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Quarkonium Spectroscopy at Babar

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Abstract. The Babar experiment at the high luminosity storage ring PEP-II offers excellent opportunities in quarkonium spectroscopy. Recent Babar results obtained in this field are reported.

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INTRODUCTION

The $X(3872)$ state was first observed by the Belle collaboration [1] in the decay $B^{\pm} \to K^{\pm} J/\psi\pi^+\pi^-$, where a narrow signal in the $J/\psi\pi^+\pi^-$ invariant mass is observed at 3872 MeV/c^2. The observation was then confirmed by CDF [2], D0 [3] and Babar [4]. The following observation of other states in the 4 GeV mass region at the B-factories ($Y(3940)$, $X(3940)$, $Z(3930)$ and $Y(4260)$), renewed the interest in quarkonium spectroscopy as well as the need to investigate their properties to shed light on their nature.

The Babar detector [5] is located at the PEP-II B-factory, an asymmetric e^+e^- collider at $\sqrt{s} = 10.58$ GeV. The experiment, designed to perform precision measurements of CP violation in the B meson system, has a much broader physics reach and an extensive program of quarkonium spectroscopy.

Quarkonium states are produced at B-factories through different processes: B decays ($B \to K + c\bar{c}$), two photon production ($\gamma^*\gamma^* \to c\bar{c}$, where two photons emitted by the e^+ and e^- interact to form even C-parity states), double charmonium production ($e^+e^- \to c\bar{c} + c\bar{c}$) and initital state radiation ($e^+e^- \to \gamma_{ISR}c\bar{c}$, where a photon is emitted by one of the $e^{\pm}$ before interaction, lowering $\sqrt{s}$ for the e^+e^- annihilation, and allowing the direct production of states with quantum numbers $J^{PC} = 1^{--}$).

INVESTIGATION OF THE $X(3872)$

The $X(3872)$ was discovered in the decay $B^{\pm} \to K^{\pm} + X(3872)$. The mass value and the fact that $B^{\pm} \to K^{\pm} + c\bar{c}$ is a typical decay mode of the B meson, suggest the possible charmonium nature of the state. However, its mass is not compatible with existing predictions from potential models, and its likely $J/\psi\rho^0$ decay mode would be forbidden for charmonium states because of isospin symmetry. Moreover the mass value is exactly at the threshold for $D^0\bar{D}^{*0}$ production.

For these reasons, other explanations have been proposed, like a $D\bar{D}^*$ molecule [6, 7] or diquark-antidiquark state [8]. To discriminate among different models, experimen-

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tal results about the quantum numbers, the decay modes, the branching fractions, the angular distributions, and the existence of charged partners are needed.

The decays $B^- \to K^- J/\psi\pi^+\pi^-$ and $B^0 \to K_s^0 J/\psi\pi^+\pi^-$ have been studied using a sample of 211 fb^{-1} of data, corresponding to 232 millions of $B\bar{B}$ pairs recorded by Babar, as reported in [9].

We obtain 61 ± 15 and 8.3 ± 4.5 $X(3872)$ decay events in B^- and B^0 decay respectively, with signal significance of 6.1σ and 2.5σ including systematic uncertainty .

The decay $B^0 \to K^0 X(3872)$ is predicted to be suppressed by one order of magnitude in the $D\bar{D}^*$ molecule hypothesis [10]. Using the number of events and the efficiency we measure $\mathscr{B}^- = \mathscr{B}(B^- \to K^- X(3872), X \to J/\psi\pi^+\pi^-) = (10.1 \pm 2.5 \pm 1.0) \times 10^{-6}$ and $\mathscr{B}^0 = \mathscr{B}(B^0 \to K^0 X(3872), X \to J/\psi\pi^+\pi^-) = (5.1 \pm 2.8 \pm 0.7) \times 10^{-6}$. In the ratio of branching fractions some sources of systematic error cancel and we have $R = \mathscr{B}^0/\mathscr{B}^- = 0.50 \pm 0.30(\mathrm{stat}) \pm 0.05(\mathrm{syst})$.

