Analysis of Elastic Neutrino-Proton Scattering*

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The recent data on $\nu_\mu p \to \nu_\mu p$ are examined from the point of view of discriminating among models of the space-time structure of the neutral weak current. The value of the total cross section appears to exclude pure S,P from the interaction and we describe tests to confirm this conclusion.

Now that the process $\nu_\mu p \to \nu_\mu p$ has been observed,[1,2] we can begin to analyze the interaction which engenders it. Elastic neutrino-proton scattering is to weak neutral-current interactions what elastic electron-proton scattering is to electromagnetic interactions, namely the simplest process that probes the hadronic part of the interaction. The aim of this Letter is to study the space-time structure of neutral currents in light of the recently obtained experimental data on $\nu_\mu p \to \nu_\mu p$.

Two other hadronic processes have already provided us with some insight into the nature of the neutral-current interaction. The data[3] for the inclusive process $\nu_\mu p \to \nu_\mu X$, when analyzed in terms of the spin-$\frac{1}{2}$ parton model,[4,5] suggest that the hadronic neutral current is predominantly V and A rather than S or P, but it is also consistent, by virtue of the "confusion theorem,"[4] with a linear combination of S, P, and T. We note, however, that the application of the naive spin-$\frac{1}{2}$ parton model to neutral-current scattering leads to problems which do not arise in either deep inelastic electromagnetic scattering, or neutrino scattering via the charged weak current. These arise from the fact that neutral vector gluons, which are thought to carry roughly half the momentum of the initial hadron, can couple to the weak neutral current but not to either the charged weak or electromagnetic current.[6] The exclusive process $\nu N \to \nu N\pi$,[7] where N is a nucleon, is sensitive both to the space-time structure of the neutral current, and to its isospin structure. An extensive analysis[8] of this process indicates that the data are consistent with several V, A or S, P, T models containing both isovector and isoscalar currents. Thus one looks to the reaction $\nu_\mu p \to \nu_\mu p$ as a possible source of information about the weak-neutral-current interaction.

The most general matrix element $\mathcal{T}^\nu$ for $\nu_\mu(Q)p(P) \to \nu_\mu(Q')p(P')$, where the particle momenta are given in parentheses, is given by

$$\mathcal{T}^\nu = \bar{u}(Q')(1+\gamma_5)u(Q)\bar{u}(P')[S(t)+i\gamma_5 P(t)]u(P) + i\bar{u}(Q')\gamma_\lambda(1+\gamma_5)u(Q)\bar{u}(P')[\gamma_\lambda F_1(t)+\tfrac{1}{2}m\sigma_{\lambda\alpha}q_\alpha F_2(t)+\gamma_\lambda\gamma_5 G_1(t)+\tfrac{1}{2}m\sigma_{\lambda\alpha}q_\alpha\gamma_5 G_2(t)]u(P) + \bar{u}(Q')\sigma_{\lambda\mu}(1+\gamma_5)u(Q)\bar{u}(P')\Big[\sum_{a=1}^{4}\Gamma_{\lambda\mu}{}^a T_a(t)\Big]u(P), \tag{1}$$

where $q = P - P'$, $t = -q^2$, m is the proton mass, and

$$\begin{aligned}
\Gamma_{\lambda\mu}{}^1 &= \sigma_{\lambda\mu} = i(\gamma_\lambda\gamma_\mu - \gamma_\mu\gamma_\lambda)/2;\\
\Gamma_{\lambda\mu}{}^2 &= (\gamma_\lambda q_\mu - \gamma_\mu q_\lambda)/m;\\
\Gamma_{\lambda\mu}{}^3 &= i[\gamma_\lambda(P+P')_\mu - \gamma_\mu(P+P')_\lambda]/m;\\
\Gamma_{\lambda\mu}{}^4 &= [q_\lambda(P+P')_\mu - q_\mu(P+P')_\lambda]/m^2.
\end{aligned} \tag{2}$$

To obtain the matrix element $\mathcal{T}^{\bar\nu}$ for incident antineutrinos we let $S(t)$, $P(t)$, $T_a(t) \to S^*(t)$, $P^*(t)$, $T_a^*(t)$, while making the usual replacements $\bar{u}(Q')(1+\gamma_5)u(Q) \to \bar{v}(Q)(1-\gamma_5)v(Q')$ and $\bar{u}(Q')\sigma_{\lambda\mu}(1+\gamma_5)u(Q) \to \bar{v}(Q)(1-\gamma_5)\sigma_{\lambda\mu}v(Q')$ in the S, P, and T matrix elements. For the V, A contribution the replacements are $u(Q) \to v(Q')$ and $\bar{u}(Q') \to \bar{v}(Q)$. The differential cross sections $d\sigma^{\nu,\bar\nu}/dt$ and the proton polarization $\vec{\mathcal{P}}$ can be computed from Eqs. (1) and (2) using standard techniques. The general results will be given elsewhere[9] along with an analysis of the consequences of time-reversal invariance for the various form factors in Eq. (1). For present purposes we limit ourselves to a qualitative description of some of the salient indicators of the space-time structure of the interaction.

