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Study of the $B^- \rightarrow J/\psi K^- \pi^+ \pi^-$ decay and measurement of the $B^- \rightarrow X(3872)K^-$ branching fraction

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STUDY OF THE $B^+ \to J/\psi K^- \pi^+ \pi^-$ DECAY…

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We study the decay $B^- \rightarrow J/\psi K^- \pi^+ \pi^-$ using 117 × 10^6 $B\bar{B}$ events collected at the $Y(4S)$ resonance with the BABAR detector at the PEP-II $e^+e^-$ asymmetric-energy storage ring. We measure the branching fractions $\mathcal{B}(B^- \rightarrow J/\psi K^- \pi^+ \pi^-)$ = (116 ± 7(stat) ± 9(sys)) × 10^{-5} and $\mathcal{B}(B^- \rightarrow X(3872)K^-) \times \mathcal{B}(X(3872) \rightarrow J/\psi \pi^+ \pi^-)$ = (1.28 ± 0.41) × 10^{-5} and find the mass of the $X(3872)$ to be 3873.4 ± 1.4 MeV/c^2. We search for the $h_\pi$ narrow state in the decay $B^- \rightarrow h_\pi K^-$, $h_\pi \rightarrow J/\psi \pi^+ \pi^-$ and for the decay $B^- \rightarrow J/\psi D^0\pi^-$, with $D^0 \rightarrow K^- \pi^+$. We set the 90% C.L. limits $\mathcal{B}(B^- \rightarrow h_\pi K^-) \times \mathcal{B}(h_\pi \rightarrow J/\psi \pi^+ \pi^-) < 3.4 \times 10^{-6}$ and $\mathcal{B}(B^- \rightarrow J/\psi D^0\pi^-) < 5.2 \times 10^{-5}$.

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The study of $B$ decays to final states containing charmonium and strange mesons is especially suited to the search for new charmonium states and for intrinsic charm. In particular, the decay $B^- \rightarrow J/\psi K^- \pi^+ \pi^-$ [1] can occur via the production of charmonium states decaying into $J/\psi \pi^+ \pi^-$ or possibly via $B^- \rightarrow J/\psi D^0\pi^-$, with $D^0 \rightarrow K^- \pi^+$. Recently the Belle [2] and CDF [3] collaborations have observed a new state, the $X(3872)$, decaying into $J/\psi \pi^+ \pi^-$. This state is either a charmonium candidate or even possibly a molecule of charmed $D$ and $D^*$ mesons [4]. In this paper, using 117 × 10^6 $Y(4S)$ decays into $B\bar{B}$ pairs, we confirm the observation of the $X(3872)$ and search for the unconfirmed charmonium $1P_1$ state $h_\pi(3526)$ [5]. In addition, we study the final state involving a $D$ meson to test models developed to explain the excess of low momentum $J/\psi$ mesons in inclusive $B$ decays [6]. The presence of intrinsic charm in $B$ mesons could explain this excess if $\mathcal{B}(B^- \rightarrow J/\psi D^0\pi^-)$ exceeds 10^{-4} [7].

The data were collected at the PEP-II asymmetric-energy $e^+e^-B$-factory with the BABAR detector, which is fully described elsewhere [8]. The detector includes a silicon vertex tracker and a drift chamber in a 1.5-T solenoidal magnetic field, which detect charged particles and measure their momentum and energy loss. Photons, electrons, and neutral hadrons are detected in a CsI(Tl)-crystal electromagnetic calorimeter. A ring-imaging Cherenkov detector is used for particle identification. Penetrating muons and neutral hadrons are identified by resistive-plate chambers in the steel of the flux return. We use a Monte Carlo simulation of the BABAR detector based on GEANT4 [9] to validate the analysis procedure and to estimate efficiency corrections.

