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Updated Measurement of the b Baryon Lifetime

The ALEPH Collaboration

Abstract

Using about 4 million hadronic Z decays recorded with the ALEPH detector, the lifetime of the b baryons has been measured using two independent data samples. From a maximum likelihood fit to the impact parameter distribution of leptons in 1085 $\Lambda\ell^-$ combinations containing a b baryon sample of 719 decays the measured b baryon lifetime is

$$\tau_{\mathrm{b-baryon}} = 1.18 \pm 0.08(\mathrm{stat}) \pm 0.07(\mathrm{syst})\ \mathrm{ps}.$$

The lifetime of the Λ_{b} baryon from a maximum likelihood fit to the proper time distribution of 193 $\Lambda_c^+\ell^-$ candidates is

$$\tau_{\Lambda_b} = 1.21^{+0.13}_{-0.12}(\mathrm{stat}) \pm 0.04(\mathrm{syst})\ \ \mathrm{ps}.$$

The combined result of the two measurements yields an averaged value

$$\tau_{\Lambda_b} = 1.19 \pm 0.08\ \ \mathrm{ps}.$$

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1 Introduction

A precise comparison of the lifetime of the B mesons and b baryons is of special interest for the understanding of non-spectator effects in the b hadron decays [1]. Previous measurements have shown that the b baryon lifetime is substantially smaller than the b meson lifetime [2, 3] . However, more precise measurements of the b baryon lifetime are essential for confirming the observed picture.

Two independent measurements of the b baryon lifetime using $\Lambda\ell^-$and $\Lambda_c^+\ell^-$ samples are reported, based on about 4 million hadronic Z decays recorded with the ALEPH detector from 1991 to 1995. The improvements of this analysis respect to the published one [2] are mainly due to an increase of a factor of more than two of the data sample.

Evidence for b baryons in Z decays via correlation between a Λ and a prompt high transverse momentum lepton has been reported previously by the ALEPH, OPAL and DELPHI collaborations [4]. The signal results from semileptonic b baryon decays[1], dominated mainly by Λ_b decays [5, 6] such as $\Lambda_b \to \Lambda_c^+\ell^-\overline{\nu}$ followed by the decay $\Lambda_c^+ \to \Lambda X$, with the Λ decaying to $p\pi^-$. In addition, Λ_b semileptonic decays with the exclusive reconstruction of the Λ_c^+ i.e. $\Lambda_b \to \Lambda_c^+\ell^-\overline{\nu}$ where $\Lambda_c^+ \to pK^-\pi^+$, have also been reported by ALEPH [7]. Although statistically less powerful for Λ_b identification compared with the $\Lambda\ell^-$ method, this decay channel gives an independent Λ_b sample and has the advantage of being insensitive to other b baryons [2].

2 Measurement of the b baryon lifetime using $\Lambda\ell^-$ correlation

The method of $\Lambda\ell$ correlation to isolate semileptonic decays of b baryons has been described in [4]. This method is sensitive to decays of various species of b baryons which have a $\Lambda\ell^-$ in the final state. For brevity of notation, throughout this section, the symbols Λ_b and Λ_c^+ are used to denote not just Λ_b and Λ_c^+ but also analogous beauty and charm baryon states such as Ξ_b and Ξ_c.

2.1 Selection of b baryons using $\Lambda\ell^-$ correlation

The Λ and lepton candidates are identified as described in [2].

There are seven possible sources of $\Lambda\ell$ combinations

$$\Lambda_b \to \Lambda_c^+ X\ell^-\overline{\nu}, \quad \Lambda_c^+ \to \Lambda X \tag{1}$$

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

$$b \to \Lambda_c^+ {D_s}^- X, \quad \Lambda_c^+ \to \Lambda X, {D_s}^- \to X\ell^-\overline{\nu} \tag{3}$$

$$b \to \Lambda_c^+ X, \quad \Lambda_c^+ \to \Lambda\ell^+ X \tag{4}$$

$$c \to \Lambda_c^+ X, \quad \Lambda_c^+ \to \Lambda\ell^+ X \tag{5}$$

[1]Charge conjugate decays are implied throughout this paper.

