Study of $B^{\pm} \to J/\psi\pi^{\pm}$ and $B^{\pm} \to J/\psi K^{\pm}$ Decays: Measurement of the Ratio of Branching Fractions and Search for Direct CP Violation

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We study $B^\pm \to J/\psi\pi^\pm$ and $B^\pm \to J/\psi K^\pm$ decays in a sample of about 89×10^6 $B\overline{B}$ pairs collected with the *BABAR* detector at the PEP-II asymmetric B factory at SLAC. We observe a signal of 244 ± 20 $B^\pm \to J/\psi\pi^\pm$ events and determine the ratio $\mathcal{B}(B^\pm \to J/\psi\pi^\pm)/\mathcal{B}(B^\pm \to J/\psi K^\pm)$ to be

[5.37 ± 0.45(stat) ± 0.11(syst)]%. The charge asymmetries for the $B^{\pm} \to J/\psi\pi^{\pm}$ and $B^{\pm} \to J/\psi K^{\pm}$ decays are determined to be $\mathcal{A}_{\pi} = 0.123 \pm 0.085(\text{stat}) \pm 0.004(\text{syst})$ and $\mathcal{A}_{K} = 0.030 \pm 0.015(\text{stat}) \pm 0.006(\text{syst})$, respectively.

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We present an analysis of $B^{\pm} \to J/\psi\pi^{\pm}$ and $B^{\pm} \to J/\psi K^{\pm}$ decays that measures the ratio of branching fractions and searches for direct *CP* violation. The Cabibbo-suppressed decay $B^{\pm} \to J/\psi\pi^{\pm}$ proceeds via a $b \to c\bar{c}d$ transition. It is expected to have a rate about 5% of that of the Cabibbo-allowed mode $B^{\pm} \to J/\psi K^{\pm}$. The standard model predicts that for $b \to c\bar{c}s$ decays the tree and penguin contributions have a small relative weak phase and thus a small direct *CP* violation is expected in $B^{\pm} \to J/\psi K^{\pm}$ decays. However, for $b \to c\bar{c}d$, the tree and penguin contributions have different phases and charge asymmetries as large as a few percent may occur [1,2]. In the absence of isospin violation, the *CP* asymmetry in $B^{\pm} \to J/\psi K^{\pm}$ provides [3] a measurement of the ratio $|\bar{A}/A|$, where A ($\bar{A}$) is the decay amplitude for the neutral mode $B^0(\overline{B}^0) \to J/\psi K^0_S$.

Previous studies of the $B^{\pm} \to J/\psi\pi^{\pm}$ mode have been performed by the CLEO [4], the CDF [5], the *BABAR* [6], and the Belle [7] collaborations. The Particle Data Group (PDG) 2002 average [8] of the ratio of $B^{\pm} \to J/\psi\pi^{\pm}$ and $B^{\pm} \to J/\psi K^{\pm}$ branching fractions is $(4.2 \pm 0.7)\%$. A recent Belle result gives $\mathcal{B}(B^{\pm} \to J/\psi\pi^{\pm}) = (3.8 \pm 0.6 \pm 0.3) \times 10^{-5}$. The PDG 2002 averages of the charge asymmetries are $\mathcal{A}_{\pi} = -0.01 \pm 0.13$ and $\mathcal{A}_{K} = -0.007 \pm 0.019$ [see Eq. (3) for the definition of the sign of the asymmetry].

The analysis reported in this paper is an update of the *BABAR* analysis in Ref. [6] and is based on a larger data set with improvements in data reconstruction. The data were recorded at the $\Upsilon(4S)$ resonance with the *BABAR* detector [9] at the PEP-II storage ring at the Stanford Linear Accelerator Center. The integrated luminosity is $81.9\ \text{fb}^{-1}$, corresponding to 89×10^6 $B\overline{B}$ pairs.

At the *BABAR* detector, a five-layer silicon vertex tracker (SVT) and a 40-layer drift chamber (DCH), in a 1.5-T solenoidal magnetic field, provide detection of charged particles and the measurement of their momenta. Electrons are detected in a CsI electromagnetic calorimeter, while muons are identified in the magnetic flux return system (IFR), which is instrumented with multiple layers of resistive plate chambers. A ring-imaging Cherenkov detector (DIRC) with quartz radiators provides charged-particle identification.

