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# A Measurement of the b Baryon Lifetime

**The ALEPH Collaboration***

## Abstract

In 451,000 hadronic $Z^0$ decays, recorded with the ALEPH detector at LEP, the yields of $\Lambda\ell^-$ and $\Lambda\ell^+$ combinations are measured. Semileptonic decays of b baryons result in a signal of $122 \pm 18(\text{stat})^{+22}_{-23}(\text{syst})$ $\Lambda\ell^-$ combinations. From a fit to the impact parameter distribution of the leptons in the $\Lambda\ell^-$ sample, the lifetime of b baryons is measured to be $1.12^{+0.32}_{-0.29}(\text{stat}) \pm 0.16(\text{syst})$ ps.

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# Introduction

The first years of LEP running have yielded measurements [1,2] of the average b hadron lifetime with much greater precision than previously obtained. The copious production of b hadrons at the $Z^0$ resonance has now made measurements of individual lifetimes possible. This letter reports the first measurement of the b baryon lifetime, based on data collected with the ALEPH detector at LEP in 1990 and 1991.

Evidence for b baryons in $Z^0$ decays via correlation between a $\Lambda$ and a high transverse momentum prompt lepton has been presented previously by the ALEPH and OPAL collaborations [3,4]. The signal consists of, for example, the decay $\Lambda_b \rightarrow \Lambda_c^+ \ell^- \bar{\nu}$ followed by the decay $\Lambda_c^+ \rightarrow \Lambda X$, with the $\Lambda$ decaying to $p\pi^-$. Charge conjugate decays are implied throughout this letter. The correlation $\Lambda\ell^-$, as opposed to $\Lambda\ell^+$, is a distinctive signature of semileptonic b baryon decay, with weak decays of the $\Lambda_b$ expected to dominate the b baryon sample [5,6]. A fit to the impact parameters of the leptons in the $\Lambda\ell^-$ sample is used to extract the lifetime of b baryons.

# The ALEPH detector

The ALEPH detector has been described in detail elsewhere [7]. Charged tracks are measured over the range $|\cos\theta| < 0.95$, where $\theta$ is the polar angle, by an inner cylindrical drift chamber (ITC) and a large cylindrical time projection chamber (TPC). These chambers are immersed in a magnetic field of 1.5 Tesla and together measure the momentum of charged particles with a resolution of $\delta p/p = (0.0008\,\mathrm{GeV}^{-1})p \oplus 0.003$ [7,8]. The TPC provides up to 330 measurements of the specific ionization, $dE/dx$, of each charged track. For electrons in hadronic events, the $dE/dx$ resolution is 4.6% for 330 ionization samples. During the 1991 data-taking period, a double-sided silicon vertex detector (VDET) was installed [9], however, since VDET data is only available for 1991, this analysis is based on TPC and ITC tracking only. Outside the TPC, but inside the coil of the superconducting solenoid, is the electromagnetic calorimeter (ECAL). The hadron calorimeter (HCAL) is composed of the iron of the magnet return yoke interleaved with 23 layers of streamer tubes, and is surrounded by the muon chambers, an additional two double layers of streamer tubes that cover the same angular range as the calorimeters, at 7.5 interaction lengths from the primary interaction point.

## Lepton and $\Lambda$ Selection

The selection of hadronic events is based on charged tracks and has been described in [10]. Detailed discussions of lepton identification are given in [11,12]. Leptons are identified in the ALEPH detector by matching a charged track measured in the TPC and ITC with either an energy deposit consistent with that of an electron in the ECAL, or a pattern of hits in the HCAL and muon chambers consistent with that of a muon. In addition, the measured $dE/dx$ of the electron candidate in the TPC is required to be within 2.5 standard deviations of the expected value, based on at least 50 ionization samples. The JADE jet clustering algorithm [13] is used to find jets in hadronic events, using both charged tracks and neutral calorimeter clusters. To obtain a sample of leptons enriched in b content, lepton candidates are required to have at least 5 GeV of momentum and a transverse momentum, $p_\perp$, with respect to the associated jet[1], of at least 1 GeV. The resulting electron identification efficiency is about 74%, with a hadron misidentification probability which varies with momentum from 0.3% to 0.1%. Muons with momenta greater than 5 GeV have an average identification efficiency of 80% and a hadron misidentification probability of typically 0.5%. The final sample of lepton candidates is expected to be 87% pure in leptons from b hadron decay, including leptons produced via b cascade to c.

