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MEASUREMENTS OF $\gamma\gamma \to K_S^0 K_S^0$ AND CHARMONIUM PRODUCTION AT BELLE*

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We use data samples collected with the Belle detector at the KEKB e^+e^- collider at $397\,\mathrm{fb}^{-1}$ integrated luminosity to measure the cross sections and angular distributions of $K_S^0 K_S^0$ production in two-photon collisions at the center-of-mass energy (W) and angle (θ^*) ranges, $2.4\,\mathrm{GeV} < W < 4.0\,\mathrm{GeV}$ and $|\cos\theta^*| < 0.6$. A $\sin^{-4}\theta^*$ behavior of the cross section in the region $2.4\,\mathrm{GeV} < W < 4.0\,\mathrm{GeV}$ is observed. Signals of χ_{c0} and χ_{c2} are also observed. Furthermore, new resonance $Z(3930)$ is observed in $\gamma\gamma \to D\overline{D}$ process using data corresponding to $280\,\mathrm{fb}^{-1}$ integrated luminosity.

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1. Introduction

We report on the measurements of the $\gamma\gamma \to K_S^0 K_S^0$ process, and on a search for χ'_{cJ} states in the mass range of 3.73–4.3 GeV/c^2 produced via the $D\overline{D}$ process, which are based on data samples collected with the Belle detector using $397\,\mathrm{fb}^{-1}$ and $280\,\mathrm{fb}^{-1}$ integrated luminosity, respectively. The results presented here are preliminary.

2. KEKB accelerator and Belle detector

The analysis is performed with the Belle detector [1] at KEKB [2], an asymmetric e^+e^- collider where an 8.0 GeV e^- beam collides with a 3.5 GeV e^+ beam with a crossing angle of 22 mrad. Momenta of charged tracks are

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measured with a cylindrical drift chamber (CDC) located in a uniform 1.5 T magnetic field which surrounds the interaction point (IP) and subtends the polar angle range $17^\circ < \theta_{\rm lab} < 150^\circ$, where $\theta_{\rm lab}$ is a scattering angle in the laboratory frame. Trajectory of charged tracks near the collision is provided by CDC and a silicon vertex detector (SVD). Neutral particles or photon detection and energy measurements are made by a CsI electromagnetic calorimeter (ECL). Species of charged hadron are identified by means of information from time-of-flight counters (TOF) and a silicaaerogel Cherenkov counters (ACC). Low energy kaons are also identified by specific ionization (dE/dx) measurements in the CDC.

3. Measurements of $\gamma\gamma \to K^0_{\rm S} K^0_{\rm S}$

For $\gamma\gamma \to \pi\pi$ and $\gamma\gamma \to KK$, quark counting rule [3] predicts a W^{-6} dependence of the cross section. Detailed leading-order QCD calculations by Brodsky and Lepage (BL) [4] predicted the dependence on the W ($\equiv \sqrt{s}$) and scattering angle θ^* for the $\gamma\gamma \to M^+M^-$ process:

$$\frac{d\sigma}{d|\cos\theta^*|}(\gamma\gamma \to M^+M^-) \simeq \frac{16\pi\alpha^2}{s}\,\frac{|F_M(s)|^2}{\sin^4\theta^*}\,, \tag{1}$$

where M is a meson and F_M is its electromagnetic form factor. Eq. (1) could also be applied to neutral pseudoscalar meson cases.

Benayoun and Chernyak (BC) [5] predict that at high energies the total cross sections should be equal to about 1/200 of that for K^+K^- after investigating in details the consequences of SU(3)-system breaking effects. Diehl, Kroll and Vogt (DKV) [6] also predict the value of $\sigma(K^0_{\rm S}K^0_{\rm S})/\sigma(K^+K^-) \sim 0.08$ because the contribution of the non-valence form factor to the amplitudes is further suppressed by the charge factor. Most recently, non-perturbative approaches [7], which base on Regge theory and Veneziano model, are introduced for the study of the low energy mechanism.

