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Observation of $\eta_c(1S)$ and $\eta_c(2S)$ decays to $K^+K^-\pi^+\pi^-\pi^0$ in two-photon interactions

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We study the processes $\gamma\gamma \to K_S^0 K^\pm \pi^\mp$ and $\gamma\gamma \to K^+K^-\pi^+\pi^-\pi^0$ using a data sample of 519.2fb^{-1} recorded by the *BABAR* detector at the PEP-II asymmetric-energy e^+e^- collider at center-of-mass energies near the $\Upsilon(nS)$ ($n = 2, 3, 4$) resonances. We observe the $\eta_c(1S)$, $\chi_{c0}(1P)$ and $\eta_c(2S)$ resonances produced in two-photon interactions and decaying to $K^+K^-\pi^+\pi^-\pi^0$, with significances of 18.1, 5.4 and 5.3 standard deviations (including systematic errors), respectively, and report 4.0σ evidence of the

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$\chi_{c2}(1P)$ decay to this final state. We measure the $\eta_c(2S)$ mass and width in $K_S^0 K^\pm \pi^\mp$ decays, and obtain the values $m(\eta_c(2S)) = 3638.5 \pm 1.5 \pm 0.8$ MeV$/c^2$ and $\Gamma(\eta_c(2S)) = 13.4 \pm 4.6 \pm 3.2$ MeV, where the first uncertainty is statistical and the second is systematic. We measure the two-photon width times branching fraction for the reported resonance signals, and search for the $\chi_{c2}(2P)$ resonance, but no significant signal is observed.

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The first radial excitation $\eta_c(2S)$ of the $\eta_c(1S)$ charmonium ground state was observed at B-factories [1–4]. The only observed exclusive decay of this state to date is to $K\bar{K}\pi$ [5]. Decays to $p\bar{p}$ and $h^+h^-h'^+h'^-$, with $h^{(\prime)} = K$, π, have been observed for the $\eta_c(1S)$ [5], but not for the $\eta_c(2S)$ [6,7]. Precise determination of the $\eta_c(2S)$ mass may discriminate among models that predict the $\psi(2S)$-$\eta_c(2S)$ mass splitting [8].

After the discovery of the $X(3872)$ state [9] and its confirmation by different experiments [10], charmonium spectroscopy above the open-charm threshold received renewed attention. Many new states have been established to date [11–13]. The $Z(3930)$ resonance was discovered by Belle in the $\gamma\gamma \to D\bar{D}$ process [12] and subsequently confirmed by *BABAR* [13]. Its interpretation as the $\chi_{c2}(2P)$, the first radial excitation of the $^3P_2$ charmonium ground state, is commonly accepted [5].

In this paper we study charmonium resonances produced in the two-photon process $e^+e^- \to \gamma\gamma e^+e^- \to f e^+e^-$, where f denotes the $K_S^0 K^\pm \pi^\mp$ or $K^+K^-\pi^+\pi^-\pi^0$ final state. Two-photon events where the interacting photons are not quasi-real are strongly suppressed by the selection criteria described below. This implies that the allowed J^{PC} values of the initial state are $0^{\pm+}, 2^{\pm+}, 4^{\pm+}, \ldots$; $3^{++}, 5^{++}, \ldots$ [14]. Angular momentum conservation, parity conservation, and charge conjugation invariance then imply that these quantum numbers apply to the final states f also, except that the $K_S^0 K^\pm \pi^\mp$ state cannot have $J^P = 0^+$.

The results presented here are based on data collected with the *BABAR* detector at the PEP-II asymmetric-energy e^+e^- collider, corresponding to an integrated luminosity of 519.2 fb^{-1}, recorded at center-of-mass (CM) energies near the $\Upsilon(nS)$ ($n = 2, 3, 4$) resonances.

The *BABAR* detector is described in detail elsewhere [15]. Charged-particles resulting from the interaction are detected, and their momenta are measured, by a combination of five layers of double-sided silicon microstrip detectors and a 40-layer drift chamber. Both systems operate in the 1.5 T magnetic field of a superconducting solenoid. Photons and electrons are identified in a CsI(Tl) crystal electromagnetic calorimeter. Charged-particle identification (PID) is provided by the specific energy loss ($\mathrm{d}E/\mathrm{d}x$) in the tracking devices, and by an internally reflecting, ring-imaging Cherenkov detector. Samples of Monte Carlo (MC) simulated events [16], which are more than 10 times larger than the corresponding data samples, are used to study signals and backgrounds. Two-photon events are generated using the GamGam generator [13].

Neutral pions and kaons are reconstructed through the decays $\pi^0 \to \gamma\gamma$ and $K_S^0 \to \pi^+\pi^-$. Photons from π^0 decays are required to have laboratory energy larger than 30 MeV. We require the invariant mass of a π^0 (K_S^0) candidate to be in the range [100–160] ([470–520]) MeV$/c^2$. Neutral pions reconstructed with these criteria are used to veto events with multiple π^0 mesons, as described below. For the $K^+K^-\pi^+\pi^-\pi^0$ mode, we refine the selection of the π^0 by requiring the laboratory energy of the lower-energy photon from the signal π^0 decay to be larger than 50 MeV. Furthermore, we require $|\cos\mathcal{H}_{\pi^0}| < 0.95$, where $\mathcal{H}_{\pi^0}$ is the angle between the signal π^0 flight direction in the laboratory frame and the direction of one of its daughters in the π^0 rest frame. These requirements are optimized by maximizing $S/\sqrt{S+B}$, where S is the number of MC signal events with a well-reconstructed π^0, and B is the combinatorial background in the signal region. Primary charged-particle tracks are required to satisfy PID requirements consistent with a kaon or pion hypothesis. A candidate event is constructed by fitting the π^0 (K_S^0) candidate and four (two) charged-particle tracks of zero net charge coming from the interaction region to a common vertex. In this fit the π^0 and K_S^0 masses are constrained to their nominal values [5]. We require the vertex fit probability of the charmonium candidate to be larger than 0.1%. The outgoing $e^\pm$ are not detected.

