Studies of $\xi(2230)$ in J/ψ Radiative Decays

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The BES experiment at the Beijing electron-positron collider has observed the $\xi(2230)$ signal in $\pi^+\pi^-$, K^+K^-, $K_S^0K_S^0$, and $p\overline{p}$ final states with 4.6σ, 4.1σ, 4.0σ, and 3.8σ statistical significances, respectively. The new observations of two nonstrange decay modes of $\xi \to \pi^+\pi^-$ and $p\overline{p}$ are important evidence for the glueball interpretation of the $\xi(2230)$. [S0031-9007(96)00037-3]

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Using 8.0×10^6 J/ψ events collected at the Beijing electron-positron collider (BEPC), the BES experiment has performed systematic studies of the $\xi(2230)$ in J/ψ radiative decays, and observed the ξ signal in $\pi^+\pi^-$, K^+K^-, $K_S^0K_S^0$, and $p\overline{p}$ final states. The resonance $\xi(2230)$ with a width of only about 20 MeV has stimulated both theoretical and experimental interest since it was first observed by Mark III Collaboration in the decays $J/\psi \to \gamma K^+K^-$ and $\gamma K_S^0K_S^0$ [1]. Several experiments searched for this narrow state. Although some experiments claimed that they found some structures around 2.2 GeV in different processes [2–4], which proceed via different mechanisms from J/ψ radiative decays, no other groups observed such narrow structure in J/ψ decays [5]. As a result, the existence of the $\xi(2230)$ has been quite controversial. It is also interesting to note that the $\xi(2230)$ has never been observed in any $p\overline{p} \to K\overline{K}$ experiments [6–9] and these nonobservations can be interpreted as upper limits for the product branching ratio $B(\xi \to p\overline{p})B(\xi \to K\overline{K})$. The unexpectedly narrow width of ξ has provoked many speculations about the nature of this state. Previous theoretical interpretations of $\xi(2230)$ included identification as a high spin $s\overline{s}$ state [10], a multiquark state (such as a 4-quark state [11,12], a $\Lambda\overline{\Lambda}$ bound state [13], a neutral color scalar bound state [14], etc.), a hybrid state [11,15], or a glueball [16]. With the only strange decay modes observed by Mark III Collaboration, the $s\overline{s}$ interpretation could not be excluded and the glueball interpretation would be disfavored. Thus new discoveries on nonstrange decay modes are extremely important to understand the nature of $\xi(2230)$ and especially to know whether it is a glueball [17].

The BES detector, fully described elsewhere [18], has the following main features: The momentum resolution of charged tracks measured by the main drift chamber (MDC) is $\delta p/p = 1.7\%(1 + p^2)^{1/2}$, where p is in GeV; the time-of-flight (TOF) counters have a resolution of 330 ps; the barrel shower counter (BSC), which covers 80% of 4π solid angle, has an energy resolution of $\delta E/E = 22\%/\sqrt{E}$ (E in GeV) and a spatial resolution of 3.6 cm in the Z direction and 7.9 mrad in the ϕ direction.

The first level of event selection requires two oppositely charged tracks for $\gamma\pi^+\pi^-$, γK^+K^-, and $\gamma p\overline{p}$ events, and requires two positive charged tracks and two negative charged tracks for $\gamma K_S^0K_S^0$ events. At least one detected photon is required for all these events. More than one photon per event is allowed due to the fake photons which come from the interactions of charged tracks in the shower counter or come from electronic noise in the shower counter. The further selection criteria of $J/\psi \to \gamma\pi^+\pi^-$ will be described in detail while others will be described briefly since the techniques used are quite similar.