[2]Semileptonic decays of other b baryons (for example, Ξ_b) involve, besides the lepton, mainly strange-charmed baryons in the final state.

$$\text{Accidental combinations} \tag{6}$$
$$\text{Fake combinations} \tag{7}$$

The accidental combinations are real Λ from fragmentation in association with real or fake leptons. Fake combinations are spurious $p\pi^-$ combinations under the Λ peak paired with real or fake leptons. By requiring a lepton candidate to have at least 3 GeV/c of momentum and a transverse momentum $p_\perp$with respect to the associated jet[3] of at least 1 GeV/c, most of the $\Lambda\ell$ combinations from processes (2) to (5) are removed. The remaining $\Lambda\ell^-$ combinations originate mostly from either b baryon semileptonic decays (1), accidental combinations (6) or fake combinations (7), while the $\Lambda\ell^+$ combinations are mostly accidental (6) and fake combinations (7). In order to reduce the contribution of accidental and fake combinations to $\Lambda\ell$ correlations, the cut on the momentum of the Λ candidates is increased from 3 GeV/c to 4 GeV/c.

The $\Lambda\ell^-$ (right-sign) and $\Lambda\ell^+$ (wrong-sign) combinations after application of the Λ and lepton selection criteria described above are shown in Fig. 1, where the $p\pi^-$ invariant mass spectrum is plotted. The two $p\pi^-$ invariant mass distributions are fitted using a Gaussian to represent the Λ signal and a second order polynomial to represent the shape of the combinatorial background. A cut of 6 MeV/c^2 around the Λ yields a final sample, including the combinatorial (fake) background under the Λ mass peak, of 1085 $\Lambda\ell^-$ candidates.

To estimate the b baryon fraction in the $\Lambda\ell^-$ sample, the residual contributions of the background processes are evaluated. A study based on Monte Carlo $Z\rightarrow q\overline{q}$ events simulated with JETSET 7.3 [8] predicts a ratio of $\Lambda\ell^-$ to $\Lambda\ell^+$ background combinations, due to processes (2) to (7) of 0.78 ± 0.12. The error is mainly due to the uncertainty in the asymmetry $\Lambda\ell^-$-$\Lambda\ell^+$ of accidental combinations, which depends on the production of Λ baryons in the process of b or $\bar{\text{b}}$ quark fragmentation.

The excess of $\Lambda\ell^-$ combinations over $\Lambda\ell^+$, after correcting for the imbalance of the right and wrong-sign is ascribed to semileptonic decay of b baryons. The resulting b baryon fraction in the selected $\Lambda\ell^-$ sample is $66 \pm 5\%$,which corresponds to a signal of 719 ± 54 events.

2.2 b baryon lifetime fit using $\Lambda\ell^-$ correlation

The lifetime of the b baryon is extracted by a maximum likelihood fit to the $r-\phi$ impact parameter distribution of lepton candidates in the $\Lambda\ell^-$ sample. The fitting procedure is the same used in the previous published measurement of the b baryon lifetime [2]. The lepton impact parameter distribution in $\Lambda\ell^-$ combinations is described as a sum of different sources of the lepton. Table 1 shows their relative contribution to the $\Lambda\ell^-$ sample for the average of the electron and muon channels.

The impact parameter distribution for prompt lepton sources (first four components) is obtained by convoluting a resolution function with a so-called "physics function" which describes the expected impact parameter for these processes. The physics function is obtained separately for each prompt lepton source from a Monte

[3]The lepton is included in the calculation of the jet direction.

