Measurement of the Angular and Lifetime Parameters of the Decays $B_d^0 \rightarrow J/\psi K^{*0}$ and $B_s^0 \rightarrow J/\phi \psi$

V. M. Abazov  
*Joint Institute for Nuclear Research, Dubna, Russia*

Kenneth A. Bloom  
*University of Nebraska-Lincoln, kbloom2@unl.edu*

Gregory Snow  
*University of Nebraska-Lincoln, gsnow1@unl.edu*

D0 Collaboration

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Measurement of the Angular and Lifetime Parameters of the Decays $B_d^0 \to J/\psi K^{*0}$ and $B_s^0 \to J/\psi \phi$


(D0 Collaboration)

1 Universidad de Buenos Aires, Buenos Aires, Argentina
2 LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil
3 Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
4 Universidade Federal do ABC, Santo Andre´ , Brazil
5 Instituto de Física Teórica, Universidade Estadual Paulista, Sa˜o Paulo, Brazil
6 University of Alberta, Edmonton, Alberta, Canada,
Simon Fraser University, Burnaby, British Columbia, Canada,
York University, Toronto, Ontario, Canada, and McGill University, Montreal, Quebec, Canada
7 University of Science and Technology of China, Hefei, People’s Republic of China
8 Universidad de los Andes, Bogota’, Colombia
9 Center for Particle Physics, Charles University, Prague, Czech Republic
10 Czech Technical University, Prague, Czech Republic
11 Center for Particle Physics, Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic
12 Universidad San Francisco de Quito, Quito, Ecuador
13 LPC, Université Blaise Pascal, CNRS/IN2P3, Clermont, France
14 LPSC, Université Joseph Fourier Grenoble I, CNRS/IN2P3, Institut National Polytechnique de Grenoble, Grenoble, France
15 CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France
16 LAL, Université Paris-Sud, IN2P3/CNRS, Orsay, France
17 LPNHE, IN2P3/CNRS, Universités Paris VI and VII, Paris, France
18 CEA, Irfu, SPP, Saclay, France
19 IPHC, Université Louis Pasteur, CNRS/IN2P3, Strasbourg, France
20 IPNL, Université Lyon 1, CNRS/IN2P3, Villeurbanne, France and Université de Lyon, Lyon, France
21 III. Physikalisches Institut A, RWTH Aachen University, Aachen, Germany
22 Physikalisches Institut, Universität Bonn, Bonn, Germany
23 Physikalisches Institut, Universität Freiburg, Freiburg, Germany
24 Institut für Physik, Universität Mainz, Mainz, Germany
25 Ludwig-Maximilians-Universität München, München, Germany
26 Fachbereich Physik, University of Wuppertal, Wuppertal, Germany
27 Panjab University, Chandigarh, India
28 Delhi University, Delhi, India
29 Tata Institute of Fundamental Research, Mumbai, India
30 University College Dublin, Dublin, Ireland
31 Korea Detector Laboratory, Korea University, Seoul, Korea
32 SungKyunKwan University, Suwon, Korea
We present measurements of the linear polarization amplitudes and the strong relative phases that describe the flavor-untagged decays $B_0^d \to J/\psi K^{*0}$ and $B_0^s \to J/\psi K^0$ in the transversity basis. We also measure the mean lifetime $\tau_0$ of the $B_0^0$ mass eigenstates and the lifetime ratio $\tau_d/\tau_s$. The analyses are based on approximately 2.8 fb$^{-1}$ of data recorded with the D0 detector. From our measurements of the angular parameters we conclude that there is no evidence for a deviation from flavor SU(3) symmetry for these decays and that the factorization assumption is not valid for the $B_0^0 \to J/\psi K^{*0}$ decay.

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$B$ mesons are fertile ground to study $CP$ violation and search for evidence of new physics. There are elements, in addition to $CP$ violation, involved in the theoretical description of $B$ meson decays, such as flavor SU(3) symmetry, factorization, and final-state strong interactions. To understand the role $CP$ violation plays in these decays, it is essential to understand and isolate the effect of each of these elements in the $B$ meson decays.

