Measurements of the Absolute Branching Fractions of $B^\pm \to K^\pm X_{c\bar{c}}$

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A study of the two body decays $B^+ \rightarrow X_{cc} K^+$, where $X_{cc}$ refers to one charmonium state, is reported by the BABar collaboration using a data sample of 424 fb$^{-1}$. The absolute determination of
branching fractions for these decays are significantly improved compared to previous BABAR measurements. Evidence is found for the decay $B^+ \rightarrow X(3872)K^+$ at the 3σ level. The absolute branching fraction $B(B^+ \rightarrow X(3872)K^+) = (2.1 \pm 0.6(stat) \pm 0.3(syst)) \times 10^{-4}$ is measured for the first time. It follows that $\mathcal{B}(X(3872) \rightarrow J/\psi\pi^+\pi^-) = (4.1 \pm 1.3)\%$, supporting the hypothesis of a molecular component for this resonance.

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In two-body $B$ decays $B \rightarrow XK$, the $X$ particle is predominantly a $cc$ system with large available phase space. Many charmonium states are thus produced, with approximately equal rates when no strong selection rules apply. They have mostly been observed using an exclusive reconstruction of the charmonium state $X_{cc} (\eta_c, J/\psi, \chi_{c1}, \chi_{c2}, \eta_c(2S), \psi')$, with possibly the associated observation of the decay $B^{+} \rightarrow X_{cc} K^{+}$. The exotic charmonium state $X(3872)$, also known as $\chi_{c1}(3872)$, has also been reconstructed in this way.

The determination of the absolute branching fraction $B(B^{+} \rightarrow X(3872)K^{+})$ will lead to the absolute $B(X(3872) \rightarrow J/\psi \pi^+ \pi^-)$, which brings useful information regarding the complex nature of the $X(3872)$ particle. The original tetraquark model predicted this branching fraction to be around 50%. A more refined tetraquark model could accommodate a much smaller branching fraction to be around 50%. A more refined description of the $B^{+}$ decays can be found in Ref. 14, 15.

The analysis method is a recoil technique similar to that presented in Ref. 12. The complete exclusive reconstruction of one of the two $B$ mesons produced in the event provides access to the rest frame of the other $B$ meson. Signal events contain two-body $B^{\pm}$ decays to $K^{\mp}X$. For such decays, the kaon momentum in the $B$ center-of-mass frame, $p_k$, exhibits a peak for each $X$ particle, with mass $m_X = \sqrt{m_B^2 + m_K^2 - 2E_Km_B}$, where $m_B$ and $m_K$ are the masses of the $B$ and $K$ mesons and $E_K$ is the kaon energy in the $B$ rest frame. The $p_k$ spectrum will contain, in addition to a series of signal peaks, a background due to kaons coming from non-two-body decays or from decays of charmed mesons. We determine the observed number of each charmonium resonance $X_{cc}$ from a fit to the kaon momentum distribution.

Event selection requires the reconstruction of a tagger $B^{\pm}$ meson in the event (B-tag). These are reconstructed as $B \rightarrow SY$ decays, where the seed $S$ is a fully reconstructed $D^0, D^{\pm}, D_s^{\pm}$ or $J/\psi$, and $Y$ represents a combination of $\pi^\pm$, $K^\mp$, $\pi^0$, and $K^0_S$ hadrons. For each mode, the purity (defined as $S/(S+B)$, where $S$ is the number of signal events and $B$ the number of background events) is determined. A minimum purity of 0.08 is required. The number of $B$ candidates is determined with a fit, shown in Fig. 1, to the distribution of the $B$-energy-substituted mass, $m_{ES} = \sqrt{E_{CM}^2/4 - p_B^2}$. Here, $E_{CM}$ is the $B$ total center-of-mass energy, determined from the beam parameters, and $p_B$ is the measured momentum of the reconstructed $B$ in the $Y$(4S) rest frame. The fit function is the sum of a Crystal Ball function describing the signal and an ARGUS function for the background. A better agreement between the data and the fit function would have required a separate fit for each running period, which is not necessary for this analysis.