The $\Lambda$ candidates are identified by their decay $\Lambda \rightarrow \mathrm{p}\pi^-$, using an algorithm which vertexes two oppositely charged tracks with at least four hits each in the TPC. The invariant mass of the two tracks is required to be incompatible with $\mathrm{K^0_S}$ or $\gamma$ mass hypotheses. To reduce combinatoric background, $\Lambda$ candidates are required to have at least 3 GeV of momentum and to have a decay length of at least 5 cm with respect to the average fill-by-fill beam centroid. The measured track $dE/dx$, when available, is also required to be compatible with that of a proton and a pion. Lepton and $\Lambda$ candidates are required to be within 45 degrees of each other.

## Isolation of the b Baryon Signal

The method of $\Lambda\ell$ correlation to isolate semileptonic decays of b baryons has been described in a previous letter [3]. There are five possible sources of $\Lambda\ell$ correlations:

$$\Lambda_\mathrm{b} \rightarrow \Lambda_c^+ \ell^- \overline{\nu}, \quad \Lambda_c^+ \rightarrow \Lambda \mathrm{X} \tag{1}$$

$$\overline{\mathrm{B}} \rightarrow \Lambda_c^+ \mathrm{X} \ell^- \overline{\nu}, \quad \Lambda_c^+ \rightarrow \Lambda \mathrm{X} \tag{2}$$

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[1] The lepton is included in the calculation of the jet direction for the purpose of obtaining $p_\perp$.

$$\mathrm{b} \rightarrow \Lambda_c^+\mathrm{X}, \quad \Lambda_c^+ \rightarrow \Lambda\ell^+\mathrm{X} \tag{3}$$

$$\mathrm{c} \rightarrow \Lambda_c^+\mathrm{X}, \quad \Lambda_c^+ \rightarrow \Lambda\ell^+\mathrm{X} \tag{4}$$

$$\text{Accidental Combinations} \tag{5}$$

By requiring a lepton candidate to have at least 1 GeV of $p_\perp$ and 5 GeV of momentum, 90% of the $\Lambda\ell$ correlations from process (2) and more than 95% of those from processes (3) and (4) are removed, while keeping over half of the $\Lambda\ell^-$ correlations from b baryon decay. The remaining $\Lambda\ell^-$ combinations originate mostly from either b baryon semileptonic decays or accidental combinations, and the $\Lambda\ell^+$ combinations are mostly accidental. From a study [3] of approximately $10^6$ $Z^0 \rightarrow b\overline{b}$ events generated with the JETSET 6.3 [14] Monte Carlo, the ratio of $\Lambda\ell^-$ to $\Lambda\ell^+$ accidental combinations is taken to be $1.0 \pm 0.4$. The excess of $\Lambda\ell^-$ combinations over $\Lambda\ell^+$ is thus due to semileptonic decay of b baryons.

This analysis is based on data taken in 1990 and 1991, consisting of 451,000 hadronic $Z^0$ decays. The yields of $\Lambda\ell^-$ and $\Lambda\ell^+$ combinations, after application of the $\Lambda$ and lepton selection criteria described above, are shown in Figure 1, where the $p\pi^-$ invariant mass is plotted. The two mass distributions are fitted simultaneously to a single Gaussian representing the signal, and a second order polynomial in each case to parameterize the shape of the combinatoric background. The fitted signals consist of $170 \pm 16$ $\Lambda\ell^-$ combinations and $53 \pm 9$ $\Lambda\ell^+$ combinations, implying an excess of $117 \pm 18$ $\Lambda\ell^-$ combinations.

To translate the observed excess into a measurement of the b baryon semileptonic decay rate, the residual contributions of the background processes are evaluated as follows. Based on a simulation of process (2) and the 90% confidence level upper limit of $Br(\overline{B} \rightarrow pe^-X) \leq 0.16\%$ set by the ARGUS collaboration [15], less than 7 $\Lambda\ell^-$ combinations are expected from this process. This possible contribution is included in the evaluation of the systematic error. The contribution to the $\Lambda\ell^+$ sample of processes (3) and (4) is estimated to be $5 \pm 5$ combinations, which is added as a correction to the observed excess. These considerations together imply a b baryon signal of $122 \pm 18(\mathrm{stat})\ ^{+22}_{-23}(\mathrm{syst})$ events.

