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Observation of the $\chi_c(2P)$ meson in the reaction $\gamma\gamma \to D\bar{D}$ at BABAR

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I. INTRODUCTION

In the field of charmonium spectroscopy, there has been renewed interest in the recent discovery of numerous charmonium and charmoniumlike states [1–11]. However, very little is known about the first radially excited mesons and charmoniumlike states [1–11]. The recent discovery of numerous charmoniumlike states has been renewed with the recent discovery of numerous charmoniumlike states [1–11]. However, very little is known about the first radially excited mesons and charmoniumlike states [1–11].

II. THE BABAR DETECTOR

The BABAR detector is described in detail elsewhere [15]. Charged particles are detected, and their momenta measured, with a combination of five layers of double-sided silicon microstrip detectors (SVT) and a 40-layer cylindrical drift chamber (DCH), both coaxial with the cryostat of a superconducting solenoidal magnet which produces a magnetic field of 1.5 T. Charged-particle identification is achieved by measurements of the energy loss $dE/dx$ in the tracking devices and by means of an internally reflecting, ring-imaging Cherenkov detector (DIRC). Photons and electrons are detected and their energies measured.

![FIG. 1. Two-photon production of the $D\bar{D}$ system.](image-url)
The instrumented flux return of the magnetic field is used to identify muons and $K_L^0$.

### III. SELECTION OF TWO-PHOTON-INTERACTION EVENTS

The selection of two-photon-interaction events for an untagged analysis is based on established procedures (see for instance Refs. [16,17]). Because of the small scattering angles involved, most of the incoming beam energy is carried away by the $e^+$ and $e^-$ (see Fig. 1). This results in a large value of the missing mass squared

$$m_{\text{miss}}^2 = (p_{e^+} + p_{e^-} - p_D - p_{\bar{D}})^2,$$

where $p_{e^\pm}$ are the four-momenta of the beam electron and positron and $p_D$, $p_{\bar{D}}$ are the four-momenta of the final state $D$ and $\bar{D}$ mesons, respectively. In addition, for these events, the resultant transverse momentum of the $D\bar{D}$ system $p_t(D\bar{D})$ is limited to small values.

In order to establish selection criteria for $\gamma\gamma \rightarrow D\bar{D}$ events, the reaction

$$e^+e^- \rightarrow K^-K^+\pi^+\pi^-X$$

(2)

is studied first using a data sample corresponding to an integrated luminosity of 235 fb$^{-1}$. The system $X$ contains no additional charged particles. This reaction has been chosen because it has the same particle configuration as one of the final states we consider in this analysis. The charged kaons and pions are identified as described in detail in Sec. IV. Neutral pions are reconstructed from pairs of photons with deposited energy in the EMC larger than 100 MeV. It is required that no $\pi^0$ meson candidate be found in a selected event.

Two-photon production of the $K^-K^+\pi^+\pi^-$ system should yield large values of $m_X^2$, the missing mass squared,

$$m_X^2 = (p_{e^+} + p_{e^-} - p_{K^+} - p_{K^-} - p_{\pi^+} - p_{\pi^-})^2.$$

In addition, production of the $K^-K^+\pi^+\pi^-$ system via initial state radiation (ISR) should yield the small values of $m_X^2$ associated with the ISR photon, for which detection is not required. The observed distribution of the $K^-K^+\pi^+\pi^-$ invariant mass, $m(K^-K^+\pi^+\pi^-)$, resulting from the reaction of Eq. (2) is shown in Fig. 2(a).

There are clear signals corresponding to the production of $\eta_c(1S)$, $\chi_{c0}(1P)$, and $\chi_{c2}(1P)$, and, since these states all have positive $C$ parity, it is natural to associate them with two-photon production. Similarly, the large $J/\psi$ signal observed would be expected to result from ISR production, because of the negative $C$ parity of the $J/\psi$. For the parameters of these states, see Table I.

The distribution of $m_X^2$ for $2.8 \leq m(K^-K^+\pi^+\pi^-) \leq 3.8$ GeV/c$^2$ is shown in Fig. 2(b). The large peak near zero is interpreted as being due mainly to ISR production.
of the $K^-K^+\pi^+\pi^-$ system, while two-photon-production events would be expected to occur at larger values of $m_X^2$. This is shown explicitly by the distributions of Figs. 2(c) and 2(d), which correspond to the requirements $m_2^2 < 10$ (GeV/c$^2$)$^2$ and $m_2^2 > 10$ (GeV/c$^2$)$^2$, respectively.

In Fig. 2(c) there is a large $J/\psi$ signal, and a much smaller $\psi(2S)$ signal can also be seen. For $e^+e^-$ collisions at a c.m. energy of 10.58 GeV, the ISR production cross section for $J/\psi$ is about 3 times larger than for $\psi(2S)$; also $\mathcal{B}(J/\psi \rightarrow K^-K^+\pi^+\pi^-)$ is approximately 9 times larger than the corresponding $\psi(2S)$ branching fraction value [14].

It follows that the observed $J/\psi$ signal would be expected to be about 27 times larger than that for $\psi(2S)$. The signals in Fig. 2(c) seem to be consistent with this expectation, and they are also in agreement with the detailed analysis of ISR production of the $K^-K^+\pi^+\pi^-$ system in Ref. [18]. There is a $\chi_{c2}(1P)$ signal in Fig. 2(c) which is comparable in size to the $\psi(2S)$ signal. The branching fraction for $\psi(2S) \rightarrow K^-K^+\pi^+\pi^-$ is $7.5 \times 10^{-4}$ [14], while the product $\mathcal{B}(\psi(2S) \rightarrow \gamma \chi_{c2}(1P)) \times \mathcal{B}(\chi_{c2}(1P) \rightarrow K^-K^+\pi^+\pi^-)$ is $7.8 \times 10^{-4}$ [14], so that the presence of such a $\chi_{c2}(1P)$ signal is consistent with the expected transition rates. For the $\chi_{c1}(1P)$, $\mathcal{B}(\psi(2S) \rightarrow \gamma \chi_{c1}(1P)) \times \mathcal{B}(\chi_{c1}(1P) \rightarrow K^-K^+\pi^+\pi^-) = 4.0 \times 10^{-4}$, and so a $\chi_{c1}(1P)$ signal of approximately half the size of the $\chi_{c2}(1P)$ signal would be expected in Fig. 2(c); again the data seem to be in reasonable agreement with this expectation.