In the analysis the selection criteria are:

(1) Only four charged tracks with zero net electric charge and two or more among the tracks satisfy the following conditions: transverse momentum in laboratory frame $p_{\rm t} > 0.4\,{\rm GeV}/c$; smallest distance to the nominal collision point in the cylindrical coordinates, $|dr| < 1$ cm, $|dz| < 5$ cm; $-0.8660 < \cos\theta_{\rm lab} < +0.9563$.

(2) No photon cluster whose energy is larger than 0.4 GeV.

(3) Momentum balance is required for all tracks in the c.m. frame of e^+e^- beams, by imposing $|\Sigma \boldsymbol{p}_{\rm t}| < 0.2\,{\rm GeV}/c$.

(4) Two $K^0_{\rm S}$ candidates which are identified using the selection rules in [9].

The W distribution and total cross section are presented in Fig. 1. We found 161 ± 14 χ_{c0} and 44 ± 7 χ_{c2} event signals with statistical significance 11.7σ and 6.3σ, where σ is the standard deviation. The $\Gamma_{\gamma\gamma}(\chi_{cJ})\mathcal{B}(\chi_{cJ} \to K_S^0 K_S^0)$ are obtained to be equal to $7.07 \pm 0.61 \pm 0.62$ eV for χ_{c0} and $0.30 \pm 0.05 \pm 0.03$ eV for χ_{c2}. From the results of previous measurements of $\Gamma_{\gamma\gamma}\mathcal{B}(K^+K^-)$ [8], the ratios $\mathcal{B}(K_S^0 K_S^0)/\mathcal{B}(K^+K^-)$ equal to $0.49 \pm 0.07 \pm 0.09$ for χ_{c0} and $0.68 \pm 0.20 \pm 0.13$ for χ_{c2}, consistent with the isospin symmetry, were obtained. Using the records on PDG [10] we obtain $\Gamma_{\gamma\gamma}(\chi_{c0}) = 3.37 \pm 0.29(\text{stat.}) \pm 0.29(\text{syst.}) \pm 0.96(\text{br.})$ keV and $\Gamma_{\gamma\gamma}(\chi_{c2}) = 0.42 \pm 0.07(\text{stat.}) \pm 0.04(\text{syst.}) \pm 0.16(\text{br.})$ keV.

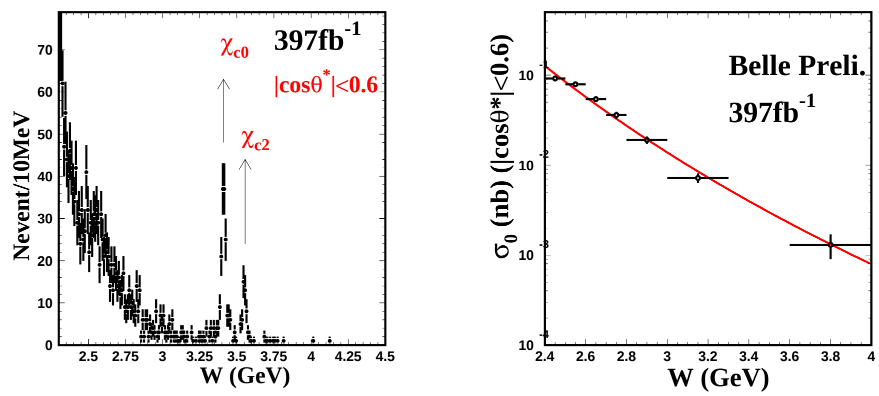

Fig. 1. Left: W distribution of the $\gamma\gamma \to K_S^0 K_S^0$ candidates ($|\cos\theta^*| < 0.6$). Right: Total cross section for $\gamma\gamma \to K_S^0 K_S^0$ in the c.m. angular region $|\cos\theta^*| < 0.6$. The curve shows the W-dependence obtained from the fit($\sigma \propto W^{-n}$, $n = 9.93 \pm 0.44$).

