

Measurement of the Cross Section of $\nu_\mu + e^- \rightarrow \nu_\mu + e^-$

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The result of a measurement of $\sigma(\nu_\mu + e^- \rightarrow \nu_\mu + e^-)$ is presented. With use of neutrinos of mean energy 1.5 GeV from the Brookhaven National Laboratory alternating gradient synchrotron and a massive, active, high-resolution detector, a signal of 51 ± 9 events with an average signal-to-background ratio greater than 2:1 is observed. $\sigma(\nu_\mu e^- \rightarrow \nu_\mu e^-) = [1.60 \pm 0.29(\text{stat}) \pm 0.26(\text{sys})] E_\nu(\text{GeV}) \times 10^{-42} \text{ cm}^2$ is obtained.

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The fundamental weak neutral-current process $\nu_\mu + e^- \rightarrow \nu_\mu + e^-$ was first observed¹ in 1978, and has since been studied in several experiments.²⁻⁶ With one exception,¹ those experiments utilized neutrinos of mean energy ≈ 20 GeV to initiate the interaction, primarily because the cross section ($\approx 10^{-42} \text{ cm}^2$ at 1 GeV) increases linearly with incident neutrino energy. This advantage in signal rate is in part, however, dissipated by backgrounds resulting from the high rate of inelastic processes and coherent neutral-pion production.⁷ Present knowledge of the total cross section $\sigma(\nu_\mu + e^- \rightarrow \nu_\mu + e^-)$ is largely determined by two experiments with the smallest quoted errors,^{4,5}

which yielded the following for $\sigma/E_\nu \times 10^{42}$: $1.4 \pm 0.3 \pm 0.2$, and $2.1 \pm 0.55 \pm 0.49$, in cm^2/GeV .

In the measurement of $\sigma(\nu_\mu + e^- \rightarrow \nu_\mu + e^-)$ reported in this paper, use is made of a low-energy ($\langle E_\nu \rangle = 1.5$ GeV) neutrino beam and a highly segmented detector of good resolution.⁸ This permits a reduction in the backgrounds mentioned above. The utilization of the high repetition rate and flux of the alternating gradient synchrotron (AGS) of the Brookhaven National Laboratory compensates for the lower cross section, resulting in an observed event rate for the signal of 1.5 events/day in the 75 metric tons (fiducial) of our 170-metric-ton detector. The measured signal

to background ratio which results is in excess of 2:1. Absolute normalization of the signal is accomplished by comparison with a specified fraction of the low- q^2 region of the well measured⁹ quasielastic process $\nu_\mu + n \rightarrow \mu^- + p$.

The detector¹⁰ is constructed of vertical planes of liquid scintillator and proportional drift tubes. A liquid-scintillator plane consists of sixteen cells, each 25 cm high by 8 cm in the beam direction by 425 cm in transverse length, viewed by a photomultiplier tube at each of its ends. A plane of proportional drift tubes (PDT) has 54 cells, each 7.5 cm high by 3.75 cm thick by 410 cm in length. Two PDT planes with sense wires oriented at right angles (x and y directions) and one liquid-scintillator plane constitute a module; there are 112 close-packed modules with total mass of 140 metric tons. Immediately downstream of the detector is a 30-ton shower counter of area 4 m \times 4 m with 12 radiation lengths to provide additional containment of showers from events occurring at the downstream end of the detector. Further downstream is a magnet of aperture 1.8 \times 1.8 \times 0.46 m³ for measurement of the antineutrino contamination present in the incident neutrino beam, and study of the very-low- q^2 region of the ν_μ -induced quasielastic process.

The detector is operated in a triggerless mode; it accepts events during neutrino bursts from the AGS (typically 40 per minute). Each burst is of 3 μ sec total duration and reflects the rf structure of the circulating proton beam in the AGS [twelve pulses of full width at half maximum (FWHM) 30 nsec spaced apart by 220 nsec], which aids in significantly reducing neutron-induced background¹¹ and the number of unrelated tracks per event. A pulse height is available from every cell in the target detector; the liquid-scintillator cells can also yield a second pulse height occurring within a 10- μ sec interval. The PDT cells yield track positions with resolution of about 1.5 mm.

