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New Spectroscopy at BaBar

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The Babar experiment at the SLAC B factory has accumulated a high luminosity that offers the possibility of systematic studies of quarkonium spectroscopy and of investigating rare new phenomena. Recent results in this field are presented.

1. Introduction

In recent times spectroscopy has become exciting again, after the discovery of new states that are not easily explained by conventional models. States such as the $X(3872)$ and the $Y(4260)$ could be new excited charmonium states, but require precise measurements for positive identification.

The BaBar experiment [1] is installed at the asymmetric storage ring PEP-II. 90% of the data accumulated by BaBar are taken at the Y(4S) (10.58 GeV) and 10% just below (10.54 GeV). The BaBar detector includes a 5-layer, double-sided silicon vertex tracker and a 40-layer drift chamber in a 1.5 T solenoidal magnetic field, which detect charged particles and measures their momenta and ionization energy losses. Photons, electrons and neutral hadrons are detected with a CsI(Tl)-crystal electromagnetic calorimeter. An internally reflecting ring-imaging Cherenkov is also used for particle id. Penetrating muon and neutral hadrons are identified by an array of resistive-plate chambers embedded in the steel of the flux return. The detector allows good track and vertex resolution, good particle id and good photon detection so it is expecially suited for specstroscopy studies.

2. The $X(3872)$ State

The $X(3872)$ was discovered by Belle [2] in the decay $B \to KX$ with $X \to J/\Psi\pi\pi$, and shortly afterwards confirmed by CDF [3], D0 [4] and BaBar [5]. The X mass, measured by all 4 experiments, is 3871.9 ± 0.5, just slightly above the D^0D^{*0} threshold; its width is less than 2.3 MeV.

The X could be one of the many missing charmonium states. However, many of the possible assignments are eliminated because of the small width of the X, others because the measured mass does not agree with the predictions of most potential models. Other interpretations have been proposed, including the diquark-antidiquark model [6] and the S-wave D^0D^{*0} molecule model [7].

The first interpretes the X as a 1^{++} diquark-antidiquark state with the two quark combinations $X_u = (cu)(\overline{cu})$ and $X_d = (cd)(\overline{cd})$ with a mass difference of 7 ± 2 MeV. These two states could form mixed states that are produced in neutral and charged B decays with different masses and rates, depending on the mixing angle. In fact the model predicts one amplitude to be dominant in the neutral mode and the other amplitude to be dominant in the charged mode.

The molecule model interpretes the X as a losely bound 1^{++} state of charm mesons that is produced in weak decays of the B-meson into D^0D^{*0} K. Using factorization, heavy quark symmetry and isospin symmetry, the model predicts the decay of the neutral B to X suppressed by an order of magnitude relative to the charged B decay.

2.1. Search for a Charged Partner

In the $X(3872)$ decays observed by Belle and BaBar, the $\pi\pi$ invariant mass peaks near the kinematic upper limit and is consistent with the ρ^0 decay. If the observed decay is indeed $X \to J/\Psi\rho^0$, and these states and their decays respect isospin symmetry, then there must be an X^- that decays to $J/\Psi\rho^-$ and the rate $B \to X^-$ should be

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twice that of $B \to X^0$

BaBar performed a search for $B^- \to K^0 X^-$ and $B^0 \to K^+ X^-$. The plots in Fig.[1] show the $J/\Psi\pi\pi$ mass spectra for neutral and charged B modes. With 211 fb^{-1} no charged X signal was found [8] and upper limits for the corresponding branching fractions were extracted: $\mathcal{B}$ $((B^0 \to K^+X^-) \times (X^- \to J/\Psi\pi^-\pi^0)) < 5.4 \times 10^{-6}$ and $\mathcal{B}$ $((B^- \to K^0X^-) \times (X^- \to J/\Psi\pi^-\pi^0)) < 22 \times 10^{-6}$.

