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High statistics study of the $f_0(980)$ resonance in $\gamma\gamma \to \pi^+\pi^-$ production

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We report on a high statistics measurement of the cross section of the process $\gamma\gamma \to \pi^+\pi^-$ in the $\pi^+\pi^-$ invariant mass range $0.8~\mathrm{GeV}/c^2 < W < 1.5~\mathrm{GeV}/c^2$ with $85.9~\mathrm{fb}^{-1}$ of data collected at $\sqrt{s} = 10.58$ GeV and 10.52 GeV with the Belle detector. A clear signal for the $f_0(980)$ resonance is observed. From a fit to the mass spectrum, the mass, $\pi^+\pi^-$ and two-photon decay widths of the resonance are found to be $985.6^{+1.2}_{-1.5}(\mathrm{stat})^{+1.1}_{-1.6}(\mathrm{syst})~\mathrm{MeV}/c^2$, $34.2^{+13.9}_{-11.8}(\mathrm{stat})^{+8.8}_{-2.5}(\mathrm{syst})$ MeV, and $205^{+95}_{-83}(\mathrm{stat})^{+147}_{-117}(\mathrm{syst})$ eV, respectively.

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The nature of low mass (below $1~\mathrm{GeV}/c^2$) scalar mesons has been a puzzle for decades with little progress made on its understanding [1]. Among the low mass scalar mesons, the existence of the $f_0(980)$ and $a_0(980)$ mesons is experimentally well established. One of the key ingredients in understanding their nature is measurement of the two-photon production cross sections and, in particular, the two-photon widths extracted from them. According to a relativistic quark model calculation, assuming the $f_0(980)$ meson to be a nonstrange $q\bar{q}$ state, its two-photon width should be in the range 1.3 keV to 1.8 keV [2]. However, a much smaller width is expected for an exotic state (0.2–0.6 keV for a $K\bar{K}$ molecule state) [3], or for an $s\bar{s}$ state (0.3–0.5 keV) [4].

A B factory is one of the best laboratories for a detailed investigation of low mass scalar mesons through two-photon production, where overwhelming statistics can be obtained. Two-photon production of mesons has advantages over meson production in hadronic processes; the production rate can be reliably calculated from QED with $\Gamma_{\gamma\gamma}$ as the only unknown parameter. In addition, a meson can be produced alone without additional hadronic debris, and the quantum numbers of the final state are restricted to states of charge conjugation $C = +1$ with $J = 1$ forbidden (Landau-Yang's theorem [5]).

In the past, using $209~\mathrm{pb}^{-1}$ of $\gamma\gamma \to \pi^+\pi^-$ data, Mark II observed a shoulder in the $1~\mathrm{GeV}/c^2$ mass region, which was tentatively identified as the $f_0(980)$ resonance [6]. The reaction $\gamma\gamma \to \pi^0\pi^0$ was analyzed using $97~\mathrm{pb}^{-1}$ of data taken with the Crystal Ball detector [7]. They found a hint of $f_0(980)$ formation with a significance of 2.2 standard deviations. Measurements of $\gamma\gamma \to \pi^0\pi^0$ were also performed with the JADE detector using $149~\mathrm{pb}^{-1}$ data [8]. They observed a small shoulder at around $1~\mathrm{GeV}/c^2$, which was interpreted as the production of the $f_0(980)$. CELLO studied the reaction $\gamma\gamma \to \pi^+\pi^-$ using a data sample of $86~\mathrm{pb}^{-1}$ and concluded that an $f_0(980)$ signal at the level reported in Refs. [6–8] cannot be excluded with their errors [9].

Using data from Mark II, Crystal Ball, and CELLO, Boglione and Pennington (BP) performed an amplitude analysis of $\gamma\gamma \to \pi^+\pi^-$ and $\gamma\gamma \to \pi^0\pi^0$ cross sections [10]. They found two distinct classes of solutions where one solution has a peak ("peak solution") and the other has a wiggle ("dip solution") in the $f_0(980)$ mass region. The two solutions give quite different results for the two-photon width of the $f_0(980)$ and the size of the S-wave component. Thus, it is important to distinguish them experimentally.

