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MEASURING THE TRANSITION FORM FACTORS OF PSEUDOSCALAR MESONS AT LOW Q^2

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Using the virtual Primakoff effect, the PrimEx Collaboration at Jefferson Lab is planning to perform the first high-precision measurements of the the π^0, η and η' transition form factors at very low Q^2 ($\sim 0.001 - 0.5$ GeV^2). The slopes of the transition form factors approximately measure the spatial distribution of the axial anomaly. The proposed instrumentation to be constructed for this program will be of general utility for both this program and future experiments, and will provide a new and powerful tool to study QCD at Jefferson Laboratory. In addition, knowledge of the transition form factors of the pseudoscalar mesons comprise an important element in the determination of the muon anomalous magnetic moment. These measurements are thus important for the search for "new physics" beyond the Standard Model.

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1. Overview

The future availability of high quality, high duty factor 11 GeV electron beams at JLab will enable unprecedented new opportunities to perform precise measurements of meson decay widths and electromagnetic transition form factors. Here, we discuss how one can exploit the high energy electroproduction of pseudoscalar mesons in the Coulomb field of a nucleus, the so called virtual Primakoff effect, to study the transition form factors, $F_{\gamma\gamma^*\mathrm{P}}$, where P represents the π^0, η, and η' pseudoscalar mesons. This is part of a planned comprehensive program to measure the electromagnetic properties of the light pseudoscalar mesons which will provide fundamental tests of both quantum chromodynamics and QCD inspired models.

Studies of the $\gamma\gamma^*$P vertex, where P represents the π^0, η, or η' pseudoscalar mesons and γ^* is a virtual photon, enable one to study the transition regime from soft nonperturbative physics to the hard processes of perturbative QCD. We plan to measure the photon momentum dependence of the form factors $F_{\gamma\gamma^*\mathrm{P}}(Q^2)$ and thereby map out an extension to the axial anomaly to provide a clean test of theoretical predictions.

The structure of the meson's electromagnetic coupling is typically parameterized in the context of the vector meson dominance model in which a photon couples to hadronic matter via an intermediate vector meson. Such a model implies a form factor of the form

$$F_\pi = \frac{1}{1 + q_\mu^2/m_\mathrm{V}}, \tag{1}$$

where m_V is the mass of the vector meson. For the charged pion case, the Coulomb form factor has been measured [1] and the charge radius was determined to be about 0.6 fm. Due to charge conjugation symmetry, however, the elastic Coulomb form factor (γPP) vanishes. The $\gamma^*\gamma$P transition vertex, on the other hand, is of great interest and has been studied theoretically from the point of view of models based on VMD as well as those involving treatments of the quark substructure [2−13]. This transition is characterized by the form factor $F(q_1^2, q_2^2)$ which, if only one photon is significantly off shell, depends upon a form factor typically parameterized by the pole form, and approximated at low q_μ^2 by

$$F_{\gamma^*\gamma\pi^0} \approx 1 - a\frac{q_\mu^2}{m_\mathrm{P}^2}, \tag{2}$$

where the slope a is a measure of the $\gamma^*\gamma$P interaction radius.

While there is currently no theoretical determination of the form factors from first principles, the low, as well as high, Q^2 behavior of this form factor has been the source of considerable theoretical effort. As pointed out by Bijnens [16], the next to leading order contributions are quite different when one of the photons is off shell. While the loop contributions tend to cancel when both photons are real, they have significant effect in the virtual case. In ChPT, there are two sources of contributions [17], one is the long distance contribution from meson loops, and the other is a counterterm or short distance contribution. ChPT pins down the first, and for the second a model is needed. The long distance contributions are small, as they only provide a small fraction of the fall off of the form factor. In addition, one important reason to better understand the transition form factors of the π^0, η and η' is that pseudoscalar exchange is the major contribution to the hadronic light-by-light scattering part of the muon anomalous magnetic moment [18] and is thus clearly crucial for future measurements of a_μ that search for "new physics" beyond the Standard model.

