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

J. Z. Bai,[1] J. G. Bian,[1] G. P. Chen,[1] H. F. Chen,[2] S. J. Chen,[1] S. M. Chen,[1] Y. Chen,[1] Y. Q. Chen,[1] Y. B. Chen,[1] B. S. Cheng,[1] X. Z. Cui,[1] H. L. Ding,[1] W. Y. Ding,[1] Z. Z. Du,[1] X. L. Fan,[1] J. Fang,[1] C. S. Gao,[1] M. L. Gao,[1] S. Q. Gao,[1] J. H. Gu,[1] S. D. Gu,[1] W. X. Gu,[1] Y. F. Gu,[1] Y. N. Guo,[1] S. W. Han,[1] Y. Han,[1] J. He,[1] M. He,[3] G. Y. Hu,[1] T. Hu,[1] X. Q. Hu,[1] D. Q. Huang,[1] T. Huang,[1] Y. Z. Huang,[1] C. H. Jiang,[1] S. Jin,[1] Y. Jin,[1] S. H. Kang,[1] Z. J. Ke,[1] Y. F. Lai,[1] H. B. Lan,[1] P. F. Lang,[1] F. Li,[1] J. Li,[1] P. Q. Li,[1] Q. Li,[1] R. B. Li,[1] W. Li,[1] W. D. Li,[1] W. G. Li,[1] X. H. Li,[1] X. N. Li,[1] S. Z. Lin,[1] H. M. Liu,[1] J. Liu,[1] J. H. Liu,[1] Q. Liu,[1] R. G. Liu,[1] Y. Liu,[1] Z. A. Liu,[1] J. G. Lu,[1] S. Q. Luo,[1] Y. Luo,[1] A. M. Ma,[1] E. C. Ma,[1] J. M. Ma,[1] H. S. Mao,[1] Z. P. Mao,[1] X. C. Meng,[1] H. L. Ni,[1] J. Nie,[1] N. D. Qi,[1] Y. K. Que,[1] G. Rong,[1] Y. Y. Shao,[1] B. W. Shen,[1] D. L. Shen,[1] H. Shen,[1] X. Y. Shen,[1] H. Y. Sheng,[1] H. Z. Shi,[1] X. R. Shi,[3] X. F. Song,[1] F. Sun,[1] H. S. Sun,[1] S. J. Sun,[1] Y. P. Tan,[1] S. Q. Tang,[1] G. L. Tong,[1] F. Wang,[1] L. S. Wang,[1] L. Z. Wang,[1] M. Wang,[1] P. Wang,[1] P. L. Wang,[1] S. M. Wang,[1] T. J. Wang,[1] Y. Y. Wang,[1] C. L. Wei,[1] D. M. Xi,[1] X. M. Xia,[1] P. P. Xie,[1] Y. G. Xie,[1] W. J. Xiong,[1] D. Z. Xu,[1] R. S. Xu,[1] Z. Q. Xu,[1] S. T. Xue,[1] J. Yan,[1] W. G. Yan,[1] C. M. Yang,[1] C. Y. Yang,[1] J. Yang,[1] W. Yang,[1] M. H. Ye,[1] S. W. Ye,[1] S. Z. Ye,[1] C. S. Yu,[1] C. X. Yu,[1] Z. Q. Yu,[1] Z. T. Yu[1] C. Z. Yuan,[1] B. Y. Zhang,[1] C. C. Zhang,[1] D. H. Zhang,[1] H. L. Zhang,[1] J. Zhang,[1] J. W. Zhang,[1] L. S. Zhang,[1] S. Q. Zhang,[1] X. Y. Zhang,[1] Y. Zhang,[1] Y. Y. Zhang,[1] D. X. Zhao,[1] H. W. Zhao,[1] J. W. Zhao,[1] M. Zhao,[1] P. D. Zhao,[1] W. H. Zhao,[1] W. R. Zhao,[1] J. P. Zheng,[1] L. S. Zheng,[1] Z. P. Zheng,[1] G. P. Zhou,[1] H. S. Zhou,[1] Li Zhou,[1] X. F. Zhou,[1] Y. H. Zhou,[1] Q. M. Zhu,[1] Y. C. Zhu,[1] Y. S. Zhu,[1] B. A. Zhuang,[1]

