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Search for the $\xi(2220)$ and Study of the $X(3872)$ at *BABAR*

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The *BABAR* Collaboration performed a search for $\xi(2220)$ production in the initial-state radiation process $e^+e^- \to \gamma J/\psi$, $J/\psi \to \gamma K^+K^-$ or $J/\psi \to \gamma K^0_S K^0_S$. No evidence for the $\xi(2220)$ resonance has been found. The 90% confidence level upper limits on the product of branching fractions are sensitive to the spin and helicity hypotheses. These upper limits are of the order 10^{-5}, below the values reported in previous experiments. Also at *BABAR*, the decays $B \to J/\psi\pi^+\pi^-\pi^0 K$ are studied to search for the decay $X(3872) \to J/\psi\omega$. This search yields a four standard deviation evidence for $X(3872) \to J/\psi\omega$, with product branching fractions of $\mathscr{B}(B^+ \to X(3872)K^+) \times \mathscr{B}(X(3872) \to J/\psi\omega) = [0.6 \pm 0.2(\text{stat}) \pm 0.1(\text{syst})] \times 10^{-5}$, and $\mathscr{B}(B^0 \to X(3872)K^0) \times \mathscr{B}(X(3872) \to J/\psi\omega) = [0.6 \pm 0.3(\text{stat}) \pm 0.1(\text{syst})] \times 10^{-5}$. A detailed study of the $\pi^+\pi^-\pi^0$ mass distribution from $X(3872)$ decay favors a negative-parity assignment but does not rule out the positive-parity hypothesis.

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1. Introduction

The $\xi(2220)$ resonance is a glue-ball candidate whose existence is not yet established. The $X(3872)$ has been observed in several decay modes and by several Collaborations. However, the nature of the $X(3872)$ is still not yet understood. We present the *BABAR* results on the search for $\xi(2220)$ in radiative J/ψ decays [1], and on the evidence for the decay $X(3872) \to J/\psi\omega$ [2].

2. Search for $\xi(2220)$ in Radiative J/ψ Decays

In 1986, the Mark III Collaboration reported [3] a narrow resonance with a mass of ~ 2.2 GeV/c^2 in the radiative decay $J/\psi \to \gamma\xi(2220)$, $\xi(2220) \to K^+K^-$ and $\xi(2220) \to K^0_S K^0_S$. A 3.6 and 4.7 standard deviation significance for $J/\psi \to \gamma K^+K^-$ and $J/\psi \to \gamma K^0_S K^0_S$ modes were reported. The BES Collaboration also reported evidence for the $\xi(2220)$ in J/ψ radiative decays at a comparable level of significance [4]. Moreover, there are indications for a similar structure in $\pi^- p$ and $K^- p$ collisions [5, 6, 7]. On the other hand, searches for $\xi(2220)$ in $p\bar{p}$ collisions [8, 9], or two photon production [10, 11], have been inconclusive.

In a recent *BABAR* search [1], the initial-state radiation (ISR) events $e^+e^- \to \gamma_{\rm ISR} J/\psi$, $J/\psi \to \gamma KK$ (KK indicates K^+K^- or $K^0_S K^0_S$), were studied to search for the $\xi(2220)$. The *BABAR* data sample is equivalent to an integrated luminosity of 460 fb^{-1}, recorded at or slightly below 10.58 GeV.

The γK^+K^- and $\gamma K^0_S K^0_S$ mass distributions are shown in Fig. 1, where a large J/ψ signal is observed in both decay modes. The background under the signal arises mainly from partially reconstructed $J/\psi \to KKX$ or $e^+e^- \to q\bar{q}\gamma_{\rm ISR}$ events, where X can be any final state system and $q = u, d, s, c$. The γKK candidates are required to originate from a common vertex and are kinematically constrained to the J/ψ nominal mass. Each K^0_S candidate in the decay $J/\psi \to \gamma K^0_S K^0_S$ is reconstructed from two oppositely charged tracks identified as pions. The photon emitted from the J/ψ has a minimum energy of 300 MeV.

