A MEASUREMENT OF THE FORM FACTORS OF LIGHT PSEUDOSCALAR MESONS AT A LARGE MOMENTUM TRANSFER

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ABSTRACT

Using the CLEO-II detector, we have studied the exclusive two-photon production of the light pseudoscalar mesons in a single tagged mode. We report on a preliminary measurement of the \(\pi^0\), \(\eta\) and \(\eta'\) electromagnetic form factors in the \(Q^2\) region from 2 \((\text{GeV}/c)^2\) to 20 \((\text{GeV}/c)^2\).

1. Introduction

The processes discussed in this report are \(e^+e^- \rightarrow e^+e^- P\) where \(P\) stands for one of the light pseudoscalar mesons \(\pi^0\), \(\eta\) and \(\eta'\). To lowest order in perturbation theory this process can be described as single meson production by means of the two space-like photons emitted by an electron or a positron. In our experiment we detect the decay products of the meson and either the electron or positron which has scattered at an angle more than 20 degrees from the \(e^+e^-\) collision axis. From now on we refer to the detected electron (positron) as the “tag”. The other scattered lepton remains undetected. We measure production rate as a function of the squared momentum transferred by the photon emitted by the tag. The momentum transfer, \(Q^2\), can be expressed in terms of the tag parameters: \(Q^2 \equiv -q^2 = 2E_{\text{beam}}E_{\text{tag}}(1 - \cos \theta_{\text{tag}})\). Here \(E_{\text{beam}}\) and \(E_{\text{tag}}\) are energies of the tag before and after scattering and \(\theta_{\text{tag}}\) is the scattering angle of the tag. The study of the deviation of the production rate from that which is predicted for point-like mesons gives a form factor measurement. This furnishes information about hadronic structure. In our analysis we measure \(\pi^0\), \(\eta\) and \(\eta'\) form factors using the following decay channels: \(\pi^0 \rightarrow \gamma\gamma\), \(\eta \rightarrow \gamma\gamma\), \(\eta \rightarrow \pi^+\pi^-\pi^0\), \(\eta' \rightarrow \rho^0\gamma\) and \(\eta' \rightarrow \pi^+\pi^-\eta\) \((\eta \rightarrow \gamma\gamma)\).

2. Apparatus and Data Sample

The measurement described here utilizes data collected with the CLEO-II general purpose magnetic detector which is operated at the Cornell Electron Storage Ring (CESR). CESR is a symmetric \(e^+e^-\) collider running at the center of mass energy around 10.6 GeV. The excellent performance of CESR has allowed us to accumulate an \(e^+e^-\) integrated luminosity of 2.88 \(\text{fb}^{-1}\). In CLEO-II charged particles trajectories are measured with a set of three concentric cylindrical drift chambers

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located inside a solenoidal magnetic field. They cover 95% of the solid angle, and the momentum resolution is \( \sigma_p/p(\%) = \sqrt{(0.15p)^2 + (0.50)^2} \) (\( p \) in GeV/c). The electromagnetic calorimeter consists of 7800 CsI scintillation crystals and is used for photon detection and electron identification. The relative energy and angular resolutions in the barrel part of the calorimeter are \( \sigma_E/E(\%) = 0.35/E^{0.75} + 1.9 - 0.1E \) and \( \sigma_\phi(m\text{rad}) = 2.8/\sqrt{E} + 2.5 \) (\( E \) in GeV), respectively. The calorimeter covers 98% of the \( 4\pi \). The time-of-flight (TOF) system (97% of \( 4\pi \)) consists of scintillation counters and is used primarily for trigger purposes.

CLEO-II has a three-level trigger system\(^2\) which consists of ten triggers suitable for different physics. In our analysis we use data collected with two triggers. The first trigger requires that both the tag and the decay products of the meson are detected. The signature of the tag includes a track reconstructed by a fast track-finding processor, a hit in the TOF counter and a shower of at least 500 MeV. In order to identify the decay products of the meson another shower of the energy above 500 MeV or two separated showers (at least of 200 MeV of deposited energy each) must be found in the barrel part of the calorimeter. The other trigger requires at least two tracks, one with momentum transverse to the beam line (\( p_\perp \)) greater than 400 MeV/c and the other with \( p_\perp \) greater than 200 MeV/c. In addition, hits in two nonadjacent TOF counters and two separated energy clusters (above 200 MeV each) must be found in the barrel part of the detector.

3. Event Selection

Event selection criteria are optimized to identify two-photon events where the only missing particle is a scattered electron or positron. We require that the following conditions are satisfied:

- Both the charged track and the shower (of the energy above 1 GeV) are found for the tag candidate. The shower centroid and the projected track impact point agree to within 20 degrees as viewed from the interaction point.

- Energy of the two-photon system is less than 60% of the Energy of the Center of Mass (ECM).

- Hadronic system has no net charge.