(BES Collaboration)

[1] *Institute of High Energy Physics, Beijing 100039, People's Republic of China*

[2] *China's University of Science and Technology, Hefei 230026, People's Republic of China*

[3] *Shandong University, Jinan 250100, People's Republic of China*

(December 6, 1995)

The BES experiment at BEPC has observed the $\xi(2230)$ signal in $\pi^+\pi^-$, K^+K^-,$K_S^0K_S^0$ and $p\bar{p}$ final states with 4.6σ, 4.1σ, 4.0σ and 3.8σ statistical significances respectively. The new observations of two non-strange decay modes of $\xi \rightarrow \pi^+\pi^-$ and $p\bar{p}$ give very important evidence for the glueball interpretation of $\xi(2230)$.

Using 8.0 million J/ψ events collected at BEPC, BES experiment has performed systematic studies of $\xi(2230)$ in J/ψ radiative decays, and observed the ξ signal in $\pi^+\pi^-$, K^+K^-, $K_S^0K_S^0$ and $p\bar{p}$ final states. The resonance $\xi(2230)$ with a width only about 20 MeV has been stimulating much, both theoretical and experimental, interest since it was first observed by Mark III Collaboration in the decays $J/\psi \rightarrow \gamma K^+K^-$ and $\gamma K_S^0K_S^0$ [1]. A lot of experiments were designed to search 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], so for a long time, whether the puzzling $\xi(2230)$ really exists has been quite controversial. It is also interesting to note that the $\xi(2230)$ has never been seen in any $p\bar{p} \rightarrow K\bar{K}$ experiments [6–9] and these non-observations can be interpreted as upper limits for the product branching rario, BR($\xi \rightarrow p\bar{p}$)BR($\xi \rightarrow K\bar{K}$). 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 $s\bar{s}$ state [10], a multiquark state (such as a 4-quark state [11,12], a $\Lambda\bar{\Lambda}$ 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 $s\bar{s}$ interpretation could not be excluded and the glueball interpretation would be disfavored. Thus the new discoveries on non-strange decay modes are extremely important to understand the nature of $\xi(2230)$ 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 $\delta E/E = 22\%/\sqrt{E}$ (E in GeV) and a spatial resolution 3.6cm in Z direction and 7.9 mrad in ϕ direction.

The event selection criteria of $J/\psi \rightarrow \gamma\pi^+\pi^-$ will be described in detail while others will be described briefly since the techniques used are quite similar.

In the event selection of $J/\psi \rightarrow \gamma\pi^+\pi^-$, the main backgrounds come from $J/\psi \rightarrow \rho\pi, K^*K, \gamma K^+K^-$, (n$\gamma$)$e^+e^-$ and other $\pi^+\pi^-$ + neutrals. The large background from (nγ)e^+e^- events is removed by requiring (1) the opening angle of two tracks $\theta_{op} < 175^0$; (2) the energy deposit in BSC of each track $E_{sc} < 600$ MeV; (3) the angle between each track and Z direction satisfies $|cos\theta| < 0.7$. No TOF selection criteria are applied. Instead, the K^*K and γK^+K^- events are removed by using a kinematic variable $U = E_{miss} - |P_{miss}|$, where E_{miss} and P_{miss} are, respectively, the missing energy and missing momentum of all charged particles [19]. A cut -0.25 GeV $< U <$ 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, about which the knowledge is still limited. The two body decay behavior of ρ and π is made use of 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 [20]. When $M_{\pi^\mp\pi^0}$ is calculated, the momentum of the π^0 is obtained from $P_{\pi^0} = P_{miss}$. The advantage of this technique is that it only uses the momenta of charged tracks measured by MDC which has good momentum resolution. In the selection of photons, the photon is required to be isolated from two charged tracks ($\theta_{\gamma\pi} > 30^o$) 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: first, the photon (γ_1 and γ_2) direction can be known from BSC and the momentum of π^0 can be known from $P_{\pi^0} = P_{miss}$ assuming this event contain only one neutral particle π^0; second, if the γ_1 direction and the momentum of π^0 are known, the direction of the other photon from possible π^0 can be calculated; the angle between the detected direction and the expected direction of γ_2 is called α_{π^0} [21]. The multiphoton events having $(\alpha_{\pi^0})_{min} < 8^o$ are discarded [22], where $(\alpha_{\pi^0})_{min}$ 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. For one photon events and the multiphoton events passing the α_{π^0} cut, another usual cut $P_{t\gamma}^2 \equiv 4|P_{miss}|^2 sin^2(\theta_{m\gamma}/2) < 1800$ (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.