The results presented here were obtained from 1.25×10^6 AGS bursts corresponding to 8.8×10^{18} protons on the neutrino-producing target. On the average, one neutrino interaction occurs in the detector per burst. The 10^6 neutrino events were subjected to a loose software filter based primarily on scintillator information to eliminate most events that did not exhibit an electromagnetic shower within a given angular interval relative to the incident neutrino beam. The 3×10^4 events that passed through the filter were scanned by eye to remove the remaining events which obvi-

ously did not qualify as electromagnetic showers (primarily misidentified muons and multiprongs). This procedure yielded a primary event sample of 316 events within a specified fiducial region with a single, clean electromagnetic shower at angle $\theta \leq 0.18$ rad.

At AGS energies, the dominant sources of background are photons from forward π^0 , and electrons from $\nu_e + n \rightarrow e^- + p$ induced by the approximately 0.5% contamination of ν_e in the incident beam. Two secondary-shower-event samples were obtained to aid in discriminating against these backgrounds. One of these samples (S1) was selected to consist primarily of events of the type $\nu_e + n \rightarrow e^- + p$. To be accepted for this sample an event must have satisfied either (a) $E > 2000$ MeV or (b) $E > 1000$ MeV and $\theta > 0.10$ rad; additionally, an energy deposit > 30 MeV in the vertex cell was required. The second sample (S2) consisted of events containing a photon-induced shower which was recognized unambiguously by its time and space relationship to an upstream event vertex. A third sample (S3) consisted of clearly recognized muons. The distributions of pulse heights from the elements of the module immediately downstream of the shower vertex are shown for the samples S3, S1, and S2 in Figs. 1(a), 1(b), and 1(c), respectively. The S2 distributions are wider, and have peaks at about twice the pulse heights of the S1 distributions.

The pulse height distributions of the 316-event primary sample are shown in Fig. 1(d). Their appearance suggests that the distributions are composed of a combination of ones similar to S1 and S2 (i.e., electrons and photons, respectively). To select a relatively clean sample of electron showers we proceed on this assumption and divide the primary sample into two subsamples by cuts on the pulse heights of the appropriate liquid-scintillator and PDT cells.¹² These loose cuts apportion the photon showers in the primary sample about equally between the two subsamples, but leave about 95% of the electron showers in one of the subsamples. In addition, the energy of selected showers is limited to the interval $210 < E < 2100$ MeV to reduce backgrounds.

Guided by the kinematic condition, $E \theta^2 = 2m_e(1 - E/E_\nu)$, for $\nu_\mu + e^- \rightarrow \nu_\mu + e^-$, we plot in Fig. 2 the distributions in θ^2 for the two subsamples. One sees in the electron-shower subsample [Fig. 2(a)] a clear peak at small θ^2 and, within statistics, a flat distribution at larger angles. The distribution in θ^2 of the photon-shower subsample in Fig.

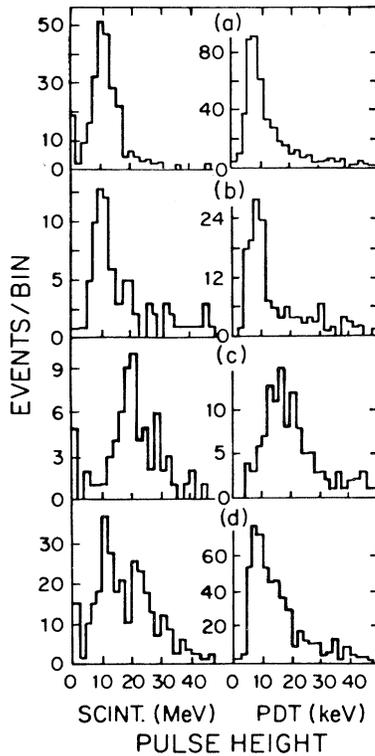


FIG. 1. The pulse height distributions observed in the detector elements (liquid scintillator and x and y proportional drift tube planes) immediately downstream of a track or event origin. Distributions are for (a) the sample (S3) of muons; (b) the sample (S1) of $e^- + p$ events; (c) the sample (S2) of photon-induced events; and (d) the primary event sample of 316 events containing the $\nu_\mu + e^- \rightarrow \nu_\mu + e^-$ signal.

2(b) is flat with no evidence of a peak at small angles. The θ^2 distribution of the photon-induced sample (S2), shown in Fig. 2(c), is also flat with no excess at small θ^2 . In Fig. 3 are shown the corresponding distributions in $E\theta^2$.