We fully reconstruct $B^{\pm} \to J/\psi h^{\pm}$ decays, where $h^{\pm} = \pi^{\pm}$ or $K^{\pm}$, from the combination of a J/ψ candidate and a charged track $h^{\pm}$. The J/ψ candidate is reconstructed via a $J/\psi \to e^+e^-$ or $J/\psi \to \mu^+\mu^-$ decay and is constrained to the nominal J/ψ mass [8]. The electron candidates are combined with reconstructed photons in the calorimeter to recover some of the energy lost through bremsstrahlung. Details of the J/ψ reconstruction are given in Ref. [10]. Depending on the final state of the charmonium meson, the $B^{\pm}$ candidates are divided into two categories, B_{ee} or $B_{\mu\mu}$. The distribution in the angle θ_{ℓ} in the J/ψ rest frame between one of the daughter leptons ℓ of the J/ψ and the line of flight of the recoiling $h^{\pm}$ is different for signal and background. The background peaks for $|\cos\theta_{\ell}|$ near one while the signal follows a $\sin^2\theta_{\ell}$ distribution. We require $|\cos\theta_e| < 0.8$ for B_{ee} candidates and $|\cos\theta_{\mu}| < 0.9$ for $B_{\mu\mu}$ candidates.

Signal yields and charge asymmetries are determined by an unbinned maximum likelihood fit to the data. A vertex constraint is applied to the reconstructed tracks before computing the kinematic quantities of the $B^{\pm}$ candidate. The beam energy-substituted mass m_{ES} is defined as

$$m_{\text{ES}} = \sqrt{(s/2 + \mathbf{p} \cdot \mathbf{p}_B)^2/E^2 - |\mathbf{p}_B|^2}, \qquad (1)$$

where $\sqrt{s}$ is the total energy of the e^+e^- system in the $\Upsilon(4S)$ rest frame, and $(E, \mathbf{p})$ and $(E_B, \mathbf{p}_B)$ are the four-momenta of the e^+e^- system and the reconstructed B candidate, both in the laboratory frame. The kinematic variable ΔE_{π} (ΔE_K) is defined as the difference between the reconstructed energy of the $B^{\pm}$ candidate and the beam energy in the $\Upsilon(4S)$ rest frame assuming $h^{\pm} = \pi^{\pm}(K^{\pm})$. Signal candidates for $B^{\pm} \to J/\psi\pi^{\pm}$ ($B^{\pm} \to J/\psi K^{\pm}$) peak in m_{ES} at the $B^{\pm}$ meson mass and peak in ΔE_{π} (ΔE_K) at 0. Candidates are required to satisfy loose requirements on these variables: $|\Delta E_{\pi}| < 120$ MeV, $|\Delta E_K| < 120$ MeV, and $m_{\text{ES}} > 5.2\ \text{GeV}/c^2$. The kinematic separation is sufficiently good (see Fig. 3) so that no explicit particle identification is required on the charged hadron $h^{\pm}$, thereby simplifying the analysis.

The selected sample contains $3801 B_{\mu\mu}$ and $4053 B_{ee}$ candidates. Figure 1(a) shows the m_{ES} distribution in data fitted to the sum of a Gaussian and an empirical phase-space function (Argus function [11]) describing the signal and background components, respectively. Figure 1(b) shows the ΔE_K distribution for data candidates with $m_{\text{ES}} > 5.27\ \text{GeV}/c^2$ fitted to the sum of a double Gaussian and a polynomial function, describing the dominant $B^{\pm} \to J/\psi K^{\pm}$ signal and the background contribution, respectively.