Background arises mainly from random combinations of particles from e^+e^- annihilation, other two-photon collisions, and initial state radiation (ISR) processes. To suppress these backgrounds, we require that each event have exactly four charged-particle tracks. The candidate event is rejected if the number of additional reconstructed photons is larger than 6 (5) for $K^+K^-\pi^+\pi^-\pi^0$ ($K_S^0 K^\pm \pi^\mp$). Similarly, the event is rejected if the number of additional reconstructed π^0's is larger than 1 (3) for a $K^+K^-\pi^+\pi^-\pi^0$ ($K_S^0 K^\pm \pi^\mp$) candidate event. We discriminate against ISR background by requiring $M^2_{\mathrm{miss}} = (p_{e^+e^-} - p_{\mathrm{rec}})^2 > 2(\mathrm{GeV}/c^2)^2$, where $p_{e^+e^-}$ (p_{rec}) is the four momentum of the initial state (reconstructed final state). The effect of this requirement on the signal efficiency is studied using a $K^+K^-\pi^+\pi^-$ control sample that contains large $\eta_c(1S)$, J/ψ, and $\chi_{c0,2}(1P)$ signals. Two-photon events are expected to have low transverse momentum (p_T) with respect to the collision axis. In Fig. 1, we show the p_T distribution for selected candidates with the

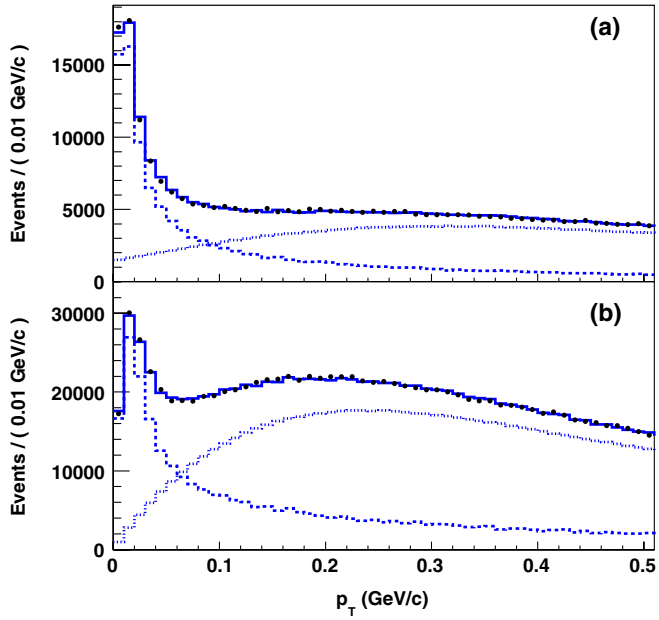

FIG. 1 (color online). The p_T distributions for selected (a) $K_S^0 K^\pm \pi^\mp$ and (b) $K^+K^-\pi^+\pi^-\pi^0$ candidates (data points). The solid histogram represent the result of a fit to the sum of the simulated signal (dashed) and background (dotted) contributions.

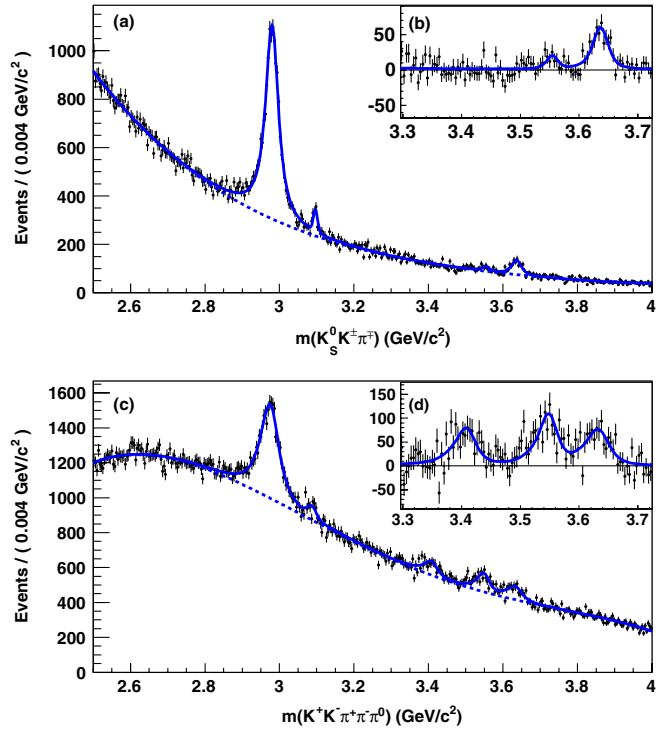

FIG. 2 (color online). Fit to (a) the $K_S^0 K^\pm \pi^\mp$ and (c) the $K^+K^-\pi^+\pi^-\pi^0$ mass spectrum. The solid curves represent the total fit functions and the dashed curves show the combinatorial background contributions. The background-subtracted distributions are shown in (b) and (d), where the solid curves indicate the signal components.

above requirements. The distribution is fitted with the signal p_T shape obtained from MC simulation plus a combinatorial background component, modeled using a sixth-order polynomial function. We require $p_T < 0.15$ GeV/c.

