SOME MEASUREMENTS FOR DETERMINING STRANGENESS MATRIX ELEMENTS IN THE NUCLEON

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SOME MEASUREMENTS FOR DETERMINING STRANGENESS MATRIX ELEMENTS IN THE NUCLEON

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Abstract

Some experiments to measure strangeness matrix elements of the proton are proposed. Two of these suggestions are described in some detail, namely electro production of phi mesons and the difference between neutrino and antineutrino scattering for isospin zero targets such as deuterium.

1. Introduction

The constituent quark model of the nucleon has been very successful in predicting some of its static properties. The model assumes that the nucleon is composed solely of three valence u and d quarks (uud or udd). However, recent measurements, particularly of the spin structure of the nucleon by the EMC group [1] reveal that we do not fully understand the structure of the proton. The measurements suggest that the quarks may only be responsible for a small fraction of the proton's spin and that the strange quarks may contribute as much as 20% to the spin. The latter conclusion has been challenged by many theorists [2]. By contrast, there are many fewer proposals to experimentally determine the strange quark matrix elements in the nucleon [3-5].

The production of pure strange hadrons from a nucleon is inhibited by the OZI rule in the absence of strangeness in the structure. Ellis, Gabañler, and Karlner [4] noted that the OZI rule appeared to be violated in phi production from nuclear targets. Parity-violating elastic electron scattering from hydrogen has been proposed to measure the vector matrix element $\langle N | \bar{s} \gamma^\mu s | N \rangle$ [6]. We have suggested [3] electron- and neutrino-production of phi mesons from a hydrogen target to measure the same matrix element and the difference between neutrino and antineutrino cross sections on an isospin zero

target to obtain the isoscalar axial current matrix element $\langle N | s \gamma^5 \gamma^3 | N \rangle$. In this talk I will describe both of these proposals in some detail.

2. Electroproduction of ϕ Mesons

If the OZI rule is exact, and the ϕ meson is a pure $s\bar{s}$ state, then the ϕ cannot be produced "directly" from a hydrogen target. We use "directly" because the ϕ can be obtained "indirectly" through a vector dominance process in electro- and neutrino-production. Despite this shortcoming, we believe that the reactions $e^- p \rightarrow e^- p \phi$ and $\nu p \rightarrow \nu p \phi$ offer opportunities for seeking vector strangeness matrix elements in the proton. First of all, the interactions of the probes with the target are well known and understood. Second, we believe that a separation of the desired "knock out" process from the vector meson background, although difficult, is feasible. Since electromagnetic probes provide a much higher count rate than parity-violating processes, we believe that the electro-production of ϕ mesons may open another avenue for seeking vector matrix elements, $\langle p | s \gamma_\mu s | p \rangle$, due to strangeness in the nucleon. We have therefore analyzed this reaction in some detail.

A constituent quark model is used to estimate the knockout production cross section of ϕ mesons near threshold and for squared momentum transfers $Q^2 = -q^2$ that are not too large, i.e. $Q^2 \lesssim 1(\text{GeV}/c)^2$. Fig. 1a illustrates the kinematics of the reaction and Fig. 1b the knock-out process. We assume, for simplicity, a two component Fock-space proton wavefunction

$$|p\rangle = A|(uud)_{1/2}\rangle + B|[\bar{u}_0(uud)_{1/2}(s\bar{s})_0 + a_1(uud)_{1/2}(s\bar{s})_1]\rangle_{1/2}, \quad (1)$$

with $|A|^2 + |B|^2 = a_0^2 + a_1^2 = 1$. In Eq. (1) B determines the admixture of strangeness in the proton, and $a_0(a_1)$ is the fraction of spin 0 (spin 1) $s\bar{s}$. Other components, and more complex wavefunctions are possible, but Eq. (1) is adequate for our purposes. In order for the parity of the proton to be +, we require the $s\bar{s}$ to be in a relative p-wave ($\ell = 1$) about the uud valence quarks. The knock-out cross section for ϕ mesons is proportional to $A^2 B^2$. We use harmonic oscillator spatial wavefunctions in order to treat the c.m. effects correctly. However, this choice has the effect of underestimating the high momentum components of the wavefunction. We base oscillator parameters on known electromagnetic charge radii, $\beta^2 = (3/2)(r^2)^{-1}$; we choose the square roots of mean square mass-distribution radii $\sqrt{\langle r^2 \rangle}$ to be 1.2 (set 1) and 1.5 (set 2) times smaller than these charge radii. If we write

$$\psi \sim e^{-\beta^2 r^2/2}$$

then the values of β used are given in Table I.

