Observation of the Reaction $\nu_\mu + p \to \nu_\mu + p$†

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(Received 24 March 1976; revised manuscript received 6 May 1976)

We have observed the elastic neutral-current reaction $\nu_\mu + p \to \nu_\mu + p$ and compared it to the quasielastic reaction $\nu_\mu + n \to \mu^- + p$. We have measured the ratio of the two reactions to be 0.23 ± 0.09.

We have observed the elastic neutral-current reaction[1]

$$\nu_\mu + p \to \nu_\mu + p \tag{1}$$

and the quasielastic reaction,

$$\nu_\mu + n \to \mu^- + p\,. \tag{2}$$

We report in this Letter the ratio of the two reactions

$$R_{\text{el}} = \sigma(\nu_\mu + p \to \nu_\mu + p)/\sigma(\nu_\mu + n \to \mu^- + p). \tag{3}$$

The experiment was performed in a fast extracted, horn-focused, wide-band neutrino beam at the Brookhaven National Laboratory alternating gradient synchrotron (AGS).[2] The description of the experimental setup and preliminary results on the observation of the reactions $\nu_\mu + n \to \mu^- + p + \pi^0$, $\nu_\mu + n \to \nu_\mu + n + \pi^0$, and $\nu_\mu + p \to \nu_\mu + p + \pi^0$ have been reported earlier.[3]

The existence of neutral currents in neutrino interactions has been reported by several groups.[4] However, the elastic neutrino scattering on protons has not been observed. There are two experimental results which have set an upper limit on the elastic scattering reaction.[5]

We now briefly describe the experimental setup. The proton beam, with an average intensity of 4.5×10^{12} protons per pulse, impinges on a sapphire target. It consists of 12 rf bunches which are 35 nsec wide and separated by 220 nsec. Secondary particles from the target are focused by a double-horn system. The neutrino flux peaks at between 1 and 2 GeV and extends to ~15 GeV. The detector is located 150 ft downstream of the main iron shield. There is an additional 8-ft-thick iron shield located 50 ft upstream of the detector. The detector consists of 21 modules of 6-ft × 6-ft narrow-gap aluminum spark chambers interspersed with scintillation counters and five 8-ft × 8-ft range chambers. The spark chambers record all interactions during the 2.4-μsec spill, while the counters record the pulse height and time of flight (TOF) of every hit during that period.

This report is based on the analysis of 170 000 pictures. The film was scanned for one- and two-prong events with a minimum visible track length of 2 in. of Al for either track. Events were measured and reconstructed in space and a 4-ft × 4-ft fiducial cut imposed. The reconstructed events were then matched to the scintillation counters hit by that event and TOF and pulse-height information were obtained.

A muon is defined as either a straight track with range greater than 2 interaction lengths, a straight track exiting from the detector, or a stopping track with visible multiple scattering. A proton is defined as a stopping track with no visible interaction and a track length equivalent to between 2 and 20 in. of Al. A proton track is also required to have at least five sparks in the chambers and hits in at least two adjacent counters for pulse-height measurements.

Candidates for the quasielastic reaction (2) are then events with one muon and one proton. Candidates for the elastic reaction (1) are events with a single proton. In both reactions, we require no additional charged tracks or neutrals pointing back to the vertex.

The reactions under discussion in this Letter are produced in C and Al nuclei instead of free protons. In order to demonstrate that we have

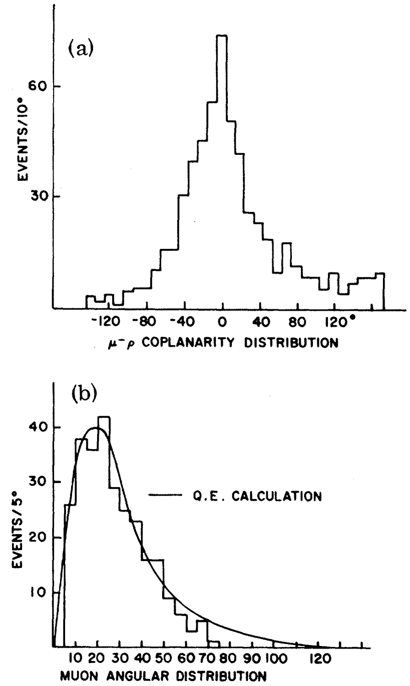

FIG. 1. (a) Coplanarity angle distribution of quasielastic candidates. (b) Muon angular distribution of quasielastic candidates.