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In the event selection of $J/\psi \to \gamma\pi^+\pi^-$, the main backgrounds come from $J/\psi \to \rho\pi, K^*K, \gamma K^+K^-$, $(n\gamma)e^+e^-$, and other $\pi^+\pi^-$ + neutrals. The large background from $(n\gamma)e^+e^-$ events is removed by requiring (1) the opening angle of two tracks $\theta_{\rm op} < 175°$, (2) the energy deposit in BSC of each track $E_{\rm sc} < 600$ MeV, and (3) the angle between each track and the Z direction (positron beam direction) satisfies $|\cos\theta| < 0.7$. No TOF selection criteria are applied. Instead, the K^*K and γK^+K^- events are removed by using the kinematic variable $U = E_{\rm miss} - |P_{\rm miss}|$, where $E_{\rm miss}$ and $P_{\rm miss}$ are, respectively, the missing energy and missing momentum of all charged particles, and they are calculated by assuming that the charged particles are $\pi^+\pi^-$ [19]. A cut $-0.25 < U < 0.08$ GeV is made. The tight cut on the positive U region not only rejects most of the K^*K,γK^+K^- events but also removes most of the events having multipions or other neutrals. The two body decay behavior of $\rho - \pi$ decay of J/ψ is used to remove $J/\psi \to \rho\pi$ events: Events having one charged pion momentum in the region $|P_{\pi^\pm} - 1450| < 40$ MeV and the invariant mass of the other charged pion and π^0 in the ρ mass region $|M_{\pi^\mp\pi^0} - M_{\rho^\mp}| < 75$ MeV are removed. When $M_{\pi^\mp\pi^0}$ is calculated, the momentum of the π^0 is obtained from $P_{\pi^0} = P_{\rm miss}$. The advantage of this technique is that it uses only the momenta of charged tracks measured by MDC which has good momentum resolution. This cut may cause a systematic error on detection efficiency for different spin and different helicity amplitude ratios, but it does not bias the invariant mass spectrum of $\pi^+\pi^-$. This factor has been included in the systematic error of the branching ratio. In the selection of photons, the photon is required to be isolated from two charged tracks ($\theta_{\gamma\pi} > 30°$) and to come from the interaction point (IP). When the number of photons $N_\gamma \geq 2$, the events with π^0 are first removed by using a new variable α_{π^0} angle. The main points are as follows: First, the photon directions are known from BSC and the momentum of the π^0 is known from $P_{\pi^0} = P_{\rm miss}$ assuming this event contains only one π^0; second, if one photon (γ_1) direction and the momentum of π^0 are known, the direction of the other photon γ_2 can be calculated assuming they are from a π^0 decay; the angle between the detected direction and the expected direction of γ_2 is called α_{π^0}. The multiphoton events having $(\alpha_{\pi^0})_{\rm min} < 8°$ are discarded, where $(\alpha_{\pi^0})_{\rm min}$ is the minimum value of all possible combinations of photon pairs. The advantage of α_{π^0} is that it is independent of the measurements of photon energy. The α_{π^0} cut does not bias the invariant mass spectrum of $\pi^+\pi^-$, though it may cause a systematic error when the efficiency is calculated for the events with fake photons. This factor is also included in the systematic error of the branching ratio. For one photon events and the multiphoton events passing the α_{π^0} cut, another cut [5,20] $P_{t\gamma}^2 \equiv 4|P_{\rm miss}|^2 \sin^2(\theta_{m\gamma}/2) < 1800\ {\rm MeV}^2$ is imposed, where $\theta_{m\gamma}$ is the angle between the missing momentum and the photon direction. Finally, events are 4-C kinematically fitted to obtain better mass resolution and to suppress backgrounds further by the requirements $\chi^2_{\gamma\pi\pi} < 16$ and $\chi^2_{\gamma KK} > 10$.

An analogous analysis is performed to select $J/\psi \to \gamma K^+K^-$ events. The backgrounds from $J/\psi \to (n\gamma)\ e^+e^-\pi^+\pi^-$ + neutrals (including $\rho\pi$), K^+K^- + neutrals (including K^*K), and $\gamma\pi^+\pi^-$ events are removed by making use of $\theta_{\rm op}$, $E_{\rm sc}$, particle identification (by requiring that at least one kaon is identified by TOF and that the track with momentum <600 MeV should be identified as kaon by TOF), variable U, two body decay behavior of $K^* - K$ decay of J/ψ, photon selection, $\alpha_{\pi^0}, P_{t\gamma}^2$, and 4-C kinematic fit.