The average number of surviving candidates per selected event is 1.003 (1.09) for the $K_S^0 K^\pm \pi^\mp$ ($K^+K^-\pi^+\pi^-\pi^0$) final state. Candidates that are rejected by a possible best-candidate selection do not lead to any peaking structures in the mass spectra, and so no best-candidate selection is performed. The $K_S^0 K^+\pi^-$ and $K^+K^-\pi^+\pi^-\pi^0$ mass spectra are shown in Fig. 2. We observe prominent peaks at the position of the $\eta_c(1S)$ resonance. We also observe signals at the positions of the J/ψ, $\chi_{c0}(1P)$, $\chi_{c2}(1P)$, and $\eta_c(2S)$ states.

The resonance signal yields and the mass and width of the $\eta_c(1S)$ and $\eta_c(2S)$ are extracted using a binned, extended maximum likelihood fit to the invariant mass distributions. The bin width is 4 MeV/c^2. In the likelihood function, several components are present: $\eta_c(1S)$, $\chi_{c0}(1P)$, $\chi_{c2}(1P)$, and $\eta_c(2S)$ signal, combinatorial background, and J/ψ ISR background. The $\chi_{c0}(1P)$ component is not present in the fit to the $K_S^0 K^\pm \pi^\mp$ invariant mass spectrum, since $J^P = 0^+$ is forbidden for this final state.

We parametrize each signal PDF as a convolution of a nonrelativistic Breit-Wigner and the detector resolution function. The J/ψ ISR background is parametrized with a Gaussian shape, and the combinatorial background PDF is a fourth-order polynomial. The free parameters of the fit are the yields of the resonances and the background, the peak masses and widths of the $\eta_c(1S)$ and $\eta_c(2S)$ signals, the width of the Gaussian describing the J/ψ ISR background, and the background shape parameters. The mass and width of the $\chi_{c0,2}(1P)$ states (and the mass of the J/ψ in the $K_S^0 K^\pm \pi^\mp$ channel), are fixed to their nominal values [5]. For the $K^+K^-\pi^+\pi^-\pi^0$ channel, the $\eta_c(2S)$ width is fixed to the value found in the $K_S^0 K^\pm \pi^\mp$ channel.

We define a MC event as "MC-Truth" (MCT) if the reconstructed decay chain matches the generated one. We use MCT signal and MCT ISR-background events to determine the detector mass resolution function. This function is described by the sum of a Gaussian plus power-law tails [17]. The width of the resolution function at half-maximum for the $\eta_c(1S)$ is 8.1(11.8) MeV/c^2 in the $K_S^0 K^\pm \pi^\mp$ ($K^+K^-\pi^+\pi^-\pi^0$) decay mode. For the $\eta_c(2S)$ decay it is 10.6(13.1) MeV/c^2 in the $K_S^0 K^\pm \pi^\mp$ ($K^+K^-\pi^+\pi^-\pi^0$) decay mode. The parameter values for the resolution functions are fixed to their MC values in the fit.

Fit results are reported in Table I and shown in Fig. 2. We correct the fitted $\eta_c(1S)$ yields by subtracting the number of peaking-background events originating from the J/ψ decay, estimated below. The statistical significances of the signal yields are computed from the ratio of the number of observed events to the sum in quadrature of the statistical and systematic uncertainties. The χ^2/ndf of the fit is

TABLE I. Extraction of event yields and mass and width of the $\eta_c(1S)$ and $\eta_c(2S)$ resonances: average signal efficiency for phase-space MCT events, corrected signal yield with statistical and systematic uncertainties, number of peaking-background events estimated with the p_T fit ($N_{\rm peak}$), number of peaking-background events from J/ψ and $\psi(2S)$ radiative decays (N_ψ), significance (including the systematic uncertainty), corrected mass, and fitted width for each decay mode. We do not report N_ψ for modes where it is negligible.