The number of fully reconstructed $B^{\pm}$ decays found by the fit is $1.67 \times 10^6 \pm 4 \times 10^5 (stat) \pm 6 \times 10^5 (syst)$. The systematic uncertainty is dominated by the background shape near the kinematic end point.
If more than one $B$ candidate is found in a given event, all candidates are retained. This is an important difference compared to Ref. [12] and also the subsequent Belle analysis [19], where only one candidate per event was retained. There are two reasons for this change: first to increase the efficiency and second to decouple as much as possible the signal and tag sides in $B^+B^−$ events. Tag $B$ candidates coming from the reconstruction of a signal decay channel should not be considered as the only tag as this could lead to discarding another genuine tag and a signal loss. The mean number of $B$-tag candidates per event is 1.85. The absence of a best-event selection is the main reason for the efficiency improvement, which reaches its maximum value of three for the $X(3872)$ because of its decays to $D$ mesons, which were previously another source of event rejection.

Event selection criteria are as follows: Each $B$-tag candidate should have $m_{ES} > 5.275$ GeV/$c^2$ and be accompanied by an opposite-sign kaon candidate, passing a tight particle identification selection. The pion contamination in this kaon sample is below 2%. A first neural network (NN) is then used to suppress the continuum background. The inputs to the NN are seven variables related to the reconstructed $B$ characteristics, to its production kinematics, to the topology of the full event and to the angular correlation between the reconstructed $B$ and the rest of the event. The NN selection has an 80% efficiency for generic $B^+B^−$ events and a factor 10 rejection against non-$B$ background events coming from $u, d, s, \text{ or } c$ quark-antiquark pairs.

A second NN is used to reject secondary kaons produced in $B$-daughter $D$ meson decays. This is a large background that increases rapidly with decreasing kaon momentum. In the $B$ rest frame, the secondary kaons are embedded in the $D$ decay products, which, given the boost of the $D$ meson and its mass, are bounded in a cone and form a wide jet, whereas primary kaons (those forming the signal of this analysis) recoil against a massive (3 to 4 GeV/$c^2$) state and tend to be more isolated, with the rest of the $B$ decay products being more spherical. The input variables to this NN take advantage of these characteristics [12]. These two NN are then combined in a single neural net, called SuperNN, to optimize further the signal to background. Because of the slow but non-negligible variation of the event topology with the mass of the charmonium particle, the SuperNN is trained separately in the $J/\psi$ and $\eta_c$ signal region, and in the $\psi'$ and $\eta_c(2S)$ region, with kaon background taken from simulation in the momentum ranges 1.6–1.9 and 1.2–1.5 GeV/$c$, respectively. The SuperNN performance corresponds to a 72% signal efficiency at the $X(3872)$ peak and a background rejection factor varying between three in the $X(3872)$ and $\psi'$ region and 4.5 in the $J/\psi$ region.

To analyze the kaon momentum spectrum we first determine the background shape and second perform a fit to the background-subtracted spectrum. The shape of the background spectrum is determined by interpolating through regions where no signal is expected, below 1.1 and above 1.9 GeV/$c$. Using only these two regions leads to a large uncertainty in the background parameters, and it is, therefore, necessary to add data points in the two regions $1.34–1.36$ GeV/$c$ and $1.53–1.57$ GeV/$c$, where there is no peak, as indicated on Fig. 2.

