Measurement of the Ratio of $B^+$ and $B^0$ Meson Lifetimes

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 Instituto de Física Teórica, Universidade Estadual Paulista, São Paulo, Brazil
5 Simon Fraser University, Burnaby, Canada, University of Alberta, Edmonton, Canada, McGill University, Montreal, Canada and York University, Toronto, Canada
6 Institute of High Energy Physics, Beijing, People’s Republic of China
7 Universidad de los Andes, Bogotá, Colombia
8 Charles University, Center for Particle Physics, Prague, Czech Republic
9 Czech Technical University, Prague, Czech Republic
10 Institute of Physics, Academy of Sciences, Center for Particle Physics, Prague, Czech Republic
11 Universidad San Francisco de Quito, Quito, Ecuador

12 Laboratoire de Physique Corpusculaire, IN2P3-CNRS, Université Blaise Pascal, Clermont-Ferrand, France
13 Laboratoire de Physique Subatomique et de Cosmologie, IN2P3-CNRS, Université de Grenoble I, Grenoble, France
14 CPPM, IN2P3-CNRS, Université de la Méditerranée, Marseille, France
15 Laboratoire de l’Accélérateur Linéaire, IN2P3-CNRS, Orsay, France
16 LPNHE, Universités Paris VI and VII, IN2P3-CNRS, Paris, France
17 DAFNIA/Service de Physique des Particules, CEA, Saclay, France
18 IReS, IN2P3-CNRS, Université Louis Pasteur, Strasbourg, France and Université de Haute Alsace, Mulhouse, France
19 Institut de Physique Nucléaire de Lyon, IN2P3-CNRS, Université Claude Bernard, Villeurbanne, France
20 RWTH Aachen, III. Physikalisches Institut A, Aachen, Germany
21 Universität Bonn, Physikalisches Institut, Bonn, Germany
22 Universität Freiburg, Physikalisches Institut, Freiburg, Germany
23 Universität Mainz, Institut für Physik, Mainz, Germany
24 Ludwig-Maximilians-Universität München, München, Germany
25 Fachbereich Physik, Universität Wuppertal, Wuppertal, Germany
26 Panjab University, Chandigarh, India
27 Tata Institute of Fundamental Research, Mumbai, India
28 University College Dublin, Dublin, Ireland
29 Korea Detector Laboratory, Korea University, Seoul, Korea
30 CINVESTAV, Mexico City, Mexico
31 FOM-Institute NIKHEF and University of Amsterdam/NIKHEF, Amsterdam, The Netherlands
32 University of Nijmegen/NIKHEF, Nijmegen, The Netherlands
33 Joint Institute for Nuclear Research, Dubna, Russia
The ratio of $B^+$ and $B^0$ meson lifetimes was measured using data collected in 2002–2004 by the D0 experiment in Run II of the Fermilab Tevatron Collider. These mesons were reconstructed in $B^+ \rightarrow \mu^+ \nu D^+ X$ decays, which are dominated by $B^0$, and $B^0 \rightarrow \mu^+ \nu D^0 X$ decays, which are dominated by $B^+$. The ratio of lifetimes is measured to be $\tau^+ / \tau^0 = 1.080 \pm 0.016$ (stat) $\pm 0.014$ (syst).

