Search for $f_J(2220)$ in Radiative J/ψ Decays

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We present a search for $f_J(2220)$ production in radiative $J/\psi \to \gamma f_J(2220)$ decays using 460 fb^{-1} of data collected with the *BABAR* detector at the SLAC PEP-II e^+e^- collider. The $f_J(2220)$ is searched for in the decays to K^+K^- and $K^0_S K^0_S$. No evidence of this resonance is observed, and 90% confidence level upper limits on the product of the branching fractions for $J/\psi \to \gamma f_J(2220)$ and $f_J(2220) \to K^+K^-(K^0_S K^0_S)$ as a function of spin and helicity are set at the level of 10^{-5}, below the central values reported by the Mark III experiment.

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Evidence for the $f_J(2220)$, a narrow resonance with a mass around 2.2 GeV/c^2 also known as $\xi(2230)$, was first presented by the Mark III Collaboration [1]. The $f_J(2220)$ was seen as a narrow signal above a broad enhancement in both $J/\psi \to \gamma f_J(2220)$, $f_J(2220) \to K^+K^-$ and $J/\psi \to \gamma f_J(2220)$, $f_J(2220) \to K_S^0 K_S^0$ decays. The charged and neutral product branching fractions (PBFs) were measured to be $(4.2^{+1.7}_{-1.4} \pm 0.8) \times 10^{-5}$ and $(3.1^{+1.6}_{-1.3} \pm 0.7) \times 10^{-5}$ with significance of 3.6 and 4.7 standard deviations, respectively. The BES Collaboration has also subsequently reported evidence in radiative J/ψ decays at a comparable level of significance [2]. They reported PBFs of $(3.3^{+1.6}_{-1.3} \pm 1.2) \times 10^{-5}$ and $(2.7^{+1.1}_{-0.9} \pm 0.8) \times 10^{-5}$ for the K^+K^- and $K_S^0K_S^0$ channels, respectively. Indications of similar structure produced in $\pi^- p$ and $K^- p$ collisions have been seen [3–5], while searches for direct formation in $p\bar{p}$ collisions [6,7] or two-photon processes [8,9] were inconclusive.

The unexpectedly narrow width of the $f_J(2220)$, approximately 20 MeV, triggered speculation about its nature. In addition to the early hypothesis of a ‘‘light Higgs’’ scalar [10], conjectures range from a multiquark state to a hybrid resonance, a $\Lambda\bar{\Lambda}$ bound state, a high-spin $s\bar{s}$ state, or a glueball [11]. Intriguingly, lattice QCD calculations predict a mass for the ground state tensor 2^{++} glueball close to 2.2 GeV/c^2 [12,13].

We report herein a search for the $f_J(2220)$ in radiative J/ψ decays, with the J/ψ produced via initial-state radiation (ISR) in e^+e^- collisions recorded at PEP-II. The emission of ISR allows the study of resonance production over a wide range of e^+e^- center-of-mass (c.m.) energies [14]. The data sample used in this analysis consists of 425 fb^{-1} recorded at $\sqrt{s} = 10.58$ GeV and 35 fb^{-1} recorded 40 MeV below this energy. With a luminosity-weighted cross section for J/ψ production of 35.7 pb, this data set contains $(16.4 \pm 0.3) \times 10^6$ directly produced J/ψ decays.

The *BABAR* detector is described in detail elsewhere [15]. Charged-particle momenta are measured in a tracking system consisting of a five-layer double-sided silicon vertex detector and a 40-layer central drift chamber, immersed in a 1.5-T axial magnetic field. Photon and electron energies are measured in a CsI(Tl) electromagnetic calorimeter. Charged-particle identification is performed by using an internally reflecting ring-imaging Cherenkov detector and the energy loss dE/dx, measured by the silicon vertex detector and central drift chamber.

Detector acceptance is studied by using Monte Carlo (MC) simulation based on GEANT4 [16]. Multiple photon emission from the initial-state charged particles is implemented by using a structure function technique [17,18]. The $f_J(2220)$ resonance is modeled by a nonrelativistic Breit-Wigner function with a mass of 2.231 GeV/c^2 and a width of 23 MeV [19]. Several hypotheses for the spin and helicity of the $f_J(2220)$ are considered: spin $J = 0$ and spin $J = 2$ with pure helicity ± 2, ± 1, or 0. The hypothesis $J = 4$ is strongly disfavored by lattice QCD calculations [20].

The $J/\psi \to \gamma K^+K^-$ decay is reconstructed by combining two oppositely charged tracks, identified as kaons, with a photon candidate. Events containing a π^0 candidate, defined as a pair of photons of energy larger than 50 MeV [21] having an invariant mass in the range 115–155 MeV/c^2, are discarded. The contamination of $J/\psi \to K^{*\pm}(892)(K^\pm\pi^0)K^\mp$, in which the π^0 is not reconstructed, is further reduced by rejecting J/ψ candidates having a kaon with a momentum larger than 1.35 GeV/c in the J/ψ c.m. frame.