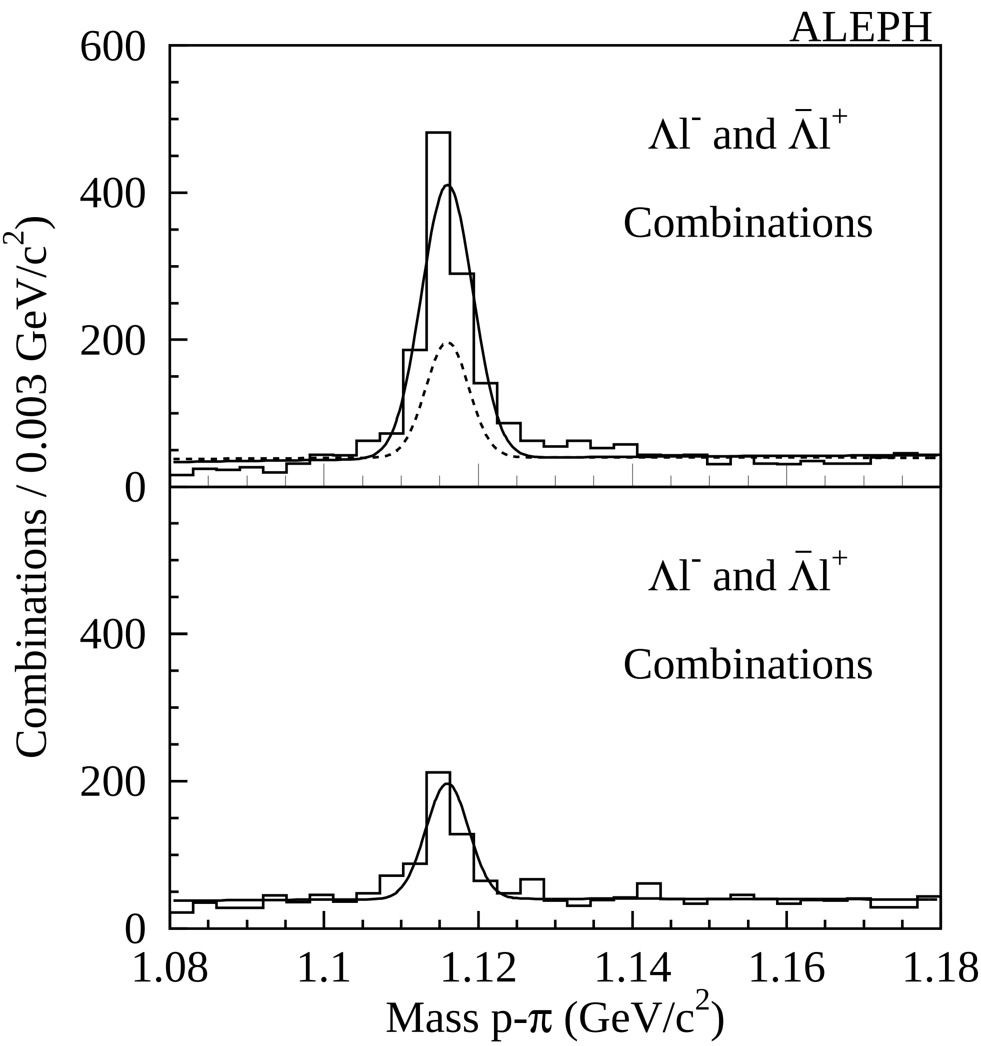

Figure 1: The $p\pi^-$ invariant mass distribution of the $\Lambda\ell^-$ and $\Lambda\ell^+$ combinations. The dashed curve represents the accidental $\Lambda\ell$ combinations in the $\Lambda\ell^-$ (right-sign) combinations estimated from the $\Lambda\ell^+$ (wrong-sign) combinations.

Lepton source	%
$\Lambda_b \to \ell$	66%
$b \to \ell$	26%
$b \to (c/\tau) \to \ell$	3.2%
$c \to \ell$	1.7%
Misidentified hadrons	1.1%
π and K decays	1.8%

Table 1: Lepton sources in the $\Lambda\ell^-$ sample.

Carlo simulation of the decay process. The signal physics function depends on the unknown b baryon lifetime, the only parameter of the fit, while the physics functions of the $b \to \ell$ and $b \to c \to \ell$ background depend on the average b hadron lifetime. The value used in the fit is a world average of all the b lifetime measurements $\tau_b = 1.537 \pm 0.021$ ps [9].

The impact parameter resolution function for the leptons is also obtained using simulated events. However, corrections to resolution function at the level of 10% are applied to account for the difference in the impact parameter resolution between data and Monte Carlo events.

The expected impact parameter distribution for hadrons misidentified as leptons is obtained from the impact parameter distribution of hadrons selected in the data with the same kinematic requirements as applied to the leptons. The distribution for the leptons coming from decay in flight of K and π is taken from the simulated events.

The unbinned maximum likelihood fit to the lepton impact parameter distribution of the 1085 $\Lambda\ell^-$ candidates yields the b baryon lifetime

$$\tau_{\mathrm{b-baryon}} = 1.18\ ^{+0.08}_{-0.08}\ \mathrm{ps},$$

where the quoted error is statistical. Fig. 2 shows the result of the fit together with the observed impact parameter distribution of the lepton candidates in the $\Lambda\ell^-$ sample.

2.3 Systematic errors

In Table 2, the various contributions to the systematic uncertainty in the b baryon lifetime measurement are listed in order of importance. The major contribution to the systematic error arises from the lack of knowledge of the Λ_b polarisation. The $\Lambda_b \to \ell$ physics function is sensitive to the polarisation of the Λ_b, because the impact parameter of the lepton is correlated with its decay angle. The measured value of the Λ_b polarisation ($\mathcal{P}_{\Lambda_b} = -30^{+20}_{-17}\%$) [10], is used in the determination of the central value and of the systematic uncertainty.