The signal of 51 ± 9 electrons from $\nu_\mu + e^- \rightarrow \nu_\mu + e^-$ (above a background of 25 ± 3) is extracted from the θ^2 distribution of Fig. 2(a); the region $0.01 \leq \theta^2 \leq 0.032$ establishes the flat background level. Within statistical errors, different cuts on the θ^2 distribution or use of the $E\theta^2$ distribution [Fig. 3(a)] yield the same result. Corrections must be made to this number for losses due to the applied cuts (pulse height, 5%; $\theta^2 < 0.01$ rad 2 , 13%; $210 < E < 2100$ MeV, 27%), and for inefficiencies (angle reconstruction, scanning, filtering, 21%).

To make an absolute determination of $\sigma(\nu_\mu + e^- \rightarrow \nu_\mu + e^-)$, we select 6022 $\nu_\mu + n \rightarrow \mu^- + p$ events with muon angle θ_μ less than 0.26 rad sampled

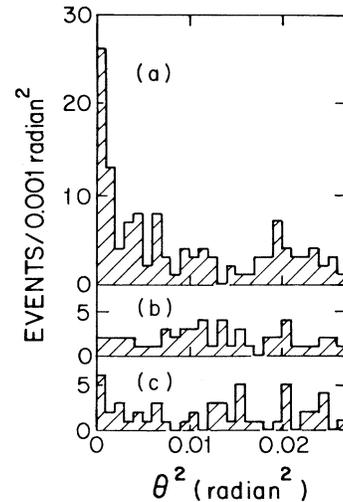


FIG. 2. (a) and (b) Division of events with $210 < E < 2100$ MeV in the primary event sample into two sub-samples: (a) Distribution in θ^2 of showers satisfying a loose requirement of a minimum-ionizing-particle pulse height immediately downstream of the shower origin (see Fig. 1); (b) distribution in θ^2 of events failing the minimum-ionizing-pulse-height criterion; (c) distribution in θ^2 of the photon-induced sample (S2).

for 13% of the data throughout the run. Backgrounds of $\mu^- n \pi^+$ and $\mu^- p \pi^+$ (13%) and $\mu^- p \pi^0$ (4%) were subtracted; the former was determined from observation of the $\pi - \mu - e$ decay chain, while the latter was estimated from events with extra

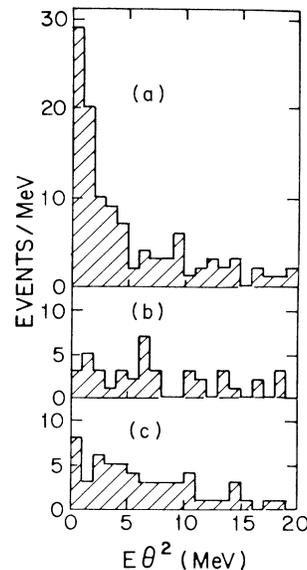


FIG. 3. Distributions in $E\theta^2$ for the same event samples as in Fig. 2. Note that the abscissa bin size is 1 MeV.

energy depositions. Corrections were made for the fraction of the $\nu_\mu + n \rightarrow \mu^- + p$ cross section actually observed (16%) and inefficiencies (filtering, reconstruction, 24%). The Monte Carlo calculation from which the value of 16% was obtained included the effects of Fermi momentum and the Pauli exclusion principle. The distributions in θ_μ and proton kinetic energy from a Monte Carlo calculation agreed well with observed distributions. Additional corrections, common to both the signal and the normalization reactions, such as hardware errors and event loss due to the presence of a simultaneous but unrelated track, cancel almost identically and are accounted for in the overall systematic error.

This analysis yields the result

$$\sigma(\nu_\mu + e^- \rightarrow \nu_\mu + e^-) = [1.60 \pm 0.29(\text{stat}) \pm 0.26(\text{sys})] \\ \times E_\nu (\text{GeV}) \times 10^{-42} \text{ cm}^2.$$

We anticipate that future running will lead to samples of more than 100 events each of $\nu_\mu + e^- \rightarrow \nu_\mu + e^-$ and $\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-$, which, in combination with the excellent signal-to-background ratio of this experiment, should lead to a precision measurement of $\sin^2\theta_w$.

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⁸The measured resolutions in θ and shower energy E are $\Delta\theta = (0.022 \text{ rad})/[E(\text{GeV})]^{1/2}$ and $\Delta E/E = 0.15/[E(\text{GeV})]^{1/2}$.

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¹²The procedure defined a photon shower as one in which the pulse height in the appropriate liquid-scintillator cell is greater than 20 MeV and a minimized average of the pulse heights in the adjacent x and y PDT cells is greater than 12 keV. An electron shower is one not satisfying those criteria.