An analogous analysis is performed to select $J/\psi \to \gamma K^+K^-$ events. The backgrounds from $J/\psi \to$ (nγ) 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 θ_{op}, E_{sc}, particle identification by TOF [23], variable U, two body decay behavior of K^* and K, photon selection, α_{π^0}, $P_{t\gamma}^2$ and 4-C kinematic fit.

When the decay $J/\psi \to \gamma K_S^0 K_S^0$ 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 $\gamma K_S^0 K^\pm\pi^\mp$, $\gamma K_S^0 K_S^0\pi^0$ events are suppressed by using particle identification by TOF , the variable U, photons selection (the energy in BSC larger than 100 MeV and coming from the IP), $P_{t\gamma}^2$ and 4-C kinematic fit.

The $J/\psi \to \gamma p\bar{p}$ events are selected by the use of θ_{op} [24], particle identification (one proton and one anti-proton) by TOF, the variable U ($|U| <$0.1 GeV), photon selection (isolated from anti-proton and coming from the IP),α_{π^0}, $P_{t\gamma}^2$ and 4-C kinematic fit to eliminating the possible backgrounds from $J/\psi \to p\bar{p}$ + neutrals, $p\bar{n}\pi$, etc.

In the studies of J/ψ radiative decays, it is crucial to suppress the backgrounds containing neutral hadrons as much as possible in order to obtain reliable physical result, especially for the weak signals as ξ, since these backgrounds are usually quite large and the knowledge about some of the backgrounds is still limited. Besides the usual techniques such as U and $P_{t\gamma}^2$, the new α_{π^0} cut can further effectively remove these backgrounds which are dominant in multiphoton events. Of course, these backgrounds can be suppressed by simply requiring that N_γ=1, but this requirement would reduce the statistical significances of signals since it loses all the signal events that have fake photons. The α_{π^0} cut provides an effective technique for rejecting the backgrounds with neutral hadrons while it is able to retain most of the signal events with fake photons.

The resulting invariant mass spectra of $\pi^+\pi^-$,K^+K^-, $K_S^0K_S^0$ and $p\bar{p}$ (Fig.1(a)-(d)) show the evidence for the $\xi(2230)$ as well as other resonances.

The invariant mass spectra (Fig.1) are fitted by unbinned maximum-likelihood method which uses a smooth background plus one or several Briet-Wigner resonances convoluted with Gaussion resolution functions in each fit(Fig.2) [25] . The mass resolutions in ξ region obtained from Monte Carlo simulation are: $\sigma_{m_{\pi^+\pi^-}}$ = 11 MeV, $\sigma_{m_{K^+K^-}}$ = 9 MeV, $\sigma_{m_{K_S^0K_S^0}}$ = 12 MeV and $\sigma_{m_{p\bar{p}}}$ = 7 MeV. The number of events in ξ singnal, as determined by the fit, is 74, 46, 23 and 32 in the $\pi^+\pi^-$, K^+K^-, $K_S^0K_S^0$ and $p\bar{p}$ channel respectively. The statistical significances of ξ signal in the $\pi^+\pi^-$, K^+K^-, $K_S^0K_S^0$ and $p\bar{p}$ modes are, respectively, 4.6 σ, 4.1σ, 4.0σ and 3.8σ [26]. 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 detection efficiencies determined by Monte Carlo studies are 16.4%,17.4%, 10.6% and 26.9% for the $\gamma\pi^+\pi^-$, γK^+K^-, $\gamma K_S^0K_S^0$ and $\gamma p\bar{p}$ events, respectively [27].

