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ELASTIC SCATTERING OF MUON NEUTRINOS AT B.N.L.

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In this paper measurement of the purely leptonic reactions: $\nu_\mu e \to \nu_\mu e$ and and $\bar{\nu}_\mu e \to \bar{\nu}_\mu e$, and the semileptonic reactions: $\nu_\mu p \to \nu_\mu p$ and $\bar{\nu}_\mu p \to \bar{\nu}_\mu p$ are presented and discussed in terms of the standard model. The data also places limits of interest on the magnitudes of a possible neutrino charge radius and a neutrino magnetic moment.

The data reported here were taken at the Brookhaven National Laboratory Alternate Gradient Synchrotron (A.G.S.) 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.[1,2]

In the standard electroweak model, the differential cross sections for neutrino electron elastic scattering are given by

$$\frac{d\sigma(\overset{(-)}{\nu}_\mu e)}{dY} = \frac{G_F^2 m_e E_\nu}{2\pi} [(g_V \pm g_A)^2 + (g_V \mp g_A)^2 (1-Y)^2]$$

where $Y = 1 - E_e\theta_e^2/2m_e$ and ; the vector and axial vector coupling constants are related to $\sin^2\theta_W$ by: $g_V = \frac{1}{2} - 2\sin^2\theta_W$ and $g_A = -\frac{1}{2}$. Within this model a precision measurement of $\sin^2\theta_W$ comes from a measurement of the ratio of the cross sections, $R = \sigma(\nu_\mu e)/\sigma(\bar{\nu}_\mu e)$.

The $\nu_\mu e$ and $\nu_\mu e$ data were collected from 2.26×10^{19} protons on the neutrino producing target (P.O.T.) and 3.4×10^{19} P.O.T. respectively. The neutrino electron elastic scattering data analysis, procedures, and the treatment of backgrounds have been described previously.[3,4]

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Shown in Figure 1 and 2 are the final $\nu_\mu e(\bar{\nu}_\mu e)$ data as a function of θ_e^2 in the interval $\theta_e<0.03$ rad with $210\text{MeV}<E_e<2100\text{MeV}$. The neutrino (antineutrino) data has been divided into "electron" and "gamma" like showers based on ionization information near the front of the showers. The presence of a signal from $\nu_\mu e\to\nu_\mu e$ and $\bar{\nu}_\mu e\to\bar{\nu}_\mu e$ is evident since kinematics require that $\theta_e^2\leq 2m_e/E_e$, and thus the signal is confined almost completely within the interval $0<\theta_e^2<.005$ rad^2. The "gamma" and "electron" distributions show a background slowly rising with decreasing θ_e^2 which consists mainly of: 1) photons from π° mesons produced in neutral current reactions, and 2) electrons from $\nu_e n\to e^- p$ ($\nu_e p\to e^+ n$) induced by a small contamination of $\nu_e(\nu_e)$ in the neutrino (antineutrino) beam. After background subtraction a signal of 107 ± 15 $\nu_\mu\bar{e}$ and 59 ± 10 $\nu_\mu e$ events remain.

To determine the cross sections $\sigma(\nu e)$ and $\sigma(\bar{\nu}_\mu e)$ and their ratio, we have indirectly measured the integrated incident neutrino fluxes using samples of quasielastic events $\bar{\nu}_\mu p\to\mu^+ n$ and $\nu_\mu n\to\mu^- p$ with small momentum transfer, $Q^2<0.4$ (GeV/c)^2. Samples of 3.38×10^4 $\mu^+ n$ and 8.87×10^4 $\mu^- p$ (after background subtraction) were obtained. Correcting the signal and normalization samples for acceptances and efficiencies yields the total cross sections:

$$\sigma(\bar{\nu}_\mu e)/E_{\bar{\nu}_\mu} = [1.16 \pm .20(\text{stat}) \pm .14(\text{syst})] \times 10^{-42}\ \text{cm}^2/\text{GeV}$$

$$\sigma(\nu_\mu e)/E_{\nu_\mu} = [1.85 \pm .25(\text{stat}) \pm .27(\text{syst})] \times 10^{-42}\ \text{cm}^2/\text{GeV}$$