In the diquark-antidiquark interpretation, the $X(3872)$ state can have quark content $X_u = (cu)(\bar{c}\bar{u})$ and $X_d = (cd)(\bar{c}\bar{d})$, and a mass difference of 7 ± 2 MeV is predicted [8]. The two different mass states should be produced differently in B^- and B^0 decay. From our data we obtained a mass difference $\Delta m = (2.7 \pm 1.3)$ MeV/c^2.

Though no clear interpretation can be obtained from the present data, the method seems promising and more data are needed to discriminate between different models.

Search for $X(3872)$ charged partners

Babar searched for $X(3872)$ charged partners in charged and neutral B decays $B^- \to \bar{K}^0 J/\psi\pi^-\pi^0$ and $B^0 \to K^+ J/\psi\pi^-\pi^0$, by looking at the $J/\psi\pi^-\pi^0$ invariant-mass distribution for 212 fb^{-1} of data; this corresponds to 234×10^6 $B\bar{B}$ events. No charged partner was observed [11], and we determined the upper limits $\mathscr{B}(B^0 \to K^+ X^-, X^- \to J/\psi\pi^-\pi^0) < 5.4 \times 10^{-6}$ and $\mathscr{B}(B^- \to \bar{K}^0 X^-, X \to J/\psi\pi^-\pi^0) < 22 \times 10^{-6}$ at 90% confidence level.

INCLUSIVE CHARMONIUM IN B DECAY

A novel technique for the study of charmonium states consists in the reconstruction of everything except the charmonium state itself. In events in which one B is fully reconstructed, it is possible to determine the rest frame of the recoiling B from the reconstructed B and the beam parameters. The distribution of the K momentum in the recoiling B system presents a series of monochromatic peaks due to two body decays $B \to K + X$, where X is predominantly a charmonium state, superimposed on a continuum background due to K's from secondary or multi-body decays. This technique allows the observation of X states independently of decay mode, and hence the measurement of absolute branching fractions $\mathscr{B}(B \to K + X)$.

The observed $K^\pm$ momentum distribution in the $B^\pm$ rest frame, after a neural network selection, is shown in Figure 1. An unbinned maximum likelihood fit is used to extract the signal yields for nine possible charmonium states. The branching fractions are summarized in Table 1.

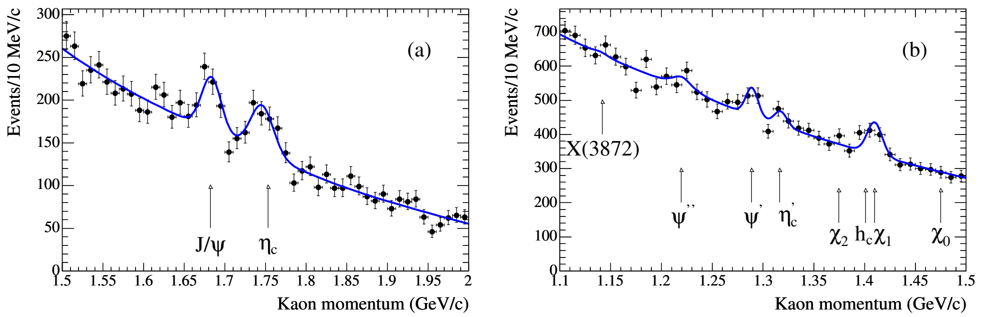

FIGURE 1. The $K^{\pm}$ momentum distribution in the $B^{\pm}$ rest frame. Peaks corresponding to $K^{\pm}\eta_c$ and $K^{\pm}J/\psi$ decay are visible in the high momentum region (a) and to $K^{\pm}\chi_{c1}$, $K^{\pm}\eta_c'$, $K^{\pm}\psi'$, and $K^{\pm}\psi''$ decay in the low momentum region (b).

TABLE 1. Yields and branching fractions for $\mathscr{B}(B^{\pm} \to K^{\pm}X)$. Upper limits are given at 90% CL.

