Study of the Reaction $\nu + n \rightarrow \mu^- + p$†

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166 events of the reaction $\nu+n\rightarrow\mu^-+p$ at an average neutrino energy of ~0.7 GeV have been observed in the Argonne National Laboratory 12-ft deuterium bubble chamber. The results are well described by the conventional current-current weak-interaction theory with three real form factors F_V^1, F_V^2, and F_A. Using electron-nucleon scattering results to fix the vector mass M_V at 0.84 GeV, and assuming a dipole form for F_A, we obtain the value 0.95 ±0.12 GeV for the axial-vector mass M_A.

We present results on the reaction

$$\nu+n\rightarrow\mu^-+p \tag{1}$$

observed in the 12-ft bubble chamber exposed to the neutrino beam at the Argonne National Laboratory zero-gradient synchrotron. This study of the simplest neutrino-hadron interaction is important since it extends nucleon β decay to larger values of the square of the four-momentum transfer, $Q^2=-(E_\nu-E_\mu)^2+(\vec{P}_\nu-\vec{P}_\mu)^2$, and so allows the cleanest determination of axial-vector form factor. This experiment is the first to study the quasielastic neutrino reaction using a deuterium target. From a scan of 231 000 pictures, 220 events of Reaction (1) were found of which 166, in a restricted fiducial volume, are used for analysis. The experimental conditions during this exposure have already been briefly described.[1]

Quasielastic neutrino events appear in the chamber as one-prong, two-prong, or three-prong events with the topology depending upon Q^2 and the spectator-proton momentum P_{p_s}. One-prong events are not used and a correction is made to the data sample to account for their loss for $Q^2<0.05$ (GeV/c).[2] The pictures were scanned using a single view at a magnification of ~0.14. All the film was rescanned using a different view and the two scans were compared using three views. To ensure both adequate track length for measurement and good event visibility, we use a fiducial volume of 10.04 m^3. This volume is entirely seen by any single camera and may be compared to the total illuminated volume of the chamber of 16 m^3. The overall scanning efficiency for Reaction (1) is $(96\pm2)\%$.

To evaluate possible contamination in the sample, we studied the quantities $M^2=(E_\mu+E_p+E_{p_s}-M_d)^2-(\vec{P}_\mu+\vec{P}_p+\vec{P}_{p_s})^2$ and φ, the space angle of the reconstructed vector sum of the momenta of the charge tracks relative to the beam direction. For neutrino-induced events, both quantities should be near zero, and a scatter plot shows a clear signal of events at the expected position over a low background of non-ν-induced events as discussed in Ref. 1; from the plot we estimate this background to be $(2\pm2)\%$. Events of the type $\nu+d\rightarrow\mu^-+p+\pi^0+p_s$ can also contaminate the elastic neutrino sample, provided the π^0 transverse momentum is small enough compared to E_ν so that the visible momentum points along the beam direction. We have checked the importance of this background by measuring the μ^- and p tracks in examples of the reaction $\nu+d\rightarrow\mu^-+p+\pi^++n_s$, and we estimate the background from this source to be $(1\pm1)\%$.

Since the neutrino beam direction is known to ~1°, a three-constraint fit to Reaction (1) was made for events with a visible spectator. For events which did not have a visible spectator, the kinematics program was given a starting value of 0 ± 50 MeV/c for P_x, P_y, and P_z of the spectator, and a three-constraint fit was also performed. Figure 1(a) shows the spectator momentum distribution[2]; events with a visible spectator have been cross hatched. The distribution is reasonably represented by a Hulthén distribution, except that there is a small excess of events with high momentum. These events are attributed to rescattering effects and are included in the sample.

The general matrix element[3] for the hadronic weak current has six complex form factors: F_V^1, F_V^2, F_V^3, F_A, F_P, and F_A^3. The simplifying assumptions which reduce the cross section to one unknown parameter M_A are as follows:

(1) Time reversal invariance. All form factors are real.

(2) Charge symmetry. F_V^1, F_V^2, F_A, and F_P are real; F_V^3, F_A^3 are imaginary and therefore

zero.