Despite the theoretical interest in pseudoscalar meson form factors, the experimental situation remains incomplete. Here, we indicate the experiments which have been performed, and the contributions which could be made with 11 GeV electron beams using the virtual Primakoff effect.

1.1. Previous measurements in the space-like region

A number of experiments have been performed to measure these transition form factors. Nevertheless, existing data in the low and intermediate regions are quite poor. The CELLO collaboration at PETRA has measured $F_{\gamma^*\gamma\mathrm{P}}$ in the space-like region at large momentum transfers using the reaction $\mathrm{e}^+\mathrm{e}^- \to \mathrm{e}^+\mathrm{e}^-\mathrm{P}$ [14]. In this experiment, two photons are radiated virtually by the colliding $\mathrm{e}^+\mathrm{e}^-$ beams. One of the virtual photons is close to real and the other has a larger q_μ^2 and is tagged by the detection of an e^+ or e^-.

Measurements were taken at momentum transfers ranging from 0.62 to 2.17 $(\mathrm{GeV}/c)^2$, and the value of a was deduced by extrapolation under the assumption of vector meson dominance. The authors quote values of $a_{\pi^0} = 0.0325 \pm 0.0026$, $a_\eta = 0.428 \pm 0.063$, and $a_{\eta'} = 1.46 \pm 0.16$. Only the statistical errors have been taken into account in these results, with systematic errors estimated to be of the same order as the statistical error. The results of these measurements are shown in Fig. 1 for the π^0 and in Fig. 2 for the η^0, with the corresponding fit to $F_{\gamma^*\gamma\mathrm{P}}$. From the plots, it is clear that any extraction of the slope parameter at $Q^2 = 0$ using the experimental data at relatively large Q^2 is highly model dependent. Data covering the higher q_μ^2 region from 2 to 20 GeV^2 on these mesons have also been reported by the CLEO collaboration [15].

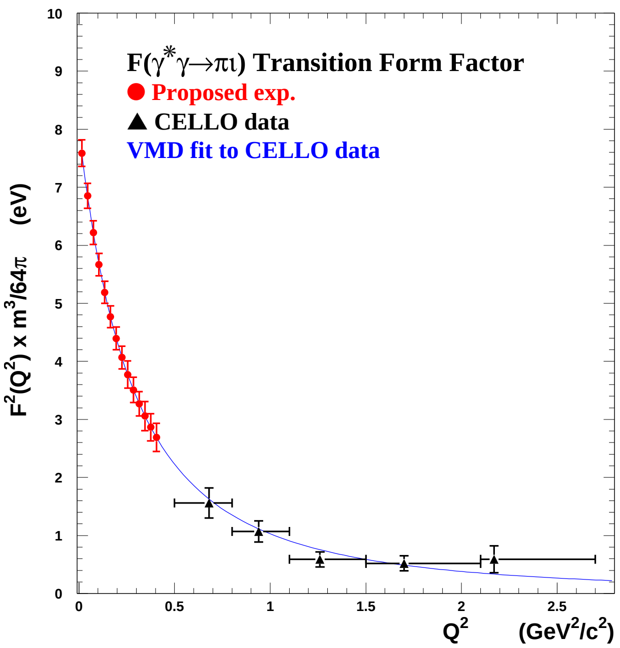

Fig. 1. The π^0 transition form factor. The proposed points are projected to the VMD prediction with expected total errors. CELLO data are from reference [14].