Decay Mode	Efficiency (%)	Corrected Yield (Evts.)	$N_{\rm peak}$ (Evts.)	N_ψ (Evts.)	Significance (σ)	Corrected Mass (MeV/c^2)	Fitted Width (MeV)
$\eta_c(1S) \to K_S^0 K^\pm \pi^\mp$	10.7	$12096 \pm 235 \pm 274$	189 ± 18	214 ± 82	33.5	$2982.5 \pm 0.4 \pm 1.4$	$32.1 \pm 1.1 \pm 1.3$
$\chi_{c2}(1P) \to K_S^0 K^\pm \pi^\mp$	13.1	$126 \pm 37 \pm 14$	-45 ± 11	–	3.2	3556.2 (fixed)	2 (fixed)
$\eta_c(2S) \to K_S^0 K^\pm \pi^\mp$	13.3	$624 \pm 72 \pm 34$	25 ± 5	–	7.8	$3638.5 \pm 1.5 \pm 0.8$	$13.4 \pm 4.6 \pm 3.2$
$\eta_c(1S) \to K^+K^-\pi^+\pi^-\pi^0$	4.2	$11132 \pm 430 \pm 442$	118 ± 32	26 ± 9	18.1	$2984.5 \pm 0.8 \pm 3.1$	$36.2 \pm 2.8 \pm 3.0$
$\chi_{c0}(1P) \to K^+K^-\pi^+\pi^-\pi^0$	5.6	$1094 \pm 143 \pm 143$	-39 ± 19	75 ± 21	5.4	3415.8 (fixed)	10.2 (fixed)
$\chi_{c2}(1P) \to K^+K^-\pi^+\pi^-\pi^0$	5.8	$1250 \pm 118 \pm 290$	14 ± 24	233 ± 73	4.0	3556.2 (fixed)	2 (fixed)
$\eta_c(2S) \to K^+K^-\pi^+\pi^-\pi^0$	5.9	$1201 \pm 133 \pm 185$	-46 ± 17	–	5.3	$3640.5 \pm 3.2 \pm 2.5$	13.4 (fixed)

1.07 (1.03), where ndf is the number of degrees of freedom, which is 361 (360) for the fit to $K_S^0 K^\pm \pi^\mp$ ($K^+K^-\pi^+\pi^-\pi^0$).

To search for the $\chi_{c2}(2P)$, we add to the fit described above a signal component with the mass and width fixed to the values reported in Ref. [13]. No significant changes are observed in the fit results.

Several processes, including ISR, continuum e^+e^- annihilation, and two-photon events with a final state different from the one studied, may produce irreducible-peaking-background events, containing real $\eta_c(1S)$, $\eta_c(2S)$, $\chi_{c0}(1P)$ or $\chi_{c2}(1P)$. Well-reconstructed signal and J/ψ ISR background are expected to peak at $p_T \sim 0$ MeV/c. Final states with similar masses are expected to have similar p_T distributions. Non-ISR background events mainly originate from events with a number of particles in the final state larger than the one in signal events. Such extra particles are lost in the reconstruction. Thus, non-ISR background events are expected to have a nearly flat p_T distribution, as observed in MC simulation. To estimate the number of such events, we fit the invariant mass distribution in intervals of p_T, thus obtaining the signal yield for each resonance as a function of p_T. The signal yield distribution is then fitted using the signal p_T shape from MCT events plus a flat background. The yield of peaking-background events originating from ψ radiative decays ($\psi = J/\psi$, $\psi(2S)$) is estimated using the number of ψ events fitted in data, and the knowledge of branching fractions [5] and MC reconstruction efficiencies for the different decays involved. The number of peaking-background events for each resonance is reported in Table I. The value of $\mathcal{B}(\chi_{c0,2} \to K^+K^-\pi^+\pi^-\pi^0)$, which is needed to estimate the number of peaking-background events from $\psi(2S) \to \gamma\chi_{c0,2}(1P)$ decays, is obtained using the results reported in this paper and the world-average values of $\Gamma_{\gamma\gamma}(\chi_{c0,2})$ [5]. We obtain $\mathcal{B}(\chi_{c0}(1P) \to K^+K^-\pi^+\pi^-\pi^0) = (1.14 \pm 0.27)\%$, and $\mathcal{B}(\chi_{c2}(1P) \to K^+K^-\pi^+\pi^-\pi^0) = (1.30 \pm 0.36)\%$, where statistical and systematic errors have been summed in quadrature. The value of $\mathcal{B}(\chi_{c2}(1P) \to K^+K^-\pi^+\pi^-\pi^0)$ is in agreement with a preliminary result reported by CLEO [19]. The number of peaking background events from $\psi(2S)$ radiative decays for $\eta_c(2S)$ and $\chi_{c2}(1P) \to K_S^0 K^\pm \pi^\mp$ (denoted by "–" in Table I) is negligible.

The ratios of the branching fractions of the two modes are obtained from

$$\frac{\mathcal{B}(\eta_c(nS) \to K^+K^-\pi^+\pi^-\pi^0)}{\mathcal{B}(\eta_c(nS) \to K_S^0 K^\pm \pi^\mp)} = \frac{N_{KK3\pi}^{\eta_c(nS)}}{N_{K_S^0 K\pi}^{\eta_c(nS)}} \cdot \frac{\epsilon_{K_S^0 K\pi}^{\eta_c(nS)}}{\epsilon_{KK3\pi}^{\eta_c(nS)}}, \qquad (1)$$

