Measurements of the Absolute Branching Fractions of $B^\pm \to K^\pm X_c$
We study the two-body decays of $B^\pm$ mesons to $K^\pm$ and a charmonium state, $X_{cc}$, in a sample of 210.5 fb$^{-1}$ of data from the BABAR experiment. We perform measurements of absolute branching fractions $B(B^\pm \to K^\pm X_{cc})$ using a missing mass technique, and report several new or improved results. In particular, the upper limit $B(B^\pm \to K^\pm X(3872)) < 3.2 \times 10^{-4}$ at 90% CL and the inferred lower limit $B(X(3872) \to J/\psi\pi^+\pi^-) > 4.2\%$ will help in understanding the nature of the recently discovered $X(3872)$.

PACS numbers: 13.25.Hw, 14.40.Gx

Several exclusive decays of $B$ mesons of the form $B^\pm \to K^\pm X_{cc}$ (where $X_{cc}$ is one of the charmonium states $\eta_c$, $J/\psi$, $\chi_{c0}$, $\chi_{c1}$, $\eta_c'$, $\psi'$, $\psi''$), have been observed by reconstructing the charmonium state from its decay to some known final state, $f$. In principle, such $B$ decays provide a direct probe of charmonium properties since the phase space is large for all known states and all should be produced roughly equally, in the absence of a strong selection rule. However, with this technique only the product of the two branching fractions $B(B^\pm \to K^\pm X_{cc}) \times B(X_{cc} \to f)$ is measured, thereby reducing the precision of $B(B^\pm \to K^\pm X_{cc})$ when the daughter branching fraction is poorly known.

We describe here a complementary approach, based on the measurement of the kaon momentum spectrum in the $B$ center-of-mass frame, where two-body decays can be identified by their characteristic monochromatic line, allowing an absolute determination of $B(B^\pm \to K^\pm X_{cc})$. Knowledge of the $B$ center-of-mass system is obtained by exclusive reconstruction of the other $B$ meson from a $\Upsilon(4S)$ decay. In addition to obtaining new information on known charmonium states, this method is used to search for the $X(3872)$ state, recently observed in $B$ mesons using a missing mass technique, and report several new or improved results. The nature of $X(3872)$ is still unclear, different interpretations have been proposed but should be produced roughly equally, in the absence of a strong selection rule. However, with this technique only the product of the two branching fractions $B(B^\pm \to K^\pm X_{cc}) \times B(X_{cc} \to f)$ is measured, thereby reducing the precision of $B(B^\pm \to K^\pm X_{cc})$ when the daughter branching fraction is poorly known.

For this analysis we use a data sample of 210.5 fb$^{-1}$ integrated luminosity, corresponding to $3 \times 10^3$ $B\bar{B}$ pairs. The data have been collected with the BABAR detector at the SLAC PEP-II asymmetric-energy collider, where 9 GeV electrons and 3.1 GeV positrons collide at a center-of-mass energy 10.58 GeV, corresponding to the mass of the $\Upsilon(4S)$ resonance. A detailed description of the BABAR detector can be found in [1]. Charged tracks are reconstructed with a 5 layer silicon vertex tracker (SVT) and a 40 layer drift chamber (DCH), located in a 1.5 T magnetic field generated by a superconducting solenoid. The energy of photons and electrons is measured with an electromagnetic calorimeter made up of CsI(Tl) crystals. Charged hadron identification is done with ionization measurements in the SVT and DCH and with an internally reflecting ring imaging Cherenkov detector. The instrumented flux return of the solenoid is used to identify muons.

The analysis is performed on a sample of events where a $B$ meson is fully reconstructed ($B_{\text{recon}}$). For these events, the momentum of the other $B$ ($B_{\text{signal}}$) can be calculated from the momentum of $B_{\text{recon}}$ and the beam parameters. We select events with a $K^\pm$ not used for the reconstruction of $B_{\text{recon}}$ and calculate its momentum ($p_K$) in the $B_{\text{signal}}$ center of mass system.

$B_{\text{recon}}$ mesons are reconstructed in their decays to exclusive $D^{(*)}H$ final states, where $H$ is one of several combinations of $\pi^\pm$, $K^\pm$, $\pi^0$ and $K_S^0$ hadrons; a detailed description of the method can be found in [2].