In the last few years, significant progress has been made, on both experimental and theoretical fronts, in the understanding of the lifetimes of hadrons containing heavy quarks. Charm and bottom meson (except $B_c$) lifetimes have been measured with precisions ranging from 0.5% to 4%, although lifetimes of heavy baryons are not known as well [1]. On the theoretical front, predictions are being made using a rigorous approach based on the heavy quark expansion (in negative powers of the heavy quark mass) [2], where the large mass of the bottom quark considerably simplifies calculations. Theoretical uncertainties are further reduced for ratios of lifetimes. For instance, the ratio of the $B^+$ and $B^0$ lifetimes has been predicted to be $1.06 \pm 0.02$ [3]. Experimentally, ratios of lifetimes have smaller uncertainties, since many common sources of systematics cancel.
In this Letter, we present a measurement of the ratio of $B^+$ and $B^0$ lifetimes using a large sample of semileptonic $B$ decays collected by the DØ experiment at Fermilab in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. The data correspond to approximately 440 pb$^{-1}$ of integrated luminosity. $B$ mesons were selected via their decays $B \to \mu^+\nu D^{*+}X$ [4] and were classified into two exclusive groups: a “$D^{*-}$” sample, containing all events with reconstructed $D^{*-} \to D^0\pi^- \nu$ decays, and a “$D^0$” sample, containing all remaining events. Both simulation and available experimental results show that the $D^{*-}$ sample is dominated by $B^0 \to \mu^+\nu D^{*-}X$ decays, while the $D^0$ sample is dominated by $B^+ \to \mu^+\nu D^0X$ decays.

The classification into these two samples was based on the presence of a slow pion from $D^{*-} \to D^0\pi^-$ decay, and thus was independent of the $B$-meson lifetime. Therefore, the ratio of the number of events in the two samples, expressed as a function of the proper decay length, depends mainly on the lifetime difference between the $B^+$ and $B^0$ mesons. The influences of the selection criteria, detector properties, and some systematic uncertainties are significantly reduced.

The DØ detector is described in detail elsewhere [5]. The detector components most important to this analysis are the central tracking and muon systems. The tracking system consists of a silicon microstrip tracker and a central fiber tracker, both located within a 2 T superconducting solenoidal magnet. The resolution for the distance of closest approach as provided by the tracking system is $\approx 50 \mu$m for tracks with $p_T \approx 1$ GeV/c, improving asymptotically to $15 \mu$m for tracks with $p_T \geq 10$ GeV/c, where $p_T$ is the component of the momentum perpendicular to the beam pipe. The muon system is located outside the calorimeters and consists of a layer of drift chambers and scintillation trigger counters in front of 1.8 T toroids, followed by two more similar layers after the toroids.

Events with semi-muonic $b$-hadron decays were selected using a suite of inclusive single-muon triggers in a three-level trigger system. Muons were identified by extrapolating tracks found in the central tracking system and matching them with muon track segments formed from hits in the muon system. Muons were required to have a transverse momentum $p_T > 2$ GeV/c and total momentum $p^\mu > 3$ GeV/c.

The primary vertex of the $p\bar{p}$ interaction was determined for each event. The average position of the beam-collision point was included as a constraint. The precision of the primary vertex reconstruction was on average about 20 $\mu$m in the plane perpendicular to the beam direction and about 40 $\mu$m along the beam direction.

$D^0$ candidates were selected using their $D^0 \to K^+\pi^-$ decay mode. All charged particles in an event were clustered into jets using the DURHAM clustering algorithm [6] with a jet $p_T$ cut-off parameter of 15 GeV/c [7]. The $D^0$ candidate was constructed from two particles of opposite charge belonging to the same jet as the reconstructed muon. Both particles were required to have $p_T > 0.7$ GeV/c and to form a common $D^0$ vertex. The $p_T$ of the $D^0$ was required to exceed 5 GeV/c. To reduce combinatorial background, we required the $D^0$ vertex to have a positive displacement in the $xy$ plane, relative to the primary vertex, with at least 4$\sigma$ significance. Although this last requirement can bias the lifetime distribution of a $B$ candidate, our analysis procedure of determining the ratio of $B^+$ and $B^0$ events in bins of proper time should remove this bias in the final result. The trajectory of the muon and $D^0$ candidates were required to originate from a common $B$ vertex. The $\mu^+D^0$ system was required to have an invariant mass between 2.3 and 5.2 GeV/c$^2$.

The masses of the kaon and pion were assigned to the $K\pi$ system after these selections is shown in Fig. 1(a). The signal in the $D^0$ peak contains 126073 ± 610 events.

