Title: Neutrino-Nucleon Scattering

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1. Introduction

In the following, I will try to summarize the current status of neutrino-nucleon scattering as it bears on contemporary issues regarding the spin structure of the nucleon. It is straightforward to express the electroweak current of a hadron in terms of its underlying electroweak partonic currents. The matrix elements of these currents are, of course, presently uncalculable but may be characterized by form factors extracted from experiment. When neutrinos are used as probes, there are several problems associated with carrying out the required cross section measurements. Active neutrino detectors of necessity contain nuclei more complex than hydrogen. These nuclei create additional backgrounds and create complications of interpretation that make these experiments challenging. However, given the continued demonstrated difficulty of measuring and extracting the spin structure functions, it appears that there are no easy measurements to investigate the nucleon spin structure save the earlier experiments that fixed the axial vector form factors of well-known baryon decays (neutron, lambda, etc.).

With the emergence of the provocative results\(^1\) from the EMC group on the spin structure function of the proton, there has been renewed interest in the information contained in the cross sections for neutral current neutrino-nucleon scattering. The theoretical background\(^2-6\) for describing this process has been worked out in detail. It is presented in briefest outline below to define the terms needed to describe experimental results.

2. Expressions for the Cross Sections

As indicated in Fig. 1(a), the charge changing weak current linking initial and final nucleon states can only involve \(u (\bar{u})\) and \(d (\bar{d})\) quarks, else the final state could not possibly be a nucleon. Figure 1(b) illustrates the neutral weak interaction in which any quark flavor can contribute as it is not forced to reveal its flavor. We
Fig. 1. (a) Charge-changing, neutrino-proton "elastic scattering." (b) Neutral current neutrino-proton elastic scattering.
will concentrate on just the axial current for simplicity. The charge changing axial current is written as

$$A_{\mu}^\pm = \left\langle N' \left| \sum_{i=u,d} \bar{q}_i \gamma_\mu \gamma^5 T_i^\pm | N \right. \right\rangle ,$$  

or in terms of an axial form factor,

$$A_{\mu}^\pm = \left\langle N' \left| -G_A(Q^2) \gamma_\mu \gamma^5 T^\pm | N \right. \right\rangle ,$$

which has been determined from numerous experiments to be

$$G_A(Q^2) = \frac{1.256}{\left( 1 + \frac{Q^2}{m_A^2} \right)^2} ,$$

with $m_A = 1.061 \pm 0.026$ GeV/$c^2$.

The nucleon's neutral weak axial current is written

$$A_{\mu}^0 = \left\langle N' \left| -\sum_i \bar{q}_i \gamma_\mu \gamma^5 T_i^0 | N \right. \right\rangle ,$$

and summing over the lightest quarks, one has

$$A_{\mu}^0 = \left\langle N' \left| -\left( \frac{\bar{u}_\mu \gamma^5 u}{2} - \frac{\bar{d}_\mu \gamma^5 d}{2} - \frac{\bar{s}_\mu \gamma^5 s}{2} \right) \right| N \right\rangle .$$

The first two terms in Eq. (5) are just the third component of the isovector axial current in Eqs. (1) and (2). The last term is isoscalar so that (5) becomes

$$A_{\mu}^0 = \left\langle N' \left| \left[ -\frac{G_A(Q^2)}{2} T_x + \frac{G_s(Q^2)}{2} \right] \gamma_\mu \gamma^5 \right| N \right\rangle ,$$

where $T_x = +1(N = p), -1(N = n)$, and $G_s(Q^2)$ is an isoscalar axial vector form factor presumably due to strange quarks. Thus, the isoscalar contribution to the nucleon axial current is readily isolated in neutral current scattering because the assumed larger isovector current changes sign between the neutron and proton, the isoscalar part therefore interferes constructively in one instance and destructively in the other.
The complete expression for neutrino-nucleon scattering\(^{7-9}\) is written