In this paper, we report on a high statistics study of the $f_0(980)$ meson in the $\gamma\gamma \to \pi^+\pi^-$ reaction based on data taken with the Belle detector at the KEKB asymmetric-energy e^+e^- collider [11]. The data sample corresponds to a total integrated luminosity of $85.9~\mathrm{fb}^{-1}$, accumulated on the $\Upsilon(4S)$ resonance ($\sqrt{s} = 10.58$ GeV) and 60 MeV below the resonance ($8.6~\mathrm{fb}^{-1}$ of the total). Since the difference in the cross sections between the two energies is only about 0.3%, we combine both samples. We observe the two-photon process $e^+e^- \to e^+e^-\pi^+\pi^-$ in the "zero-tag'' mode, where neither the final-state electron nor positron is detected, and the $\pi^+\pi^-$ system has small transverse momentum.

A comprehensive description of the Belle detector is given in Ref. [12]. Charged track coordinates near the collision point are measured by a silicon vertex detector (SVD) that surrounds a 2 cm radius beryllium beam pipe. Track trajectory coordinates are reconstructed in a central drift chamber (CDC), and momentum measurements are made together with the SVD. An array of 1188 silica-aerogel Cherenkov counters (ACC) provides separation between kaons and pions for momenta above 1.2 GeV/c. The time-of-flight counter (TOF) system consists of a barrel-like arrangement of 128 plastic scintillation counters and is effective for K/π separation for tracks with momenta below 1.2 GeV/c. Low energy kaons and protons are also identified by specific ionization (dE/dx) measurements in the CDC. Photon detection and energy measurements of photons and electrons are provided by an electromagnetic calorimeter (ECL) consisting of an array of 8736 CsI(Tl) crystals all pointing toward the interaction point. These detector components are located in a uniform magnetic field of 1.5 T provided by a superconducting solenoid coil. An iron flux-return located outside the solenoid coil is instrumented to detect K_L^0 mesons and to identify muons (KLM).

Signal candidates are primarily triggered by a two-track trigger that requires two CDC tracks with associated TOF hits and ECL clusters with an opening angle greater than 135 degrees. Exclusive $e^+e^- \to e^+e^-\pi^+\pi^-$ events are selected by requiring two oppositely charged tracks coming from the interaction region; each track is required to satisfy $dr < 0.1$ cm and $|dz| < 2$ cm, where dr (dz) is the r (z) component of the closest approach to the nominal collision point. The z axis of the detector is defined to be opposite to the direction of the positron beam and r is the transverse distance from the z axis. The difference of the dz's of the two tracks must satisfy the requirement $|dz_+ - dz_-| \leq 1$ cm. The event must contain one and only one positively charged track that satisfies $p_t > 0.3$ GeV/c and $-0.47 < \cos\theta < 0.82$, where p_t and θ are the transverse component of momentum and the angle with respect to the z-axis. The scalar sum of track momenta in each event is required to be smaller than 6 GeV/c, and the sum of the ECL energies of the event must be less than 6 GeV. Events should not include an extra track with $p_t > 0.1$ GeV/c. The cosine of the opening angle of the tracks must be greater than -0.997 to reject cosmic-ray events. The sum of the transverse momentum vectors of the two tracks ($\sum \boldsymbol{p}_t^*$) should satisfy $|\sum \boldsymbol{p}_t^*| <0.1$ GeV/c; this requirement separates exclusive two-track events from quasireal two-photon collisions.