where $\eta_c(nS)$ denotes $\eta_c(1S)$, $\eta_c(2S)$; $N_{KK3\pi}^{\eta_c(nS)}$ and $N_{K_S^0 K\pi}^{\eta_c(nS)}$ ($\epsilon_{KK3\pi}^{\eta_c(nS)}$ and $\epsilon_{K_S^0 K\pi}^{\eta_c(nS)}$) represent the peaking-background-subtracted $\eta_c(nS)$ yield (the efficiency) for the $K^+K^-\pi^+\pi^-\pi^0$ and $K_S^0 K^\pm \pi^\mp$ channels, respectively. The efficiencies are parametrized using MCT events. The $K_S^0 K^\pm \pi^\mp$ efficiency is parametrized as a two-dimensional histogram of the invariant $K\pi$ mass versus the angle between the direction of the K^+ in the $K\pi$ rest frame and that of the $K\pi$ system in the $K_S^0 K^\pm \pi^\mp$ reference frame. The $K^+K^-\pi^+\pi^-\pi^0$ efficiency is parametrized as a function of the K^+K^-, $\pi^+\pi^-$, and $\pi^+\pi^-\pi^0$ (3π) masses, and the five angular variables, $\cos\theta_K$, $\cos\Theta$, Φ, $\cos\theta_{\pi\pi}$, and θ_π, as defined in Fig. 3; θ_K is the angle between the K^+ and the 3π recoil direction in the K^+K^- rest frame. The angles Θ and Φ describe the orientation of the normal $\hat{n}$ to the 3π decay plane with respect to the K^+K^- recoil direction in the 3π rest frame; θ_π is the angle describing a rotation of the 3π system about its decay plane normal; $\theta_{\pi\pi}$ is the angle between the π^+ and π^- directions in the 3π reference frame. The correlations between $\cos\theta_K$, Θ, Φ, and θ_π and the invariant masses are negligible. The correlation between $\cos\theta_{\pi\pi}$ and $m_{\pi\pi}$ is -0.70 and is not considered in the efficiency parametrization. Neglecting such a correlation introduces a change in the efficiency of 1.4% (1.1%) for the $\eta_c(1S)$ ($\eta_c(2S)$), which is taken as a systematic uncertainty. The efficiency dependence on $\cos\theta_K$, $\cos\theta_{\pi\pi}$, and Φ ($\cos\Theta$ and θ_π) is parametrized using uncorrelated fourth (second)-order polynomial shapes. A three-dimensional histogram is

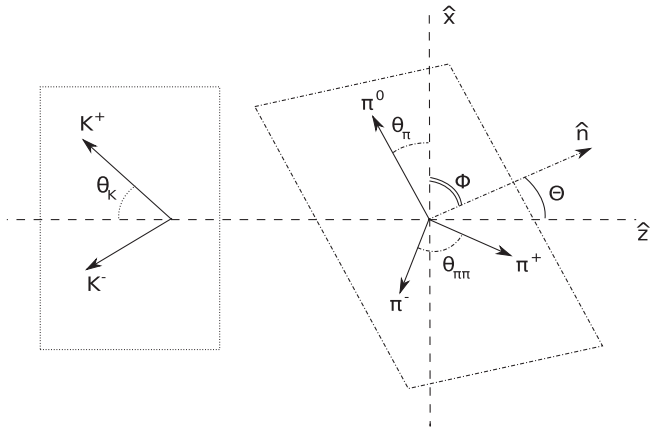

FIG. 3. Angles used to describe the $K^+K^-\pi^+\pi^-\pi^0$ decay kinematics.

used to parametrize the dependence on the invariant masses. The efficiency is calculated as the ratio of the number of MCT events surviving the selection to the number of generated events in each bin, in both channels. We assign null efficiency to bins with less than 10 reconstructed events. The fraction of data falling in these bins is 0.5% (3.0%) in the $K_S^0K^\pm\pi^\mp$ ($K^+K^-\pi^+\pi^-\pi^0$) channel. We assign a systematic uncertainty to cover this effect. The average efficiency $\bar{\epsilon}$ for each decay, computed using flat phase-space simulation, is reported in Table I.

The ratio N_f^η/ϵ_f^η of Eq. (1) is equal to $N_f^\eta/(\epsilon_f^{*\eta}\times\bar{\epsilon}_f^\eta)$, where we have defined $\epsilon_f^{*\eta}=\epsilon_f^\eta/\bar{\epsilon}_f^\eta$. The value of $N_f^\eta/\epsilon_f^{*\eta}$ is extracted from an unbinned maximum likelihood fit to the $K_S^0K^\pm\pi^\mp$ and $K^+K^-\pi^+\pi^-\pi^0$ invariant mass distributions, where each event is weighted by the inverse of $\epsilon_f^{*\eta}$. We use $\epsilon_f^{*\eta}$ instead of ϵ_f^η to weight the events since weights far from one might result in incorrect errors for the signal yield obtained in the maximum likelihood fit [20]. Since the kinematics of peaking-background events are similar to those of the signal, we assume the signal to peaking-background ratio to be unaffected by the weighting technique. The fit is performed independently in the $\eta_c(1S)$ ([2.5, 3.3] MeV/c^2) and $\eta_c(2S)$ ([3.2, 3.9] MeV/c^2) mass regions. The mass and width for each signal PDF are fixed to the values reported in Table I. The free parameters of the fit are the yields of the background and the signal resonances, the mean and the width of the Gaussian describing the J/ψ background, and the background shape parameters. We compute a χ^2 using the total fit function and the binned $K_S^0K^\pm\pi^\mp$ ($K^+K^-\pi^+\pi^-\pi^0$) mass distribution obtained after weighting. The values of χ^2/ndf are 1.16 (1.15) and 1.20 (1.00) in the $\eta_c(1S)$ and $\eta_c(2S)$ mass regions, in the $K_S^0K^\pm\pi^\mp$ ($K^+K^-\pi^+\pi^-\pi^0$) channel.