The JETSET 6.3 prescription is used to model semileptonic b baryon decay as well as the decay $\Lambda_c^+ \rightarrow \Lambda X$. It is assumed that three-body decays such as $\Lambda_b \rightarrow \Lambda_c^+\ell^-\overline{\nu}$ dominate the semileptonic decay of b baryons. The b quarks produced in the decay of the $Z^0$ are polarized, and some or all of this polarization could be retained in the subsequent hadronization of the b quark into a b baryon. A polarized b baryon has harder lepton momentum and $p_\perp$ spectra, and consequently the overall signal detection efficiency would be larger. The effects of $\Lambda_b$ polarization are investigated using a generator based on the JETSET 7.2 program, modified [16] to produce $\Lambda_b$ with the (maximal) polarization of 94% from the b quark. A polarization of $(47 \pm 47)\%$ is assumed in obtaining the central values quoted, giving a detection efficiency of $(9.0 \pm 1.6)\%$, where the

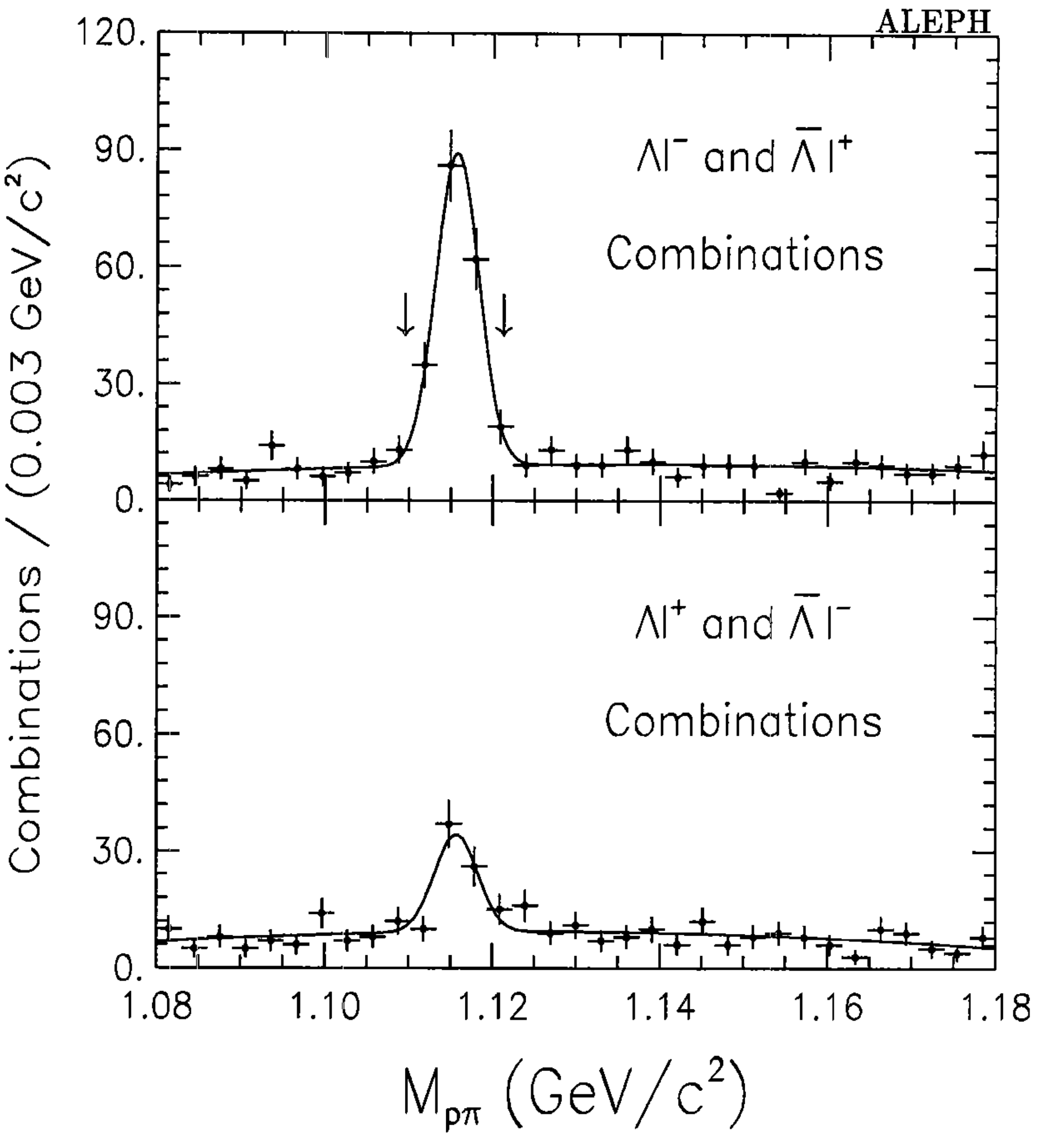

Figure 1: The $p\pi^-$ invariant mass distribution of the $\Lambda\ell^-$ and $\Lambda\ell^+$ combinations. Arrows indicate the region used for the $\Lambda_b$ lifetime analysis.

error includes uncertainty due to polarization. Assuming the Standard Model value for the partial width of $Z^0 \to b\overline{b}$, applying the above corrections yields a product branching ratio

$$Br(b \to \Lambda_b) \cdot Br(\Lambda_b \to \Lambda_c^+ \ell^- \overline{\nu} X) \cdot Br(\Lambda_c^+ \to \Lambda X) = (0.70 \pm 0.10_{\mathrm{stat}} \pm 0.18_{\mathrm{syst}})\%.$$

This is in good agreement with ALEPH's previously published value based on the 1990 data [3], which is contained in this result.

## Measurement of the b Baryon Lifetime

To obtain a b baryon lifetime, $\tau_{\Lambda_b}$, from the $\Lambda\ell^-$ sample, a fit is performed to the $r\phi$ impact parameter distribution of the leptons in these events. The approach closely follows the average b hadron lifetime analysis based on 1990 ALEPH data [1]. Tracks with poorly measured impact parameters are removed from the lifetime measurement by requiring at least 6 associated hits in the TPC, 2 associated hits in the ITC, and a $\chi^2$/d.o.f. of the track fit of less than 4. These cuts, together with a $p\pi^-$ mass cut of $M_\Lambda \pm 5$ MeV, yield 178 $\Lambda\ell^-$ combinations.

