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Quasi-Elastic Neutrino Scattering and the Axial Vector Form Factor*

E.G. Cazzoli, A.M. Cnops, P.L. Connolly, M.J. Murtagh,

R.B. Palmer, N.P. Samios and T.T. Tso

Brookhaven National Laboratory, Upton, New York 11973

ABSTRACT

An analysis of 168 quasi-elastic neutrino interactions $\nu n \rightarrow \mu^- p$ in deuterium yields a value of $M_A = .76^{+.14}_{-.40}$ GeV for the axial vector mass.

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The electromagnetic structure of the nucleon has been successfully explored utilizing high energy electrons as probes.⁽¹⁾ An investigation of the corresponding weak structure of the nucleon has been under way for some time via an examination of the quasi-elastic neutrino reaction

$$\nu n \rightarrow \mu^- p. \quad (1)$$

The bulk of these investigations have been performed on complex nuclei⁽²⁾ with one experiment performed on deuterium.⁽³⁾ In addition, attempts have been made to study the same quantities via single-pion electroproduction⁽⁴⁾ ($ep \rightarrow e\pi^+ n$ and $ep \rightarrow e\pi^- p$), the theoretical assumptions being more extensive in this instance. As emphasized by Perkins⁽⁵⁾ there appears to be a systematic difference as well as uncertainties in the weak axial vector form factor derived by these two methods; the preferred value from neutrino reactions is $M_A \approx 0.9$ and from electron reactions is $M_A \approx 1.2$. The importance of attaining the value for this parameter has recently been reemphasized in the analysis of neutrino and antineutrino elastic scattering⁽⁶⁾ and its consequences pertaining to the nature of the basic neutral current interaction.

In this letter we present the results of a neutrino experiment examining reaction (1), at energies similar to but somewhat higher than those in reference (3). We obtain a value $M_A = .76^{+.14}_{-.40}$ GeV. This result is in good agreement with the previous neutrino experiment.

The data was obtained by exposing the 7-ft. bubble chamber filled with deuterium to the broad-band, horn-focussed neutrino beam at the BNL

Alternating Gradient Synchrotron. From a sample of $\approx 275,000$ pictures, 700 neutrino interactions have been analyzed, of which 175 are ascribed to reaction (1). The film was completely double-scanned with a net efficiency of 97%. The chamber systematics, i.e. magnetic field, measurement accuracy, neutron background, have been carefully studied in the analysis of the charm event already published.⁽⁸⁾ The events corresponding to reaction (1) come in two varieties since the neutrino reactions occur in deuterium, namely two-prong (μ^-p) and three-prong ($\mu^-pp_{\text{spectator}}$)⁽⁹⁾ events. The events corresponding to reaction (1) are highly over-constrained, the only unknown being the incoming neutrino energy. Their selection can be accomplished in many ways, the particular manner chosen in this instance being to require that (a) the angle θ between the vector sum of the visible tracks and the known neutrino beam direction be less than 7° , and (b) the absolute value of the quantity $EMPX = (E_v - m - P_{v,v})$ be less than 150 MeV, E_v being the visible energy, $P_{v,v}$ the visible momentum in the incoming neutrino direction, and m the proton mass for two-prong events and deuterium mass for three-prong events. Figures 1a and 1b show the distribution of all candidates in the two variables $EMPX$ and θ and the area represented by the cuts. 175 events lie within the cuts. The main source of events outside the cuts is single π^0 production with smaller contributions from neutron-induced events, neutral current events, multiple pion production, etc. Examination of Figure 1 as well as a study of the dynamics of single pion production indicates that the background of such events is at the few percent level ($\sim 6\%$).

