Recent BABAR results on two-photon processes are presented. A high statistics study of the two-photon production of the charmonium states $\eta_c$ and $\eta_c(2S)$ is performed. The mass and width of $\eta_c$ and $\eta_c(2S)$ are measured; the ratio of the decay probabilities to $K_S K_+ \pi^-$ and $K^+ K^- \pi^+ \pi^- \pi^0$ are determined. The latter mode is studied for the first time. The reactions $e^+ e^- \rightarrow e^+ e^- g^* \rightarrow e^+ e^- + \text{pseudoscalar meson}$ are studied in the single-tag mode for $\pi^0$, $\eta$, $\eta'$, and $\eta_c$. From the measured differential cross sections the $Q^2$ dependencies of the photon-meson transition form factors are extracted. From these measurements we conclude that the pion distribution amplitude strongly differs from the distribution amplitudes of $\eta$ and $\eta'$ mesons.

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1. Introduction

Two-photon production of a resonance $R$ is studied at $e^+e^-$ colliders in the process $e^+e^- \rightarrow e^+e^-R$. The electrons in this process are scattered predominantly at small angles. For the pseudoscalar meson production, the effect of strong interactions is described by only one form factor $F(q^2_1,q^2_2)$ depending on the squared momentum transfers to the electrons.

Two-photon processes are usually studied in so called no-tag mode with both final electrons undetected. In this case the virtual photons emitted by electrons are practically real, the momentum transfers squared are close to zero. In no-tag mode the meson-photon transition form factor at zero $q^2$’s and the meson two-photon width are measured.

In the single tag-mode one of the final electrons is detected. The corresponding virtual photon is highly off-shell. From the measurement of the cross section richer information is extracted: the dependence of the meson form factor on $Q^2 = -q^2_1$.

In this report we present results of no-tag and single-tag measurements performed with the BABAR detector at the PEP-II $e^+e^-$ collider. The results are based on data with integrated luminosity of about 500 fb$^{-1}$ collected at the center-of-mass energy of 10.6 GeV.

No-tag two-photon events are selected by the requirement that the transverse momentum of the electron-plus-meson system be low and the missing mass in an event be close to zero.

2. Measurement of $\eta_c$ and $\eta_c(2S)$ parameters in the no-tag mode

The $K_S K^\pm \pi^\mp$ mass spectrum for no-tag events is shown in Fig. 1(a). The $\eta_c$, $J/\psi$, and $\eta_c(2S)$ peaks are clearly seen over a non-resonant smooth background. The $J/\psi$’s are produced in the initial state radiation process $e^+e^- \rightarrow J/\psi \gamma$. An evidence for the $\chi_{c2} \rightarrow K_S K^\pm \pi^\mp$ decay is also seen in Fig. 1b. From the fit to the mass spectrum the following $\eta_c$ parameters are determined [1]:

$$m = 2982.2 \pm 0.4 \pm 1.5 \text{ MeV}/c^2, \quad \Gamma = 31.7 \pm 1.2 \pm 0.8 \text{ MeV},$$

(2.1)

$$\Gamma(\eta_c \rightarrow \gamma \gamma)B(\eta_c \rightarrow K\bar{K}\pi) = 0.379 \pm 0.009 \pm 0.031 \text{ keV}.$$  

(2.2)

These are the most precise measurements of the $\eta_c$ mass and width to date. The obtained value of $\Gamma(\eta_c \rightarrow \gamma \gamma)B(\eta_c \rightarrow K\bar{K}\pi)$ agrees with the CLEO measurement $0.407 \pm 0.022 \pm 0.028$ keV [2].