indeed observed the quasielastic reaction, we show in Fig. 1(a) the distribution in φ, the angle between the transverse proton direction and the plane made by $\vec{P}_\nu$ and $\vec{P}_\mu$. Figure 1(b) shows the angular distribution of the muon as well as the Monte Carlo prediction. The inputs to this Monte Carlo calculation are the well-known quasielastic dynamics[6] and the neutrino spectrum calculated from 7-ft-bubble-chamber data. Most of the quasielastic events are in the range $1 < E_\nu < 2$ GeV. The Monte Carlo calculation also includes the effect of Fermi momentum of the initial nucleon. Based on these distributions, we believe that we have observed quasielastic events.

One of the major issues in this experiment is to show that the single straight track identified as a proton is induced by a neutrino and not a neutron. Since the detector is located far from all sources of neutrons, we measure the TOF of events to differentiate neutron- from neutrino-induced reactions. Figure 2(b) shows the TOF for all proton tracks. An in-time signal is observed above a substantial background. Using a right-handed coordinate system centered on the chambers with y up and z along the neutrino beam, we define an azimuthal angle φ in the x, y plane with $\varphi = 0$ along the x axis. We find that the background is strongly correlated with events interacting high in the detector (large y) with azimuthal angles ($-30 < \varphi < -150°$) towards the ground. We make the following cuts to reduce the neutron background: Reject events with (1)

$$y > 0.3 \text{ ft}, \quad -35° > \varphi > -150°,$$

$$|x| > 1.5 \text{ ft}, \quad 0 > \varphi > -180°;$$

and (2)

$$P_p < 550 \text{ MeV}/c, \quad \theta_p < 25°.$$

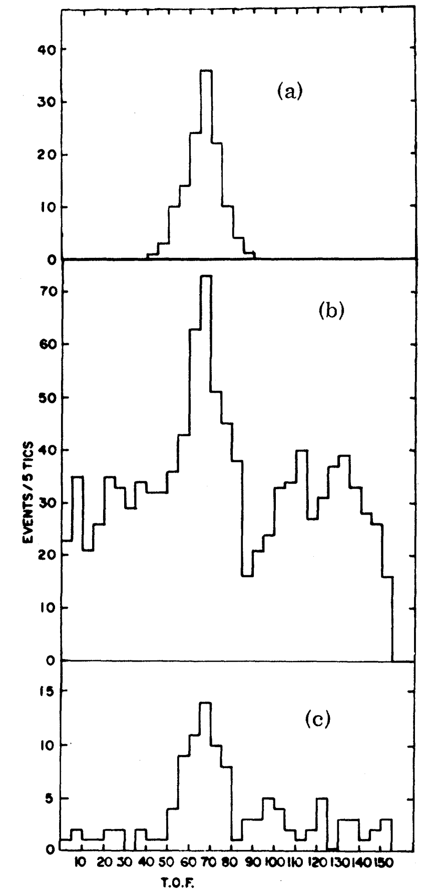

FIG. 2. TOF distribution (1 bin is 7 nsec) of (a) quasielastic candidates, (b) elastic candidates before cuts, (c) elastic candidates after γ-φ cuts and with $P_p > 550$ MeV/c and $\theta_p > 25°$.

The first cut reduces "sky-shine" background while the second enhances the elastic signal since most protons from elastic events are expected to have a proton angle of $> 25°$. The TOF of remaining events is shown in Fig. 2(c). The TOF distribution for quasielastic events is shown in Fig. 2(a).