The K^+K^- and $K^0_S K^0_S$ mass distributions are shown in Fig. 2. The inclusive background and background events corresponding to $J/\psi \to \gamma f_2'(1525)$ and $J/\psi \to \gamma f_0(1710)$, are present. The small data excess at ~ 1.25 GeV/c^2 in the charged mode may be due to the process $J/\psi \to \rho^0\pi^0$, with $\rho^0 \to \pi^+\pi^-$, where both pions are misidentified as kaons, and one of the photons from the π^0 is undetected. To extract the $\xi(2220)$ yield, unbinned-maximum likelihood fits in the range $1.9 \le m_{KK} \le 2.6$ GeV/c^2 are performed. The signal is described as a Breit-Wigner function convolved with a Gaussian resolution function. The background is parametrized as a second-order Chebychev polynomial. Both the mass and width of the $\xi(2220)$ are fixed. There is no evidence for $\xi(2220)$ state. The upper limits on the product of branching fractions depend on the spin and helicity assignment. For all hypotheses of spin and helicity, the 90% confidence level upper limits for the $J/\psi \to \gamma\xi(2220)$, $\xi(2220) \to KK$ product branching fractions are in the range $(1.2 - 3.6) \times 10^{-5}$, smaller or close to the values reported by the Mark III Collaboration.

3. Evidence for $X(3872) \to J/\psi\omega$

With the discovery [12] of the $X(3872)$ by the Belle Collaboration in 2003, interest in charmonium spectroscopy has been renewed. Confirmation of this state was obtained by CDF, D0, and

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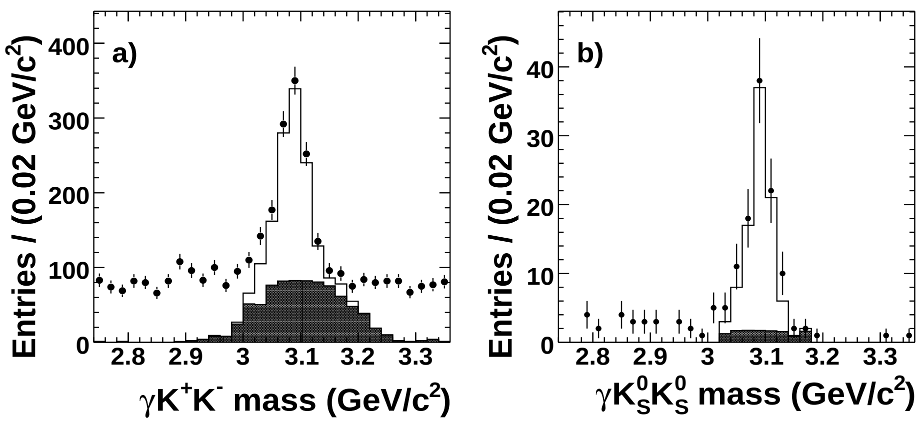

Figure 1: The mass distribution of (a) γK^+K^- and (b) $\gamma K^0_S K^0_S$ for the final sample. The dots represent the data and the histograms show the fits to the data when requiring a fit probability above 0.01. The shaded histograms represent the estimated background.

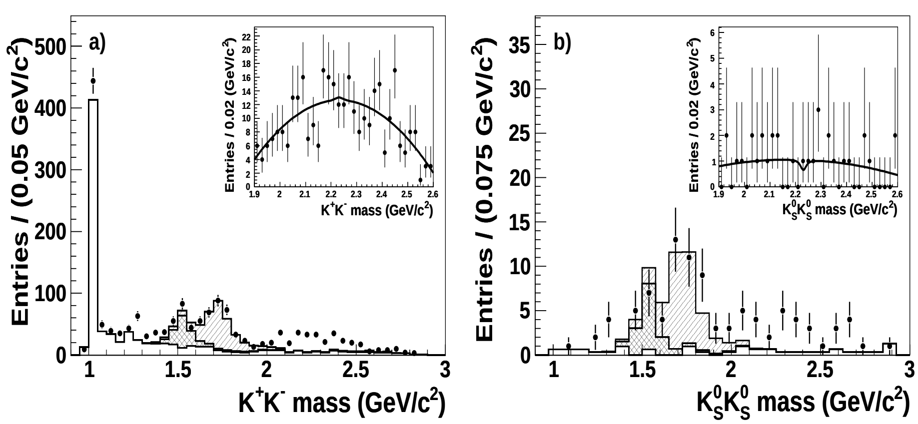

Figure 2: The fitted mass distribution for (a) K^+K^- and (b) $K^0_S K^0_S$. The contributions of the inclusive background (open histograms), $J/\psi \to \gamma f_2'(1525)$ (cross hatched histograms), and $J/\psi \to \gamma f_0(1710)$ (hatched histograms) are shown. The insets show the fit results in the $\xi(2220)$ region.