All reconstructed $\mu^+D^0$ events were classified into three non-overlapping samples. For each $\mu^+D^0$ candidate, a search was made for an additional pion. The mass difference $\Delta m = m(D^0\pi) - m(D^0)$ for all such pions, when $1.8 < m(D^0) < 1.9$ GeV/c$^2$, is shown in Fig. 1(b). The peak in this figure corresponds to the production of the $\mu^+D^{*-}$ system. All events containing a pion with a charge opposite to that of the muon (wrong-charge combination) and 0.1425 < $\Delta m$ < 0.1490 GeV/c$^2$ were included in the $D^{*-}R$ sample. All events containing a pion with the same charge as the muon (wrong-charge combination) and 0.1425 < $\Delta m$ < 0.1490 GeV/c$^2$ were included in the auxiliary $D^{*-}W$ sample. This sample contains true $D^0$ but fake $D^{*-}$ events and gives an estimate of the combinatorial background for selected $\mu^+D^{*-}$ candidates. The $\Delta m$ distribution for such events is shown in Fig. 1(b) as the filled histogram. All remaining events were assigned to the $D^0$ sample.

Since the final (semileptonic) state has missing particles, including the neutrino, the proper de-
cay length was not determined. Instead, for each reconstructed candidate, the measured visible proper decay length $x^M$ was computed as $x^M = m_B c (L_T \cdot p_T(\mu^+ D^0))/|p_T(\mu^+ D^0)|^2$. $L_T$ is the vector in the axial plane from the primary to the $B$-meson decay vertex, $p_T(\mu^+ D^0)$ is the transverse momentum of the $\mu^+ D^0$ system and $m_B$ is the mass of the $B$ meson, for which the value 5.279 GeV/c$^2$ was used [1]. The pion from the $D^{*-}$ decay was not used for the computation of the transverse momentum and the decay length.

Candidates in each of the samples were divided into eight groups according to their $x^M$ value. The number of $\mu^+ D^0$ events $N_{iR}$ (from the $D^{*-R}$ sample), $N_{iW}$ (from the $D^{*-W}$ sample), and $N_i^0$ (from the $D^0$ sample) in each interval $i$ (where $i$ ranges from one to eight) were determined from the fit to the $K\pi$ mass spectrum between 1.72 and 2.16 GeV/c$^2$ with the sum of a Gaussian signal function and a polynomial background function. The mean and width of the Gaussian function were fixed to the values obtained from the fit of the overall mass distribution in each sample. The fitting procedure was the same for all samples. Table I gives the numbers obtained for each $x^M$ interval.

The number of $\mu^+ D^{*-}$ events for each interval $i$ of $x^M$ was defined as $N_i(\mu^+ D^{*-}) = N_{iR} - C \cdot N_{iW}^0$, where $C \cdot N_{iW}^0$ accounts for the combinatorial background under the $D^{*-}$ peak as shown in Fig. 1(b). The coefficient $C = 1.27 \pm 0.03$ reflects the difference in the combinatorial background between $\mu^+ D^0\pi^-$ and $\mu^+ D^0\pi^+$ events. It was determined from the ratio of the numbers of these events in the interval 0.153 < $\Delta m$ < 0.160 GeV/c$^2$. The number of $\mu^+ D^0$ events in each interval $i$ in $x^M$ was defined as $N_i(\mu^+ D^0) = N_{iR} + N_{iW}^0 + C \cdot N_{iW}^0$.