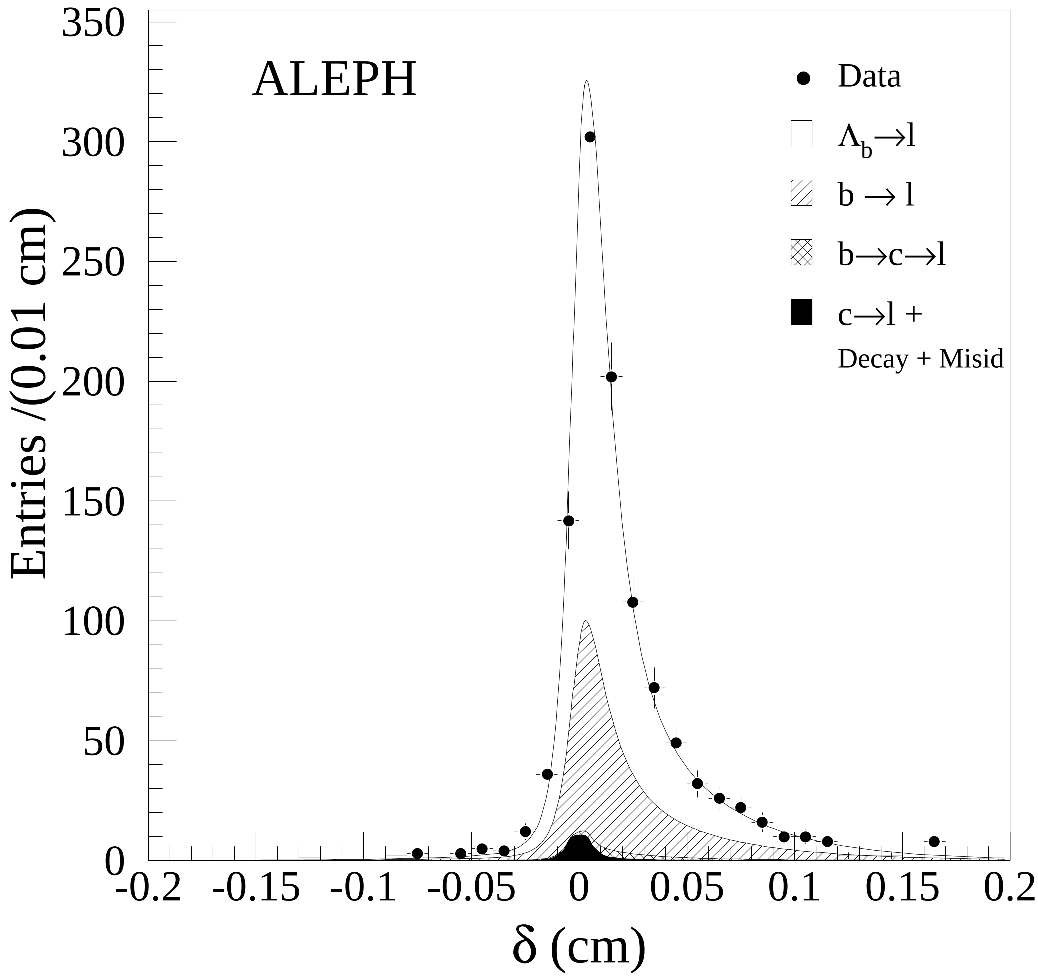

Figure 2: Impact parameter distribution of the selected $\Lambda\ell^-$ candidates. The solid line is the probability function at the fitted value of the lifetime.

A further systematic uncertainty is due to the statistical uncertainties in the parameters of the physics function for the signal ($\Lambda_b \to \ell$) and for the background ($b \to \ell$, $b \to c/\tau \to \ell$ and $c \to \ell$).

The determination of the physics functions depends on the modelling of the semileptonic b baryon decay and on the b fragmentation. An uncertainty in the 4-body semileptonic b hadron decay rate (relative to the total b hadron semileptonic decay rate) of $\pm 20\%$ is assumed in the estimation of the systematic error. A variation of the Peterson fragmentation function [11], which covers the measured uncertainty of the b hadron momentum ($\langle x_b \rangle = 0.714 \pm 0.012$), [12] is considered.

