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# Measurement of the $B^+$ and $B^0$ Lifetimes using Topological Vertexing*

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## Abstract

The lifetimes of $B^+$ and $B^0$ mesons have been measured using a sample of 150,000 hadronic $Z^0$ decays collected by the SLD experiment at the SLC between 1993 and 1995. The analysis reconstructs the decay length and charge of the $B$ meson using a novel topological vertexing technique. This method results in a high statistics sample of 6033 (3665) charged (neutral) vertices with good charge purity. A maximum likelihood fit procedure finds: $\tau_{B^+} = 1.67 \pm 0.07(\mathrm{stat}) \pm 0.06(\mathrm{syst})$ ps, $\tau_{B^0} = 1.66 \pm 0.08(\mathrm{stat}) \pm 0.08(\mathrm{syst})$ ps, $\tau_{B^+}/\tau_{B^0} = 1.01^{+0.09}_{-0.08}(\mathrm{stat}) \pm 0.05(\mathrm{syst})$.

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The spectator model predicts that the lifetime of a heavy hadron depends upon the properties of the constituent weakly decaying heavy quark $Q$ and is independent of the remaining, or spectator, quarks in the hadron. This model fails for the charm hadron system for which the lifetime hierarchy $\tau_{D^+} \sim 2\tau_{D_s^+} \sim 2.5\tau_{D^0} \sim 5\tau_{\Lambda_c^+}$ is observed. Since corrections to the spectator model are predicted to scale with $1/m_Q^2$ the $B$ meson lifetimes are expected to differ by less than 10% [1]. Hence a measurement of the $B^+$ and $B^0$ lifetimes provides a test of this prediction. In addition, the specific $B$ meson lifetimes are needed to determine the element $V_{cb}$ of the CKM matrix.

The analysis is performed on the 1993-5 data sample of 150,000 $Z^0$ decays collected by SLD at the SLC. The excellent 3D vertexing capabilities of SLD are exploited with a novel topological vertexing technique [2] to identify $B$ hadron vertices produced in hadronic $Z^0$ decays with high efficiency. The decay length is measured using the reconstructed vertex location while the $B$ hadron charge is determined from the total charge of the tracks associated with the vertex. This inclusive technique has the advantage of very efficient $B$ vertex reconstruction since essentially all $B$ decays are used.

The components of the SLD utilized by this analysis are the Central Drift Chamber (CDC)[3] for charged track reconstruction and momentum measurement and the CCD pixel Vertex Detector (VXD)[3] for precise position measurements near the interaction point. These systems are immersed in the 0.6 T field of the SLD solenoid. Charged tracks reconstructed in the CDC are linked with pixel clusters in the VXD by extrapolating each track and selecting the best set of associated clusters[3]. For a typical track from the primary vertex or heavy hadron decay, the total efficiency of reconstruction in the CDC and linking to a correct set of VXD hits is 94% for the region $|\cos\theta| < 0.74$. The track impact parameter resolutions at high momentum are 11 $\mu$m and 38 $\mu$m in the $r\phi$ and $rz$ projections respectively ($z$ points along the beam direction), while multiple scattering contributions are $70\,\mu\text{m}\ /(p\sin^{3/2}\theta)$ in both projections (where the momentum $p$ is expressed in GeV/c).

The centroid of the micron-sized SLC Interaction Point (IP) in the $r\phi$ plane is reconstructed with a measured precision of $\sigma_{IP} = (7 \pm 2)\,\mu$m using tracks in sets of $\sim 30$ sequential hadronic $Z^0$ decays. The median $z$ position of tracks at their point of closest approach to the IP in the $r\phi$ plane is used to determine the $z$ position of the $Z^0$ primary vertex on an event-by-event basis. A precision of $\sim 52\,\mu$m [3] on this quantity is estimated using $Z^0 \to b\bar{b}$

Monte Carlo simulation.

The simulated events are generated using JETSET 7.4 [4]. The $B$ meson decays are simulated using the CLEO $B$ decay model [5] tuned to reproduce the spectra and multiplicities of charmed hadrons, pions, kaons, protons and leptons as measured at the $\Upsilon(4S)$ by ARGUS and CLEO [6, 7]. The branching fractions of the charm hadrons are tuned to the existing measurements [8]. The $B$ mesons and baryons are generated with a lifetime of 1.55 ps and 1.10 ps respectively, while the $b$-quark fragmentation follows the Peterson *et al.* parametrization [9]. The SLD detector is simulated using GEANT 3.21 [10].