Particle	**Yield**	$\mathscr{B}$ (10^{-4})	**Particle**	**Yield**	$\mathscr{B}$ (10^{-4})
η_c	273 ± 43	$8.4 \pm 1.3 \pm 0.8$	η_c'	98 ± 52	$3.4 \pm 1.8 \pm 0.3$
J/ψ	259 ± 41	$8.1 \pm 1.3 \pm 0.7$	ψ'	139 ± 44	$4.9 \pm 1.6 \pm 0.4$
χ_0	9 ± 21	< 1.8	ψ''	99 ± 69	$3.5 \pm 2.5 \pm 0.3$
$\chi_1 + h_c$	227 ± 40	$8.0 \pm 1.4 \pm 0.7$	$X(3872)$	15 ± 39	< 3.2
χ_2	0 ± 36	< 2.0			

No signal is found for the decay $B^{\pm} \to K^{\pm}X(3872)$, and we obtain an upper limit for the corresponding branching fraction (Table 1). Using the Belle/Babar average $\mathscr{B}(B^{\pm} \to K^{\pm}X(3872)) \cdot \mathscr{B}(X(3872) \to J/\psi\pi^+\pi^-) = (13.3 \pm 2.5) \cdot 10^{-6}$ we can extract a lower limit $\mathscr{B}(X(3872) \to J/\psi\pi^+\pi^-) > 4.2\%$ at 90% CL. No signal of two body decay is observed looking at the $K^{\pm}$ momentum distribution in B^0 decay, therefore we determine the upper limit $\mathscr{B}(B^0 \to K^{\pm}X(3872)^{\mp}) < 5 \times 10^{-4}$ at 90% CL for the production of $X(3872)$ charged partners in B decays.

In the fit to the $K^{\pm}$ momentum distribution, the central value for each signal peak is usually fixed at the value expected from the mass of the corresponding charmonium state. If the peak position is left floating in the fit it is possible to measure the recoiling mass, in this way we obtain $m_{\eta_c} = 2982 \pm 5$ MeV/c^2 and $m_{\eta_c'} = 3639 \pm 7$ MeV/c^2.

DOUBLE CHARMONIUM PRODUCTION

Charmonium states can be observed through the process of double charmonium production $e^+e^- \to \gamma^* \to J/\psi c\bar{c}$. In the recoil of a J/ψ, only $c\bar{c}$ states with even C-parity are expected, although a production of odd C-parity states is possible through $e^+e^- \to \gamma^*\gamma^* \to J/\psi c\bar{c}$.

The invariant mass distribution recoiling against a J/ψ is shown in Figure 2. Clear signals are observed for η_c, χ_{c0} and η_c', while there is no evidence of χ_{c1}, χ_{c2} and odd C-parity states [12]. The measured cross sections agree with the Belle results [13] and

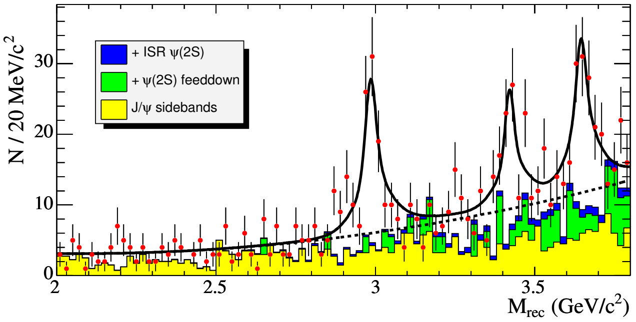

FIGURE 2. The distribution of missing mass recoiling against inclusively-produced J/ψ. The fit result (solid curve) shows clear evidence of η_c, χ_{c0} and η_c' production over background (dashed curve). The histograms represent the contributions from different sources of background.

are larger with respect to NRQCD expectations [14, 15]. Because of the requirement in the event selection of 5 or more tracks to be detected, we measure $\sigma(e^+e^- \to J/\psi c\bar{c}) \times \mathscr{B}(c\bar{c} \to> 2 \text{ charged}) = 17.6 \pm 2.8^{+1.5}_{-2.1}$ fb for $J/\psi\eta_c$, $10.3 \pm 2.5^{+1.4}_{-1.8}$ fb for $J/\psi\chi_{c0}$, and $16.4 \pm 3.7^{+2.4}_{-3.0}$ fb for $J/\psi\eta_c'$.