Finally, for the $\chi_{c0}(1P)$, $\mathcal{B}(\psi(2S) \rightarrow \gamma \chi_{c0}(1P)) \times \mathcal{B}(\chi_{c0}(1P) \rightarrow K^-K^+\pi^+\pi^-) = 16.8 \times 10^{-4}$, and the corresponding signal in Fig. 2(c) would be expected to be about twice the size of the $\psi(2S)$ signal. The $\chi_{c1}(1P)$ signal seems to be larger than that of the $\psi(2S)$, but not by a factor of 2; this may be because the larger energy photon from the $\psi(2S) \rightarrow \gamma \chi_{c0}(1P)$ transition, when combined with the ISR photon, can yield a value of $m_X^2$ which is larger than 10 (GeV/c$^2$)$^2$. In summary, the signals observed in Fig. 2(c) appear consistent with those expected for an ISR-production mechanism, especially since there is no indication of any remnant of the large $\eta_c(1S)$ of Fig. 2(a). Furthermore, the $\chi_{cJ}$ signals in Fig. 2(c) are removed by requiring that the transverse momentum of the $K^-K^+\pi^+\pi^-$ system be less than 50 MeV/c [see discussion of Fig. 2(d) below], which indicates clearly that they do not result from two-photon production.

In Fig. 2(d), the $\eta_c(1S)$ signal of Fig. 2(a) appears to have survived the $m_2^2 > 10$ (GeV/c$^2$)$^2$ requirement in its entirety, and the $\chi_{c0}(1P)$ and $\chi_{c2}(1P)$ signals have been reduced slightly, as discussed in the previous paragraph; in both Figs. 2(a) and 2(d) there is some indication of a small signal in the region of the $\eta_c(2S)$ mass. A $J/\psi$ signal of about one-third of that in Fig. 2(a) is present also in Fig. 2(d). This is interpreted as being primarily due to (a) the emission of more than one initial state photon, with the consequence that values of $m_X^2$ greater than 10 (GeV/c$^2$)$^2$ are obtained, (b) the ISR production of the $\psi(2S)$ with subsequent decay to $J/\psi +$ neutrals, and (c) two-photon production of the $\chi_{c2}(1P)$ followed by $\chi_{c2}(1P) \rightarrow \gamma J/\psi$, which has a 20% branching fraction [14].

It follows from the above that the requirement $m_2^2 > 10$ (GeV/c$^2$)$^2$ significantly reduces ISR contributions to the $K^-K^+\pi^+\pi^-$ final state while leaving signals associated with two-photon production essentially unaffected. For this reason, the requirement that $m_{\text{mass}}^2$ of Eq. (1) be greater than 10 (GeV/c$^2$)$^2$ is chosen as a principal selection criterion for the isolation of events corresponding to $\gamma\gamma \rightarrow D\bar{D}$.

As mentioned above, it is expected that for an untagged analysis of $\gamma\gamma \rightarrow D\bar{D}$, the transverse momentum $p_t(D\bar{D})$ should be small. In order to quantify this statement, the data of Fig. 2(d) were divided into intervals of 50 MeV/c in the transverse momentum of the $K^-K^+\pi^+\pi^-$ system with respect to the $e^+e^-$ collision axis, which is considered also to be the collision axis for two-photon-production events. For each interval a fit was made to the $m(K^-K^+\pi^+\pi^-)$ mass distribution in the mass region $2.7 \leq m(K^-K^+\pi^+\pi^-) \leq 3.3$ GeV/c$^2$. The function used consists of a second-order polynomial to describe the background, a Gaussian function for the $J/\psi$ signal, and a Breit-Wigner for the $\eta_c(1S)$ signal convolved with a Gaussian to account for the resolution. The $p_t$ dependence of the resulting $\eta_c(1S)$ yield is shown in Fig. 3(a), and that of the $J/\psi$ yield is shown in Fig. 3(b). The shapes of the distributions are quite similar for $p_t > 100$ MeV/c, but the interval from 50–100 MeV/c contains about 180 more $\eta_c(1S)$ signal events, and that for 0–50 MeV/c exhibits an excess of about 800 signal events. This behavior is expected for two-photon production of the $\eta_c(1S)$. Thus, the requirement $p_t(D\bar{D}) < 50$ MeV/c is imposed as the second principal selection criterion for the extraction of $\gamma\gamma \rightarrow D\bar{D}$ events.

Since the two-photon reactions $\gamma\gamma \rightarrow K^-K^+\pi^+\pi^-$ and $\gamma\gamma \rightarrow D\bar{D}$ are quasixclusive in the sense that only the final state particles $e^+$ and $e^-$ are undetected it is required in both instances that the total energy deposits $E_{\text{EMC}}$ in the EMC which are unmatched to any charged-particle track be less than 400 MeV. The net effect is a small reduction in
the smooth background. The histogram of Fig. 3(c) corresponds to the $K^-K^+\pi^+\pi^-$ candidates of Fig. 2(d) after requiring $p_t(K^-K^+\pi^+\pi^-) < 50$ MeV/$c$ and that the EMC energy sum be less than 400 MeV. The $p_t$ criterion reduces the $\eta_c(1S)$ signal by a factor $= 2$, while the $J/\psi$ signal is reduced by a factor $= 5$, as is the continuum background at 2.7 GeV/$c^2$. More significantly, the continuum background at 3.7 GeV/$c^2$, just below the $D\bar{D}$ threshold, is reduced by a factor $= 10$.