Factorization states that the decay amplitude of $B$ meson decays can be expressed as the product of two single current matrix elements and this implies that the relative strong phases are $0 \mod \pi$ [2]. A different measured value for the strong phases would indicate the presence of final-state strong interactions. The $B^0$ meson can be formed by replacing the $s$ quark with the $d$ quark in the $B^0$ meson. From flavor SU(3) symmetry applied to the $B^0 - B^0_s$ system one expects that the theoretical description is similar; in particular, the $B^0_s \rightarrow J/\psi K^{*0}$ and $B^0 \rightarrow J/\psi \phi$ [3] decays, can be described in the transversity basis [2] by the relative strong phases $\delta_1$ and $\delta_2$, and by the three independent components $A_0, A_\parallel$, and $A_\perp$. The components $A_0$ and $A_\parallel$ represent the $CP$-even and $A_\perp$ the $CP$-odd contributions to the decay amplitude.

Other observables of these decays are the lifetimes of both mesons, which allow us to compare with theoretical predictions of the lifetime ratio. Phenomenological models predict differences of about $1\%$ [4,5] between the predictions of the lifetime ratio. Phenomenological models both mesons, which allow us to compare with theoretical $B$ meson lifetime measurements [6] are consistent with these predictions.

In this Letter we report the measurements of the parameters that describe the time-dependent angular distributions of the decays $B^0_s \rightarrow J/\psi K^{*0}$ and $B^0 \rightarrow J/\psi \phi$ in the transversity basis, where the initial $B$ meson flavor is not determined ("untagged"). We study the $B^0_s$ and $B^0$ mesons to verify the validity of the factorization assumption [2] and to check if flavor SU(3) symmetry [2] holds for these decays. We also report the lifetime ratio $\tau_s/\tau_d$ for these mesons and the width difference $\Delta \Gamma_s$ between the light and heavy $B^0_s$ mass eigenstates. The analyses were performed using data collected with the D0 detector [7] in Run II of the Fermilab Tevatron Collider during 2003–2007 with an integrated luminosity of approximately 2.8 fb$^{-1}$ of $p\bar{p}$ collisions at a center-of-mass energy of 1.96 TeV. In contrast with the flavor-tagged analysis reported in Ref. [8], in this Letter we report a simultaneous analysis of both the $B^0_s$ and $B^0$ meson decays, carried out in such a way that a straightforward comparison between their angular and lifetime parameters can be performed.

We use the $B^0_s \rightarrow J/\psi \phi, J/\psi \rightarrow \mu^+ \mu^-, \phi \rightarrow K^+ K^-$ selection described in Ref. [9]. The decay $B^0_s \rightarrow J/\psi K^{*0}$, $J/\psi \rightarrow \mu^+ \mu^-, K^{*0} \rightarrow K^\pm \pi^\mp$ is reconstructed using similar selection criteria and algorithms as the $B^0$ channel because they have the same four-track topology in the final state. The differences are the requirement that the transverse momentum of the pion be greater than 0.7 GeV/c, the invariant mass for the ($J/\psi, K^{*0}(892)$) pair be in the range 4.93–5.61 GeV/c$^2$, and the selection of the $K^{*0}(892)$ candidates by demanding the two-particle invariant mass between 850 and 930 MeV/c$^2$. Because of the lack of charged particle identification, we assign the mass of the pion and kaon to the latter two tracks and use the combination with invariant mass closest to the $K^{*0}$ mass.

The proper decay length (PDL), defined as in Refs. [10,11], for a given $B^0_s$ or $B^0$ candidate is determined by measuring the distance traveled by each $b$-hadron candidate in a plane transverse to the beam direction, and then applying a Lorentz boost correction. In the $B^0_s$ and $B^0$ final selection, we require a PDL uncertainty of less than 60 $\mu$m. We find 334199 and 41691 candidates that pass the $B^0_s$ and $B^0$ selection criteria, respectively (see Fig. 1).