- Events with hadronic tracks have \( E_{\text{isolated}} \) less than 300 MeV where \( E_{\text{isolated}} \) is a total energy of the extra photon-like clusters in the calorimeter not associated with the process under consideration. Hadrons interacting strongly in the material of the electromagnetic calorimeter are primary sources of these clusters. We require \( E_{\text{isolated}} \) to be equal to zero when no charged tracks besides the tag candidate are found in the whole detector.
• The scattering angle of the unobserved electron (positron) is less than 20 degrees. This angle is determined from the direction of the missing momentum which we assume to be due solely to the undetected electron (positron). The missing momentum ($\vec{P}_{\text{missing}}$) is a vector opposite to the vector sum of the momenta of all reconstructed charged particles and photons.

• $|\vec{P}_{\text{missing}}|$ and the missing energy ($E_{\text{missing}}$) which is calculated by subtracting the total detected energy ($E_{\text{visible}}$) from the ECM of the experiment must satisfy the following criteria:

\[
2.0 \text{ GeV} \leq E_{\text{missing}} \leq 6.0 \text{ GeV} \\
2.0 \text{ GeV} \leq |\vec{P}_{\text{missing}}| \leq 6.0 \text{ GeV} \\
-2.0 \text{ GeV} \leq (E_{\text{missing}} - |\vec{P}_{\text{missing}}|) \leq 2.0 \text{ GeV}
\]

* A tighter cut was imposed in the $\eta \rightarrow \pi^+\pi^-\pi^0$ analysis. See section 4 for the details.

We show the distributions of the hadronic system masses for the candidate events in Fig. 1. The shapes of the signal are obtained using a GEANT-based detector simulation program. The shapes of the background are approximated by smooth functions that are discussed below.

![Fig. 1. The mass distributions for a) $\pi^0 \rightarrow \gamma\gamma$, b) $\eta \rightarrow \pi^+\pi^-\pi^0$ and c) $\eta' \rightarrow \eta\pi^+\pi^- (\eta \rightarrow \gamma\gamma)$ signals. The curves show the results of the fits described in the text.](image)

4. Background Estimates

Background events in which the final state is not fully reconstructed may contribute to the $\pi^0$, $\eta$ and $\eta'$ signals. In order to estimate this background we have run an extensive Monte Carlo (MC) simulation of different two-photon processes. Typically our MC sample size exceeded our data by a factor of 30. We identified the following process which feeds into the $\eta \rightarrow \pi^+\pi^-\pi^0$ signal: $\eta' \rightarrow \eta\pi^0\pi^0$. In order to supress this background a more restrictive cut is applied in the $\eta \rightarrow \pi^+\pi^-\pi^0$ analysis: 

\[-0.6 \text{ GeV} \leq (E_{\text{missing}} - |\vec{P}_{\text{missing}}|) \leq 0.6 \text{ GeV}.
\]
Simulation has been also performed for the single-photon annihilation process, i.e. $e^+e^- \rightarrow \gamma^* \rightarrow$ lepton pairs or hadrons. We can make an independent estimate of the possible contribution from this process by taking advantage of our knowledge of the tag charge. In two-photon signal events the untagged electron (positron) is scattered at a very small angle and is travelling along the direction of the incident electron (positron) beam. Thus, the direction of the missing momentum uniquely determines the charge of the tag. This is not the case for the single-photon annihilation events. The observed rate for events with a wrong charge of the tag is comparable to the charge misidentification probability of $\approx 0.5\%$. This implies that the background from the annihilation processes is negligible.

Electro-production of a meson in the field of a beam-gas nucleus is also a possible source of background. We estimate this background using distributions of the event vertex position along the beam line and $x = E_{\text{visible}}/E_{\text{beam}}$ which are shown in Fig.2. We assume that beam-gas events peak at $x = 1.0$ and are uniformly distributed along the beam line. From the number of events in the tails of the distributions we conclude that beam-gas contamination is insignificant.

The total contribution from all background processes associated with resonance production is estimated to be less than 1 event in each channel studied.

![Fig. 2. a) The position of the event vertex along the beam line for $\eta'$ signal, b) $x = E_{\text{visible}}/E_{\text{beam}}$ for the $\pi^0$ signal (background subtracted using sidebands in the mass distribution)](image)

The background contribution from all other processes is approximated by the polynomial of the first order except for the background under the $\pi^0$ signal peak. This background (shown in Fig.1a)) comes from the radiative Bhabha events, i.e. $e^+e^- \rightarrow e^+e^-\gamma$. In these events a $\gamma$ converts into $e^+e^-$ pair in the outer layers of the drift chamber. The 1.5 Tesla magnetic field causes a spatial separation of the produced pair and the electromagnetic showers developed in the calorimeter are indistinguishable from the showers caused by real photons when no tracks are found. We use an exponential to approximate contribution from this process.

5. Analysis and Fits to the Form Factors

In order to achieve the best possible resolution in $Q^2$, we employ the following
techniques:

- For \( \eta' \rightarrow \pi^+\pi^-\eta (\eta \rightarrow \gamma\gamma) \) and \( \eta \rightarrow \pi^+\pi^-\pi^0 \) events a full kinematic fit is performed where the photon pair is constrained to have exactly \( \eta \) or \( \pi^0 \) mass.