It follows that the net effect of the three principal selection criteria described above [missing mass $m_{\text{miss}} > 10$ (GeV/$c^2$)$^2$, resultant transverse momentum $p_t(D\bar{D}) < 50$ MeV/$c$, and total energy deposit in the calorimeter $E_{\text{EMC}} < 400$ MeV] is to significantly enhance the number of two-photon-production events relative to the events resulting from ISR production, continuum production, and combinatoric background.

Concerning the histogram of Fig. 3(c), the product $\Gamma_{\gamma\gamma}(\eta_c(1S)) \times B(\eta_c(1S) \rightarrow K^-K^+\pi^+\pi^-)$ is $1.7 \pm 1.0$ times that for the $\chi_{c0}(1P)$ state [14], and in Fig. 3(c) the $\eta_c(1S)$ signal contains $= 950$ events [cf. the 0–50 MeV/$c$ interval of Fig. 3(a)], while the $\chi_{c0}(1P)$ signal contains $= 550$ events. It follows that the signal sizes agree well with the ratio expected on the basis of a two-photon production mechanism. In a similar vein, the ratio of the partial width $\Gamma_{\gamma\gamma}(\chi_{cJ}) \times B(\chi_{cJ} \rightarrow K^-K^+\pi^+\pi^-)$ for $\chi_{c0}(1P)$ and $\chi_{c2}(1P)$ is $9 \pm 2$ [14], so that after taking into account the $(2J + 1)$ spin factors, the signals observed in Fig. 3(c) would be expected to be approximately in the ratio $1.8 \pm 0.4$. The $\chi_{c2}(1P)$ signal contains $= 200$ events, and so is consistent with this expectation.

**IV. RECONSTRUCTION OF $D\bar{D}$ EVENTS**

Candidate $D\bar{D}$ events are reconstructed in the five combinations of $D$ decay modes listed in Table II (the use of charge conjugate states is implied throughout the text). Events are selected by requiring the exact number of charged-particle tracks defined by the relevant final state.

Track selection requirements include transverse momentum $p_t > 0.1$ GeV/$c$, at least 12 coordinate measurements in the DCH, a maximum distance of closest approach (DOCA) of 1.5 cm to the $z$ axis, with this point at a maximum DOCA of 10 cm to the $xy$ plane at $z = 0$.

Kaon candidates are identified based on the normalized kaon, pion, and proton likelihood values ($L_k/L_\pi$, $L_\pi$), which obtained from the particle identification system, by requiring $L_k/(L_k + L_\pi) > 0.9$ and $L_\pi/(L_k + L_\pi) > 0.2$. Tracks that fulfill $L_k/(L_k + L_\pi) < 0.82$ and $L_\pi/(L_k + L_\pi) < 0.98$ are selected as pions. Additionally, in both cases the track should be inconsistent with electron identification.

Photon candidates are selected when their deposited energy in the EMC is larger than 100 MeV. Neutral pions are reconstructed from pairs of photons with combined mass within [0.115, 0.155] GeV/$c^2$ and a $\pi^0$ mass constraint is applied to them.

The $D$ candidate decay products are fitted to a common vertex with a $D$ meson mass constraint applied; candidates with a $\chi^2$ fit probability greater than 0.1% are retained. Accepted $D\bar{D}$ pairs are refitted to a common vertex consistent with the $e^+e^-$ interaction region, and those with a $\chi^2$ fit probability $p_{\text{fit}}(D\bar{D})$ greater than 0.1% are retained.

**TABLE II.** $D$ decay final states studied in this analysis; for channels N5, N6, and N7, inclusion of the corresponding charge conjugate combination is implied.

| Channel | $D$ decay mode | $\bar{D}$ decay mode |
|---------|----------------|---------------------|
| N4      | $D^0\bar{D}^0$ | $D^0 \rightarrow K^-\pi^+$ | $\bar{D}^0 \rightarrow K^+\pi^-$ |
| N5      | $D^0\bar{D}^0$ | $D^0 \rightarrow K^-\pi^+$ | $\bar{D}^0 \rightarrow K^+\pi^-\pi^0$ |
| N6      | $D^0\bar{D}^0$ | $D^0 \rightarrow K^-\pi^+$ | $\bar{D}^0 \rightarrow K^+\pi^-\pi^0$ |
| N7      | $D^0\bar{D}^0$ | $D^0 \rightarrow K^-\pi^+\pi^-$ | $\bar{D}^0 \rightarrow K^+\pi^-\pi^0$ |
| C6      | $D^+D^-$       | $D^+ \rightarrow K^-\pi^+\pi^-$ | $D^- \rightarrow K^+\pi^-\pi^0$ |
with free parameters $\sigma_0$, $r$ (minimal and maximal width) and $m_0$; the background is described by a polynomial. The full width at half maximum (FWHM) of the signal line shape in data is used to define each $D$ signal region; $D$ candidates are selected from a region of width $\pm 1.5$ FWHM around the mean mass. The mass windows are listed in Table III.

From the list of accepted $D\bar{D}$ candidates those produced in two-photon events are then selected by applying the three criteria defined in Sec. III (summarized in Table IV). These criteria are also identical for all combinations of $D$ decay modes.

Depending on the decay mode, up to 2.5% of the events have multiple candidates which passed all selection criteria. In this case, the candidate with the best fit probability $p_{\chi}(D\bar{D})$ is chosen. Based on Monte Carlo (MC) studies, the correct candidate is selected in more than 99% of the cases with this method.

