Measurement of the Weak-Neutral-Current Coupling Constants of the Electron and Limits on the Electromagnetic Properties of the Muon Neutrino

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The weak coupling constants of the electron, g_V^e and g_A^e, are determined from measurements of the total and differential cross sections for the reaction $\nu_\mu e \rightarrow \nu_\mu e$. The data also place limits of interest on the magnitudes of a neutrino charge radius and a possible neutrino dipole moment.

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The elastic scattering of neutrinos by electrons is a sensitive and accurate probe of the fundamental features of the standard electroweak theory, and of model-independent intrinsic properties of neutrinos as well. Thus, measurement of the ratio of the total cross sections for neutrino- (ν_μ) and antineutrino- ($\bar{\nu}_\mu$) electron scattering,[1,2] $R=\sigma(\nu_\mu e \rightarrow \nu_\mu e)/\sigma(\bar{\nu}_\mu e \rightarrow \bar{\nu}_\mu e)$, yields a value of the fundamental parameter of the electroweak theory, $\sin^2\theta_W$, essentially independent of theoretical uncertainty,[3] or equivalently the two cross sections yield values of g_V^e and g_A^e, the weak polar and axial-vector couplings of the electron.[4] Alternatively, knowledge of a differential cross section, say, $d\sigma(\nu_\mu e)/dy$, $y=E_e/E_\nu$, in conjunction with knowledge of the total cross section $\sigma(\nu_\mu e)$, yields discrete values of g_V^e and g_A^e. Furthermore, significant quantitative departures from the values of these cross sections expected in the standard electroweak model (with $\sin^2\theta_W$ taken from weak-neutral-current experiments other than neutrino-scattering experiments) might indicate an appreciable neutrino charge radius or be interpreted as evidence for a nonzero magnetic dipole moment.[5]

In this paper we determine a value of $\sigma(\nu_\mu e)$ and infer the behavior of $d\sigma(\nu_\mu e)/dy$ from the measured θ_e^2 distribution of the electrons. The data also allow limits of interest to be placed on the magnitudes of a neutrino charge radius and a possible neutrino magnetic dipole moment.

The data reported here were taken at the Brookhaven National Laboratory Alternating-Gradient Synchrotron (AGS) in a 170-ton, fine-grained target-detector. The neutrino beam and the apparatus and its performance have been described in detail in earlier publications.[6,7] The data were collected from an exposure of 2.62×10^{19} protons on the neutrino-producing target. Data-analysis procedures, the treatment of backgrounds, and results from the earlier data have also been presented previously.[2,8]

The measured distribution in θ_e^2 in the interval $\theta_e^2<0.030$ rad^2 is shown as the points in Fig. 1. The presence of a signal from $\nu_\mu e \rightarrow \nu_\mu e$ is evident, since kinematics require that $\theta_e^2 \leq 2m_e/E_e$, and therefore, to a good approximation, the signal must be confined within the interval $0<\theta_e^2\leq 0.005$ rad^2. The histogram in Fig. 1, rising slowly with decreasing θ_e^2, is a Monte Carlo representation of the background, which consists of misidentified photons from neutral-current single-π^0 production and a small number of misidentified low-energy hadrons.[2,8]

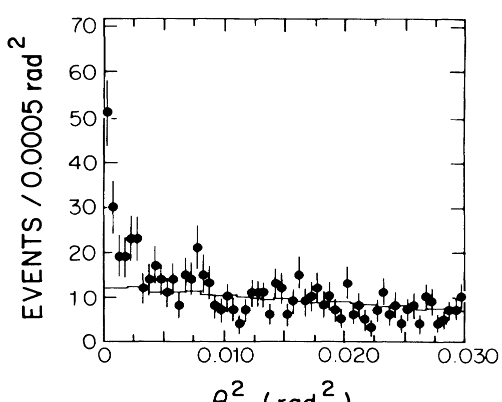

FIG. 1. The observed distribution in θ_e^2, the square of the angle between the incident ν_μ and the outgoing electron from the reaction $\nu_\mu e^- \rightarrow \nu_\mu e^-$. The histogram of slightly negative slope is a fit to the background. After subtraction there remain $107\pm15(\text{stat})\pm5(\text{syst})$ $\nu_\mu e$ events.