We begin by calculating the total cross section σ_ν for $\nu_\mu p \to \nu_\mu p$ and the neutral- to charged-current ratio, $R_\nu = \sigma(\nu p \to \nu p)/\sigma(\nu n \to \mu^- p)$, for various models. In all of these calculations we integrate over the observed range of momentum transfers, namely $0.3 \leqslant |t| \leqslant 0.9$ $(\mathrm{GeV}/c)^2$, and perform an average over the Brookhaven National Laboratory neutrino energy spectrum. We assume that all form factors have the usual dipole[10] form $(1 - t/\Lambda^2)^{-2}$ except in the case of the pseudoscalar interaction for which we also consider the pion pole $(1 - t/m_\pi^2)^{-1}$. Our results are displayed in Table I; the values of R_ν are fairly sensitive to the numerical value[10] $\Lambda = 0.84$ GeV in the sense that a 10% change in Λ causes a comparable shift in R_ν.

The Weinberg-Salam (W-S) model,[12] for a given value of $\sin^2\theta_W$, fixes the overall strength of the neutral current as well as the form of the hadronic current, and so the magnitudes of σ_ν and R_ν represent a direct test of the model. The same is not true for other V, A models, or for the S, P model, because there presently exists no fundamental theory to fix the scale of these couplings. We therefore follow the procedure of Sakurai and Urrutia,[11] and fix the scale for these other models by normalizing them to the data on inclusive reactions $\nu p \to \nu X$. From Table I we see that the experimental values $R_\nu = 0.23 \pm 0.09$[2] and 0.17 ± 0.05[1] fall within the range predicted by the W-S model, but appear to be larger than the predictions of S, P models. This suggests that the neutral current is not predominantly S, P.

We now turn to other properties of neutrino-proton elastic scattering that can be used to confirm this conclusion. The simplest such property is the cross section $\sigma_{\bar\nu}$ for *antineutrino* scattering $\bar\nu_\mu p \to \bar\nu_\mu p$; if the neutral-current interaction is S, P then, independently of the admixture of S and P and of the hadronic form factors, the cross sections for neutrino-proton and antineutrino-proton scattering must be precisely equal to each other at the same energy. *Thus the experimental observation that $\sigma_\nu \neq \sigma_{\bar\nu}$ would immediately imply that the neutral current is not S, P in character; it would also exclude pure V models.*[13] The W-S model predictions for $\sigma_{\bar\nu}$ and $R_{\bar\nu}$ are shown in Table I.

Other tests of the nature of the neutral current are based on properties of the differential cross section: (1) $d\sigma(t=0)/dt \neq 0$ implies that some V, or A, or T is present in the interaction. (2) $Q_0^2 d\sigma/dt \neq \mathrm{const}$ for a fixed value of t, and any range of laboratory neutrino energies Q_0, implies that some V, or A, or T must be present in the interaction. When $Q_0^2 \gg m^2$ and t, the latter interac-

TABLE I. Flux-averaged neutrino- and antineutrino-proton total cross sections. In the Weinberg-Salam model the weak neutral current is given by $\mathfrak{F}_\lambda{}^3 + \mathfrak{F}_{5\lambda}{}^3 - 2xj_\lambda$ where the $\mathfrak{F}$'s are the usual octet currents, j_λ is the electromagnetic current, and $x = \sin^2\theta_W$. The remaining models are defined similarly in terms of the $\mathfrak{F}$'s. For the S, P currents $\mathcal{S}^{3,8}$ and $\mathcal{P}^{3,8}$ correspond respectively to $\mathfrak{F}_{3,8}$ and $\mathfrak{F}_{3,8}{}^5$ of Adler *et al.*, Ref. 8. The flux-averaged charged-current cross sections used in computing R_ν and $R_{\bar\nu}$ are $\sigma(\nu n \to \mu^- p) = 3.02 \times 10^{-39}$ cm^2 and $\sigma(\bar\nu p \to \mu^+ n) = 1.14 \times 10^{-39}$ cm^2.