Hadronic $Z^0$ event selection requires at least 7 CDC tracks which pass within 5 cm of the IP in $z$ at the point of closest approach to the beam and which have momentum transverse to the beam direction $p_T$ >200 MeV/$c$. The sum of the energy of the charged tracks passing these cuts must be greater than 18 GeV. These requirements remove background from $Z^0 \rightarrow l^+l^-$ events and two-photon interactions. In addition, the thrust axis determined from energy clusters in the calorimeter must have $|\cos\theta| < 0.71$, within the acceptance of the vertex detector. These requirements yield a sample of $\sim 96,000$ hadronic $Z^0$ decays.

Good quality tracks used for vertex finding must have a CDC hit at a radius<39 cm, and have ≥40 hits to insure that the lever arm provided by the CDC is appreciable. The CDC tracks must have $p_T$ >400 MeV/$c$ and extrapolate to within 1 cm of the IP in $r\phi$ and within 1.5 cm in $z$ to eliminate tracks which arise from interaction with the detector material. The fit of the track must satisfy $\chi^2$/d.o.f.< 5. At least one good VXD link is required, and the combined CDC/VXD fit must also satisfy $\chi^2$/d.o.f.< 5.

The topological vertex reconstruction is applied separately to the tracks in each hemisphere (defined with respect to the event thrust axis). This analysis is the first application of the algorithm which is described in detail in Ref. [2] and summarized here. The vertices are reconstructed in 3D coordinate space by defining a vertex function $V(\mathbf{r})$ at each position $\mathbf{r}$. The helix parameters for each track $i$ are used to describe the 3D track trajectory as a Gaussian tube $f_i(\mathbf{r})$, where the width of the tube is the uncertainty in the measured track location close to the IP. A function $f_0(\mathbf{r})$ is used to describe the location and uncertainty of the IP. $V(\mathbf{r})$ is defined as a function of $f_0(\mathbf{r})$ and the $f_i(\mathbf{r})$ such that it is small in regions where fewer than two tracks (required for a vertex) have significant $f_i(\mathbf{r})$, and large in regions of high track multiplicity. Maxima are found in $V(\mathbf{r})$ and clustered into resolved spatial regions. Tracks are associated with these regions to form a set of topological vertices.

The efficiency for reconstructing $B$ hadron decay vertices is 80% for true decay lengths greater than 3mm, as estimated by the simulation. The efficiency falls at shorter decay length as it becomes harder to resolve the secondary vertex from the IP. The efficiency for reconstructing at least one secondary vertex is $\sim 50\%$ in $b$ hemispheres, $\sim 15\%$ in charm hemispheres and $\sim 3\%$ in light quark hemispheres. The efficiency for reconstructing more than one secondary vertex is $\sim 5\%$ in $b$ hemispheres. For hemispheres containing secondary vertices, the 'seed' vertex is chosen to be the one furthest from the IP. Vertices consistent with a $K_s^0 \to \pi^+\pi^-$ decay are excluded from the seed vertex selection and the two tracks are discarded.

A vertex axis is formed by a straight line joining the IP to the seed vertex. The 3D distance of closest approach of a track to the vertex axis, T, and the distance from the IP along the vertex axis to this point, L, are calculated for all quality tracks. Monte Carlo studies show that tracks which are not directly associated with the seed vertex but which pass T$<$ 0.1 cm and L/D$>$ 0.3 (where D is the distance from the IP to the seed vertex) are more likely to have been produced by the $B$ decay sequence than to have an alternative origin. Hence such tracks are added to the set of tracks in the seed vertex to form the candidate $B$ decay vertex, containing tracks from both the $B$ and cascade $D$ decays. The distance from the IP to the location determined by fitting this set of tracks to a common vertex is the reconstructed decay length. Since the purity of the $B$ charge reconstruction is lower for decays close to the IP, where tracks are more likely to be wrongly assigned, decay lengths are required to be $> 1$ mm.