Differential cross sections with normalization in different W ranges are shown in Fig. 2. A $\sin^{-4}\theta^*$ behavior of the angular distribution, predicted by BL model, is obtained. Total cross sections in $|\cos\theta^*| < 0.6$ are also obtained (Fig. 1, right). The ratio of the measured total cross section for $K_S^0 K_S^0$ and K^+K^- is $\simeq 0.04 \pm 0.009$ for $W > 3.0$ GeV, which is in disagreement to the prediction of DKV model($\simeq 0.08$) or BC predictions ($\simeq 0.005$). W-dependence ($\sigma \propto W^{-n}$) of the $K_S^0 K_S^0$ cross section, which shows a property of the leading term of the amplitude, is also studied. We find $n = 9.93 \pm 0.44(\text{stat.})$ for $2.4\,\text{GeV} < W < 4.0\,\text{GeV}$. The result shows a different feature than in K^+K^- production for $3.0 < W < 4.1$ GeV where $n = 7.3 \pm 0.3(\text{stat.}) \pm 1.5(\text{syst.})$. This is compatible with a W^{-6} dependence predicted by quark counting rule. The smallness of the $K_S^0 K_S^0$ cross section compared to the K^+K^- gives an evidence that the leading term in QCD prediction (W^{-6}) no longer dominates, but next power correction (W^{-10}) contributes.

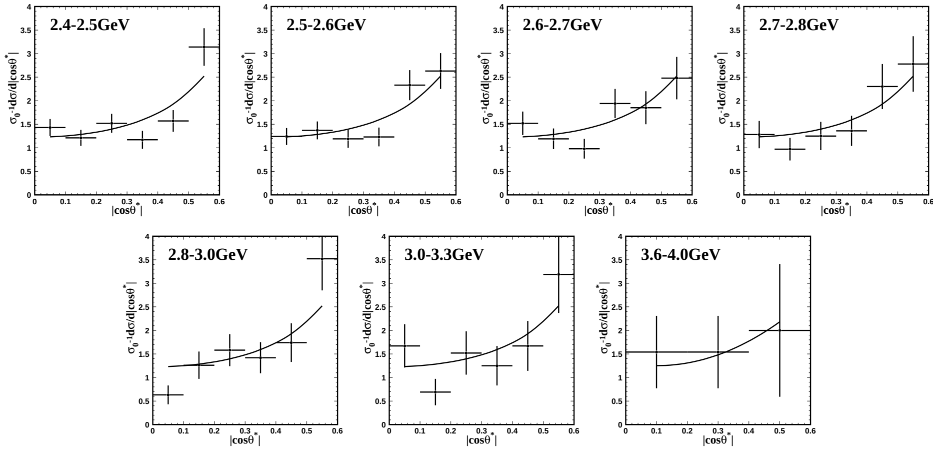

Fig. 2. Angular dependence of the cross section, $\sigma_0^{-1} d\sigma/d|\cos\theta^*|$, for $\gamma\gamma \to K_S^0 K_S^0$ process. The curves correspond to $1.227 \sin^{-4}\theta^*$. The errors are statistical only.

We assign a 9–10% total systematic error to the present measurement. This is primarily due to uncertainties in the trigger efficiency (4%), luminosity function (5%), non-exclusive events (1–5%), K_S^0 particle identification (6%), and integrated luminosity (1%).

4. Observation of $Z(3930)$

Radial excitation states of charmonium have been found only for the $^3S_1$ states (ψ) and $^1S_0$ states (η_c) [11], but no radially excited ^3P_J states (χ_{cJ}) have yet been found. The first radially excited χ_{cJ} states are predicted to have masses 3.9–4.0 GeV, which is considerably above $D\overline{D}$ threshold [12]. Two new charmonium-like states in this mass region were reported by Belle [13]. Here we report on a search for the χ'_{cJ} ($J = 0$ or 2) states in the mass range of 3.73–$4.3\,\mathrm{GeV}/c^2$ produced via the $D\overline{D}$ process [14].