The fully corrected ratios of the normalized cross sections for $\nu_\mu e$ and $\bar{\nu}_\mu e$ scattering yield directly the ratio, R:

$$R = \sigma(\nu_\mu e)/\sigma(\bar{\nu}_\mu e) = 1.60 \begin{matrix} +\ .41 \\ -\ .31 \end{matrix} \pm .17$$

(stat) (syst)

The systematic error on this ratio is smaller than the systematic error on the individual cross sections due to cancellation of systematic uncertainties (e.g. acceptances, energy scales, ...) in the ratio. Comparing this ratio[5] to the standard model cross section we obtain

$$\sin^2\theta_W = .192 \begin{matrix} +\ .027 \\ -\ .022 \end{matrix} \text{(stat)} \pm .013 \text{(syst)}$$

This value is dominated by systematic errors.

Even though these results are statistically, limited systematic errors important to any future elastic scattering experiments, will be discussed. The dominant systematic error arises from uncertainties in the backgrounds of the normalization samples. With tight cuts on the quasielastic data[3,4], 36% (27%) of the final $\mu^- p$ ($\mu^+ n$) samples consisted of single pion events ($\mu N\pi$) with an additional 4% (3%) from multipion events ($\mu N\pi\pi$). Uncertainties in the cross sections and acceptances of these backgrounds led to an uncertainty in R of 7%.

The excellent experimental resolution in θ_e (13 mrad/$\sqrt{E_e}$) combined with the large $\nu_\mu e$ statistics led us to consider the θe^2 dependence on the two Y in $d\sigma(\nu_\mu e)/dY$; namely the flat Y term and the term in $(1-Y)^2$. Monte Carlo shapes corresponding to the two terms are shown in addition to the data points in Figures 3a and 3b.

Fitting the relative contribution to the θ_e^2 shapes to the data points in θ_e^2 distribution determines $(g_V+g_A)^2$ and $(g_V-g_A)^2$, and yields the four 67% C.L. regions shown in Figure 4. Only one region is seen to be consistent with $\nu_\mu e \rightarrow \nu_\mu e$ in the standard model with $\sin\theta w=.231$, the world average value.[7] The region also contains the more precise values: $g_V=-.079\pm.060$ and $g_A=-.483\pm.042$ determined previously from the $\nu_\mu e$ and $\nu_\mu e$ cross sections. This calculation is first use of a Y-distribution in a νe elastic scattering measurement.

The $\overset{(-)}{\nu}_\mu e$ elastic scattering also proves to be a sensitive probe of neutrino structure. Any gauge theory of weak and electromagnetic interactions allows a non-zero charge radius, $\langle r^2\rangle$. The additional contribution to the $\nu_\mu e$ *cross section is:*

$$\frac{2}{3\pi} m_e E_\nu \left[\frac{\pi}{\sqrt{2}} \alpha_{em} G_F \langle r^2\rangle \left(\frac{8}{3}\sin^2\theta w-1\right) + \frac{\pi^2}{2}\frac{4}{9}\alpha_{em}^2 \langle r^2\rangle\right]$$

where for reasonable values of $\langle r^2\rangle$ the interference term dominates. Fixing $\sin^2\theta w=.232\pm.008$ from measurements of the W and Z masses and assuming $\langle r^2\rangle$ positive a 90% C.L. limit is found fitting our data: $\langle r^2\rangle \leq 0.81\times10^{-32}$ cm^2. This value is superior to the limit found in inelastic μ-N and ν_μ-N scattering.

In the standard model with massless, left-handed neutrinos, the magnetic dipole moment, defined as $fe/2m_e$ is identically zero. The contribution to $d\sigma(\nu_\mu e)/dY$, of a possible magnetic dipole moment is: $\alpha_{em} f^2[(1-Y)^2/Y]$ Fixing $\sin^2\theta w$ as in the charge radius limit, we obtain a 90% C.L. limit on f of: $f<.95\times10^{-9}$ Bohr Magnatons. This limit approaches in sensitivity the bound, $f<10^{-10}$, obtained from astrophysical arguments.