Figure 2 also shows the fit to the simulated signal $K^\pm$ momentum spectrum for all charmonia peaks in the simulation. A good description is obtained when using, for each peak, a narrow Gaussian, whose width depends on momentum varying from 13 MeV/$c$ for the $J/\psi$ to 9 MeV/$c$ for the $\psi'$, and a two-piece Gaussian, 100 MeV/$c$ wide on the left and 60 MeV/$c$ wide on the right. A similar fit is performed for the $X(3872)$ with a dedicated Monte Carlo sample and is shown in Fig. 3. The narrow width is measured to be 7 MeV/$c$ and the wide Gaussian tails are 47 MeV/$c$ on each side. All parameters describing the shape of various signal peaks will be kept fixed to these values in the fit to data. The wide Gaussian is associated with candidates where the $B$-tag has a reconstructed $m_{ES}$ in the signal region but is not built with the correct set of $B$ decay products and, therefore, provides an incorrect boost. The relative importance of the wide Gaussian term is proportional to the background under the $B$ mass peak. The level of this background depends on the signal-side final state, particularly on whether the charmonium state decays to a final state containing open-charm mesons, such as the $\psi(3770)$ or the $X(3872)$. This effect induces a higher efficiency for the $X(3872)$: the MC efficiency is found to be $(0.25 \pm 0.07)\%$ for $J/\psi K^\pm$ events and $(0.77 \pm 0.02)\%$ for $X(3872) K^\pm$ events. It also gives rise to systematic uncertainties in the signal shape, due to the limited knowledge of the decay channels of the particle under study.

When using the intermediate points to interpolate the
background, the tails from the $J/\psi$ and $\eta_c(2S)$ peaks extending into these intermediate regions are subtracted using the simulation with the known branching fractions for these resonances [20]. The fit function is a product of fifth-order Chebyshev polynomials and an exponential function. The relative systematic uncertainty of the signal yields resulting from the uncertainty in the estimation of these tails is found to be 4%.

Small deviations are observed in the simulation between the background kaon momentum distribution and the fit function. These defects in background shape do not affect the visibility of narrow peaks, such as that of the $X(3872)$ since the expected width of 7 MeV/c is much smaller than the $\sim 50$ MeV/c typical width of the local deviations. The observed residuals in the 1.1 to 1.2 GeV/c region are corrected for, and the resulting uncertainty taken into account.

The kaon momentum spectrum between 1.5 and 2 GeV/c is expected to exhibit two peaks, one at $p_K = 1.684$ GeV/c corresponding to the $J/\psi$ and a second at $p_K = 1.754$ GeV/c for the $\eta_c$ meson. The SuperNN is trained in the $J/\psi-\eta_c$ region and the SuperNN output is required to be $>0.85$ with a $B$ purity larger than 0.08. A fit to the background-subtracted spectrum is performed with the two signal functions determined above, the only free parameters being the charmonia yields. The fit results are displayed in Fig. 3 with the following charmonium yields: $N_{J/\psi} = 2364 \pm 189$ and $N_{\eta_c} = 2259 \pm 188$. The statistical precision obtained on the yields is 8%, a factor of about two improvement compared to Ref. [12].

The branching fraction $\mathcal{B}(B^{\pm} \to K^{\pm}\eta_c)$ is computed using the world average $\mathcal{B}(B^{\pm} \to K^{\pm}J/\psi)$ [20] and the ratio of the yields quoted above, to obtain:

$$\mathcal{B}(B^{\pm} \to K^{\pm}\eta_c) =$$

$$(0.96 \pm 0.12{\text{(stat)}} \pm 0.06{\text{(syst)}} \pm 0.03{\text{("ref")}}) \times 10^{-3},$$

where the systematic uncertainty is detailed in Table I and "ref" refers to the uncertainty in $\mathcal{B}(B^{\pm} \to K^{\pm}J/\psi)$ [20]. This result agrees with the world average for this branching fraction $(1.09 \pm 0.09) \times 10^{-3}$ [20]. As a cross-check, $\mathcal{B}(B^{\pm} \to K^{\pm}J/\psi)$ is also extracted from the ratio of observed $J/\psi$ events obtained in data and simulation: $\mathcal{B}(B^{\pm} \to K^{\pm}J/\psi) = (1.09 \pm 0.09{\text{(stat)}} \pm 0.06{\text{(syst)}}) \times 10^{-3}$, in agreement with the world average.