When the decay $J/\psi \to \gamma K_S^0K_S^0$ is studied, both K_S^0's are selected by imposing a cut on the second vertex and a cut on the mass of pion pairs $|M_{\pi^+\pi^-} - M_{K_S^0}| < 50$ MeV, where $M_{\pi^+\pi^-}$ is calculated at the K_S^0 decay vertex. The main backgrounds from $\gamma K_S^0K^\pm\pi^\mp$, $\gamma K_S^0K_S^0\pi^0$ events are suppressed by using particle identification by TOF, the variable U, photon selection, $P_{t\gamma}^2$, and 4-C kinematic fit.

The $J/\psi \to \gamma p\overline{p}$ events are selected by the use of $\theta_{\rm op}$ [21], particle identification (one proton and one antiproton) by TOF, the variable U ($|U| < 0.1$ GeV), photon selection (isolated from antiproton and coming from the IP), $\alpha_{\pi^0}, P_{t\gamma}^2$, and 4-C kinematic fit to eliminate the possible backgrounds from $J/\psi \to p\overline{p}$ + neutrals, $p\overline{n}\pi$, etc.

The resulting invariant mass spectra of $\pi^+\pi^-$,K^+K^-, $K_S^0K_S^0$, and $p\overline{p}$ [Figs. 1(a)–1(b)] show evidence for the $\xi(2230)$ as well as other resonances, including some known particles, e.g., $f_2(1270)$ and $f_4(2050)$ in $\pi^+\pi^-$ mode.

Monte Carlo studies are performed to obtain the mass resolutions and the detection efficiencies and to assure that the selection criteria do not bias the invariant spectra. The mass resolutions in the ξ region are $\sigma_{m_{\pi^+\pi^-}} = 11$ MeV, $\sigma_{m_{K^+K^-}} = 9$ MeV, $\sigma_{m_{K_S^0K_S^0}} = 12$ MeV, and $\sigma_{m_{p\overline{p}}} = 7$ MeV. For each decay mode, the detection efficiency is obtained from Monte Carlo simulation based on the assumptions of ξ that the spin is $J = 2$ and that the helicity amplitude ratios are $x = 1.0$ and $y = 0.0$. The detection efficiencies are 0.164, 0.174, 0.106, and 0.269 for the ξ signal in the $\gamma\pi^+\pi^-$, γK^+K^-, $\gamma K_S^0K_S^0$, and $\gamma p\overline{p}$ channels, respectively, and they all vary smoothly by less than 25% in the fit mass region. Different spins ($J = 0, 4$) and different (x, y) values are tested. The relative acceptances differ by less than 25%. This factor has been included in the systematic error of branching ratio for each channel, respectively.

The invariant mass spectra (Fig. 1) are fitted by an unbinned maximum-likelihood method which uses a smooth background plus one or several Breit-Wigner resonances convoluted with Gaussian resolution functions in each fit (Fig 2) [22]. The number of events in the ξ signal, as determined by the fit, is 74, 46, 23, and 32 in the $\pi^+\pi^-$, K^+K^-, $K_S^0K_S^0$, and $p\overline{p}$ channels, respectively. The

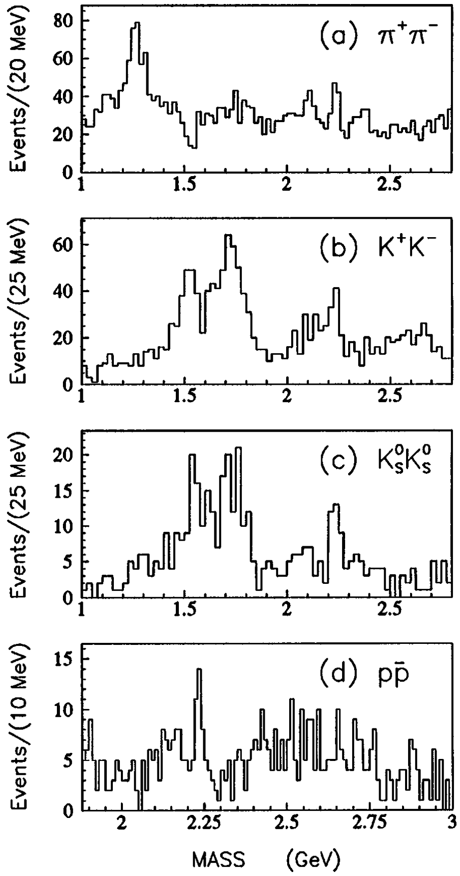

FIG. 1. Invariant mass spectra of (a) $\pi^+\pi^-$, (b) K^+K^-, (c) $K_S^0K_S^0$, and (d) $p\overline{p}$.