Several sources contribute to systematic uncertainties on the resonance yields and parameters. Systematic uncertainties due to PDF parametrization and fixed parameters in the fit are estimated to be the sum in quadrature of the changes observed when repeating the fit after varying the fixed parameters by ± 1 standard deviation (σ). The uncertainty associated with the peaking background is taken to be $\sqrt{(\max[0, N_{\rm peak}])^2+\sigma^2_{N_{\rm peak}}}$, where $N_{\rm peak}$ is the estimated number of peaking-background events reported in Table I, and $\sigma_{N_{\rm peak}}$ is its uncertainty. The systematic errors on the $\chi_{c0,2}(1P)$ yields are taken to be $\sqrt{(\max[0, N_{\rm peak}])^2+\sigma^2_{N_{\rm peak}}+N^2_\psi+\sigma^2_{N_\psi}}$, where N_ψ is the number of peaking-background events from the $\psi(2S)\to\gamma\chi_{c0,2}(1P)$ processes. The uncertainty on $N_{\rm peak}$ due to differences in signal and ISR background p_T distribution is estimated by adding an ISR background component to the fit to the p_T yield distribution described above. The ISR background p_T shape is taken from MC simulation and its yield is fixed to N_ψ. This uncertainty is found to be negligible. We take the systematic error due to the $J/\psi\to\gamma\eta_c(1S)$ peaking-background subtraction to be the uncertainty on the estimated number of events originating from this process. We assign an uncertainty due to the background shape, taking the changes in results observed when using a sixth-order polynomial as the background PDF in the fit.

An ISR-enriched sample is obtained by reversing the $M^2_{\rm miss}$ selection criterion. The ISR-enriched sample is fitted to obtain the shift ΔM between the measured and the nominal J/ψ mass [5], and the difference in mass resolution between MC and data. The corrected masses in Table I are $m^{\rm corr}=m^{\rm fit}-\Delta M$, where $m^{\rm fit}$ is the mass determined by the fit. The mass shift is -0.5 ± 0.2 MeV/c^2 in $K_S^0K^\pm\pi^\mp$ and -1.1 ± 0.8 MeV/c^2 in $K^+K^-\pi^+\pi^-\pi^0$. We assign the statistical error on ΔM as a systematic uncertainty on $m^{\rm corr}$. The difference in mass resolution is $(24\pm 5)\%$ in $K_S^0K^\pm\pi^\mp$ and $(9\pm 5)\%$ in $K^+K^-\pi^+\pi^-\pi^0$. We take the difference in fit results observed when including this correction in the $\eta_c(1S)$, $\chi_{c0}(1P)$, $\chi_{c2}(1P)$, and $\eta_c(2S)$ resolution functions as the systematic uncertainty due to the mass-resolution difference between data and MC. A systematic uncertainty on the mass accounts for the different kinematics of two-photon signal and ISR J/ψ events.

The distortion of the resolution function due to differences between the invariant mass distributions of the decay products in data and MC produces negligible changes in the results. We take as systematic uncertainty the changes in the resonance parameters observed by including in the fit the effect of the efficiency dependence on the invariant mass and on the decay dynamics. The effect of the interference of the $\eta_c(1S)$ signal with a possible $J^{PC}=0^{-+}$ contribution in the $\gamma\gamma$ background is considered. We model the mass distribution of the $J^{PC}=0^{-+}$ background component with the PDF describing combinatorial background. The changes in the fitted signal yields are negligible. The changes of the values of the $\eta_c(1S)$ mass and width with respect to the nominal results are

$+1.2\ \mathrm{MeV}/c^2$ and $+0.2$ MeV for $K_S^0 K^\pm \pi^\mp$, and $+2.9\ \mathrm{MeV}/c^2$ and $+0.6$ MeV for $K^+K^-\pi^+\pi^-\pi^0$. We take these changes as estimates of the systematic uncertainty due to interference. The effect of the interference on the $\eta_c(2S)$ parameter values cannot be determined due to the small signal to background ratio and the smallness of the signal sample. We therefore do not include any systematic uncertainty due to this effect for the $\eta_c(2S)$.

Systematic uncertainties on the efficiency due to tracking (0.2% per track), K_S^0 reconstruction (1.7%), π^0 reconstruction (3.0%) and PID (0.5% per track) are obtained from auxiliary studies. The statistical uncertainty of the efficiency parametrization is estimated with simulated parametrized experiments. In each experiment, the efficiency in each histogram bin and the coefficients of the functions describing the dependence on $\cos\theta_K$, $\cos\theta_{\pi\pi}$, $\cos\Theta$, θ_π and Φ are varied within their statistical uncertainties. We take as systematic uncertainty the width of the resulting yield distribution. The fit bias is negligible. The small impact of the presence of events falling in bins with zero efficiency is accounted for as an additional systematic uncertainty.

