sion angle. Study of Fig. 3 reveals that in the angular domain $-60° < \theta < 80°$ energy deposition is dominated by elastic scattering and meson production on a single nucleon.

In conclusion, accepting one of the premises of EFM we set a new lower limit for the proton-proton interaction time.[9] The independence of the aluminum to hydrogen multiplicity ratio at small lab emission angles, under large variations of missing mass and transverse momentum, suggests that there is only one inelastic collision per nucleus in which the effective mass of EF is formed. The equality of the positive to negative track ratios for both p-p and p-Al interactions shows that energy deposition in Reaction (2) is dominated by meson production.

Collaboration of our colleagues at Brookhaven National Laboratory, Virginia Polytechnic Institute, University of Wisconsin, and University of Pennsylvania in the data taking is appreciated. We would like to thank Professor K. Gottfried for illuminating explanations of some aspects of EFM and for his critical remarks.

*Work supported in part by the U. S. Energy Research and Development Administration.

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[6]Thus a measurement of the multiplicity ratio *after* the angular average has been carried out is not as sensitive a test of EFM as our approach. See J. R. Elliot *et al.*, Phys. Rev. Lett. 34, 607 (1975).

[7]A. Ramanauskas *et al.*, Phys. Rev. Lett. 31, 22 (1973); E. W. Anderson *et al.*, Phys. Rev. Lett. 34, 294 (1975).

[8]Our apparatus can detect protons with $p \gtrsim 270$ MeV/c.

[9]Applying our Eq. (3) to a recent low-energy experiment an even higher limit of $\tau_0 > \hbar/m_\pi c^2$ can be obtained. See G. Burleson *et al.*, Phys. Rev. D 12, 2557 (1975). Note that the absorptive model description of ρ^0 and Δ^{++} production makes use of the hypothesis that $\rho^0 + p \to \rho^0 + p$ and $\Delta^{++} + p \to \Delta^{++} + p$ elastic scattering take place in pion- and proton-induced ρ^0 and Δ^{++} production. If we regard ρ^0 and Δ^{++} as a particular form of energy flux and denote their widths by Γ we obtain the bounds $2\hbar/\Gamma > \tau_0 > \hbar/m_\pi c^2$. See also P. M. Fishbane and J. S. Trefil, Phys. Rev. D 9, 168 (1974).

Testing the Muon-Number Conservation Law in $\bar{\nu}_\mu + e^-$ Interactions at High Energies*

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(Received 21 May 1976)

We propose to test the validity of the multiplicative muon-number conservation law by comparing the quasielastic reactions $\bar{\nu}_\mu + e^- \to \mu^- + \bar{\nu}_e$ and $\nu_\mu + e^- \to \mu^- + \nu_e$ at $\gtrsim 400$ GeV. We note that the measured electron spectrum in muon decay places strong constraints on the effective Lagrangian for the $\bar{\nu}_\mu$-induced process.

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

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

and the neutrino reaction

$$\nu_\mu + e^- \to \mu^- + \nu_e \tag{2}$$

to occur 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

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

The interaction Hamiltonians that give rise to quasielastic neutrino-electron scattering also give rise to muon decays,

$$\mu^- \to e^- + \nu_e + \bar{\nu}_\mu, \tag{1'}$$

$$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu, \tag{2'}$$

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

$$H(\nu_\mu e) = 2^{-1/2} G \cos\alpha [\bar{\nu}_e \gamma_\rho (1+\gamma_5) e][\bar{\mu}\gamma_\rho(1+\gamma_5)\nu_\mu] + \text{H.c.}, \tag{4}$$

$$H(\bar{\nu}_\mu e) = 2^{-1/2} G \sin\alpha [\bar{\nu}_\mu \gamma_\rho (1+\gamma_5) e][\bar{\mu}\gamma_\rho(1+\gamma_5)\nu_e] + \text{H.c.}, \tag{5}$$

where G is the universal weak-interaction coupling constant, $G = 10^{-5} m_p{}^{-2}$, and the angle α 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 the $\bar{\nu}_\mu + e^-$ system is

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

where s is the square of the available total energy of the $\bar{\nu}$-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. (5) it scatters from a left-handed electron. By contrast, the differential cross section for Reaction (2) is isotropic in the ν_μ-e c.m. system:

$$\frac{d\sigma(\nu_\mu e)}{d\Omega'} = \frac{G^2 \cos^2\alpha}{(2\pi)^2} \frac{(s-m_\mu{}^2)^2}{s}, \tag{7}$$

because the incident ν_μ and electron now have the same, left-handed helicity.

