Measurement of the angular and lifetime parameters of the decays $B_d^0 \to J/\psi K^{*0}$ and $B_s^0 \to J/\psi \phi$


(The D0 Collaboration)

1Universidad de Buenos Aires, Buenos Aires, Argentina
2LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil
3Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
4Universidade Federal do ABC, Santo André, Brazil
5Instituto de Física Teórica, Universidade Estadual Paulista, São Paulo, Brazil
6University of Alberta, Edmonton, Alberta, Canada, Simon Fraser University, Burnaby, British Columbia, Canada, York University, Toronto, Ontario, Canada, and, McGill University, Montreal, Quebec, Canada
7University of Science and Technology of China, Hefei, People's Republic of China
8Universidad de los Andes, Bogotá, Colombia
9Center for Particle Physics, Charles University, Prague, Czech Republic
10Czech Technical University, Prague, Czech Republic
11Center for Particle Physics, Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic
12Universidad San Francisco de Quito, Quito, Ecuador
13LPSC, Université Blaise Pascal, CNRS/IN2P3, Clermont, France
14LPSC, Université Joseph Fourier Grenoble 1, CNRS/IN2P3, Institut National Polytechnique de Grenoble, Grenoble, France
15CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France
16LAL, Université Paris-Sud, IN2P3/CNRS, Orsay, France
17LPNHE, IN2P3/CNRS, Universités Paris VI and VII, Paris, France
18CEA, Ifica, SPP, Saclay, France
19IPHC, Université Louis Pasteur, CNRS/IN2P3, Strasbourg, France
20IPNL, Université Lyon I, CNRS/IN2P3, Villeurbanne, France and Université de Lyon, Lyon, France
21III. Physikalisches Institut A, RWTH Aachen University, Aachen, Germany
22Physikalisches Institut, Universität Bonn, Bonn, Germany
23Physikalisches Institut, Universität Freiburg, Freiburg, Germany
24Institut für Physik, Universität Mainz, Mainz, Germany
25Ludwig-Maximilians-Universität München, München, Germany
26Fachbereich Physik, Universität Wuppertal, Wuppertal, Germany
27Panjab University, Chandigarh, India
28Delhi University, Delhi, India
We present measurements of the linear polarization amplitudes and the strong relative phases that describe the flavor-untagged decays $B^{0}_{s} \rightarrow J/\psi K^{*0}$ and $B^{0}_{s} \rightarrow J/\psi$ in the transversity basis. We also measure the mean lifetime $\tau_{s}$ of the $B^{0}_{s}$ mass eigenstates and the lifetime ratio $\tau_{s}/\tau_{d}$. 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 $B^{0}_{s} \rightarrow J/\psi K^{*0}$ decay.
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 [1] and this implies that the relative strong phases are 0 (mod π) [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 system one expects that the theoretical description is similar; in particular the B^0-B^0 system is very small [3]. In this analysis, we assume CP conservation and express the differential decay rate for the untagged decay B^0 → J/ψK^0 in terms of these inverse lifetimes. The angular distribution in the B^0 system is very small [13]. In this analysis, we assume CP conservation and express the differential decay rate for the untagged decay B^0 → J/ψK^0 as [2]:

\[
d^4\varphi/(d\omega\,dt) \propto e^{-\Gamma_L t} \left[ |A_0|^2 f_1(\omega) + |A_\parallel|^2 f_2(\omega) + |A_\perp|^2 f_3(\omega) \right]
\]

where Γ_L and Γ_H are the decay rates for the B^0 to J/ψK^0 and B^0 to J/ψK^0, respectively. The factors f_i(\omega) are defined in Ref. [2]. In this decay, we have access to the phase δ_i = arg(A_i^*A_i), which is related to δ_1 by δ_1 = δ_2 - δ_0.

In the B^0 system, there is evidence of interference between the P- and S-wave Kπ amplitudes [14], which is taken into account in this analysis. The differential decay rate for the untagged decay B^0 → J/ψK^0 is given by [2, 14]:

\[
d^4\varphi/(d\omega\,dt) \propto e^{-\Gamma_L t} \left[ |A_0|^2 f_1(\omega) + |A_\parallel|^2 f_2(\omega) \right]
\]
+ |A_1|^2 f_3(\omega) - \zeta \text{Im}(A_1^* A_2) f_4(\omega) + \text{Re}(A_0^* A_2) f_5(\omega) + \zeta \text{Im}(A_0^* A_1) f_6(\omega) \\
+ \sin^2 \lambda \cdot f_7(\omega) \\
+ \frac{1}{2} \sin 2\lambda \left[ f_8(\omega) \cos (\delta_1 - \delta_2) |A_1| + f_9(\omega) \sin (\delta_1 - \delta_2) |A_1| + f_{10}(\omega) \cos \delta_s \cdot |A_0| \right], \tag{2} \]

where $\Gamma_d \equiv 1/\tau_d$ is the inverse of the $B_d^0$ lifetime, $\zeta = 1/(-1)$ for $K^+(K^-)$; $\lambda$, $\delta_s$, and $f_6(\omega)$ are defined in Refs. [2, 14]. For the $B_d^0$, $\Delta \Gamma_d$ is expected to be zero [13].