The resulting invariant mass spectra for $D$ meson candidates after all selection criteria have been applied are shown in Fig. 4 for events in which the mass of the recoil $\bar{D}$

![Graphs showing candidate $D$ invariant mass distributions after all selection criteria.](image)

**FIG. 4.** Candidate $D$ invariant mass distributions after all selection criteria. The mass of the accompanying $\bar{D}$ candidate is required to lie within its signal region as defined in Table III. (a) $K^-\pi^+$ in N4; (b) $K^+\pi^-\pi^0$ in N5; (c) $K^-\pi^+\pi^-\pi^+$ in N6; (d) $K^+\pi^-\pi^0$ in N7; (e) $K^-\pi^+\pi^+$ in C6.
candidate lies within the defined signal region. In all modes, clear signals with small backgrounds are obtained. The resulting $D\bar{D}$ invariant mass distributions are shown in Figs. 5(a) and 5(b) for the neutral modes ($N_4, N_5, N_6, N_7$), and for the charged mode ($C_6$), respectively. The combined spectrum is shown in Fig. 5(c). An enhancement near 3.93 GeV/$c^2$ is visible.

To estimate the amount of combinatoric background in the signal region, the two-dimensional space spanned by the invariant masses of the $D$ and $\bar{D}$ candidates is divided into nine regions: one central signal region and eight sideband regions above and below the signal region as shown in Fig. 6 for the $C_6$ mode. GAMGAM two-photon event generator was used to simulate MC events, while the decays of the $D$ and $\bar{D}$ mesons were generated by EVTGEN [20]. The detector response was simulated using the GEANT4 [21] package. The program GAMGAM uses the formalism suggested by Budnev, Ginzburg, Meledin, and Serbo (BGMS) [22]. It was developed for CLEO and was used, for example, in the analysis of $\chi_{c0}(1P), \chi_{c2}(1P) \rightarrow 4\pi$ decays [23]. GAMGAM was later adapted to BABAR and used for the analysis of $\eta_c(1S, 2S) \rightarrow K^0L^\pm\pi^\mp$ [16].

For small photon virtualities $|q_1,q_2|^2$ (see Fig. 1) the differential cross section for the process $e^+e^- \rightarrow e^+e^-\gamma\gamma$, $\gamma\gamma \rightarrow X$, where $L$ is the two-photon flux. The form factor $F$ extrapolates the process to virtual photons and is a priori not known. A plausible model

$$F = \frac{1}{1 - \frac{1}{m_\gamma^2/m_e^2}} \times \frac{1}{1 - \frac{1}{m_\gamma^2/m_e^2}}$$

is used [24], with $m_e$ being the mass of an appropriate
vector boson ($\rho, J/\psi, Z^0$). In the calculations relevant to this analysis $m_\psi = m(J/\psi)$ was used, as the $Z(3930)$ is expected to be a charmonium state. An alternative model was used in order to evaluate systematic uncertainties associated with MC simulations (see Sec. XI).

To validate the GAMGAM generator its output was compared to that of another two-photon generator (TREPS) used by Belle [25]. The cross sections for the reactions $e^+e^- \rightarrow e^+e^- \gamma\gamma, \gamma\gamma \rightarrow \eta_c(1S, 2S)$ were calculated in GAMGAM and compared to the Belle values [26]. In order to compare the different generators, the cross sections were calculated using the hypothetical values $\Gamma_{\gamma\gamma} \times B(\eta_c(1S, 2S) \rightarrow \text{final state}) = 1$ keV, and $q_{1,2}^2$ was restricted to values smaller than 1 (GeV/c$^2$)$^2$. The TREPS results were 2.11 pb for $\eta_c(1S)$ and 0.86 pb for $\eta_c(2S)$. The corresponding GAMGAM values were 2.13 and 0.84 pb, respectively. The two generators are in agreement at the level of a few percent.

For a global check, the cross sections for the continuum reaction $e^+e^- \rightarrow e^+e^- \gamma\gamma, \gamma\gamma \rightarrow \mu^+\mu^-$ were calculated with GAMGAM for various c.m. energies and compared to QED predictions [27, 28], which describe the data with high accuracy [29]. Here, the agreement was slightly worse, due to the imperfect tuning of the GAMGAM program. Similar results were obtained when checking against calculations with nonrelativistic models for $\eta_c(1S)$ and $\chi_{c2}(1P)$ [30]. Nevertheless this comparison showed that GAMGAM works properly under these conditions also. These studies lead to the assignment of a total systematic uncertainty of $\pm 3\%$ associated with the MC simulation (see Sec. XI).

VI. PURITY OF THE $\gamma\gamma \rightarrow D\bar{D}$ SAMPLE

The selection criteria used to enhance the two-photon content of the $D\bar{D}$ sample were discussed in Sec. III. They were developed by investigating the reaction $e^+e^- \rightarrow K^+K^-\pi^+\pi^-X$ of Eq. (2). Figure 3(c) shows that after the selection procedure the signals associated with $\gamma\gamma$ reactions, like that for the $\eta_c(1S)$, are enhanced, while signals such as that for the $J/\psi$, which are typical of ISR production, are suppressed. The $p_\text{t}(DD)$ distribution shown in Fig. 7 for events in the $Z(3930)$ signal region, defined as the region from 3.91 to 3.95 GeV/c$^2$. Here the $p_\text{t}(DD)$ selection criterion has not been applied. The data are fitted with a curve for $\gamma\gamma$ events obtained from MC, plus a linear background derived from sideband studies of the $D\bar{D}$ mass spectrum. The fit indicates that the majority of $D\bar{D}$ candidates in the signal region result from two-photon interactions.