A further contribution to the systematic error is from the uncertainty in the b baryon fraction ($66 \pm 5\%$) which is dominated by the error of the estimate, from simulated events, of the number of accidental combinations of $\Lambda\ell^-$ with respect to

Source of systematic error	Uncertainty (ps)
Λ_b polarisation ($\mathcal{P}_{\Lambda_b} = -30^{+20}_{-17}\%$)	$^{+0.03}_{-0.02}$
$\Lambda_b \to \ell$ physics function	± 0.03
Background physics functions	± 0.02
Λ_b decay model (4-body decay $20 \pm 20\%$)	± 0.02
Fragmentation ($\langle x_b \rangle = 0.714 \pm 0.012$)	± 0.02
b baryon fraction ($f_{\Lambda_b} = 66 \pm 5\%$)	± 0.02
Background lepton fractions	± 0.02
Decay and misidentification background functions	± 0.02
Resolution function	± 0.02
Effective background lifetime ($\tau_b = 1.537^{+0.054}_{-0.021}$ ps)	$^{+0.01}_{-0.02}$
Fragmentation Λ spectrum ($\pm 10\%$)	± 0.01
Level of combinatorial Λ ($\pm 15\%$)	± 0.01
Total	± 0.07

Table 2: Contributions to the systematic uncertainty in the b baryon lifetime measurement using $\Lambda\ell^-$ sample.

$\Lambda\ell^+$.

The relative fractions of the various background sources are obtained from the Monte Carlo simulation and their uncertainties are transalted in a systematic error to the b baryon lifetime.

The statistical error in the parametrisation of the misidentification and decay background probability function is negligible. Nevertheless, uncertainties in the simulation of the decay background events used to derive the expected shape of the function contribute to the systematic error of the b baryon lifetime.

The statistical error on the parametrisation of the resolution function gives a negligible uncertainty to the b baryon lifetime measurement. The systematic uncertainty is estimated from the variation in the b baryon lifetime when the data correction factors are removed.

The physics functions depend on the average lifetimes of the b and c hadrons which populate the right-sign ($\Lambda\ell^-$) peak. A variation in the effective background lifetime of $^{+0.05}_{-0.02}$ ps, which covers the case of b baryons suppression in the accidental combinations, is taken for estimating the systematic error.

The shape of the $b \to \ell$ physics function is different for true Λ's produced during fragmentation and combinatorial $p\pi^-$ combinations and, in particular, it is sensitive to a change in the Λ momentum spectrum.

The momentum spectrum of Λ's produced in hadronic events simulated with JETSET 7.3 has been compared with the data [13], showing a good agreement. However, an uncertainty of 10% in the shape of the fragmentation Λ momentum spectrum is assumed.

The number of combinatorial $\Lambda\ell^-$ combinations contains an uncertainty of 10% due to the fit of the $p\pi^-$ invariant mass.

Summing all the systematic contributions in quadrature yields a total systematic error on the b baryon lifetime of ± 0.07 ps.

3 Measurement of Λ_b using $\Lambda_c^+\ell^-$ correlation

The $\Lambda_c^+\ell^-$ correlation is expected to have a large contribution from Λ_b semileptonic decay $\Lambda_b \rightarrow \Lambda_c^+\ell^-\bar{\nu}$. The $\Lambda_c^+\ell^-$ combinations allow a measurement of the Λ_b decay vertex and hence its decay length on an event-by-event basis. From the decay length and the Λ_b momentum estimation it is possible to obtain the proper time and therefore extract the Λ_b lifetime by performing a maximum likelihood fit.

3.1 Selection of Λ_b using $\Lambda_c^+\ell^-$ correlation

Besides $\Lambda_c^+\ell^-$ pairs from Λ_b semileptonic decay, two physics background processes can contribute to $\Lambda_c^+\ell^-$ combinations in hadronic Z decays. These background sources are the same as the processes (2) and (3) discussed in section 2. The third background component consists of combinatorial "$\Lambda_c^+\ell^-$" events, mainly a fake Λ_c^+ associated with a real or a fake lepton.