Electrons and positrons are distinguished from hadrons using the ratio E/p, where E is the energy measured in the ECL, and p is the momentum from the CDC. Kaon (proton) candidates are identified using normalized kaon (proton) and pion likelihood functions obtained from the particle identification system (L_K (L_p) and L_π, respectively) with the criterion $L_K/(L_K + L_\pi) > 0.25$ ($L_p/(L_p + L_\pi) > 0.5$), which gives a typical identification efficiency of 90% with a pion misidentification probability of 3%. All charged tracks that are not identified as electrons, kaons or protons are treated as pions. We require both tracks to be pions.

In this measurement, the KLM detector cannot be used for muon identification, since it is insensitive in the region of interest where the transverse momenta of tracks are below 0.8 GeV/c. Therefore, we have developed a method for statistically separating $\pi^+\pi^-$ and $\mu^+\mu^-$ events using ECL information; muons deposit energy corresponding to the ionization loss for minimum ionizing particles, while pions give wider energy distributions since they interact hadronically in the ECL, which corresponds to approximately one interaction length of material. Probability density functions (PDFs) for the distributions of energy deposits from $\mu^+\mu^-$ ($\pi^+\pi^-$) pairs $P^{(i)}_{\mu^+\mu^-}(E_+, E_-)$ ($P^{(i)}_{\pi^+\pi^-}(E_+, E_-)$) are obtained with GEANT-3 [13] Monte Carlo (MC) simulation. Here i represents the ith bin of (W, $|\cos\theta^*|$) in 20 MeV/c^2 and 0.1 steps, where W is the invariant mass of the $\pi^+\pi^-$ (or $\mu^+\mu^-$) pair in each event (the pion mass is assumed in the calculation), and θ^* is the polar angle of the produced $\pi^\pm$ meson (or $\mu^\pm$ lepton) in the center-of-mass system of two initial photons. Note that the effect of muons from pion decays is taken into account by the pion PDFs using this method. We obtain $r^{(i)}$, the fraction of $\mu^+\mu^-$ in the ith bin through the equation:

$$N^{(i)}_{\rm data}(E_+, E_-) = N^{(i)}_{\rm tot}(r^{(i)}P^{(i)}_{\mu^+\mu^-}(E_+, E_-) + (1 - r^{(i)})P^{(i)}_{\pi^+\pi^-}(E_+, E_-)),$$

where $N^{(i)}_{\rm data}(E_+, E_-)$ is the distribution of data and $N^{(i)}_{\rm tot}$ is the total number of events in that bin. The values of ratios $r^{(i)}$ obtained must be corrected since the MC cannot simulate hadronic interactions accurately enough. By introducing mis-ID probabilities, $P_{\pi\pi\to\mu\mu}$ and $P_{\mu\mu\to\pi\pi}$, the r value for each bin (the bin number i is omitted) can be written as

$$r = \frac{N_{\mu\mu} + N_{\pi\pi}P_{\pi\pi\to\mu\mu} - N_{\mu\mu}P_{\mu\mu\to\pi\pi}}{N_{\mu\mu} + N_{\pi\pi}},$$

where $N_{\mu\mu}$ ($N_{\pi\pi}$) is the number of true $\mu^+\mu^-$ ($\pi^+\pi^-$) pair events in that bin. We assume that $P_{\pi\pi\to\mu\mu}$ and $P_{\mu\mu\to\pi\pi}$ are independent of W. Applying the μ/π separation method described above to a sample of data events positively identified as muons by the KLM, we find that $P_{\mu\mu\to\pi\pi}$ is statistically consistent with zero. The values of $P_{\pi\pi\to\mu\mu}$ in each $|\cos\theta^*|$ bin are determined such that the ratio of the data and MC for $\mu^+\mu^-$ pairs, which is ideally one, gives a straight line in the W spectrum. The values of $P_{\pi\pi\to\mu\mu}$ vary between 0.08 to 0.13 in $|\cos\theta^*|$ bins. Because they are determined for each bin of $|\cos\theta^*|$, the bin-by-bin variation of systematic errors is rather large in the angular distribution.

