Measurement of the $B_s^0$ lifetime in the exclusive decay channel $B_s^0 \to J/\psi \phi$

Using the exclusive decay $B_s^0 \rightarrow J/\psi(\mu^+\mu^-)\phi(K^+K^-)$, we report the most precise single measurement of the $B_s^0$ lifetime. The data sample corresponds to an integrated luminosity of approximately 220 pb$^{-1}$ collected with the DØ detector at the Fermilab Tevatron Collider in 2002–2004. We reconstruct 337 signal candidates, from which we extract the $B_s^0$ lifetime, $\tau(B_s^0) = 1.444^{+0.098}_{-0.090}$ (stat) ± 0.020 (sys) ps. We also report a measurement for the lifetime of the $B^0$ meson using the exclusive decay $B^0 \rightarrow J/\psi(\mu^+\mu^-)K^{*0}(892)(K^+\pi^-)$. We reconstruct 1370 signal candidates, obtaining $\tau(B^0) = 1.473^{+0.052}_{-0.050}$ (stat) ± 0.023 (sys) ps, and the ratio of lifetimes,
\[ \tau(B_d^0)/\tau(B^0) = 0.980^{+0.076}_{-0.071} \text{ (stat)} \pm 0.003 \text{ (sys)}. \]

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Lifetime differences among hadrons containing \( b \) quarks can be used to probe decay mechanisms that go beyond the quark-spectator model [1]. In the charm sector, lifetime differences are quite large [2]; however, in the bottom sector, due to the larger \( b \)-quark mass, these differences are expected to be smaller. Phenomenological models predict differences of about 5% between the lifetimes of \( B^+ \) and \( B^0 \), but no more than 1% between \( B^0 \) and \( B_s^0 \) lifetimes [1]. These predictions are consistent with previous measurements of \( B \)-meson lifetimes [2]. It has also been postulated [3] that the lifetimes of the two \( CP \) eigenstates (of the \( B^0_s \)-\( \bar{B}^0_s \) system) differ. This could be observed as a difference in lifetime between \( B^0_s \) semileptonic decays, which should have an equal mixture of the two \( CP \) eigenstates, and the lifetime for \( B_s^0 \to J/\psi \phi \), which is expected to be dominated by the \( CP \)-even eigenstate [3].

In this Letter, we report a measurement of the lifetime of the \( B_d^0 \) meson using the exclusive decay channel \( B_d^0 \to J/\psi \phi \), followed by \( J/\psi \to \mu^+ \mu^- \) and \( \phi \to K^+ K^- \). The lifetime is extracted using a simultaneous unbinned maximum likelihood fit to masses and proper decay lengths. We also measure the lifetime of the \( B^0 \) meson in the exclusive decay \( B^0 \to J/\psi K^{*0}(892) \), followed by \( J/\psi \to \mu^+ \mu^- \) and \( K^{*0}(892) \to K^+ \pi^- \), and extract the ratio of the lifetimes of the \( B_d^0 \) and \( B^0 \) mesons. The analysis is based on data collected with the DØ detector in Run II of the Fermilab Tevatron Collider during the period September 2002–February 2004, which corresponds to approximately 220 \( \text{pb}^{-1} \) of \( p\bar{p} \) collisions at \( \sqrt{s} = 1.96 \text{ TeV} \).

The DØ detector is described in detail elsewhere [4]. We describe here only the detector components most relevant to this analysis. The central-tracking system consists of a silicon microstrip tracker (SMT) and a central fiber tracker (CFT), both located inside a 2 T superconducting solenoidal magnet [4]. The tracking system and solenoid is surrounded by a liquid argon calorimeter. The SMT has \( \approx 800,000 \) individual strips, with typical pitch of 50 – 80 \( \mu m \), and a design optimized for tracking and vertexing capability for \( |\eta| < 3 \), where \( \eta = -\ln[\tan(\theta/2)] \) is the pseudorapidity and \( \theta \) is the polar angle measured relative to the proton beam direction. The system has a six-barrel longitudinal structure, each with a set of four layers arranged axially around the beam pipe, and interspersed with sixteen radial disks. The CFT has eight thin coaxial barrels, each supporting two doublets of overlap-

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1 Unless explicitly stated, the appearance of a specific charge state will also imply its charge conjugate throughout this Letter.
the \( J/\psi \) mass. The resulting \( B_s^0 \) candidate is required to have \( p_T > 6.5 \text{ GeV}/c \). We allow only one \( B_s^0 \) candidate per event, and when multiple candidates exist, we choose the one with the best vertex probability. The resulting invariant mass distribution of the \( J/\psi \cdot \phi \) system is shown in Fig. 1(a).