Table I

Wavefunction	Harmonic Oscillator Parameters		
	β	Set 1 (fm^{-1})	Set 2 (fm^{-1})
Relative motion of s and $\bar{s}$ in proton	β_s	1.63	2.04
Motion of ss c.m. in proton	β_{ss}	1.94	2.43
ϕ	β_ϕ	1.63	2.04

Fig. 1. Leptoproduction of ϕ mesons: a) kinematics, b) knock out contribution, and c) diffractive production via pomeron exchange.

In the laboratory frame, we obtain for the cross section

$$\frac{d^3\sigma}{dW dQ^2 dt} = \frac{W}{M} \frac{(E - \nu)}{2E} \frac{E_p^2}{2M Q^4} \frac{1}{Q^4} (16\pi^2 \alpha^2) Q_s^2 A^2 B^2 (2u_0)^2 |F|^2 \times \frac{|f|^2}{|q|} \theta(1 - |h|) \left(\frac{|q|}{2m_s} \right)^2 \frac{1}{4\pi} [1 - \hat{q} \cdot \hat{k}' \hat{q} \cdot \hat{k}], \quad (2a)$$

$$f \equiv \nu + M - E_p', \quad (2b)$$

$$h \equiv \frac{m_\phi^2 + q^2 + p'^2 - f^2}{2|q||p'|}, \quad (2c)$$

$$|F|^2 \equiv \frac{8}{3\sqrt{\pi}} (\beta_\phi \beta_p \beta_s)^3 \left(\frac{2\beta_\phi^2}{1 + (\beta_\phi/\beta_s)^2} \right)^3 \exp \left\{ -\frac{|q|^2}{4(\beta_\phi^2 + \beta_s^2)} \right\} \times \left(\frac{|p'|^2}{\beta_s^2} \right) \exp \left\{ -\frac{|p'|^2}{\beta_s^2} \right\}, \quad (2d)$$

with $m_\phi = 1020$ MeV and $q = q'/|q|$, $\nu = E - E_p'$, $Q_s = \frac{1}{2}$, $m_s \approx 500$ MeV/c² are the strange quark change and mass; $W^2 \equiv (p + q)^2 = (p' + k_\phi)^2$ is the invariant squared mass of the photon-hadron system; and $t \equiv (p' - p)^2 \approx -p'^2$ for small t . It should be noted that a_1 does not contribute to the triple differential cross section. The cross section is plotted in Figs. 2 and 3 for 20% strangeness, $B^2 = 0.2$, and with $a_0^2 = a_1^2 = 0.5$.

Electroproduction studies of ϕ mesons have been carried out [7], but not with sufficient accuracy and detail to establish the knock-out component. The experiments have been analyzed on the basis of a vector dominance model, illustrated in Fig. 1c. Here the virtual photon is transformed into a vector ϕ meson, which scatters diffractively (Pomeron exchange) from the hydrogen target. The observed Q^2 behavior agrees with the model, within errors of $\sim 15\%$, but the W dependence and width of the forward ($t \approx t_{min}$) peak are in less satisfactory agreement. The cross section can be written as

$$\frac{d^3\sigma_{diff}}{dW dQ^2 dt} = \frac{\alpha}{4\pi} \frac{W}{ME^2} \frac{W^2 - M^2}{MQ^2} \frac{b_\phi}{1 - \varepsilon} \frac{\sigma(0, W)}{[1 + (Q^2/m_\phi^2)]^2} \left[\frac{p_\gamma^{(0)}(Q^2)}{p_\gamma(Q^2)} \right] (1 + \varepsilon R_\phi) \times \exp \{ b_\phi(|t| - |t_c(Q^2)|) \}, \quad (3)$$

