EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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Update Measurement of the b Baryon Lifetime

The ALEPH Collaboration

Abstract

Using about 3 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 849 $\Lambda\ell^-$ combinations containing a b baryon sample of 546 decays the measured b baryon lifetime is

$$\tau_{\mathrm{b-baryon}} = 1.21 \pm 0.09(\mathrm{stat}) \pm 0.07(\mathrm{syst})\ \mathrm{ps}.$$

The lifetime of the Λ_b^0 baryon from a maximum likelihood fit to the proper time distribution of 143 $\Lambda_c^+\ell^-$ candidates containing a Λ_b^0 sample of 107 decays, is

$$\tau_{\Lambda_b^0} = 1.24^{+0.15}_{-0.14}(\mathrm{stat}) \pm 0.05(\mathrm{syst})\ \mathrm{ps}.$$

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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. 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.

This analysis is an update of the recently published letter [2]. The b baryon lifetime is measured using two independent methods based on the lepton impact parameter in $\Lambda\ell^-$ events and on the reconstruction of the proper time in $\Lambda_c^+\ell^-$ events. Compared to the published result the available data sample has doubled, thanks to the inclusion of the data collected during 1994. The analysis procedure follows exactly the one in [2], except for some optimization of the cuts to make better use of the increased statistics.

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^0 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

$$\Lambda_b \to \Lambda_c^+ X \ell^- \overline{\nu}, \quad \Lambda_c^+ \to \Lambda X \tag{1}$$
$$\overline{B} \to \Lambda_c^+ X \ell^- \overline{\nu}, \quad \Lambda_c^+ \to \Lambda X \tag{2}$$
$$b \to \Lambda_c^+ {D_s}^- X, \quad \Lambda_c^+ \to \Lambda X, {D_s}^- \to X \ell^- \overline{\nu} \tag{3}$$
$$b \to \Lambda_c^+ X, \quad \Lambda_c^+ \to \Lambda \ell^+ X \tag{4}$$
$$c \to \Lambda_c^+ X, \quad \Lambda_c^+ \to \Lambda \ell^+ X \tag{5}$$
$$\text{Accidental combinations} \tag{6}$$
$$\text{Fake combinations} \tag{7}$$

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[1] of at least 1 GeV/c, most of the $\Lambda\ell$ combinations from processes (2)

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

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).

The incresed statistics allows harder cuts to improve the purity of the sample. The gain in the systematic error overcompensates the loss in statistics. Therefore the cut on the momentum of the Λ candidates has been increased from 3 to 4 GeV/c.