An unbinned likelihood fit is performed to extract all the $B_d^0$ and $B_s^0$ parameters. For the $j$th $B$ meson candidate, the inputs for the fit are the mass $m_j$, PDL $\sigma_{ct_j}$, PDL uncertainty $\sigma_{ct_j}$, and the angular variables $\omega_j$. The likelihood function $\mathcal{L}$ for the untagged decays $B_d^0 \to J/\psi K^{*0}$ and $B_s^0 \to J/\psi \phi$, is defined by

$$
\mathcal{L} = \prod_{j=1}^{N} \left[ f_s \mathcal{F}_s + (1 - f_s) \mathcal{F}_b \right], \tag{3}
$$

where $N$ is the total number of selected events and $f_s$ is the fraction of signal events in the sample, a free parameter in the fit.

$\mathcal{F}_s$ is the product of the signal probability distribution functions (PDF) of mass, PDL, and transversity angles, and the angular acceptances, which are determined via Monte Carlo simulations. The mass and PDL signal distributions are modeled for both decays in the same way. The mass distribution is modeled by a Gaussian function with free mean and width. The PDL distribution is described [10] by the convolution of an exponential, whose decay constant is one of the fit parameters with a resolution function represented by two weighted Gaussian functions centered at zero. The widths $\sigma_{ct_j}$ of each Gaussian with scale factors $s_i (i = 1, 2)$ are free parameters in the fit to allow for a possible misestimate of the PDL uncertainty. The transversity angular distributions are modeled by the corresponding normalized Eqs. (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.

$\mathcal{F}_b$ is the product of the background PDF of the same variables and the angular acceptance as in the signal. We separate the background contributions into two types. The prompt background accounts for directly produced $J/\psi$ mesons combined with random tracks. Non-prompt background is due to $J/\psi$ mesons produced by a $b$ hadron decay combined with tracks that come from either a multibody decay of the same $b$ hadron or from hadronization. The mass distribution for the background is modeled by two independent normalized negative-slope exponentials, one for the prompt and one for the non-prompt contributions. The PDL distribution for the prompt background is parameterized by the resolution function described above. The PDL distribution for the non-prompt background is modeled by a sum of two exponential components for positive $ct$ and one for negative $ct$ that account for a mix of heavy flavor meson decays and their possible misreconstruction. The angular distributions for the background components are modeled by a shape similar to that of the signal, but with an independent set of amplitudes and phases.

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$B_d^0$</th>
<th>$B_s^0$</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>A_0</td>
<td>^2$</td>
<td>0.587 ± 0.011</td>
</tr>
<tr>
<td>$</td>
<td>A_1</td>
<td>^2$</td>
<td>0.230 ± 0.013</td>
</tr>
<tr>
<td>$\delta_1$</td>
<td>$-0.38 ± 0.06$</td>
<td>$-^{+}$</td>
<td>rad</td>
</tr>
<tr>
<td>$\delta_2$</td>
<td>3.21 ± 0.06</td>
<td>$-^{+}$</td>
<td>rad</td>
</tr>
<tr>
<td>$\tau$</td>
<td>1.414 ± 0.018</td>
<td>1.487 ± 0.060</td>
<td>ps</td>
</tr>
<tr>
<td>$\Delta \Gamma_d$</td>
<td>$-0.38 ± 0.06$</td>
<td>$0.0065 ± 0.0078$</td>
<td>$-^{+}$</td>
</tr>
</tbody>
</table>

Table II summarizes the systematic uncertainties in our measurements for $B_d^0$ and $B_s^0$ 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 pseudo-experiments for $B_d^0$ and 1000 for $B_s^0$, 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 $\delta_1$ reported for this source is due to an intrinsic ambiguity for this parameter in Eq. (1). The pseudo-experiments produced also cover the other solution for $\delta_1$. 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 $\tau_s/\tau_q$ 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.