The resultant $\nu_\mu e$ signal from Fig. 1, $107 \pm 15(\text{stat}) \pm 5(\text{syst})$ $\nu_\mu e$ events, was then corrected for detection efficiency, and was normalized to a corrected number of quasielastic events, $\nu_\mu n \to \mu^- p$, obtained from an observed sample of 8.87×10^4 $\mu^- p$ events (after background subtraction) satisfying criteria described previously.[2,8,9] This yielded the total cross section

$$\sigma(\nu_\mu e \to \nu_\mu e)/\langle E_\nu \rangle = [1.85 \pm 0.25(\text{stat}) \pm 0.27(\text{syst})] \times 10^{-42}\ \text{cm}^2/\text{GeV}, \tag{1}$$

to be compared with the value $[1.60 \pm 0.29(\text{stat}) \pm 0.27(\text{syst})] \times 10^{-42}$ cm^2/GeV found earlier[8] with a preliminary sample of 51 ± 9 events.

The standard model gives

$$d\sigma_{\text{SM}}(\nu_\mu e)/dy = (G_F m_e E_\nu/2\pi)[(g_V^e + g_A^e)^2 + (g_V^e - g_A^e)^2(1-y)^2], \tag{2}$$

and kinematic conditions require that $y = 1 - E_e\theta_e^2/2m_e$. The experimental resolution in θ_e, shown in Fig. 2(a), was superior to the resolution in E_e which, in conjunction with the energy spread of the incident beam, led us to consider the dependence of the θ_e^2 distribution on the two terms in $d\sigma_{\text{SM}}(\nu_\mu e)/dy$, namely, the y-independent term and the term in $(1-y)^2$. Each term generates a certain shape in the θ_e^2 distribution. The shapes corresponding to the two terms appropriate to this experiment have been obtained with a Monte Carlo calculation, and are shown, in addition to the data points, in Figs. 2(b) and 2(c).

Fitting the relative contributions of the θ_e^2 shapes in Figs. 2(b) and 2(c) to the data points in the θ_e^2 distribution determines $(g_V^e + g_A^e)^2$ and $(g_V^e - g_A^e)^2$. The normalized fit is made by the maximizing of a likelihood function in each θ_e^2 bin where the likelihood is a function of the sum of three terms (one for each θ_e^2 shape and one for the background) with appropriate weighting factors. The sum of the weighting factors is constrained to equal within statistical error the total number of observed events. The resulting fit is stable against changes in the number of bins, inclusion of E_e dependence in the sum, and possible errors in the experimental resolutions as determined from test-beam measurements. The fit yields the four 67%-C.L. regions in the g_V^e vs g_A^e space shown in Fig. 3. Only one region is seen to be consistent with the values $g_V^e = -\frac{1}{2} + 2\sin^2\theta_W$ and $g_A^e = -\frac{1}{2}$ expected for $\nu_\mu e \to \nu_\mu e$ scattering in the standard model with $\sin^2\theta_W = 0.229$, the world-average value.[10] This region also contains the more precise values $g_V^e = -0.079 \pm 0.060$ and $g_A^e = -0.483 \pm 0.042$ determined previously[4] from measurements[2] of $\sigma(\nu_\mu e)$ and $\sigma(\bar{\nu}_\mu e)$.

Any gauge theory of weak and electromagnetic interactions allows a nonzero neutrino charge radius, $\langle r^2 \rangle$. Because the charge radius involves only the replacement of the neutral intermediate vector boson Z^0 by the photon in the exchange between ν_μ and e, the two processes interfere. Hence terms in $\alpha_{\text{em}} G_F \langle r^2 \rangle$ as well as terms in $\alpha_{\text{em}}^2 \langle r^2 \rangle^2$ are present in the expressions for the differential and total cross sections, where α_{em} is the fine-structure constant of QED. For reasonable values of $\langle r^2 \rangle$, the interference terms are more important.

On the other hand, in the standard model with massless, left-handed neutrinos, the neutrino magnetic dipole moment, defined as $fe/2m_e$, is identically zero. In simple extensions of the model with neutrinos of both helicities a very small magnetic moment [of order $(10^{-19}\ \text{eV}^{-1}) m_\nu e/2m_e$] might be generated by radiative corrections. Scattering by the magnetic moment involves a change in helicity between the incident and outgoing neutrinos; hence there is no interference between weak and magnetic moment scattering of ν_μ by e.