The parameters of $\xi(2230)$ (mass M_ξ, width Γ_ξ and branching ratio BR) 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 [28] are due to the uncertainty of detection efficiency [20,22,27], the uncertainty of background shape, the systematic error of the number of produced J/ψ and event selection criteria.

In conclusion, our results show that $\xi(2230)$ does exist and two new non-strange decay modes of $\xi \to \pi^+\pi^-$ and $p\bar{p}$ 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 $K\bar{K}$ [28]. (2) Copious production in radiative J/ψ decays. From the BES's results and the upper limit [6,29] $\mathrm{BR}(\xi \to p\bar{p})\ \mathrm{BR}(\xi \to K\bar{K}) < 1\times10^{-4}$, one can easily estimate that $\mathrm{BR}(J/\psi \to \gamma\xi) > 3\times10^{-3}$. (3) Narrow width. The width of $\xi(2230)$ is only about 20 MeV. (4) Small branching ratios to $\pi\pi$, $K\bar{K}$ and $p\bar{p}$. From BES's results and $\mathrm{BR}(J/\psi \to \gamma\xi) > 3\times10^{-3}$, it can also be easily estimated that $\mathrm{Br}(\xi \to K^+K^-)$ and $\mathrm{Br}(\xi \to \pi^+\pi^-)$ are smaller than 2%, and $\mathrm{Br}(\xi \to p\bar{p})$ is smaller than 1%. From (3) (4), the partial width $\Gamma_{\pi^+\pi^-}$ and $\Gamma_{K^+K^-}$ are smaller than 400 keV.

The $q\bar{q}$ model, multiquark model and hybrid model would face many difficulties in explaining the special properties of $\xi(2230)$. As a result of the observation of flavor symmetric couplings and small partial widths of $\xi \to \pi\pi$ and $K\bar{K}$, the $\xi(2230)$ cannot be interpreted as a $q\bar{q}$ meson [17]. The rich production in radiative J/ψ decay would disfavor the interpretation of a multiquark state. For example, with the observed upper limit [29] $\mathrm{BR}(J/\psi \to\gamma\Lambda\bar{\Lambda})<1.3\times10^{-4}$, we can hardly expect a $\Lambda\bar{\Lambda}$ bound state has so high production rate as ξ in J/ψ radiative decay. As for a hybrid state, it would also face much trouble in explaining the narrow width of $\xi(2230)$ (esp. $\Gamma_{\pi\pi}$ and Γ_{KK}). On the contrary, these features are just the expectations for a glueball [17]. For example, the narrow width is naively expected since glueball decay to $q\bar{q}$ state is suppressed by so called $\sqrt{OZI}$ rule [30] . Therefore, these features would strongly favor the glueball interpretation of $\xi(2230)$.

We would like to thank the staff of the BEPC accelerator and the IHEP Computing Center. We are grateful to Prof. K. T. Chao, Prof. K. F. Liu, Prof. S. L. Olsen, Prof. F. Porter, Prof. Q. X. Shen, Prof. W. Toki, Prof. J. M. Wu and Prof. H. Yu for their useful discussions. This work was supported in part by the National Natural Science Foundation under Contract No. 19290400(IHEP) and by Academia Sinica under Contract No. KJ85.

---

[1] R. M. Baltrusait *et al.*,Phys. Rev. Lett. **56**, 107 (1986); K. F. Einsweiler, Ph.D thesis, Stanford Linear Accelerator Center Report No. SLAC-272, 1984 (unpublished).

[2] D. Alde *et al.*, Phys. Lett. **B177**, 120 (1986).

[3] D. Aston *et al.*, Nucl. Phys. **B301**, 525 (1988) and Phys. Lett. **B177**, 120 (1988).

[4] B. V. Bolonkin *et al.*, Nucl. Phys. **B309**, 426 (1988).

[5] J. Augustin *et al.*, Phys. Rev. Lett. **60**, 2238 (1988).