VII. RECONSTRUCTION EFFICIENCY

The reconstruction efficiency for each decay mode is calculated as a function of $m(D\bar{D})$ using MC events which pass the same reconstruction and selection criteria as real events and includes detector acceptance, track reconstruction, and particle identification efficiencies. The mass-dependent efficiency $e_i(m(D\bar{D}))$ for each channel $i$ is fitted with a polynomial in $m(D\bar{D})$ and is found in each case to decrease with increasing $D\bar{D}$ mass. For the combination of modes [Fig. 5(c)], an overall weighted efficiency $e^b(m(D\bar{D}))$, which includes the branching fractions for the $D$ decays, is computed using

$$e^b(m(D\bar{D})) = \frac{5}{2} \frac{\sum_{i=1}^{5} N_i(m(D\bar{D})) - 1}{\sum_{i=1}^{5} e_i^2(m(D\bar{D}))},$$

as was done in Ref. [31]; $N_i(m(D\bar{D}))$ is the number of $D\bar{D}$ candidates in the data mass spectrum for channel $i$, and $e_i^2(m(D\bar{D}))$ is defined as the product of the efficiency $e_i$ as parametrized by the fitted polynomial and the branching fraction $\mathcal{B}_i$ for the $i$th channel, as follows:

$$e_i(m(D\bar{D})) = e_i(m(D\bar{D})) \times \mathcal{B}_i.$$

The factor $\frac{5}{2}$ originates from referring to $D\bar{D}$ ($D^0\bar{D}^0$ and $D^+\bar{D}^-$) events, and the factor 5 from summing over the five channels. Figure 8 shows the mass dependence of $e^b(m(D\bar{D}))$, which is parametrized by a straight line. The large uncertainties are due to the limited statistics available in the data samples. The error bars do not contain the uncertainties in the branching fractions; these will be discussed separately in Sec. XI in the context of systematic error estimation. The data are weighted by this mean efficiency, which is scaled by a constant value $d$ to obtain weights near 1,

$$e(m(D\bar{D})) = d \times e^b(m(D\bar{D}))$$

as weights far from 1 might result in incorrect errors for the
signal yield obtained in the maximum likelihood fit [32]. The resulting $D\bar{D}$ mass distribution will be discussed in Sec. VIII.

VIII. DETECTOR RESOLUTION AND SIGNAL YIELD

Monte Carlo events are used for the calculation of the mass-dependent detector resolution. The mass resolution is determined by studying the difference between the reconstructed and the generated $D\bar{D}$ mass ($\Delta m_{\text{res}}$). As an example, the distribution for channel C6 is shown in Fig. 9(a). A good description of the distribution is obtained using a multi-Gaussian fit [Eq. (4)]. The parameters $r$ and $\sigma_0(m(D\bar{D}))$ were determined for every decay channel. The variation of $\sigma_0(m(D\bar{D}))$, which is parametrized by a second-order polynomial, and of the width (FWHM) of the resolution function with increasing mass are shown in Figs. 9(b) and 9(c). For channel C6, $r = 5.380 \pm 0.137$ and $\sigma_0(m(D\bar{D})) = (-0.038 \pm 0.018m - 0.002m^2)$ GeV/c$^2$, where $m(D\bar{D})$ is given in units of GeV/c$^2$. The distributions of Fig. 9 are well described by the fitted curves shown. Comparing the generated $Z(3930)$ mass with the reconstructed MC value shows that the latter is systematically low by about 0.9 MeV/c$^2$, independently of the fit model. This effect is observed both in the combined fit and in fits to the individual channels. The measured $J/\psi$ mass in the $K^+K^-\pi^+\pi^-$ test sample (Sec. III) differs by the same value from the world average [14]; this offset has been seen in other $\gamma\gamma$ studies at BABAR [16] as well. Accordingly, the mass value obtained from the fit to data will be corrected by +0.9 MeV/c$^2$. This offset value will also be used as a conservative estimate of the systematic uncertainty in the mass scale. The difference between the generated and reconstructed decay width values amounts to 0.14 MeV, and is discussed in Sec. XI with respect to systematic error estimation.

In order to describe the signal structure in data around 3.93 GeV/c$^2$ a relativistic Breit-Wigner function $BW(m)$ is used, where

$$BW(m) = \left( \frac{p_m}{p_m'} \right)^{2L+2} \frac{F^2}{(m^2 - m_0^2)^2 + \frac{1}{\Gamma_m^2} m_0^2}$$

with $m_0$ as the nominal mass of the resonance; the Blatt-Weisskopf coefficients $F_r$ for different angular momentum values $L$ are given by

$$F_r(L = 0) = 1,$$

$$F_r(L = 1) = \frac{1 + (R p_m')^2}{\sqrt{1 + (R p_m')^2}},$$

$$F_r(L = 2) = \frac{\sqrt{9 + 3(R p_m')^2 + (R p_m')^4}}{\sqrt{9 + 3(R p_m')^2 + (R p_m')^4}},$$

and the value

$$R = 1.5 \text{ (GeV/c)}^{-1}.$$
is used, corresponding to the value given in Ref. [33]. The mass-dependent width is given by

$$
\Gamma_m = \Gamma_r \left( \frac{p_m}{p_{m_0}} \right)^{2\ell+1} \left( \frac{m_0}{m} \right) F_r^2
$$

(13)

with $\Gamma_r$ the total width of the resonance. Here the existence of other possible decay modes is ignored. The momentum of a given $D$ candidate in the $D\bar{D}$ center of mass frame is denoted by $p_m$; $p_{m_0}$ is the corresponding value for $m = m_0$. In the standard fit, spin $J = 2$ ($L = 2$) is chosen on the basis of the angular distribution analysis described in Sec. IX.

The signal function is convolved with the mass- and decay-mode-dependent resolution model parametrized as discussed previously in this section. The background is parametrized by the function

$$
D(m) \propto \sqrt{m^2 - m_i^2} (m - m_i)^n \exp[-\beta(m - m_i)]
$$

(14)

which takes the $D\bar{D}$ threshold $m_i$ into account. In the lower mass region, the line shape does not describe the background exactly. Other functional forms were tried (Sec. XI), but no improvement was obtained. The data and the curves which result from the standard ($J = 2$) fit are shown in Fig. 10.

From the unbinned maximum likelihood fit to the five mass spectra the $Z(3930)$ values $m_0 = (3925.8 \pm 2.7)$ MeV/$c^2$ and $\Gamma_r = (21.3 \pm 6.8)$ MeV are obtained for the mass and total width, respectively (all errors in this section are statistical only). The mass is corrected by +0.9 MeV/$c^2$ as described above, resulting in a final mass value of $(3926.7 \pm 2.7)$ MeV/$c^2$. The efficiency-corrected yield amounts to $N_s = (76 \pm 17)$ signal events. This value is based on weights around 1 as discussed in Sec. VII; taking the constant used to scale the efficiency into account [see Eq. (8)], this corresponds to a total $Z(3930)$ signal of $N_{s\theta} = (285 \pm 64) \times 10^3$ events.