\[
\frac{d\sigma}{dQ^2} = \frac{G_F^2}{2\pi} \frac{Q^2}{E^2} [A \pm B\omega + C\omega^2] ,
\]

\[
\omega \equiv \frac{4E\nu - Q^2}{m_p^2} , \quad \tau \equiv \frac{Q^2}{4m_p^2} ,
\]

\[
A = \frac{1}{4} \left[ G_1^2(1 + \tau) - (F_1^2 - \tau F_2^2)(1 - \tau) + 4\tau F_1 F_2 \right] ,
\]

\[
B = \frac{1}{4} G_1(F_1 + F_2) ,
\]

\[
C = \frac{1}{16} \frac{m_p^2}{Q^2} [G_1^2 + F_1^2 + \tau F_2^2] .
\]

Note that \(G_1, F_1,\) and \(F_2\) are functions of \(Q^2\).

\[
F_{1,2}(Q^2) = \left( \frac{1}{2} - \sin^2 \theta_W \right) (F_{1,3}^\gamma(Q^2) - F_{1,3}^{\gamma^*}(Q^2)) T_z
\]

\[
- \sin^2 \theta_W [F_{1,2}^\gamma + F_{1,2}^{\gamma^*}] + \frac{F_{1,2}^\gamma(Q^2)}{2}
\]

and

\[
G_1(Q^2) = -\frac{G_A(Q^2)}{2} T_z + \frac{G_S(Q^2)}{2}
\]

in obvious notation. The functions \(F_1^\gamma(Q^2), \) etc., are well known from the nucleon electromagnetic form factors, so that there are only three unknown form factors \(F_1^\gamma(Q^2), F_2^\gamma(Q^2),\) and \(G_s(Q^2)\). Parameterizing the \(Q^2\) dependence of these additional form factors in dipole form is likely incorrect, as they should asymptotically be proportional to \(Q^{-6}\) rather than \(Q^{-4}\), as is typical of dipole form factors. Figures 2(a) and (b) show the effect on the \((\nu, p)\) and \((\nu, n)\) elastic scattering cross sections of a value for \(G_s(0) = -0.19\), the value extracted from the EMC experiment. Because of the low neutrino energy entering these calculations, the role played by the \(Q^2\) dependence of the form factors is small and further the contributions of \(F_1^\gamma\) and \(F_2^\gamma\) are very small. This is not the case at larger momentum transfer.

3. Quasielastic Scattering from Isoscalar Nuclei

Direct measurement of the \(\nu p\) cross section is difficult for at least two reasons. First, background processes in active neutrino detectors such as \(\nu + ^{12}\text{C} \to \nu + p + X\), where \(X\) produces no visible signal, are readily confused with \(\nu + p \to \nu + p'\).
Fig. 2. (a) Cross sections for neutral-current neutrino-proton elastic scattering at different incident neutrino energies. The plots show the effect of including a strange axial vector contribution $G_s(0)$. (b) Same as above but for neutrino-neutron elastic scattering.
Secondly, knowledge of the absolute neutrino flux is difficult to establish to better than, say, 7%. Both of these difficulties can be circumvented by measuring the ratio\textsuperscript{10,11} of proton to neutron quasielastic yield from an isoscalar nucleus such as \textsuperscript{12}C. In order not to confuse the neutrino-proton yield from \textsuperscript{12}C nuclei with that from hydrogen, protons must be selected with energies exceeding that available to free nucleons. These greater final-state energies result from the Fermi momentum in the \textsuperscript{12}C bound states. Figure 3 shows a calculation of the ratio of proton to neutron quasielastic yield for 200-MeV \(\nu\) on \textsuperscript{12}C from Ref. 10. In the absence of a strange quark contribution, the value of this calculated ratio for \(E_N > 60\) MeV is 0.88; however, with \(G_s = -0.19\), the EMC value, the ratio becomes 1.45. In a very different calculation performed in Ref. 11 at \(E_\nu = 150\) MeV, the ratio for \(E_N > 36\) MeV, the