[6] P. D. Barnes *et al.*, Phys. Lett. **B309**, 469 (1993).

[7] A. Hasan *et al.*, Nucl. Phys. **B378**, 3 (1992).

[8] J. Sculli *et al.*, Phys. Rev. Lett. **58**, 1715 (1987).

[9] G. Bardin *et al.*, Phys. Lett. **B195**, 292 (1987).

[10] S. Godfrey, R. Kokoski, and N. Isgur, Phys. Lett. **141B**, 439 (1984);

[11] K. T. Chao, Phys. Rev. Lett. **60**, 2579 (1988); K. T. Chao, Commun. Theor. Phys. **3**, 757 (1984).

[12] S. Pakvasa, M. Suzuki and S. F. Tuan, Phys. Lett. **145B**, 135 (1984).

[13] S. Ono, Phys. Rev. **D35**, 944 (1987).

[14] M. P. Shatz, Phys. Lett. **138B**, 209 (1984).

[15] M. S. Chanowitz and S. R. Sharpe, Phys. Lett. **132B**, 413 (1983); M. Le Yaouanc et al., Z. Phys. **C28**, 309 (1985).

[16] B. F. L. Ward, Phys. Rev. **D31**, 2849 (1985).

[17] T. Huang *et al.*, BIHEP-TH-95-11 / PUTP-95-09; K. T. Chao, PUTP-94-26 (hep-ph/9502408), talk given at the CCAST Workshop on Tau-Charm Factory, Beijing, November 1994.

[18] J. Z. Bai *et al.*, Nucl. Instr. And Methods **A344**, 319 (1994); J. Z. Bai *et al.*, Phys. Rev. Lett. **69**, 3021 (1992).

[19] E_{miss} and P_{miss} are calculated by assuming that the charged particles are $\pi^+\pi^-, K^+K^-, p\bar{p}$ and $\pi^+\pi^-\pi^+\pi^-$ in selecting $\gamma\pi^+\pi^-, \gamma K^+K^-, \gamma p\bar{p}$ and $\gamma K^0_S K^0_S$ events respectively.

[20] 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.

[21] There are two α_{π^0}'s in each photon pair. The smaller one is used.

[22] The α_{π^0} cut 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.

[23] TOF is used to do particle identification when it is necessary and when it is available not to lose much efficiency, e.g., in the selection of $J/\psi \to \gamma K^+K^-$, it is required that at least one kaon is identified by TOF and the track with momentum $<$ 600 MeV should be identified as kaon by TOF.

[24] The cut $\theta_{op} < 175^0$ loses the η_c signal in $\gamma p\bar{p}$ channel.

[25] The invariant mass spectra show evidence for, besides ξ signal, other resonances in 2.0 GeV - 2.5 GeV region in different channels, e.g., the resonance in $\gamma p\bar{p}$ channel with the observed mass M_X=$(2144\pm13\pm9)$MeV, width Γ_X=$(114^{+80}_{-46}\pm30)$MeV and branching ratio $\mathrm{BR}(J/\psi \to \gamma X)\mathrm{BR}(X \to p\bar{p})$ =$(4.6^{+4.4}_{-2.0}\pm1.5)\times10^{-5}$.

[26] 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^-, $K^0_S K^0_S$ and $p\bar{p}$ modes, respectively.

[27] For each decay mode, the detection efficiency is obtained from Monte Carlo simulation based on the assumptions that spin of ξ J=2 and that helicity amplitude ratios

x=1.0 and y=0.0. Different spins (J=0,4) and different (x,y) values were tested. The relative acceptances differed by less than 25%. This factor has been included in the systematic error of branching ratio for each channel respectively.

[28] Although the systematic error of branching ratio of each decay channel is large (> 30%), the systematic error of the ratio of BR($\xi \rightarrow \pi^+\pi^-$)/ BR($\xi \rightarrow K^+K^-$) is small (< 15%).

[29] L. Montanet *et al.* (Particle Data Group), *Review of Particle Properties*, Phys. Rev. **D50**, 1173 (1994).

