η and η' Scattering: A Probe of the Strange-Quark ($s\bar{s}$) Content of the Nucleon?

Carl B. Dover
Physics Department, Brookhaven National Laboratory, Upton, New York 11973

Paul M. Fishbane
Physics Department and Institute of Nuclear and Particle Physics, University of Virginia, Charlottesville, Virginia 22901
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We propose that the relative cross sections for the reaction processes $\eta p, \eta' p \rightarrow \eta p, \eta' p, K^+\Lambda$ and $\pi^- p \rightarrow \eta n, \eta' n$, induced by pseudoscalar mesons on a proton target, provide a sensitive test for the presence of a strange-antistrange ($s\bar{s}$) quark component in the nucleon's wave function.

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In the naive quark model, the structure of the proton is $|p\rangle = |uud\rangle$. The question of the quark content has been raised again by recent analyses of measurements[1] of the polarized structure function of the proton. Some authors[2] argue that these data imply a significant admixture of strange-antistrange ($s\bar{s}$) pairs in the nucleon, even for small momentum transfers (large distances), while others[3] dispute this interpretation. The $s\bar{s}$ content in the nucleon can also be probed in low-energy pion-nucleon scattering[4] (via the so-called "σ term") or in nucleon-antinucleon ($N\bar{N}$) annihilation processes. In the latter case, it has been suggested[5] that the $s\bar{s}$ component is revealed in terms of a breakdown of the Okubo-Zweig-Iizuka (OZI) rule at some level. This interpretation has been questioned.[6] According to the OZI rule,[7] for example, the ratio of cross sections $\sigma(A+B\rightarrow \phi + X)/\sigma(A+B\rightarrow \omega+X)$, where A, B, and X do not contain strange quarks, is of order 1%. The dynamical origin of the OZI rule has been recently discussed by Lipkin.[8] Tests of the type mentioned above involve an amplitude proportional to the square of the $s\bar{s}$ component of the nucleon wave function.

In this Letter, we propose a first-order test of the strange-quark content of the nucleon. Specifically, we consider the pseudoscalar meson-baryon reactions $\pi^- p\rightarrow \eta n, \eta' n$ and $\eta p, \eta' p \rightarrow \eta p, \eta' p, K^+\Lambda$. We focus on the η and η', since these mesons contain significant components of *both* strange ($\eta_s = s\bar{s}/\sqrt{2}$) and nonstrange [$\eta_{ud} = (u\bar{u} - d\bar{d})/2$] quark-antiquark ($Q\bar{Q}$) configurations. Because of this fortunate circumstance, *interference effects* between the η_s and η_{ud} components could be substantial in the reaction amplitudes. These amplitudes contain a term *linear* in the strength $C_{s\bar{s}}$ of the $s\bar{s}$ component of the proton, written schematically as

$$|p\rangle = C|uud\rangle + C_{s\bar{s}}|uuds\bar{s}\rangle + \cdots . \quad (1)$$

In contrast, the amplitude for $\pi p\rightarrow \pi p$ is quadratically dependent on $C_{s\bar{s}}$, since the pion has no $s\bar{s}$ component.

An interference effect in η, η' reactions arises because the relative phase of the η_{ud} and η_s components is opposite in the η and η'. Explicitly, we have the flavor wave functions

$$\eta = \alpha\eta_{ud} - \beta\eta_s ,$$
$$\eta' = \beta\eta_{ud} + \alpha\eta_s , \quad (2)$$

where we have ignored a possible gluonic component[9-11] of the η'. Our normalization is thus $\alpha^2+\beta^2=2$. In terms of the conventional mixing angle θ, defined by

$$\eta = \cos\theta|8\rangle - \sin\theta|1\rangle ,$$
$$\eta' = \sin\theta|8\rangle + \cos\theta|1\rangle , \quad (3)$$

where $|8\rangle = (u\bar{u}+d\bar{d}-2s\bar{s})/\sqrt{6}$ and $|1\rangle = (u\bar{u}+d\bar{d}+s\bar{s})/\sqrt{3}$ are SU(3) octet and singlet combinations, respectively, we have

$$\alpha = \left(\frac{2}{3}\right)^{1/2}\cos\theta - \frac{2\sin\theta}{\sqrt{3}} ,$$
$$\beta = \left(\frac{2}{3}\right)^{1/2}\sin\theta + \frac{2\cos\theta}{\sqrt{3}} . \quad (4)$$

Most recent decay analyses[12] suggest $\theta\approx -20°$, for which $\alpha\approx 1.162$, $\beta\approx 0.806$.