![Graph](https://example.com/graph.png)

**Fig. 3.** Ratio of the \((\nu, \nu'p)\) to \((\nu, \nu'n)\) yield from \(\nu^{12}C\) as a function of \(E_N = E_p = E_n + 2.2\) MeV. Taken from Ref. 10, the ratios are shown for \(G_s(0) = 0\) and for \(G_s(0) = -0.19\).
corresponding ratios are calculated to be 0.81 and 1.36. Thus, the calculated ratio of proton-to-neutron yield is very sensitive to $G_s$ and found to be rather insensitive to the details of the neutrino flux distribution. A 10% measurement of the ratio fixes the values of $\Delta G_s(0)$ to $\pm 0.044$, absent other uncertainties [i.e., $F_2^p(0)$]. Thus, it appears that measuring the ratio of $\nu, p$ to $\nu, n$ yield from an isoscalar target is an excellent procedure; however, at LAMPF it requires that neutrons with energies above 60 MeV be detected with an efficiency known to better than 10%.

There has been a measurement of $\nu p$ and $\bar{\nu} p$ scattering at higher energy ($E_\nu \sim 3$ GeV) at the AGS. I will discuss this important experiment later, but it will be seen not to have any weight in fixing $G_s(0)$.

4. The LSND Setup

Let me now bring you up to date on the Liquid Scintillator Neutrino Detector (LSND) at LAMPF.

In neutrino-proton elastic scattering, the observed signal must arise from the recoiling proton. As

$$ T_p = \frac{Q^2}{2M_p} = \frac{(2E_\nu \sin^2 \frac{\theta}{2})^2}{2M_p \left(1 + \frac{2E_\nu \sin^2 \frac{\theta}{4}}{M_p} \right)}, $$

The neutrinos resulting from $\pi$ and $\mu$ decay at rest ($E_p^{\text{max}} = 52$ MeV) are not useful because the recoiling protons do not produce a readily observable signal ($E_p^{\text{max}} = 5$ MeV) in the large detector masses ($\sim 100$ tons) required to obtain a sufficient number of events. Hence, neutrinos produced by decay in flight are required. Pions produced by the 800-MeV LAMPF beam yield neutrinos in a useful energy range ($E_\nu = 150 - 250$ MeV). Figure 4 shows the neutrino flux at the center of the LSND detector, some 29.5 m from the pion production target. The neutrinos are produced at the beam stop area so that they are available whenever the LAMPF beam is on.

LSND is a $\nu$ detector that employs 200 tons of mineral oil (CH$_2$) with the addition of a small amount of scintillator (0.03 g/l Butal PPD). This mixture permits the detection of scintillation light without obscuring the Čerenkov light produced by highly relativistic ($\nu/c > 0.66$) particles in the detector.

Figure 5 is a diagram of the detector. The scintillation and Čerenkov light is sensed by 1240, 20.3-c diameter Hamamatsu photomultipliers, which provide 25% coverage. There is an elaborate data acquisition system that records the photomultiplier pulse heights and times. It continuously updates the detector and veto shield history over 200 $\mu$s. When triggered, it provides a complete previous 50-$\mu$s
Fig. 4. Neutrino flux at LAMPF.

Fig. 5. Diagram of the LSND.
history for every event. The triggering system also allows a 1-ms search for subsequent low-energy activity in the detector following certain specified triggers. The detector was rendered operable in August 1993 and recorded events with LAMPF beam in September and October of last year (1993).