The higher-mass region was blinded during the initial part of the analysis. Here, the SuperNN is trained in the $\psi'$ region and the SuperNN output is required to be $>0.6$ with a $B$ purity larger than 0.10. The $p_K$ spectrum is fitted using the same procedure as above. The
The background shape is determined using a fit to the signal-free region after correction for the small residual signal in that region estimated from MC simulation. The kaon momentum spectrum before background subtraction is displayed in Fig. 5, and after background subtraction in Fig. 6.

The fit to the background-subtracted signal spectrum (Fig. 6) is a sum of nine signal-peak functions corresponding to the nine particles: $X(3872)$, $\psi(3770)$, $\psi'$, $\eta_c(2S)$, $\chi_{c2}$, $\chi_{c1}$, $\chi_0$, $J/\psi$, and $\eta_c$. The peak locations are taken from Ref. [20] and the widths are obtained from fits to MC signal samples and include both detector resolution and the natural width of each resonance. The peak labelled $\chi_{c1}$ refers to both $\chi_{c1}$ and $h_c$ since these two states cannot be distinguished from each other in this analysis. A binned maximum likelihood fit is performed, with the nine charmonium yields as free parameters. Table II contains the fit results. Signal peaks are visible for $\eta_c$, $J/\psi$, $\chi_{c1}$, $\psi'$, and $X(3872)$. A separate fit in which the $X(3872)$ signal is forced to 0 has a $\chi^2$ larger than that of the nominal fit by 11.1 units, which reduces to 9.0 when accounting for the uncertainty in the background shape in the 1.1 to 1.2 GeV/c region. Thus, there is 3$\sigma$ evidence of the decay $B^\pm \rightarrow X(3872)$, detected for the first time using this recoil technique.

The systematic uncertainties associated with this analysis mainly stem from the imperfect description of the data by the simulation. These uncertainties are similar for all the resonances studied and are computed in detail for the $\eta_c$. The systematic uncertainty attached to the $X(3872)$ must be however treated separately since it suffers from a much larger interpolation error, and from a more limited knowledge regarding its decay modes:

- **Peak position.** A deviation from the known peak position can induce an uncertainty in the number of events from the fit integral, estimated at 1%.
- **Signal shape.** Four parameters are used to describe the signal shape: the main narrow width of the signal peak, the widths of the left-hand side and right-hand side Gaussian tails, and the relative fraction under the narrow Gaussian. The systematic uncertainty resulting from the uncertainty in the signal shape is estimated using the signal-only fit to the simulation sample. When the resonance has a non-negligible natural width, as in the case of the $\eta_c$, the uncertainty in this width is also included.
- **Background subtraction.** The uncertainty of the background fit is propagated, including correlations, into the signal statistical uncertainty and is, therefore, not accounted as a systematic uncertainty. However, the correction due to the signal subtraction in the 1.1 to 1.2 GeV/c region implies a sizeable uncertainty for the $X(3872)$ yield. This uncertainty is determined by taking the effect on the $X(3872)$ yield introduced by a one-sigma deviation of the correction function, and is determined to be 13%.
- **Efficiency determination.** Uncertainties in detection efficiency arise in the kaon reconstruction and particle identification efficiencies, and in the SuperNN-based selection. It is important to note that these uncertainties cancel to a very good approximation in the ratios of the branching fractions of all resonances to the $J/\psi$.

Finally, another systematic uncertainty, specific to the $X(3872)$, results from the uncertainty in its decay model. The signal shape, as mentioned above, is not the same for $DD$ and $J/\psi X$ decays and this effect induces a small
the partial width \( \Gamma(\eta \to \eta c) \) for the \( \eta c(3668) \) total width, as measured in its \( \psi c (2 S) \rightarrow \eta c(3668) c \) has a significant molecular component.