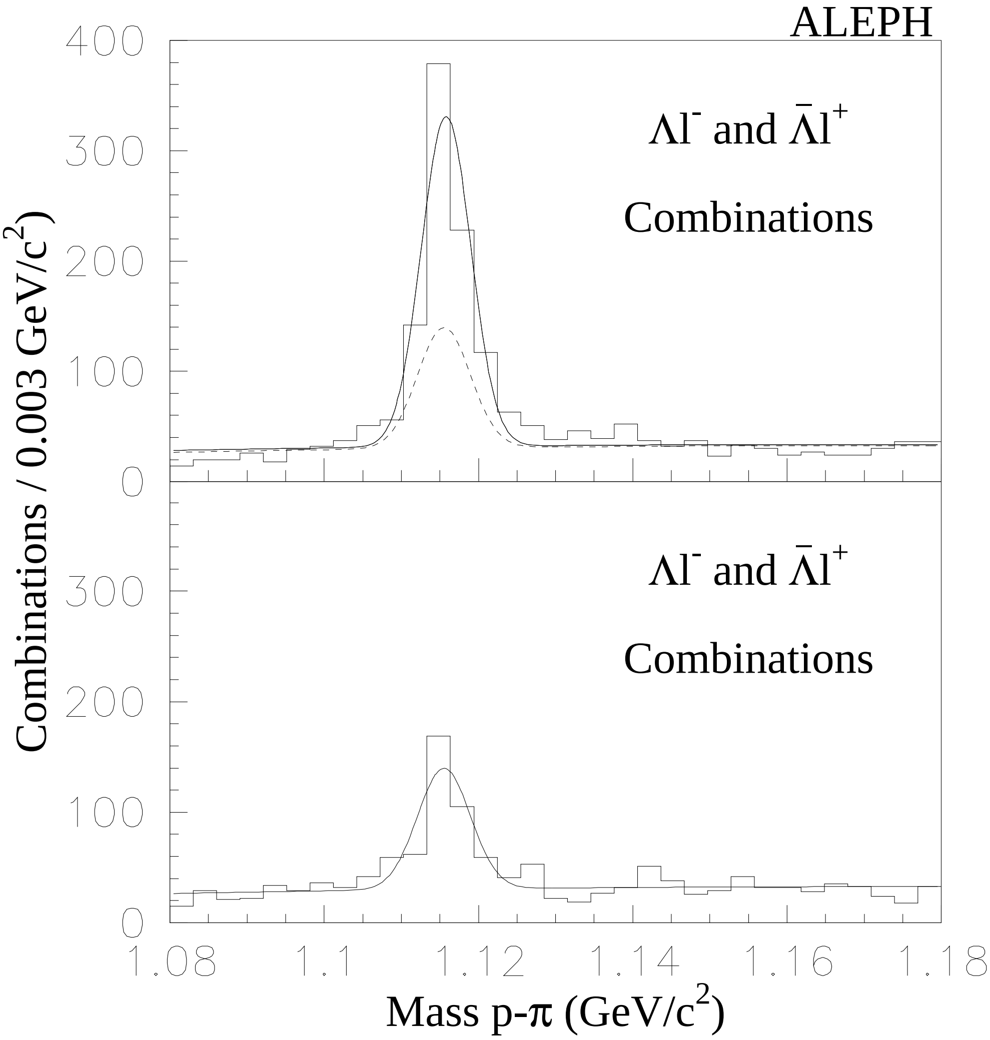

Figure 1: The $p\pi^-$ invariant mass distribution of the $\Lambda\ell^-$ and $\Lambda\ell^+$ combinations. The dashed curve represents the accidental $\Lambda\ell$ combinations in the $\Lambda\ell^-$ (right-sign) combinations estimated from the $\Lambda\ell^+$ (wrong-sign) combinations.

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 the final sample of 849 $\Lambda\ell^-$ candidates, including the combinatorial (fake) background under the Λ mass peak.

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 $Z \to q\overline{q}$ 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 0.80 ± 0.13. 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 $\bar{b}$ 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 $64 \pm 6\%$.

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.

Lepton source	%
$\Lambda_b \to \ell$	64%
$b \to \ell$	28%
$b \to (c/\tau) \to \ell$	3.1%
$c \to \ell$	1.6%
Misidentified hadrons	1.3%
π and K decays	1.8%

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

The impact parameter distribution for prompt lepton sources (first four components) is obtained by convoluting a resolution function with a physics function which describes the expected impact parameter for these processes. The physics functions and the resolution function are obtained from simulated events as described in [2]. The $\Lambda_b \to \ell$ physics function depends on the unknown b baryon lifetime, only parameter of the fit, while the $b \to \ell$ and $b \to c \to \ell$ physics functions depend on the average b hadron lifetime. The value used in the fit is the published world average, $\tau_{\rm b} = 1.537 \pm 0.021$ ps [9].

