Nucleon Strangeness Content through Vector Meson Dominance

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It is demonstrated that $N(\pi, e^+e^-)N$ measurements will provide new information about the nucleon timelike form factor in the ϕ meson region including the value of the ϕN coupling $g_{\phi NN}$. Using vector meson dominance, $N(\pi, e^+e^-)N$ calculations reveal a 3 order of magnitude enhancement from the ϕ resonance coupled to the nucleon compared to the expected background ϕ production from the $\rho\pi\phi$ contribution through ρ exchange. The effect from ϕN coupling in the nucleon form factors yields a novel experimental signature for OZI (Okubo-Zweig-Iizuka) violation and the related strangeness content of the nucleon. [S0031-9007(96)00845-9]

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Dilepton production is becoming widely recognized as an effective means for probing hadronic structure. In this Letter we report calculations for the $N(\pi, e^+e^-)N$ reaction which document a dramatic, novel effect. In particular, assuming only the validity of vector meson dominance (VMD), we predict 3 order of magnitude cross section enhancements for virtual photon four-momentum near the low-lying vector meson masses ($q^2 \sim M_V^2$ for $V = \rho, \omega, \phi$). The resonances originate from vector mesons coupling in the timelike nucleon form factor which, unfortunately, cannot be measured in this kinematic region with e^+e^- annihilation reactions. To date, all experimental timelike data have been obtained using the two-body annihilation processes $e^+e^- \leftrightarrow N\bar{N}$ which, due to four-momentum conservation, is only kinematically accessible at much higher momentum, $q^2 \geq 4M_N^2$. In contrast, $N(\pi, e^+e^-)N$ entails a three-body final state with an effectively unrestricted virtual photon mass $q^2 \geq 4M_e^2 \sim 0$. Measurements will therefore provide significant new information which will permit investigating several important physics issues discussed below.

One such issue, which is of intense current interest, is the strangeness content of the nucleon. As argued elsewhere [1,2], possible direct evidence for hidden strangeness (strange sea quarks) would be measuring ϕ production using hadron-lepton (i.e., photon induced) reactions. The contention is that if there are no $s\bar{s}$ pairs in the nucleon then ϕN coupling will be significantly suppressed due to the predominantly $s\bar{s}$ structure of the ϕ and the Okubo-Zweig-Iizuka (OZI) rule [3]. Accordingly, observed ϕ production under such circumstances is characterized as OZI violating (also termed OZI evading). Violations of the OZI rule which apparently contradict the results from previous measurements have recently been observed in ϕ production from $p\bar{p}$ annihilation experiments at LEAR by the ASTERIX, Crystal Barrel, and OBELIX Collaborations. For a review of the current experimental evidence for hidden strangeness in the nucleon, see Ref. [4]. The strong momentum and channel dependence observed in OZI violations demonstrate the complexity of the hidden strangeness problem and suggest the need for complementary and alternative experimental investigations. In this respect it is noteworthy that ϕ electromagnetic production experiments will soon be conducted at CEBAF. Assessing ϕN coupling through photoproduction and electroproduction will require large $|t|$ measurements to reduce the dominating t-channel diffractive scattering involving possible Pomeron exchange (see measurements and discussion in Ref. [5]). Fortunately, as pointed out in Ref. [2], detecting the ϕ through $K\bar{K}$ decay permits measuring the ϕ polarization which will be a useful tool to distinguish between ϕ diffractive production and knockout.

Assessing ϕN coupling using $N(\pi, e^+e^-)N$ involves both hadronic and electromagnetic aspects and complements the above reaction studies. It is also an attractive alternative since in leading order ϕ production occurs either from coupling directly to the nucleon (p or n), nonstrange N^* or Δ^* resonances or from $\rho\pi\phi$ coupling in the t-channel ρ exchange. However, the $\rho\pi\phi$ coupling is known to be small ($\phi \rightarrow \rho\pi$ branch is 12.9%), but nonzero because of nonstrange (u- and d-) quark mixing in the ϕ. In this analysis we neglect the (unknown) OZI violating ϕ couplings to the N^* and Δ^* resonances. To fully understand their role in OZI violating ϕ production would require a much more extensive theoretical treatment and partial wave analysis of future data. We include the ρ exchange contribution (see below) since it provides a useful "background" ϕ signal to contrast our significantly larger ϕ prediction arising from ϕN coupling. There is no direct t-channel competition from π exchange since $\phi\pi$ coupling is categorically suppressed by G-parity conservation (e.g., $\phi \rightarrow \pi^+\pi^-$ branching ratio $\sim 8 \times 10^{-5}$). Equally significant, from a theoretical