Each primary vertex is reconstructed using tracks and the mean beam-spot position. The latter is determined for every data run, where a typical run lasts several hours. The initial primary vertex seed is constructed using all available tracks; a track is removed when it causes a change of more than 9 units in the \( \chi^2 \) for a fit to a common vertex. The process is repeated until no more tracks can be removed [5].

![Diagram](image-url)

FIG. 1: (a) Mass distribution for \( B_s^0 \) candidate events. Points with error bars show the data, and the solid curve represents the result of the fit. The mass distribution for the signal is shown in gray; (b) same distribution after requiring the significance of the lifetime measurement to be \( c\tau /\sigma(c\tau) > 5 \).

We take the four-track vertex as the position of the secondary vertex. To determine the distance traveled by each \( B_s^0 \) candidate, we calculate the signed transverse decay length (in a plane transverse to the direction of the beam), \( L_{xy} = \vec{x} \cdot (\vec{p}_T/p_T) \), where \( \vec{x} \) is the length vector pointing from the primary to the secondary vertex and \( \vec{p}_T \) is the reconstructed transverse momentum vector of the \( B_s^0 \). The proper decay length of the \( B_s^0 \) candidate is then defined as \( c\tau = L_{xy}(M_{B_s^0}/p_T) \), where \( M_{B_s^0} \) is taken as the world average mass of the \( B_s^0 \) meson 5.3696 \text{ GeV}/c^2 [2].

Figure 1(b) shows the reconstructed invariant mass distribution of the \( B_s^0 \) candidates after a proper decay length significance requirement of \( c\tau /\sigma(c\tau) > 5 \) is imposed, where \( \sigma(c\tau) \) is the uncertainty on \( c\tau \). The strong suppression of the background by this cut implies that the background is dominated by zero lifetime vertices, as expected.

The proper decay length (without any restriction on significance) and the invariant mass distributions for candidates passing the above criteria are fit simultaneously using an unbinned maximum likelihood method. The likelihood function \( \mathcal{L} \) is given by:

\[
\mathcal{L} = \prod_i \left[ f_s \mathcal{F}_s + (1 - f_s) \mathcal{F}_b \right],
\]

where \( \mathcal{F}_s \) is the product of probability density functions for mass and proper decay length for \( B_s^0 \), \( \mathcal{F}_b \) is the equivalent for background, \( f_s \) is the fraction of signal, and \( N \) is the total number of candidate events in the sample.

The proper decay length for signal events is modeled by a normalized exponential-decay function convoluted with a Gaussian function of width equal to the uncertainty on the proper decay length, which is typically \( \approx 25 \mu \text{m} \). This uncertainty is obtained from the full covariance (error) matrix of tracks at the secondary vertex and the uncertainty in the position of the primary vertex. The uncertainty is multiplied by a scale factor that is a parameter in the fit to allow for a possible misestimate of the decay length uncertainty. The mass distribution of signal events is modeled by a Gaussian function.

The proper decay length for the background is parametrized as a sum of a Gaussian function centered at zero and exponential decay functions, with two short-lived components and a long-lived term. The long-lived component accounts for heavy-flavor backgrounds, while the other terms account for resolution and prompt contributions to background. The mass distribution for the background is modeled by a first-order polynomial.

To determine the background we use a wide mass range of 5.078–5.636 \text{ GeV}/c^2 in the fit, corresponding to 4236 \( B_s^0 \) candidates. The number of background candidates in this range is sufficiently large to measure the parameters of the background with high accuracy and therefore extract a good measurement of the signal fraction and \( c\tau /\sigma(c\tau) \). The fit provides the \( c\tau \) and mass of the \( B_s^0 \), the shapes of the proper decay length and mass distributions for the background, and the signal fraction. Table I lists the fit values of the parameters and their uncertainties. The distribution of proper decay length and fits to the \( B_s^0 \) candidates are shown in Fig. 2(a).
TABLE I: Values of the extracted $M_B$, resolution on the reconstructed mass $\sigma_M$, the measured $ct$, the signal fractions $f_s$, and the scale factor $s$.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$B_s^0 \rightarrow J/\psi K^{*0}(892)$</th>
<th>$B^0 \rightarrow J/\psi K^{*0}(892)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_B$</td>
<td>$5357.0 \pm 2.5$ MeV/$c^2$</td>
<td>$5271.2 \pm 1.5$ MeV/$c^2$</td>
</tr>
<tr>
<td>$\sigma_M$</td>
<td>$32.9^{+2.5}_{-2.3}$ MeV/$c^2$</td>
<td>$37.9^{+1.2}_{-1.4}$ MeV/$c^2$</td>
</tr>
<tr>
<td>$ct$</td>
<td>$433^{+30}_{-27}$ $\mu$m</td>
<td>$442^{+16}_{-15}$ $\mu$m</td>
</tr>
<tr>
<td>$f_s$</td>
<td>$0.0796 \pm 0.0058$</td>
<td>$0.0446 \pm 0.0018$</td>
</tr>
<tr>
<td>$s$</td>
<td>$1.142 \pm 0.028$</td>
<td>$1.128 \pm 0.009$</td>
</tr>
</tbody>
</table>