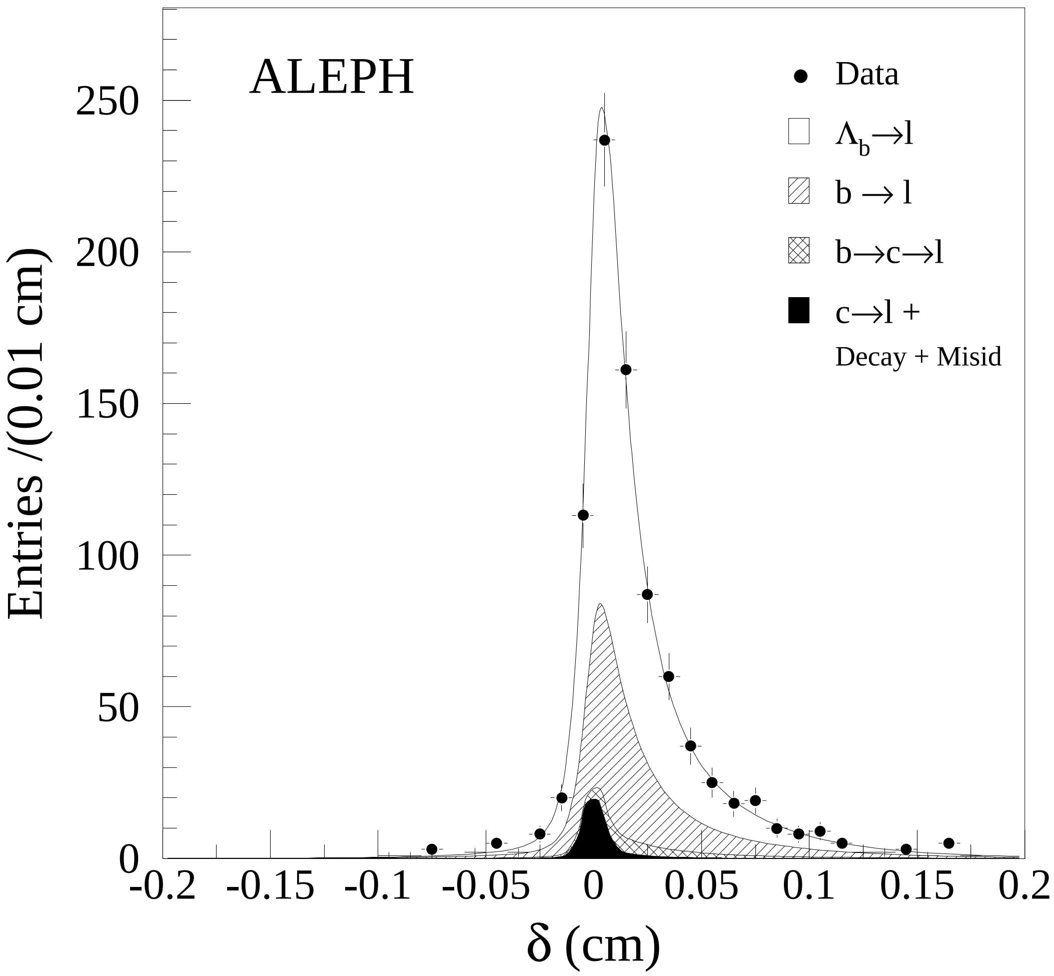

Figure 2: Impact parameter distribution of the selected $\Lambda\ell^-$ candidates. The solid line is the probability function at the fitted value of the lifetime.

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 in the 849 $\Lambda\ell^-$ candidates yields the b baryon lifetime

$$\tau_{\rm b-baryon} = 1.21 \ ^{+0.09}_{-0.09} \ \ {\rm ps},$$

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.

The stability of the result is checked repeating the fit after having varied the kinematic cuts on lepton p, $p_\perp$ and the Λ momentum. The resulting deviations in the fitted lifetime values are within the range for the given statistical uncertainty.

The background physics functions and the lepton background fractions are checked by fitting the events in the side bands of the $p\pi^-$ invariant mass for the average b hadron lifetime. The fit yields $\tau(\text{side band}) = 1.53 \pm 0.05$ ps, in agreement with the average b hadron lifetime value.

2.3 Systematic errors

Source of systematic error	Uncertainty (ps)
Λ_b polarisation ($\mathcal{P}_{\Lambda_b} = -30^{+32}_{-27}\%$)	± 0.04
b baryon fraction ($f_{\Lambda_b} = 64 \pm 6\%$)	± 0.02
Background lepton fractions	± 0.02
$\Lambda_b \to \ell$ physics function	± 0.02
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
Decay background and Misid function	± 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.

In Table 2, the various contributions to the systematic uncertainty in the b baryon lifetime measurement are listed in order of importance. The analysis follows exactly the same of the published measurement [2] and therefore details on the different contributions to the systematic error can be found there. The higher cut in the Λ momentum yields a sample with higher purity. This allows the reduction of the systematic error due to the uncertainty in the b baryon fraction from $^{+0.04}_{-0.05}$ ps to ± 0.02 ps. The systematic contributions due to the background lepton fractions and background lifetime are reduced from ± 0.03 ps to ± 0.02 ps for the same reason. The 4 GeV/c cut in the Λ momentum gives a more powerful rejection of Λ's produced during fragmentation. Therefore the systematic error due to an uncertainty in the shape of the fragmentation Λ momentum spectrum is reduced from ± 0.02 ps to

±0.01 ps. The systematic error due to the parametrisation of the physics functions is reduced from ±0.03 ps to ±0.02 ps, making use of a bigger sample of Monte Carlo events.

The major contribution to the systematic error arises from the lack of knowledge of the Λ_b polarisation. The uncertainty in the knowledge of the Λ_b polarisation ($\mathcal{P}_{\Lambda_b} = -30^{+32}_{-27}\%$) [10], used in this analysis, leads to a systematic error of ±0.04 ps.

Altough the systematic error due to the Λ_b polarisation increased from ±0.03 ps to ±0.04 ps, the total systematic error on the b baryon lifetime improved from ±0.09 to ±0.07 ps.