The lifetime measurement relies on the ability to separate $B^+$ and $B^0$ decays by making use of the vertex charge. Monte Carlo studies show that the purity of the charge reconstruction is more likely to be eroded by losing tracks from the $B$ decay chain through track selection inefficiencies and track mis-assignment than by gaining mis-assigned tracks originating from the primary or other background to the $B$ decay. Furthermore, the decays which are missing some $B$ tracks tend to have lower vertex mass as well as lower charge purity. (The mass is calculated by assuming each track associated with the vertex has the mass of a pion.) Hence the vertex mass is required to be $> 2$ GeV/$c^2$ to improve the charge reconstruction purity. In addition, the mass

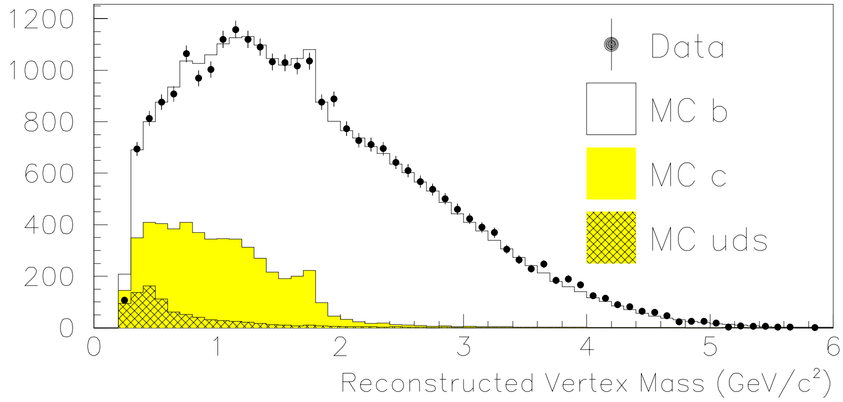

Figure 1: Mass of reconstructed vertex for data (points) and Monte Carlo (histogram).

distribution (see Fig. 1) shows that a large fraction of the charm and light flavor contamination is eliminated by this cut. A sample of 9719 candidate $B$ decay vertices remains, with a mean track multiplicity of 5.0.

To improve the $B$ hadron charge reconstruction, tracks which fail the initial selection but have $p_T > 200$ MeV/$c$ and $\sqrt{\sigma_{r\phi}^2 + \sigma_{rz}^2} < 700\,\mu$m, where $\sigma_{r\phi}$ ($\sigma_{rz}$) is the uncertainty in the track position in the $r\phi$ ($rz$) plane close to the IP, are considered as decay track candidates. The charge of these tracks which pass the cuts T< 0.1 cm and L/D> 0.3 is added to the $B$ decay charge. On average, 0.5 of these lower quality tracks pass these criteria in $b$ hemispheres.

Fig. 2 shows a comparison of the reconstructed charge between data and Monte Carlo. The charged sample consists of 6033 vertices with vertex charge equal to ± 1,2 or 3, while the neutral sample consists of 3665 vertices with charge equal to 0. Monte Carlo studies indicate that the charged sample is 97.8% pure in $B$ hadrons consisting of 52.8% $B^+$, 32.1% $B^0$, 8.6% $B_s^0$, and 4.3% $B$ baryons. (Charge conjugation is implied throughout this paper.) Similarly, the neutral sample is 98.3% pure in $B$ hadrons consisting of 25.3% $B^+$, 52.9% $B^0$, 13.9% $B_s^0$ and 6.2% $B$ baryons. The statistical precision of the measurement depends on the separation between the $B^+$ and $B^0$ in these samples.

The lifetimes are extracted from the decay length distributions, shown in Fig. 3, for the selected charged and neutral $B$ decay samples using a

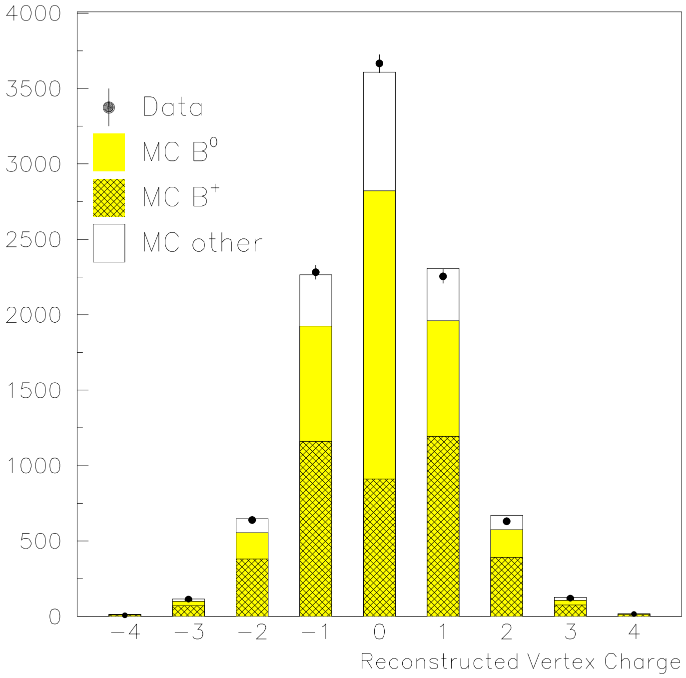

Figure 2: Reconstructed vertex charge for data (points) and Monte Carlo (histogram).