The interaction point is approximated using the beam centroid, measured fill-by-fill to a precision of about 15 $\mu$m. Combining the resolution effects of the track fit and beam envelope, a final average impact parameter resolution of approximately 200 $\mu$m is obtained. The reconstructed jet direction is used to approximate the direction of the b baryon. Tracing a lepton track back towards the interaction point, its impact parameter is signed positive if the lepton track crosses the jet axis before reaching the point of closest approach to the beam centroid, and negative otherwise. The distribution of lepton impact parameters in the $\Lambda\ell^-$ sample is shown in Figure 2(a); it has a mean of $184 \pm 33\,\mu$m.

The lepton impact parameter distribution is fit to a sum of contributions from the possible sources: semileptonic b baryon decay, semileptonic decay of b or c hadrons, cascade decays ($b \to c/\tau \to \ell$), hadron misidentification, the decay of $\pi$ or K, and photon conversions in the material of the detector. The b baryon contribution is taken to be the convolution of two functions. One, a "physics function", obtained from Monte Carlo simulation, gives the shape of the impact parameter distribution expected for a given b baryon lifetime in the case of perfect impact parameter resolution. This is convoluted with a resolution function, obtained from data, describing the effects of detector resolution. The contributions to the $\Lambda\ell^-$ sample from semileptonic b and c hadron decay are described by the same resolution function, but separate physics functions with fixed lifetimes. The shapes of the other background sources and the relative normalization of all of the sources are derived from data. An unbinned maximum