The event reconstruction and selection follow closely those described in an earlier paper [10]. The present analysis has been optimized to maximize the sensitivity to $B^- \rightarrow J/\psi K^- \pi^+ \pi^-$ decays. We reconstruct $J/\psi \rightarrow e^+e^-$ candidates from pairs of tracks selected with criteria that are 98% (7%) efficient for electrons (pions). To account for energy losses, we combine the electron pairs with bremsstrahlung-photon candidates and use an asymmetric mass window, 2.95 < $m_{ee}(\gamma)$ < 3.14 GeV/c^2. We reconstruct $J/\psi \rightarrow \mu^+\mu^-$ candidates from pairs of tracks selected with criteria that are 77% (8%) efficient for muons (pions), satisfying 3.06 < $m_{\mu\mu}$ < 3.14 GeV/c^2. The nominal $J/\psi$ mass [11] is imposed as a constraint on $J/\psi$ candidates, thereby improving the resolution on the $B$ four-momentum and on any charmonium states in its decay. Kaons are identified using criteria that have an efficiency of 97%, with a 15% pion-misidentification rate. $B$-meson candidates are formed by combining a $J/\psi$ candidate with a kaon candidate and two additional oppositely charged tracks. To suppress further the background from light-quark production, which is characterized by back-to-back jets, the angle $\theta_J$ between the thrust axes of the reconstructed $B$ candidate and the rest of the event in the center-of-mass system is required to satisfy $|\cos\theta_J| < 0.8(0.9)$ for $J/\psi \rightarrow e^+e^-$ ($J/\psi \rightarrow \mu^+\mu^-$) candidates.

Signal and combinatorial background are discriminated using two kinematic variables: the beam-energy-substituted mass, $m_{ES} = \sqrt{(\sqrt{s}/2)^2 - p_B^2}$, and the difference of the $B$ candidate’s measured energy from the beam energy, $\Delta E = E_B^* - (\sqrt{s}/2)$. Here $E_B^*$ ($p_B^*$) is the energy (momentum) of the $B$ candidate in the center-of-mass frame and $\sqrt{s}$ is the total center-of-mass energy. The signal region is defined to be $|\Delta E| < 3\sigma$, where the resolution $\sigma$, determined with data, is 12 MeV. A binned likelihood fit to the $m_{ES}$ distribution [Fig. 1(a)] is used to separate the signal, taken as a Gaussian distribution with a fitted width of about 2.5 MeV/c^2, plus a small low-mass tail to account for energy losses [12], from the combinatorial background distributed as an ARGUS threshold function [13]. We have checked with Monte Carlo simulation that there is no significant background from $B$ decays that has the same $m_{ES}$ distribution as the signal.

To reduce systematic uncertainties, we measure

$$R = \frac{\mathcal{B}(B^- \rightarrow J/\psi K^- \pi^+ \pi^-)}{\mathcal{B}(B^- \rightarrow J/\psi(2S)K^-)}$$

$$= \frac{N_{events} \epsilon_{\psi(2S)}}{N_{\psi(2S)} \epsilon} \mathcal{B}(\psi(2S) \rightarrow J/\psi \pi^+ \pi^-),$$

where $N_{events} = 2540 \pm 72$ is the number of $B^- \rightarrow J/\psi K^- \pi^+ \pi^-$ signal events extracted from the fit to the $m_{ES}$ distribution. The number of $\psi(2S)$ events, $N_{\psi(2S)} = 556 \pm 30$, is obtained by fitting the $m_{J/\psi \pi\pi}$ distribution, after subtracting combinatorial background [14], with two Gaussian distributions representing the $\psi(2S)$ signal and a
We estimate the uncertainty on the fit to the distribution in $m_{ES}$ (Fig. 2(c) shows the corresponding unsubtracted distribution). This binned $\chi^2$ fit gives a resolution on $m_{J/\psi\pi\pi}$ of $3.1 \pm 0.2$ MeV/$c^2$ for the core Gaussian containing 70% of the events and $12 \pm 3$ MeV/$c^2$ for the broader Gaussian. The total $B^- \rightarrow J/\psi K^- \pi^+ \pi^-$ and the $B^- \rightarrow \psi(2S)K^-$ selection efficiencies, $\epsilon$ and $\epsilon_{\psi(2S)}$, are extracted from Monte Carlo simulation: we obtain $\epsilon_{\psi(2S)}/\epsilon = 1.17 \pm 0.03$. We use $B(\psi(2S) \rightarrow J/\psi\pi^+\pi^-) = (31.8 \pm 1.0)\%$ [11].