where ε is the virtual photon polarization parameter, $\sigma(0, W)$ is the observed photo-production cross section, $p_\gamma^{(0)}(Q^2)$ is the virtual photon flux in the photon-hadron c.m., and $|t_4|$ are the kinematic limits of t . A term $\propto e^{-b_\phi|p_\perp|}$ has been dropped. The values used to fit the data are $b_\phi = 3.46 \pm 0.22$ GeV⁻², $\sigma(0, W) = 0.45 \pm 0.02 \mu b$ for $W \gtrsim 2.4$ GeV and $\sigma(0, W) = 0.22 \pm 0.03$ at $W \approx 2.1$ GeV due to the reduced phase space near threshold; ε and $p_\gamma^{(0)}/p_\gamma(Q^2)$ are given by expressions in Ref. 8. Plots of the diffractive cross section are also shown in Figs. 2 and 3.

Fig. 2. Virtual photoproduction cross section $\sigma(Q^2, W)$ for $W = 2.1$ GeV as a function of Q^2 . The dash-dot curve is the diffractive cross section. The dashed and solid curves are the predicted knock-out cross section for $B^2 = 0.2$ and cases 1 and 2 (see text), respectively.

Fig. 3. The t dependence of the electroproduction cross section for $W = 2.1$ GeV and $Q^2 = 0.02$ (GeV/c)². The curves have the same correspondence as in Fig. 1.

The major difference between the two cross sections, which are of the same order of magnitude for a 20%-strange quark presence ($B^2 = 0.2$) occurs for small $t \equiv (p' - p)^2 \approx -\vec{p}'^2$. For the knock-out cross section there is an extra factor of t , whereas the diffractive one is purely exponential. Because the latter cross section is due to a natural parity (0^+) exchange and is s-channel helicity conserving, a polarization experiment would help to isolate the knock-out contribution more clearly.

In conclusion, accurate measurements of electro-pion production cross section, especially with polarized targets, are a means to obtain information on the vector strangeness matrix elements in the proton.

The analysis for neutrino production of phi mesons is quite similar, but is also sensitive to the axial vector strangeness matrix elements of the proton.

3. Neutrino and Antineutrino Elastic Scattering from ^2H

The coupling, $g_A^{(0)}$, of the axial vector current to the nucleon is poorly known. We define it by $\frac{1}{2} \langle p | \gamma^\mu \gamma^5 | p \rangle = + \langle n | \gamma^\mu \gamma^5 | n \rangle$, and not $\frac{1}{2} \langle p | u \gamma^\mu \gamma^5 u + d \gamma^\mu \gamma^5 d | p \rangle$ [9]. In terms of the u , d , s quark structure and the standard model $g_A^{(p)} \equiv \frac{1}{2} \langle p | u \gamma^\mu \gamma^5 u + d \gamma^\mu \gamma^5 d + s \gamma^\mu \gamma^5 s | p \rangle$; with the assumption of isospin symmetry $g_A^{(n)} \equiv \frac{1}{2} \langle n | u \gamma^\mu \gamma^5 u + d \gamma^\mu \gamma^5 d + s \gamma^\mu \gamma^5 s | p \rangle$, the assumption of isospin symmetry $g_A^{(n)}$ is then given by $g_A^{(p)} = - \langle p | s \gamma^\mu \gamma^5 s | p \rangle$. The EMC measurements [1] suggest $g_A^{(p)} \approx -0.22 \pm .07$, whereas the axial anomaly [10] predicts $|g_A^{(p)}| \approx 0.05-0.15$ [11]. It is clearly of interest to measure $g_A^{(0)}$ directly. This can be carried out for a proton target [12], but the term is isolated most directly for an isospin zero target since the cross section vanishes unless $g_A^{(0)} \neq 0$. Because the leading non-relativistic term for the axial vector current is the spin, we need a target with spin > 0 . The deuteron is the lightest such target. The difference between neutrino and antineutrino elastic scattering cross sections on deuterium is directly proportional to $g_A^{(0)}$ for small $g_A^{(0)}$. The neutrino and antineutrino fluxes could be normalized by measuring their scattering cross sections on ^{12}C .