From Figs. 2(b) and 2(c) it is clear that the θ_e^2 distribution is weakly dependent on the $(1-y)^2$ term in $d\sigma_{\text{SM}}(\nu_\mu e)/dy$. Furthermore, the detection efficiency as a function of y in the experiment reported here attenuated the sensitivity of the data to possible departures from $d\sigma_{\text{SM}}(\nu_\mu e)/dy$. As a result the principal differences among the y-dependent terms $(1-y)^2$, approximately $1 + 4y\sin^2\theta_W - 2y^2\sin^2\theta_W$, and $(1-y)/y$, corresponding, respectively, to the standard model, the charge radius, and the magnetic moment, were largely vitiated.

The coefficients of the charge-radius and magnetic-moment terms in the total cross section are sufficiently large relative to $G_F^2 m_e E_\nu/2\pi$ to allow limits of interest to be placed on $\langle r^2 \rangle$ and f from total cross-section measurements[2] of $\sigma(\nu_\mu e)$ and $\sigma(\bar{\nu}_\mu e)$ alone.

The gauge-invariant total cross section for $\nu_\mu e \to \nu_\mu e$ including photon as well as Z^0 exchange but no spin flip of the incident neutrino is

$$\sigma(\nu_\mu e) = \sigma(\nu_\mu e)_{\text{SM}} + (2/3\pi) m_e E_\nu [(\pi/\sqrt{2})\alpha_{\text{em}} G_F \langle r^2 \rangle (\tfrac{8}{3}\sin^2\theta_W - 1) + \tfrac{1}{2}\pi^2 \tfrac{4}{9}\alpha_{\text{em}}^2 \langle r^2 \rangle^2]. \tag{3}$$

The total cross section for $\bar{\nu}_\mu e \to \bar{\nu}_\mu e$ is obtained by replacing $g_A^e(\nu_\mu e) = -\frac{1}{2} + 2\sin^2\theta_W$ with $g_A^e(\bar{\nu}_\mu e) = \frac{1}{2} - \sin^2\theta_W$. This leads to an $\alpha_{\text{em}} G_F \langle r^2 \rangle$ term in $\sigma(\bar{\nu}_\mu e)$ of the form $\frac{1}{3}(8\sin^2\theta_W - 1)$ which improves the sensitivity of the limit on $\langle r^2 \rangle$ when measurements of both cross sections[2] are utilized. *A priori,* the sign of $\langle r^2 \rangle$ can be positive or negative. If $\langle r^2 \rangle$ is taken to be positive, the 90%-C.L. limit[11] found is