Since the magnetic dipole moment contributes as f^2 to the elastic scattering cross section it will be difficult to improve the quoted limit on f. A future experiment decreasing the overall experimental error by a factor of ten will only improve this limit by slightly better than a factor of three. Low energy $\nu_e e$ elastic scattering experiments are very sensitive to a magnetic dipole moment and should improve this limit in the near future. Due to the interference term, it will be easier for future experiments to improve on the quoted charge radius limit. Unfortunately the standard model prediction of $\langle r^2\rangle \sim 10^{-34}$ cm^2 is probably unattainable in neutrino electron elastic scattering experiments.

The νp and $\bar{\nu}p$ elastic scattering data were obtained from separate exposures of $.55\times10^{19}$ P.O.T. and 2.5×10^{19} P.O.T. respectively. The $\nu_\mu p$ and $\bar{\nu}_\mu p$ differential cross sections depend on the quantities: G_F, M_V and M_A, and and μ_p and μ_n, in addition to $\sin^2\theta w$. Details of these differential cross

sections are given in reference.[10] All these quantities are known to a precision better than that required by the measurement with the exception of M_A which we chose to constrain to the world average value.

The neutrino proton elastic scattering data analysis, procedures, and the treatment of backgrounds have been described previously. Elastic proton scattering candidates were single tracks ($Q^2 \geq .35(GeV/c)^2$) fully contained in our detector. To separate protons from pions (muons), separate confidence levels (C.L.) for each hypothesis were constructed for each candidate event from the observed energy deposits in the scintillators and PDT's. The results are shown in Figure 5. Clear separation between protons and pions (muons) is observed.

After data selection the resulting samples of 1686 $\nu_\mu p$ and 1821 $\bar{\nu}_\mu p$ candidates contain backgrounds from: a) $\nu_\mu n \rightarrow \nu_\mu n$, b) neutral current single pion production, and c) a small contribution from multipion reactions. In addition corrections were necessary for elastic scatters produced by the measured contamination of "wrong-helicity" neutrinos in the beam. After background subtraction final samples of 951 $\nu_\mu p \rightarrow \nu_\mu p$ and 776 $\bar{\nu}_\mu p \rightarrow \bar{\nu}_\mu p$ remain

To determine the differential cross section the integrated incident neutrino flux was calculated as in the $\nu_\mu e$ analysis using quasielastic events. Shown in Figure 6 are the extracted absolute differential cross sections $d\sigma(\nu_\mu^2 p)/dQ$ and $d\sigma(\bar{\nu}_\mu p)/dQ^2$. The error bars are statistical in nature with an additional shape systematic error of 18% and 8% added to the points at Q^2=.45 and .55$(GeV/c)^2$ respectively. An additional 11% scale uncertainty has been assigned to each of the cross section measurements. Constraining M_A to the present world average value and fitting the differential cross sections to the standard model we obtain:

$$\sin^2\theta w = .220 \pm .016(stat) \begin{smallmatrix} + .023 \\ - .031 \end{smallmatrix} (syst)$$

The solid curves in Figure 5 represent this best fit to the data. Unlike the $\nu_\mu e$ analysis the result is dominated by systematic uncertainties.

The dominant sources of systematic error in the $\nu_\mu p(\bar{\nu}_\mu p)$ differential cross section consisted of: 1) 4% (4%) uncertainty from the single and multipion backgrounds to signal and normalization reactions, 2) 6% (3%) uncertainty due to knowledge of the neutrino flux shape as a function of energy, and 3) 4% (4%) uncertainty from secondary scattering of protons leaving the C^{12} nucleus. This last uncertainty required detailed nuclear Monte Carlo calculations which are discussed in detail along with these other systematic uncertainties in reference 12.

If $\sin^2\theta w$ is fixed to the value .220 and M_A is constrained to the world average value, a search may be made for additional terms in the axial vector form factor, $G_A(Q^2)$, due to neutral current contributions from heavy quark currents or a "non-standard" isoscalar axial vector current[10]. Writing $G_A(Q^2)=G_A^3(Q^2)(1+\eta)$, one finds η=.12±.07, one finds η=.12±.07, or equivalently $0.0<\eta<.25$ at 95% C.L. . The value extracted for $\sin^2\theta w$ is

insensitive to the choice of any η in this range. Any future experiment measuring neutrino proton elastic scattering will have to deal with this fundamental form factor uncertainty.