The background (bkg) from continuum and generic $B\overline{B}$ decays is characterized using events that are outside the

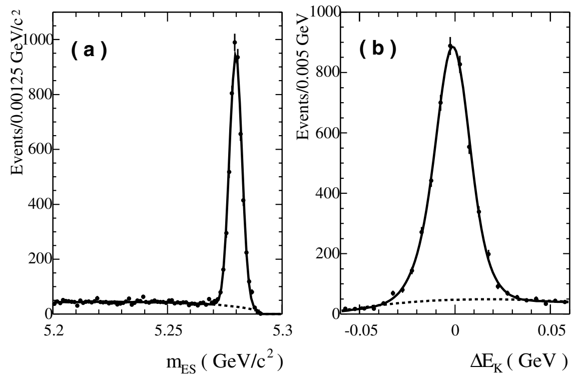

FIG. 1. (a) The m_{ES} distribution for the $B^{\pm}$ candidates in data. A fit to the sum of a Gaussian and an empirical threshold function (dashed curve) is superimposed. The fitted resolution is approximately 2.5 MeV$/c^2$. (b) The ΔE_K distribution for the $B^{\pm}$ candidates in data with $m_{\mathrm{ES}} > 5.27$ GeV$/c^2$. A fit to the sum of a double Gaussian and a 3rd order polynomial function (dashed curve) is superimposed. The fitted resolution is approximately 10.5 MeV.

signal regions (sidebands of the data sample). Candidates in the m_{ES} sideband are defined by the requirement $5.20 < m_{\mathrm{ES}} < 5.27$ GeV$/c^2$, where the upper limit is approximately 4 times the experimental resolution below the B mass. Candidates in the ΔE_K and ΔE_π sidebands are defined by the requirement $42 < |\Delta E_K| < 120$ MeV and $42 < |\Delta E_\pi| < 120$ MeV, where the lower limit is approximately 4 times the ΔE resolution obtained from the fit shown in Fig. 1(b).

We maximize the following extended likelihood function:

$$L = e^{-\sum_i N_i} \prod_{j=1}^{M} \sum_i P_i(\Delta E_\pi^j, p_h^j, m_{\mathrm{ES}}^j) c_i(q^j) N_i,$$

where j is the index of the event, i is the index of the hypothesis ($i = \pi, K, \mathrm{bkg}$), N_i is the yield for each hypothesis, and M is the total number of events in the sample. The arguments of the probability density functions (PDFs) P_i are the kinematic observables ($\Delta E_\pi, p_h, m_{\mathrm{ES}}$), where p_h is the $h^{\pm}$ momentum in the laboratory frame. We use different PDFs for B_{ee} and $B_{\mu\mu}$ candidates, while we assume the same PDFs for B^+ and B^- candidates.

The factor $c_i(q)$ is the fraction of candidates with charge q in hypothesis i:

$$c_i(q) = \begin{cases} 1/2\,(1 - \mathcal{A}_i), & \text{if } q = +1, \\ 1/2\,(1 + \mathcal{A}_i), & \text{if } q = -1, \end{cases} \tag{2}$$

where $\mathcal{A}_i$ is the charge asymmetry:

$$\mathcal{A}_i = \frac{N_i^- - N_i^+}{N_i^- + N_i^+}. \tag{3}$$

The yields N_i and the asymmetries $\mathcal{A}_i$ are free parameters in the likelihood fit.

Since the measured variables ΔE_π and p_h are correlated, we define a new set of variables:

$$D = \Delta E_K - \Delta E_\pi = \gamma\left(\sqrt{p_h^2 + m_K^2} - \sqrt{p_h^2 + m_\pi^2}\right),$$

$$\Sigma = (\Delta E_K + \Delta E_\pi)/(D - a),$$

$$\Pi = D(D/2 - a),$$

where γ is the Lorentz boost from the laboratory frame to the $\Upsilon(4S)$ rest frame and $a = 240$ MeV is twice the maximum $|\Delta E_\pi|$ or $|\Delta E_K|$ value for the data sample. These variables have the property that ($\Delta E_\pi, D$) in the pion hypothesis, ($\Delta E_K, D$) in the kaon hypothesis, and (Σ, Π) in the background hypothesis are correlated at less than the few percent level. Therefore each P_i can be written as a product of one-dimensional PDFs:

$$P_\pi(\Delta E_\pi, p_h, m_{\mathrm{ES}}) = f_\pi(\Delta E_\pi) g_\pi(D) h_\pi(m_{\mathrm{ES}}),$$

$$P_K(\Delta E_\pi, p_h, m_{\mathrm{ES}}) = f_K(\Delta E_K) g_K(D) h_K(m_{\mathrm{ES}}),$$

$$P_{\mathrm{bkg}}(\Delta E_\pi, p_h, m_{\mathrm{ES}}) = f_{\mathrm{bkg}}(\Sigma) g_{\mathrm{bkg}}(\Pi) h_{\mathrm{bkg}}(m_{\mathrm{ES}}).$$

