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New Determination of $\sin^2\theta_W$ from Ratio of Neutrino and Anti-Neutrino Elastic Scattering by Electrons

U.S.A.-JAPAN NEUTRINO COLLABORATION*

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Abstract

Measurements are made of the purely leptonic weak neutral current processes $\nu_\mu + e^- \to \nu_\mu + e^-$ and $\bar{\nu}_\mu + e^- \to \bar{\nu}_\mu + e^-$. Cross sections, the vector and axial vector couplings, and the Standard Model parameters $\sin^2\theta_W$ and ρ are determined. Results are: $\sigma_o(\nu_\mu) = 1.60\pm0.29\pm0.26$, $\sigma_o(\bar{\nu}_\mu) = 1.16\pm0.20\pm0.14$ (both in units of $10^{-42}\,cm^2/GeV$), $g_V^e = -0.079\pm0.060$, $g_A^e = -0.483\pm0.042$, $\rho = 0.967\pm0.082$, $\sin^2\theta_W = 0.209\pm0.029\pm0.013$.

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We report results on the weak neutral current parameters for the purely leptonic channels

$$\nu_\mu + e^- \to \nu_\mu + e^- \tag{1}$$

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

The individual cross sections for these reactions are given by

$$\sigma\left(\begin{matrix}\nu\\ \bar{\nu}\end{matrix}\right) = \frac{G_F^2 m_e}{2\pi} E_\nu \rho \left[(g_V^e \pm g_A^e)^2 + \frac{1}{3}(g_V^e \mp g_A^e)^2\right] \tag{3}$$

where g_V^e and g_A^e are the vector and axial vector couplings of the electron to the neutral intermediate vector boson and ρ is a parameter expressing the neutrino coupling. In the Standard Model of Glashow-Weinberg-Salam the values are

$$g_A^e = -\frac{1}{2};\quad g_V^e = (-\frac{1}{2} + 2\sin^2\theta_W);\quad \rho = 1$$

An important consequence of this model is the fact that the ratio of the cross sections (3) is given by

$$R = \frac{\sigma(\nu_\mu e)}{\sigma(\bar{\nu}_\mu e)} = 3\left[\frac{1 - 4\sin^2\theta_W + \frac{16}{3}\sin^4\theta_W}{1 - 4\sin^2\theta_W + 16\sin^4\theta_W}\right] \tag{4}$$

R is thus a quantity independent of ρ, depending only upon $\sin^2\theta_W$, and free from the complications of Q.C.D.

An additional, important practical result is that the error in $\sin^2\theta_W$ is given by

$$\Delta(\sin^2\theta_W) \simeq \frac{1}{8}(\Delta R/R) \tag{5}$$

when $\sin^2\theta_W$ is near 0.23. Hence, an eight percent error on $\Delta R/R$ would lead to $\Delta(\sin^2\theta_W) \simeq 0.01$ and corresponds to an equivalent error in intermediate vector boson masses of about $1.2 GeV/c^2$. In practice, since the absolute fluxes of neutrinos are not known, the cross sections of reactions (1) and (2) are normalized to the well measured quasi-elastic cross sections for $\nu_\mu + n \to \mu^- + p$ and $\bar{\nu}_\mu + p \to \mu^+ + n$. The practical limit on the systematic error of this approach is determined by the knowledge of the inelastic subtraction for these channels.

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This experiment (AGS E-734) was carried out at the alternating gradient synchrotron (A.G.S.) of the Brookhaven National Laboratory (B.N.L.). The neutrinos were obtained using a pulsed horn for focussing into a wide-band beam spectrum of average energy 1.5GeV (1.4GeV) for neutrinos (anti-neutrinos). The intensity was about 10^{10} neutrinos per GeV - m^2 - 10^{13} protons-on-target; this is sufficient to produce about one neutrino interaction (σ_{TOT}) per second in the 80 fiducial Mtons of our detector.