There is seen to be good agreement between $\sin^2\theta_W$ obtained from $\overset{(-)}{\nu}_\mu e$ and $\overset{(-)}{\nu}_\mu p$ elastic scattering. Furthermore these values of $\sin^2\theta_W$ are in good agreement with values of $\sin^2\theta_W$ determined from masses of the W- and Z-bosons[9], and inelastic electron-deuteron scattering, and from deep inelastic scattering[7]. Within present experimental errors of about seven percent, the weak neutral current parameter is a universal constant.

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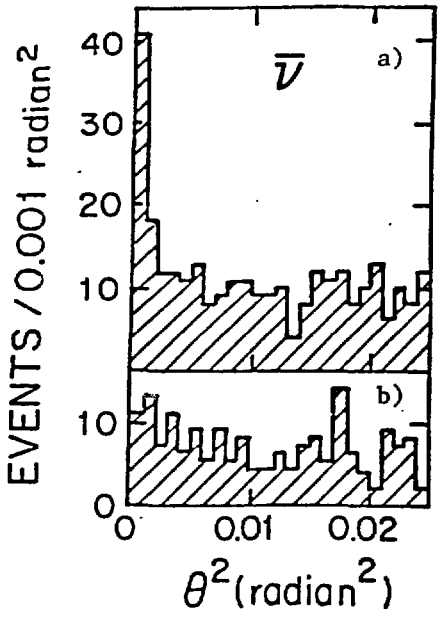

Fig. 1 The $\bar{\nu}_\mu e$ distribution in θ_e^2 for a) predominantly electron events, and b) predominantly photon events.

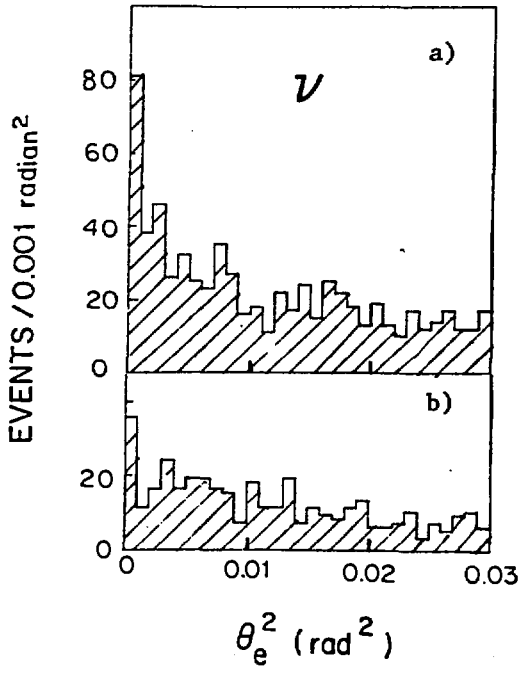

Fig. 2 The $\nu_\mu e$ distribution in θ_e for a) predominantly electron events, and b) predominantly photon events.