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viewpoint, the resonant signature for ϕN coupling is based only upon VMD as any dynamic approach incorporating VMD would generate vector meson resonances. To help motivate future measurements we have adopted a treatment which has successfully described elementary pseudoscalar (pion and kaon) electromagnetic production and kaon radiative capture data. The model, which is based upon quantum hadrodynamics, is explicitly covariant, gauge invariant, and incorporates crossing symmetry and duality constraints. Full theoretical details are contained in Ref. [6] with additional information in Ref. [7] where we applied this approach to $p(K^-, e^+e^-)Y$ for $Y = \Lambda$, Σ^0, and $\Lambda(1405)$.

Before showing results we need to further comment on our implementation of VMD to compute the hadron form factors. We utilize a hybrid formalism [8,9] which is a generalization of the vector dominance model developed by Gari and Krümpelmann [10]. This approach incorporates $SU(3)_F$ symmetry relations and Sakurai's universality hypothesis to analyze and describe the baryon octet electromagnetic form factors. Our treatment provides a good quantitative description of the data with specific vector meson-nucleon couplings, $C_\rho(N) = 0.4$, $C_\omega(N) = 0.2$, and $C_\phi(N) = -0.1$. Here $C_V(N) = g_{VNN}/f_V$ is the ratio of the meson-nucleon hadronic coupling g_{VNN} to the meson-leptonic decay constant f_V [see Ref. [8] where the value of $C_\phi(N)$ was optimized to the G_E^n data]. Our ϕN coupling constant relative to ωN is $g^2_{\phi NN}/g^2_{\omega NN} = 0.14$, slightly smaller but still consistent with Ref. [1]. There is considerable uncertainty in $g_{\phi NN}$ whose magnitude is governed by the currently unknown nucleon strangeness content as well as the small, but much better known, u- and d-quark content of the ϕ (see below). The $\rho\pi\gamma$ transition form factor is computed from ω and ϕ vector meson states with couplings determined directly from the $\phi \to \rho\pi$, $\phi \to e^+e^-$, $\omega \to e^+e^-$, and $\rho \to \pi\gamma$ decay widths. The $\omega\rho\pi$ coupling is determined by the universality condition $C_\omega(\rho\pi) = -C_\phi(\rho\pi)$ (see Ref. [9]). Figure 1 depicts our calculated proton form factors along with available data. Note in Fig. 1 that near $q^2 = 1.0$ GeV^2 (i.e., $q^2 = M_\phi^2$) the magnetic and electric proton form factors exhibit a dip and peak, respectively. If we take the OZI limit and set the ϕ coupling to zero, the form factors are nearly unchanged in the spacelike region and the ϕ peak or dip in the timelike region becomes absent (dotted curve). We observe similar behavior in the neutron form factors (not displayed), except spacelike G_E^n is sensitive to $C_\phi(N)$.

