Study of productions of $K_S^0 K_S^0$ (single-tag) and $\eta'\pi^+\pi^-$ (no-tag) in two-photon collisions

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A measurement of the cross section for $K_S^0$ pair production in single-tag two-photon collisions, $\gamma\gamma \rightarrow K_S^0 K_S^0$, for $Q^2$ up to 30 GeV$^2$ is reported. Here $Q^2$ is the negative of the invariant mass squared of the tagged photon. For the first time, the transition form factor of the $f_2^\prime(1525)$ meson is measured separately for the helicity $-0$, $-1$, and $-2$ components and compared with theoretical calculations. The $\gamma\gamma$ partial decay widths of the $\chi_{c0}$ and $\chi_{c2}$ charmonia are measured as a function of $Q^2$. The measurements of $\gamma\gamma \rightarrow \eta_c(1S), \eta_c(2S) \rightarrow \eta'\pi^+\pi^-$ with $\eta'$ decays to $\gamma p$ and $\eta\pi^+\pi^-$ are reported as well. First observation of $\eta_c(2S) \rightarrow \eta'\pi^+\pi^-$ with a significance $5.5\sigma$ including systematic error is obtained. The products of the two-photon decay width and branching fraction of decays to $\eta'\pi^+\pi^-$ are determined for the $\eta_c(1S)$ and $\eta_c(2S)$, respectively. The cross section for $\gamma\gamma \rightarrow \eta'\pi^+\pi^-$ and $\eta'/f_2(1270))$ are measured for the first time. These results for the $K_S^0 K_S^0$ ($\eta'\pi^+\pi^-$) production are based on the data sample of $759 \text{ fb}^{-1}$ ($941 \text{ fb}^{-1}$) collected with the Belle detector at the KEKB asymmetric-energy $e^+e^-$ collider.

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1. Introduction

A \( Q^2 \) dependence of the transition form factor (TFF) of a meson produced by a formation process from two-photon fusion can be measured in the single-tag two-photon processes, where either photon is highly virtual and the other photon regarded as (quasi-) real. The measurements of TFF or the \( \gamma^* \gamma \) cross sections are applied for studies of QCD based on models of \( q\bar{q} \) mesons [3] and exotic hadrons, and hadron tomography through an extraction of generalized distribution amplitude (GDA)\[2\]. In addition, the size of the cross sections can be a reference of the Light-by-Light hadronic contribution which is used in a theoretical evaluation of the anomalous magnetic moment of the muon \((g - 2)\) [3].

Precise measurement of the \( \eta_c(1S) \) and \( \eta_c(2S) \) two-photon decay widths may provide sensitive tests for QCD models [3]. CLEO made the first measurement of the \( \eta_c(2S) \) two-photon decay width \( \Gamma_{\gamma\gamma} \) via \( K_S^0K^+\pi^- \) but observed no signal for the \( \eta_c(2S) \rightarrow \eta'_c \pi^+\pi^- \) decay [5]. The cross sections for two-photon production of meson pairs have been predicted in the leading term QCD calculation [3] and the handbag model [3], and measured in the experiments by Belle [3]. There is no specific QCD prediction for the two-photon production of either the pseudoscalar-tensor meson pair \( \eta'_c f_2(1270) \) or the three-body final state \( \eta'_c \pi^+\pi^- \).

The measurements are performed using the Belle detector [3] at the asymmetric \( e^+e^- \) collider KEKB [3]. The collision data collected at \( e^+e^- \) c.m. energies near the \( \Upsilon(4S) \) mass (10.6 GeV), 60 MeV below it, and the \( \Upsilon(5S) \) mass (10.9 GeV) are used.

2. Study of \( \gamma^* \gamma \rightarrow K^0_\pi K^0_\pi \)

The \( \gamma^* \gamma \)-based cross section as a function of \( W \) for five \( Q^2 \) regions from 3 GeV\(^2\) to 30 GeV\(^2\), in \( W \) region below 2.6 GeV, is derived and shown in Figure I. We find the cross section has peaks near the threshold and the mass of \( f'_2(1525) \), but no significant enhancement in the \( f_2(1270)/a_2(1320) \) region. The cross section gradually decreases according to \( Q^2 \).

Because the peaks from the \( \chi_{c0} \) and \( \chi_{c2} \) charmonia are as narrow as the mass resolution of the detector, we evaluate the peak yields with the product of the two-photon decay width \( \Gamma_{\gamma\gamma} \) and the branching fraction to the final state, instead of the \( W \) dependence of the cross section. The experimental results are plotted as a function of \( Q^2 \) in Fig. 2 as a ratio to the corresponding zero-tag measurement (at \( Q^2 = 0 \)).

We have performed a partial-wave analysis to obtain the TFF of \( f'_2(1525) \). The obtained \( Q^2 \) dependences of the \( f'_2(1525) \) TFFs are plotted in Fig. 3. The curves are the theoretical prediction [3]. They show good agreement for the helicity\( -0 \) and \( -2 \) states. As for the helicity\( -1 \), the prediction is slightly larger, but is not inconsistent.