The number of $B^\pm$ events in the data is determined with a fit to the distribution of the beam energy substituted mass $m_{ES} = \sqrt{E_{CM}^2/4 - p_T^2}$, where $E_{CM}$ is the total center-of-mass energy, determined from the beam parameters, and $p_T$ is the measured momentum of $B_{\text{recon}}$ in the center-of-mass frame. The fit function is the sum of a Crystal Ball function describing the signal and an ARGUS function for each background component ($e^+e^- \to q\bar{q}$ where $q$ is $u$, $d$, $s$ or $c$ or misreconstructed $B$s), the relative weights of which are obtained from a Monte Carlo simulation (MC), while the total normalization factor is determined from the data. A total of $378580 \pm 1110$ events with a fully reconstructed $B^\pm$ is obtained.

Fifteen variables related to the $B_{\text{recon}}$ decay characteristics, its production kinematics, the topology of the full event, and the angular correlation between $B_{\text{recon}}$ and the rest of the event are used in a neural network (NN1) to reduce the large background, mainly due to non-$B$ events. The network has 80% signal efficiency while rejecting 90% of the background. The $m_{ES}$ distribution after this selection is shown in Fig. [3]. Only events with $5.275 < m_{ES} < 5.285$ GeV/$c^2$ are used in the analysis.

We now consider only tracks not associated with
$B_{\text{recon}}$. Most $K^\pm$ produced in $B^\pm$ decays originate from $D$ mesons and their spectrum, although broad, peaks at low $p_K$. In the $B^\pm$ rest frame, these $K^\pm$ are embedded in a “minijet” of $D$ decay products, while signal $K^\pm$ recoil against a massive (3–4 GeV/c$^2$) state and therefore tend to be more isolated. A second neural network (NN2) rejects background from secondary $K^\pm$, by using fifteen input variables describing the energy and track multiplicities measured in the $K^\pm$ hemisphere, the sphericity of the recoil system, and the angular correlations between the $K^\pm$ and the recoil system. These variables have been chosen to be independent of the particular decay topology of the recoil system. Since the topology of the event changes with the recoil mass, we have considered separately two recoil mass regions in the training of this neural network: the “high-mass” region, corresponding to $1.0 < p_K < 1.5$ GeV/c and the “low-mass” region, for $1.5 < p_K < 2.0$ GeV/c. The signal training sample is $B^\pm \rightarrow K^\pm X_{c\bar{c}}$ MC simulation while the background sample consists of simulated $K^\pm$ from $D$ meson decays in the same momentum range. The chosen cuts on the NN2 outputs correspond to 85% signal efficiency; the background rejection factor varies between 2.5 in the $X(3872)$ and $\psi'$ region and 1.5 in the $J/\psi$ region. The selection criteria are optimized for MC signal significance with the high-mass region blinded.

The kaon momentum distribution shows a series of peaks due to the two-body decays $B^\pm \rightarrow K^\pm X_{c\bar{c}}$ corresponding to the different $X_{c\bar{c}}$ masses, superimposed on a smooth spectrum due to $K^\pm$ coming from multibody $B^\pm$ decays, or non-$B^\pm$ background. The mass of the $X_{c\bar{c}}$ state ($m_X$) can be calculated directly from $p_K$ using $m_X = \sqrt{m_B^2 + m_K^2 - 2E_Km_B}$, where $m_B$ and $m_K$ are the $B^\pm$ and $K^\pm$ masses and $E_K$ is the $K^\pm$ energy. The resonance width $\Gamma_X$ can be obtained from the Breit-Wigner width of the peak in the $p_K$ spectrum $\Gamma_K$, obtained after deconvolution with the momentum resolution function, using $\Gamma_X = \Gamma_K\beta_Km_B/m_X$, where $\beta_K = p_K/E_K$.