We have calculated the ratio

$$R = \frac{\frac{d\sigma}{dQ^2}(\nu d \rightarrow \nu d) - \frac{d\sigma}{dQ^2}(\nu d \rightarrow \nu d)}{\frac{d\sigma}{dQ^2}(\nu d \rightarrow \nu d) + \frac{d\sigma}{dQ^2}(\bar{\nu} d \rightarrow \bar{\nu} d)}, \quad (4)$$

where $Q^2 \equiv -q^2$ is the negative of the 4-momentum transfer to the deuteron. Our calculation uses a multipole decomposition and an extended Siegert theorem [13] at low Q^2 , a covariant formalism [14] together with a nonrelativistic deuteron wavefunction for intermediate Q^2 [01] ($\text{GeV}/c^2 \lesssim Q^2 \lesssim 1(\text{GeV}/c)^2$) and a light-cone impulse approximation at the highest Q^2 [15]. These methods overlap and agree with each other in their applicable regions. I shall illustrate our development for the covariant method. The weak current matrix elements can be written as

$$\begin{aligned} \langle D' | J_\mu | D \rangle &= \frac{-1}{\sqrt{4D_0 D_0'}} \left[G_1(Q^2) (\xi'^* \cdot \xi) P_\mu \right. \\ &\quad + G_2(Q^2) [\xi_\mu (\xi'^* \cdot q) - \xi'_\mu (\xi \cdot q)] \\ &\quad \left. - G_3(Q^2) (\xi \cdot q) (\xi'^* \cdot q) P_\mu / 2M^2 \right], \\ \langle D' | J_\mu^{(5)} | D \rangle &= \frac{-1}{\sqrt{4D_0 D_0'}} \left[i G_4(Q^2) \varepsilon_{\mu\alpha\beta\gamma} \xi'^{\alpha\ast} \xi^\beta P^\gamma \right. \\ &\quad \left. + \frac{i G_5(Q^2)}{M^2} \varepsilon_{\mu\alpha\beta\gamma} q'^\alpha P^\beta [\xi_\mu (\xi'^* \cdot q) - \xi'_\mu (\xi \cdot q)] \right], \end{aligned} \quad (5)$$

where $P_\mu = D'_\mu + D_\mu$, with $D(D')$ the initial (final) deuteron momentum, M is the mass of the deuteron, $D_0 = \sqrt{M^2 + Q^2}/4$ is the deuteron energy in the Breit frame, and $\xi_\mu (\xi'_\mu)$ is the polarization 4-vector for the initial (final) deuteron. The neutrino deuteron elastic scattering cross section can be written as

$$\frac{d\sigma}{dQ^2} \left(\nu d \right) = \frac{G_F^2}{2\pi} r \left[2W_1 \sin^2 \frac{\theta}{2} + W_2 \cos^2 \frac{\theta}{2} + \frac{2}{M} (E_\nu + E'_\nu) W_3 \sin^2 \frac{\theta}{2} \right] \quad (6)$$

where θ is the scattering angle, $(1 - \cos \theta) = Q^2/(2E_\nu E'_\nu)$, and r is the nuclear recoil factor, $r \equiv [1 + Q^2/2ME'_\nu]$. The response functions are

$$\begin{aligned} W_1(Q^2) &= \frac{Q^2}{6M^2} (1 + Q^2/4M^2) G_M^2 + \frac{2}{3} (1 + Q^2/4M^2)^2 G_A^2, \\ W_2(Q^2) &= \left[G_C^2 + \frac{Q^2}{6M^2} G_M^2 + \frac{Q^4}{18M^4} G_C^2 + \frac{2}{3} (1 + Q^2/4M^2) G_A^2 \right], \\ W_3(Q^2) &= \frac{2}{3} (1 + Q^2/4M^2) [G_M G_A], \end{aligned} \quad (7)$$