![Diagram](image_url)

FIG. 2: Proper decay length distributions for (a) $B_s^0$ and (b) $B^0$ candidates. The points with error bars show the data. The solid curve shows the total fit, the dashed curve the background component, and the shaded region the signal.

With a very similar four-track topology in the final state, the exclusive decay $B^0 \rightarrow J/\psi K^{*0}(892)$ followed by $J/\psi \rightarrow \mu^+\mu^-$ and $K^{*0}(892) \rightarrow K^+\pi^-$ is reconstructed using the same selection criteria and algorithms as for the $B_s^0$ channel described above. The only differences are the requirement that the $p_T$ of the pion be greater than 0.5 GeV/$c$, and the selection of the $K^{*0}(892)$ candidates. The combination of two oppositely charged tracks, assuming the pion mass for one and the kaon mass for the other, that gives an invariant mass closest to the mass of the $K^{*0}(892)$ [2] is selected for further study. The invariant mass of these combinations is required to be between 0.850 and 0.930 GeV/$c^2$. Using the sample of $B^0$ candidates in the mass range 4.935–5.610 GeV/$c^2$, corresponding to 30692 candidates, we determine the $ct$ and mass of the $B^0$ using exactly the same procedure as used for $B_s^0$ mesons. Results are also given in Table I, and the distribution of proper decay length is shown in Fig. 2(b).

Detailed Monte Carlo studies were performed on ensembles of events comparable to data samples, with similar resolutions, pulls, fitting and selection criteria. No significant biases resulting from our analysis procedures were observed. To test the stability of the fit results for $B_s^0$ and $B^0$ mesons, we split each data sample into two roughly equal parts in order to study different kinematic and geometric parameters, compared the fit results, and found consistency within their uncertainties. We varied the selection criteria and mass ranges, and did not observe any significant shifts. Using Monte Carlo samples with different input proper decay lengths in the range 340 to 560 $\mu$m, we checked the response of our fits to this variation, and found it to be linear in this range. We studied the contamination of our sample from cross-feed between $B_s^0$ and $B^0$ using Monte Carlo events. The estimated contamination is 4.4% for $B_s^0$ and 1.1% for $B^0$, with invariant mass spread almost uniformly across the entire mass range. Therefore, their contributions are included in the long-lived heavy-flavor component of the background. To study possible biases from our fitting procedure, we used toy Monte Carlo ensembles with the same statistics as our data and with distributions matching those in data. These samples were fit, and the resulting means and widths of the distributions of extracted parameters are consistent with the fits to data.

Other sources of systematic uncertainty have been considered, and the contributions are listed in Table II. For the $B_s^0$ lifetime, there are major contributions from determination of the background, the model for resolution, and the reconstruction of the secondary vertex. To determine the systematic error due to the uncertainty in the background, we considered different models for the mass and decay-length distributions. In particular, to account for any model dependence on the invariant mass of misreconstructed heavy-flavor hadrons, we fit the probability distributions separately in the lower-mass and higher-mass side-band regions, and found the long-lived component to have different exponents. Combining the two lifetime values for the long-lived components, we modified the functional form of the long-lived component for the global background in our fit. The two long-lived components were combined using a weighting parameter $w = 0.98^{+0.02}_{-0.03}$. This weighting parameter was varied by its uncertainty. The largest difference in the $ct(B_s^0)$ observed in these variations of background modeling was
found to be 4 µm, and is taken as the systematic uncertainty due to this source. The effect of uncertainty in the proper decay length resolution was studied by using an alternative resolution function consisting of two Gaussian functions (with the same mean but different width), resulting in a difference in the fitted \(ct(B^0_s)\) of 3 µm. Uncertainty or biases in the determination of the secondary vertex were estimated using secondary vertices constructed with the \(J/\psi\) tracks only, resulting in a \(ct(B^0_s)\) shift of 3 µm. The contribution from the uncertainty on the detector alignment is estimated by reconstructing the \(B^0_s\) candidate events with the position of the SMT sensors shifted radially outwards by the alignment error in the radial position of the sensors. The resulting difference in fitted proper decay length of 2 µm is taken as the systematic uncertainty due to possible misalignment. The total systematic uncertainty from all these sources added in quadrature is 6 µm. The systematic uncertainties in the measurement of the \(ct(B^0)\) are determined in the same way as for the \(B^0_s\), and each contribution is listed in Table II.