The total cross section for $\gamma\gamma \to \pi^+\pi^-$ with $|\cos\theta^*| < 0.6$ is evaluated using the following equation:

$$\sigma_{\gamma\gamma\to\pi^+\pi^-} = \frac{\Delta N_{e^+e^-\to e^+e^-\pi^+\pi^-}}{\epsilon_{\rm trg}\cdot\epsilon_{\rm det}\cdot\Delta W\cdot\frac{d\mathcal{L}}{dW}\cdot\int L dt}.$$

Here $\Delta N_{e^+e^-\to e^+e^-\pi^+\pi^-}$ is the number of events in a W bin, $\frac{d\mathcal{L}}{dW}$ is the two-photon luminosity function [14] and $\int L dt = 85.9\ \text{fb}^{-1}$ is the integrated luminosity. The W bin size is chosen to be 5 MeV$/c^2$; a typical mass resolution for a $\pi^+\pi^-$ system is 2 MeV$/c^2$ according to a MC study. The detection (trigger) efficiencies, $\epsilon_{\rm det}$ ($\epsilon_{\rm trg}$) are estimated with a MC simulation. Events of the process $\gamma\gamma \to \pi^+\pi^-$ are generated using TREPS [15]. The detection efficiency is extracted from MC simulation and the trigger efficiency is estimated with the trigger simulator. Since the trigger simulator does not simulate triggers well, particularly in the low energy region, the efficiency values have to be corrected. We calculate the correction factors by comparing $e^+e^- \to e^+e^-e^+e^-$ events in data and MC that are triggered by the two-track trigger. The resulting factors steeply rise from 0.5 at $W = 0.8$ GeV$/c^2$ to 0.8 at $W = 1$ GeV$/c^2$ and then increase gradually for higher W. The muon-background subtraction and all the correction factors are applied using smooth functions obtained by parametrizing the results of bin-by-bin analyses. Background from $\eta'(958) \to \rho^0\gamma \to \pi^+\pi^-(\gamma)$ is subtracted. The contribution to the cross section is about 5% at 0.8 GeV$/c^2$ and dies away quickly to zero above 0.9 GeV$/c^2$. Other backgrounds are negligible.

The total cross section obtained is shown in Fig. 1 together with the results of some past experiments; an expanded view of the $f_0(980)$ region is shown in Fig. 2(a). A clear peak corresponding to the $f_0(980)$ meson is visible, and thus the peak solution of the BP analysis is selected. Systematic errors for the total cross section are summarized in Table I. They are dominated by the uncertainty of the μ/π separation and that of the trigger efficiency. Systematic errors arising from the μ/π separation are estimated by changing the value $P_{\pi\pi\to\mu\mu}$ in the allowable range in each angular bin. Since $\mu^+\mu^-$ events are well identified for $W > 1.6$ GeV$/c^2$, the allowable range is determined in this region. These well identified $\mu^+\mu^-$ events are also used in estimating systematic errors of the trigger efficiency. Comparing data and MC for $\mu^+\mu^-$ events in the region $W > 1.6$ GeV$/c^2$ and extrapolating linearly downward, the systematic errors are found to be 4% at $W = 1.5$ GeV$/c^2$ and 10% at $W = 0.8$ GeV$/c^2$. The total systematic error is obtained by summing the systematic errors in quadrature and is also shown in Fig. 1.