The analysis depends on two kinematical quantities, E_ν the neutrino energy and q^2 the momentum transfer to the nucleon given by $q^2 = 2E_\nu E_\mu (1 - \cos\theta)$ where θ is the angle between the neutrino and muon directions. The neutrino energy is calculated from the measured momenta utilizing energy and momentum conservation. The neutrino energy distribution for these events (Fig. 2a) peaks at 1.5 GeV and extends out to 6 GeV, while the q^2 distribution (Fig. 2b) peaks at low q^2 and extends out to $q^2 = 1.5(\text{GeV}/c)^2$. The differential cross section for this process, assuming locality and a V-A interaction, can be expressed as follows:

$$\frac{d\sigma}{dq^2} = \frac{G^2 m^2 \cos^2 \theta_c}{8\pi E_\nu^2} \left\{ A(q^2) \pm W B(q^2) + W B'(q^2) + W^2 C(q^2) \right\} \quad (2)$$

$$\text{with } W = \frac{4E_\nu}{m} + \frac{q^2}{2} - \frac{\mu^2}{2} \quad \begin{array}{l} m = \text{proton mass} \\ \mu = \text{muon mass} \end{array}$$

and A , B , B' , and C are functions of q^2 and six complex form factors, G is the weak coupling constant, θ_c the Cabibbo angle and the $\pm$ signs refer to $\nu(+)$ and $\bar{\nu}(-)$ incident beams. The detailed form of these functions can be found in many sources.⁽¹⁰⁾ With sufficient data these four important functions can be independently determined; however, with the more limited sample available it is necessary to restrict the scope of the inquiry. This is accomplished by imposing the following reasonable assumptions:

- (1) Conserved vector current hypothesis
- (2) Time reversal invariance, and
- (3) $\Delta I = 1$ rule.

This reduces the form factors to four real functions, two of which (the vector electric and magnetic) can be derived⁽¹¹⁾ from elastic electron scattering. The induced pseudoscalar form factor is assumed to be dominated by

a pion pole and is then negligible. The only remaining unknown is the axial vector form factor for which, according to custom, we adopt the dipole form:

$$F_A = -1.23(1 + q^2/M_A^2)^{-2} \quad (3)$$

We have used a maximum likelihood method to extract M_A from the observed quasi-elastic events. In particular, we perform the analysis on the shape of the q^2 distribution for each observed neutrino energy. The probability (P_i) of obtaining an event with a particular q_i^2 from a neutrino of energy E_i is

$$P_i = \frac{d\sigma/dq^2(q_i^2, E_i, M_A) K(q_i^2) dq^2}{\int d\sigma/dq^2(q^2, E_i, M_A) K(q^2) dq^2} \quad (4)$$

where the form of $d\sigma/dq^2$ is given by equation (2), and $K(q^2)$ is the calculated⁽¹²⁾ correction due to the Pauli exclusion principle for two final-state protons.

Events with very small q^2 have short proton tracks, and when the proton is so short as not to be seen, the events appear as single e^- tracks and these are not in the sample. To avoid bias from this loss, a cut was applied at $q^2 = 0.05 \text{ (GeV/c)}^2$ (corresponding to proton range of 5 cm). This cut reduced the sample from 175 to 168 events. The integral in the denominator of equation (4) must now be taken from this q^2 lower limit up to the kinematic upper limit.

The likelihood ($\mathcal{L}$) of obtaining these 168 events each with their particular values of q_i^2 is then

$$\mathcal{L} = \prod_{i=1}^{168} P_i$$

and is flux independent.⁽¹³⁾ The logarithm of this likelihood function

for various values of M_A is shown in Fig. 2c. One obtains for the maximum likelihood

$$M_A = .76 \begin{matrix} + .14 \\ - .40 \end{matrix} \quad (5)$$

where the statistical error corresponds to a change in the likelihood by 0.5 units. One notes that the likelihood function is far from parabolic indicating that the result does not have a gaussian error distribution; thus the one-standard-deviation errors given must be treated with caution. Only on the high M_A side can a strong statement be made where we obtain

$$M_A \leq 1.12 \text{ GeV at } 99\% \text{ confidence level.} \quad (6)$$

The calculated q^2 distribution for the best value of M_A is plotted on Fig. 2b and is in good agreement with the data.

Systematic errors could arise due to the inclusion of background events in the sample or due to the systematic removal of events by the cuts applied. Such errors were investigated by performing the complete analysis with progressively looser cuts. The value of M_A changed very slowly, indicating that the distributions of the sample and background are sufficiently similar that the result is quite insensitive to the cuts employed.