We determine the number of $B^\pm \rightarrow K^\pm X_{c\bar{c}}$ events ($N_X$) from a fit to the $p_K$ distribution. The branching fraction for the decay channel is calculated as:

$$B(B^\pm \rightarrow K^\pm X_{c\bar{c}}) = \frac{N_X}{\epsilon_X \cdot N_B},$$

where $\epsilon_X$ is the efficiency determined from the MC and $N_B$ the number of $B^\pm$ mesons in the sample. An alternative method, which we use to improve the branching fraction measurement in the case of $\eta_c$, is to normalize to the channel $B^\pm \rightarrow K^\pm J/\psi$, which is well-measured in the literature, according to:

$$B(B^\pm \rightarrow K^\pm X_{c\bar{c}}) = \frac{N_X}{N_{J/\psi}} \cdot \frac{\epsilon_{J/\psi}}{\epsilon_X} \cdot B(B^\pm \rightarrow K^\pm J/\psi).$$

In this relative measurement, the systematic errors that are common to both resonances cancel in the ratio. The two methods are combined to extract $B(B^\pm \rightarrow K^\pm \eta_c)$, taking into account the correlations between them.

We fit the $p_K$ spectrum using an unbinned maximum likelihood method. The background is well modeled by a
third degree polynomial and each signal is a Breit-Wigner function folded with a resolution function. The masses and widths of the $\eta_c$ and $\eta_c'$ mesons are left free; all others are fixed to values from reference [11]. The resolution function has two parts: a Gaussian with $\sigma$ varying from 6 MeV/c at $p_K = 1.1$ GeV/c to 12 MeV/c at $p_K = 1.7$ GeV/c describes the 72.5% of the signal where the $B$-recon is correctly reconstructed; if $B$-recon is incorrect, but has $m_{BS}$ within our range, the $p_K$ resolution is a bifurcated Gaussian with $\sigma = 78$ and 52 MeV/c on the left and right hand side of the peak respectively.

The spectrum in the low-mass region is expected to exhibit two peaks, at $p_K = 1.683$ GeV/c corresponding to the $J/\psi$, and at $p_K = 1.754$ GeV/c for the $\eta_c$ meson. These two peaks are clearly seen in Fig. 2(a); both have a significance of $\sim 7\sigma$. The number of events under each peak obtained from the fit is $N(\eta_c) = 259 \pm 41$ and $N(\eta_c') = 273 \pm 43$.

The spectrum in the high-mass region is fitted with a background and seven signal functions, corresponding to the following states: $\psi', \chi_{c0}, \chi_{c1}, \chi_{c2}, \psi''', \eta_c'$ and $X(3872)$. The resulting fit is shown in Fig. 2(b), with the yields given in Table I. The $h_c$ charmonium state lies near the $\chi_{c1}$, and it is difficult to distinguish the peaks from these two decays. A fit including the $h_c$ yields a number of $h_c$ events consistent with zero, and a fit performed with free $\chi_{c1}$ mass and width gives values consistent with a narrow $\chi_{c1}$, therefore we have no evidence for $h_c$ production.

Several sources of systematic error affecting these measurements have been evaluated. The relative errors on absolute measurements are the same for all states; many of these cancel partially in relative measurements, and all are summarized in Table II. “$B$ counting” refers to uncertainties in the fit parametrization used to determine the number of fully reconstructed $B_{\text{recon}}^\pm$. It is one of the largest errors in absolute measurements, and cancels in ratios. The mass scale is verified to a precision of 1.5 MeV/c in $p_K$ by floating the masses of the well-measured $J/\psi$, $\chi_{c1}$ and $\psi''$ peaks; we assign a systematic error corresponding to this shift. We also consider variations in the background and signal model parametrizations, which partially cancel in the case of ratios. Errors in the $K^\pm$ track reconstruction and identification efficiency are evaluated by comparing data and MC control samples. The systematic error in the NN1 and NN2 selections is evaluated by comparing efficiencies and distributions in data and MC, and studying efficiency variation with $p_K$. We verified that the NN2 selection is not dependent on visible energy or multiplicity of the recoil part of the $B$ meson decay. Adding in quadrature, the total relative error on an absolute measurement is 9.0%. The total is reduced to 3.3% for the relative measurement of $J/\psi$ and $\eta_c$, and to 5.9% for states in the high-mass region relative to $J/\psi$. For the extraction of relative branching fractions, an additional 4% error, labeled (ext) in the following, comes from the present uncertainty of $B(B^\pm \rightarrow K^\pm J/\psi) = (10.0 \pm 0.4) \times 10^{-4}$ [13].