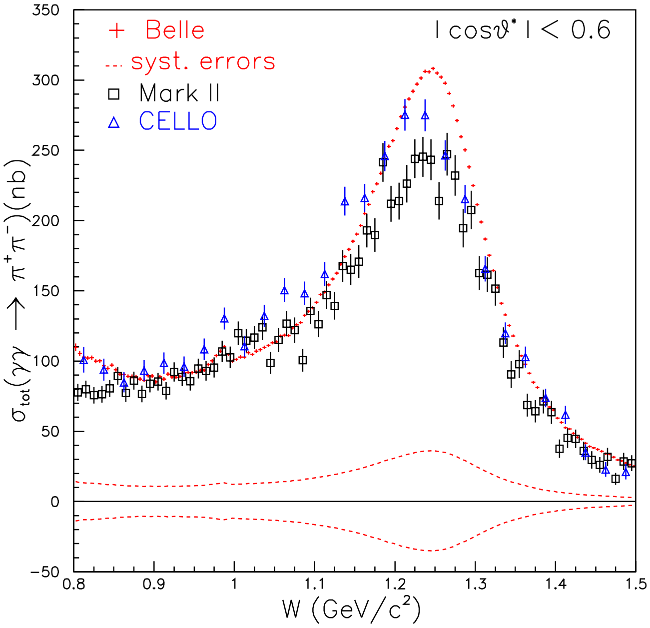

FIG. 1 (color online). The total cross section of $e^+e^- \to e^+e^-\pi^+\pi^-$ between 0.8 and 1.5 GeV$/c^2$ for $|\cos\theta^*| < 0.6$. The Belle data are represented by crosses with statistical error bars, the CELLO data are the triangles and the Mark II data are squares. Dashed lines are upper and lower systematic uncertainties for the Belle data. We do not show systematic errors for the other experiments; they are of similar size or larger.

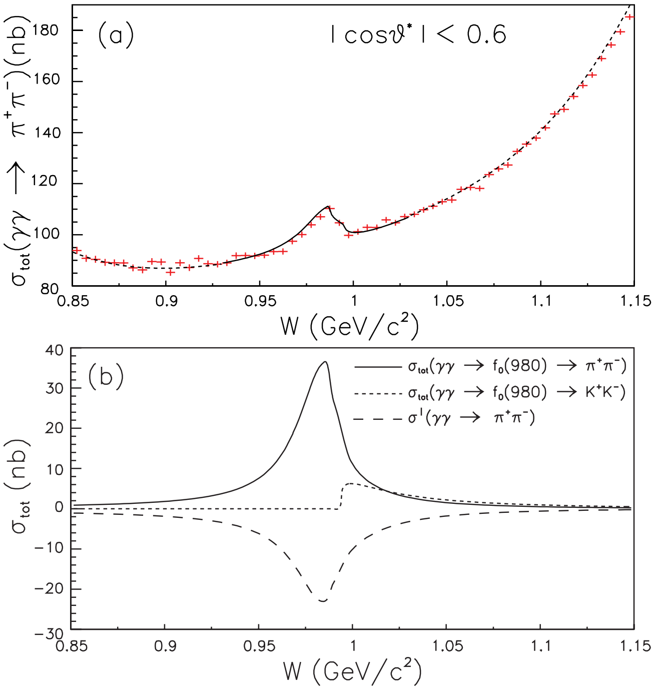

FIG. 2 (color online). Fitted curve: (a) shows the total cross section and (b) shows contributions of the resonance $[\sigma(\gamma\gamma \to f_0(980) \to \pi^+\pi^-)]$ (solid line) and the interference (dashed line). The cross section of $\sigma(\gamma\gamma \to f_0(980) \to K^+K^-)$ is also shown (dotted line).

TABLE I. Summary of systematic errors for the $\gamma\gamma \to \pi^+\pi^-$ cross section. A range is shown when the uncertainty has W dependence.

Parameter	Syst. error (%)
Tracking efficiency	2.4
Trigger efficiency	4–10
K/π-separation	0–1
μ/π-separation	5–7
Luminosity function	5
Integrated luminosity	1.4
Total	11.1–12.3

Our results are in good agreement with past experiments except for the $f_2(1270)$ mass peak region, where they are about 10% to 15% larger, but still within the systematic errors.