Another possible source of systematic error could be a systematic difference of scanning efficiency as a function of q^2 . Since all the film had been double-scanned, this efficiency was determined for different q^2 regions. No statistically significant trend was observed and all regions yielded efficiencies greater than 95%. Even a 20% relative difference

between high and low q^2 will move the value of M_A by only .04 GeV. Systematic errors from this source are thus negligible.

Our final results thus remain those given in Eqns. (5) and (6). Comparison with the only other available data obtained with deuterium shows good agreement (ANL⁽³⁾ obtain $M_A = .89 \pm .08$ GeV). The result is, however, in disagreement with some of the electron scattering experiments and with the current algebra prediction⁽⁶⁾ $M_A = \sqrt{2} M_V$.

We are grateful to the bubble chamber operating crew and the scanning and measuring personnel for their dedicated efforts.

REFERENCES

1. C. de Vries, R. Hofstadter, et al., Phys. Rev. Lett. 8, 381 (1962).
2. M. Holder, et al., Nuovo Cimento 57A, 338 (1961); R. L. Kustom, et al., Phys. Rev. Lett. 22, 1014 (1969); I. Budagov, et al., Lett. Nuovo Cimento 2, 689 (1969); D. Perkins, in Proc. of XVIth International Conference on High Energy Physics, The University of Chicago and National Accelerator Laboratory, 1972, ed. by J. D. Jackson and A. Roberts (NAL, Batavia, Ill., 1973), Vol. IV, p. 189.
3. W. A. Mann, et al., Phys. Rev. Lett. 31, 844 (1973); see also Ref. 5.
4. A Del Guerra et al., Nucl. Phys. B99, 253 (1975); E. Amaldi et al., Phys. Lett. 41B, 216 (1972); P. Brauel et al., Phys. Lett. 45B, 389 (1973); E.D. Bloom et al., Phys. Rev. Lett. 30, 1186 (1973); P. Joos et al., Phys. Lett. 62B, 230 (1976).
5. D. H. Perkins, ibid., p. 571.
6. D. Cline, et al., Phys. Rev. Lett. to be published; W. Lee, et al., Phys. Rev. Lett. to be published; D. P. Sidhu, Phys. Rev. Lett. and Phys. Rev. D, to be published; C. H. Albright, et al., Fermi Lab Publication 76/45 THY.
7. S. Weinberg, Phys. Rev. Lett. 18, 507 (1967).
8. E. G. Cazzoli, et al., Phys. Rev. Lett. 34, 1125 (1975).
9. Events in which both protons are too short to be seen are not included in the sample. They would in any case be removed by the requirement of $q^2 > 0.05$ applied later.
10. C. H. Llewellyn Smith, Physics Reports 3, 262 (1972); A. Pais, Theoretical Physics Lectures Presented at a Seminar, Trieste, Italy, 16 July-25 August, 1962 (Vienna, 1963) p. 593.

REFERENCES (Cont'd.)

11. The electric and magnetic form factors used were

$$G_E^V = 1/(1 + q^2/M_V^2)^2, \quad G_M^V = 4.71 G_E^V$$

where $M_V = .84$ GeV.

12. S.K. Singh, Nucl. Phys. B36, 419 (1972).
13. It should be noted that this likelihood function requires no prior knowledge of the energy distribution of the neutrino flux. This is not the case in the analysis used in Ref. 3 where the shape, although not the absolute value, of the energy distribution is used. Although our analysis did not use the energy distribution, the data is in fact found to be consistent with that distribution as calculated from the measured K and π production.

FIGURE CAPTIONS

- 1a. Distribution of two-prong (μ^+p) events in the variables θ and EMPX. The dotted line indicates the selection criteria for the sample of $\nu n \rightarrow \mu^+p$ events.
- 1b. Distribution of three-prong ($\mu^+pp_{\text{spectator}}$) events in the variables θ and EMPX. The dotted line indicates the selection criteria for the sample of $\nu n(p_s) \rightarrow \mu^+p(p_s)$.
- 2a. Energy distribution of selected $\nu n \rightarrow \mu^+p$ candidates.
- 2b. q^2 distribution of selected $\nu n \rightarrow \mu^+p$ candidates. The curve indicated the distribution calculated for a value of $M_A = .76$ GeV.
- 2c. Distribution of log of the likelihood as a function of the axial vector form factor mass M_A .

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