The f_π and f_K components are represented by double Gaussians, while h_π and h_K are described by single Gaussians. The parameters of f_π and h_π are constrained to be equal to the parameters of f_K and h_K, respectively. They are free parameters in the likelihood fit and are extracted together with the yields. This strategy reduces the systematic error due to possible inaccuracies of the Monte Carlo (MC) simulation in describing the ΔE and m_{ES} distributions.

The g_π and g_K components are each represented by a phenomenological function with seven fixed parameters estimated from the MC simulation. They follow an exponential shape with Gaussian edges.

The f_{bkg} component is represented by a linear phenomenological function with fixed parameters estimated from the distribution of Σ for events in the m_{ES} sideband [Fig. 2(a)].

The g_{bkg} component is represented by a phenomenological function with 12 fixed parameters, all estimated from the distribution of Π for events in the m_{ES} sideband [Fig. 2(b)].

The h_{bkg} component is represented by the sum of an Argus function and a Gaussian function, with fixed parameters. The shape parameters are estimated from the distribution of m_{ES} for events in both the ΔE_K and ΔE_π sidebands. The small number of background events peaking in the m_{ES} signal region is due to candidates reconstructed from other $B \to J/\psi X$ decays. From detailed MC simulations of inclusive charmonium decays we

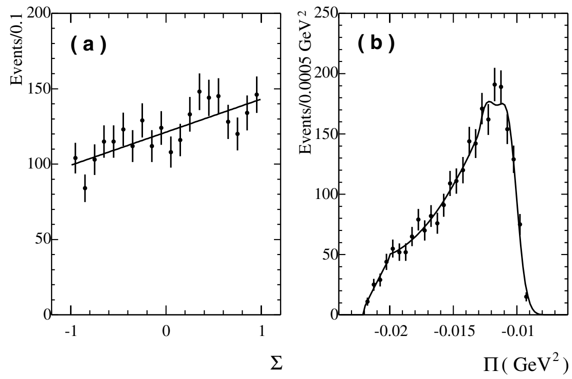

FIG. 2. The distribution of (a) Σ and (b) Π for events in the $m_{\rm ES}$ sideband in data. The curve corresponds to the projection of the best fit.

determine 40 ± 7 peaking background events in our sample.

The yields determined with the unbinned maximum likelihood fit to the data sample are reported in Table I. The correlation coefficient between N_π and N_K is -0.02. The probability to obtain a maximum value of the likelihood smaller than the observed value is 50% , estimated by MC techniques. Figure 3 shows the distributions of ΔE_π for the events in the data, compared with the distributions obtained by generating events with a parametric MC simulation based on the PDFs used in the fit.

Possible biases in the likelihood estimates were investigated by performing the fit on simulated samples of known composition and of the same size as the data. The samples were generated with parametric MC simulations based on the PDFs used in the fit. There is no evidence of bias in the fitted asymmetries, while a less than 1% deviation in the fitted yields from the nominal values is present. After correcting the yields for the observed bias, we obtain $N_\pi = 244 \pm 20$, $N_K = 4548 \pm 70$, and a ratio of branching fractions of $(5.37 \pm 0.45)\%$ with an absolute systematic error of 0.11%. The dominant source of systematic error is the fixed parameters of the PDFs, primarily the PDFs that describe the background. Other sources of systematic uncertainty, such as differences in the reconstruction efficiencies for $J/\psi\pi^\pm$ and $J/\psi K^\pm$ events and inaccuracies in the description of the tails of the ΔE resolution function, are found to be negligible.