By taking advantage, as we discuss below, of the special kinematic features of Reaction (1) and the well-defined nature of a dichromatic $\bar{\nu}_\mu$ beam available at Fermilab, we find that the difference between the angular distributions of Eqs. (6) and (7) provides us with a possible means of distinguishing between muons created in Reaction (1) and those created in Reaction (2).

The unique kinematic features of Reaction (1) can be visualized in the terms of the laboratory variables as follows:

$$E_\mu \geq E_{\min} = (m_e{}^2 + m_\mu{}^2)/2m_e \simeq 10 \text{ GeV}, \tag{8}$$

$$\frac{d\sigma}{dE_\mu} = \frac{2G^2 \sin^2\alpha}{\pi} m_e \left[1 - \frac{E_\mu}{E_{\bar{\nu}}} + \frac{m_e}{E_{\bar{\nu}}}\right]\left[1 - \frac{E_\mu}{E_{\bar{\nu}}} + \frac{1}{2}\frac{m_e}{E_{\bar{\nu}}} + \frac{m_\mu{}^2}{s}\right], \tag{9}$$

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

$$\theta_\mu \leq \theta_\mu{}^{\max} = \left[\frac{m_e{}^2}{m_\mu{}^2 - m_e{}^2}\right]^{1/2} \frac{s - m_\mu{}^2}{(s^2 - m_e{}^2 m_\mu{}^2)^{1/2}} \simeq 5 \text{ mrad}. \tag{10}$$

Thus, a fast forward *negative* muon unaccompanied by anything detectable (other than neutrinos) provides us, in principle, a unique signature of Reaction (1). Now, the fact is that at Fermilab, (a) the $\bar{\nu}$-beam direction is well defined, possibly known to within 1 mrad; (b) the Coulomb multiple scattering of a 15-GeV μ^- in Ne or Al is less than 2 or 3 mrad in a path of 1 m; (c) the ν_μ background in the $\bar{\nu}_\mu$

beam can be measured to an accuracy of 30% via the study of the reactions

$$\nu_\mu + n \to \mu^- + p, \tag{11}$$

$$\bar{\nu}_\mu + p \to \mu^+ + n; \tag{12}$$

and (d) a dichromatic beam allows us to calculate the μ^- angular distribution in the c.m. system, and it also removes another major background for Reaction (1) originating from the much more likely reaction

$$\nu_\mu + \text{nucleons} \to \mu^- + \text{neutrals} \tag{13}$$

at low energies ($E_\nu < E_{\rm th}$).

At high energy, the phase space for seeing a μ^- originating from (13), characterized by the features (8)–(10), and unaccompanied by any detectable hadronic showers is practically zero (e.g., because of an observed flat y distribution).

To determine the angle α, we propose to measure the ratio of the $\bar{\nu}_\mu$ flux to the ν_μ flux in a $\bar{\nu}_\mu$ beam via the study of Reactions (11) and (12).[3] We then select the μ^- candidates of (1) and (2) according to the kinematic criteria given by (8)–(10). 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 $\frac{1}{3}$ the rate for Reaction (2), and $\sim 10^{-3}$ times the rate for Reaction (13), its clean signature (namely, a fast, forward, negatively charged, single muon) is unique and easy to identify.

Experimentally, the validity of the 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. For instance, we can expose either the 15-ft bubble chamber filled with Ne or the Fermilab-Harvard-Penn-Wisconsin calorimeter[5] or the Chicago-Oxford νe detector[6] coupled with a muon identifier to the narrow-band dichromatic $\bar{\nu}_\mu$ beam.[7] Since the quantity $(2G^2/\pi)m_e$ appearing in (9) is 1.72×10^{-41} cm^2/GeV, with the 15-ft bubble chamber filled with Ne, one expects to see only 12 to 20 events of Reaction (1) in one million pictures. It would be nice to arouse the attention of every involved experimental group who may have a chance to search for the existence of such a reaction. On the other hand, with the counter type of experiment this is not an uninteresting search to pursue.

Note added.—After this work was completed, we learned that H. Chen, P. Condon, B. Barish, and F. Sciulli have also considered looking for Reaction (1) as a test of multiplicative law (H. Chen, private communication).

*Work supported in part by the U. S. Energy Research and Development Administration.

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