Model	σ_ν (10^{-40} cm^2)	$\sigma_{\bar\nu}$ (10^{-40} cm^2)	R_ν	$R_{\bar\nu}$
Weinberg-Salam				
$x=0$	7.97	3.00	0.264	0.264
0.20	3.90	1.29	0.129	0.113
0.40	2.14	1.89	0.071	0.166
0.60	2.70	4.80	0.089	0.421
0.80	5.58	10.04	0.185	0.881
1.00	10.77	17.60	0.357	1.544
$\mathfrak{F}_\lambda{}^3 + \mathfrak{F}_{5\lambda}{}^3$	3.19	1.20	0.105	0.105
$\mathfrak{F}_\lambda{}^3 + \sqrt{\tfrac{1}{3}}\mathfrak{F}_\lambda{}^8 + \mathfrak{F}_{5\lambda}{}^3 + \sqrt{\tfrac{1}{3}}\mathfrak{F}_{5\lambda}{}^8$	5.15	2.31	0.170	0.203
$\mathfrak{F}_\lambda{}^3 + \sqrt{\tfrac{1}{3}}\mathfrak{F}_\lambda{}^8$	5.21	5.21	0.172	0.457
$\mathfrak{F}_\lambda{}^0$ [a]	5.46	5.46	0.181	0.487
$\mathcal{S}^8 + \mathcal{P}^8$	1.57	1.57	0.052	0.138
$\mathcal{S}^3 + \mathcal{P}^3$	0.146	0.146	0.005	0.013

[a]We have used the fermion-current model of Ref. 11.

tions lead to $Q_0^2 d\sigma/dt \propto Q_0^2$ at fixed t. (3) $d\sigma^{\nu}/dt \neq d\sigma^{\bar{\nu}}/dt$ implies that the interaction is not pure V, or A, or T, or any combination of only S and P. (4) Proton-polarization effects, should they become measurable at some future time, could provide unambiguous evidence for the presence of V or A.

Points (1) and (2) follow from the observation that if the interaction contains *neither* V, nor A, nor T, then the cross section must have the simple form $d\sigma/dt = tf(t)/Q_0^2$, where $f(t)$ is essentially a proton form factor. With respect to point (1), the behavior of the cross section at $t=0$ cannot be measured directly, but can be inferred from measurements at sufficiently small, nonvanishing values of t; how small they need be will be explored below. With regard to point (2), revealing measurements of the energy dependence of the cross section may be possible at Brookhaven National Laboratory. Point (3) is an important test of special theories of the neutral current with pure-V couplings.[13]

The distinction between V, A and S, P can be seen if we plot $d\sigma/dt$ as a function of $|t|$, as shown in Fig. 1. For V, A couplings in general, and for the Weinberg-Salam model in particular, the differential cross section has its largest value at $t=0$ and then decreases as $|t|$ increases; this decrease results partly from the kinematic features of the coupling and partly from damping by the hadronic form factors. The S, P differential cross section vanishes at $t=0$, and so it should be an increasing function of $|t|$ for small momentum transfers; at some point, however, the form-factor damping will set in and the cross section will begin to fall. To compare the shape of the S, P cross section, we use the results of Adler *et al.*[8] for the values of the form factors at $t=0$, and we normalize $d\sigma/dt$ to the data of Ref. 1 at $t=0.65$ (GeV/c)^2.

In Fig. 1 we compare the experimental data of Ref. 1 with the theoretical curves for the S, P interaction, and for the Weinberg-Salam model with values of $\sin^2\theta_W$ which envelop the predictions of the model. For $0.3 \leq |t| \leq 0.9$ (GeV/c)^2, the differential cross sections for S, P and for W-S are both decreasing functions of $|t|$, and hence the distinction between them occurs in the region $0 \leq |t| \leq 0.2$ (GeV/c)^2 where the S, P cross section is an increasing function of $|t|$ while the W-S one is a decreasing function. Therefore a measurement of the differential cross section at $t = 0.2$ (GeV/c)^2 would be extremely useful in determining the nature of the weak neutral-current interaction.