We denote the set of the angular variables defined in the transversity basis, where the decays $B^0_s \rightarrow J/\psi K^{*0}$ and $B^0 \rightarrow J/\psi \phi$ are studied, as $\omega = \{\varphi, \cos \theta, \cos \phi\}$. The description of these decays in this basis gives us access to the three linear polarization amplitudes at production time, $t = 0$, $|A_0(0)|$, $|A_\parallel(0)|$, and $|A_\perp(0)|$, satisfying
The differential decay rate for the untagged decay $B^0 \to J/\psi K^{*0}$ is given by [2,14]:

$$d^4 \mathcal{P} / (dt \, d\omega) \propto e^{-\Gamma_\mu / \tau_L} |A_\mu|^2 f_1(\omega) + \text{Re}(A_\mu A_\bar{\mu}) f_5(\omega) + |A_\perp|^2 f_2(\omega) + e^{-\Gamma_\mu / \tau_L} |A_{1-}|^2 f_3(\omega),$$

where $\Gamma_\mu = 1 / \tau_L(\tau_H)$ is the inverse of the lifetime corresponding to the light (mass) eigenstate. The measured parameters, the width difference $\Delta \Gamma_\mu = \Gamma_L - \Gamma_H$ and the mean lifetime $\bar{\tau}_\mu = 1 / \bar{\Gamma} = 2 / (\Gamma_L + \Gamma_H)$, are given in terms of these inverse lifetimes. The angular functions $f_i(\omega)$ are defined in Ref. [2]. In this decay, we have access to the phase $\delta_\| = \arg(A_\mu A_\bar{\mu})$, which is related to $\delta_1$ and $\delta_2$ by $\delta_\| = \delta_2 - \delta_1$.

Table I. Figures 1 and 2 show the mass and the PDL distributions for the background in the same way. The PDLa distributions are modeled by the corresponding normalized equations (1) and (2). The contribution where the mass of the $K$ and $\pi$ are misassigned in our data is estimated by using Monte Carlo studies to be about 13% and is taken into account.

The results of our measurements are summarized in Table I. Figures 1 and 2 show the mass and the PDL distributions for the $B^0_d$ and $B^0_s$ candidates, respectively, with the projected results of the fits. The parameters with
the strongest correlations are the linear amplitudes for the $B^0_{d}$ and the width difference and the mean lifetime for the $B^0_s$.

Table II summarizes the systematic uncertainties in our measurements for $B^0_{d}$ and $B^0_s$ decays. To study the systematic uncertainty due to the model for the mass distributions, we vary the shapes of the mass distributions for background by using two normalized first-order polynomials instead of the nominal two negative exponentials. We estimate the systematic uncertainty due to the resolution on the PDL by using one Gaussian function for the resolution model. The fitting code is tested for the presence of biases by generating 1300 pseudoexperiments for $B^0_{d}$ and 1000 for $B^0_s$, each with the same statistics as our data samples. We generated the events following the PDL, mass, and transversity angular distributions described above. The differences between the input and output values are quoted as the systematic uncertainty due to the fitting. The systematic uncertainty for $\delta^H$ reported for this source is due to an intrinsic ambiguity for this parameter in Eq. (1). The pseudoexperiments produced also cover the other solution for $\delta^H$. The contribution from the detector alignment uncertainty is taken from Ref. [11]. Other potential sources of systematic uncertainties have been investigated and found to give negligible variations in the measured parameters. The systematic uncertainties for the ratio $\tilde{\tau}_s/\tau_d$ are obtained by finding the ratio of the lifetimes for each systematic variation on Table II and taking the difference between this value and the nominal ratio.

In conclusion, we have measured the angular and lifetime parameters for the time-dependent angular untagged decays $B^0_{d} \rightarrow J/\psi K^{*0}$ and $B^0_{d} \rightarrow J/\psi \phi$, the lifetime ratio of both $B$ mesons, and the width difference $\Delta \Gamma_s$ for the $B^0_s$ meson. From the measured lifetime parameters $\tilde{\tau}_s$ and $\tau_d$ we obtain the ratio $\tilde{\tau}_s/\tau_d = 1.052 \pm 0.061$(stat) $\pm 0.015$(syst) which is consistent with the theoretical prediction [5] and previous measurements [6]. The measurement of the width difference $\Delta \Gamma_s = 0.085^{+0.072}_{-0.072}$(stat) $\pm 0.006$(syst) ps$^{-1}$ is consistent with the theoretical prediction [5,13] and with the value reported in Refs. [6,15]. D0 also has a measurement of $\Delta \Gamma_s$ in a flavor-tagged analysis of $B^0_{d} \rightarrow J/\psi \phi$ in Ref. [8].