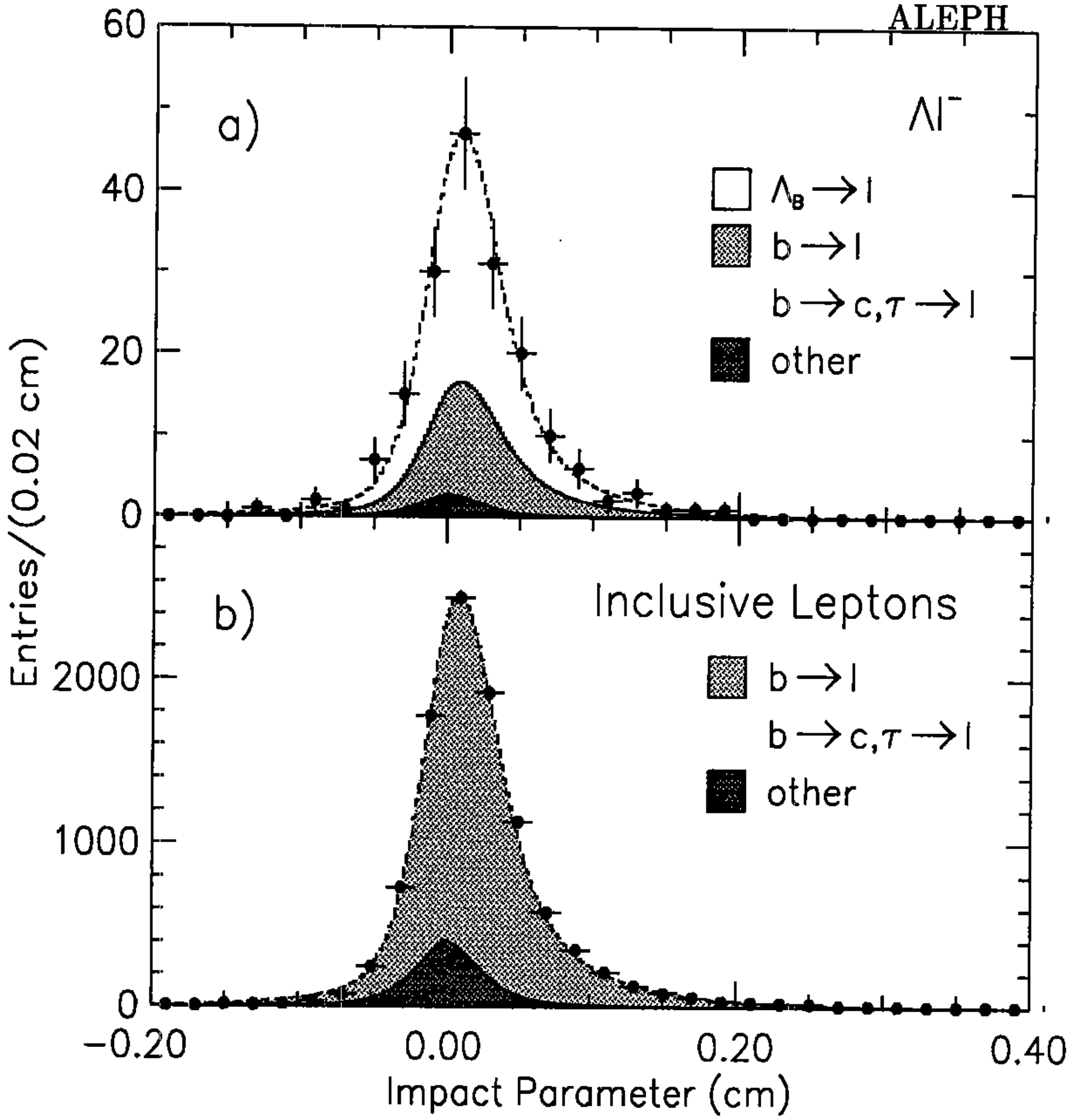

Figure 2: Lepton impact parameter distributions for the a) $\Lambda\ell^-$ sample and b) inclusive lepton sample, together with the results of the unbinned maximum likelihood fits.

likelihood fit is then performed to the impact parameter distribution of the leptons, with $\tau_{\Lambda_b}$ as the only free parameter.

The physics functions are determined from Monte Carlo simulation. The impact parameter of the generated lepton track is used, calculated with respect to the generated production point, but the sign of the impact parameter is determined using the reconstructed jet direction. This procedure excludes track reconstruction resolution and the beam spot size from the physics function (they are accounted for in the resolution function), but includes impact parameter sign errors from the jet angle resolution. The resulting distributions are then parameterized by sums of four exponentials, two for positive impact parameters, two for negative. The central value for $\tau_{\Lambda_b}$ is the average of a fit using a physics function with zero polarization and one using a physics function where the b baryons carry the full 94% polarization of b quarks in the Standard Model.