TABLE I. Uncorrected yields N_i and uncorrected charge asymmetries $\mathcal{A}_i$ from the fit to the data sample.

i	N_i	$\mathcal{A}_i$
π	242 ± 20	0.117 ± 0.084
K	4538 ± 70	0.028 ± 0.015
bkg	3074 ± 60	0.019 ± 0.020

The sample that is used to determine the charge asymmetries is defined by imposing as a further requirement that the charged track $h^\pm$ has a polar angle in the range [0.41, 2.54] radians, includes at least 12 DCH hits, has a momentum in the transverse plane $p_t > 100\,\text{MeV}/c$, and points back to the nominal interaction point within 1.5 cm in the transverse plane and within 3 cm along the longitudinal direction. For these tracks the difference in tracking efficiency between positively and negatively charged tracks—primarily pions—has been studied in hadronic events by comparing independently the SVT and DCH tracking systems.

The selected sample contains 3902 $B^- \to J/\psi h^-$ and 3696 $B^+ \to J/\psi h^+$ candidates. From the likelihood fit we obtain the charge asymmetries reported in Table I. The correlation coefficient between $\mathcal{A}_\pi$ and $\mathcal{A}_K$ is -0.003. Using MC techniques we estimate that the probability to obtain a fitted asymmetry $\mathcal{A}_K$ greater or equal to the one observed, in the hypothesis of zero asymmetry, is 6.7%.

We correct the fitted asymmetries for the small observed difference in tracking efficiency between positively and negatively charged tracks, obtaining $\mathcal{A}_\pi = 0.123 \pm 0.085$ and $\mathcal{A}_K = 0.030 \pm 0.015$. The uncertainty on the corrections contributes 0.004 and 0.005 to the systematic error on $\mathcal{A}_\pi$ and $\mathcal{A}_K$, respectively. The asymmetry induced by the different probability of K^+ and K^- interactions in the detector material before the DCH is estimated to be -0.004. This value is conservatively assumed to be a contribution to the systematic uncertainty. The uncertainty in the fixed parameters of the PDFs, determined by fits to simulated or nonsignal data sets, contributes 0.001 to the systematic errors on both $\mathcal{A}_\pi$ and $\mathcal{A}_K$.

Summing in quadrature statistical and systematic errors, we obtain a 90% C.L. interval of $[-0.017, 0.263]$ for $\mathcal{A}_\pi$ and $[0.003, 0.057]$ for $\mathcal{A}_K$.

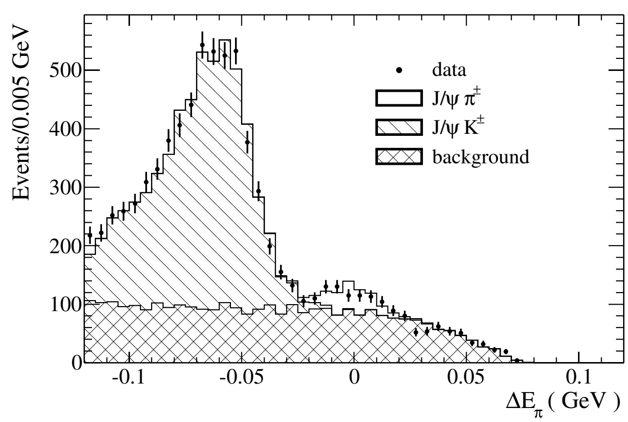

FIG. 3. The ΔE_π distribution in data (points) compared with the distribution obtained from a simulated experiment (histogram). The distributions for each simulated component in the sample, normalized to the fitted event yields, are also displayed.

In conclusion we measure the ratio of branching fractions

$$\frac{\mathcal{B}(B^{\pm} \to J/\psi \pi^{\pm})}{\mathcal{B}(B^{\pm} \to J/\psi K^{\pm})} = [5.37 \pm 0.45(\text{stat}) \pm 0.11(\text{syst})]\%,$$

which is consistent with theoretical expectations and with previous measurements. We also determine the charge asymmetries

$$\mathcal{A}_{\pi} = 0.123 \pm 0.085(\text{stat}) \pm 0.004(\text{syst}),$$

$$\mathcal{A}_{K} = 0.030 \pm 0.015(\text{stat}) \pm 0.006(\text{syst}).$$

Our results are consistent with previous measurements but with significant improvement in the precision.

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