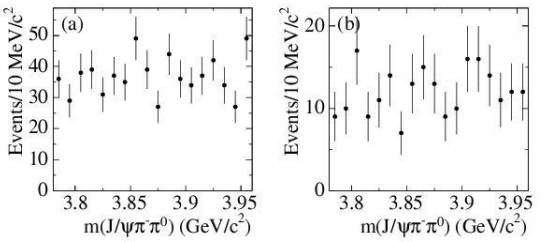

Figure 1. Invariant mass of the $J/\Psi\pi\pi$ system for (a) $B^0 \to K^+J/\Psi\pi^-\pi^0$ decays and (b) $B^- \to K^0J/\Psi\pi^-\pi^0$.

2.2. Exclusive Decays

BaBar searched for the $X(3872)$ in the decay $B^0 \to K_sX$, $X \to J/\Psi\pi\pi$, and updated the original study in charged B decays [9] . The measured mass difference between the two possible states is $2.7 \pm 1.3 \pm 0.2$ MeV, compatible both with the diquark-antidiquark prediction and with 0. The measured branching fractions are $\mathcal{B}$ $((B^0 \to K^0X) \times (X \to J/\Psi\pi\pi)) = (5.1 \pm 2.8 \pm 0.7) \times 10^{-6}$, $\mathcal{B}$ $((B^+ \to K^+X) \times (X \to J/\Psi\pi\pi)) = (8.5 \pm 2.4 \pm 0.8) \times 10^{-6}$. Their ratio is, at 90% C.L, 0.15 <R< 1.34. So the ratio is well compatible with 1, which is what is expected in the diquark-antidiquark model, while in the molecule model the neutral mode branching fraction is predicted to be at least 10 time smaller than the charged mode.

2.3. Direct Measurement of $\mathcal{B}(B \to KX)$

When the $X(3872)$ is reconstructed from its decay to a certain final state what is measured is the product of two branching fractions, and the knowledge on $\mathcal{B}(B \to KX)$ is diluted. There is a complementary approach, which is based on the measurement of the Kaon momentum spectrum in the B rest frame, that allows a direct measurement of the $B \to KX$ branching fraction.

With this technique, access to the B rest frame is provided by the complete reconstruction of the other B of the event. Once the other B is reconstructed, a recoiling Kaon is found and its momentum is calculated in the first B rest frame. The distribution of the Kaon momentum shows a series of monochromatic peaks due to two-body $B \to Kx$ decays superimposed to a background due to Kaons from secondary or multi-body decays. Since the event topology changes with the

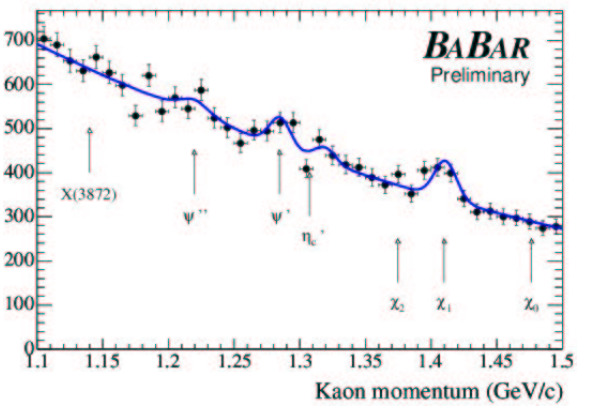

Figure 2. Kaon momentum in the B rest frame (high mass region). The solid curve represents the result of the fit described in the text.

recoil mass, two mass regions were considered separately in the event selection. The high mass spectrum [Fig. 2] was fitted with a background + seven signal functions, that correspond to the possible x states. The results are summarized in

Table 1
Branching fractions for $B \to K X_{c\overline{c}}$

	Inclusive	PDG(2004)
η_c	8.9 ± 1.5	9.0 ± 2.7
J/Ψ	8.1 ± 1.6	10.0 ± 0.4
χ_{c0}	< 1.8	$6.0 \pm 2.4 \pm 2.1$
χ_{c1}	7.0 ± 1.6	6.8 ± 1.2
χ_{c2}	< 2	
η_c(2S)	3.1 ± 1.5	
$\Psi^{'}$	4.2 ± 1.4	6.8 ± 0.4
$\Psi^{''}$	3.1 ± 2.3	
$X(3872)$	< 3.2	

Table 1. No signal was found for the χ_{c0}, for the χ_{c0}, or for the $X(3872)$.

