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TESTING THE MUON NUMBER CONSERVATION LAW IN $\bar{\nu}_\mu + e^-$ INTERACTIONS AT HIGH ENERGIES [†]

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ABSTRACT

We propose to test the validity of the multiplicative muon number conservation law by comparing the quasi-elastic reactions $\bar{\nu}_\mu + e^- \to \mu^- + \bar{\nu}_e$ and $\nu_\mu + e^- \to \mu^- + \nu_e$ at Fermi-Lab energies. We note that the measured electron spectrum in muon decay places strong constraints on the effective Lagrangian for the $\bar{\nu}_\mu$-inducted process.

At the present time it is not known whether muon number is conserved additively or multiplicatively.[1] In this paper we examine the feasibility of answering this question via the study of quasi-elastic $\bar{\nu}_\mu$ and ν_μ scattering from electrons. If the multiplicative conservation law is valid, then we expect the anti-neutrino reaction

$$\bar{\nu}_\mu + e^- \to \mu^- + \bar{\nu}_e \qquad (1)$$

to occur as frequently as the neutrino reaction

$$\nu_\mu + e^- \to \mu^- + \nu_e \qquad (2)$$

at the same energy. If, on the other hand, the additive law holds, then reaction (1) is forbidden, and reaction (2) is the only one allowed. The threshold for these reactions is given by

$$E_{th} = (m_\mu^2 - m_e^2)/2m_e \approx 10 \text{ GeV} \tag{3}$$

and so we must use the FermiLab neutrino beam to study them.

The interaction Hamiltonians that give rise to quasi-elastic neutrino-electron scattering also give rise to muon decay,

$$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu \tag{1'}$$

$$\mu^- \to e^- + \nu_e + \bar{\nu}_\mu \tag{2'}$$

and so they must both be consistent with the observed properties of the electron spectrum. As is well known,[2] the measured values of the Michel parameter ρ, the angular correlation parameter ξ of the electrons with respect to the muon spin direction, and the helicity of the electron all imply that the interaction must be dominantly V-A in character. Therefore we take the Hamiltonians to be

$$H(\nu_\mu e) = \frac{G \cos\phi}{\sqrt{2}} (\bar{\nu}_e \gamma_\rho (1 + \gamma_5) e)(\bar{\mu}\gamma_\rho (1 + \gamma_5)\nu_\mu) + \text{h.c.} \tag{4}$$

$$H(\bar{\nu}_\mu e) = \frac{G \sin\phi}{\sqrt{2}} (\bar{\nu}_\mu \gamma_\rho (1 + \gamma_5) e)(\bar{\mu}\gamma_\rho (1 + \gamma_5)\nu_e) + \text{h.c.} \tag{5}$$

where G is the universal weak interaction coupling constant, $G = 10^{-5}\, m_p^{-2}$, and the angle ϕ is to be determined by experiment. The second Hamiltonian is obtained from the first merely by interchanging the e and μ subscripts on the neutrino fields; it cannot arise from a gauge model of weak interactions unless there are substantial violations of muon and electron number conservation.

The differential cross section calculated for reaction (1) according to (5) in the rest frame of $\bar{\nu}_\mu + e^-$ is

$$\frac{d\sigma}{d\Omega}(\bar{\nu}_\mu e) = \frac{G^2 \sin^2\phi}{(2\pi)^2} \frac{(s - m_\mu^2)^2}{4s^3} \left[(s - m_e^2) \cos\theta + s + m_e^2\right] \times \left[(s - m_\mu^2) \cos\theta + s + m_\mu^2\right] \tag{6}$$

where $s = (p_\nu + p_e)_\mu^2 \simeq 2m_e E_\nu$ is the square of the available total energy of the ν-e system, and θ is the production angle of μ^- relative to the incident neutrinos in the c.m. system. The angular dependence $(1 + a\cos\theta + b\cos^2\theta)$ of the differential cross section comes about because the incident $\bar{\nu}_\mu$ is right-handed, and in the V-A Hamiltonian of eq^{n}(5), it scatters off a left-handed electron. By contrast, the differential cross-section for reaction (2) is isotropic in the ν_μ-e center-of-mass system.

$$\frac{d\sigma}{d\Omega}(\nu_\mu e) = \frac{G^2\cos^2\phi}{(2\pi)^2}\ \frac{(s - m_\mu^2)^2}{s} \qquad (7)$$

because the incident ν_μ and electron now have the same, left-handed helicity. The difference between the angular distributions of eq$\frac{n}{}$s(6) and (7) provide us with a possible means of distinguishing between muons created in reaction (1) and those created in reaction (2).