A fit to the $\gamma\gamma \to \pi^+\pi^-$ total cross section is performed to obtain the parameters of the $f_0(980)$ meson. We have to take into account the effect of the $K\bar{K}$ channel that opens within the $f_0(980)$ mass region. The fitting function for the scalar resonance $f_0(980)$ is parametrized as follows:

$$\sigma = \left|\frac{\sqrt{4.8\pi\beta_\pi}}{W}\mathcal{F}^{f_0}e^{i\varphi} + \sqrt{\sigma_0^{\rm BG}}\right|^2 + \sigma^{\rm BG} - \sigma_0^{\rm BG}, \tag{1}$$

where the factor 4.8 includes the fiducial angular acceptance $|\cos\theta^*| < 0.6$, $\beta_X = \sqrt{1 - \frac{4M_X^2}{W^2}}$ is the velocity of the particles X with mass M_X in the two-body final states, $\mathcal{F}^{f_0}$ is the amplitude of the $f_0(980)$ meson, which interferes with the helicity-0-background amplitude $\sqrt{\sigma_0^{\rm BG}}$ with relative phase φ, and $\sigma^{\rm BG}$ is the total background cross section. The amplitude $\mathcal{F}^{f_0}$ can be written as

$$\mathcal{F}^{f_0} = \frac{g_{f_0\gamma\gamma}g_{f_0\pi\pi}}{16\pi}\cdot\frac{1}{D_{f_0}}, \tag{2}$$

where g_{f_0XX} is related to the partial width of the $f_0(980)$ meson via $\Gamma_{XX}(f_0) = \frac{\beta_X g_{f_0XX}^2}{16\pi M_{f_0}}$. The factor D_{f_0} is given as follows [16]:

$$\begin{aligned} D_{f_0}(W) = M_{f_0}^2 - W^2 + \Re\Pi_\pi^{f_0}(M_{f_0}) - \Pi_\pi^{f_0}(W) \\ + \Re\Pi_K^{f_0}(M_{f_0}) - \Pi_K^{f_0}(W), \end{aligned}$$

where for $X = \pi$ or K,

$$\Pi_X^{f_0}(W) = \frac{\beta_X g_{f_0XX}^2}{16\pi}\left[i + \frac{1}{\pi}\ln\frac{1-\beta_X}{1+\beta_X}\right]. \tag{3}$$

The factor β_K is real in the region $W \geq 2M_K$ and becomes imaginary for $W < 2M_K$. The mass difference between $K^\pm$ and K^0 ($\bar{K}^0$) is included by using $\beta_K = \frac{1}{2}(\beta_{K^\pm} + \beta_{K^0})$.

In the fit, we assume $\sigma_0^{\rm BG}$ to be constant and the relative phase to be a slowly varying function of W; this is motivated by the nearly energy-independent behavior of the scalar Born amplitude [17]. We fix $g_{f_0KK}^2/g_{f_0\pi\pi}^2 = 4.21 \pm 0.25(\text{stat}) \pm 0.21(\text{syst})$ taking the latest value from the BES measurement [18]. The background function $\sigma^{\rm BG}$ is evaluated by fitting the cross section with a 4th order polynomial in W outside of the $f_0(980)$ region $0.85\ \text{GeV}/c^2 < W < 0.93\ \text{GeV}/c^2$ and $1.03\ \text{GeV}/c^2 < W < 1.15\ \text{GeV}/c^2$. We fit first outside of the signal region in order to stabilize the fit, constrain the background shape and avoid bias in the determination of $f_0(980)$ properties.

The value of χ^2/ndf for the fit is 0.88 for 46 degrees of freedom (ndf). A fit to the $f_0(980)$ resonance is then performed with Eq. (1) in the region $0.93\ \text{GeV}/c^2 < W < 1.03\ \text{GeV}/c^2$, where the parameters of $\sigma^{\rm BG}$ are fixed; the free parameters are M_{f_0}, $g_{f_0\pi\pi}$, $\Gamma_{\gamma\gamma}$ (evaluated at the $f_0(980)$ mass), $\sigma_0^{\rm BG}$ and φ.