Using the upper limit on the $B \to KX$ branching fraction and the BaBar-Belle average on the product of this branching fraction and of the branching fraction of $X \to J/\Psi\pi\pi$ we obtained the lower limit $\mathcal{B}\ (X \to J/\Psi\pi\pi) > 4.3\%$ @90% $C.L.$.

The same inclusive technique was used to search for a charged partner of the $X(3872)$ in neutral B decays. No signal was found, and the limit for the corresponding branching fraction is 5×10^{-4}.

2.4. ISR Production

The $X(3872)$ direct production in e^+e^- annihilations through initial-state radiation is possible only if the X is a 1^{--} state, which is unlikely for a narrow state well above the $D\overline{D}$ threshold.

The reaction $e^+e^- \to \gamma J/\Psi\pi\pi$, with the J/Ψ recontructed from its $\mu\mu$ decay, was studied in BaBar using 89 fb^{-1}. No signal for the $X(3872)$ was observed (Fig. 3), and the limit on $\mathcal{B}\ (X \to J/\Psi\pi\pi)\ \times\Gamma^X_{ee} < 6.2\ eV$ was set.

3. The $Y(4260)$ State

The ISR process gives access to e^+e^- annihilations to vector mesons for a continuous spectrum of energies below the beam energy.

BaBar is studying $e^+e^- \to \gamma J/\Psi\pi\pi$ across the whole charmonium mass range. The $J/\Psi\pi\pi$ invariant mass spectrum in the range $3.8 - 5.0\ GeV$ is shown in Fig. 3. An enhancement near 4.26 GeV is clearly visible, while no other structures are evident at the masses of the 1^{--} charmonium states or at the $X(3872)$. An unbinned maximum likelihood fit was performed to the mass distribution using a a second-order polynomial background + a relativistic Breit-Wigner signal function, multiplied by a phase space factor and convoluted with the mass resolution function. The

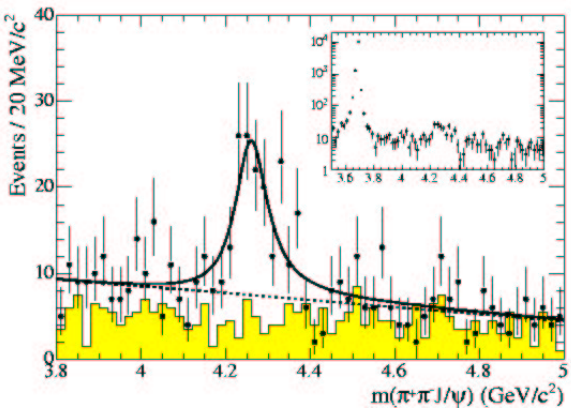

Figure 3. Invariant mass of the $J/\Psi\pi\pi$ system in the range $3.8 - 5.0\ GeV$ and (inset) over a wider range that includes the $\Psi(2S)$.The points represent the selected data, the histogram the scaled data from sidebands. The solid curve shows the result of the fit described in the text; the dashed curve represents the background.

Table 2
Double charmonium production. Cross sections measured (fb): $\sigma \times \mathcal{B}_2(c\bar{c} \to > 2$ charged tracks), and theory predictions.