Candidates for the decay $\Lambda_b \rightarrow \Lambda_c^+\ell^-\overline{\nu}$ are identified in hadronic Z events where a Λ_c^+ is associated with a lepton in the same hemisphere with respect to the thrust axis. The Λ_c^+ candidates are reconstructed in four decay modes, namely, $\Lambda_c^+ \rightarrow pK^-\pi^+$, $\Lambda_c^+ \rightarrow \Lambda\pi^+\pi^+\pi^-$, $\Lambda_c^+ \rightarrow p\bar{K}^0$ and $\Lambda_c^+ \rightarrow \Lambda\pi^+$. The selection procedure is the same to that used in [2], except for some optimization of the cuts for the $\Lambda_c^+ \rightarrow pK^-\pi^+$ channel and for $\Lambda_c^+ \rightarrow \Lambda\pi^+$ which has been included. The $\Lambda_c^+ \rightarrow pK^-\pi^+$ channel suffers most from combinatorial background which could be suppresed by introducing a cut on $l_{\Lambda_c}/\sigma_{l_{\Lambda_c}} > -0.5$, where l_{Λ_c} is the distance between the Λ_b and the Λ_c^+ vertices projected on the Λ_c^+ momentum. According to studies with simulated events, this cut introduces a negligible bias on the Λ_b lifetime. For the $\Lambda_c^+ \rightarrow \Lambda\pi^+$ channel, the Λ, selected as described in [2], is associated with a charged particle with a momentum greater than 3.5 GeV/c and the dE/dx measurement, when available, consistent with that expected for a pion of similar momentum. The Λ_c^+ selected candidates with momentum greater than 8 GeV/c are combined with an identified lepton with momentum above 3 GeV/c in a 45 degree cone around the Λ_c^+ direction, on the same side of the event. The $\Lambda_c^+\ell^-$ system is required to have a momentum greater than 20 GeV/c and an invariant mass above 3.5 GeV/c^2. These two requirements reduce the combinatorial background and the contribution of physics background from non Λ_b semileptonic decays. In addition further requirements on the track quality and vertexing are applied. To ensure a good reconstruction of the decay length, the lepton and the pion are required to have one or more associated hits in the VDET. The χ^2 probability of the Λ_c^+ and the Λ_b vertices are both required to be greater than 1%. The selection cuts yield a final sample of 193 $\Lambda_c^+\ell^-$ combinations selected in a $\pm 2\sigma$ window around the nominal Λ_c^+ mass. Fig. 3 shows the individual contributions of the four Λ_c^+ decay channels to the right-sign $\Lambda_c^+\ell^-$

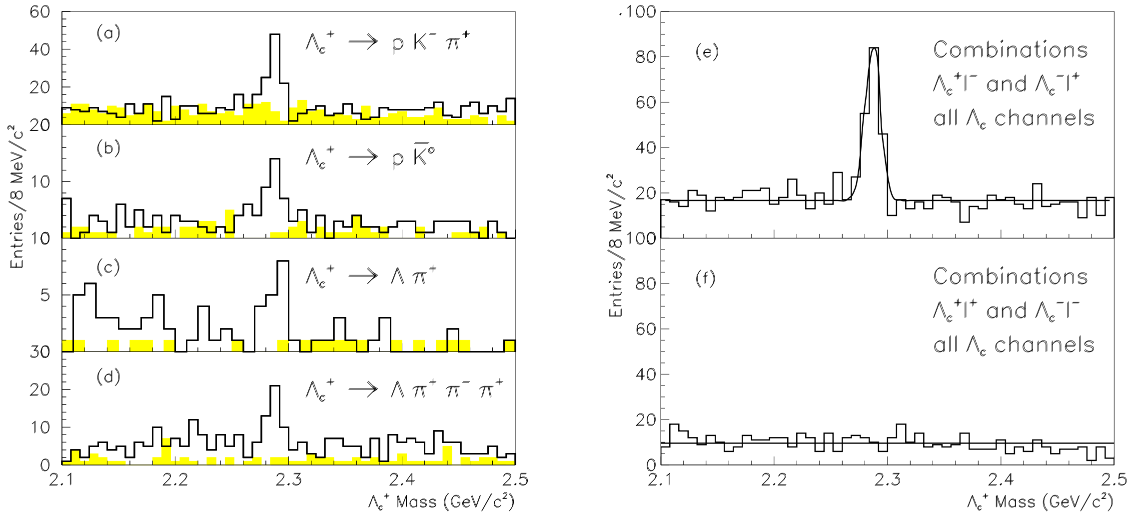

Figure 3: Invariant mass of the selected combinations of $pK^-\pi^+$ (a), pK^0 (b), $\Lambda\pi^+$ (c) and $\Lambda\pi^+\pi^+\pi^-$(d) for the right-sign $\Lambda_c^+\ell^-$ correlations. The dashed plots show the corresponding wrong-sign $\Lambda_c^+\ell^+$ combinations. The invariant mass distributions for the total selected combinations in the four Λ_c^+ decay modes are shown in figure (e) and (f) for the right and wrong sign $\Lambda_c\ell$ combinations respectively.

combinations and their sum after all cuts. A clear enhancement is observed at the nominal Λ_c^+ mass value in the right-sign $\Lambda_c^+\ell^-$ combinations while this is not the case for wrong-sign $\Lambda_c^+\ell^+$ combinations. Table 3 summarises the number of $\Lambda_c^+\ell^-$ candidates selected in the four Λ_c^+ decay channels. The fraction of combinatorial background within the same mass window results from a straight line fit to the invariant mass distributions.