A fast-neutron background may still produce events in and near the rf bucket. In our study of the reaction $\nu_\mu + p \to \nu_\mu + p + \pi^0$, we are quite sensitive to $n + p \to n + p + \pi^0$ contamination. Based on the distribution of $\nu + N \to \nu + N + \pi^0$ events along 5 interaction lengths of apparatus, we estimate a background of < 5% for neutrons with > 1 GeV/c momenta. Using the measured cross sections for $n + p \to p + n$ and $n + p \to n + p + \pi^0$, we compute a negligible background due to $n + p \to p + n$ near the rf bucket. The other possible background is due to neutrinos interacting near the detector and producing prompt neutrons. The apparatus is supported 7 ft above the ground with no nearby masses so that the ground is the only source of such events. Since a neutron from the ground would produce protons with upward azimuthal angles and would have to pass through 2–3 interaction lengths to interact in the top half of the detector, such a source would produce ~8 times as many upward pointing protons in the bottom half of the apparatus as in the top. The number of observed events pointing up is 17 for $y < 0$ and 14 for $y > 0$. We conclude that there is negligible background from this source. From Fig. 2(c) we have 55 events in 6 bins centered on the rf bucket. We estimate the residual sky-shine background to be 12 events, assuming a flat subtraction. We obtain 92 $\nu_\mu + n \to \mu^- + p$ and 43 $\nu_\mu + p \to \nu_\mu + p$ candidates.

Protons and pions can be separated in our apparatus by pulse-height characteristics. In the energy range of interest, protons are approximately twice minimum ionizing while pions remain minimum ionizing over most of their range. In determining the pulse height for each track, we average the pulse height of the last two counters. Figure 3 shows the pulse-height distribution of in-time elastic candidates, protons from quasielastic events, and minimum-ionizing particles. Because our counters are thin, pions do not stop in them so that the average sampled energy loss is very close to minimum ionizing. The total sample of pions which can contribute to the elastic signal will have a pulse-height distribution which is given by minimum-ionizing particles. A pulse height cut of > 12 then reduces the pion background by a factor of 3. After pulse-height cuts we obtain 77 $\nu_\mu + n \to \mu^- + p$ and 38 $\nu_\mu + p \to \nu_\mu + p$ candidates. The neutron background is now estimated to be 10 events.

Another source of background for the $\nu_\mu + p \to \nu_\mu + p$ reaction are the $\nu_\mu + n \to \mu^- + p$ events where the μ^- escapes detection. This correction is (0.08 ± 0.02) of the observed quasielastic signal

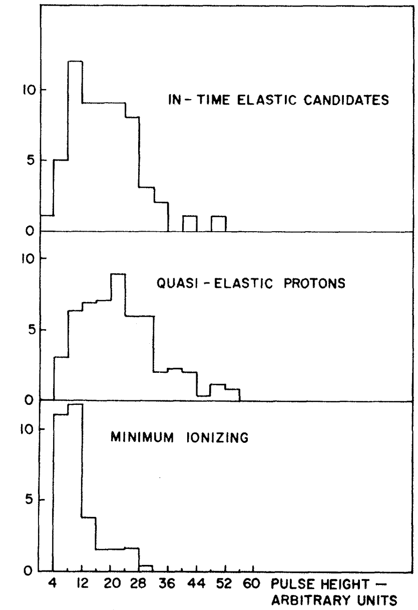

FIG. 3. Pulse height distributions for in-time elastic candidates, protons from quasielastic events, and minimum-ionizing particles. All distributions are normalized to elastic events.

[see Fig. 1(b)].

After pulse-height cuts, of 38 elastic candidates, 10 are estimated to be due to residual sky shine, 6 to the wide-angle muon problem, and 3 to pion contamination if $I(\pi N) = \frac{1}{2}$. Nineteen events remain if $I(\pi N) = \frac{1}{2}$ and 21 if $I(\pi N) = \frac{3}{2}$. As to the statistical significance of whether we have observed the elastic reaction, we have 4.4σ and 5.1σ, respectively. Increasing the pion contamination by a factor of 2 does not change the statistical significance of our data. The systematic errors are believed to be smaller than the statistical ones. We conclude that we have clearly observed neutral currents. For the measurement of $R_{\rm el}$, our statistical errors are larger, and we find $R_{\rm el} = 0.23 \pm 0.09$. Previous searches for this reaction[5] have obtained $R_{\rm el} = -0.08 \pm 0.20$ by Barish *et al.* and $R_{\rm el} = 0.12 \pm 0.06$ by Cundy *et al.*

There are several theoretical predictions of this ratio.[7] From the Weinberg-Salam model, the prediction is $R_{\rm el} = 0.07$ for $\sin^2\theta_W = 0.4$ and $0.3 < q^2 < 1.0$ GeV^2. We have observed the reaction $\nu_\mu + p \to \nu_\mu + p$ but our measurement of $R_{\rm el}$ is not sufficiently accurate to rule out any particular model.