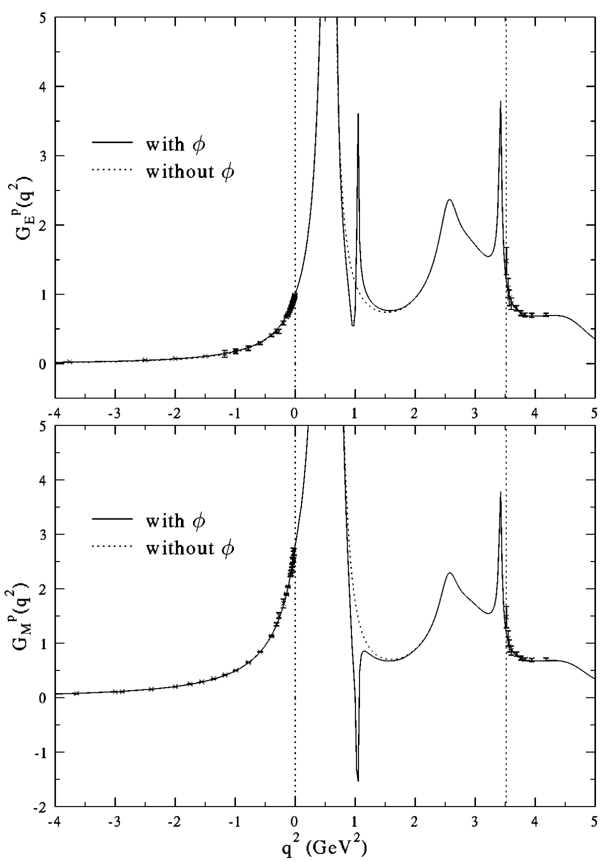

FIG. 1. Proton electric and magnetic form factor in both spacelike and timelike regions. Solid (dotted) curve represents generalized VMD with (without) ϕ coupling. Note the dramatic resonance structure predicted by VMD in the region below the $p\bar{p}$ threshold.

To illustrate the phenomenological reliability of our reaction model, we display in Fig. 2 an analysis of π^+ photoproduction data. Our quantum hadrodynamical (QHD) pion model incorporates Born amplitudes (i.e., proton,

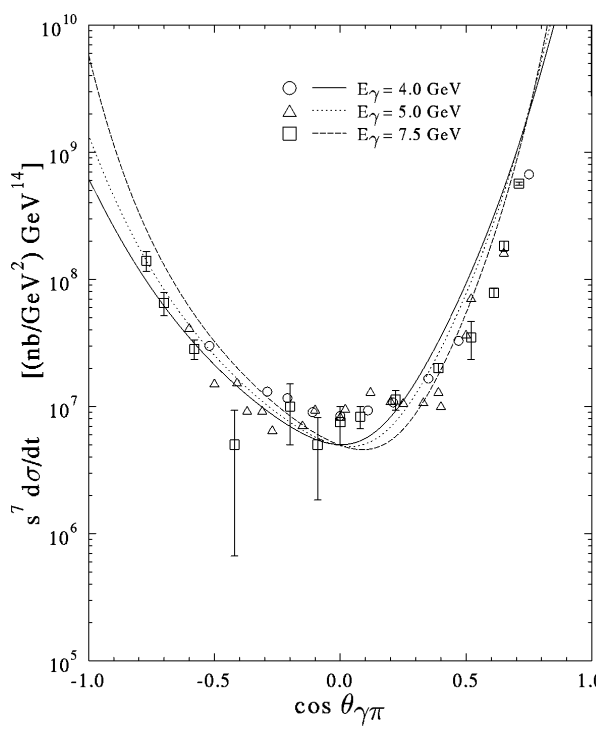

FIG. 2. Pion photoproduction for three different energies. Curves represent phenomenological QHD model analysis. Data are from Ref. [12].

neutron, pion, and rho graphs) with a phenomenological treatment of the hadronic vertex factors and final state absorption effects. The accepted πNN, $\rho\pi\pi$, $\rho\pi\phi$, and $\rho\pi\gamma$ coupling constants are used [11] and each electromagnetic form factor is multiplied by a Lorentzian function which accounts for the dynamical self-energy (i.e., modified propagators) of the off-shell composite particles. Final state absorption effects are modeled by an overall crossing symmetric function $[A(s,u) = (s_{\min} + u_{\min})/(s + u)]$ which multiplies the amplitude. We note that $d\sigma/dt$ demonstrates the $1/s^7$ scaling behavior which is empirically observed (see Fig. 2) and predicted by quark counting rules. With all model parameters fixed by the photoproduction and form factor data, we employ crossing symmetry to make a consistent prediction for the $p(\pi^-, e^+e^-)n$ reaction, shown in Fig. 3. This figure contains our key findings and illustrates several important points. Most significantly, note that the relatively small ϕ contribution to the nucleon form factors dramatically leads to a 3 order of magnitude enhancement in the cross section (represented by the solid curve) for the peak near $\theta_{n\pi} \sim 4°$. The dotted curve (overlapping the dashed curve) is the same calculation with all ϕN couplings set to zero and hence the other ϕ resonance near $\theta_{n\pi} \sim 27°$ and reduced residual peak at 4° are the effect of the $\rho\pi\phi$ coupling due to ρ exchange between π and N. This smaller peak should provide a realistic ϕ background for assessing possible excess ϕ production such as that predicted by our model. Also notice in Fig. 3 that the ϕ peak is dual valued as a function of the neutron laboratory angle $\theta_{n\pi}$. The peaks kinematically correspond to $q^2 \rightarrow M_V^2$ and are dual valued due to the nonlinear relation between q^2 and $\theta_{n\pi}$. For the ϕ with $E_\pi = 3.0$ GeV and $\theta_{\gamma\pi} = 30.0°$ this occurs at $\theta_{n\pi} = 3.7°$ and 27.3° while for the almost equal mass ρ and ω the angles are near 0° and 34.1°.