Figure 6 presents an overview of the reconstructed events that are at least 50 cm inside the volume defined by the PMT faces. The number of events is shown as a function of the number of tubes registering one or more photoelectrons. The largest number of hit tubes result from cosmic-ray muons that escape \(10^{-4}\) the first level (>8 hit tubes) trigger of the veto shield. The events between 200 and 600 hit tubes are mostly Michel electrons that survive the 15.2-\(\mu\)s detector dead time imposed by the veto trigger. The peak above channel 100 is due to \(^{12}\)B beta decay produced subsequent to \(\mu^- + ^{12}\text{C} \rightarrow ^{12}\text{B} + \nu_\mu\). The events with the smallest number of hit tubes are due to radioactivity (photons) detected when the threshold is lowered for the 1-ms intervals mentioned above.

![Figure 6](image)

**Fig. 6.** The events recorded in the LSND detector as a function of the number of hit tubes. The detector trigger level is set at 100 hit tubes. When the number of hit tubes exceeds 300, the trigger level drops to 18 hit tubes for 1 ms. The rate of Michel electrons is suppressed by a factor of \(7 \times 10^4\) by the 15.2 \(\mu\)sec dead time imposed by triggering the veto shield.
Figure 6 shows the remarkable dynamic range of this detector. The cosmic-ray muons deposit up to 2 GeV in the detector volume, while the γ rays detected in the 1-ms window are as low as 0.6 MeV. Unfortunately, there has been only 1 month (October 1993) of operation of the detector with an intense beam (0.8 ma) from LAMPF, so the following is necessarily a preliminary report on LSND’s performance.

Figure 7 shows the particle identification capability of the detector. Some 180 $\nu_\mu + ^{12}\text{C} \rightarrow \mu^- + X$ in beam events with subsequent $\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$ have been readily detected by the close time and position correlation of the $\mu^-$ and the subsequent $e^-$. Figure 7 presents the distribution of the “identification signal” for the Michel electrons and that for the muons, which are below the Čerenkov threshold. The identification signal is formed via a threefold product of the variance in an event’s position, the variance in the corrected time of the PMT discriminator firing, and the event’s fit to the angular distribution of the observed light, assuming the event is produced by an electron. As Fig. 7 shows, there is good separation between the Michel electrons and the muons which produce only scintillation light.

![Diagram of particle identification signals](image)

**Fig. 7.** Plot of the particle identification signals for muons and electrons from a sample of $\nu_\mu + ^{12}\text{C} \rightarrow \mu^- + ^{12}\text{N}$ events.
Neutron identification is facilitated via detection of the 2.2-MeV gamma ray following neutron thermalization and capture by the hydrogen in the detector. The gamma-ray rate in the detector is 1 KH, so that the rate per cubic meter is 6 H. The mean time to capture of thermal neutrons is calculated to be 186 $\mu$s. Figure 8(a) shows the spacial distribution of events within 500 $\mu$s of a potential neutron event. Phase space increases as $(\Delta r)^2$ out to $\Delta r = 1.5$ m, and then remains approximately constant to $\Delta r = 3.5$ m and then slowly decreases to $\Delta r \approx 7$ m. Figure 8(b) shows two "gamma-ray" spectra. One consists of events within 150 $\mu$s and 1.5 m of the primary event. It clearly is different from that seen at separation out to 7 m and $\Delta t < 1000 \mu$s. The observed spectrum for the tighter time and space correlation corresponds to that expected for a 2.2-MeV photon. Figure 8(c) shows the time interval ($\Delta t$) for events within 2 m of the primary. The capture time corresponds to $190 \pm 4.0 \mu$s, in excellent agreement with the calculation mentioned above. We have yet to determine the efficiency for detecting the associated neutron capture $\gamma$ ray, but it is in excess of 75%.