BABAR experiments [13, 14, 15, 16, 17]. Since then, several other charmonium-like states have been discovered [18]. The $X(3872)$ is the most-studied state and the only one which has been identified in more than one decay mode, assuming that the reported X, Y, and Z states are actually different states. A great deal of effort has been expended to understand the nature of the $X(3872)$ especially its spin-parity assignment (J^{PC}). So far, $J^{PC} = 1^{++}$ or 2^{-+} can be assigned to the $X(3872)$. The radiative decays $X(3872) \to \gamma J/\psi$ [19, 20, 21] and $X(3872) \to \gamma\psi(2S)$ [21] indicate positive C parity. At *BABAR*, no charged-partner for the $X(3872)$ has been observed [22]. This establishes $I = 0$.

In a previous *BABAR* analysis [23] of $B \to J/\psi\omega K$ decays, the observation of the $Y(3940)$ meson in the decay $Y(3940) \to J/\psi\omega$, as reported by the Belle Collaboration [24], was confirmed. In this analysis, $\omega \to \pi^+\pi^-\pi^0$ ($\omega \to 3\pi$) candidates were required to satisfy $0.7695 \leq m_{3\pi} \leq 0.7965\ \mathrm{GeV}/c^2$, and no evidence for the decay $X(3872) \to J/\psi\omega$ was found.

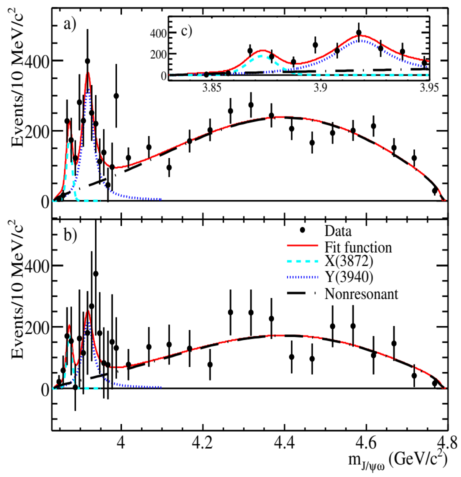

Figure 3: The $J/\psi\omega$ mass distribution for (a) $B^+ \to J/\psi\omega K^+$ and (b) $B^0 \to J/\psi\omega K^0_S$ decays; (c) shows the region $m_{J/\psi\omega} < 3.95$ GeV/c^2 of (a). The curves show the fit results and the individual fit contributions.

In a more recent *BABAR* analysis [2] the same decay mode $B \to J/\psi\omega K$ has been revisited using a slightly larger dataset and extending the range of the ω-mass region to $0.74 \le m_{3\pi} \le 0.7965$ GeV/c^2. All other selection criteria are the same as in the previous analysis [23]. The efficiency as a function of $m_{J/\psi\omega}$ varies between 5 and 7%, and the mass resolution degrades from 6.5 MeV/c^2 to 9 MeV/c^2, over the accessible mass range. The $J/\psi\omega$ mass ($m_{J/\psi\omega}$) distribution, after background subtraction, shows a clear signal corresponding to $Y(3940) \to J/\psi\omega$, and evidence for $X(3872) \to J/\psi\omega$. These signals are present in both B^+ and B^0 samples [25] as shown in Fig. 3. The $m_{J/\psi\omega}$ distributions are fitted simultaneously after correcting for efficiency and branching fractions. The function used in the fit has three components: an $X(3872)$ component which is a Gaussian function with fixed $\sigma = 6.7$ MeV/c^2; a $Y(3940)$ contribution described by a relativistic S-wave Beit-Wigner function; and a nonresonant contribution given by a broad Gaussian function multiplied by $m_{J/\psi\omega}$. The $Y(3940)$ and nonresonant components are multiplied by the phase space factor pq, where p is the kaon momentum in the B rest frame and q is the J/ψ momentum in the $J/\psi 3\pi$ system. A good fit is obtained ($\chi^2/NDF = 54.7/51$). The fit results are summarized in Table 1.

When combined with the product branching fraction for $B \to X(3872)K$, $X(3872) \to J/\psi\pi^+\pi^-$ [17], the *BABAR* ratio of branching fractions $\mathscr{B}(X(3872) \to J/\psi\omega)/\mathscr{B}(X(3872) \to J/\psi\pi^+\pi^-)$ has the value 0.7 ± 0.3 and 1.7 ± 1.3 (combined uncertainties) for B^+ and B^0, respectively. These results provide an average ratio of 0.8 ± 0.3, which is in agreement with the Belle result [19] of $1.0 \pm 0.4 \pm 0.3$.