where G_C , G_Q , G_M , and G_A are the charge, quadrupole magnetic, and axial deuteron form factors. They are related to $G_1 - G_5$ by

$$\begin{aligned} G_C(Q^2) &\equiv G_1(Q^2) - (Q^2/6M^2) G_Q(Q^2), \\ G_Q(Q^2) &\equiv G_1(Q^2) - G_2(Q^2) + (1 - Q^2/4M^2) G_3(Q^2), \\ G_M(Q^2) &\equiv G_2(Q^2), \\ G_A(Q^2) &\equiv G_4(Q^2) + (Q^2/M^2) G_5(Q^2). \end{aligned} \quad (8)$$

These form factors are evaluated in the Breit frame with a non-relativistic deuteron wavefunction and non-relativistic reduction of nucleon-current operators. In most of our work the deuteron wavefunction has been taken to be that obtained from the Paris

Fig. 4. Neutrino (solid) and antineutrino (dashed) elastic differential cross sections as a function of Q^2 for $E_\nu = E_{\bar{\nu}} = 500$ MeV, $g_A^{(0)} = 0.2$ (solid) and 0.1 (dashed).

Fig. 5. The ratio R as a function of Q^2 at $E_\nu = E_{\bar{\nu}} = 500$ MeV for $g_A^{(0)} = 0.2$ (solid) and 0.1 (dashed).

Fig. 6. Same as Fig. 5, but at $E_\nu = E_{\bar{\nu}} = 2$ GeV.

Fig. 7. The ratio R at $E_\nu = E_{\bar{\nu}} = 500$ MeV for $g_A^{(0)} = 0.2$ and $g_A^{(0)} = 0.1$ (dashed), 0 (solid), and 0.2 (dots).

potential [17]. The isoscalar axial vector form factor is assumed to be similar to that of its isospin 1 partner, i.e., of the dipole form $(1 + Q^2/M_A^2)^2$, with $M_A = 1.03 \text{ GeV}/c^2$.

Results are shown in Figs. 4-7. Fig. 4 shows the differential cross sections for ν and $\bar{\nu}$ elastic scattering as a function of Q^2 . Fig. 5 shows the features we wish to highlight. Here we plot R as a function of Q^2 for $E_\nu = E_{\bar{\nu}} = 500 \text{ MeV}$ for $g_A^{(0)} = 0.1$ and 0.2 . Of course, $R = 0$ if $g_A^{(0)} = 0$; for $g_A^{(0)} = 0.1$ and 0.2 , R grows smoothly and monotonically from 0 to 1 and is larger than $1/4$ for $Q^2 > 0.4 \text{ (GeV}/c^2)^2$. For lower energies the dependence of R on Q^2 is comparable to that shown, but for $E_\nu \gtrsim 1 \text{ GeV}$, the growth of R with Q^2 is stunted by the zeroes of the deuteron form factor. Fig. 6 shows R vs Q^2 at $E_\nu = E_{\bar{\nu}} = 2 \text{ GeV}$. Thus, average energies of several hundreds of MeV seem preferable. It is also better to stay away from the maximum possible Q^2 , because the sensitivity to the numerical value of $g_A^{(0)}$ is reduced at 180° . In Fig. 7, we show that the results also depend on the s-quark contribution to the nucleon's magnetic form factor, which is presently unconstrained by experiment [6]. The contribution enters by modifying the deuteron's weak magnetic form factor with which the axial one interferes. The dependence of R on $g_M^{(s)}$ is similar to that of a variation of $g_A^{(0)}$. The two effects may be separated at small Q^2 , where the contribution from $g_M^{(s)}$ is suppressed by a factor of Q^2/M^2 .

Despite the shortcoming of the necessity to isolate $g_M^{(s)}$, or to measure it separately from $g_A^{(0)}$, we believe that the neutrino experiments are feasible at LAMPF, TRIUMF or similar accelerators. We hope they will be undertaken.

In summary, I have described in some detail two difficult, but feasible experiments to measure the presence of strangeness in nucleons.

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References

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