- The tag scattering angle is measured from the centroid of the shower associated with the tag rather than from the reconstructed charged track.

- The magnitude of the transverse momentum of the tag \( (p^\text{tag}_\perp) \) is constrained to be equal to the \( p_\perp \) of the hadronic system.

- The energy of the tag \( (E\text{tag}) \) is obtained using scattering angle and \( p^\text{tag}_\perp \). Since shower leakage at small angles is significant, this method gives a better \( E\text{tag} \) resolution than the endcap calorimeter energy measurement.

For the purposes of obtaining the detection efficiency we use MC generators based on the formalism of Budnev with a simple double pole vector meson dominance (VMD) form factor incorporated. We measure trigger efficiencies by using redundancies between different triggers. Overall detection efficiency is obtained in bins of \( Q^2 \) and this efficiency changes from 5% to up to 30% as \( Q^2 \) grows. We extract the \( Q^2 \) dependence of the form factor by comparing the measured production rate with that which is predicted for point-like pseudoscalar mesons. Our preliminary results are shown in Fig.3. The choice of the bin centers in \( Q^2 \) is made on the basis of the VMD MC simulation. We interpret our results in terms of \( \Lambda_p \), the mass parameter which governs the \( Q^2 \) evolution of the form factor. This parameter is obtained by fitting our data with a function of the following form:

\[
F^2(Q^2,0) * M^3/64\pi = \Gamma_{\gamma\gamma}/(1 + Q^2/\Lambda_p^2)^2
\]

Here \( F^2(Q^2,0) \) is the square of the form factor which is a function of \( Q^2 \), \( M \) is the mass of the meson and \( \Gamma_{\gamma\gamma} \) is the two-photon width of the resonance (7.35 eV, 0.463 KeV and 4.3 KeV for \( \pi^0 \), \( \eta \) and \( \eta' \), respectively). We estimate the average squared momentum of the second photon to be less than 0.001 (GeV/c)^2. It is predicted

![Fig. 3. The \( \pi^0 \), \( \eta \) and \( \eta' \) pseudoscalar meson form factors (preliminary). Description of the pole mass fit can be found in the text.](image-url)
Table 1. Summary of the results on pole mass $\Lambda_p$ [MeV], governing $Q^2$ evolution of the form factors

|       | Lepton-Gγ | TPC/2γγ | CELLOγγ | CLEO (this study) |
|-------|-----------|---------|----------|-------------------|
| $\pi^0$ |           |         |          | 748 ± 30          |
| $\eta$  | 720 ± 90  | 700 ± 80| 839 ± 63 | 771 ± 18          |
| $\eta'$ |           | 850 ± 70| 794 ± 44 | 821 ± 15          |

Table 2. Summary of the results on the $f_p$ [MeV], pseudoscalar meson coupling constant

|       | Lepton-Gγ | TPC/2γγ | CELLOγγ | CLEO (this study) |
|-------|-----------|---------|----------|-------------------|
| $\pi^0$ |           |         | 84 ± 3   | 87 ± 2            |
| $\eta$  | 81 ± 10   | 91 ± 6  | 94 ± 7   | 89 ± 3            |
| $\eta'$ |           | 78 ± 5  | 89 ± 5   | 92 ± 2            |

that in the asymptotic limit ($Q^2 \to \infty$) the pole mass can be expressed in terms of the pseudoscalar meson coupling constant $f_p$ as $f_p^2 = \Lambda_p^2/(8\pi^2)$. Interpretation of our results in terms of $\Lambda_p$ and $f_p$ and a comparison with the previous measurements are shown in Tables 1 and 2. Note that the errors quoted are only statistical. The major source of the systematic error in the pole mass (a relative error of 5%) is the experimental uncertainty on $\Gamma_{\gamma\gamma}$. Other sources of the systematic error include trigger and detector simulation, tracking, variation in the event selection criteria, background estimates and an uncertainty in the $Q^2$ of the photon emitted by the missing electron (positron). Taken in quadrature they correspond to a relative systematic error of the order of less than 5% for one-prong and of less than 10% for three-prong events. More careful treatment of the systematic errors is forthcoming.

6. Summary, Conclusions and Plans

We reported on the current status of the analysis of electromagnetic form factors of the light pseudoscalar mesons $\pi^0$, $\eta$ and $\eta'$. In terms of the pole mass fit and decay coupling constant our results are consistent with previous measurements. For the first time $\pi^0$ and $\eta$ form factors are measured at $Q^2$ above 2.7 and 3.4 (GeV/c)$^2$ respectively. Also, this is the first statistically significant measurement for the $\eta'$ at $Q^2$ above 8 (GeV/c)$^2$. With a better understanding of the trigger we plan to extend our analysis to events with tags scattering at a smaller angles down to 16.5 degrees.

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