3 Measurement of Λ_b^0 lifetime using $\Lambda_c^+\ell^-$ correlation

The $\Lambda_c^+\ell^-$ correlation is expected to have a large contribution from Λ_b^0 semileptonic decay $\Lambda_b^0 \to \Lambda_c^+\ell^-\overline{\nu}$. The $\Lambda_c^+\ell^-$ combinations allow a measurement of the Λ_b^0 decay vertex and hence its decay length on an event-by-event basis. It permits a complementary and independent measurement of the Λ_b^0 lifetime.

3.1 Selection of Λ_b^0 using $\Lambda_c^+\ell^-$ correlation

Besides $\Lambda_c^+\ell^-$ pairs from Λ_b^0 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 3. 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 $\Lambda_b^0 \to \Lambda_c^+\ell^-\overline{\nu}$ 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 three decay modes, namely, $\Lambda_c^+ \to pK^-\pi^+$, $\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-$ and $\Lambda_c^+ \to p\bar{K}^0$. The selection procedure is the same to that described in [2], except for the $\Lambda_c^+ \to pK^-\pi^+$ channel. This channel suffers most from combinatorial background which could be suppressed by introducing a cut on $l_{\Lambda_c^+}/\sigma(l_{\Lambda_c^+}) > -0.5$, where $l_{\Lambda_c^+}$ is the distance between the Λ_b^0 and the Λ_c^+ vertices. This cut, according to studies with simulated events, introduces a negligible bias to the Λ_b^0 lifetime.

The selection cuts yield a final sample of 143 $\Lambda_c^+\ell^-$ combinations selected in a $\pm2\sigma$ window around the nominal Λ_c^+ mass. Fig. 3 shows the individual contributions of the three Λ_c^+ decay channels to the right-sign $\Lambda_c^+\ell^-$ combinations and their sum after all cuts. Table 3 summarises the number of $\Lambda_c^+\ell^-$ candidates selected in the three Λ_c^+ decay channels and the fraction of combinatorial background.