We now define the following amplitudes:

$$A = \langle \eta_{ud}p|T|\eta_{ud}p\rangle ,$$
$$B = \langle \eta_s p|T|\eta_s p\rangle , \quad (5)$$
$$C = \langle \eta_{ud}p|T|\eta_s p\rangle .$$

Some quark diagrams, involving $Q\bar{Q}$ or QQQ exchanges, contributing to A, B, and C are displayed in Fig. 1. The essential point is the following: If there is no strange-quark component in the proton ($C_{s\bar{s}}=0$), and if the OZI rule holds (no disconnected quark graphs allowed), then B and C should vanish, assuming we can neglect exotic $Q^2\bar{Q}^2$ or $Q^4\bar{Q}$ exchanges. We can then isolate a combination of the cross sections $\sigma(\eta p\rightarrow \eta p)$ and $\sigma(\eta p \rightarrow \eta' p)$, for instance, which is *linear* in B and C, and hence also linear in $C_{s\bar{s}}$. Ignoring phase-space differ-

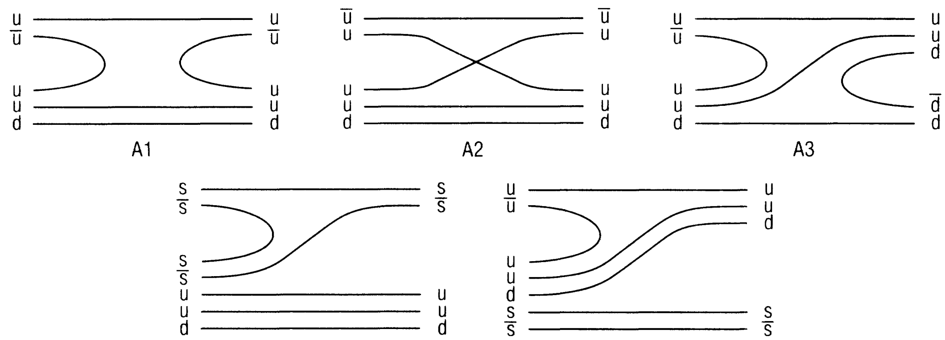

FIG. 1. Quark-flavor graphs for the reactions $\pi^0 p, \eta p \to \eta p, \eta' p$. Processes $A1$, $A2$ and $A3$ correspond to meson- and baryon-exchange mechanisms, respectively, and involve the uud valence-quark part of the proton, while B and C reflect the presence of a $uuds\bar{s}$ component in the proton wave function. Amplitudes initiated by a $d\bar{d}$ pair are not shown.

ences, we have

$$\langle \eta p | T | \eta p \rangle = \alpha^2 A + \beta^2 B - 2\alpha\beta \mathrm{Re} C\,, \quad \langle \eta' p | T | \eta' p \rangle = \beta^2 A + \alpha^2 B + 2\alpha\beta \mathrm{Re} C\,, \quad \langle \eta p | T | \eta' p \rangle = \alpha\beta(A - B) + \alpha^2 C - \beta^2 C^*\,. \tag{6}$$

To first order in the amplitudes B and C, we have

$$\frac{\beta^2 \sigma(\eta p \to \eta p) - \alpha^2 \sigma(\eta p \to \eta' p)}{\sigma(\eta p \to \eta p)} = \frac{4\beta}{\alpha} \mathrm{Re} \left[\left(\frac{\beta B}{\alpha} - C \right) \Big/ A \right]. \tag{7}$$

If there is no strange-quark content in the nucleon, the right-hand side of Eq. (7) should vanish to the 1% level typical of OZI-rule violations, whereas if $C_{s\bar{s}} \neq 0$, the right-hand side could be substantially larger. A sizable violation of the OZI rule would thus signal the presence of an $s\bar{s}$ component in the proton. Another interesting ratio is

$$\frac{\sigma(\eta' p \to \eta' p)\sigma(\eta p \to \eta p)}{\sigma^2(\eta p \to \eta' p)} = 1 + 8[\mathrm{Re}(AB^*) - \alpha\beta \mathrm{Im} A \, \mathrm{Im} C]/\alpha^2\beta^2 |A|^2 \tag{8}$$

valid to first order in B and C. In this case, after phase-space corrections are applied, deviations from unity reflect a nonvanishing $C_{s\bar{s}}$.

