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Study of inclusive charmonium production in e^+e^- annihilation and B decays at *BABAR*

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We report on new charmonium studies performed by the *BABAR* experiment located at the PEP-II asymmetric energy e^+e^- collider at the SLAC National Accelerator Laboratory.

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1. Charmonium Spectroscopy

Charmonium, since its discovery in 1974 [1, 2], has been a powerful tool for the understanding of the strong interaction. The charmonium spectrum consists of eight narrow states below the open charm threshold at 3.73 GeV/c^2, the $\psi(3770)$, and a significant number of states above the threshold. Below the threshold all of the states are well established, and no additional states are expected. On the other hand, our understanding is still very limited above the threshold, where there are several new "Charmonium-like" states that are very difficult to accommodate in the charmonium spectrum.

The B-factories are an ideal place to study charmonium states since they may be produced in four different processes:

- B decays, in which charmonium states with any quantum numbers can be produced.
- Two photon production where two virtual photons are emitted by the colliding e^+e^- pair ($e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-(c\bar{c})$) and charmonium states with $J^{PC} = 0^{\pm+}, 2^{\pm+}, 4^{\pm+}, ..., 3^{++}, 5^{++}$... can be produced.
- Initial State Radiation (ISR), in which a photon is emitted by the incoming electron or positron in the reaction $e^+e^- \to \gamma_{ISR}c\bar{c}$, where only states with $J^{PC} = 1^{--}$ can be formed.
- Double charmonium production, where a J/ψ or a $\psi(2S)$ is produced together with another charmonium state.

2. Measurements of the inclusive production of charm(-onium) states in the quasi-two-body decays $B \to X + K$

In the inclusive B decay process to a two-body final state, $B^\pm \to X + K^\pm$, the state X is predominantly a $c\bar{c}$ state with large available phase space and a priori no strong selection rules. It is therefore expected that X will range over the complete charmonium spectrum, and that the production rate of all charmonium states will be roughly equal [3]. This is what has been observed up to now using exclusive reconstruction of many charmonium states X ($\eta_c, J/\psi, \chi_{c0}, \chi_{c1}, \eta_c(2S), \psi', \psi''$) and subsequent observation of the decay $B^\pm \to X + K^\pm$ [4, 5].

BABAR proposed a complementary approach, based on the measurement of the kaon momentum spectrum measured in the B center of mass frame, where two body decays can be identified by their characteristic monochromatic kaon momentum. The B center of mass frame is determined event-by-event by fully reconstructing the other B meson. The branching ratios for the two-body decays $B \to X + K$ can thus be measured independently of any a-priori knowledge of the X decay properties.

BABAR updated and extended the previous analysis [6], which was based on 210 fb^{-1}. The available statistics have been doubled (424 fb^{-1}), the recoil B reconstruction efficiency has been increased and the mass range has been extended in both the low and high mass region.

The charged kaon momentum spectrum between 1.5 and 2 GeV/c is expected to exhibit two peaks, one at $p = 1.684$ GeV/c corresponding to the J/ψ and the second at $p = 1.754$ GeV/c for the η_c meson. This double peak structure is unambiguously observed in Figure 1(a). The kaon

momentum spectrum between 1.05 and 1.6 GeV/c is shown in Figure 1(b), where clear signals are found for four states: χ_{c0}, χ_{c1} (they refer the unknown admixture of χ_{c1} and h_c as χ_{c1}), $\eta_c(2S)$ and ψ'. No signal is found for the χ_{c2} and for the X(3872) state. The search for massive narrow resonances is shown in Figure 1(c); no signal has been observed. The fit results and the branching fraction measurements are summarized in Table 1; the upper limits are specified at 90% confidence level.

In the kaon momentum region from 1.9 to 2.5 GeV/c, the two-body peaks corresponding to the Cabibbo-suppressed decays $B^\pm \to K^\pm + \bar{X^0}$ and $B^- \to K^- D^0$ (where D^0 represents any excited state of the $D^0/\bar{D^0}$ meson) can be studied. Figure 1(d) shows clear peaks for the D^0 and D^{*0}. There is also the observation of $D^{**}(2680)$ with 3.3σ significance. The fit results and the branching fraction measurements are summarized in Table 2.