(3) Isotriplet current hypothesis. F_V^1 and F_V^2 are related to the isovector electromagnetic form factors which have been determined in electron scattering experiments.[4]

(4) Negligible induced pseudoscalar term. Using the partial-conservation of axial-vector currents suggestion of dominance of F_P by the pion pole, the induced pseudoscalar term has less than 1% effect on the cross section.[3]

(5) Dipole axial-vector form factor:

$$F_A = -1.23/(1+Q^2/M_A^2)^2. \quad (2)$$

The differential cross section can then be represented by the equation

$$d\sigma/dQ^2 = (M^2G^2\cos^2\theta_C/8\pi E_\nu^2)[A(Q^2) - B(Q^2)M^{-2}(4ME_\nu - Q^2 - M_\mu^2) + C(Q^2)M^{-4}(4ME_\nu - Q^2 - M_\mu^2)^2], \quad (3)$$

where G is the weak-interaction coupling constant ($GM^2 = 1.023\times10^{-5}$); θ_C is the Cabbibo angle ($\cos^2\theta_C = 0.94$); A, B, and C are functions of Q^2 and the three real form factors F_V^1, F_V^2, and F_A. Equation (3) must be modified to account for the effects due to the Pauli exclusion principle on the two final-state protons, as well as the Fermi motion in the deuterium nucleus.[5] This correction depends strongly on Q^2 and weakly on E_ν. It is shown in Fig. 1(b) as the factor $R(Q^2)$ by which one must multiply the free-neutron cross section to account properly for the deuteron effects.

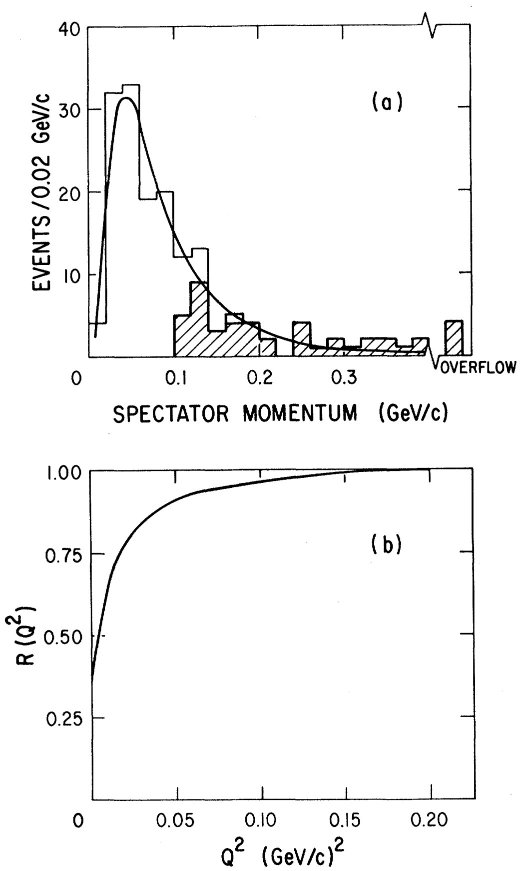

FIG. 1. (a) Fitted spectator-proton momentum distribution. Cross-hatched area, visible spectators; solid curve, Hulthên distribution. (b) Correction factor for the differential cross section to account for the Pauli exclusion principle and Fermi motion in the deuterium nucleus; see Ref. 5.

The determination of the neutrino flux requires a detailed discussion which we defer to a subsequent publication. The flux relies on extensive measurements of the pion production cross section from p-Be collisions at our beam energy,[6] together with careful monitoring of the proton beam intensity during the run. For these results, the total number of protons incident on the π-production target was 3.37×10^{17}, and we assign a $\pm15\%$ uncertainty to the overall neutrino-flux normalization. The flux used is shown in Fig. 2(a) together with the computed $\bar{\nu}$ contamination.

Figure 2(b) shows the total quasielastic cross section as a function of E_ν, and Fig. 2(c) shows the number of events, summed over all E_ν, as a function of Q^2. The solid curves in these figures are obtained by making a maximum-likelihood fit of the data with Eq. (3) modified by the low-Q^2 correction factor of Fig. 1(b). In this analysis, we define $\mathfrak{L}^{\text{tot}} = \mathfrak{L}^{\text{rate}} \times \mathfrak{L}^{\text{shape}}$, with

$$\mathfrak{L}^{\text{rate}} = \frac{1}{(2\pi)^{1/2}\sigma_N}\exp\left[-\frac{1}{2}\left(\frac{N-N(M_A)}{\sigma_N}\right)^2\right], \quad (4)$$

where N is the total number of observed events,

TABLE I. Measurements of the axial-vector mass M_A.

Reaction	M_A (GeV)	Reference
$\nu + d$	0.95 ±0.12	This experiment
$\nu + CF_3Br$	0.75 ±0.25	8
$\nu + Al$	0.65 ±0.42	9
$\nu + Fe$	1.05 ±0.20	10
$\nu + C_3H_8$	0.70 ±0.20	11
$ep \to e\Delta^+$	1.02 ±0.04	12
$ep \to e\Delta^+$	0.98 ±0.14	13
$ep \to e\Delta^+$	1.521 ±0.064	14