The $J/\psi \to \gamma K_S^0K_S^0$ channel, examined in $J/\psi \to \gamma\pi^+\pi^-\pi^+\pi^-$, is reconstructed by using events containing a photon and four charged tracks. Neutral kaon candidates are reconstructed from $K_S^0 \to \pi^+\pi^-$, combining a pair of oppositely charged tracks identified as pions, with an invariant mass in the range $|M_{\pi^+\pi^-} - M_{K_s}| < 15$ MeV/c^2. To improve the signal purity, the angle in the transverse plane between the momentum and the flight direction of each kaon is required to be less than 0.1 rad. No π^0 veto is applied, as the $J/\psi \to K_S^0K_S^0\pi^0$ decay is forbidden by C-parity conservation and the overall π^0 contamination is negligible.

Events with additional charged tracks are rejected. The photon emitted by the J/ψ is also required to have an energy larger than 300 MeV to suppress background from additional ISR photons or noise from the calorimeter. Finally, the helicity angle of each kaon, ζ_K, must satisfy $|\cos\zeta_K| < 0.7$.

Radiative $e^+e^- \to \gamma_{\rm ISR} J/\psi$ events are then identified. Clusters in the electromagnetic calorimeter not associated with charged-particle tracks and having energy larger than 1 GeV are taken as ISR photon candidates. Events in which the ISR photon falls within the detector acceptance are selected by demanding an angle between the J/ψ candidate and the ISR photon in the c.m. frame larger than 3.12 (3.10) rad for the charged (neutral) mode. In the opposite case, the square of the mass recoiling against the J/ψ is required to lie between -2.0 (-2.0) and 2.0 GeV^2/c^4 (5.0 GeV^2/c^4) for $J/\psi \to \gamma K^+K^-(K_S^0K_S^0)$ candidates. In both cases, no additional photons with energy exceeding 300 MeV can be present. For the charged mode, the cosine of the polar angle of the photon emitted by the J/ψ is required to be less than 0.8, and, for events where the ISR photon is undetected, that of each kaon must be less than 0.9. The distribution of the recoiling mass squared after applying all other cuts is displayed in Fig. 1 for combinations having a mass in the range $2.8 < m_{\gamma KK} < 3.4$ GeV/c^2. Clear peaks corresponding to ISR events are visible.

The resulting γK^+K^- and $\gamma K_S^0K_S^0$ mass distributions are displayed in Fig. 2. A large J/ψ signal over a smooth background is observed for both channels. This background, hereafter referred to as inclusive, arises mainly

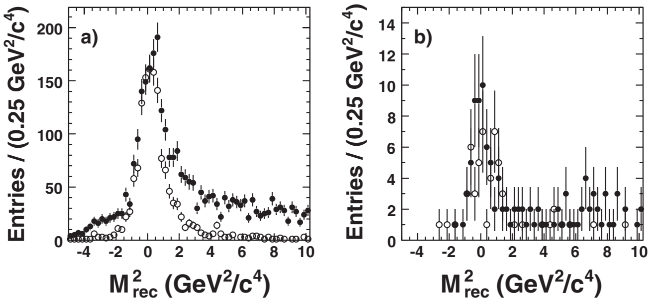

FIG. 1. The distribution of $M^2_{\rm rec}$, the square of the recoiling mass against the $J/\psi \rightarrow \gamma K^+K^-$ (a) and $J/\psi \rightarrow \gamma K^0_S K^0_S$ (b) candidates, after all other selection criteria are applied for events in which the ISR photon is detected (open circle) or undetected (solid circle).

from partially reconstructed $J/\psi \rightarrow KK + X$ decays and $e^+e^- \rightarrow q\bar{q}\gamma_{\rm ISR}$ ($q = u, d, s, c$) production. Its level in the J/ψ region is determined by fitting the data with a Gaussian and a second- (first-)order polynomial for the charged (neutral) mode. The J/ψ candidates are then fitted, constraining their mass to the world-average value [19] and requiring a common vertex for the decay products. A mass constraint on both K^0_S candidates is also imposed for the neutral channel. Combinations having a fit probability larger than 0.01 are retained to form the final sample. The corresponding inclusive background is evaluated by correcting the values extrapolated from the unconstrained mass spectra for the efficiency of the fit probability cut.