Similar considerations apply to the reactions $\pi^- p \to \eta n, \eta' n$, except that the amplitude B must vanish since the π^- contains no $s\bar{s}$ component. We define

$$A_\pi = \langle \pi^- p | T | \eta_{ud} n \rangle\,, \qquad C_\pi = \langle \pi^- p | T | \eta_s n \rangle \tag{9}$$

and note that C_π should vanish if the proton contains no $s\bar{s}$ component and the OZI rule is valid. To first order in C_π, we have

$$\frac{\alpha^2 \sigma(\pi^- p \to \eta' n) - \beta^2 \sigma(\pi^- p \to \eta n)}{\sigma(\pi^- p \to \eta' n) + \sigma(\pi^- p \to \eta n)} = 2\alpha\beta \mathrm{Re} \left(\frac{C_\pi}{A_\pi} \right). \tag{10}$$

Setting $R = \sigma(\pi^- p \to \eta' n)/\sigma(\pi^- p \to \eta n)$, we may write

$$R \approx \frac{\beta^2}{\alpha^2} \left[1 + \frac{2}{\alpha\beta} \mathrm{Re} \left(\frac{C_\pi}{A_\pi} \right) \right]. \tag{11}$$

In the range 15–40 GeV/c, a ratio $R \approx 0.55 \pm 0.06$ has been measured[13] at forward angles. This value is consistent with the conventional estimate $R = \beta^2/\alpha^2$, which assumes the values 0.64, 0.56, and 0.48, respectively, for $\theta = -16°$, $-18°$, and $-20°$, in the range suggested by other measurements.[12] Alternatively, we may use R to place limits on $\mathrm{Re}(C_\pi/A_\pi)$ for an assumed value of θ. For $\theta = -18°$, we find $-0.06 \le \mathrm{Re}(C_\pi/A_\pi) \le 0.04$, while for $\theta = -20°$, the result is $0.01 \le \mathrm{Re}(C_\pi/A_\pi) \le 0.12$. For reasonable choices of θ, there is no need for a sizable amplitude C_π.

In summary, the data on the pion-induced reactions $\pi^- p \to \eta n, \eta' n$, do *not* suggest a sizable amplitude C_π which could arise from a nonzero $s\bar{s}$ component in the proton wave function. Note, however, that C_π, as depicted in Fig. 1, involves a "preformed" $s\bar{s}$ pair in the nucleon with the quantum numbers (0^{-+}) of η_s. Thus the vanishing of C_π does not imply that $s\bar{s}$ pairs with vacuum quantum numbers (0^{++}), for instance, are not present in the nucleon. These vacuum pairs could be probed via amplitude B, which contributes to η-induced but not π-induced processes on a proton target. Thus it is important to measure the $\eta p \to \eta p, \eta' p$ cross sections. They reveal additional information not obtainable from π-induced reactions.

Another handle on the $s\bar{s}$ content of the proton could be provided by the associated production reactions $\pi^0 p, \eta p, \eta' p \to K^+ \Lambda$ (or $K\Sigma$). The relevant flavor graphs

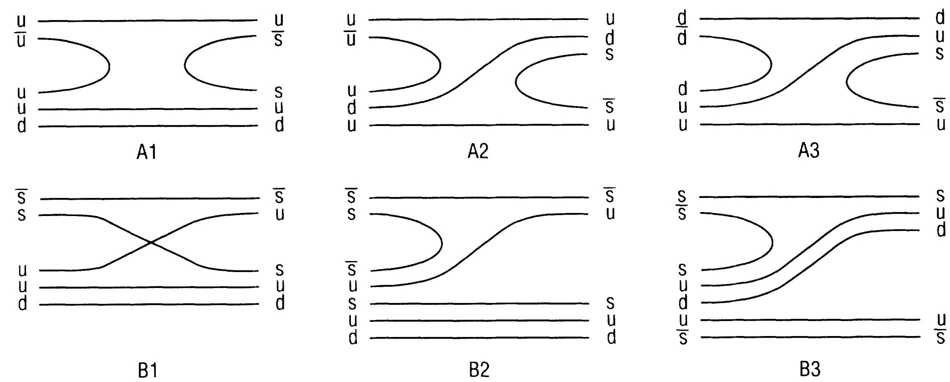

FIG. 2. Quark graphs for the associated production reactions $\pi^0 p, \eta p, \eta' p \rightarrow K^+\Lambda$, $K^+\Sigma^0$. The graphs $B2$ and $B3$ are due to a $uuds\bar{s}$ piece in the wave function of the proton.