The experimental observable $r_i$ is the ratio of $\mu^+ D^{*-}$ and $\mu^+ D^0$ events in interval $i$ of $x^M$, i.e., $r_i = N_i(\mu^+ D^{*-})/N_i(\mu^+ D^0)$. Values of $r_i$ and statistical uncertainties are given in Table I. The measurement of the lifetime difference between $B^+$ and $B^0$ is given by $\tau = \tau^0/\tau^+ - 1$. It was determined from the minimization of $\chi^2(\varepsilon, k)$:

$$\chi^2(\varepsilon, k) = \sum_i \frac{(r_i - r_i^e(\varepsilon, k))^2}{\sigma^2(r_i)},$$

where $r_i^e(\varepsilon, k)$ is the expected ratio of $\mu^+ D^{*-}$ and $\mu^+ D^0$ events, and $\varepsilon$ is the efficiency to reconstruct the slow pion in the $D^{*-} \rightarrow D^0\pi^-$ decay. $\varepsilon$ was assumed to be independent of $x^M$ and, along with $k$, was a free parameter in the minimization. We present evidence for the validity of this assumption in the discussion of systematic uncertainties. The sum $\sum_i$ was taken over all intervals with positive $x^M$.

Information used to determine the expected ratio, $r_i^e(\varepsilon, k)$, included both experimental measurements as well as results from Monte Carlo simulations. For the $j$th $B$-meson decay channel, the distribution of the visible proper decay length ($x$) is given by $P_j(x) = \int dK D_j(K) \cdot \theta(x - K \cdot \tau^0).$ $D_j$ is the lifetime of the $B$ meson, the $K$-factor, $K = p_T^{D^0}/p_T^B$, reflects the difference between the observed and true momentum of the $B$ meson, and $\theta(x)$ is the step function. The function $D_j(K)$ is the normalized distribution of the $K$-factor for the $j$th decay channel.

Transformation from the true value of $x$ to the experimentally measured value $x^M$ is given by $f_j(x^M) = \int dx \cdot R_j(x - x^M) \cdot \varepsilon_j(x) \cdot P_j(x)$, where $R_j(x - x^M)$ is the detector resolution, and $\varepsilon_j(x)$ is the reconstruction efficiency of $\mu^+ D^0$ for the $j$th decay. It does not include $\varepsilon$ for channels with $D^{*-}$. Finally, the expected value $r_i^e(\varepsilon, k)$ is given by:

$$r_i^e(\varepsilon, k) = \frac{\varepsilon \cdot f_i^e(k)}{f_i^e(k) + (1 - \varepsilon) \cdot f_i^e(k)}.$$  

Here $f_i^0 = \int dx^M \sum_j B_j \cdot f_j(x^M)$ with the summation $\sum_j$ taken over all decays to $D^{*-}$ ($D^+$) for $f_i^e (F_i^e)$.  

For the computation of $r_i^e$, the world average of the $B^+$ lifetime [1] was used. The $B^0$ lifetime $\tau^0$ was expressed as $\tau^0 = \tau^+/\tau^+ - 1$. The branching fractions $B \rightarrow \mu^+ \nu D$ and $B \rightarrow \mu^+ \nu D^*$ were taken from Ref. [1]. The following branching fractions were derived from experimental measurements [1, 8, 9, 10]: $Br(B^+ \rightarrow \mu^+ \nu D^{**0}) = (2.67 \pm 0.37)\%$, $Br(B^+ \rightarrow \mu^+ \nu D^{**0} \rightarrow D^{*-}X) = (1.07 \pm 0.25)\%$, and $Br(B^0 \rightarrow \mu^+ \nu D^{**+}) = (2.3\pm2.4)\%$. $D^{**}$ states include both narrow and wide $D^{**}$ resonances and nonresonant $D X$ and $D^* X$ production. Regarding the possible decays of $D^{**}$, there is no experimental data on the $Br(D^{** \rightarrow D^{*-} X})$. Its central value was therefore set to 0.35 and it was varied between 0.0 and 1.0 to estimate the systematic uncertainty from this source. All other branching fractions were derived assuming isospin invariance.