The fitted K^+K^- and $K^0_S K^0_S$ mass spectra are shown in Fig. 3, together with the contribution of various J/ψ decays and the inclusive background. The shape of the inclusive background is modeled by using sideband data taken from the unconstrained mass spectra in the ranges $2.7 < m_{\gamma KK} < 2.9$ and $3.2 < m_{\gamma KK} < 3.4$ GeV$/c^2$. The contributions of the $J/\psi \rightarrow \gamma f'_2(1525)$, $J/\psi \rightarrow \gamma f_0(1710)$, and $J/\psi \rightarrow K^{*\pm}K^{\mp}$ channels are estimated from MC simulation by using world-average branching fractions [19]. Contamination from $J/\psi \rightarrow K^{*\pm}K^{\mp}$ decays is found to be negligible. The $f'_2(1525) \rightarrow K^+K^-$ and $f'_2(1525) \rightarrow K^0_S K^0_S$ decays are modeled by using helicity amplitude ratios $x^2 = 1.0$ and $y^2 = 0.44$ [22]. No interference between the $f_0(1710)$ and the inclusive background is considered. The sum of these components accounts for most of the data in the region below 2 GeV$/c^2$ and reproduces well the contribution of $\phi(1020)$ mesons. The excess seen around 1.25–1.30 GeV$/c^2$ in the charged mode is likely due to $J/\psi \rightarrow \rho^0\pi^0$, $\rho^0 \rightarrow \pi^+\pi^-$ decays, where both charged pions are misidentified as kaons, and a photon from the π^0 decay goes undetected. The data above 2 GeV$/c^2$ are dominated by partially reconstructed J/ψ decays.

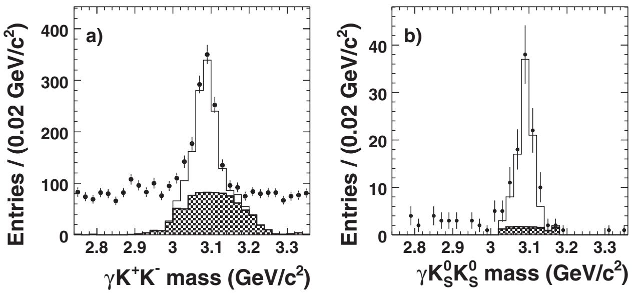

FIG. 2. The γK^+K^- (a) and $\gamma K^0_S K^0_S$ (b) mass spectra after all selection criteria are applied. The points represent data, and the plain histograms show combinations having fit probability larger than 0.01. The estimated inclusive background in the final sample is shown as a filled histogram.

The number of signal events is determined by using an unbinned maximum likelihood fit in the range $1.9\ {\rm GeV}/c^2 < m_{KK} < 2.6\ {\rm GeV}/c^2$. The signal is described by a Breit-Wigner distribution convolved with a Gaussian resolution function, while the background is modeled by a second-order Chebychev polynomial. The mass and width of the resonance are fixed to 2.231 GeV$/c^2$ and 23 MeV, respectively. The Gaussian resolution, taken from MC simulations, is set to 8 MeV$/c^2$ (6 MeV$/c^2$) for the K^+K^- ($K^0_S K^0_S$) channel. We have checked on a number of independent control samples that the two-body invariant mass resolution is well reproduced by the MC simulation

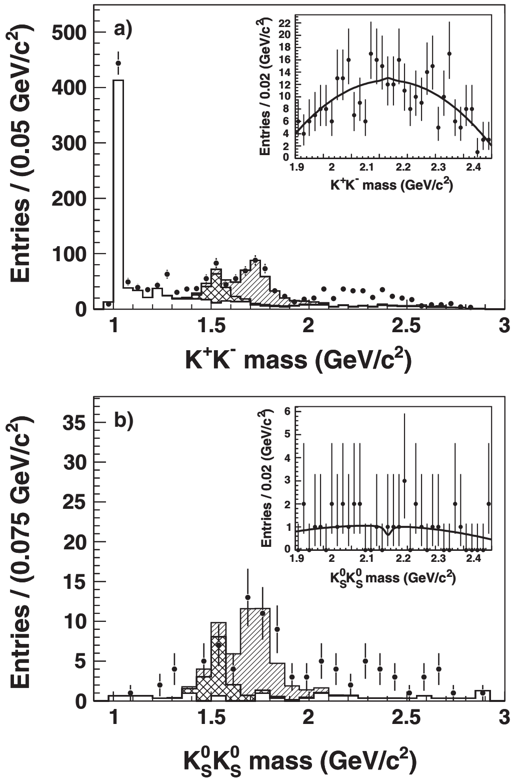

FIG. 3. The fitted K^+K^- (a) and $K^0_S K^0_S$ (b) mass spectra. The expected contributions of the inclusive background (plain histogram), $J/\psi \rightarrow \gamma f'_2(1525)$ (cross-hatched histogram), and $J/\psi \rightarrow \gamma f_0(1710)$ (hatched histogram) are also shown. The results of the fits are displayed in the insets.