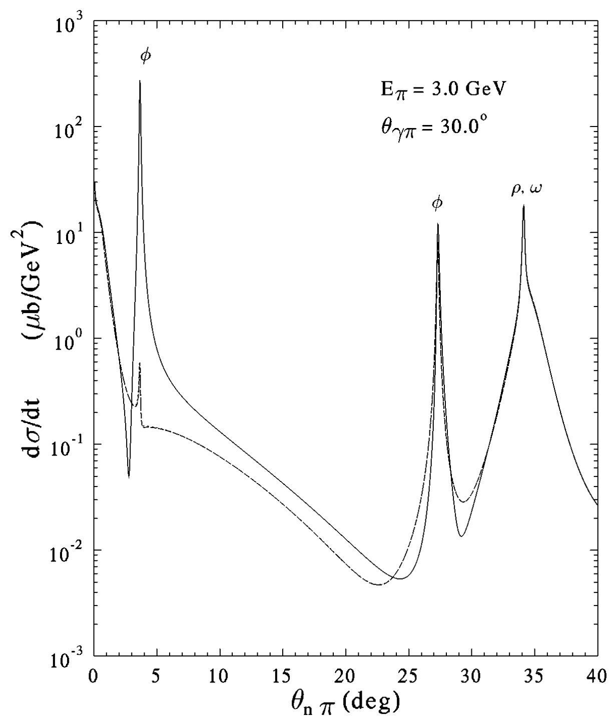

FIG. 3. VMD crossing prediction for $p(\pi^-, \gamma_v)n$ versus the neutron laboratory angle. Solid curve is full calculation detailing dramatic, dual peaked resonances from vector mesons as labeled. The dotted curve represents no ϕN coupling and is essentially identical to the dashed curve which represents ϕN coupling in only the neutron. All curves include the $\rho\pi\phi$ contribution.

The dual peak feature seen in Figs. 3 and 4 provide a useful experimental technique for separately studying ϕ production from s-channel (N) and t-channel (ρ) mechanisms. Because both the energy and angular dependence is very strong, the kinematic Mandelstam variables s, t, and u can be chosen to select the relative ϕ meson production from the proton, neutron, and ρ exchange. In Fig. 3, the dashed curve represents ϕN coupling in only the neutron form factor and the $\rho\pi\phi$ t-channel contribution [i.e., $C_\phi(p) \rightarrow 0$]. We conclude that the s-channel production of the ϕ from the neutron is negligible for the $p(\pi^-, e^+e^-)n$ reaction at $E_\pi = 3.0$ GeV. The s-channel production is suppressed because s is large, $|u| \ll s$, and this amplitude is suppressed by roughly $(|u|/s)^3$ relative to the u-channel production from the proton. Depending upon the value of $\theta_{\gamma\pi}$, the relative proton and ρ exchange contributions can be modulated, providing a kinematic filter for the experimentalist. Further, measurements of the crossing complementary process $n(\pi^+, e^+e^-)p$ could be performed using a deuteron target. In this case the e^+e^- production is predominantly from the neutron as shown in