Using the efficiency-weighted yields of the $\eta_c(1S)$ and $\eta_c(2S)$ resonances, the number of peaking-background events, and $\mathcal{B}(K_S^0 \to \pi^+\pi^-) = (69.20 \pm 0.05)\%$ [5], we find the branching fraction ratios

$$\frac{\mathcal{B}(\eta_c(1S) \to K^+K^-\pi^+\pi^-\pi^0)}{\mathcal{B}(\eta_c(1S) \to K_S^0 K^\pm \pi^\mp)} = 1.43 \pm 0.05 \pm 0.21, \quad (2)$$

$$\frac{\mathcal{B}(\eta_c(2S) \to K^+K^-\pi^+\pi^-\pi^0)}{\mathcal{B}(\eta_c(2S) \to K_S^0 K^\pm \pi^\mp)} = 2.2 \pm 0.5 \pm 0.5, \quad (3)$$

where the first error is statistical and the second is systematic. The uncertainty in the efficiency parametrization is the main contribution to the systematic uncertainties and is equal to 0.17 and 0.3, in Eqs. (2) and (3), respectively. Using Eqs. (2) and (3), $\mathcal{B}(\eta_c(1S) \to K\bar{K}\pi) = (7.0 \pm 1.2)\%$ and $\mathcal{B}(\eta_c(2S) \to K\bar{K}\pi) = (1.9 \pm 1.2)\%$ [5], and isospin relations, we obtain $\mathcal{B}(\eta_c(1S) \to K^+K^-\pi^+\pi^-\pi^0) = (3.3 \pm 0.8)\%$, and $\mathcal{B}(\eta_c(2S) \to K^+K^-\pi^+\pi^-\pi^0) = (1.4 \pm 1.0)\%$, where we have summed in quadrature the statistical and systematic errors.

For each resonance and each final state, we compute the product between the two-photon coupling $\Gamma_{\gamma\gamma}$ and the resonance branching fraction $\mathcal{B}$ to the final state, using 473.8 fb^{-1} of data collected near the $\Upsilon(4S)$ energy. The efficiency-weighted yields for the resonances, and the integrated luminosity near the $\Upsilon(4S)$ energy are used to obtain $\Gamma_{\gamma\gamma} \times \mathcal{B}$ with the GamGam generator [13]. The mass and width of the resonances are fixed to the values reported in Table I. The uncertainties on the luminosity (1.1%) and on the GamGam calculation (3%) [13] are included in the systematic uncertainty of $\Gamma_{\gamma\gamma} \times \mathcal{B}$. For the $K_S^0 K^\pm \pi^\mp$ decay mode, we give the results for the isospin-related $K\bar{K}\pi$ final state, taking into account $\mathcal{B}(K_S^0 \to \pi^+\pi^-) = (69.20 \pm 0.05)\%$ [5] and isospin relations. For the $\chi_{c2}(2P)$, we compute $\Gamma_{\gamma\gamma} \times \mathcal{B}$ using the fitted $\chi_{c2}(2P)$ yield, the integrated luminosity near the $\Upsilon(4S)$ energy, and the average detection efficiency for the relevant process. The average detection efficiency is equal to 13.9% and 6.4% for the $K_S^0 K^\pm \pi^\mp$ and $K^+K^-\pi^+\pi^-\pi^0$ modes, respectively. The mass and width of the $\chi_{c2}(2P)$ resonance are fixed to the values reported in [13]. Since no significant $\chi_{c2}(2P)$ signal is observed, we determine a Bayesian upper limit (UL) at 90% confidence level (CL) on $\Gamma_{\gamma\gamma} \times \mathcal{B}$, assuming a uniform prior probability distribution. We compute the UL by finding the value of $\Gamma_{\gamma\gamma} \times \mathcal{B}$ below which lies 90% of the total of the likelihood integral in the $(\Gamma_{\gamma\gamma} \times \mathcal{B}) \geq 0$ region. Systematic uncertainties are taken into account in the UL calculation. Results for $\Gamma_{\gamma\gamma} \times \mathcal{B}$ for each resonance and final state are reported in Table II. The $\eta_c(1S) \to K\bar{K}\pi$ measurement is consistent with, but slightly more precise than, the PDG value [5]; the other entries are first measurements.

In conclusion, we report the first observation of $\eta_c(1S)$, $\chi_{c0}(1P)$ and $\eta_c(2S)$ decays to $K^+K^-\pi^+\pi^-\pi^0$, with significances (including systematic uncertainties) of 18σ, 5.4σ and 5.3σ, respectively. This is the first observation of an exclusive hadronic decay of $\eta_c(2S)$ other than $K\bar{K}\pi$. We also report the first evidence of $\chi_{c2}(1P)$ decays to $K^+K^-\pi^+\pi^-\pi^0$, with a significance (including systematic uncertainties) of 4.0σ, and have obtained first measurements of the $\chi_{c0}(1P)$ and $\chi_{c2}(1P)$ branching fractions to $K^+K^-\pi^+\pi^-\pi^0$. The measurements reported in this paper are consistent with previous *BABAR* results [3,18], and with world-average values [5]. The measurement of the $\eta_c(2S)$ mass and width in the the $K_S^0 K^\pm \pi^\mp$ decay supersedes the previous *BABAR* measurement [3]. The measurement of the $\eta_c(1S)$ mass and width in the $K_S^0 K^\pm \pi^\mp$ decay does not supersede the previous *BABAR* measurement [18]. The value of $\Gamma_{\gamma\gamma} \times \mathcal{B}$ is measured for each observed resonance for both $K\bar{K}\pi$ and $K^+K^-\pi^+\pi^-\pi^0$ decay

TABLE II. Results for $\Gamma_{\gamma\gamma} \times \mathcal{B}$ for each resonance in $K\bar{K}\pi$ and $K^+K^-\pi^+\pi^-\pi^0$ final states. The first uncertainty is statistical, the second systematic. Upper limits are computed at 90% confidence level.