### Table II: Summary of systematic uncertainties.

<table>
<thead>
<tr>
<th>Source</th>
<th>(ct(B^0_s)) (µm)</th>
<th>(ct(B^0)) (µm)</th>
<th>(\tau(B^0_s)/\tau(B^0))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alignment</td>
<td>2</td>
<td>2</td>
<td>0.000</td>
</tr>
<tr>
<td>J/\psi vertex</td>
<td>3</td>
<td>4</td>
<td>0.002</td>
</tr>
<tr>
<td>Model for resolution</td>
<td>3</td>
<td>3</td>
<td>0.000</td>
</tr>
<tr>
<td>Background</td>
<td>4</td>
<td>5</td>
<td>0.002</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>6</strong></td>
<td><strong>7</strong></td>
<td><strong>0.003</strong></td>
</tr>
</tbody>
</table>

We determine the lifetimes of the \(B^0_s\) and \(B^0\) mesons,

\[
\tau(B^0_s) = 1.444^{+0.096}_{-0.096} \text{ (stat)} \pm 0.020 \text{ (sys) ps},
\]

\[
\tau(B^0) = 1.473^{+0.052}_{-0.050} \text{ (stat)} \pm 0.023 \text{ (sys) ps}.
\]

Both results are consistent with the current world averages of \(\tau(B^0_s) = 1.461 \pm 0.057 \text{ ps and } \tau(B^0) = 1.536 \pm 0.014 \text{ ps} \) [2]. We note that measurements using \(B^0_s\) semileptonic events, where there is an equal mixture of \(CP\)-even and \(CP\)-odd states, dominate the current world average, while \(B^0 \rightarrow J/\psi\phi\) has a different composition of \(CP\)-even and \(CP\)-odd states as discussed earlier [6].

Using our results we determine the ratio of \(B^0_s/B^0\) lifetimes to be

\[
\frac{\tau(B^0_s)}{\tau(B^0)} = 0.980^{+0.076}_{-0.071} \text{ (stat)} \pm 0.003 \text{ (sys)},
\]

where statistical uncertainties were propagated in quadrature, and the systematic uncertainty was evaluated by adding each contribution to the corresponding central value, and evaluating a new ratio, with the difference from the nominal value taken as the systematic uncertainty of that source, as shown in Table II. The sum in quadrature of all contributions is reported as the overall systematic uncertainty on the ratio of lifetimes including correlations between the two lifetime measurements.

In conclusion, we have measured the \(B^0_s\) and \(B^0\) lifetimes in exclusive decay modes in \(p\bar{p}\) collisions. The measurements are consistent with previous results [2]. The value of the \(B^0_s\) lifetime obtained in this analysis is the most precise measurement from any single experiment. The ratio of the lifetimes is also in good agreement with QCD models based on a heavy quark expansion, which predict a difference between \(B^0_s\) and \(B^0\) lifetimes of the order of 1% [1].

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[6] The exact fraction of \(CP\)-even and \(CP\)-odd decays is un-
known. In this analysis, from Monte Carlo, the relative efficiency for $CP$-even and $CP$-odd states is $0.99 \pm 0.01$.

**APPENDIX: $B^0$ MASS DISTRIBUTIONS**

Figure 3 shows the invariant mass distributions for reconstructed $B^0$ candidates before and after the $c\tau$ cut.

FIG. 3: (a) Mass distribution for $B^0$ candidate events. Points with error bars show the data, and the solid curve represents the result of the fit. The mass distribution for the signal is shown in gray; (b) same distribution after requiring the significance of the lifetime measurement to be $c\tau/\sigma(c\tau) > 5$. 