A similar analysis has been performed with charged kaons selected with a fully reconstructed B^0 meson. No evidence for any charmonium-like charged states has been found in the kaon momentum spectrum for a charged kaon recoiling against a B^0 meson. Figure 2(a) shows the kaon momentum in the D region with clear signal seen, for the $D^\pm$, $D^{*\pm}$ and $D^{*\pm}(2420)$. No higher mass states are observed. No evidence for a $D^{**}(2680)$. The fit results and the branching fraction measurements are summarized in Table 3.

Table 1: $B^\pm \to K^\pm X^0$: Results obtained from the fit to the kaon momentum spectrum.

Particle	Yield	Peak (MeV/c^2)	Width (MeV)	BF(10^{-4})
J/ψ	516 ± 67			9.6 ± 1.2(stat) $\pm$ 0.8(syst)
η_c	655 ± 77	2982 ± 5	< 43	13.3 ± 1.8(stat) $\pm$ 0.4(syst) $\pm$ 0.3(ref)
χ_{c0}	218 ± 76			4.4 ± 0.9(stat)
χ_{c1}	192 ± 35			7.0 ± 1.3(stat) $\pm$ 1.0(syst)
χ_{c2}	0 ± 32			< 1.2
$\eta_c(2S)$	283 ± 94	3632 ± 0.007	< 33	6.0 ± 2.1(stat) $\pm$ 0.4(syst)
ψ'	293 ± 90			6.2 ± 2.0(stat) $\pm$ 0.6(syst)
$\psi(3770)$	0 ± 49			< 2.0
$X(3872)$	75 ± 81			1.4 ± 1.5(stat) or < 4.4

Table 2: $B^\pm \to K^\pm X^0$: Results obtained from the fit to the kaon momentum spectrum in the D mass region.

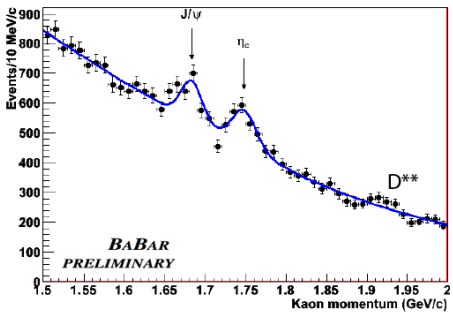
Particle	Yield	Peak (MeV/c^2)	BF(10^{-4})	PDG 2014 [7]
D^0	126 ± 20		3.5 ± 0.5(stat) $\pm$ 0.3(syst)	3.7 ± 0.17
D^{*0}	126 ± 21		3.5 ± 0.5(stat) $\pm$ 0.3(syst)	4.2 ± 0.34
$D_1(2420)^0$	97 ± 25		2.1 ± 0.5(stat) $\pm$ 0.3(syst)	-
$D^{**0}(2680)$	95 ± 29	2.68 ± 0.003	2.1 ± 0.6(stat) $\pm$ 0.3(syst)	-

3. Conclusion

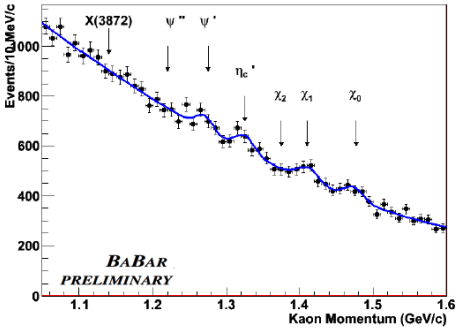
We report on preliminary results on the measurements of the inclusive production of charm(-onium) in the quasi-two-body decays $B \to X + K$.

Table 3: $B^0 \to K^{\pm}X^{\mp}$: Results obtained from the fit to the kaon momentum spectrum in the D mass region.