We estimate the systematic error due to the choice of the signal $m_{ES}$ shape function by replacing it with a simple Gaussian. We estimate the uncertainty on the fit to the $m_{J/\psi\pi\pi}$ distribution by using the signal resolution function as measured on Monte Carlo and by varying the background shape. Including all these errors, we measure $R = 1.70 \pm 0.10(\text{stat.}) \pm 0.09(\text{syst.})$ which, combined with $B(B^- \rightarrow \psi(2S)K^-) = (6.8 \pm 0.4) \times 10^{-4}$ [11], yields

$$B(B^- \rightarrow J/\psi K^- \pi^+ \pi^-) = (116 \pm 7(\text{stat.}) \pm 9(\text{syst.})) \times 10^{-5}. \quad (2)$$

Note that this measurement includes $B(B^- \rightarrow \psi(2S)K^-)$.

To investigate the possible presence of narrow charmonium states decaying to $J/\psi\pi^-\pi^+$, we have studied the distribution in $m_{J/\psi\pi\pi}$ [Fig. 2(a)]. We observe an excess in the region of the $X(3872)$ [Fig. 2(d)], but do not find any excess in the $h_c$ region [Fig. 2(b)]. The mass of the $X(3872)$ state is extracted from an unbinned maximum likelihood fit to the two-dimensional distribution in $m_{ES}$ and $m_{J/\psi\pi\pi}$. The probability density function (PDF) is taken to be the relative to the $X(3872)$ PDF, the region [Fig. 2(d)], but do not find any excess in the $h_c$ region [Fig. 2(b)]. The mass of the $X(3872)$ state is extracted from an unbinned maximum likelihood fit to the two-dimensional distribution in $m_{ES}$ and $m_{J/\psi\pi\pi}$.

The requirement $m_{J/\psi\pi\pi} > 5.27$ GeV/$c^2$ is applied.

FIG. 1. Distribution of $m_{ES}$ for (a) $B^- \rightarrow J/\psi K^- \pi^+ \pi^-$ candidates, and (b) events in the $X(3872)$ region, $3862 < m_{J/\psi\pi\pi} < 3882$ MeV/$c^2$. The solid curves represent the binned likelihood fits described in the text; the combinatorial components are indicated by the dashed curves.

FIG. 2. Distribution of $m_{J/\psi\pi\pi}$ (a) in the entire range, (b) in the $h_c$ region, (c) at the $\psi(2S)$, and (d) in the region of the $X(3872)$ with the projection of the unbinned likelihood fit superimposed. The measurement of the branching fraction $B(B^- \rightarrow X(3872)K^-) \times B(X(3872) \rightarrow J/\psi\pi^-\pi^+)$ is performed with a counting technique. We select events in a $\pm 10$ MeV/$c^2$ window around $m_{J/\psi\pi\pi} = 3872$ MeV/$c^2$, and find the number of events with $m_{ES} > 5.27$ GeV/$c^2$ to be $N_{data} = 63$. We estimate the number of these events
due to combinatorial background ($N_{\text{comb}} = 22.0 \pm 4.3$) from a fit to the $m_{\text{ES}}$ distribution [Fig. 1(b)]. The number of events with the same final state $B^- \rightarrow J/\psi K^- \pi^+ \pi^-$, but not belonging to the $X(3872)$ signal, is estimated to be $N_{\text{peak}} = 10.5 \pm 3.2$ from a fit to the $m_{\text{ES}}$ distribution in the symmetric sideband $15 < |m_{J/\psi \pi \pi} - 3872| < 45$ MeV/$c^2$. The resulting number of signal events is $30.5$ which agrees within the errors with the number of signal events, $25.4 \pm 8.7$, obtained from the fit to the $X(3872)$ in Fig. 2(d). The branching fractions are determined using a frequentist confidence level [15]. This technique treats properly the small number of events and includes the systematic errors directly in the computation of confidence intervals or limits. The confidence level, $\alpha$, a function of $B(B^- \rightarrow X(3872)K^-) \times B(X(3872) \rightarrow J/\psi \pi^+ \pi^-)$ is computed as the fraction of times that a random number generated according to a Poisson distribution with a mean value of $\mu = N_{\text{bkg}} + N_{\phi(2S)} \epsilon_w \frac{B(B^- \rightarrow X(3872)K^-)B(X(3872) \rightarrow J/\psi \pi^+ \pi^-)}{B(B^- \rightarrow \psi(2S)K^-)B(\psi(2S) \rightarrow J/\psi \pi^+ \pi^-)}$ (3)