The result of the fit is shown in Figs. 2(a) and 2(b). The resulting resonant structure is well within the region used to fit for the $f_0(980)$; it is clear that this region covers a sufficient range for fitting. In Fig. 2(b), one can see a significant interference effect, which is visible as a deviation from a Breit-Wigner-like shape in Fig. 2(a). In the same figure, the cross section $\sigma(\gamma\gamma \to f_0(980) \to K^+K^-)$ is also plotted, which is obtained by evaluating the first term in Eq. (1), substituting β_K instead of β_π and in Eq. (2) g_{f_0KK} instead of $g_{f_0\pi\pi}$. Note that the cross section is zero below the threshold even though the amplitude is nonzero. The value of χ^2/ndf of the fit is 1.04 for 15 ndf. The helicity-0-background component that interferes with the $f_0(980)$ meson ($\sigma_0^{\rm BG}$) is found to be $3.7^{+1.2}_{-0.5}$ nb. The value of φ is $1.74 \pm 0.09^{+0.04}_{-0.34}$, which is approximately $\pi/2$, consistent with the general phase shift study [10].

The parameters of the $f_0(980)$ meson are found to be

$$\begin{aligned} M_{f_0} &= 985.6^{+1.2}_{-1.5}(\text{stat})^{+1.1}_{-1.6}(\text{syst})\ \text{MeV}/c^2 \\ \Gamma_{\pi^+\pi^-}(f_0) &= 34.2^{+13.9}_{-11.8}(\text{stat})^{+8.8}_{-2.5}(\text{syst})\ \text{MeV} \\ \Gamma_{\gamma\gamma}(f_0) &= 205^{+95}_{-83}(\text{stat})^{+147}_{-117}(\text{syst})\ \text{eV}. \end{aligned}$$

The two-photon width given by the PDG [19] is $\Gamma_{\gamma\gamma}(f_0) = 310^{+80}_{-110}(\text{stat})$ eV, and the value found by BP is 280^{+90}_{-130} eV. Our results are consistent with both within errors as well as with the prediction of the four-quark model of 270 eV [20].

The dominant systematic errors come from fitting. The value of $\Gamma_{\gamma\gamma}(f_0)$ is quite sensitive to changes in parameters of the background cross section [fitted outside of the $f_0(980)$ resonance]. Systematic errors are evaluated by changing each background parameter by $\pm 1\sigma$, taking their correlations into account; the error is strongly correlated with that of $g_{f_0\pi\pi}$ [i.e. $\Gamma_{\pi^+\pi^-}(f_0)$]. The error in the normalization of the total cross section has little effect on the value of the $f_0(980)$ mass, however it is a significant contribution to the error in $\Gamma_{\gamma\gamma}(f_0)$ and $\Gamma_{\pi^+\pi^-}(f_0)$. The errors in $g_{f_0KK}^2/g_{f_0\pi\pi}^2$ are also taken into account in the systematic errors. Individual systematic errors are summed in quadrature to obtain the total uncertainty.

In summary, we have made a high statistics measurement of the $\gamma\gamma \to \pi^+\pi^-$ cross section in the $\pi^+\pi^-$ invariant mass region $0.80\ \mathrm{GeV}/c^2 \leq W \leq 1.5\ \mathrm{GeV}/c^2$ in fine bins of W (5 MeV) and $\cos\theta^*$ (0.05) with the Belle detector at the KEKB accelerator. We have observed a significant signal corresponding to the $f_0(980)$ resonance. Our data clearly select the peak solution of the Boglione-Pennington amplitude analysis [10]. The total cross section is fitted to obtain the parameters of the $f_0(980)$ meson. Its two-photon width is found to be $205^{+95}_{-83}(\mathrm{stat})^{+147}_{-117}(\mathrm{syst})$ eV, consistent with past experiments.

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