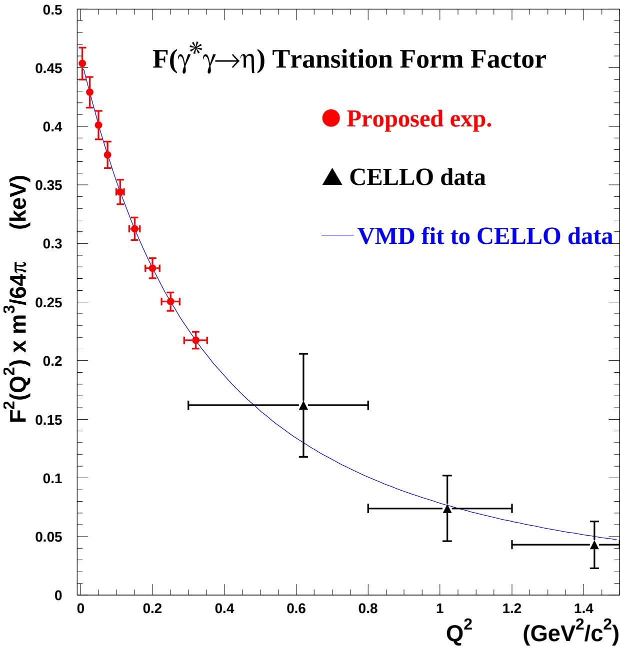

Fig. 2. The η transition form factor. The proposed points are projected to the VMD prediction with expected total errors, in comparison with CELLO data [14].

The low and intermediate momentum transfer region for these mesons is largely unexplored experimentally. While the L3 Collaboration has some results (with very poor Q^2 resolution) in the low Q^2 region for the η', low and intermediate Q^2 data on the π^0 and η are totally lacking.

1.2. Previous experiments in the time-like region

A number of experiments aimed at measuring a have been performed in the time-like momentum transfer region utilizing the π^0 and η Dalitz decay $\pi^0/\eta \to \mathrm{e}^+\mathrm{e}^-\gamma$ reaction [19–28]. The amplitude for this process involves the $F_{\gamma^*\gamma\mathrm{P}}$ form factor which, in the usual linear expansion

$$F(x) \approx 1 + a\frac{m^2_{\mathrm{e}^+\mathrm{e}^-}}{m^2_{\mathrm{P}}}. \tag{3}$$

A summary of these measurements on the pion is shown in Fig. 3, where it can be seen that the published values for the slope range from -0.24 to $+0.12$. Such experiments suffer from small kinematically accessible ranges and significant backgrounds, and they require large final-state radiative corrections. As such, these experiments have not been able to determine even the sign of the form factor slope.

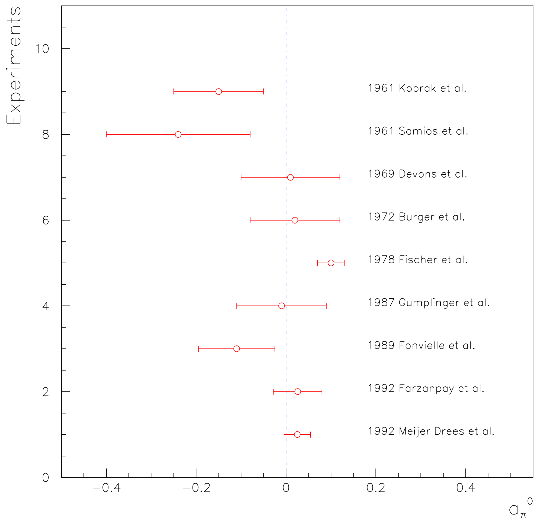

Fig. 3. Summary of the previous slope measurements for the π^0 in the time-like region.

1.3. $F_{\gamma^*\gamma\mathrm{P}}(q_\mu^2)$ using the virtual Primakoff effect

In 1989, Hadjimichael and Fallieros [29] suggested that the virtual Primakoff effect could access fundamental information about the pion, as the cross section is proportional to $|F_{\gamma^*\gamma\pi^0}(q_\mu^2)|^2$. The full expression for the virtual Primakoff scattering cross section is

$$\frac{\mathrm{d}^3\sigma}{\mathrm{d}\epsilon_2\mathrm{d}\Omega_2\mathrm{d}\Omega_\mathrm{P}} = \frac{Z^2\eta^2}{\pi}\sigma_\mathrm{M}\frac{\vec{q}_\mathrm{P}^{\,4}}{\vec{k}^{\,4}}\frac{\beta_\mathrm{P}^{-1}}{\omega_\mathrm{P}}|F_\mathrm{N}(K^2)|^2|F_{\gamma^*\gamma\mathrm{P}^0}(q_\mu^2)|^2\sin^2\frac{\theta_\mathrm{e}}{2}\sin^2\theta_\mathrm{P} \times[4\epsilon_1\epsilon_2\sin^2\phi_\mathrm{P}+|\vec{q}|^2/\cos^2\frac{\theta_\mathrm{e}}{2}] \tag{4}$$