	$J/\Psi\eta_c$	$J/\Psi\chi_{c0}$	$J/\Psi\eta_c^{'}$
BaBar	$17.6 \pm 2.8 \pm 2.1$	$10.3 \pm 2.5 \pm 1.8$	$16.4 \pm 3.7 \pm 3.0$
Belle [12]	$25.6 \pm 2.8 \pm 3.4$	$6.4 \pm 1,7 \pm 1.0$	$16.5 \pm 3.0 \pm 2.4$
NRQCD [10]	2.31 ± 1.09	62.28 ± 1.03	0.96 ± 0.45
NRQCD [11]	5.5	6.9	3.7

fit gives 125 ± 23 events, $M_Y = 4259 \pm 8^{+2}_{-6}\ MeV$ and $\Gamma_Y = 88 \pm 23^{+6}_{-4}\ MeV$. The systematic uncertainties include contributions from the fitting procedures, the mass scale, the mass resolution function and the model of the $Y \to J/\Psi\pi\pi$ decay. The likelihood difference between signal and null hypothesis corresponds to a significance $> 8\sigma$.

We measured $\mathcal{B}\ (Y \to J/\Psi\pi\pi)\ \times\Gamma^Y_{ee} = 5.5 \pm 1.0^{+0.8}_{-0.7}\ eV$. For a Γ^Y_{ee} of the order of the corresponding $\Psi(4040)$ width, the branching fraction would be of the order of 1%.

4. Double Charmonium Production

Both BaBar and Belle observed prompt J/Ψ and $\Psi^{'}$ production in e^+e^- reactions. These interactions offer the possibility to search for excited charmonium states, while the charmonium mass spectrum can provide important information on interquark forces and confinement. In addition, the production and decay of these $c\bar{c}$ states is very important in testing and understanding perturbative and non-perturbative QCD.

The invariant mass spectrum of the system that recoils against a J/Ψ which is fully reconstructed from its dilepton decays is shown in Fig.4. The spectrum is fitted to a background plus signal functions representing η_c, χ_{c0} and $\eta_c^{'}$.

The $\eta_c^{'}$-$\Psi^{'}$ mass splitting is important to understand spin-spin interactions in the confinement region. We measured the mass difference $M_{\eta_c^{'}} - M_{\eta_c} = 660.2 \pm 6.8 \pm 7.6 MeV$, in good agreement with other recent measurements.

The cross sections measured for each of the 3 $c\bar{c}$ states are shown in Table 2, together with theoretical predictions [10,11] and with Belle's [12] measurements. The agreement with Belle is good, while both experiments are in disagreement with

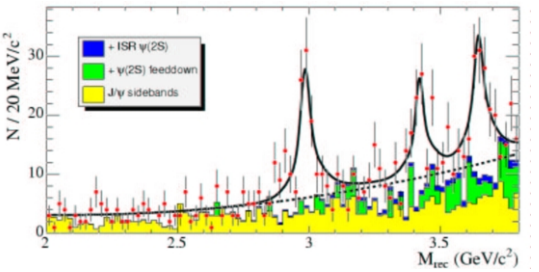

Figure 4. Mass recoiling against a J/Ψ. The solid curve shows the result of the fit described in the text; the dashed curve represents the background.

NRQCD calculations. It has been suggested however [13] that the disagreement be due to a poor approximation of the real dynamics of c quarks by NRQCD.

The charmonium states observed have even C-parity, and can be produced by one-virtual-photon interactions. It has been also suggested [14] that part of the charmonium production may be due to two-virtual-photon interactions. Only these intractions can produce odd C-parity states, such as for instance J/Ψ. Including odd C-parity states in the fit, we find no evidence for such states, so no evidence for two-photon interactions.

5. Summary

The large statistics which is being accumulated at the B factories offers the possibility of systematic studies of (quarkonium) spectroscopy. We have reported on some of such studies, studies intended to understand the nature of the $X(3872)$

and the mass spectrum and production cross section of excited charmonium states. We have also reported the observation in ISR events of a new state, the $Y(4260)$.

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