TABLE I. The efficiency, the PBF of the decays $J/\psi \rightarrow \gamma f_J(2220)$, $f_J(2220) \rightarrow K^+K^-$ and $J/\psi \rightarrow \gamma f_J(2220)$, $f_J(2220) \rightarrow K^0_S K^0_S$, and corresponding 90% confidence level upper limit (U.L.) as a function of the spin J and helicity h assumed for the $f_J(2220)$. The number of $f_J(2220) \rightarrow K^+K^-(K^0_S K^0_S)$ events determined from the fit is $1.0^{+8.9}_{-7.9} \pm 1.5$ $(-0.8^{+2.1}_{-1.2} \pm 0.6)$. The first uncertainty is statistical and the second systematic.

Spin/helicity hypothesis	Efficiency (%)	PBF ($\times 10^{-5}$)	U.L. ($\times 10^{-5}$)
$f_J(2220) \rightarrow K^+K^-$			
$J = 0$	5.15 ± 0.03	$0.12^{+1.05}_{-0.94} \pm 0.17$	<1.9
$J = 2/h = 0$	2.74 ± 0.04	$0.22^{+1.97}_{-1.76} \pm 0.33$	<3.6
$J = 2/h = \pm 1$	5.22 ± 0.05	$0.12^{+1.03}_{-0.93} \pm 0.17$	<1.9
$J = 2/h = \pm 2$	6.69 ± 0.05	$0.09^{+0.81}_{-0.72} \pm 0.13$	<1.5
$f_J(2220) \rightarrow K^0_S K^0_S$			
$J = 0$	1.32 ± 0.01	$-0.39^{+0.96}_{-0.56} \pm 0.28$	<1.7
$J = 2/h = 0$	0.74 ± 0.01	$-0.69^{+1.71}_{-1.00} \pm 0.49$	<2.9
$J = 2/h = \pm 1$	1.39 ± 0.02	$-0.37^{+0.92}_{-0.54} \pm 0.26$	<1.6
$J = 2/h = \pm 2$	1.75 ± 0.02	$-0.29^{+0.73}_{-0.42} \pm 0.21$	<1.2

over the whole invariant mass range studied in this Letter. The results of the fits are displayed in Fig. 3. No evidence of a $f_J(2220)$ signal is observed.

The largest sources of systematic uncertainty arise from the parametrization of the signal and background shapes. An uncertainty of 0.2 events arises from fixing the mass, width, and resolution of the signal in each channel. This contribution is estimated by varying each parameter by $\pm 1\sigma$ in the fitting procedure. Similarly, the uncertainty due to the background parametrization, evaluated to be 1.4 (0.6) events for the K^+K^- $(K^0_S K^0_S)$ mode, is assessed by repeating the fit with a third-order Chebychev polynomial. Multiplicative systematic uncertainties on the charged (neutral) PBF include the selection procedure [4.0% (2.2%)], the determination of the number of J/ψ mesons [3.0% (3.0%)], the trigger efficiencies [3.1% (3.5%)], the track and neutral cluster reconstruction [1.9% (3.3%)], the particle identification [1.4% (-)], and the MC statistics [1.0% (1.4%)].

The $J/\psi \rightarrow \gamma f_J(2220)$, $f_J(2220) \rightarrow K^+K^-$ and $J/\psi \rightarrow \gamma f_J(2220)$, $f_J(2220) \rightarrow K^0_S K^0_S$ PBFs are given in Table I as a function of the spin and helicity assumed for the $f_J(2220)$. The efficiencies are determined from the corresponding MC simulation and include the $K^0_S \rightarrow \pi^+\pi^-$ branching fraction as well as corrections for particle identification, photon detection, and K^0_S reconstruction. The 90% confidence level (C.L.) Bayesian upper limits, based on priors uniform in branching fraction and including systematic uncertainties, are also shown.

In conclusion, no evidence is observed for the $f_J(2220)$ in radiative J/ψ decay in ISR events produced in e^+e^- collisions at $\sqrt{s} = m_{\Upsilon(4S)}$. For all hypotheses of spin and helicity, the 90% C.L. upper limits on the $J/\psi \rightarrow \gamma f_J(2220)$, $f_J(2220) \rightarrow K^+K^-$ and $J/\psi \rightarrow \gamma f_J(2220)$, $f_J(2220) \rightarrow K^0_S K^0_S$ PBFs are below the central values reported by Mark III. Only one hypothesis of spin and helicity ($J = 2$ and $h = 0$) is compatible with the BES results for both final states, while all other possibilities are clearly excluded.

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