The statistical significance of the peak is $5.8\sigma$ and is derived from the difference $\Delta \ln L$ between the negative logarithmic likelihood of the nominal fit and that of a fit where the parameter for the signal yield is fixed to zero. This is then used to evaluate a $p$ value:

$$
p = \int_{2\Delta \ln L}^{\infty} f(z; n_d) dz,
$$

(15)

where $f(z; n_d)$ is the $\chi^2$ probability density function and $n_d$ is the number of degrees of freedom, 3 in this case. We then determine the equivalent one-dimensional significance from this $p$ value.

**IX. ANGULAR DISTRIBUTION AND SPIN OF THE Z(3930) STATE**

General conservation laws limit the possibilities for the $J^{PC}$ values of the $Z(3930)$ state. For two-photon production the initial state has positive $C$ parity and hence the final state must have positive $C$ parity also. For the $D\bar{D}$ final state, $C = (-1)^L S = (-1)^L$ since the total spin $S$ is zero. Positive $C$ parity then implies that the $D\bar{D}$ system must have orbital angular momentum $L$ which is even, and hence have even parity. It follows that for the $Z(3930)$ state $J^{PC} = J^++$ with $J = 0, 2, 4, \ldots$ In order to investigate the possible values of $J$, we have compared the decay angular distribution measured in the $Z(3930)$ signal region to the distributions expected for $J = 0$ and $J = 2$; higher spin values are very unlikely for a state only 200 MeV/$c^2$ above threshold.

The decay angle $\theta$ is defined as the angle of the $D$ meson in the $D\bar{D}$ system relative to the $D\bar{D}$ lab momentum vector. Figure 11 shows the $Z(3930)$ signal yield obtained from fits to the $D\bar{D}$ mass spectrum for ten regions of $|\cos \theta|$. The data have been weighted by a $\cos \theta$-dependent efficiency, which was determined in a similar manner as described in Sec. VII for the mass-dependent efficiency (Fig. 12). In these fits, the mass and width of the resonance have been

![FIG. 10](color online). Efficiency-corrected mean $D\bar{D}$ mass distribution with standard fit. The dashed curve shows the background line shape (see Sec. VIII).

![FIG. 11](Signal yield as a function of $|\cos \theta|$ derived from fits to the efficiency-corrected $D\bar{D}$ spectrum. The solid curve is the expected distribution for spin 2 with dominating helicity-2 contribution, the dotted straight line is for spin 0.)
fixed to the values found in Sec. VIII, and Eq. (14) has been used to describe the background. Other background models have been tried, obtaining distributions fully consistent with Fig. 11.

The function describing the decay angular distribution for spin 2 has been calculated using the helicity formalism and has the form

$$\frac{dN}{d\cos\theta} \propto \sin^4 \theta, \quad (16)$$

It has been assumed that the dominating amplitude has helicity 2. This is in agreement with previous measurements [34] and theoretical predictions [24,30]. The distribution of Eq. (16) was fitted to the experimental angular distribution, and a $\chi^2$/NDF value of 5.63/9 was obtained, with NDF indicating the number of degrees of freedom. For a flat distribution, which is expected for spin 0, a $\chi^2$/NDF = 15.55/9 was obtained. It follows that the preferred $J^{PC}$ assignment is $2^{++}$.

X. TWO-PHOTON WIDTH OF THE Z(3930) STATE

From the efficiency-corrected number of observed signal events, $N_{\text{sig}}$, we determine the total experimental cross section

$$\sigma_{\text{exp}}(e^+e^- \to e^+e^-\gamma\gamma, \gamma\gamma \to Z(3930), Z(3930) \to D\bar{D}) = N_{\text{sig}}/\int L dt = 741 \pm 166 \text{ fb}, \quad (17)$$

where the integrated luminosity for the data sample analyzed is $\int L dt = (384 \pm 4) \text{ fb}^{-1}$ and the error is only statistical. On the other hand, the cross section for Z(3930) production is given by

$$\sigma(e^+e^- \to \gamma\gamma, \gamma\gamma \to Z(3930)) = L \times F \times \sigma(\gamma\gamma \to Z(3930)) \quad (18)$$

with

$$\sigma(\gamma\gamma \to Z(3930)) = \int 4\pi(2J + 1)(hc)^210^{-6}m_2^3 \frac{\Gamma_{\gamma\gamma}}{\sqrt{K}m} \frac{\Gamma_{\gamma\gamma}}{m_2^2 - m^2} + m_2^2 \Gamma_{\gamma\gamma}^2 dm^2 \quad (19)$$

and can be calculated using GAMGAM. Here $L$ is the two-photon flux, $F$ is the form factor (see Sec. V), $m_2$ ($\Gamma_{\text{tot}}$) is the resonance mass (width), and $\Gamma_{\gamma\gamma}$ is the two-photon width of the resonance. The kinematical factor $K$ is given by $K = (q_1q_2)^2 - q_1^2q_2^2$ ($q_i$ represent four vectors of photons). Further information can be found in Refs. [22,24,35]. The cross section depends on the spin of the resonance and on $\Gamma_{\gamma\gamma}$. It is plotted for $J = 2$ and $J = 0$ in Fig. 13 as a function of $\Gamma_{\gamma\gamma}$. From a comparison to the experimental cross section [Eq. (17)], the partial width $\Gamma_{\gamma\gamma} \times B(Z(3930) \to D\bar{D})$ is found to have the value $(0.24 \pm 0.05) \text{ keV}$ when $J = 2$ is chosen as the most probable spin value (see Sec. IX).