A background of neutrinos always exists in an anti-neutrino beam. Therefore the observation of a high energy μ^- in reaction (1) can always be contaminated by μ^- mesons coming either from reaction (2) or from the much more likely reaction

$$\nu_\mu + \text{nucleons} \rightarrow \mu^- + \text{anything}. \qquad (8)$$

Nevertheless, reaction (1) can distinguish itself from the backgrounds because of the following unique kinematic features:

$$\text{(i)}\quad E_\mu \geq E_{min} = \frac{m_e^2 + m_\mu^2}{2m_e} \approx 10\ \text{GeV}; \qquad (9)$$

$$\text{(ii)}\quad \frac{d\sigma}{dE_\mu} = \frac{16G^2 m_e}{4(2\pi)}\left[\frac{E_\nu + m_e - E_\mu}{E_{\bar{\nu}}}\right] \times \left[\frac{E_{\bar{\nu}} - E_\mu + \frac{1}{2}m_e + \frac{m_\mu^2}{2m_e}}{E_{\bar{\nu}}}\right]$$

$$\approx \frac{2G^2 m_e}{\pi}\left[1 - \frac{E_\mu}{E_{\bar{\nu}}}\right] \times \left[1 - \frac{E_\mu}{E_{\bar{\nu}}} + \frac{m_\mu^2}{s}\right] \qquad (10)$$

which drops sharply as the muon laboratory energy E_μ increases from 10 GeV to $E_{max} \simeq E_{\bar{\nu}}$;

$$\text{(iii)} \quad \theta_{\mu \, lab} \lesssim \theta^{max}_{\mu \, lab} = \sqrt{\frac{m_e^2}{m_\mu^2 - m_e^2}} \times \frac{s - m_\mu^2}{\sqrt{s^2 - m_e^2 m_\mu^2}} \simeq 5 \text{ m rad} \qquad (11)$$

The phase space for seeing a μ^- originating from (8), characterized by the features (i, ii & iii), and unaccompanied by anything detectable (other than neutrinos) is practically zero.

To determine the angle ϕ, we propose to measure the ratio of $\bar{\nu}_\mu$ - flux to ν_μ - flux in a $\bar{\nu}_\mu$-beam via the study of the reactions:

$$\nu_\mu + n \rightarrow \mu^- + p \qquad (12)$$

and

$$\bar{\nu}_\mu + p \rightarrow \mu^+ + n \, . \qquad (13)$$

We then select the μ^- - candidates of (1) and (2) according to the kinematic criteria given by (i) (ii) and (iii). The number of events expected from (2) can be calculated from the ν_μ-flux. Hence the excess of μ^- can be assigned as candidates for reaction (1). Although, reaction (1) has a rate which is roughly 1/3 the rate for reaction (2), and 1/5000 times the rate for reaction (8), its clean signature, namely a fast forward single muon, is unique and easy to identify.

Experimentally, the validity of multiplicative lepton number conservation law has been tested with various techniques at low energies.[4] With a precise knowledge of the incident beam, the target, and outgoing μ^-, reaction (1) provides us a direct test of the conservation law, and so we propose to search for it with the present available facilities at FermiLab.

Taking into account the special kinematic features of reaction ( ), we can expose either the 15' bubble chamber filled with Ne, or the FHPW Calorimeter[5] to the narrow band dichromatic $\bar{\nu}_\mu$-beam.[6] The facts are:

(i) The $\bar{\nu}_\mu$-beam direction is well defined, possibly known to within 1 mrad;

(ii) The Coulomb multiple scattering of a 15 GeV μ^- in Ne or Al is less than 2 or 3 mrad in a path of one meter;

(iii) The ν_μ background in the $\bar{\nu}_\mu$-beam can be measured to an accuracy of 30%;[6]

(iv) The $E_{\bar{\nu}}$ - spectrum of the present FNAL dichromatic beam, which ranges from 30 GeV to 60 GeV and includes a 10% component of higher energy kaon anti-neutrinos, is most suitable for this experiment. Its particular advantages are: (a) it removes all $\bar{\nu}$'s with $E_{\bar{\nu}} < E_{th}$ for reaction (1); and (b) its high energy component contributes fewer events with fast forward muons;

(v) The dichromatic beam allows us to calculate the μ^- angular distribution in the c.m. system.

(vi) The quantity $\frac{2G^2 me}{\pi}$ appearing in (10) is 1.72×10^{-41} cm^2/GeV.

Thus, the experiment is feasible. For instance, with the 15' bubble chamber, one expects to see 12 to 20 events of reaction (1) in one million pictures. On the other hand, with the FHPW Calorimeter, one can search for high energy forward μ^-'s unaccompanied by hadronic showers.

Footnotes and References

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