We are just beginning to investigate the time distribution of photoelectrons in the primary neutron event. As the light produced by a stopping neutron originates from several recoiling sources distributed in time and space, it should be different

![Histogram of gamma-ray events](image)

Fig. 8. (a) Spatial correlation between a primary trigger event and a subsequent event that occurs within 500 $\mu$s.
Fig. 8 (continued). (b) The number of hit tubes following an event with greater than 300 hit tubes. The bar graph is anywhere in the tank and within 1 ms of the trigger. The shaded distribution are those events within 150 cm and 150 μs of the primary event. These events show a spectrum expected from $n + p \rightarrow d + γ$ (2.22 MeV). (c) Distribution of time intervals for events that occur within 2 m of the primary. The fit to the exponential decay ($190.4 ± 4$ μs) corresponds to the 186-μs computed for neutron capture in the CH$_2$ medium.
than a single ionizing event. We expect this to be another handle on neutron identification. Lastly, the beam excess in October for non-electron events above 35 MeV was 179.2 ± 72, and we expected 163.

4.1. Conclusions

It appears that measuring the axial vector from factors in low-energy $\nu$-nucleon elastic scattering is an excellent way to probe the spin structure of the nucleon. While experimentally difficult, it does not suffer from the problems that beset interpreting spin structure functions (extrapolation to $x = 0$, higher twist corrections, assuming SU3 flavor symmetry). The early results from the LSND are encouraging but do not allow us to predict the accuracy that $G_s(0)$ will be traced with after the 94–95 runs at LAMPF.

5. High-Energy $\nu-N$ Scattering—AGS E734

Before concluding, I want to briefly mention the recent reanalysis\textsuperscript{14} of the currently best experiment\textsuperscript{6} on high-energy ($E_\nu > 1$ GeV) neutrino-nucleon elastic scattering. Using the results of earlier analysis, several authors\textsuperscript{4} had cited AGS-E734 as supporting the EMC value for $G_s(0)$. However, this is too strong a statement. Using the formalism indicated in Eqs. (5)–(7), along with a standard parameterization of the known form factors, E734 was reanalyzed.\textsuperscript{14} In its original analysis,\textsuperscript{6} E734 used the then world average for $M_A$ (1.032 ± 0.036 MeV/c\two) in the isovector axial form factor, which yielded $G_s = -0.12 ± 0.07$. However, in a subsequent publication,\textsuperscript{15} E734 reported a new value $M_A = 1.09 ± 0.03 ± 0.02$ MeV/c\two, which raised the world average to its present value of $M_A = 1.061 ± 0.026$. As shown in Table I (from Ref. 14), the data can readily be fit within the new world average for $M_A$ with all strange form factors equal to zero. A lower value of $\chi^2$ can be

<table>
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<th>Fit</th>
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<th>$F_1^s$</th>
<th>$F_2^s(0)$</th>
<th>$M_A$</th>
<th>$\chi^2/N_{\text{DOF}}$</th>
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achieved by allowing $M_A$ to drop to 1.049 GeV, whereupon $G_s(0) = -0.15 \pm 0.07$. However, it is clear that little progress can be made in the determination of $G_s(Q^2)$, $Q^2 > 0.5$ GeV$^2$ unless $M_A$ is more precisely determined. This appears possible to do in a new dedicated experiment, which would have to obtain both precise charged and neutral current data.

The E734 data do, however, an excellent job of fixing the sum of the strange vector form factors $F_1(Q^2) + F_2(Q^2)$ at $Q^2 = 0.75$ GeV/c$^2$. This is because E734 obtained $d\sigma/dQ^2$ for both $\nu p$ and $\bar{\nu}p$, and their difference is governed by the interference term appearing in Eq. (5). Figure 9 shows the value extracted from the analysis of Ref. 14, along with some of the theoretical predictions for these quantities.

REFERENCES

Fig. 9. The value of $G_M(Q^2) \equiv F_1(Q^2) + F_2(Q^2)$ at $Q^2 = 0.75 \text{ GeV}/c^2$ extracted from E734 (AGS). The other points are projected from approved experiments employing parity-violating $e,e$ scattering. The central values of these projections use predictions\textsuperscript{16} for the strange vector form factors. The figure is from Ref. 17.
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