From the fit to the $K_S K^\pm \pi^\mp$ mass spectrum in the vicinity of the $\eta_c(2S)$ resonance the following values of the $\eta_c(2S)$ mass and width are obtained:

$$m = 3638.3 \pm 1.5 \pm 0.6 \text{ MeV}/c^2, \quad \Gamma = 14.2 \pm 4.4 \pm 2.5 \text{ MeV}.$$  

(2.3)

These results are preliminary. They are in reasonable agreement with the previous BABAR measurements [3]: $m = 3630.8 \pm 3.4 \pm 1.0 \text{ MeV}/c^2$ and $\Gamma = 17.0 \pm 8.3 \pm 2.5 \text{ MeV}$, obtained using 88 fb$^{-1}$ data. The current PDG values for these parameters are $m = 3637 \pm 4 \text{ MeV}/c^2$ and $\Gamma = 14 \pm 7 \text{ MeV}$ [2]. The measured value of the $\eta_c(2S)$ width is also in good agreement with an estimation based on a quark model: $\Gamma(\eta_c(2S) \rightarrow gg) \approx \Gamma(\eta_c(1S) \rightarrow gg)\Gamma(\psi(2S) \rightarrow ee)/\Gamma(\psi(1S) \rightarrow ee) = 12.1 \pm 1.0 \text{ MeV}$. 


as a convolution of a calculable amplitude for agreement with both VDM and QCD predictions, and with the result of the lattice QCD calculation: 

\[ \text{Experimental data can be used to test different DA models. The BABAR results [8] on the scaled function with a pole parameter } h \text{ from asymptotic DA. The models with wide or very wide, flat DA’s were proposed (see, for example, Refs. [11, 12, 13, 14, 15, 16, 17]) to describe the } Q^2 \text{ dependence of the pion form factor observed by BABAR.} \]

**3. Measurement of meson-photon transition form factors**

In perturbative QCD, at large \( Q^2 \), the meson-photon transition form factor can be represented as a convolution of a calculable amplitude for \( \gamma\gamma \rightarrow q\bar{q} \) with a nonperturbative meson distribution amplitude (DA) [5]. The latter describes the transition of the meson into two quarks.

Due to the relatively large c-quark mass, the \( \eta_c \) form factor is rather insensitive to the shape of the \( \eta_c \) distribution amplitude. Its \( Q^2 \) dependence is expected to be described by a monopole function with a pole parameter \( \Lambda \sim 10 \text{ GeV}^2 \) [6]. This value is close to the VDM prediction: \( \Lambda = m_{J/\psi}^2 = 9.6 \text{ GeV}^2 \).

The BABAR data on the \( Q^2 \) dependence of the normalized \( \gamma\gamma \rightarrow \eta_c \) transition form factor [1] is fitted well by a monopole function. The found pole parameter \( \Lambda = 8.5 \pm 0.6 \pm 0.7 \text{ GeV}^2 \) is in agreement with both VDM and QCD predictions, and with the result of the lattice QCD calculation: \( \Lambda = 8.4 \pm 0.4 \text{ GeV}^2 \) [7].

For light pseudoscalars, the form factor depends strongly on the shape of the meson DA. Experimental data can be used to test different DA models. The BABAR results [8] on the scaled (multiplied by \( Q^2 \)) \( \gamma\gamma \rightarrow \pi^0 \) transition form factor is shown in Fig. 2(a) together with CLEO and CELLO data [8, 10]. The horizontal dashed line indicates the asymptotic limit for the scaled form factor \( (Q^2 F(Q^2) = \sqrt{2} f_\pi \approx 0.185 \text{ GeV}) \) predicted by pQCD [8]. The measured form factor exceeds the asymptotic limit at \( Q^2 > 10 \text{ GeV}^2 \). This means that the pion DA is significantly wider than the asymptotic DA. The models with wide or very wide, flat DA’s were proposed (see, for example, Refs. [11, 12, 13, 14, 15, 16, 17]) to describe the \( Q^2 \) dependence of the pion form factor observed by BABAR.

**Figure 1:** The \( K_3 K^\pm \pi^\mp \) (a) and \( K^+ K^- \pi^+ \pi^- \) (c) mass spectra. The solid line is the fit result. The dashed line represents non-resonant background. The plots (b) and (d) show background subtracted spectra for the mass range 3.3–3.7 GeV/c².