To judge whether the 3π originate from ω decays or not, 3π events in the mass range of ω and η signals are selected. The sum of the ω-Dalitz-plot weights [23] is consistent with the number of 3π events around the ω signal. The same sum for the events around η signal is consistent with zero. The sum for the weighted 3π mass distribution associated with the $X(3872)$ is consistent with the number of events observed. This justifies the ω interpretation of the events in the $X(3872)$ region.

Quantity	Measurement
Mass $X(3872)$ (MeV/c^2)	$3873.0^{+1.8}_{-1.6} \pm 1.3$
Mass $Y(3940)$ (MeV/c^2)	$3919.1^{+3.8}_{-3.4} \pm 2.0$
Width $Y(3940)$ (MeV)	$31^{+10}_{-8} \pm 5$
$\mathscr{B}(B^0 \to X(3872)K^0) \times \mathscr{B}(X(3872) \to J/\psi\omega)$ (10^{-5})	$0.6 \pm 0.3 \pm 0.1$
$\mathscr{B}(B^+ \to X(3872)K^+) \times \mathscr{B}(X(3872) \to J/\psi\omega)$ (10^{-5})	$0.6 \pm 0.2 \pm 0.1$
$\mathscr{B}(B^0 \to Y(3940)K^0) \times \mathscr{B}(Y(3940) \to J/\psi\omega)$ (10^{-5})	$2.1 \pm 0.9 \pm 0.3$
$\mathscr{B}(B^+ \to Y(3940)K^+) \times \mathscr{B}(Y(3940) \to J/\psi\omega)$ (10^{-5})	$3.0^{+0.7}_{-0.6}{}^{+0.5}_{-0.3}$
$\mathscr{B}(B^0 \to J/\psi\omega K^0)$ (10^{-4})	$2.3 \pm 0.3 \pm 0.3$
$\mathscr{B}(B^+ \to J/\psi\omega K^+)$ (10^{-4})	$3.2 \pm 0.1^{+0.6}_{-0.3}$
R_X (ratio of B^0 to B^+ branching fraction to $B \to X(3872)K$)	$1.0^{+0.8}_{-0.6}{}^{+0.1}_{-0.2}$
R_Y (ratio of B^0 to B^+ branching fraction to $B \to Y(3940)K$)	$0.7^{+0.4}_{-0.3} \pm 0.1$
$R_{\rm NR}$ (ratio of B^0 to B^+ branching fraction to nonresonant $J/\psi\omega K$)	$0.7 \pm 0.1 \pm 0.1$

Table 1: Results obtained from the most recent *BABAR* analysis of $B \to J/\psi\omega K$ decays [2].

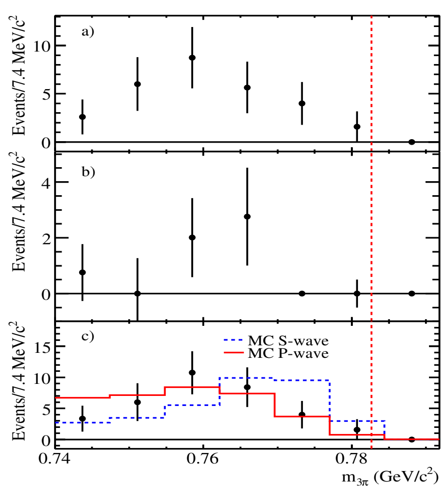

Figure 4: The $m_{3\pi}$ distribution for events that satisfy $3.8625 \leq m_{J/\psi\omega} \leq 3.8825$ GeV/c^2 for (a) B^+, (b) B^0, and (c) combined. The vertical line shows the ω nominal mass. In (c), the solid (dashed) histogram shows the P-wave (S-wave) Monte Carlo events normalized to the number of data events.

The events with $3.8625 \leq m_{J/\psi\omega} \leq 3.8825$ GeV/c^2 are selected for further investigation of the $X(3872)$ parity. For those events, the $m_{3\pi}$ distributions are shown in Fig. 4 and compared with the Monte Carlo simulation for different spin assignment. The P-wave assignment is favored ($\chi^2/NDF = 3.53/5$) over the S-wave ($\chi^2/NDF = 10.17/5$), hence $J^P = 2^-$ is favored over $J^P = 1^+$, but the latter cannot be ruled out. Clearly this analysis would benefit greatly from the much larger datasets available from future facilities such as the Super B-factories.

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