Table I: Summary of measurements for the decays $B_d^0 \to J/\psi K^{*0}$ and $B_s^0 \to J/\psi \phi$. The uncertainties are only statistical.

Table II: Systematic uncertainties in our measurements for $B_d^0$ and $B_s^0$ decays.
TABLE II: Summary of systematic uncertainties in the measurement of angular and lifetime parameters. The total uncertainties are given combining individual uncertainties in quadrature.

| Source               | $|A_0|^2$ | $|A_1|^2$ | $\delta_1$ (rad) | $\delta_2$ (rad) | $\tau_d$ (ps) | $|A_0|^2$ | $|A_1|^2$ | $\delta_1$ (rad) | $\delta_2$ (rad) | $\Delta \Gamma_s$ (ps$^{-1}$) | $\tau_s$ (ps) | $\tau_s/\tau_d$ |
|----------------------|----------|----------|------------------|------------------|----------------|----------|----------|------------------|------------------|----------------------|----------------|----------------|
| Mass background      | —        | 0.024    | 0.09             | 0.05             | 0.030          | 0.004    | 0.002    | 0.02             | —                | —                    | 0.021          | 0.009          |
| PDL resolution       | 0.013    | 0.008    | 0.02             | 0.03             | 0.013          | 0.005    | 0.003    | —                | —                | —                    | 0.016          | 0.012          |
| Fitting code         | 0.001    | —        | —                | —                | —              | 0.004    | 0.014    | 0.26             | —                | 0.001                | 0.008          | 0.003          |
| Alignment            | —        | —        | —                | —                | —              | —        | —        | —                | —                | —                    | 0.007          | —              |
| Total                | 0.013    | 0.025    | 0.09             | 0.06             | 0.034          | 0.006    | 0.014    | 0.26             | —                | 0.001                | 0.028          | 0.015          |

In conclusion, we have measured the angular and lifetime parameters for the time-dependent angular untagged decays $B^0 \to J/\psi K^{*0}$ and $B^0 \to J/\psi \phi$, the lifetime ratio of both $B$ mesons, and the width difference $\Delta \Gamma_s$ for the $B^0$ meson. From the measured lifetime parameters $\tau_s$ and $\tau_d$ we obtain the ratio $\tau_s/\tau_d = 1.052 \pm 0.061 \text{ (stat)} \pm 0.015 \text{ (syst)}$ which is consistent with the theoretical prediction [5] and previous measurements [6]. The measurement of the width difference $\Delta \Gamma_s = 0.085^{+0.074}_{-0.076} \text{ (stat)} \pm 0.006 \text{ (syst)}$ ps$^{-1}$ is consistent with the theoretical prediction [5, 13] and with the value reported in Refs. [6, 16]. D0 also has a measurement of $\Delta \Gamma_s$ in a flavor-tagged analysis of $B^0 \to J/\psi \phi$ in Ref. [8].

Our measurements for the linear polarization amplitudes for the $B^0_d$, taking into account the interference between the $K \pi$ $S$-wave and $P$-wave, are $|A_0|^2 = 0.587 \pm 0.011 \text{ (stat)} \pm 0.013 \text{ (syst)}$ and $|A_1|^2 = 0.290 \pm 0.013 \text{ (stat)} \pm 0.025 \text{ (syst)}$; and for $B^0_s$: $|A_0|^2 = 0.555 \pm 0.027 \text{ (stat)} \pm 0.006 \text{ (syst)}$, and $|A_1|^2 = 0.244 \pm 0.032 \text{ (stat)} \pm 0.014 \text{ (syst)}$ are consistent and competitive with those reported in the literature [6, 14, 15]. Our measurement of the strong phases $\delta_1$ and $\delta_2$ indicates the presence of final-state interactions for the decay $B^0_d \to J/\psi K^{*0}$ [2] since $\delta_2 = -0.38 \pm 0.06 \text{ (stat)} \pm 0.09 \text{ (syst)}$ 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 $B^0_d$ and $B^0_s$ 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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[a] Visitor from Augustana College, Sioux Falls, SD, USA.
b] Visitor from The University of Liverpool, Liverpool, UK.
c] Visitor from Rutgers University, Piscataway, NJ, USA.
d] Visitor from II. Physikalisches Institut, Georg-August-University, Göttingen, Germany.
e] Visitor from Centro de Investigacion en Computacion - IPN, Mexico City, Mexico.
f] Visitor from ECFM, Universidad Autonoma de Sinaloa, Culiacá, Mexico.
g] Visitor from Helsinki Institute of Physics, Helsinki, Finland.
h] Visitor from Universitä Bern, Bern, Switzerland.

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