binned maximum likelihood technique, in which the Monte Carlo $B^+$ and $B^0$ decays are weighted to yield decay length distributions for varying $B^+$ and $B^0$ lifetimes that are compared to the data [11]. A two parameter fit (over the range 1 mm to 25 mm) yields lifetimes of $\tau_{B^+} = 1.67 \pm 0.07$ ps and $\tau_{B^0} = 1.66 \pm 0.08$ ps, with a ratio of $\tau_{B^+}/\tau_{B^0} = 1.01^{+0.09}_{-0.08}$ and a combined $\chi^2$/d.o.f. = 90.0/76.

Table 1 summarizes the systematic errors on the $B^+$ and $B^0$ lifetimes and their ratio. To account for a discrepancy between data and Monte Carlo in the fraction of tracks passing the selection criteria, a 4% tracking efficiency correction with dependence on track momenta and angles is applied to the simulation [3]. The corrected Monte Carlo is used in the lifetime fits, with the effect of the entire correction taken as the systematic error. The decay length distribution of the smaller neutral sample, and hence the measured $B^0$ lifetime, is perturbed more than the charged sample by this conservative estimate of the tracking efficiency uncertainty. The uncertainty due to

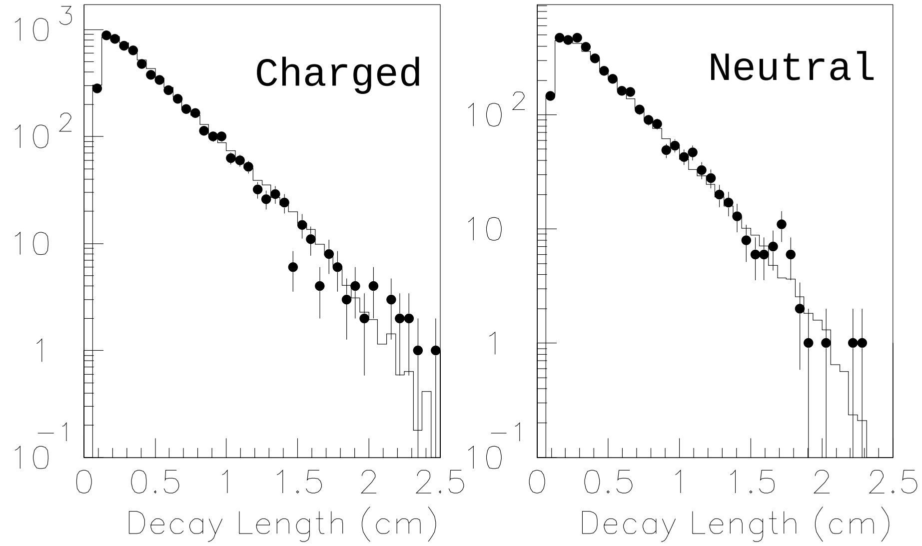

Figure 3: Decay length distributions for data (points) and best fit Monte Carlo (histogram).

tracking resolution, mainly due to remaining vertex detector misalignments in the $rz$ plane, is estimated by applying to the Monte Carlo track $rz$ impact parameter $\phi$ dependent systematic shifts of up to 20 $\mu$m and a random Gaussian smear with $\sigma = 20\mu\mathrm{m}/\sin\theta$. The total effect of this correction is again assigned as a systematic error. We have also made cross checks by performing the lifetime fits for $B$ decay candidates in different $\phi$ regions and different data taking time periods separately. The results are found to be consistent within statistics.

The physics modeling systematic uncertainties were determined as follows. The mean fragmentation energy $< x_E >$ of the $B$ hadron [12] and the shape of the $x_E$ distribution [13] were varied. Since the fragmentation is assumed to be identical for the $B^+$ and $B^0$ mesons, this uncertainty has little effect on the lifetime ratio. The four branching fractions for $B^+/B^0 \to \overline{D^0}/D^- X$ were varied by twice the uncertainty in the current world average for $B \to \overline{D^0}/D^- X$ [7]. The fraction of $B^+/B^0$ decays producing a $D\overline{D}$ pair was also varied. The average $B^+$ and $B^0$ decay multiplicity was varied by ±0.3 tracks [14] in an anticorrelated manner. Uncertainties in the $B_s^0$ and $B$ baryon lifetimes and production fractions mostly affect the $B^0$

