

Forward scattering corresponds to $y = 0$, and backward to $y = 1$. Combining neutrino and antineutrino cross sections, we define a ratio

$$R_\rho = \frac{[d\sigma(\nu_L e)/dy + d\sigma(\bar{\nu}_R e)/dy]_{y=0}}{[d\sigma(\nu_L e)/dy + d\sigma(\bar{\nu}_R e)/dy]_{y=1}} = \frac{2(A + 2B + C)}{(A + C)}. \tag{8}$$

In terms of the coupling constants of the effective Hamiltonian [Eq. (1)], the ratio takes the form

$$R_\rho = \frac{2(g_V^2 + g_A^2 + 2C_T^2)}{(g_V^2 + g_A^2 + C_+^2 + C_-^2 + C_T^2)} \tag{9}$$

for Dirac neutrinos [Eqs. (6) and (7)], and

$$R_\rho = \frac{2(g_V^2 + g_A^2)}{(g_V^2 + g_A^2 + C_+^2 + C_-^2)} \tag{10}$$

for Majorana neutrinos [Eqs. (6), (7), and (4)].

It is readily apparent that the bounds on R_ρ differ for the two types of neutrino: for Dirac,

$$0 \leq R_\rho \leq 4; \tag{11D}$$

for Majorana,

$$0 \leq R_\rho \leq 2. \tag{11M}$$

Therefore, if R_ρ is found to lie between 2 and 4, we can conclude immediately that ν_l is a Dirac neutrino; however, if R_ρ is found to lie between 0 and 2, then the possibility that ν_l is a Majorana neutrino cannot be ruled out.

In order to measure the value of R_ρ, it is not absolutely necessary to measure the forward and backward scattering cross sections: We can, instead, extract A, B, C from the cross section measured over a range of energies [Eq. (5)], and then compute R_ρ from Eq. (9). Since A and C are positive definite [Eq. (6)], it is the value of B that determines whether R_ρ is greater than 2 or not: If B turns out to be positive, then tensor coupling must be present in the Hamiltonian [Eqs. (6) and (1)], R_ρ will be greater than 2, and the neutrino must be a Dirac particle. If B turns out to be negative, or zero, then the possibility of a Majorana neutrino cannot be excluded.

The determination of R_ρ by this method requires neutrino-electron scattering data which can be divided into a least three bins. Unfortunately present data are not sufficiently refined for this purpose, and so we must wait until more data become available. In the meantime, we note that there is another process to which the above analysis applies, namely neutrino-quark scattering. Assuming that this process is also an elementary, pointlike interaction, we can define a forward-to-backward ratio the bounds on which are exactly those in (11D) or (11M) depending on the Dirac or Majorana nature of the incident neutrino. To extract this parameter from deep-inelastic neutrino neutral-current interactions, we must analyze the y distributions in terms of the appropriate A, B, C coefficients for the various quarks. While no strong evidence for a positive B coefficient has emerged to date, it is not clear that such a possibility can be ruled out altogether.[5]

In the event that the B coefficients for neutrino-electron and neutrino-quark scattering all turn out to be zero or negative, then one must make use of the much more detailed tests of Kayser and Shrock[3] to decide the Majorana versus Dirac issue for neutrinos. Or, alternatively, one must search for the occurrence of no-neutrino double-β decay.[6]

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New Result for the Lifetime of the D^0 Meson

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In an experiment measuring charmed-particle lifetimes with a hybrid emulsion spectrometer, 1248 neutrino and antineutrino interactions produced by the wide-band beam at Fermi National Accelerator Laboratory have been located. Twenty-one candidates for the decay of neutral charmed particles are found. The lifetime for the D^0 based on the sixteen constrained events of this sample is measured to be $2.3^{+0.8}_{-0.5}\times 10^{-13}$ sec.

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In the spectator quark model all charmed particles are predicted to have the same lifetime. Experimentally the neutral D mesons are shorter lived than the charged D's and in fact have lifetimes similar to those of the weakly decaying charmed particles F and Λ_c.[1-5] Previous analy-