The distributions $D_j(K)$, $R_j(x)$, and $\varepsilon_j(x)$ were taken from the Monte Carlo simulation, and the corresponding systematic uncertainties were taken into account. All processes involving $b$ hadrons were simulated using the EVTGEN [11] generator interfaced to PYTHIA [7] and followed by the full modeling of the detector response and event reconstruction. The semileptonic $b$-hadron decays were generated using the ISGW2 model [12].

Assuming the given branching fractions and reconstruction efficiencies, the decay $B \rightarrow \mu^+ D^{*-} X$ contains (89 ± 3)% $B^+$, (10 ± 3)% $B^0$, and (1 ± 1)% $B_s^0$, while the decay $B \rightarrow \mu^+ D^0 X$ contains (83 ± 3)% $B^+$, (15 ± 4)% $B^0$, and (2 ± 1)% $B_s^0$.

A special study showed that in addition to the main decay $B \rightarrow \mu^+ D^{0}X$, the decay $B \rightarrow \tau^+ D^0X \rightarrow \mu^+ \nu \nu D^{0}X$ results in a (5 ± 2)% contribution and the process $\bar{c}c \rightarrow \mu^+ D^{0}X$ a (10 ± 7)% contribution to the selected $\mu^+ D^0$ sample. These processes were taken into account in the analysis.
TABLE I: Definition of the intervals in visible proper decay length, $x^M$. For each interval $i$, the number of events in the $D^{*-W}$, $D^{*-W}$ and $D^0$ samples, the ratio $r_i$, and the expected value $r_i^e$ for $\tau^+ / \tau^0 - 1 = 0.080$ are given.

<table>
<thead>
<tr>
<th>$i$</th>
<th>$x^M$ range (cm)</th>
<th>$N_i^{R}$</th>
<th>$N_i^{W}$</th>
<th>$N_i^{D}$</th>
<th>$r_i$</th>
<th>$r_i^e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$-0.1 - 0.0$</td>
<td>1714 ± 53</td>
<td>89 ± 22</td>
<td>5225 ± 151</td>
<td>0.295 ± 0.015</td>
<td>0.309</td>
</tr>
<tr>
<td>2</td>
<td>$0.0 - 0.02$</td>
<td>6213 ± 94</td>
<td>200 ± 28</td>
<td>18134 ± 222</td>
<td>0.321 ± 0.007</td>
<td>0.315</td>
</tr>
<tr>
<td>3</td>
<td>$0.02 - 0.04$</td>
<td>5941 ± 91</td>
<td>169 ± 22</td>
<td>17703 ± 208</td>
<td>0.317 ± 0.007</td>
<td>0.313</td>
</tr>
<tr>
<td>4</td>
<td>$0.04 - 0.07$</td>
<td>6424 ± 94</td>
<td>213 ± 23</td>
<td>19797 ± 216</td>
<td>0.305 ± 0.006</td>
<td>0.308</td>
</tr>
<tr>
<td>5</td>
<td>$0.07 - 0.10$</td>
<td>4029 ± 74</td>
<td>115 ± 17</td>
<td>12885 ± 171</td>
<td>0.295 ± 0.007</td>
<td>0.300</td>
</tr>
<tr>
<td>6</td>
<td>$0.10 - 0.15$</td>
<td>3459 ± 68</td>
<td>106 ± 16</td>
<td>11532 ± 162</td>
<td>0.282 ± 0.007</td>
<td>0.294</td>
</tr>
<tr>
<td>7</td>
<td>$0.15 - 0.25$</td>
<td>2253 ± 57</td>
<td>58 ± 13</td>
<td>7567 ± 137</td>
<td>0.283 ± 0.009</td>
<td>0.276</td>
</tr>
<tr>
<td>8</td>
<td>$0.25 - 0.40$</td>
<td>518 ± 28</td>
<td>2 ± 6</td>
<td>1875 ± 75</td>
<td>0.274 ± 0.019</td>
<td>0.256</td>
</tr>
</tbody>
</table>

FIG. 2: Points with the error bars show the ratio of the number of events in the $\mu^+ D^-$ and $\mu^+ D^0$ samples as a function of the visible proper decay length. The result of the minimization of Eq. (1) with $k = 0.080$ is shown as a histogram.
TABLE II: Summary of systematic uncertainties.