$N(M_A)$ is the expected number of events, and σ_N is the error on the expected number of events. Defining $\Phi(E_\nu)$ as the ν path length in the energy interval dE_ν at E_ν, we have

$$\mathcal{L}^{\text{shape}} = \prod_{i=1}^{N} \frac{(d\sigma/dQ^2)(Q_i^2, E_\nu{}^i, M_A)\,\Phi(E_\nu{}^i)R(Q_i^2)}{\iint (d\sigma/dQ^2)\Phi(E_\nu)R(Q^2)\,dE_\nu\,dQ^2}. \tag{5}$$

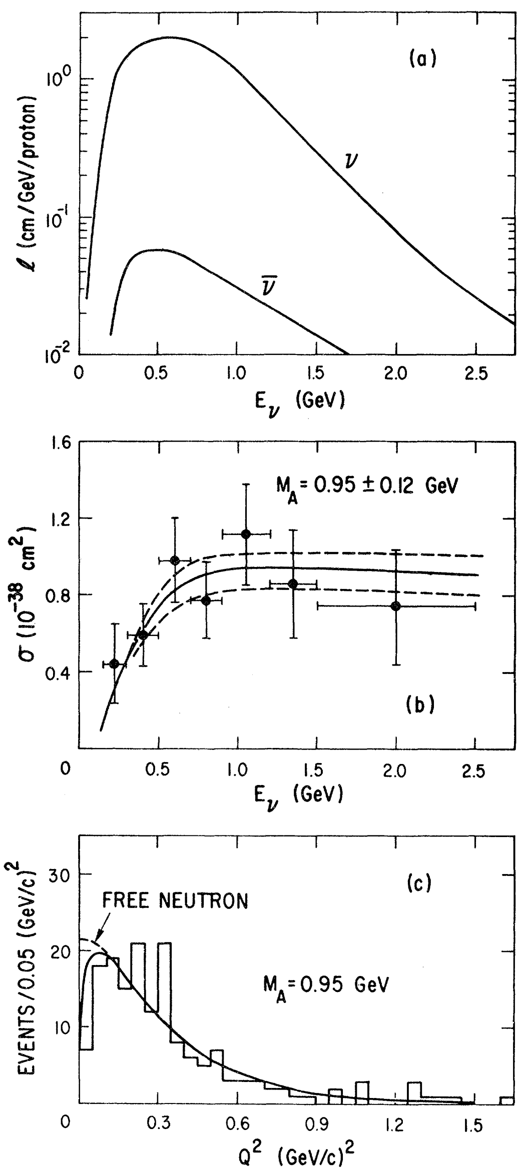

FIG. 2. (a) Incident ν and $\bar{\nu}$ flux distribution as a function of energy. (b) Cross section for $\nu + n \to \mu^- + p$ as a function of ν energy, obtained from the measured cross section for $\nu + d \to \mu^- + p + p_s$ corrected for low-Q^2 deuterium effects and the loss of one-prong events with $Q^2 \leq 0.05$ (GeV/c)^2. Error bars include all systematic errors. Curves correspond to Eq. (3) and indicate the one-standard-deviation limit with $M_A = 0.95 \pm 0.12$ GeV. (c) Measured differential cross section for $\nu + d \to \mu^- + p + p_s$ summed over all E_ν. Solid curve, Eq. (3) with $M_A = 0.95$ GeV and the $R(Q^2)$ function folded in; dashed curve, free-neutron differential cross section.

The first bin in Fig. 2(c), $Q^2 \leq 0.05$ (GeV/c)^2, contains all the one-prong events and has not been used in the fit. Fits to the shape and rate terms individually give $M_A{}^{\text{shape}} = 0.94 \pm 0.18$ GeV and $M_A{}^{\text{rate}} = 0.97 \pm 0.16$ GeV; the overall best fit is $M_A{}^{\text{tot}} = 0.95 \pm 0.12$ GeV. The errors include the effect of the flux uncertainty. The curves shown in Figs. 2(b) and 2(c) give the predicted values, with M_A as the parameter.[7]

We have found that our result for M_A is stable against subdivisions of the data, such as into high E_ν and low E_ν, position in the chamber, visible spectator and invisible spectator, etc. We have performed Monte Carlo trials and have found that the height of the likelihood function is well within the expected range, indicating that at least at the present statistical level, the theoretical formulas and assumptions are adequate and, in particular, the neutrino flux description is adequate in both absolute normalization and shape. If we allow M_V to be variable as well as M_A and make a two-parameter fit (using dipole form factors for both), we find $M_V = 0.72^{+0.20}_{-0.14}$ GeV and $M_A = 1.15^{+0.20}_{-0.35}$ GeV. We have also tried fitting the data with a monopole axial-vector form factor, with the vector form factor again fixed by the electron-scattering results. The monopole form gives an equally acceptable fit with $M_A = 0.57 \pm 0.10$ GeV.