are shown in Fig. 2. These have the same structure as Fig. 1, but the different flavor flow leads to important changes: The amplitude B is now nonvanishing when $C_{s\bar{s}}=0$, due to the rearrangement graph $B1$, and only the $u\bar{u}$ part of η_{ud} contributes to A. We define

$$A_{K^+} = \langle \eta_{ud} p \,|\, T \,|\, K^+\Lambda \rangle ,$$
$$B_{K^+} = \langle \eta_s p \,|\, T \,|\, K^+\Lambda \rangle . \tag{12}$$

Then we find, to first order in B_{K^+}/A_{K^+},

$$\frac{\sigma(\eta p \rightarrow K^+\Lambda)}{\sigma(\pi^0 p \rightarrow K^+\Lambda)} = \frac{\alpha^2}{2}\left[1 - \frac{2\beta}{\alpha}\mathrm{Re}\left(\frac{B_{K^+}}{A_{K^+}}\right)\right],$$
$$\frac{\alpha^2\sigma(\eta' p \rightarrow K^+\Lambda) - \beta^2\sigma(\eta p \rightarrow K^+\Lambda)}{\sigma(\eta' p \rightarrow K^+\Lambda) + \sigma(\eta p \rightarrow K^+\Lambda)} = 2\alpha\beta\,\mathrm{Re}\left(\frac{B_{K^+}}{A_{K^+}}\right). \tag{13}$$

These ratios are sensitive to $C_{s\bar{s}}$ in a different way, however, since in Fig. 2, the $s\bar{s}$ pair in the proton is broken up, while in Fig. 1, the $s\bar{s}$ pair is either exchanged or proceeds to the final state as a unit.

Recently, tagged η beams have been produced at the SATURNE facility[14] at Saclay via the $p+d \rightarrow \eta + {}^3\mathrm{He}$ reaction and at LAMPF, using the $\pi^- + {}^3\mathrm{He} \rightarrow \eta + t$ process.[15] Another possibility[16] is $p+p \rightarrow p+p+\eta$. Such η beams could be used to explore some of the η-induced reactions we have discussed, albeit at relatively low energies where the relations derived above surely require important phase-space corrections. We remark that the thresholds for the $\eta p \rightarrow K^+\Lambda$ and $\eta p \rightarrow \eta' p$ reactions correspond to η laboratory momenta of 0.51 and 1.16 GeV/c, respectively. The η has a decay width Γ of about 1 keV in its rest frame, so it will travel a mean distance of $(4\text{–}5)\times 10^5$ fm in the laboratory frame for momenta p_η in the range 1.2–1.5 GeV/c. If the η is produced on one proton in a hydrogen target, it has a probability

$$P = 1 - \exp(-c\tau_0\beta\gamma/\langle r\rangle) \tag{14}$$

of arriving at the site of a second proton. Here $\tau_0 = 1/\Gamma$, $\beta = v/c$, $\gamma = (1-\beta^2)^{-1/2}$, and $\langle r\rangle$ is the mean spacing between protons. In liquid hydrogen, $\langle r\rangle \approx 10^5$ fm, so $P \geq 0.98$ for $p_\eta > 1.2$ GeV/c; in a gaseous target $P \approx 0.1$ for $1.2 \leq p_\eta \leq 1.5$ GeV/c. Experimentally, it should be possible to use this density dependence to extract a signal for $\eta p \rightarrow \eta p, \eta' p$ events from the background. Because of the short η' lifetime, the cross section for $\eta' p \rightarrow \eta' p$ cannot be obtained in this way; however, one could extract this cross section from observation of multiple scattering in complex nuclei.

To summarize, a comparison of the relative cross sections for pion- and η-induced reactions on proton targets offers a first-order test for a strange-quark ($s\bar{s}Q^3$) component of the nucleon wave function. The η and η' (unlike ω, or ϕ, for instance) are useful because *both* mesons contain a significant $s\bar{s}$ admixture, but of *opposite phase* with respect to the nonstrange $u\bar{u}+d\bar{d}$ component. Significant interference effects involving the strange-quark piece of the nucleon wave function are therefore possible.

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