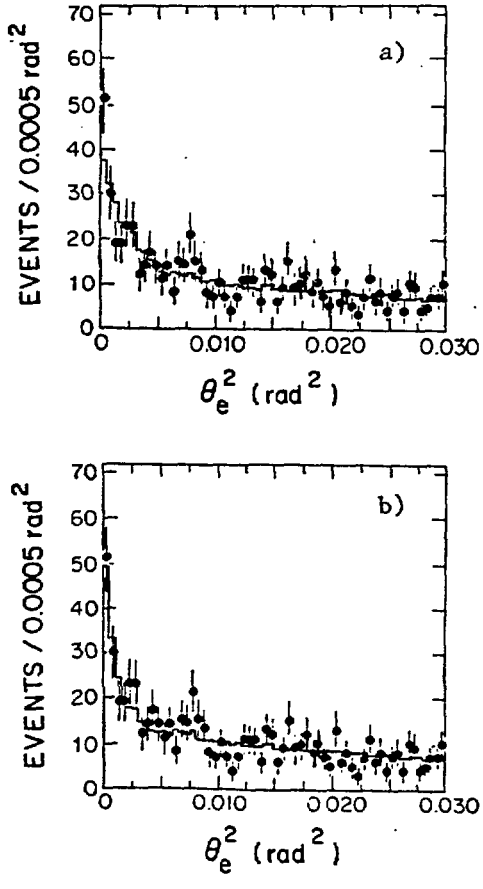

Fig. 3 The observed distribution in θ_e^2 (points and the Monte Carlo distribution (histogram) for:
a) a $(1-Y)^2$ term and
b) a flat term plus background.

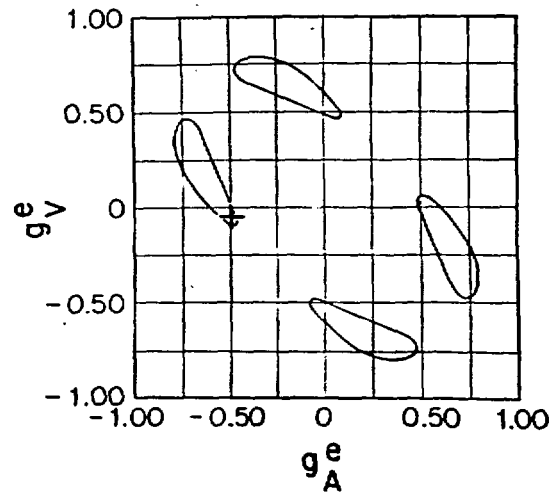

Fig. 4 The four areas in g_V vs g_A space (67% C.L.) allowed by the measurement of $d\sigma(\nu_\mu e)/dY$.

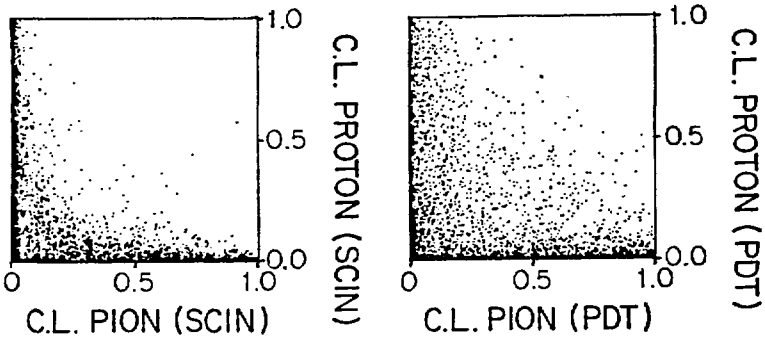

Fig. 5 C.L. for proton hypothesis vs C.L. for pion hypothesis by measurements in the scintillators (left) and PDT's (right).

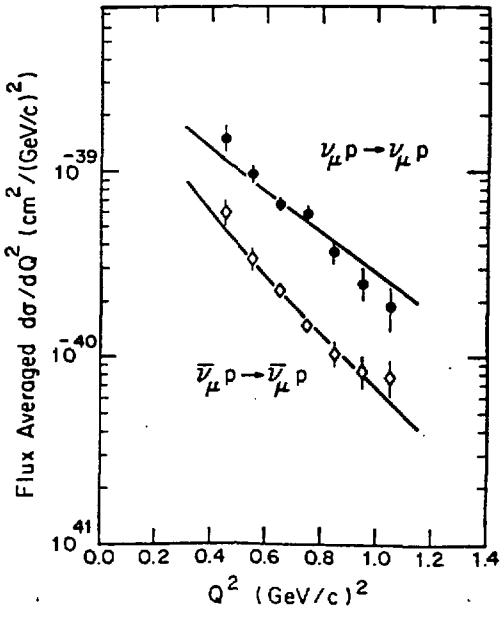

Fig. 6 The measured (data points) flux averaged differential cross sections for $\nu_\mu P$ and $\bar{\nu}_\mu P$ elastic scattering.