XI. SYSTEMATIC ERROR ESTIMATION

Several sources of systematic uncertainty have been considered for the mass, decay width, and signal yield of the Z(3930) state. The yield determines the value of...
TABLE V. Results of the systematic uncertainty studies for the mass, decay width, and efficiency-corrected signal yield of the $Z(3930)$ state. Listed are the differences with respect to the standard values. $\Delta(\Gamma_{\gamma\gamma} \times \mathcal{B})$ numbers are given for spin $J = 2$ only. For the combined error, the values are added in quadrature.

| Source of systematic uncertainty | $\Delta m(\text{Z}(3930))$ (MeV/$c^2$) | $\Delta \Gamma(\text{Z}(3930))$ (MeV) | $\Delta(\Gamma_{\gamma\gamma} \times \mathcal{B})$ (keV) |
|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| Choice of spin $J = 1, J = 0$  | $<0.05$                         | $<0.05$                         | $\cdots$                        |
| Value of $R$ (Breit-Wigner)    | $<0.05$                         | $<0.05$                         | $<0.0005$                       |
| Background $D'(m)$             | 0.4                             | 3.0                             | 0.029                           |
| Fit precision and mass scale   | 0.9                             | 0.1                             | 0.001                           |
| Convolution steps = 35        | 0.2                             | 0.2                             | 0.003                           |
| Convolution range $+0.02$ MeV/$c^2$ | $<0.05$                       | 0.9                             | 0.003                           |
| Resolution multi-Gauss $r \pm \delta r$ | $<0.05$                       | 0.1                             | $<0.0005$                       |
| Combined reconstr. efficiency: polynomial | $<0.05$                       | 0.4                             | $<0.0005$                       |
| Tracking efficiency correction | $<0.05$                         | $<0.05$                         | 0.022                           |
| $\pi^0$ efficiency correction  | $<0.05$                         | $<0.05$                         | 0.003                           |
| Error in $D$ branching fractions | $<0.05$                       | $<0.05$                         | 0.010                           |
| Efficiency: angular distribution | $\cdots$                     | $\cdots$                        | 0.018                           |
| Generator precision            | $\cdots$                        | $\cdots$                        | 0.007                           |
| Choice of form factor          | $\cdots$                        | $\cdots$                        | 0.002                           |
| PID                             | 0.4                             | 1.8                             | 0.004                           |
| Uncertainty in $D$ mass        | 0.3                             | $\cdots$                        | $\cdots$                        |
| Luminosity                      | $\cdots$                        | $\cdots$                        | 0.002                           |
| Combined error                  | $\pm 1.1$                      | $\pm 3.6$                       | $\pm 0.04$                      |

$\Gamma_{\gamma\gamma} \times \mathcal{B}(Z(3930) \rightarrow DD)$. The standard fit to the efficiency-corrected mass spectrum is repeated with appropriate modifications. The differences $\Delta$ between the results obtained and the standard results are used as estimates of systematic uncertainty. No correlations have been taken into account. The results are summarized in Table V. Deviations for the mass ($|\Delta m|$), total width ($|\Delta \Gamma|$), and two-photon width ($|\Delta(\Gamma_{\gamma\gamma} \times \mathcal{B})|$) are considered negligible if they are less than 0.05 MeV/$c^2$, 0.05 MeV, and 0.0005 keV, respectively.

A. Fit parametrization

Signal line shape.—The standard fit has assumed spin $J = 2$ for the resonance (Sec. VIII). Using different spin values and $R$ values has no significant impact on the results [Table V; $\Delta(\Gamma_{\gamma\gamma} \times \mathcal{B})$ numbers are given for spin $J = 2$ only].

Background description.—Different parametrizations of the background in the $m(DD)$ distribution have been used. Besides the nominal background [Eq. (14)], the following background shape was tried:

$$ D'(m) \propto \left(1 - \exp\left[-\frac{(m - \alpha)}{\beta}\right]\right)\frac{m^\beta}{\alpha} + \gamma\left(\frac{m}{\alpha} - 1\right); $$

the fit had a slightly worse, but still acceptable, likelihood value. The mass value changes by $\Delta m = +0.4$ MeV/$c^2$, the width by $\Delta \Gamma = +3.0$ MeV, the signal yield by $+9$ events with respect to the standard fit, and $\Gamma_{\gamma\gamma} \times \mathcal{B}$ changes accordingly by $+0.029$ keV (Table V). Other

background models yield consistent estimates for this source of systematic uncertainty.

B. Detector resolution

Fit precision and mass scale.—A fit of the convolution of signal line shape and resolution model to the MC sample has been performed. The mass offset observed in MC has been included by correcting the mass value by $+0.9$ MeV/$c^2$. As a conservative estimate, this number is also used as the systematic uncertainty for the mass scale. The deviation between the generated width and the value obtained from the fit is 0.14 MeV, and again this is used as a conservative estimate of systematic uncertainty. Based on the uncertainty of the width, a value of $\Delta \Gamma_{\gamma\gamma} \times \mathcal{B} = 0.001$ keV is derived.

Resolution model.—The parameters of the multi-Gaussian resolution model were modified. The number of steps was enlarged from 25 to 35, the total convolution range for each data point enlarged by $+0.02$ MeV/$c^2$, and the parameter $r$ of the multi-Gaussian was varied within its fit uncertainty $\delta r$. The corresponding shifts in the mass are $\Delta m = +0.2$, $<0.05$, and $<0.005$ MeV/$c^2$. For $\Delta \Gamma$, shifts of $-0.2$, $-0.9$, and $-0.1$ MeV are obtained; from the modified signal yield, shifts of $-0.003$, $-0.003$, and $<0.0005$ keV were obtained for $\Gamma_{\gamma\gamma} \times \mathcal{B}$ (Table V).

C. Combined reconstruction efficiency

Parametrization.—The average mass-dependent reconstruction efficiency has been parametrized by a straight line in the standard fit (Fig. 8). Using a fit with a second-
order polynomial, the width changes by $-0.4$ MeV; no mass shift was observed with respect to the standard fit result. For the signal yield, $+1$ entry is obtained; this yields no significant shift for $\Gamma_{\gamma\gamma} \times B$ (Table V).