Process	$\Gamma_{\gamma\gamma} \times \mathcal{B}$ (keV)
$\eta_c(1S) \to K\bar{K}\pi$	$0.386 \pm 0.008 \pm 0.021$
$\chi_{c2}(1P) \to K\bar{K}\pi$	$(1.8 \pm 0.5 \pm 0.2) \times 10^{-3}$
$\eta_c(2S) \to K\bar{K}\pi$	$0.041 \pm 0.004 \pm 0.006$
$\chi_{c2}(2P) \to K\bar{K}\pi$	$<2.1 \times 10^{-3}$
$\eta_c(1S) \to K^+K^-\pi^+\pi^-\pi^0$	$0.190 \pm 0.006 \pm 0.028$
$\chi_{c0}(1P) \to K^+K^-\pi^+\pi^-\pi^0$	$0.026 \pm 0.004 \pm 0.004$
$\chi_{c2}(1P) \to K^+K^-\pi^+\pi^-\pi^0$	$(6.5 \pm 0.9 \pm 1.5) \times 10^{-3}$
$\eta_c(2S) \to K^+K^-\pi^+\pi^-\pi^0$	$0.030 \pm 0.006 \pm 0.005$
$\chi_{c2}(2P) \to K^+K^-\pi^+\pi^-\pi^0$	$<3.4 \times 10^{-3}$

modes. We provide an UL at 90% CL on $\Gamma_{\gamma\gamma} \times \mathcal{B}$ for the $\chi_{c2}(2P)$ resonance.

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[1] S. K. Choi *et al.* (Belle Collaboration), Phys. Rev. Lett. **89**, 102001 (2002); K. Abe *et al.* (Belle Collaboration), Phys. Rev. Lett. **89**, 142001 (2002).
[2] D. M. Asner *et al.* (CLEO Collaboration), Phys. Rev. Lett. **92**, 142001 (2004).
[3] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **92**, 142002 (2004).
[4] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **96**, 052002 (2006).
[5] Particle Data Group, K. Nakamura *et al.*, J. Phys. G **37**, 075021 (2010).
[6] S. Uehara *et al.* (Belle Collaboration), Eur. Phys. J. C **53**, 1 (2008).
[7] M. Ambrogiani *et al.* (E835 Collaboration), Phys. Rev. D **64**, 052003 (2001).
[8] S. Godfrey and N. Isgur, Phys. Rev. D **32**, 189 (1985); L. P. Fulcher, Phys. Rev. D **44**, 2079 (1991); J. Zeng *et al.*, Phys. Rev. D **52**, 5229 (1995); S. N. Gupta and J. M. Johnson, Phys. Rev. D **53**, 312 (1996); D. Ebert *et al.*, Phys. Rev. D **67**, 014027 (2003); E. Eichten *et al.*, Phys. Rev. D **69**, 094019 (2004).
[9] S.-K. Choi *et al.* (Belle Collaboration), Phys. Rev. Lett. **91**, 262001 (2003).
[10] D. E. Acosta *et al.* (CDF Collaboration), Phys. Rev. Lett. **93**, 072001 (2004);V. M. Abazov *et al.* (D0 Collaboration), Phys. Rev. Lett. **93**, 162002 (2004);B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. D **71**, 071103 (2005).
[11] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **95**, 142001 (2005);T. E. Coan *et al.* (CLEO Collaboration), Phys. Rev. Lett. **96**, 162003 (2006); C. Z. Yuan *et al.* (Belle Collaboration), Phys. Rev. Lett. **99**, 182004 (2007); B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **98**, 212001 (2007); X. L. Wang *et al.* (Belle Collaboration), Phys. Rev. Lett. **99**, 142002 (2007); S.-K. Choi *et al.* (Belle Collaboration), Phys. Rev. Lett. **94**, 182002 (2005); B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **101**, 082001 (2008).
[12] S. Uehara *et al.* (Belle Collaboration), Phys. Rev. Lett. **96**, 082003 (2006).
[13] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. D **81**, 092003 (2010).
[14] C. N. Yang, Phys. Rev. **77**, 242 (1950).
[15] B. Aubert *et al.* (*BABAR* Collaboration), Nucl. Instrum. Methods Phys. Res. Sect. A, **479**, 1 (2002).
[16] The *BABAR* detector Monte Carlo simulation is based on GEANT4: S. Agostinelli *et al.*, Nucl. Instrum. Methods Phys. Res. Sect. A, **506**, 250 (2003).
[17] The power-law tails are described by the function $B(x) = \frac{(\Gamma_{(1,2)}/2)^{\beta_{(1,2)}}}{|x-x_0|^{\beta_{(1,2)}} + (\Gamma_{(1,2)}/2)^{\beta_{(1,2)}}}$, where x_0 is a parameter, $\Gamma_1(\Gamma_2)$ and $\beta_1(\beta_2)$ are used when $x < x_0$ ($x > x_0$) see Ref. [18] for more information.
[18] J. P. Lees *et al.* (*BABAR* Collaboration), Phys. Rev. D **81**, 052010 (2010).
[19] K. Gao, Ph. D. thesis, University of Minnesota, 2008 [arXiv:0909.2812]; B. Heltsley, The Sixth International Workshop on Heavy Quarkonia, Nara, Japan, 2008, http://www-conf.kek.jp/qwg08/session1_3/heltsley.pdf.
[20] A. G. Frodesen *et al.*, *Probability and Statistics in Particle Physics* (Universitetsforlaget, Bergen, Norway, 1979).