Decay Channel	N_{peak}	$f_{back}(\%)$
$\Lambda_c^+ \to pK^-\pi^+$	103	27 ± 2
$\Lambda_c^+ \to p\bar{K}^0$	35	29 ± 3
$\Lambda_c^+ \to \Lambda\pi^+$	18	39 ± 4
$\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-$	37	31 ± 3
Total	193	–

Table 3: The number of $\Lambda_c^+\ell^-$ candidates N_{peak} and the fraction f_{back} of combinatorial background within $\pm 2\sigma$ of the nominal Λ_c^+ mass in the four Λ_c^+ decay modes after all requirements.

3.1.1 Measurement of Λ_b proper decay time and lifetime fit

The Λ_b lifetime is determined from the proper decay time distributions of the four $\Lambda_c^+\ell^-$ event samples. For each Λ_b candidate, the proper time is obtained from the

Λ_b decay length and the Λ_b momentum.

The Λ_b decay length is measured in three dimensions by projecting the vector joining the interaction point and the Λ_b decay vertex onto the Λ_b direction of flight as estimated from the $\Lambda_c^+\ell^-$ combinations. From the Monte Carlo simulation, the resolution of the Λ_c^+ and the Λ_b decay vertices along their directions of flight are 330 μm and 180 μm respectively. For each event, the error on the Λ_b decay length is calculated from the track trajectory errors and it is increased by 10% as described in [2].

The Λ_b momentum is determined event by event from the measured $\Lambda_c^+\ell^-$ energy and reconstructing the neutrino energy in the $\Lambda_c^+\ell^-$ hemisphere. The technique used to reconstruct the missing neutrino energy is similar to that described in ref. [14]. A resolution function which takes into account the uncertainty on the Λ_b momentum reconstruction is obtained from the Monte Carlo simulation and is used to correct the data.

For the Λ_b mass, the ALEPH recently measured value $M_{\Lambda_b} = 5614 \pm 21$ MeV/c^2 [15] is used.

The Λ_b lifetime is extracted from a simultaneous unbinned maximum likelihood fit to the proper time distribution of the four $\Lambda_c^+\ell^-$ event samples shown in Table 3. The background parametrisation is obtained by fitting simultaneously the signal wrong sign and sideband region right and wrong sign events.

Fig. 4 shows the results of the simultaneous fit of the Λ_b signal and combinatorial background events. The fitted Λ_b lifetime is

$$\tau_{\Lambda_b} = 1.21\ ^{+0.13}_{-0.12}\ \mathrm{ps},$$

where the quoted error is statistical only.

3.2 Systematic errors

Several sources of systematic errors affecting this τ_{Λ_b} measurement are investigated and their respective contributions are summarized in table 4. With respect to the published analysis, the increase in statistics allows the reduction of the systematic error due to the fraction and the shape of the combinatorial background.

The dominant systematic error is due to the physics background which contribute with 4 ± 4 events to the $\Lambda_c^+\ell^-$ sample, to the parametrisation of the combinatorial background shape and to the Λ_b decay modelling.

Combining the systematic errors listed in table 4, the total systematic error is ± 0.04 ps.

4 Conclusion

From a total of about 4 million hadronic Z decays collected with the ALEPH detector between 1991 and 1995, the lifetime of b baryons is measured from a maximum likelihood fit to the impact parameter distribution of the candidate lepton tracks in