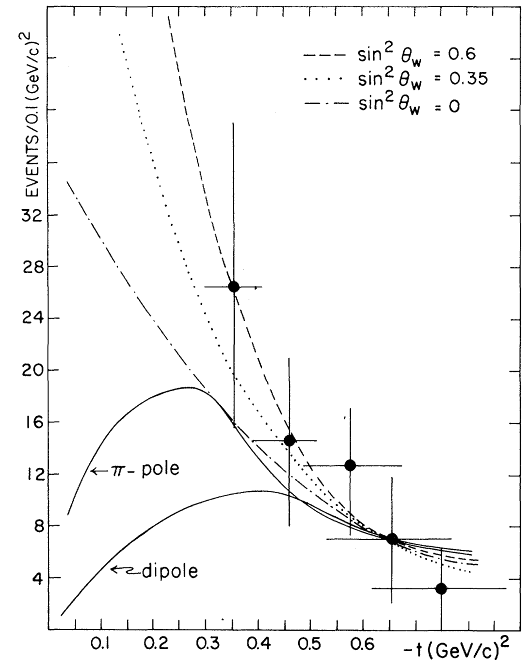

FIG. 1. Plot of $d\sigma/dt$ versus t for the Weinberg-Salam and S,P models of the neutral current. The broken lines give the predictions for the W-S model. The solid lines give the predictions for the S,P model described in the text. All form factors are assumed to be characterized by a dipole t dependence $(1-t/\Lambda^2)^{-2}$, with $\Lambda = 0.84$ GeV, except for the case labeled π pole in which the t dependence of the pseudoscalar form factors is given by $(1-t/m_\pi^2)^{-1}$. All of the curves are normalized to the data at $|t| = 0.65$ (GeV/c)^2; only the shapes are significant.

Another way of determining whether or not the neutral current contains V, A or T is to measure the energy dependence of the differential cross section at fixed t [see point (2) above]. Since measurements of the energy of the recoil proton, and its direction with respect to the neutrino beam, enable us to infer the energy of the incident neutrino, it may be possible to extract this information from the present data together with the known spectrum of the wideband neutrino beam at Brookhaven National Laboratory. Alternatively, the energy dependence can be measured by using a narrowband beam and allowing its peak energy to vary. If the data fail to fall like Q_0^{-2} then V, or A, or T must be present in the interaction.

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Alpha Decay of the Giant Quadrupole Resonance in ^{238}U†

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Evidence for the α decay of the giant quadrupole resonance is reported. Measurements of the reaction ^{238}U$(e,e',\alpha)^{234}$Th in the region 9-24 MeV are presented. The results imply that the reaction goes dominantly through $E2$ absorption. The amount of $E2$ strength used by the α emission channel exhausts 50% of the isoscalar energy-weighted sum rule.

It has recently been suggested that the study of (γ,α) and (α,γ) reactions could reveal interesting features of the giant quadrupole resonance (GQR) since in these reactions the effects of the isovector giant dipole resonance (GDR) are supressed.[1] In this Letter, evidence that the GQR decays strongly by α emission is presented.

The GQR has been extensively studied by electron and hadron scattering. From these measurements it is possible to observe the strength of quadrupole absorption by the nucleus. While for the dipole absorption the dominant mode of decay of the GDR is by neutron emission and fission, no measurements have been reported on the decay modes of the GQR.

The electrodisintegration cross section by emission of a particle x (integrated over all scattering angles), $\sigma_{e,x}(E_0)$, is related to the corresponding photodisintegration cross section, $\sigma_{\gamma,x}{}^{\lambda L}(E)$, through

$$\sigma_{e,x}(E_0)=\int_0^{E_0}\sum_{\lambda L}\sigma_{\gamma,x}{}^{\lambda L}(E)N^{\lambda L}(E_0,E)E^{-1}dE, \tag{1}$$

where E_0 is the electron bombarding energy, E is the photon energy, $N^{\lambda L}$ is the virtual photon spectrum, and $\sigma_{\gamma,x}{}^{\lambda L}$ is the cross section for photodisintegration through a nuclear transition of multipolarity λL. Gargaro and Onley[2] have obtained computable expressions for $N^{\lambda L}$ using the distorted-wave approximation and agreement with experimental results has been shown by Nascimento, Wolynec, and Onley[3] and Wolynec and co-workers.[4,5]

If we know that in the energy range under study there are one or two dominant multipoles in the absorption, then the sum in expression (1) reduces to one or two terms. It is possible in this case to obtain the multipolarity of the transitions involved in the photodisintegration by measuring the electrodisintegration cross positions.

Since the quadrupole component of virtual photons is one order of magnitude larger than the dipole for high Z (see Fig. 1), while real plane-wave photons have all multipole components in equal amounts, the relative magnitude of the cross section for the quadrupole to the dipole