The resolution function is measured using tracks from the data passing the lepton kinematic cuts but failing lepton identification. The normalized signed impact parameter is formed by dividing the signed impact parameter by its error, calculated from the track fit error and the projected beam spot size. The effect of b and c hadron lifetimes is minimized by using only tracks whose $p_\perp$ with respect to the jet direction is mostly in the $z$ direction and whose impact parameter is negative. The resulting distribution is fit to a sum of two Gaussians, where the second Gaussian is used to parameterize the tails in the tracking resolution. The r.m.s. of the central Gaussian is 1.02 for the 1990 data and 1.04 for the 1991 data. In both years about 10% of the tracks are contained in the second Gaussian, whose r.m.s. is 3.9. For electrons, the contribution of the second Gaussian is increased to $(15 \pm 3)\%$ due to bremsstrahlung.

The shape of the impact parameter distribution from hadrons misidentified as leptons is obtained from data, by parameterizing the impact parameter distribution of hadrons passing all kinematic selection criteria imposed on the lepton candidates, but explicitly failing the calorimetric and $dE/dx$-based lepton tagging cuts.

The impact parameter distribution from $\pi$ and K decays is obtained by replacing tracks in data with simulated K or $\pi$ tracks that decay before exiting the TPC, and parameterizing the resulting distribution of impact parameters. This shape is also used to approximate the impact parameter distribution of electrons from $\gamma$ conversions; Monte Carlo studies show acceptable agreement between the two distributions.

The fractional composition of the leptons in the $\Lambda\ell^-$ sample is determined as follows. The purity in leptons from $\Lambda_b \to \ell$ decay is obtained from the simultaneous fit to the $p\pi^-$ invariant mass spectra in Figure 1, giving $(57 \pm 14)\%$. The remaining 43% of the lepton candidates originate from the sources described above, and are predominantly from semileptonic b hadron decay. The relative contributions of the background sources to the $\Lambda\ell^-$ sample are determined from a fit to the inclusive lepton $p$ and $p_\perp$ spectra, analogous to the fit described in [17], updated to include the improvements in jet clustering with the use of the neutral clusters.

At this point, two parameters remain to be determined to describe the impact parameter distribution of the leptons in the $\Lambda\ell^-$ sample: $\tau_{\Lambda_b}$, the lifetime of the b baryons, and $\tau_{\mathrm{back}}$, describing the background. As the background is dominated by b hadrons, $\tau_{\mathrm{back}}$ is estimated from a fit to the impact parameter distribution of the full lepton sample of 10899 electron and muon candidates. The result of the fit is shown in Figure 2(b) and yields a value for $\tau_{\mathrm{back}}$ of $1.46 \pm 0.03$(stat) ps which is consistent with the latest ALEPH measurement of the average b hadron lifetime of $1.49 \pm 0.03$(stat) $\pm$ 0.06(syst) [18] using the improved resolution in the 1991 data with the VDET.

A fit to the 178 lepton candidates from the $\Lambda\ell^-$ sample yields a b baryon lifetime of

$$\tau_{\Lambda_b} = 1.12^{+0.32}_{-0.29}(\mathrm{stat})\ \mathrm{ps}.$$

The fit to the lepton impact parameter distribution in the $\Lambda\ell^-$ sample is shown in Fig 2(a).

## Systematic errors

A summary of the systematic errors contributing to this measurement of $\tau_{\Lambda_b}$ is shown in Table 1. Some of the largest systematic errors are of a statistical nature, but at a level which is still small compared to the present experimental statistical precision.

The systematic uncertainty on $\tau_{\Lambda_b}$ due to the various parameterizations used in the fit is dominated by statistics. The statistics of the Monte Carlo simulation used to obtain the physics functions leads to uncertainties on $\tau_{\Lambda_b}$ of $\pm 0.09$ ps ($\Lambda_b \to \ell$) and $\pm 0.02$ ps (combining $b \to \ell$, $b \to c/\tau \to \ell$, and $c \to \ell$). The statistics of the event samples used to obtain the shapes of the hadron misidentification and decay backgrounds leads to uncertainties of $\pm 0.01$ ps and $\pm 0.02$ ps, respectively. The error from the statistics of the $b \to \ell$ physics function includes the statistical error on $\tau_{\mathrm{back}}$ from the fit to the inclusive lepton sample. The error on the average c hadron lifetime has a negligible effect on $\tau_{\Lambda_b}$, as does a variation of 20% in the $K/\pi$ production ratio in hadronic events. The statistical uncertainty on the lepton source fractions leads to an uncertainty of $\pm 0.05$ ps on $\tau_{\Lambda_b}$.