[30] D. Robson, Nucl. Phys. **B130**, 328 (1977).

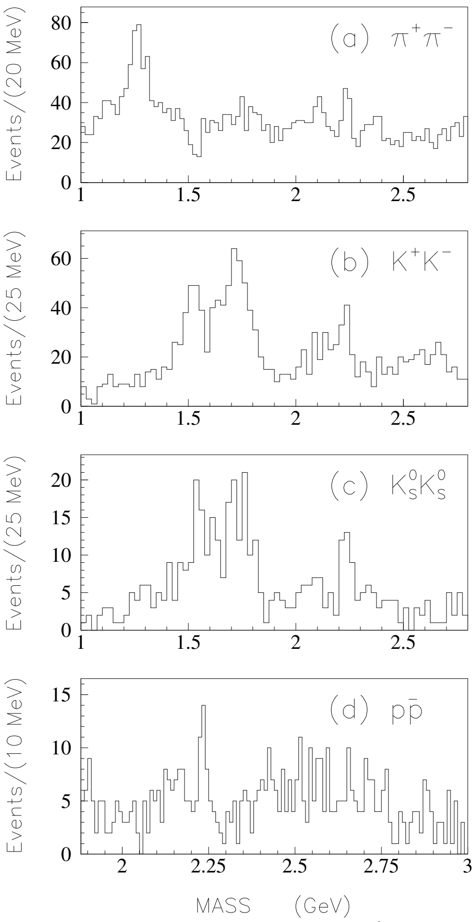

FIG. 1. Invariant mass spectra of (a) $\pi^+\pi^-$, (b) K^+K^-, (c) $K^0_S K^0_S$ and (d) $p\bar{p}$.

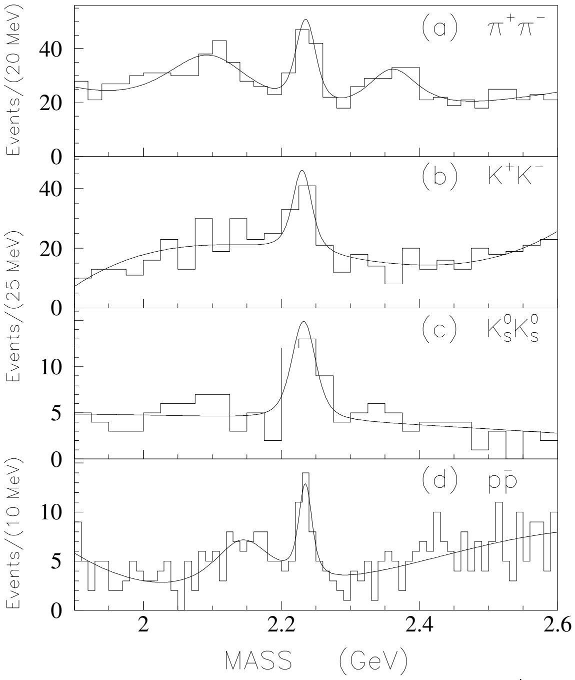

FIG. 2. Fitted invariant mass spectra of (a) $\pi^+\pi^-$, (b) K^+K^-, (c) $K^0_S K^0_S$ and (d) $p\bar{p}$.

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)	BR($J/\psi \rightarrow \gamma\xi$)BR($\xi \rightarrow X$) ($\times 10^{-5}$)
$\pi^+\pi^-$	$2235 \pm 4 \pm 6$	$19^{+13}_{-11} \pm 12$	$5.6^{+1.8}_{-1.6} \pm 2.0$
K^+K^-	$2230^{+6}_{-7} \pm 16$	$20^{+20}_{-15} \pm 17$	$3.3^{+1.6}_{-1.3} \pm 1.2$
$K^0_S K^0_S$	$2232^{+8}_{-7} \pm 15$	$20^{+25}_{-16} \pm 14$	$2.7^{+1.1}_{-0.9} \pm 0.8$
$p\bar{p}$	$2235 \pm 4 \pm 5$	$15^{+12}_{-9} \pm 9$	$1.5^{+0.6}_{-0.5} \pm 0.5$