where σ_M is the Mott cross section, $\eta^2 = (4/\pi m^3)/\tau$, τ is the meson lifetime, K is the (nearly real) photon four momentum from the Coulomb field, the meson four momentum is $Q = (\vec{q}_\mathrm{P}, \omega_\mathrm{P})$, $\beta_\mathrm{P} = \vec{q}_\mathrm{P}/\omega_\mathrm{P}$, and $F_\mathrm{N}(K^2)$ is the nuclear charge form factor. This expression for the cross section is similar to that for the real Primakoff effect, with the notable exception of the form factor $|F_{\gamma^*\gamma\mathrm{P}}(q_\mu^2)|^2$ which is of interest here.

Hadjimichael and Fallieros examined the sensitivity of the π^0 Primakoff cross section to a for energy transfers up to 1.6 GeV. They saw only moderate sensitivity and noted that the cross section is optimized for $\theta_\mathrm{e} \to 0$ and $\theta_\pi \to 0$ whereas pion energies above 2 GeV are favored for probing the $\gamma^*\gamma\pi^0$ vertex. We have extended these calculations to kinematical ranges available with the proposed 11 GeV electron beam at JLab and note that good sensitivity to the $\gamma^*\gamma$P form factor is present.

Figure 4 shows the cross sections for the virtual Primakoff pion electroproduction process on helium-4 as a function of $E_{e'}$, with an electron scattering angle of 2 degrees and a pion angle, $\theta_{\pi^0\vec{q}}$, of 0.1 degrees. The incident energy is 11 GeV. The two curves are for the VMD prediction ($a = 0.03$) and that using the slope parameter determined by the $\pi^o \to e^+e^-\gamma$ experiment ($a = 0.1$) of Ref. [24]. From the plot, one can see that the cross sections are large, and are quite sensitive to the pion transition form factor.

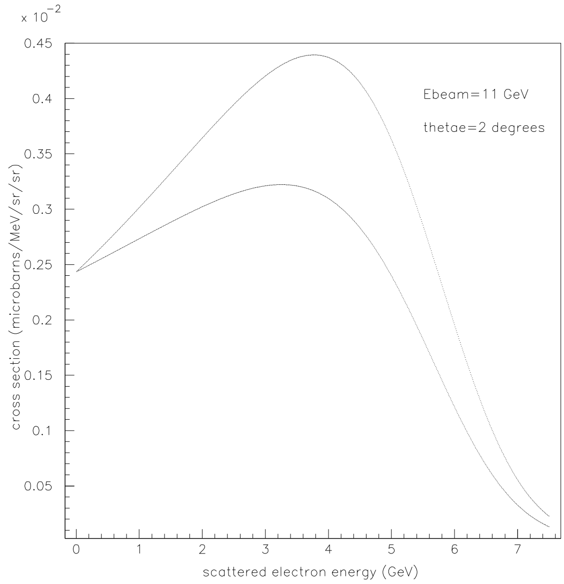

Fig. 4. Cross section versus scattered electron energy for π^0 production on helium-4. The incident electron energy is 11 GeV*. The electron scatering angle is* $2°$.

We argue that with minor modifications, one can use the highly segmented calorimeter currently under development by the PrimEx Collaboration to perform measurements of the light pseudoscalar transition form factors in the very low Q^2 region. Photons from the two gamma decay of the mesons, as well as the scattered electrons, will be detected in the calorimeter which is planned to be 1.5 m ×1.5 m in size, with a 12 cm ×12 cm central hole through which the beam will pass.