In the high-mass region, clear signals are found for $\chi_{c1}$ and $\psi''$ (with significance 6.0 and 3.2$\sigma$ respectively), an excess of events is present for $\eta_c$ and $\psi''$ [12], while no signal is found for $\chi_{c2}$ and $X(3872)$. The branching fractions and upper limits are summarized in Table II. In the low-mass region, our $J/\psi$ measurement is consistent with the world average. From the $\eta_c$ and $J/\psi$ yields and the reference branching fraction we can derive the result with the relative measurement method $B(B^\pm \rightarrow K^\pm \eta_c)_{rel} = (10.6 \pm 2.3\text{(stat)} \pm 0.4\text{(sys)} \pm 0.4\text{(ext)}) \times 10^{-4}$. We combine this result with the absolute measurement of Table II taking the correlated errors into account, to obtain $B(B^\pm \rightarrow K^\pm \eta_c) = (8.7 \pm 1.5) \times 10^{-4}$.

We obtain from our fits the $\eta_c$ and $\eta_c'$ masses and widths and find $m_{\eta_c} = 2982 \pm 5$ MeV/$c^2$, $\Gamma_{\eta_c} < 43$ MeV and $m_{\eta_c'} = 3639 \pm 7$ MeV/$c^2$, $\Gamma_{\eta_c'} < 23$ MeV, where the
width limits are both at 90\% CL.

Taking $B(B^+ \to K^+ X(3872)) < 3.2 \times 10^{-4}$, and using an average of the Belle [4] and BABAR [5] measurements of $B(B^+ \to K^+ X(3872)) \times B(X(3872) \to J/\psi \pi^+ \pi^-)$ we set a lower limit $B(X(3872) \to J/\psi \pi^+ \pi^-) > 4.2\%$ at 90\% CL. This branching fraction, for which there are not yet any predictions, is sensitive to the distribution of charm quarks inside the $X(3872)$. A search for charged partners of the $X(3872)$ is performed by examining $K^\pm$ recoiling from a sample of 245.6k reconstructed $B^0$ decays. No signal is seen and we find $B(B^0 \to K^\pm X(3872)\mp) < 5 \times 10^{-4}$ at 90\% CL.

We combine our $B(B^\pm \to K^\pm \eta_c)$ with a previous BABAR measurement of $B(B^\pm \to K^\pm \eta_c) \times B(\eta_c \to K\bar{K}\pi)$ [13] to obtain $B(\eta_c \to K\bar{K}\pi) = (8.5 \pm 1.8)\%$, significantly improving the precision of the world average [11]. Since this branching fraction is used as a reference for all $\eta_c$ yield measurements, our result will lead to more precise $\eta_c$ partial widths and more stringent comparisons with theoretical models. For example, from an average of $B(J/\psi \to \eta_c) \times B(\eta_c \to K\bar{K}\pi)$ measured by Mark-III [14], DM2 [15] and BES [16], we obtain $B(J/\psi \to \gamma\gamma) = (0.79 \pm 0.20)\%$, and using the value $\Gamma(\eta_c \to \gamma\gamma) \times B(\eta_c \to K\bar{K}\pi) = 0.48 \pm 0.06$ keV [11] we calculate $\Gamma(\eta_c \to \gamma\gamma) = (5.6 \pm 1.4)$ keV. Both results are more precise than the world average [11]. Similarly, we obtain $B(\eta_c \to K\bar{K}\pi) = (8 \pm 5)\%$ and $\Gamma(\eta_c \to \gamma\gamma) = (0.9 \pm 0.5)$ keV.

In conclusion, a novel technique is used to measure directly the absolute branching fractions of the various charmonium states $X_{cc}$ in two-body decays $B^\pm \to K^\pm X_{cc}$ (Table I). The results for $X_{cc} = \eta_c, J/\psi, \psi'$ are in agreement with previous measurements, and the $\eta_c$ result significantly improves the present world average. Upper limits are set for $\chi_{c0}$ and $\chi_{c2}$, confirming factorization suppression [17]. Measurements of $B^{\pm} \to K^{\pm} \eta_c'$ and $B^{\pm} \to K^{\pm} \psi''$ branching fractions are reported, although with poor significance. Upper limits are given for $X(3872)$ and for production of a possible charged partner in $B^0$ decays.