The number of \( X(3872) \) events is converted into an absolute branching fraction using the number of observed \( J/\psi \) events, its absolute branching fraction, and the relative efficiency ratio, with the result: \( B(B^+ \to X(3872)K^+) = (2.1 \pm 0.6(\text{stat}) \pm 0.3(\text{syst}) \pm 0.1(\text{ref})) \times 10^{-4} \). Using the measured product branching fraction \( B(B^+ \to X(3872)K^+) \times B(X(3872) \to J/\psi \pi^+ \pi^-) = (8.6 \pm 0.8) \times 10^{-6} \) [20], this translates into \( B(X(3872) \to J/\psi \pi^+ \pi^-) = (4.1 \pm 1.3)\% \). From this, an upper limit on \( B(B^+ \to \eta_c K^+) \) can be set in the 100 keV range, using 3 MeV as an upper limit for the \( X(3872) \) total width, as measured in its \( DD \) decay channel [21, 22]. Our measurement therefore suggests that the \( X(3872) \) has a significant molecular component.

**CONCLUSIONS**

We report an update to our first analysis [12] with the full \( B\bar{B} \) statistics. Two new features are introduced: the inclusion of all \( B \) candidates has led to an increase of efficiency and a better separation between signal and tag sides of an event; the fit to a polynomial background in regions where no signal is present reduces the statistical and systematic uncertainties related to the background subtraction. We obtain the following results:

\[
B(B^+ \to \eta_c K^+) = (0.96 \pm 0.12(\text{stat}) \pm 0.06(\text{syst}) \pm 0.03(\text{ref})) \times 10^{-3},
\]

\[
B(B^+ \to X(3872)K^+) = (2.1 \pm 0.6(\text{stat}) \pm 0.3(\text{syst}) \pm 0.1(\text{ref})) \times 10^{-4},
\]

\[
B(X(3872) \to J/\psi \pi^+ \pi^-) = (4.1 \pm 1.3)\%.
\]

This result will certainly contribute to the determination of the complex nature of the \( X(3872) \) particle.

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**TABLE I.** Summary of relative systematic uncertainties (in \%) for the \( \eta_c \) and \( X(3872) \) branching fractions, relative to \( B(B^+ \to J/\psi K^+) \).

| Uncertainty source       | \( \eta_c \) (%) | \( X(3872) \) (%) |
|--------------------------|------------------|-------------------|
| \( K \) identification   | 1                | 5                 |
| Decay model              | 0                | 5                 |
| Efficiency               | 0                | 5                 |
| \( p_K \) spectrum: peak position | 2   | 2                 |
| \( p_K \) spectrum: signal narrow width | 1  | 1                 |
| \( p_K \) spectrum: signal wide width | 5  | 5                 |
| \( p_K \) spectrum: narrow width fraction | 2  | 2                 |
| \( p_K \) spectrum: background shape | -  | 13                |
| Decay width              | 1                | -                 |
| Correction in signal-free regions | -  | 4                 |
| Total                    | 6                | 16.3              |

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**TABLE II.** Results from fits to the kaon momentum spectrum. \( B \) stands for the branching fraction for \( B^+ \to X(3872)K^+ \). An additional 3% uncertainty must be added to these results, reflecting the present knowledge of the reference \( B(B^+ \to J/\psi K^+) \).

| Particle | Yield       | \( B(10^{-3}) \) |
|----------|-------------|------------------|
| \( J/\psi \) | 2364\pm189 | 10.1\pm0.29 (Ref. [20]) |
| \( \eta_c \) | 2259\pm188 | 9.6\pm1.2(stat)\pm0.6(syst) |
| \( \chi_0 \) | 287\pm181 | 2.0\pm1.3(stat)\pm0.3(syst) |
| \( \chi_1 \) | 1035\pm193 | 4.0\pm0.8(stat)\pm0.6(syst) |
| \( \chi_2 \) | 200\pm164 | <2.0 |
| \( \eta_c(2S) \) | 527\pm271 | 3.4\pm1.7(stat)\pm0.5(syst) |
| \( \psi' \) | 1278\pm285 | 4.6\pm1(stat)\pm0.7(syst) |
| \( \psi(3770) \) | 497\pm308 | 3.2\pm2(stat)\pm0.5(syst) |
| \( X(3872) \) | 992\pm285 | 2.1\pm0.6(stat)\pm0.3(syst) |

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