3. Study of \( \gamma\gamma \rightarrow \eta'_c \pi^+\pi^- \)

The fit results for the \( \eta_c(1S) \) and \( \eta_c(2S) \) signals are shown in Fig. 4. The products of the two-photon decay width and branching fraction \( (B) \) of decays to \( \eta'_c \pi^+\pi^- \) are determined to be \( \Gamma_{\gamma\gamma}B(\eta_c(1S)) = [65.4 \pm 2.6 \text{ (stat)} \pm 6.9 \text{ (syst)}] \text{ eV} \) and \( \Gamma_{\gamma\gamma}B(\eta_c(2S)) = [5.6^{+1.2}_{-1.1} \text{ (stat)} \pm 1.1 \text{ (syst)}] \text{ eV} \).
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Figure 1: The $\gamma' \gamma$ based total cross section for $\gamma' \gamma \rightarrow K^0_L K^0_S$ as a function of $W$ for the five $Q^2$ regions whose central value is shown in the subpanel.

Figure 2: $Q^2$ dependence of the two-photon decay width of $\chi_{c0}$ (left) and $\chi_{c2}$ (right) normalized by that for $Q^2 = 0$. Refer to the paper [11].

Figure 3: TFFs for the three helicity states of the $f_2(1525)$ from the present measurement. The gray band shows the normalization error. The curves are from a theoretical prediction [11].

An enhancement near 1960 MeV/$c^2$ is observed in the $\eta_c(1S)$ signal window, but no such excess is seen in the $\eta_c(1S)$ sideband region. We label it the $f_0(2080)$, with mass and spin to be given in study. The fit results for the $f_0(980)$, $f_2(1270)$ and $f_0(2080)$ components are shown in Fig. 1(a), where the $M_{\pi^+ \pi^-}$ distribution is filled with the fitted $\eta_c(1S)$ bin-by-bin yields including the $\eta_c(1S)$ decays to both two-body and three-body final states. Figure 1(b) shows the distribution of $\cos \theta_{hel}$ for the $f_0(2080)$ candidate events, which are extracted by fitting the $f_0(2080)$ signal in each angular bin, together with MC expectations for $J^{PC} = 0^{++}$ and $2^{++}$.

We utilize the data sample selected in the $\eta' \rightarrow \eta \pi^+ \pi^-$ mode to measure the non-resonant production of $\eta' \pi^+ \pi^-$ final states via two-photon collisions. The $W$-dependent cross sections of the production processes $\gamma \gamma \rightarrow \eta' f_2(1270)$ and $\gamma \gamma \rightarrow \eta' \pi^+ \pi^-$ after subtraction of the $\eta' f_2(1270)$ contribution are measured. The measured differential cross sections in $|\cos \theta^*|$ for $\gamma \gamma \rightarrow \eta' f_2(1270)$ show an ascending trend, and its rate of increase is greater in the larger $W$ ranges.

4. summary

For the first time, we find production of the $f_2(1525)$, $\chi_{c0}(1)$, and $\chi_{c2}(1P)$ mesons in high-$Q^2$ $\gamma' \gamma$ scattering [11]. We have measured the $\chi_{c0}$ and $\chi_{c2}$ partial decay widths $\Gamma_{\gamma' \gamma}$ as a function of $Q^2$, as well as the total cross section near the $K^0_L K^0_S$ mass threshold. A partial-wave analysis has been conducted, and the helicity-0, -1, and -2 transition form factors (TFFs) of the $f_2(1525)$ meson are measured. The $Q^2$ dependence of the above resonances and structures are compared with the


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Figure 4: The invariant mass distribution for the $\eta' \pi^+ \pi^-$ candidates for (a) [(c)] the $\eta \pi \pi$ mode and (b) [(d)] the $\gamma \gamma$ mode, in the $\eta_c (1S)$ [$\eta_c (2S)$] region.

Figure 5: The fit results for the $f_0(980)$, $f_2(1270)$ and $f_0(2080)$ (a) and the distribution of the cosine of helicity angle $\theta_{\text{hel}}$ for the $f_0(2080)$ candidate events (b). See the paper [12] in details.

$q\bar{q}$-meson model predictions [11], and the comparisons show that they are not inconsistent for all of them.

The $\eta_c (1S)$, $\eta_c (2S)$ and non-resonant $\eta' \pi^+ \pi^-$ production via two-photon collisions is measured [12]. We report the first observations of the signals for $\eta_c (1S)$ decays to $\eta' f_0(2080)$ with $f_0(2080) \to \pi^+ \pi^-$ and $\eta_c (2S)$ decays to $\eta' \pi^+ \pi^-$, the measured products of the two-photon decay width and the branching fraction for the $\eta_c (1S)$ and $\eta_c (2S)$ decays to $\eta' \pi^+ \pi^-$, and the measurement of non-resonant production of two-body $\eta' f_2(1270)$ and three-body $\eta' \pi^+ \pi^-$ final states via two-photon collisions.

References