The most important requirements for achieving a good signal to noise for reactions (1) and (2) are angular resolution and a measurement of dE/dx early in the electromagnetic shower to distinguish between electron- and photon-initiated events.

From the point of view of systematic errors, the relative normalization in the flux ratio $\phi(\bar{\nu})/\phi(\nu)$ is dominant; the systematic error in the electron signal ratio, $N_e(\bar{\nu})/N_e(\nu)$, canceling almost exactly.

The detector[1] has been designed and constructed with the above points in mind. It is a very fine grain, fully active (liquid scintillator) electronic device of 200 Mtons (80 Mtons fiducial) with an effective radiation length of 60 cm (real space). The angular resolution (achieved with arrays of ~15,000 drift tubes) is $\Delta\theta_{x,y} \approx (16\ \text{mrad})/\sqrt{E(\text{GeV})}$; this is less than one half the kinematic limit for reactions (1) and (2). The energy resolution of the electromagneic showers is determined (2000 cells of liquid scintillator) to be $\Delta E_e/E_e = (13\%)/\sqrt{E_e(\text{GeV})}$. For particle identification, dE/dx is measured in both the drift tubes and scintillators which provide six measurements in the early part of the shower on 90% of the electrons. Out-of-time background (neutrons, cosmic rays, muon decays) are discriminated against by ±2 nsec timing and two-hit electronics. Additionally, a magnetic spectrometer at the end of the detector measures the beam composition for ν_μ and $\bar{\nu}_\mu$. The energy, angle and particle identification have been verified with appropriate test beam exposures.

The kinematics of reactions (1) and (2) is particularly distinctive; given in an obvious notation by

$$E_e\theta_e^2 = 2m_e(1 - E_e/E_\nu). \tag{6}$$

Thus there is a kinematic limit in E_e vs. θ_e^2 space of

$$E_e\theta_e^2 \lesssim 2m_e \tag{7}$$

At A.G.S. energies, this implies an average electron angle of roughly 40 milliradians.

The backgrounds are dominated by beam contamination of $\nu_e(\bar{\nu}_e)$ and by neutral current production of pi-zeros. There is a small contribution from very low energy mis-identified hadrons. The $\nu_e(\bar{\nu}_e)$ background occurs primarily via $\nu_e(\bar{\nu}_e) + n(p) \rightarrow e^-(e^+) + p(n)$ and is supressed by second prongs, Pauli exclusion, energy and angle cuts. The pi-zero neutral current production occurs dominantly through the 3/2 - 3/2 isobar channel; however, at AGS energies coherent production (a severe problem at FNAL and CERN energies) is small with no forward peak. The pi-zero background is suppressed by multiple photon conversions and energy-angle cuts as well as by dE/dx discrimination. All the backgrounds are nearly flat in θ^2 whereas 96% of the signal is contained within $\theta_e^2 < 0.01(\text{rad})^2$.

The results reported here derive from exposures of $8.8 \times 10^{18}(\nu_\mu)$ and $3.5 \times 10^{19}(\bar{\nu}_\mu)$ protons on target. This corresponds to about one-third of our neutrino data and all of our present anti-neutrino data. The analysis procedure and data flow is illustrated in Figure 1.