The mass spectrum for \( K^+ K^- \pi^+ \pi^- \pi^0 \) two-photon events is shown in Fig. 1(c). The signals from \( \eta_c, \eta_c(0), \eta_c(2S) \) are seen. This is a first observation of the \( K^+ K^- \pi^+ \pi^- \pi^0 \) decay for these resonances. The \( \eta_c(2S) \) meson was previously observed in only \( K_3 K \pi \) decay mode. We have determined the ratios of the branching fractions into the two decay modes for \( \eta_c \) and \( \eta_c(2S) \):

\[
B(\eta_c \rightarrow K^+ K^- \pi^+ \pi^- \pi^0)/B(\eta_c \rightarrow K_3 K^\pm \pi^\mp) = 1.42 \pm 0.06 \pm 0.26, \tag{2.4}
\]

\[
B(\eta_c(2S) \rightarrow K^+ K^- \pi^+ \pi^- \pi^0)/B(\eta_c(2S) \rightarrow K_3 K^\pm \pi^\mp) = 2.1 \pm 0.4 \pm 0.5. \tag{2.5}
\]

These results are preliminary.
Figure 2: The scaled photon-meson transition form factors for $\pi^0$ (a), $\eta$ (b), and $\eta'$ (c) mesons. The dashed lines indicate the asymptotic limits for the scaled form factors.

The BABAR preliminary results on the scaled $\gamma \gamma' \rightarrow \eta$ and $\eta'$ transition form factors measured in the $e^+e^- \rightarrow e^+e^-\eta^{(1)}$ reactions are shown in Figs. 2(b) and (c) in comparison with previous CLEO measurements [10]. We significantly improve the precision and extend the $Q^2$ region for form factor measurements. For $\eta'$ our results and CLEO measurements are in good agreement. For $\eta$ the agreement is worse. The CLEO point at 7 GeV$^2$ lies higher than our data by about 3 sigmas.

The $e^+e^- \rightarrow \eta^{(1)}\gamma$ reactions also can be used to determine the transition form factors, but in the time-like region $q^2 = s > 0$. The time- and space-like form factors are expected to be close to each other at high $Q^2$. The form factors at $Q^2 = 14.2$ GeV$^2$

$$Q^2 F_\eta(Q^2) = 0.187 \pm 0.030 \text{ GeV}, \quad Q^2 F_{\eta'}(Q^2) = 0.222 \pm 0.035 \text{ GeV}$$

are obtained from the values of the $e^+e^- \rightarrow \eta^{(1)}\gamma$ cross sections measured by CLEO [13] near the maximum of the $\psi(3770)$ resonance. The assumption is used that the contributions of the $\psi(3770) \rightarrow \eta^{(1)}\gamma$ decays to the $e^+e^- \rightarrow \eta^{(1)}\gamma$ cross sections are negligible. The time-like form factors at $Q^2 = 14.2$ GeV$^2$ are close to the corresponding space-like values. The BABAR measurements of the $e^+e^- \rightarrow \eta^{(1)}\gamma$ cross sections [13] near the maximum of the $Y(4S)$ resonance allows us to extend the $Q^2$ region for the $\eta$ and $\eta'$ form factor measurements up to 112 GeV$^2$. The time-like form-factor values at 112 GeV$^2$ are as follows:

$$Q^2 F_\eta(Q^2) = 0.229 \pm 0.031 \text{ GeV}, \quad Q^2 F_{\eta'}(Q^2) = 0.251 \pm 0.021 \text{ GeV}.$$  (3.2)

The dashed lines in Figs. 2(b) and (c) indicate the asymptotic limits for the scaled $\eta$ and $\eta'$ form factors calculated in Ref. [20]. It is seen that $Q^2$ dependencies of the form factors for $\eta$ and $\eta'$ differ from that for $\pi^0$. We conclude that BABAR results on the meson-photon transition form factors for light pseudoscalars indicate that the pion DA is significantly wider than the DA’s of $\eta$ and $\eta'$ mesons.

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