We would like to thank R. Rau, D. Berley, H. Foelsche, W. Walker, A. Penzick, and the operating staff of the alternating gradient synchrotron for their excellent support during the setting up and running of this experiment. L. Holloway and C. Wang made important contributions in the early stages of the experiment. K. Gray, S. Marino, and G. Alverson provided indispensible technical expertise. The scanning and measuring staffs at Nevis Laboratory and the University of Illinois are thanked for their excellent work. Finally, we would like to thank Professor S. Adler and Professor C. Baltay for many interesting discussions.

†Research supported by the National Science Foundation and the U. S. Energy Research and Development Administration.

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[1]C. Y. Pang, in Second International Conference at Vanderbilt University, Nashville, Tennessee, 1–2 March 1976 (to be published).

[2]The neutrino spectrum used in this Letter is a calculation by R. Palmer (unpublished).

[3]W. Lee, in *Proceedings of the Seventeenth International Conference on High Energy Physics, London, 1974*, edited by J. R. Smith (Rutherford High Energy Laboratory, Didcot, Berkshire, England, 1975); W. Lee *et al.*, Colloq. Int. CNRS 245, 205 (1975); P. Sokolsky, in *Particles and Fields, 1975*, edited by H. Lubatti and P. M. Mockett (Univ. of Washington, Seattle, Wash., 1975).

[4]F. J. Hasert *et al.*, Phys. Lett. 46B, 121 (1973); A. C. Benvenuti *et al.*, Phys. Rev. Lett. 32, 127 (1974); B. Aubert *et al.*, Phys. Rev. Lett. 32, 1454 (1974), and 32, 1457 (1974); S. J. Barish *et al.*, Phys. Rev. Lett. 33, 448 (1974); Lee, in first paper of Ref. 3; B. C. Barish *et al.*, Phys. Rev. Lett. 35, 1316 (1975).

[5]D. C. Cundy *et al.*, Phys. Lett. 31B, 478 (1970); S. J. Barish *et al.*, in *Proceedings of the Seventeenth International Conference on High Energy Physics, London, 1974*, edited by J. R. Smith (Rutherford High Energy Laboratory, Didcot, Berkshire, England, 1975).

[6]T. D. Lee and C. N. Yang, Phys. Rev. Lett. 4, 307 (1960); C. H. Llewellyn-Smith, Phys. Rep. 3, 261 (1972).

[7]S. Weinberg, Phys. Rev. D 5, 1412 (1972); M. A. B. Bég and A. Zee, Phys. Rev. Lett. 30, 675 (1973); J. J. Sakurai, Phys. Rev. D 9, 250 (1974); J. J. Sakurai and L. F. Urrutia, Phys. Rev. D 11, 159 (1975); S. Adler, in Proceedings of the Sixth Topical Conference in Particle Physics, Honolulu, Hawaii, August 1975 (to be published).

Measurement of the Ratio $\sigma_c(\overline{\nu}_\mu + N \to \mu^+ + X)/\sigma_c(\overline{\nu}_\mu + N \to \mu^- + X)$ at High Energy*

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(Received 15 March 1976)

Using a sample of 4994 neutrino events and 2408 antineutrino events we have measured the ratio of antineutrino to neutrino charged-current cross sections up to 100 GeV. Neutrino flux-independent and flux-dependent measurements were carried out with good agreement between the two methods. Below 30 GeV the ratio was found to be 0.38 ± 0.06. The cross-section ratio shows a significant departure from this value above 50 GeV.

The ratio of antineutrino to neutrino charged-current cross sections on isoscalar targets and at high energy is an important parameter in neutrino physics. Previous measurements have established a ratio of approximately 0.4 in the vicinity of 30 GeV and below in energy.[1-4] We report here a measurement of this ratio at higher energies.[5]

Neutrino and antineutrino events were collected in the Harvard-Pennsylvania-Wisconsin-Fermilab detector at Fermilab.[2,3,6] The cross-section ratio was determined by two independent techniques using two samples of data: (a) a sample of 2900 neutrino and 570 antineutrino events which were obtained from a run in a neutrino beam focused by quadrupole triplet (the "quadrupole-triplet beam"), in which both neutrino and antineutrino events were detected simultaneously[7]; (b) the full sample of 4994 neutrino and 2408 antineutrino events which were obtained using