Guided by the kinematic conditions stated in (6) and (7) we plot in Figure 2 the resulting θ_e^2 distributions. A clear signal peak at small θ_e^2 upon an approximately flat distribution is visible in the samples containing dominantly electrons (Fig. 2a and 2c), while the distribution of the mainly photon samples (Fig. 2b and 2d) is seen to be without significant small angle enhancement. To extract the number of events in the signal region, $\theta_e^2 < 0.01(\text{rad})^2$, we have determined the backgrounds in the region $0.01 < \theta_e^2 < 0.03(\text{rad})^2$ and extrapolated them into the signal region. The fraction of photons in the signal region (typically, 38% of the total background in that region) is calculated directly from the electron-photon selection process. The remaining background in the signal region is attributed to $\nu_e(\bar{\nu}_e)$ quasi-elastics and to low energy hadrons that scatter inelastically or are attended by small showers (typically for $\bar{\nu}_e$, 44% quasi-elastic and 18% hadrons). The electron quasi-elastic component was obtained from a Monte Carlo calculation that satisfactorily describes data used in our oscillation study.[2] After background subtraction, which was done fitting the θ_e^2 distribution to the sum of the background components (taking the photon and low energy hadron distributions as flat) and the expected shape of reaction (2) including angular resolution, a signal of 59±10 events remains. Two other independent methods were used to perform this extraction and achieved excellent consistency. Following a similar procedure a signal of 51±9 events were found for reaction (1). These signals must be further corrected for acceptance, filter-scan efficiency, cuts, and "wrong sign" neutrino beam contamination -- typically, a total correction of a factor of two.

In order to normalize the fluxes and determine the cross sections we use a sample of charged current quasi-elastic $\nu_\mu(\bar{\nu}_\mu)$ events sampled uniformly throughout the running. We also measure the shape of ν_μ and $\bar{\nu}_\mu$ spectra for use in calculating appropriate averages. These samples are selected to be of low-Q^2 by requiring for the muon: $\theta_\mu < 15^\circ$, $p_\mu > 400$MeV/c, a single prong at vertex and the vertex contained in the same fiducial volume as that used for the $\nu_\mu(\bar{\nu}_\mu) - e^-$ signal. These normalization samples must also be corrected for acceptance, (0.16±.009 (ν_μ) and 0.29±0.008 ($\bar{\nu}_\mu$) and backgrounds (0.31±.03 (ν_μ) and 0.28±.03 ($\bar{\nu}_\mu$)).

Combining the signal and normalization data, we obtain

$$\sigma_o(\nu_\mu) = \frac{\sigma(\nu_\mu - e^-)}{E_\nu} = 1.60\pm0.29 \text{ Stat.}\pm0.26 \text{ Sys.} \times 10^{-42}\frac{\text{cm}^2}{\text{GeV}}$$

$$\sigma_o(\bar{\nu}_\mu) = \frac{\sigma(\bar{\nu}_\mu - e^-)}{E_{\bar{\nu}}} = 1.16\pm0.20 \text{ Stat.}\pm0.14 \text{ Sys.} \times 10^{-42}\frac{\text{cm}^2}{\text{GeV}}$$

leading to the ratio

$$R = 1.38^{+0.40}_{-0.31} \text{ Stat.}\pm0.17 \text{ Syst.}$$

and

$$\sin^2\theta_W = 0.209\pm0.029 \text{ Stat.} \pm 0.013 \text{ Sys.}$$

Figure 3 illustrates the functional relation between R and $\sin^2\theta_W$ as well as the principal values and their errors. The best value for the parameter ρ is 0.967±0.082 at this value of $\sin^2\theta_W$.

This result for the weak mixing parameter is in good agreement with that of CHARH[3] collaboration. Combining our result (E-734) with that of CHARH leads to $\sin^2\theta_W$ (combined) = 0.212±0.023.

As was mentioned previously, the model independent couplings, g_V^e and g_A^e, can also be extracted from these data. Figure 4a shows the elliptic bands allowed by this experiment. The four-fold ambiguity represented by the intersection of the bands is removed by the $\bar{\nu}_e - e$ reactor data[4] and the combined $e^+e^- \to \mu^+\mu^-$ asymmetry experiments.[5] The single resulting solution derived from this experiment is shown with 67% and 90% C.L. contours in Figure 4b; it yields the values

$$g_A^e = -0.483\pm0.042$$

$$g_V^e = -0.079\pm0.060$$

As is to be expected, these values are consistent with the G-W-S weak isospin assignments for the electron with $T_{3L} = -1/2$ and $T_{3R} = 0$.