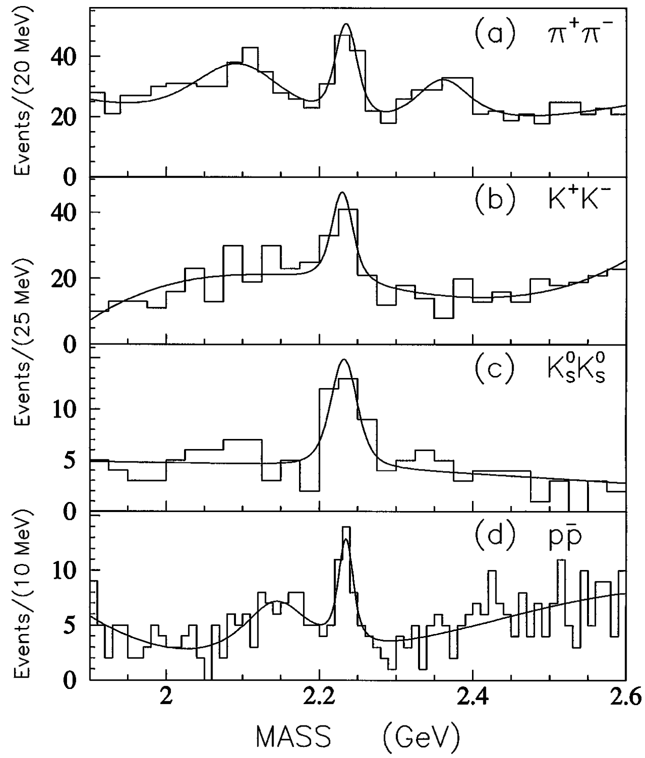

FIG. 2. Fitted invariant mass spectra of (a) $\pi^+\pi^-$, (b) K^+K^-, (c) $K_S^0K_S^0$, and (d) $p\overline{p}$.

statistical significances of the ξ signal in the $\pi^+\pi^-$, K^+K^-, $K_S^0K_S^0$, and $p\overline{p}$ modes are, respectively, 4.6σ, 4.1σ, 4.0σ, and 3.8σ [23]. The statistical significance of a signal is determined by the difference between the logarithm of the likelihood value for the fit with the signal and that for the fit without the signal [1].

The parameters of the $\xi(2230)$ (mass M_ξ, width Γ_ξ, and branching ratio B) measured in each channel are listed in Table I. The systematic errors of mass and width are due to the uncertainty of the background shape and event selection criteria. The systematic errors of branching ratios [24] are due to the uncertainty of detection efficiency, the uncertainty of background shape, the systematic error of the number of produced J/ψ, and event selection criteria.

TABLE I. Mass, width, and branching ratios of $\xi(2230)$. The first error is statistical and the second is systematic.

Decay mode	M_ξ (MeV)	Γ_ξ (MeV)	$B(J/\psi \to \gamma\xi)B(\xi \to X)$ (10^{-5})
$\pi^+\pi^-$	$2235 \pm 4 \pm 6$	$19^{+13}_{-11} \pm 12$	$5.6^{+1.8}_{-1.6} \pm 2.0$
K^+K^-	$2230^{+6}_{-7} \pm 16$	$20^{+20}_{-15} \pm 17$	$3.3^{+1.6}_{-1.3} \pm 1.2$
$K_S^0K_S^0$	$2232^{+8}_{-7} \pm 15$	$20^{+25}_{-16} \pm 14$	$2.7^{+1.1}_{-0.9} \pm 0.8$
$p\overline{p}$	$2235 \pm 4 \pm 5$	$15^{+12}_{-9} \pm 9$	$1.5^{+0.6}_{-0.5} \pm 0.5$