Table 1: Summary of systematic uncertainties in the $B^+$ and $B^0$ lifetimes and their ratio.

| Systematic Error | | $\Delta\tau_{B^+}$ (ps) | $\Delta\tau_{B^0}$ (ps) | $\Delta\frac{\tau_{B^+}}{\tau_{B^0}}$ |
|---|---|---|---|---|
| Detector Modeling | | | | |
| Tracking efficiency | | 0.011 | 0.035 | 0.028 |
| Tracking resolution | | 0.012 | 0.011 | 0.010 |
| Physics Modeling | | | | |
| $b$ fragmentation | 0.700 ± 0.011 | 0.035 | 0.037 | 0.005 |
| BR($B \rightarrow DX$) | | 0.010 | 0.012 | 0.010 |
| BR($B \rightarrow D\overline{D}X$) | 0.15 ± 0.05 | 0.006 | 0.006 | 0.006 |
| $B$ decay multiplicity | 5.3 ± 0.3 | 0.016 | 0.012 | 0.003 |
| $B_s^0$ fraction | 0.115 ± 0.040 | 0.012 | 0.004 | 0.005 |
| $B$ baryon fraction | 0.072 ± 0.040 | 0.013 | 0.039 | 0.017 |
| $B_s^0$ lifetime | 1.55 ± 0.10 ps | <.003 | 0.025 | 0.016 |
| $B$ baryon lifetime | 1.10 ± 0.08 ps | <.003 | 0.006 | 0.004 |
| $D$ decay multiplicity | | 0.011 | 0.006 | 0.010 |
| $D$ decay $K^0$ yield | | 0.005 | 0.020 | 0.010 |
| Monte Carlo and Fitting | | | | |
| Fitting systematics | | 0.024 | 0.013 | 0.022 |
| MC statistics | | 0.012 | 0.013 | 0.015 |
| TOTAL | | 0.055 | 0.078 | 0.050 |

lifetime since the neutral $B_s^0$ and $B$ baryon are a more significant background for the $B^0$ decays. The systematic errors due to uncertainties in charmed meson decay topology were estimated by changing the Monte Carlo $D$ decay charged multiplicity and $K^0$ production according to the uncertainties in experimental measurements [15]. The effect of varying the lifetime of charm hadrons ($D^+$, $D^0$, $D_s$, $\Lambda_c$), as well as their momentum spectra in the $B$ decay rest frame was found to be negligible.

The fitting uncertainties were determined by varying the bin size used in the decay length distributions, and by modifying the cuts on the minimum

(0–2 mm) and maximum (12–25 mm) decay lengths used in the fit. Fit results are consistent within statistics for these variations, but a systematic error is conservatively assigned using the RMS variation of the results.

In summary, from 150,000 $Z^0$ decays collected by SLD between 1993 and 1995, the $B^+$ and $B^0$ lifetimes have been measured using a novel topological technique. The analysis isolates 9698 $B$ hadron candidates with good charge purity and determines the lifetimes of $B^+$ and $B^0$ mesons to be $\tau_{B^+} = 1.67 \pm 0.07(\mathrm{stat}) \pm 0.06(\mathrm{syst})$ ps, $\tau_{B^0} = 1.66 \pm 0.08(\mathrm{stat}) \pm 0.08(\mathrm{syst})$ ps, with a ratio $\frac{\tau_{B^+}}{\tau_{B^0}} = 1.01^{+0.09}_{-0.08}(\mathrm{stat}) \pm 0.05(\mathrm{syst})$. Combining this measurement with that obtained using a complementary analysis based on semileptonic decays [11], taking into account correlated statistical and systematic errors, yields the following SLD averages:

$$\begin{aligned} \tau_{B^+} &= 1.66 \pm 0.06(\mathrm{stat}) \pm 0.05(\mathrm{syst})\ \mathrm{ps}, \\ \tau_{B^0} &= 1.64 \pm 0.08(\mathrm{stat}) \pm 0.08(\mathrm{syst})\ \mathrm{ps}, \\ \frac{\tau_{B^+}}{\tau_{B^0}} &= 1.01 \pm 0.07(\mathrm{stat}) \pm 0.06(\mathrm{syst}). \end{aligned}$$

These results are consistent with the expectation that the $B^+$ and $B^0$ lifetimes are nearly equal and have a statistical accuracy among the best of the current measurements [16].

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