Four combinations of decays are used: $D^0\overline{D^0}$, $D^0 \to K^-\pi^+$, $\overline{D^0} \to K^+\pi^-$; $D^0\overline{D^0}$, $D^0 \to K^-\pi^+$, $\overline{D^0} \to K^+\pi^-\pi^0$; $D^0\overline{D^0}$, $D^0 \to K^-\pi^+$, $\overline{D^0} \to K^+\pi^-\pi^+\pi^-$; D^+D^-, $D^+ \to K^-\pi^+\pi^+$, $D^- \to K^+\pi^-\pi^-$. Kaons are separated from pions using likelihood method based on information from the particle identification detectors. We rejected the events from initial-state radiation processes using the z-component of the momentum of the $D\overline{D}$ system. We take the candidate events in the transverse momentum range $|\Sigma p_{\mathrm{t}}(D\overline{D})| < 0.05\,\mathrm{GeV}/c$.

We show the $M(D\overline{D})$ distributions in Fig. 3 (left). We find a resonant structure with a $5.5\,\sigma$ statistical significance in the vicinity of $3.93\,\mathrm{GeV}/c^2$. We tentatively designate this state as $Z(3930)$. The total yield of the reso-

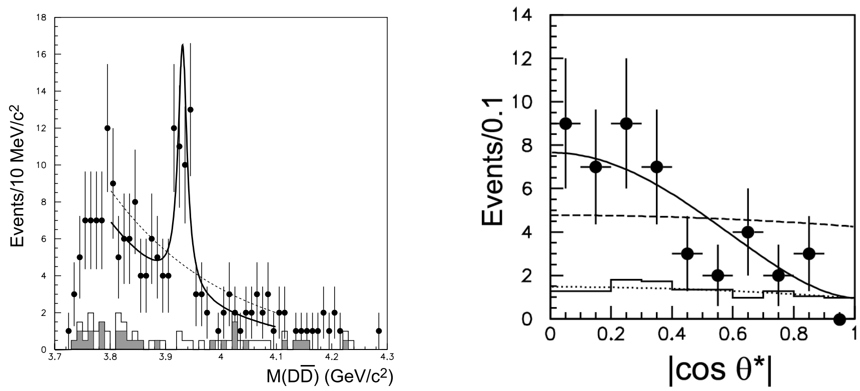

Fig. 3. Left: The sum of the $M(D\overline{D})$ invariant mass distributions for all four processes. The curves show the fits with (solid) and without (dashed) a resonance component. Right: The $|\cos\theta^*|$ distributions in the $3.91 < M(D\overline{D}) < 3.95\,\mathrm{GeV}/c^2$ region (points with error bars) and background scaled from the $M(D\overline{D})$ sideband (solid histogram). The solid and dashed curves show the expectations from a $J = 2$ (helicity $= 2$) resonance and a $J = 0$ resonance, respectively.

nance, mass and width are equal to $N = 41 \pm 11(\mathrm{stat.})$, $M = 3931 \pm 4(\mathrm{stat.}) \pm 2(\mathrm{syst.})\,\mathrm{MeV}/c^2$ and $\Gamma = 20 \pm 8(\mathrm{stat.}) \pm 3(\mathrm{syst.})\,\mathrm{MeV}$, respectively. The points with error bars in Fig. 3(right) show that the $|\cos\theta^*|$ distribution in the $Z(3930)$ region prefers a spin two over spin zero assignment. We obtain $\Gamma_{\gamma\gamma}\mathcal{B}(Z(3930) \to D\overline{D}) = 0.23 \pm 0.06(\mathrm{stat.}) \pm 0.04(\mathrm{syst.})\,\mathrm{keV}$ for $J = 2$ assumption. All results are consistent with expectations for the χ'_{c2}, the 2^3P_2 charmonium state.

5. Conclusion

The cross sections and angular distributions of the $K^0_S K^0_S$ production from two-photon collisions in the ranges $2.4\,\mathrm{GeV} < W < 4.0\,\mathrm{GeV}$ and $|\cos\theta^*| < 0.6$ are measured. A $\sin^{-4}\theta^*$ behavior of the angular distribution and W-dependence ($\sigma \propto W^{-n}$) which $n = 9.93 \pm 0.44(\mathrm{stat.})$ are obtained. Signals of χ_{c0} and χ_{c2} are also observed. New resonance $Z(3930)$ is observed in the $D\overline{D}$ process, and all measured numbers show that it is a candidate of χ'_{c2} .

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