The measured parameters in $K\overline{K}$ channels are in agreement with the MARK III's results [1]. The measured branching ratio for the $\pi^+\pi^-$ decay mode is larger than the MARK III's upper limit $B(J/\psi \to \gamma\xi)B(\xi \to \pi^+\pi^-) < 2 \times 10^{-5}$ (95% C.L.) while the branching ratio for the $p\overline{p}$ decay mode is within the MARK III's upper limit $B(J/\psi \to \gamma\xi)B(\xi \to p\overline{p}) < 2 \times 10^{-5}$ (95% C.L.) [1].

In conclusion, our results show that $\xi(2230)$ does exist and two new nonstrange decay modes of $\xi \to \pi^+\pi^-$ and $p\overline{p}$ are observed. These new discoveries give very important evidence for the identification of $\xi(2230)$.

Compared with other mesons, $\xi(2230)$ has many distinctive properties [17]. (1) Flavor-symmetric decays to $\pi\pi$ and $K\overline{K}$ [24]; with the phase spaces removed, the decay probability of $\xi \to \pi^+\pi^-$ is of the same order as that of $\xi \to K^+K^-$. (2) Narrow width; the width of $\xi(2230)$ is only about 20 MeV. (3) Large production rate in radiative J/ψ decays; from the mean values of the branching ratios of the BES's results and the PS185 experimental upper limit [6,25] $B(\xi \to p\overline{p})B(\xi \to K\overline{K}) < 1.5 \times 10^{-4}$ (99.9% C.L.) which assumes $\Gamma_\xi > 10$ MeV, one can roughly estimate that $B(J/\psi \to \gamma\xi)$ is of the order 3×10^{-3} or even larger [26]. This means that the production rate of ξ in J/ψ radiative decay could be as large as or larger than those of some conventional $q\overline{q}$

mesons such as $f_2(1270)$ and $f_2'(1525)$. Consequently, the decay branching ratios of ξ decays into $\pi^+\pi^-$ and K^+K^- are about or even smaller than 2%, and thus the partial decay widths $\Gamma_{\pi^+\pi^-}$ and $\Gamma_{K^+K^-}$ are approximately several hundred keV. However, a narrow resonance in the ξ mass region with large production rate is not seen in the crystal ball results on the J/ψ inclusive photon spectrum [27].

The $q\overline{q}$, multiquark, and hybrid models cannot easily explain the special properties of the $\xi(2230)$. As a result of the observation of flavor-symmetric couplings and small partial widths of $\xi \to \pi\pi$ and $K\overline{K}$, the $\xi(2230)$ cannot be interpreted as a $q\overline{q}$ meson [17]. The large production rate in radiative J/ψ decay would disfavor the interpretation of a multiquark state. With the observed upper limit [25] $B(J/\psi \to \gamma\Lambda\overline{\Lambda}) < 1.3 \times 10^{-4}$, we do not expect a $\Lambda\overline{\Lambda}$ bound state to have a large production rate as the ξ in J/ψ radiative decay. Also a hybrid state is not expected to have as narrow a width as the $\xi(2230)$ (especially $\Gamma_{\pi\pi}$ and Γ_{KK}). In contrast, these features are just the expectations for a glueball [17]. For example, the narrow width is naively expected since glueball decay to a $q\overline{q}$ state is suppressed by the so-called Okubo-Zweig-Iizuka rule [28]. The qualitative similarity between the decay properties of the $\xi(2230)$ and those of the χ_{c0} and χ_{c2} suggests that the ξ decay via gluons. Therefore, these features would strongly favor the glueball interpretation of $\xi(2230)$.

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[23] For other background parametrizations, the statistical significances of ξ signal vary from 4.0σ, 3.9σ, 3.6σ and 3.6σ to 5.1σ, 4.7σ, 4.3σ, and 4.1σ in the $\pi^+\pi^-$, K^+K^-, $K_S^0K_S^0$, and $p\overline{p}$ modes, respectively. For example, the statistical significance will be 4.2σ if we do not include the $X(2360)$ structure in the fit in the $\pi^+\pi^-$ channel.
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