exceeds the observed data. For a given value of $B(B^- \rightarrow X(3872)K^-) \times B(X(3872) \rightarrow J/\psi \pi^+ \pi^-)$ the variables $N_{\text{bkg}}$, $N_{\phi(2S)}$, $B(B^- \rightarrow \psi(2S)K^-)$, and $B(\psi(2S) \rightarrow J/\psi \pi^+ \pi^-)$ are randomly generated to determine a value of $\mu$, which is then used in a Poisson distribution to generate a new value of the number of detected events. The generation is repeated many times and the fraction of times the random number exceeds $N_{\text{data}} = 63$ yields the value of $\alpha$. The variables $N_{\text{bkg}}$, $N_{\phi(2S)}$, $B(B^- \rightarrow \psi(2S)K^-)$, and $B(\psi(2S) \rightarrow J/\psi \pi^+ \pi^-)$, are generated according to Gaussian distributions. The mean of $N_{\phi(2S)}$ is 556 and $\sigma = 30$. The mean of $N_{\text{bkg}}$ is $N_{\text{comb}} + N_{\text{peak}} = 32.5$ and $\sigma = 5.9$, which includes a systematic error on $N_{\text{peak}}$ calculated by varying the boundaries of the sideband. We use published values [11] for the remaining branching fractions and their errors, assumed to be Gaussian. Finally, $\epsilon_w = (92 \pm 2\%)$ is the fraction of events that fall in the $m_{J/\psi \pi \pi}$ window, from applying the same mass window cut to the $\psi(2S)$ and assuming the same efficiency. From the values of $B(B^- \rightarrow X(3872)K^-)$ at which $\alpha = 16\%$ and $84\%$ we measure

\[ B(B^- \rightarrow X(3872)K^-) \times B(X(3872) \rightarrow J/\psi \pi^+ \pi^-) = (1.28 \pm 0.41) \times 10^{-5}. \] (4)

The probability that the observed events are a background fluctuation in the considered mass window is $5.4 \times 10^{-4}$, corresponding to 3.5 Gaussian standard deviations. As a check, we performed the same measurement on the $J/\psi \rightarrow e^+ e^-$ and $J/\psi \rightarrow \mu^+ \mu^-$ samples separately, obtaining $B(B^- \rightarrow X(3872)K^-) \times B(X(3872) \rightarrow J/\psi \pi^+ \pi^-) = (1.94 \pm 0.62) \times 10^{-5}$ and $(0.52 \pm 0.46) \times 10^{-5}$ respectively, consistent within 1.8 standard deviations.

The decay of a charmonium state into $\rho J/\psi$ is a strongly suppressed isospin-violating process. In order to investigate the nature of the $X(3872)$ state, we plot the invariant mass of the $\pi^+ \pi^-$ system in both the $X(3872)$ and the $\psi(2S)$ region (Fig. 3). In the $\psi(2S)$ case, the events are concentrated near the kinematic limit. Such behavior is not excluded for the $X(3872)$, but the statistics are too small to allow a clear conclusion. Measuring both the $m_{\pi^+ \pi^-}$ and angular distributions with significantly greater statistics would provide important information on the nature of the $X(3872)$.