<table>
<thead>
<tr>
<th>Source</th>
<th>$\Delta(\tau^+ / \tau^0)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{Br}(B^0 \rightarrow \mu^+ \nu D^*)$</td>
<td>0.0005</td>
</tr>
<tr>
<td>$\text{Br}(B^+ \rightarrow \mu^+ \nu D^0)$</td>
<td>0.0010</td>
</tr>
<tr>
<td>$\text{Br}(B^+ \rightarrow \mu^+ \nu D^{*0})$</td>
<td>0.0009</td>
</tr>
<tr>
<td>$\text{Br}(B^+ \rightarrow \mu^+ \nu D^\pi \pi)$</td>
<td>0.0059</td>
</tr>
<tr>
<td>$\text{Br}(B^0 \rightarrow \mu^+ \nu D^- \pi X)$</td>
<td>0.0009</td>
</tr>
<tr>
<td>$D^\pi \rightarrow D^- \pi X$</td>
<td>0.0020</td>
</tr>
<tr>
<td>$\alpha \rightarrow \mu^+ \nu D^0 \chi$ contribution</td>
<td>0.0015</td>
</tr>
<tr>
<td>Other contributions</td>
<td>0.0006</td>
</tr>
<tr>
<td>$\varepsilon(B \rightarrow \mu^+ \nu D^0 X)$, decay length dependence</td>
<td>0.0014</td>
</tr>
<tr>
<td>$\varepsilon(B \rightarrow \mu^+ \nu D^0 X)$, average value</td>
<td>0.0030</td>
</tr>
<tr>
<td>$\varepsilon_\tau$, decay length dependence</td>
<td>0.0036</td>
</tr>
<tr>
<td>Decay length resolution</td>
<td>0.0024</td>
</tr>
<tr>
<td>Difference in $D^\pi$ and $D^0$ resolution</td>
<td>0.0053</td>
</tr>
<tr>
<td>K-factors, average value</td>
<td>0.0032</td>
</tr>
<tr>
<td>K-factors, difference between channels</td>
<td>0.0013</td>
</tr>
<tr>
<td>Fitting procedure</td>
<td>0.0086</td>
</tr>
<tr>
<td>Background level under $D^\pi$</td>
<td>0.0004</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.0136</strong></td>
</tr>
</tbody>
</table>

This result is the most precise measurement of this parameter, and agrees well with the world average value $k = 0.086 \pm 0.017$ [1]. Improved precision of the ratio of $B^+$ and $B^0$ lifetimes will allow a better test of theoretical predictions, especially those inputs to the calculations that rely on lattice QCD or on other non-perturbative methods [2, 3].

We thank the staffs at Fermilab and collaborating institutions, and acknowledge support from the Department of Energy and National Science Foundation (USA), Commissariat à l’Energie Atomique and CNRS/Institut National de Physique des Particules (France), Ministry of Education and Science, Agency for Atomic Energy and RF President Grants Program (Russia), CAPES, CNPq, FAPERJ, FAPESP and FUNDUNESP (Brazil), Departments of Atomic Energy and Science and Technology (India), Colciencias (Colombia), CONACyT (Mexico), KRF (Korea), CONICET and UBACyT (Argentina), The Foundation for Fundamental Research on Matter (The Netherlands), PPARC (United Kingdom), Ministry of Education (Czech Republic), Natural Sciences and Engineering Research Council and WestGrid Project (Canada), BMBF and DFG (Germany), A.P. Sloan Foundation, Research Corporation, Texas Advanced Research Program, and the Alexander von Humboldt Foundation.

[4] Charge conjugate states are always implied in this Letter.