Our measurements for the linear polarization amplitudes for the $B^0_{d}$, taking into account the interference between the $K\pi\Sigma$ wave and $P$ wave, are $|A_1|^2 = 0.587 \pm 0.011$(stat) $\pm 0.013$(syst) and $|A_2|^2 = 0.230 \pm 0.013$(stat) $\pm 0.025$(syst); and for $B^0_s$: $|A_1|^2 = 0.555 \pm 0.027$(stat) $\pm 0.006$(syst), and $|A_2|^2 = 0.244 \pm 0.032$(stat) $\pm 0.014$(syst) are consistent and competitive with those reported in the literature [6,14,16]. Our measurement of the strong phases $\delta_1$ and $\delta_2$ indicates the presence of final-state interactions for the decay

![FIG. 2 (color online). PDL distribution for selected (a) $B^0_{d}$ and (b) $B^0_s$ candidate events. The points with error bars represent the data, and the curves represent the fit projections for the total, signal, and background components.](image)

| Source               | $|A_1|^2$  | $|A_2|^2$  | $\delta_1$(rad) | $\delta_2$(rad) | $\tau_d$(ps) | $|A_1|^2$  | $|A_2|^2$  | $\delta_1$(rad) | $\delta_2$(rad) | $\Delta \Gamma_s$(ps$^{-1}$) | $\tilde{\tau}_s$(ps) | $\tilde{\tau}_s/\tau_d$ |
|----------------------|-----------|-----------|-----------------|-----------------|-------------|-----------|-----------|-----------------|-----------------|--------------------------|----------------|-----------------|
| Mass background      | $\cdots$  | 0.024     | 0.09            | 0.05            | 0.030       | $0.004$   | $0.002$   | 0.02            | $\cdots$         | 0.021         | 0.009               |
| PDL resolution       | 0.013     | 0.008     | 0.02            | 0.03            | 0.013       | $0.005$   | $0.003$   | $\cdots$         | 0.016           | 0.012               |
| Fitting code         | 0.001     | $\cdots$ | $\cdots$        | 0.004           | $\cdots$   | 0.004     | 0.014     | 0.26            | $\cdots$         | 0.008         | 0.003               |
| Alignment            | $\cdots$ | $\cdots$ | $\cdots$        | 0.007           | $\cdots$   | $\cdots$ | $\cdots$ | $\cdots$         | 0.007           | $\cdots$         | $\cdots$            |
| Total                | 0.013     | 0.025     | 0.09            | 0.06            | 0.034       | 0.006     | 0.014     | 0.26            | 0.001           | 0.028         | 0.015               |

TABLE II. Summary of systematic uncertainties in the measurement of angular and lifetime parameters. The total uncertainties are given combining individual uncertainties in quadrature.
$B_d^0 \to J/\psi K^{*0}$ [2] since $\delta_1 = -0.38 \pm 0.06 (\text{stat}) \pm 0.09 (\text{syst})$ rad is $3.5\sigma$ away from zero, where $\sigma$ is the total uncertainty. From the comparison of the measured amplitudes and strong phases [17] for both decays we conclude that they are consistent with being equal for $B_d^0$ and $B_s^0$, and hence there is no evidence for a deviation from flavor SU(3) symmetry. In our sample we find that the $K\pi$ S-wave intensity, as described in Ref. [14], is $(4.0 \pm 1.0)\%$.

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[3] Unless explicitly stated, the appearance of a specific charge state will also imply its charge conjugate throughout the Letter.
[12] Throughout the paper, if not explicit dependence on time is stated, we denote $A_i(0) = A_i$ for $i = \{0, \|, \perp\}$.
[17] Using the relation between these phases we obtain $\delta_{\|,B_d^0} = 3.59 \pm 0.06 \pm 0.09$ rad.