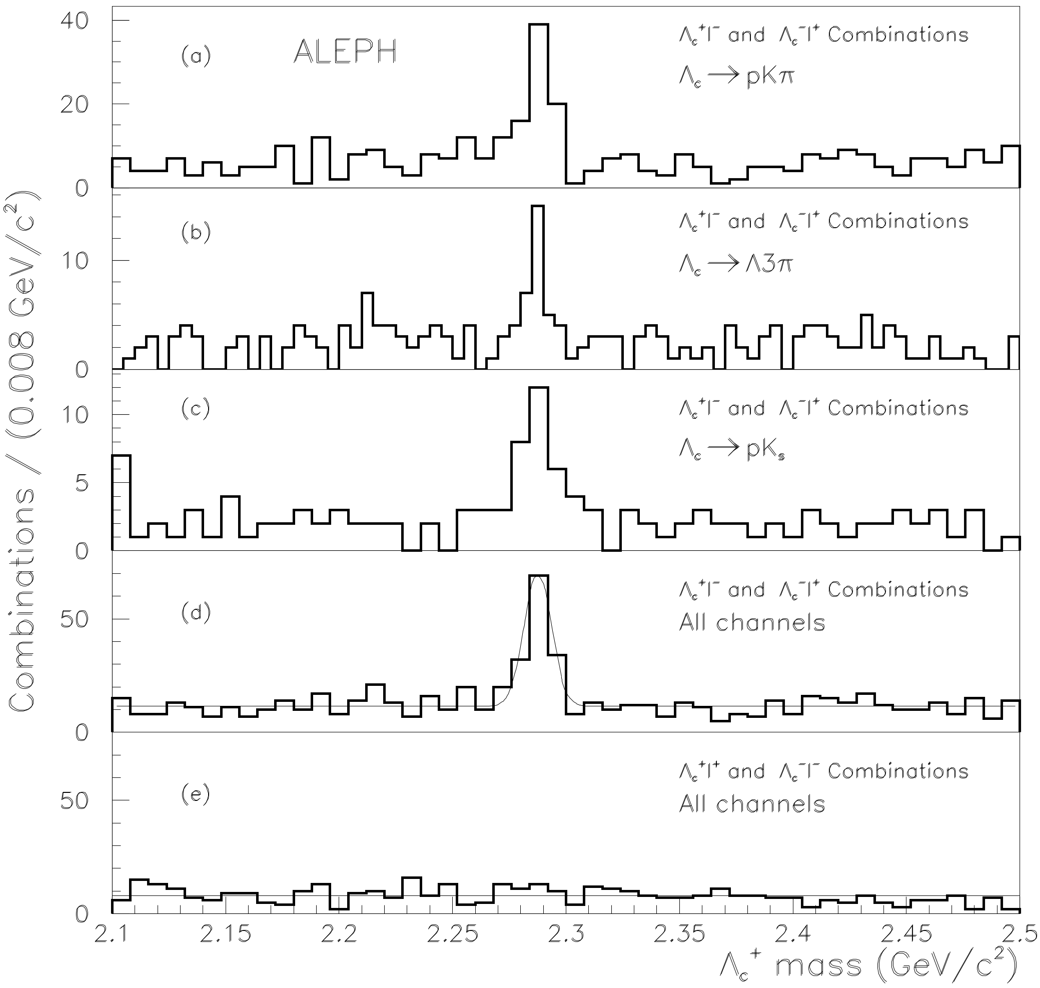

Figure 3: The $\mathrm{p K^-}\pi^+$ (a), the $\Lambda\pi^+\pi^+\pi^-$ (b), and the $\mathrm{p}\bar{\mathrm{K}}^0$ (c) invariant mass distributions for right-sign $\Lambda_c^+\ell^-$ combinations and their sum (d). The sum of wrong-sign $\Lambda_c^+\ell^+$ combinations is displayed in (e).

Decay Channel	N_{peak}	$f_{back}(\%)$
$\Lambda_c^+ \to \mathrm{pK^-}\pi^+$	85	27 ± 2
$\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-$	30	31 ± 3
$\Lambda_c^+ \to \mathrm{p}\bar{\mathrm{K}}^0$	28	29 ± 3
Total	143	–

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 three Λ_c^+ decay modes after all requirements.

3.2 Measurement of Λ_b^0 proper decay time and lifetime fit

The Λ_b^0 lifetime is determined from the proper decay time distributions of the three $\Lambda_c^+\ell^-$ event samples. For each Λ_b^0 candidate, the proper time is obtained from the Λ_b^0 decay length and the Λ_b^0 momentum.

The Λ_b^0 decay length is measured in three dimensions by projecting the vector joining the interaction point and the Λ_b^0 decay vertex onto the Λ_b^0 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^0 decay vertices along their directions of flight are 330 μm and 180 μm respectively. For each event, the error on the Λ_b^0 decay length is calculated from the track trajectory errors and it is increased by 10% as described in [2].

The Λ_b^0 momentum is determined event by event from the 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. [13]. A resolution function which takes into account the uncertainty on the Λ_b^0 momentum reconstruction is obtained from Monte Carlo simulation and is used to correct the data.

For the Λ_b^0 mass, the quark model prediction of $M = 5.6$ GeV/c^2 [5] is used.

The Λ_b^0 lifetime is extracted from a simultaneous unbinned maximum likelihood fit to the proper time distribution of the three $\Lambda_c^+\ell^-$ event samples, shown in Table 3. The background parametrisation is obtained by fitting simultaneously the signal and the sideband regions of the right and wrong sign events.

Fig. 4 shows the result of the simultaneous fit of the Λ_b^0 signal and combinatorial background events. The fitted Λ_b^0 lifetime is

$$\tau_{\Lambda_b^0} = 1.24\ ^{+0.15}_{-0.14}\ \mathrm{ps},$$

where the quoted error is statistical.

3.3 Systematic errors

Various sources of systematic uncertainties in τ_{Λ_b} measurement have been considered. Their contributions are summarised in Table 4. Compare to the published analysis [2], 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 process $B \to \Lambda_c^+ X \ell^- \nu$, which contributes with 4 ± 4 events to the $\Lambda_c^+\ell^-$ sample.

Combining the systematic errors from the sources shown in table 4, the total systematic error is ± 0.05 ps.