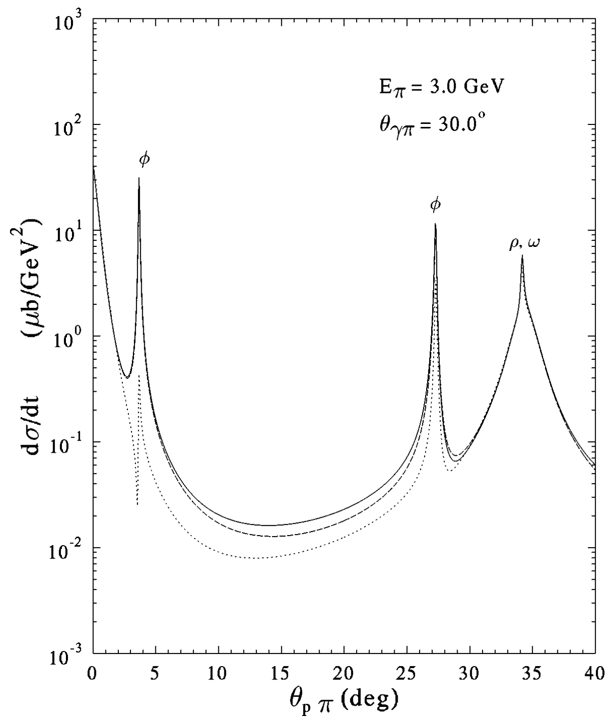

FIG. 4. VMD crossing prediction for $n(\pi^+, \gamma_v)p$ versus proton laboratory angle. Same curve labeling as Fig. 3.

Fig. 4. Now the roles of s and u are interchanged permitting measurements to study the timelike neutron form factor and the ϕN coupling to the neutron.

An indication of the level of strangeness in the nucleon is the ratio of the ϕ to ω peak cross sections, $R = d^3\sigma(q^2 = M_\phi^2)/d^3\sigma(q^2 = M_\omega^2)$ at the same s and t using the triple differential cross section (not shown). This scales as the ratio of nucleon form factors and from vector dominance on resonance is given by $R = (g_{\phi NN}^2/g_{\omega NN}^2)f$, where f is a known kinematic factor (note the $g_{\rho NN}$ contribution is suppressed by the large ρ width). We have numerically confirmed our predicted ϕ and ω peaks satisfy this relation yielding $R \sim 0.14f$, as given above and consistent with one of the OZI violating values quoted in Ref. [1]. This should be contrasted with the no nucleon strangeness OZI prediction [4] $R = \tan^2\delta f' = 4.2 \times 10^{-3} f'$, where f' is another kinematic factor (of order unity) and δ is the deviation from ideal mixing involving the small u, d quark components in the ϕ. Clearly, $p(\pi^-, e^+e^-)n$ measurements will help resolve the significant differences between predicted values for R with attending implications.

To further quantitatively relate $g_{\phi NN}$ to hidden strangeness requires a detailed model which also includes higher order $K\Lambda$, $K^*\Lambda^*, \ldots,$ loop diagrams that preserve the OZI rule and require no hidden strangeness. As calculated in Ref. [13], these loop diagrams strongly cancel, suggesting that an appreciable ϕN coupling would be direct evidence for hidden strangeness since any intrinsic $\bar{s}s$ in the nucleon always leads to an enhancement of $g_{\phi NN}$ [4].

We note that other baryon resonances (e.g., N^*, Δ^*) will contribute even at large $|t|$. Therefore until a more comprehensive calculation is conducted, one cannot unambiguously extract the proton (or neutron) timelike form factors or ϕN couplings. Nevertheless, any ϕ peak comparable with our prediction constitutes an appreciable OZI violation and is a signal for hidden strangeness.

Finally, $p(\pi, e^+e^-)n$ measurements are quite feasible and are in progress at BNL [14], although at somewhat higher energies, and are planned at GSI for energies calculated here. Both the BNL Multiple Particle Spectrometer and the Crystal Ball [14] detector have sufficient sensitivity to measure the minimal, but expected, ϕ background production signal from the $\rho\pi\phi$ contribution.

In summary, we conclude that the (π, e^+e^-) process is ideal for investigating the timelike nucleon form factor which is currently not known below $q^2 = 4M_N^2 \sim 3.5\ \text{GeV}^2$. Assuming the validity of vector dominance with OZI evading ϕN couplings, we predict a novel resonant structure in the e^+e^- spectrum that is narrow, nearly 3 orders of magnitude in enhancement, and dual peaked as a function of the recoil nucleon laboratory angle. The resonances represent a clear signature for experimentally confirming the validity of the vector dominance prescription for the ρ and ω, which is anticipated, and also for assessing the degree of OZI violation which is related to hidden strangeness.

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