We are grateful for the excellent luminosity and machine conditions provided by our PEP-II colleagues, and for the substantial dedicated effort from the computing organizations that support BABAR. The collaborating institutions wish to thank SLAC for its support and kind hospitality. This work is supported by DOE and NSF (USA), NSERC (Canada), IHEP (China), CEA and CNRS-IN2P3 (France), BMBF and DFG (Germany), INFN (Italy), FOM (The Netherlands), NFR (Norway), MIST (Russia), and PPARC (United Kingdom). Individuals have received support from CONACyT (Mexico), A. P. Sloan Foundation, Research Corporation, and Alexander von Humboldt Foundation.

\* Also with Universit\`a di Perugia, Dipartimento di Fisica, Perugia, Italy
\dagger Also with Universit\`a della Basilicata, Potenza, Italy
Deceased

[1] B. Aubert et al. [BABAR Collaboration], Phys. Rev. D 67, 032002 (2003) [arXiv:hep-ex/0207097].
[2] S. K. Choi et al. [Belle collaboration], Phys. Rev. Lett. 89, 102001 (2002) [Erratum-ibid. 89, 129901 (2002)] [arXiv:hep-ex/0206002].
[3] C. Quigg, arXiv:hep-ph/0403187, and references therein.
[4] S. K. Choi et al. [Belle Collaboration], Phys. Rev. Lett. 91, 262001 (2003) [arXiv:hep-ex/0309032].
[5] B. Aubert et al. [BABAR Collaboration], arXiv:hep-ex/0406022.
[6] T. Barnes and S. Godfrey, Phys. Rev. D 69 (2004) 054008 [arXiv:hep-ph/0311162]. E. J. Eichten, K. Lane and C. Quigg, Phys. Rev. D 69, 094019 (2004) [arXiv:hep-ph/0401210]. E. S. Swanson, Phys. Lett. B 588, 189 (2004) [arXiv:hep-ph/0311229]. N. A. Tornqvist, Phys. Lett. B 590, 209 (2004) [arXiv:hep-ph/0402237]. L. Maiani, F. Piccinini, A. D. Polosa and V. Riquer, Phys. Rev. D 71, 014028 (2005) [arXiv:hep-ph/0412098].
[7] B. Aubert et al. [BABAR Collaboration], Nucl. Instrum. Meth. A 479, 1 (2002) [arXiv:hep-ex/0105044].
[8] B. Aubert et al. [BABAR Collaboration], Phys. Rev. Lett. 92, 071802 (2004) [arXiv:hep-ex/0307062].
[9] The Crystal Ball function is a gaussian with a small power-law term added to the left, used to describe the mass spectrum in exclusive $B$ decays. T. Skwarnicki et al. [Crystal Ball Collaboration], DESY F31-86-02, 1986 (unpublished).
[10] The Argus function is commonly used to describe continuum background in $B$ mass spectra. H. Albrecht et al. [ARGUS Collaboration], Phys. Lett. B 316, 608 (1993).
[11] S. Eidelman et al. [Particle Data Group], Phys. Lett. B 592, 1 (2004).
[12] K. Abe et al. [Belle Collaboration], Phys. Rev. Lett. 93, 051803 (2004) [arXiv:hep-ex/0307061].
[13] B. Aubert et al. [BABAR Collaboration], Phys. Rev. D 70, 011101 (2004) [arXiv:hep-ex/0403007].
[14] R. M. Baltrusaitis et al. [Mark-III Collaboration], Phys. Rev. D 33, 629 (1986).
[15] D. Bisello et al. [DM2 collaboration], Nucl. Phys. B 350, 1 (1991).
[16] J. Z. Bai et al. [BES Collaboration], Phys. Lett. B 578, 16 (2004) [arXiv:hep-ex/0308073].
[17] C. Meng, Y. J. Gao and K. T. Chao, arXiv:hep-ph/0502240, arXiv:hep-ph/0506222.