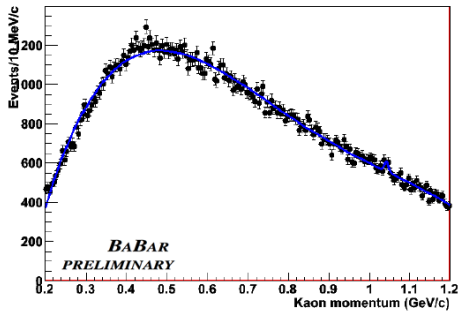
Particle	Yield	Peak (MeV/c^2)	BF(10^{-4})	PDG 2014 [7]
$D^{\pm}$	44 ± 10		3.3 ± 0.8(stat) $\pm$ 0.3(syst)	2.0 ± 0.2
$D^{*\pm}$	40 ± 10		3.0 ± 0.8(stat) $\pm$ 0.3(syst)	2.1 ± 0.2
$D^*(2420)^{\pm}$	52 ± 13		3.9 ± 1.0(stat) $\pm$ 0.3(syst)	-



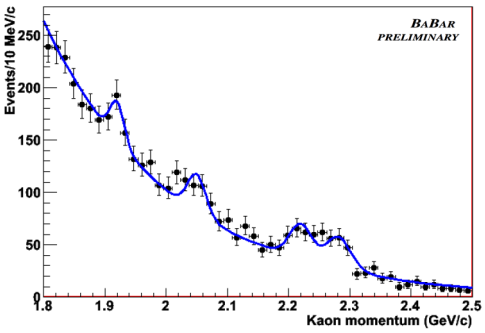
(a) Kaon momentum spectrum for the η_c - J/ψ region.



(b) Kaon momentum spectrum between 1.05 and 1.6 GeV/c.



(c) Kaon momentum spectrum in the range 200 MeV/c to 1 GeV/c corresponding to the search of high mass, small-width, charmonium-like states.



(d) Kaon momentum spectrum in the D region

Figure 1: $B^{\pm} \to K^{\pm}X^0$: Measured kaon momentum spectra.

Because these measurements are inclusive, they can be used in conjunction with exclusive final state masurements to determine absolute charmonium and $D^{(*)}$ branching fractions, particularly for the η_c and $\eta_c(2S)$. They also provide lower bounds for observed $X(3872)$ modes. With the 100x statistics anticipated from Belle II, the precision of branching fraction measurements will become a few percent.

We observe a new D^{**} with mass (2680$\pm$3) MeV/c^2 with 3.3σ significance. We do not observe the charged analogue.

The measured branching fractions are consistent with PDG 2014 [7] values.

References

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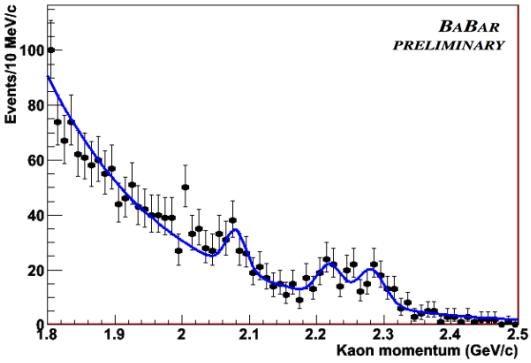
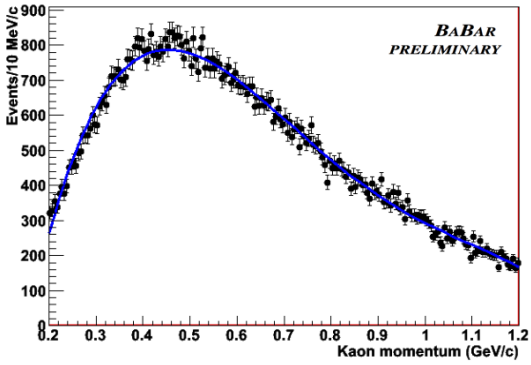


(a) Kaon momentum spectrum for events with a fully reconstructed B^0 candidate in the D region.



(b) Kaon momentum spectrum for events with a fully reconstructed B^0 candidate in the high mass region.

Figure 2: $B^0 \to K^{\pm}X^{\mp}$: Measured kaon momentum spectra.

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