In order to distinguish the Primakoff mechanism from other processes, one must separate it from competing electroproduction mechanisms. Fig. 5 shows the θ_π angular dependence of the cross section on helium for pion electroproduction with the contributions from Primakoff, nuclear coherent, and their interference as indicated. It is this angular dependence which we plan to measure with the proposed highly segmented calorimeter in order to separate the electroproduction amplitudes.

With this experimental setup, we expect a yield of $\sim 1.0 \times 10^5$ π^0's and $\sim 2.0 \times 10^4$ η's per day for a 100 nA electron beam current, where the branching ratio for two photon decay of the η was taken to be 39%. Anticipated results for a 30 day run are shown in Figs. 1 and 2.

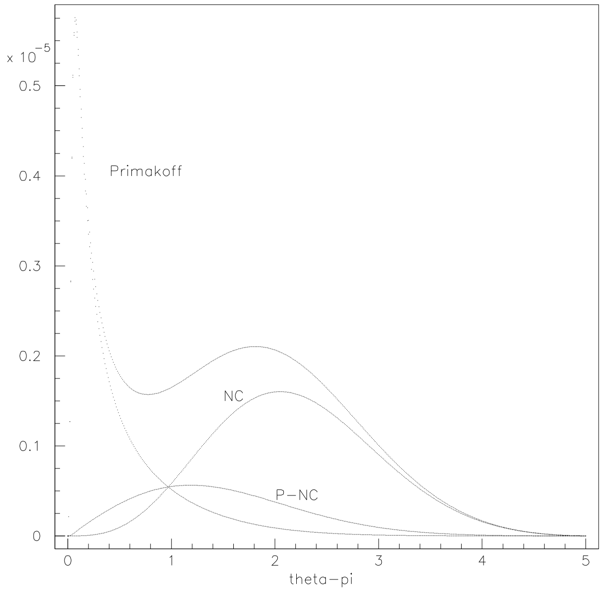

Fig. 5. Cross section versus θ_π weighted by $\sin\theta_\pi$ showing Primakoff, nuclear coherent, and their interference. In the plot, $E_e = 11$ GeV, $\omega_\pi = 7$ GeV, $\theta_e = 2°$.

2. *Summary*

We have described a planned program to measure the transition form factors of the light pseudoscalar mesons which would be possible with the advent of 11 GeV CW electron beams at Jefferson Lab. The proposed measurements of the π^0, η and η' transition form factors at very low Q^2 ($\sim 0.001 - 0.5$ GeV^2) would provide a first measurement of these important quantities. Physically, these can be approximately thought of as measuring the spatial distribution of the axial anomaly for each of the mesons. In addition, one important reason to better understand the transition form factors of the π^0, η and η' is that pseudoscalar exchange is the major contribution to the hadronic light-by-light scattering part of the muon anomalous magnetic moment [18]. It is thus important for future measurements of a_μ that search for "new physics" beyond the Standard model.

We believe the proposed instrumentation to be constructed for this program will be of general use to both this program, and future high precision experiments, and will provide a new and powerful experimental window on QCD at JLab.

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MJERENJE PRIJELAZNIH FAKTORA OBLIKA PSEUDOSKALARNIH MEZONA ZA MALE Q^2

Suradnja PrimEx u JLabu planira izvesti prva precizna mjerenja prijelaznih faktora oblika π^0, η i η' na vrlo malim Q^2 ($\sim 0.001 - 0.5$ GeV^2) primjenom virtualnog Primakoffovog efekta. Gradijenti prijelaznih faktora oblika približno daju prostornu raspodjelu aksijalne anomalije. Predloženi uređaji, koje treba sagraditi za taj program, bit će od opće koristi i za kasnija mjerenja, i predstavljat će novu i moćnu opremu za istraživanje QCD u Jeffersonovom laboratoriju. K tome će poznavanje prijelaznih faktora oblika pseudoskalarnih mesona pružiti važan element za određivanje anomalnog magnetskog momenta muona. Ta su mjerenja važna i u traženju novih pojava izvan standardnog modela.