The search for the $h_c$ is performed with the same frequentist technique in a $\pm 10$ MeV/$c^2$ mass window centered on $m_{J/\psi \pi \pi} = 3526$ MeV/$c^2$ [5]. With $N_{\text{data}} = 9$, $N_{\text{comb}} = 6.9 \pm 3.5$, $N_{\text{peak}} = 0.6 \pm 1.5$, and assuming the same efficiency $\epsilon_w = (92 \pm 2\%)$, we set a 90\% C.L. limit $B(B^- \rightarrow h_c K^-) \times B(h_c \rightarrow J/\psi \pi^+ \pi^-) < 3.4 \times 10^{-6}$. The probability that we would see a signal as large as the one observed from background fluctuations alone is 39\%.

Finally, we search for $B^- \rightarrow J/\psi D^0 \pi^+$ decays with $D^0 \rightarrow K^- \pi^+$. The decay $D^0 \rightarrow K^- \pi^+$ would have an r.m.s. width of 5.4 MeV/$c^2$ in $m_{K^- \pi^+}$ as determined from Monte Carlo. We study this distribution in the same way we studied $m_{J/\psi \pi \pi}$. The $m_{K^- \pi^+}$ combinatorial-subtracted distribution (Fig. 4) shows no significant structure, and it is therefore used to set a limit. We fit the

FIG. 3. Distribution of $m_{\pi^+ \pi^-}$ (a) at the $X(3872)$ and (b) at the $\psi(2S)$, after subtraction of combinatorial and peaking background.
FIG. 4. Distribution of $mK^-\pi^+$ in events $B^-\rightarrow J/\psi K^-\pi^+\pi^-$, with combinatorial background removed. Overlaid is an exponential fit. The arrow indicates the $3\sigma$ region expected for $D^0\rightarrow K^-\pi^+\pi^-$. Background from other $B^-\rightarrow J/\psi K^-\pi^+\pi^-$ decays with an exponential function of $m_{K^-\pi^+}$ and obtain $N_{\text{peak}} = 2.9 \pm 1.4$. The frequentist approach described above, with $N_{\text{data}} = 10$, $N_{\text{comb}} = 7.8 \pm 2.8$ and $\epsilon/\epsilon_{\phi(2S)} = 1.00 \pm 0.07$ yields the 90% C.L. limit $\mathcal{B}(B^-\rightarrow J/\psi D^0\pi^-) < 5.2 \times 10^{-5}$.

In summary, we measured $\mathcal{B}(B^-\rightarrow J/\psi K^-\pi^+\pi^-) = (116 \pm 7(\text{stat.}) \pm 9(\text{syst.})) \times 10^{-5}$ with an error almost a factor two smaller than the present average [11] and we confirmed the observation of $B^-\rightarrow X(3872)K^- [2,3]$. We performed an accurate measurement of the branching fraction $\mathcal{B}(B^-\rightarrow X(3872)K^-) \times \mathcal{B}(X(3872)\rightarrow J/\psi\pi^+\pi^-) = (1.28 \pm 0.41) \times 10^{-5}$ and of the mass $m_{X(3872)} = 3873.4 \pm 1.4$ MeV/c$^2$. We also studied the $m_{J/\psi\pi\pi}$ distributions searching for $B^-\rightarrow h^-_1K^-$ decays and set limits on their branching fractions, $\mathcal{B}(B^-\rightarrow h^-_1K^-) \times \mathcal{B}(h^-_1\rightarrow J/\psi\pi^+\pi^-) < 3.4 \times 10^{-6}$ at 90% C.L. Finally, from the $m_{K^-\pi^+\pi^-}$ distribution we find $\mathcal{B}(B^-\rightarrow J/\psi D^0\pi^-) < 5.2 \times 10^{-5}$ at 90% C.L., thus ruling out the explanation of the inclusive $J/\psi$ momentum spectrum with intrinsic charm proposed in [7].

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[1] Charge-conjugate reactions are included implicitly throughout this paper.
[14] Throughout this paper the distributions after combinatorial-background subtraction are obtained by fitting the $m_{ES}$ distribution of the events within each bin of the variable of interest ($m_{J/\psi\pi\pi}$ in this case).