INITIAL STATE RADIATION

In initial state radiation (ISR) processes, a photon is radiated from either the e^+ or the e^- before the interaction, so the e^+e^- annihilation occurs at an energy smaller than the nominal energy of the machine. This technique is particularly interesting at the B-factories, where the nominal center of mass energy of the interaction is fixed, since it permits an energy scan of e^+e^- annihilation interactions. In the $e^+e^- \to \gamma_{ISR}X$ process, only X states with $J^{PC} = 1^{--}$ are produced.

The ISR photon is not necessarily detected in the analysis, but its presence can be inferred from the small values of the missing mass squared recoiling against the final state and the missing transverse momentum. Moreover, the process $e^+e^- \to \gamma_{ISR}\psi'$ provides a well known benchmark channel.

The reaction $e^+e^- \to \gamma_{ISR}J/\psi\pi^+\pi^-$ has been studied using 233 fb^{-1} of data, and the corresponding $J/\psi\pi^+\pi^-$ invariant mass distribution for the selected events is shown in Figure 3. A broad enhancement at 4260 MeV/c^2, called $Y(4260)$, is clearly observed [16]. An unbinned fit with a Breit-Wigner signal function and a second order polynomial background yields 125 ± 23 $Y(4260) \to J/\psi\pi^+\pi^-$ events, with a mass $M_Y = 4259 \pm 8(\text{stat})^{+2}_{-6}(\text{syst})$ MeV/c^2 and a width $\Gamma_Y = 88 \pm 23(\text{stat})^{+6}_{-4}(\text{syst})$ MeV.

Search for the $Y(4260)$ in B decays

A search for the $Y(4260)$ in B decays has been performed by studying the decay $B^\pm \to K^\pm J/\psi\pi^+\pi^-$ using 211 fb^{-1} of data. Fixing M_Y and Γ_Y to the values measured in the ISR production process, an excess of 128 ± 42 events compatible with $B^\pm \to$

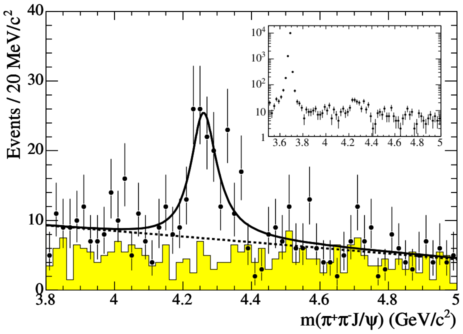

FIGURE 3. The $J/\psi\pi^+\pi^-$ invariant-mass distribution in the range 3.8-5.0 GeV/c^2 for $e^+e^- \rightarrow \gamma_{ISR}J/\psi\pi^+\pi^-$ events; the same distribution for the 3.5-5.0 GeV/c^2 region, including the ψ' peak, is shown in the inset. The solid line is the fit of the distribution with a relativistic Breit-Wigner and a second order polynomial background (dashed line). The histogram represents the background estimated from the J/ψ sideband regions.

$K^{\pm}Y(4260)$, $Y(4260) \rightarrow J/\psi\pi^+\pi^-$ is observed [9]. More data are needed therefore for a study of $Y(4260)$ production in B decay.

SUMMARY

The Babar experiment is performing an extensive study of the spectroscopy and production mechanisms of the new charmonium states. Recent results on the $X(3872)$ state have been presented, and a new state called $Y(4260)$ has been observed recently in ISR processes.

Further investigation and new data will help in the study of quarkonium spectroscopy and in understanding the nature of the states whose interpretation is still unclear.

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