$$\langle r^2 \rangle \leq 0.81 \times 10^{-32}\ \text{cm}^2, \tag{4}$$

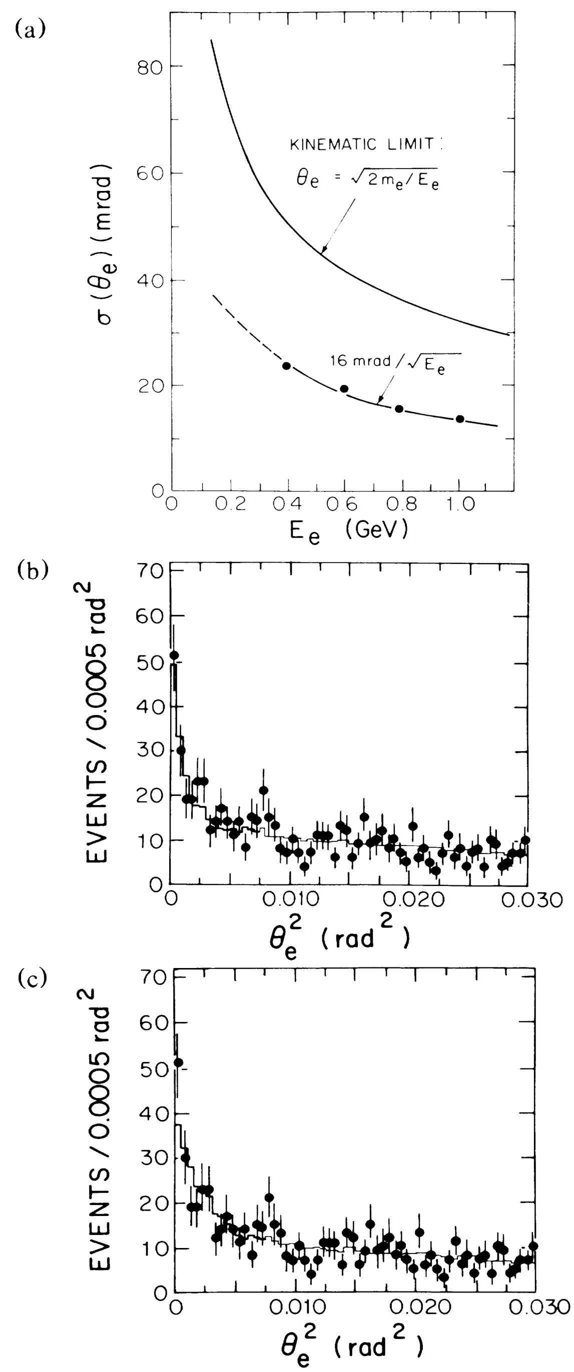

FIG. 2. (a) The resolution in electron angle $\sigma(\theta_e)$ as a function of electron energy E_e of the detector with which the angular distribution in Fig. 1 was obtained. The points were measured in a test beam with a number of detector elements identical to those of the full detector. (b) The observed distribution in θ_e^2 (points) and the Monte Carlo–calculated distribution (histogram) with the experimental angular resolution included but the y dependence of $d\sigma(\nu_\mu e)/dy$ suppressed. (c) Points are the same as in (b) but the Monte Carlo histogram is calculated for only the y-dependent term in $d\sigma(\nu_\mu e)/dy$, again allowing for experimental resolution.

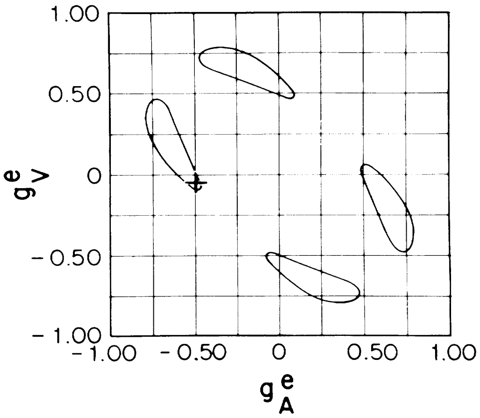

FIG. 3. The four areas in the g_V^e vs g_A^e space allowed by the measurements of $d\sigma(\nu_\mu e)/dy$ and $\sigma(\nu_\mu e)$ reported here. The cross is the value expected from the electroweak theory with $\sin^2\theta_W = 0.229$. Both statistical and systematic errors have been taken into account in the construction of these 67%-C.L. contours.

while if $\langle r^2 \rangle$ is taken as negative, the 90% C.L. becomes

$$\langle r^2 \rangle \geq -7.3\times 10^{-32}\ \mathrm{cm}^2. \tag{5}$$

The contribution to $\sigma(\nu_\mu e)$ of a possible neutrino magnetic moment is of the form

$$\alpha_{\mathrm{em}} f^2 [\ln(E_\nu/E_e^{\mathrm{min}}) - 1 + E_e^{\mathrm{min}}/E_\nu],$$

where $E_e^{\mathrm{min}} = 0.2$ GeV is the experimental low-energy cutoff on E_e. The 90%-C.L. limit[11] on f is then

$$f \leq 0.95\times 10^{-9}. \tag{6}$$

The measurements presented here of $\sigma(\nu_\mu e)$ and of $d\sigma(\nu_\mu e)/dy$ inferred from the θ_e^2 distribution yield values of the weak coupling constants of the electron, g_V^e and g_A^e, which are completely consistent with the standard electroweak model. This is the first instance in which values of g_V^e and G_A^e have been obtained from a single experiment that determined the total and differential cross sections of $\nu_\mu e \to \nu_\mu e$. The well understood statistical and systematic errors of the experiment lead to limits on the neutrino charge radius and possible neutrino magnetic dipole moment which are consistent with earlier limits on those quantities[5] determined by different experimental techniques. The limit on the muon-neutrino charge radius in Eq. (4) is superior to the limit on the structure of the muon neutrino ($\sim 7\times 10^{-16}$ cm) found by comparison of the Q^2 dependence of the nucleon structure function $F_2(x,Q^2)$ measured in inelastic μ-N and ν_μ-N scattering.[12] It is of particular interest that the limit on the muon-neutrino charge radius found here is similar in magnitude to the limit of $\sim 10^{-16}$ cm on possible internal structure of the electron and muon.[13]

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