4 Conclusion

From a total of about 3.2 million hadronic Z decays collected with the ALEPH detector between 1991 and 1994 the lifetime of b baryons is measured from a maximum

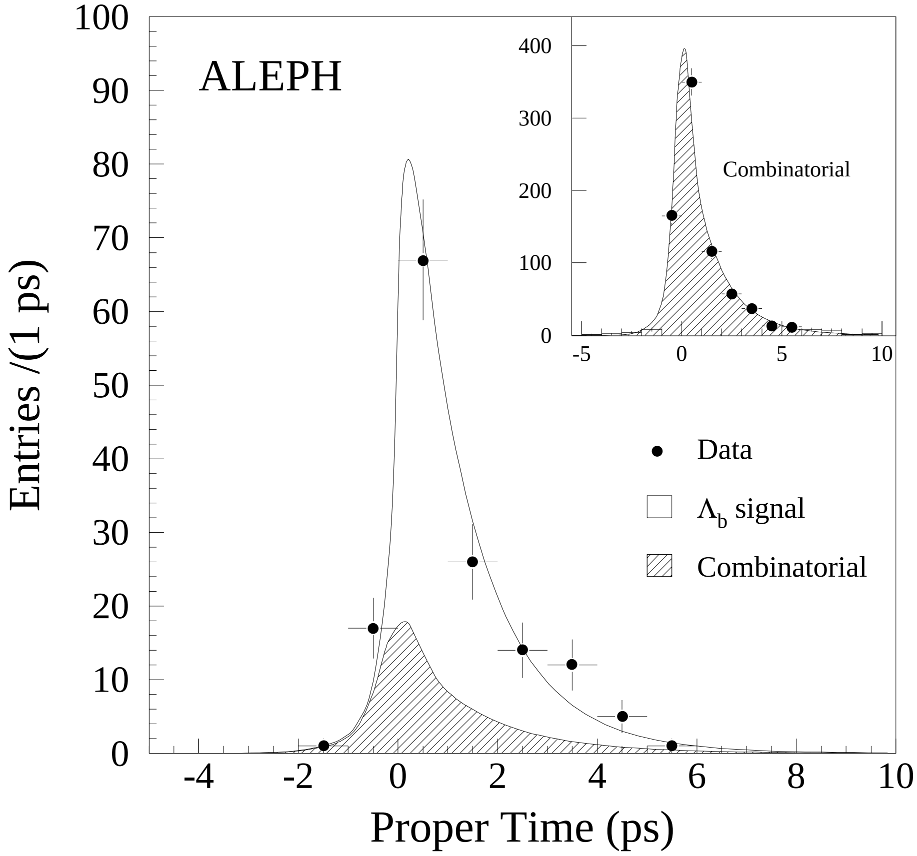

Figure 4: The proper-time distribution of the Λ_b^0 candidates in the $\Lambda_c^+\ell^-$ sample. The shaded area corresponds to the proper-time distribution of the combinatorial background. The solid line is the result of the maximum likelihood fit described in the text. The inset shows the proper time 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 3 Λ_c^+ decay modes. It is 27% on average.

likelihood fit to the impact parameter distribution of the candidate lepton tracks in the $\Lambda\ell^-$ sample. The result is

$$\tau_{\mathrm{b-baryon}} = 1.21 \pm 0.09(\mathrm{stat}) \pm 0.07(\mathrm{syst})\ \mathrm{ps}.$$

The $\Lambda_c^+\ell^-$ combinations from semileptonic decay of the Λ_b^0 are also identified via fully reconstructed $\Lambda_c^+ \to \mathrm{p}K^-\pi^+$, $\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-$, and $\Lambda_c^+ \to \mathrm{p}\bar{K}^0$ decays. The Λ_b^0 lifetime measured from a maximum likelihood fit of the proper decay time distribution of 143 $\Lambda_c^+\ell^-$ combinations is

$$\tau_{\Lambda_b^0} = 1.24^{+0.15}_{-0.14}(\mathrm{stat}) \pm 0.05(\mathrm{syst})\ \mathrm{ps}.$$

Source	Uncertainty (ps)
Physics background (4 ± 4 event)	± 0.03
Combinatorial background shape	± 0.02
Λ_b^0 mass (5.6 ± 0.1) GeV/c^2	± 0.02
Λ_b^0 decay model (20% ±20% four-body)	± 0.02
b fragmentation	± 0.01
Resolution function	± 0.01
Λ_b^0 polarization ($\mathcal{P}_{\Lambda_b^0} = -30^{+32}_{-27}\%$)	≤ 0.01
Combinatorial background fraction	≤ 0.01
E_ν calibration	≤ 0.01
total	± 0.05

Table 4: Sources of systematic uncertainty in the Λ_b^0 lifetime

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 is no a priori prescription for averaging the two lifetime measurements described above. Assuming that the Λ_b^0 is the dominant source of b baryons produced at the Z resonance and the differences among the lifetimes of b baryons (Λ_b^0 , Ξ_b , Ω_b) are small, the two measurements can be averaged [2] to give:

$$\tau_{\Lambda_b^0} = 1.22 \pm 0.09 \text{ ps}.$$

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