The statistical errors from the fit for the resolution function introduce an uncertainty of $\pm 0.03$ ps on $\tau_{\Lambda_b}$. To this $\pm 0.06$ ps is added in quadrature, based on Monte Carlo studies comparing resolution functions obtained from electrons,

Table 1: Contributions to the systematic error on $\Lambda_b$ lifetime. Values are in picoseconds.

| Contribution | Error |
|---|---|
| $\Lambda_b \to \ell$ Phys. Fun. | 0.09 |
| b and c Phys. Fun. | 0.02 |
| Misid. Background | 0.01 |
| Decay Background | 0.02 |
| Lepton Source Fractions | 0.05 |
| Resolution Function | 0.07 |
| Bremsstrahlung | 0.03 |
| Decay and Fragm. Models | 0.04 |
| Polarization | 0.03 |
| Background Lifetime | 0.06 |
| Beam Spot Position, Size | 0.03 |
| TOTAL | 0.16 |

muons, and hadrons, yielding a total uncertainty of ±0.07 ps from the resolution function. The effect of electron bremsstrahlung on the resolution function results in a systematic uncertainty of ±0.03 ps.

Several sources of systematic uncertainty due to decay and fragmentation models are considered. The b hadron decay model used in the analysis is that of Korner-Shuler [19]. Using instead the Bauer-Stech-Wirbel [20], Grinstein-Wise-Isgur [21], or standard JETSET decay schemes leads to a maximal variation of ±0.02 ps on the average b hadron lifetime, which is taken as the appropriate systematic uncertainty on $\tau_{\Lambda_b}$. Variation of the fragmentation parameter, $\epsilon_b$, of the Peterson *et. al.* function between 0.003 and 0.010 [11] also leads to a variation of ±0.02 ps. Finally, varying the branching fraction of b hadrons to four-body final states from 15% to 30% of the total semileptonic branching fraction has a small effect upon $\tau_{\Lambda_b}$. Combining all of these errors together gives a net systematic uncertainty of ±0.04 ps on $\tau_{\Lambda_b}$ due to decay and fragmentation model dependence. In addition, the uncertainty on $\tau_{\Lambda_b}$ resulting from $\Lambda_b$ polarization of $(47 \pm 47)\%$ is ±0.03 ps.

The assumption that the leptons from the background in the $\Lambda\ell^-$ sample have the same impact parameter distribution as that of the inclusive lepton sample is checked using the events in the sidebands of the $p\pi^-$ invariant mass distribution. A fit is performed to the impact parameters of the leptons from these events, analogous to the fit for the average b hadron lifetime, yielding

1.63 ± 0.14 ps. This is consistent with the value from the inclusive lepton sample, given the low statistics in the sidebands. The difference in the fitted $\tau_{\Lambda_b}$ when using a background lifetime of 1.46 ps or 1.63 ps is 0.06 ps, which is taken as the systematic uncertainty on $\tau_{\Lambda_b}$ due to the possible variation in the background lifetime.

Errors in the measured beam envelope size do not have a significant effect on the result, as they are compensated to first order by the resolution function. An error on the beam centroid measurement would be more noticeable; introducing a systematic three standard deviation shift in the vertical dimension, where it would have the largest effect, yields a shift in the fitted value of $\tau_{\Lambda_b}$ of 0.03 ps.

# Conclusion

In 451,000 $Z^0$ decays measured with the ALEPH detector at LEP in 1990 and 1991, the product branching ratio

$$Br(\mathrm{b} \to \Lambda_b) \cdot Br(\Lambda_b \to \Lambda_c^+ \ell^- \bar{\nu} X) \cdot Br(\Lambda_c^+ \to \Lambda X) = (0.70 \pm 0.10_{\mathrm{stat}} \pm 0.18_{\mathrm{syst}})\%.$$

is measured using $\Lambda \ell^-$ correlations. The lifetime of b baryons is measured using the impact parameter distribution of the leptons in the $\Lambda \ell^-$ sample to be

$$\tau_{\Lambda_b} = 1.12^{+0.32}_{-0.29}(\mathrm{stat}) \pm 0.16(\mathrm{syst})\ \mathrm{ps}.$$

This represents the first measurement of the b baryon lifetime.

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