In Table I, we summarize the previous measurements of M_A, using dipole form factors, from neutrino interactions[8-11] (all of which were done using a complex nucleus target), as well as the indirect estimates using threshold electroproduction data.[12-14] The five neutrino experiments are consistent with each other; their weighted average is 0.89 ± 0.08 GeV.

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[1]J. Campbell *et al.*, Phys. Rev. Lett. 30, 335 (1973).

[2]In this histogram, we have called the spectator the proton with the lower momentum. While this may distort somewhat the spectator distribution, it does not affect the essential physics results reported here, since the variables of interest are Q^2 and E_ν, neither of which depends on correct spectator identification.

[3]See, for example, the review article by C. H. Llewellyn Smith, Phys. Rep. 3C, 261 (1972).

[4]We have used the measured vector form factors as given by B. Bartoli *et al.*, Riv. Nuovo Cimento 2, 241 (1972). With $M_V = 0.84$ GeV, $F_V{}^1$ and $F_V{}^2$ differ from a dipole form by at most 5% for our range of Q^2.

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[7]A recent calculation [R. Tarrach and P. Pascual, "Relativistic Study of the Reaction $\nu + d \to p + p + \mu^-$" (to be published)] suggests that the effects of the deuteron D wave may lower our value for M_A by ~ 0.05 GeV.

[8]D. Perkins, in *Proceedings of the Sixteenth International Conference on High Energy Physics, The University of Chicago and National Accelerator Laboratory, 1972,* edited by J. D. Jackson and A. Roberts (National Accelerator Laboratory, Batavia, Ill., 1973), Vol. IV, p. 189.

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Test of the $\Delta S = \Delta Q$ Rule in K_{e_3} Decay*

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We report here the results of a test of the $\Delta S = \Delta Q$ rule in K_{e3} decay in which we observed ~ 1700 K_{e3} decays in the sensitive region of 0.25 to 4.8 $K_S{}^0$ mean lifetimes. We find, where X is the ratio of the $\Delta S/\Delta Q$ nonconserving to conserving amplitudes, $\mathrm{Re}X = -0.008 \pm 0.044$, $\mathrm{Im}X = -0.017 \pm 0.060$, and $|X| = 0.019$. The origin lies on the 0.65-standard-deviation likelihood contour; hence we find no evidence for a violation of the $\Delta S = \Delta Q$ rule in K_{e3} decay. $\Delta m = M_L - M_S$ and τ_S were also measured, giving $\Delta m = (0.557 \pm 0.038) \times 10^{10}\hbar$ sec^{-1} and $\tau_S = (0.867 \pm 0.024) \times 10^{-10}$ sec.

sec.

The $\Delta S = \Delta Q$ rule states that the change in strangeness must equal the change in electric charge for the hadrons in a weak decay. The K^0 decays show a CP nonconservation as yet unconnected with the rest of weak interactions, and a violation of the $\Delta S = \Delta Q$ rule could provide a link. While maximal $\Delta S/\Delta Q$ violation has already been ruled out, a violation at the limits of present experiments would impose a major constraint on theories of weak interactions. This rule has been most often studied in the decays $K^0, \bar{K}^0 \to \pi e \nu$ ("K_{e3}" decays), where a $\Delta S = -\Delta Q$ term would alter the temporal development of the amplitudes of the charge-conjugate channels, $\pi^- e^+ \nu$ and $\pi^+ e^- \bar{\nu}$. Assuming CPT invariance and neglecting terms of order ϵ, the CP-nonconserving amplitude, the temporal K_{e3} decay distribution $N^\pm(t)$ can be written

$$N^\pm(t) \propto |1+X|^2 \exp(-t/\tau_S) + |1-X|^2 \exp(-t/\tau_L) + [\pm 2(1-|X|^2)\cos(\Delta m t) - 4\,\mathrm{Im}X \sin(\Delta m t)] \exp[-\tfrac{1}{2}t(1/\tau_S + 1/\tau_L)],$$

where $\pm$ refers to the lepton's charge, $\Delta m \equiv M_L - M_S$, τ_S and τ_L are the lifetimes of the $K_S{}^0$ and $K_L{}^0$, and X is the complex ratio of the $\Delta S/\Delta Q$ nonconserving to conserving amplitudes. A violation would be most evident in the early $\pi^+ e^- \bar{\nu}$ decays of an initially pure K^0 beam.

Previous experimental results[1] are scattered around the origin in the X plane, but no single published experiment sets $|X| < 0.15$ to better than about 1 standard deviation. This experiment obtained some 1700 K_{e3}'s in the decay region 0.25 to 4.8 $K_S{}^0$ mean lifetimes. At the 1-standard-deviation level we conclude $|X| < 0.075$, and we believe our systematic errors in $|X|$ are no larger than 0.01.