**Tracking and neutrals correction.**—For the tracking efficiency a correction by $-0.8\%$ is applied per charged-particle track. This gives a correction factor of 0.908 for modes N4, N5, and 0.953 for N6, N7, and C6. The systematic uncertainty assigned to the tracking efficiency is 1.4\% per track for decays with more than 5 charged-particle tracks and 1.3\% otherwise. The resulting uncertainty for $\Gamma_{\gamma\gamma} \times B$ is 0.022 keV. Concerning efficiency corrections for neutral particles, a correction factor of 0.984 with an uncertainty of 3\% per $\pi^0$ is used for modes N5 and N7. The resulting uncertainty for $\Gamma_{\gamma\gamma} \times B$ is 0.003 keV (Table V).

**Uncertainty on the D branching fractions.**—The errors on the $D$ branching fractions have been taken into account by varying the values of $B_i$ used in Eq. (6) within their standard deviations. No significant change is observed in mass and decay width. For the two-photon width $\Delta(\Gamma_{\gamma\gamma} \times B) = \pm 0.001$ keV is obtained (Table V).

**Effect of angular distribution on efficiency.**—The MC data sample used to obtain the efficiency and resolution was generated with a flat distribution in $\cos\theta$. To estimate the effect of the angular distribution on the reconstruction efficiency, a MC sample described by a $\sin^4\theta$ distribution has been generated and reconstructed. Comparing these reconstructed data with the nominal MC sample, the mean efficiencies differ by 8\%, relatively, resulting in $\Delta(\Gamma_{\gamma\gamma} \times B) = \pm 0.018$ keV.

**D. Cross-section calculation from GAMGAM**

**Precision.**—In Sec. V a relative uncertainty of $\pm 3\%$ was obtained for the calculated cross section. Propagating this error into the calculation of $\Gamma_{\gamma\gamma} \times B$, an uncertainty $\Delta(\Gamma_{\gamma\gamma} \times B) = \pm 0.007$ keV results.

**Form factor.**—In the standard analysis the form factor of Eq. (5) has been used with $m_\pi = m(1/\psi)$. In order to estimate potential systematic effects, the cross section was evaluated using a model predicted by perturbative QCD [36]

$$F = \frac{1}{(1 - q_1^2/m_\pi^2 - q_2^2/m_\pi^2)^{\frac{1}{2}}}.$$  (21)

The cross section calculated with GAMGAM does not increase significantly (\(\approx 0.1\%\)) compared to that obtained using Eq. (5). Simultaneously the experimental efficiency decreases by 1\%, so that the net effect on $\Gamma_{\gamma\gamma} \times B$ is small. Similar effects have been observed when data and calculations with and without $q^2$ selection criteria are compared [25,26,37], and also in a previous CLEO analysis [38]. As a result a systematic uncertainty of $\pm 1\%$ is attributed to form factor uncertainty and this yields a deviation $\Delta(\Gamma_{\gamma\gamma} \times B) = \pm 0.002$ keV.

**E. Other uncertainties**

**Particle identification (PID).**—For PID studies, the pion selection criteria have been tightened significantly, and the efficiency has been recalculated accordingly. The fit to the mass spectrum yields a change of $-0.4$ MeV/$c^2$ for the mass and $-1.8$ MeV for the width. For $\Delta(\Gamma_{\gamma\gamma} \times B)$ a change of $-0.004$ keV results.

**D mass uncertainty.**—The uncertainty of the $D$ meson mass is taken into account. Both for $D^0$ and $D^\ast$, the uncertainty is 0.17 MeV/$c^2$ [14], which results in an uncertainty of $\pm 0.34$ MeV/$c^2$ in the mass of the $Z(3930)$ state.

**Integrated luminosity uncertainty.**—For the integrated luminosity, an uncertainty of $\pm 1\%$ is assigned. From this an uncertainty $\Delta(\Gamma_{\gamma\gamma} \times B) = \pm 0.002$ keV is obtained.

**F. Total systematic uncertainty**

The systematic uncertainty estimates discussed in Secs. XIA, XIB, XIC, XID, and XIE are summarized in Table V. The individual estimates are combined in quadrature to yield net systematic uncertainty estimates on the $Z(3930)$ mass, total width, and value of $\Gamma_{\gamma\gamma} \times B(Z(3930) \rightarrow D\bar{D})$ of 1.1 MeV/$c^2$, 3.6 MeV, and 0.04 keV, respectively, as reported on the last line of Table V.

**XII. SUMMARY**

In the $\gamma\gamma \rightarrow D\bar{D}$ reaction a signal in the $D\bar{D}$ mass spectrum has been observed near 3.93 GeV/$c^2$ with a significance of 5.8\$ which agrees with the observation of the $Z(3930)$ resonance by the Belle Collaboration [13]. The mass and total width of the $Z(3930)$ state are measured to be $(3926.7 \pm 2.7({\text{stat}}) \pm 1.1({\text{syst}}))$ MeV/$c^2$ and $(21.3 \pm 6.8({\text{stat}}) \pm 3.6({\text{syst}}))$ MeV, respectively.

The production and decay mechanisms allow only positive parity and $C$ parity, and an analysis of the $Z(3930)$ decay angular distribution favors a tensor over a scalar interpretation. The preferred assignment for spin and parity of the $Z(3930)$ state is therefore $J^{PC} = 2^{++}$. The product of the branching fraction to $D\bar{D}$ times the two-photon width of the $Z(3930)$ state is measured to be $\Gamma_{\gamma\gamma} \times B(Z(3930) \rightarrow D\bar{D}) = (0.24 \pm 0.05({\text{stat}}) \pm 0.04({\text{syst}}))$ keV, assuming spin $J = 2$. The parameters obtained are consistent with the Belle results, and with the expectations for the $\chi_{c2}(2P)$ state.

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