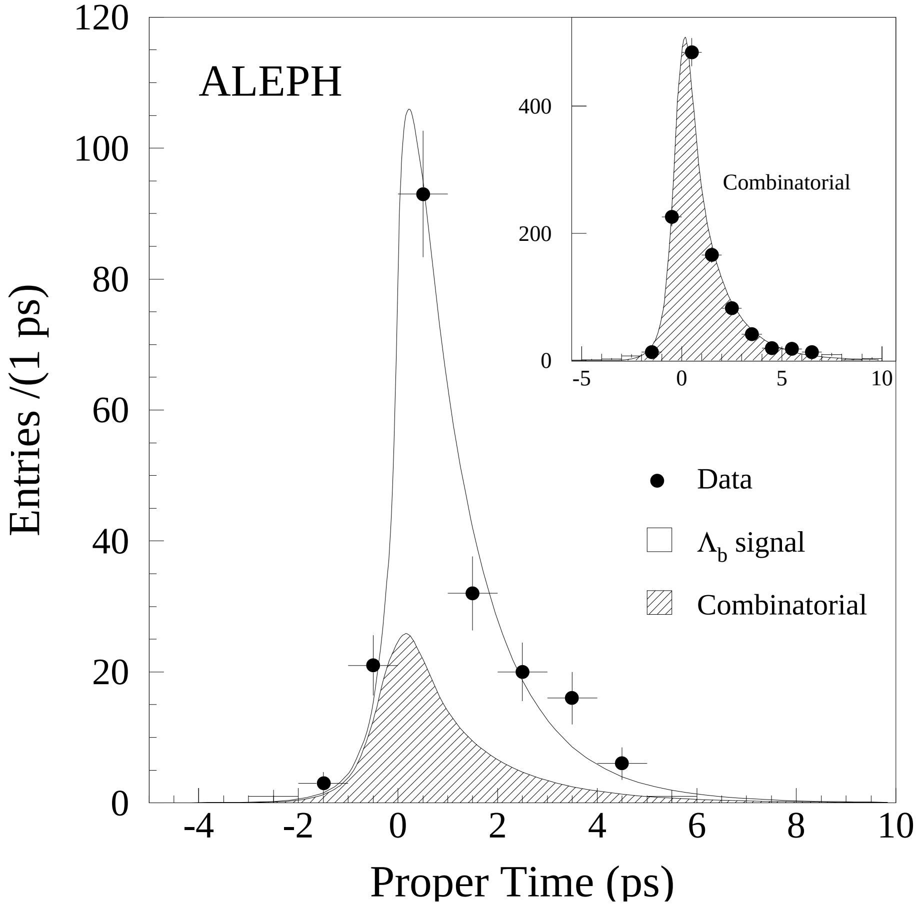

Figure 4: The proper-time distribution of the Λ_b candidates in the $\Lambda_c^+\ell^-$ sample. The shaded area corresponds to the proper-time distribution of the combinatorial background. The solid line is the result of the maximum likelihood fit. The inset shows the proper time distribution of the combinatorial background from wrong-sign events and events in right-sign sidebands. The fraction of combinatorial background events with zero lifetime differs among the four Λ_c^+ decay modes.

the $\Lambda\ell^-$ sample. The result is

$$\tau_{\mathrm{b-baryon}} = 1.18 \pm 0.08(\mathrm{stat}) \pm 0.07(\mathrm{syst})\ \mathrm{ps}.$$

For the $\Lambda_c\ell$ correlations analysis, a clear enhancement is observed at the nominal Λ_c^+ mass value in the right-sign $\Lambda_c^+\ell^-$ combinations due to semileptonic decay of the Λ_b , while this is not the case for wrong-sign $\Lambda_c^+\ell^+$ events. A maximum likelihood fit to the proper decay time distribution of 193 $\Lambda_c^+\ell^-$ combinations leads to a value for the Λ_b lifetime of:

$$\tau_{\Lambda_b} = 1.21^{+0.13}_{-0.12}(\mathrm{stat}) \pm 0.04(\mathrm{syst})\ \mathrm{ps}.$$

Since the relative contribution of various b baryon species in the $\Lambda\ell^-$ sample is not well known and depends on their relative production rate and lifetime, there

Source	Uncertainty (ps)
Combinatorial background fraction	< 0.01
Combinatorial background shape	± 0.02
Physics background	± 0.02
Resolution function	± 0.01
Λ_b decay model (20% ±20% four-body)	± 0.02
b fragmentation	± 0.01
Λ_b polarization ($\mathcal{P}_{\Lambda_b} = -30^{+20}_{-17}\%$)	< 0.01
E_ν calibration	< 0.01
Λ_b mass (5614 ± 21) MeV/c^2	< 0.01
total	0.04

Table 4: Sources of systematic uncertainty in the Λ_b lifetime

is no a priori prescription for averaging the two lifetime measurements. Assuming that the Λ_b is the dominant source of b baryons produced at the Z resonance and the differences among the lifetimes of b baryons (Λ_b , Ξ_b , Ω_b) are small, the two measurements can be averaged [4] to give:

$$\tau_{\Lambda_b} = 1.19 \pm 0.08 \text{ ps.}$$

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