What is the ultimate limit of this type of experiment and this one in particular? Can one hope to obtain errors on $\sin^2\theta_W$ significantly smaller than the radiative corrections? Currently, our precision is limited by the numbers of $\bar{\nu}_\mu e$ and $\nu_\mu e$ events; however, ultimately backgrounds in the normalization samples dominate.[6] These backgrounds arise from the presence of charged-current soft single-pion and multipion events. Our present error on the $\nu_\mu/\bar{\nu}_\mu$ flux ratio as determined from the μ^-p/μ^+n ratio is estimated to be 9%; more than half of this arises from uncertainties in pion production cross sections and nuclear effects. Thus, while there is still room for improvement, the range is not great. The contribution to the uncertainty in R from systematic differences in the treatment of $\nu_\mu e$ and $\bar{\nu}_\mu e$ samples is 8%; improved knowledge and understanding of our filter process gained during this analysis will lead to significant reductions when the remaining data is added to these and processed in a common way.

Another, large data taking run is scheduled for autumn 1985 this should bring the total number of events to 300 (ν_μ) and 150 ($\bar{\nu}_\mu$) leading to $\Delta R/R$ of perhaps 0.08 and $\Delta(\sin^2\theta_W) \cong 0.01$. While some further improvement in normalization backgrounds is possible, this experiment with the present detector size and available running time will not reach a level of ±0.003 without a herculean effort.

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References

1. L. A. Ahrens et al, Phys. Rev. Lett. 51, 1514 (1983), G. Gidal et al (Particle Data Group), L.B.L. Report No. LBL-91, Suppl. UC-37, 1983 (unpublished), section on "Major particle detectors in elementary particle physics."

2. See L. A. Ahrens et al, "New Limit on the Strength of Mixing Between ν_μ and ν_e," Phys. Rev. D31, 2732 (1985); and same title in Proceedings of this conference.

3. F. Bergsma et al, Phys. Lett. 147B, 485 (1984).

4. F. Reines & H. Sobel, Phys. Rev. Lett. 37, 315 (1976).

5. See for example, A. Bohm, Proceedings of HEP83 International Europhysics Conference on High Energy Physics, Brighton, p. 686 (1983).

6. A further discussion of how the systematic errors are established is contained in L. A. Ahrens et al, Phys. Rev. Lett. 54, 18 (1985).

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DATA TAKEN TO DATE:

ν	$\bar{\nu}$
2.9×10^{19}	3.5×10^{19}

Protons on Target

SIGNAL PROCESSED TO DATE:

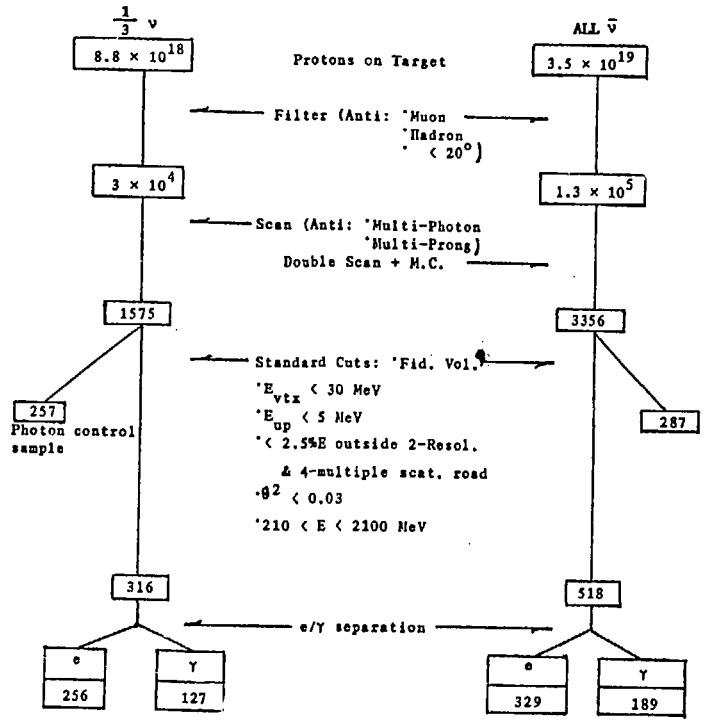

Figure 1
Data Analysis Flow Diagram

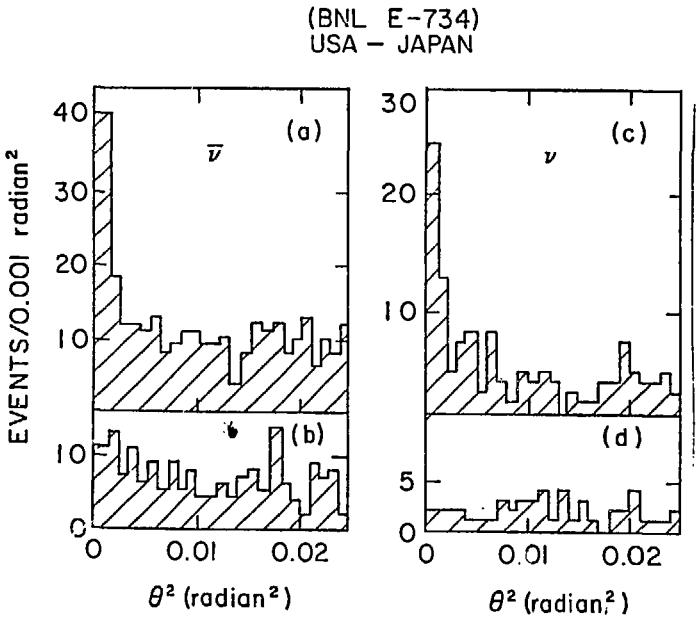

FIG. 2

Angle squared distribution of showers. dE/dx separated events are: photon candidates, (b) and (d); electron candidates, (a) and (c).

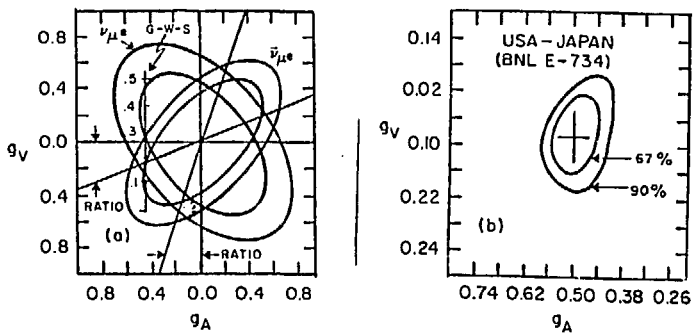

FIG. 4

a) Neutral current couplings, allowed regions (this experiment only). Cross hatched regions consistent from $\bar{\nu}_e$-e experiments. b) Only solution allowed by this experiment consistent with $\bar{\nu}_e$-e and e^+e^- experiments. See text for best fit values.

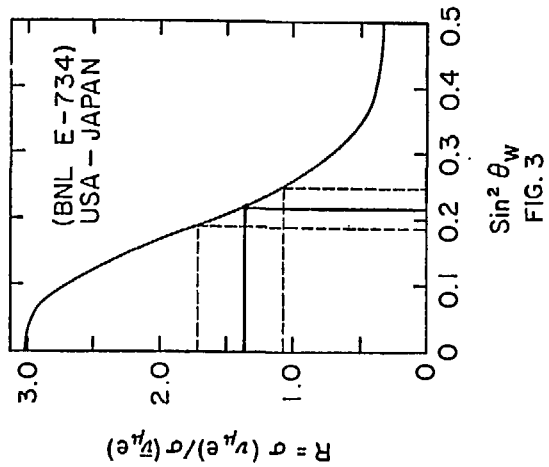

FIG. 3

R versus $\sin^2\theta_W$, solid (light) curve; measures principal values, solid (heavy) lines; errors, dashed lines.