TESTS OF HQET WITH $B^*$, $B^{**}$ AND LIFETIME MEASUREMENTS OF $B$, MESONS AND BEAUTY BARYONS AT DELPHI

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ABSTRACT

Heavy Quark Effective Theory allows calculations in non-perturbative QCD in the limit where the mass of the heavy quark is much larger than the scale $\Lambda_{QCD}$ of the strong interactions. In this way predictions are made on the mass splittings of the $B$ meson excited states and on the individual $B$ hadron lifetimes.

Recent DELPHI results yield an accurate measurement of the $B^*-B$ mass difference of $45.5 \pm 0.3 \pm 0.8 \text{ MeV}/c^2$ and a first observation of orbitally excited $B^{**}$ mesons. The measured $B^{**}_{ud}-B^{**}_{ud}$ mass splitting of $453 \pm 5 \pm 20 \text{ MeV}/c^2$ agrees well with HQET predictions and confirms the existence of broad and narrow resonances.

High statistics has also allowed significant measurements of the average lifetimes of $B$, mesons and beauty baryons, including a first observation of the $\Xi_b$ baryon:

$$\tau(B_s) = 1.42^{+0.25}_{-0.22} \pm 0.14 \text{ ps},$$
$$\tau(A_s) = 1.21^{+0.21}_{-0.18} \pm 0.04 \text{ ps},$$
$$\tau(\Xi_b) = 1.5^{+0.7}_{-0.6} \pm 0.3 \text{ ps}.$$}

Crucial points in these studies are the accuracy of the Vertex Detector and the particle identification capabilities of the RICH.

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1 Introduction

More than 3 million hadronic $Z$ decays have been collected with the DELPHI detector at LEP in the years 1991 to 1994. This has lead to accurate measurements of excited beauty meson states and significant progress in the lifetime measurements of $B_s$ mesons and beauty baryons, both of which are produced at low rates in the fragmentation process.

DELPHI is a general purpose detector at LEP [1]. Accurate vertex reconstruction is provided by three layers of silicon vertex detectors placed directly outside the beampipe, which measure $b$ hadron flight distances, typically of the order of several millimeters, with a resolution of about 300 $\mu m$. The angular coverage of this detector restricts the presented analyses to events that have their thrust axis within the barrel region.

The most outstanding feature of the DELPHI detector is the Ring Imaging CHERENKOV (RICH) detector which offers pion–kaon–proton separation over a wide momentum range, supported in part of the momentum range by a dE/dx measurement in the main tracking chamber. The electromagnetic calorimeter allows 3-dimensional shower reconstruction with high granularity.

The $B^*$ and $B^{**}$ analyses employ a $b\bar{b}$ tagging algorithm that exploits the capability of the vertex detector in detecting long lived $B$ hadrons. It accepts only events with a low probability of all well-measured tracks to come from one common primary vertex. This tagging algorithm has an efficiency of $64 \pm 3\%$ and a purity of $84 \pm 4\%$ for $b\bar{b}$ events, resulting in a sample of 333,738 events for the $B^*$ analysis (including 1994 data) and 175,960 events for the $B^{**}$ analysis (1991–1993). The presented $B_s$ meson and beauty baryon studies use data collected in the years 1991 to 1993.

2 $B^* \rightarrow B\gamma$

Due to the small $B^*-B$ mass difference of 46 $MeV/c^2$, the dominant decay of the vector meson is $B^* \rightarrow B\gamma$. Experimentally, three variables are necessary to reconstruct the mass difference: the photon energy, the momentum of the $B$ meson, and the angle between the two.

The photon energy in the labframe at LEP lies below 800 $MeV$, at which low energies the electromagnetic calorimeter is not well suited. Therefore, only converted photons are used, that are reconstructed from track fragments in the tracking chambers. The reconstructed photons have an energy resolution of 1 $\%$, an angular resolution of 1.5 mrad and a conversion radius resolution of 5 $mm$.

The $B$ mesons are inclusively reconstructed using their general properties: they closely follow the original $b$ quark direction and inherit a large fraction of its energy. Therefore, $B$ meson decay products tend to have higher momenta and are closer to the thrust axis than other particles produced in the fragmentation process.

The rapidity $y = \frac{1}{2} \log \left( \frac{E + p_{long}}{E - p_{long}} \right)$ is used to express the vicinity to the thrust axis. Here $p_{long}$ is the longitudinal momentum of the particle with respect to the thrust
axis and $E$ is its energy. Both charged and neutral particles are considered. Particles with $y > 1.5$ are accepted as $B$ meson decay products. The $B$ momentum is then defined as the sum of the momenta of all selected particles. Finally a correction is made for the observed hemisphere energy and the total invariant mass of the collected momentum. The resulting $B$ energy resolution is approximately 7 GeV, the angular resolution is 15 mrad for 60 % of the data and 38 mrad for the remaining 40 %.

The result is the following mass difference [4] listed with a summary of previous measurements:

$$\Delta M(B^*-B) = 45.5 \pm 0.3 \pm 0.8 \text{ MeV/c}^2 \quad \text{DELPHI}$$
$$= 45.4 \pm 1.0 \text{ MeV/c}^2 \quad \text{CUSB2}$$
$$= 46.2 \pm 0.3 \pm 0.8 \text{ MeV/c}^2 \quad \text{CLEO2}$$
$$= 46.3 \pm 1.9 \text{ (stat)} \text{ MeV/c}^2 \quad \text{L3}$$

The mass difference distribution is shown in figure 2(a), where the systematic error on the position of the peak is dominated by the uncertainty in the $B$ momentum reconstruction.

The width of the signal peak of about 5 MeV is dominated by the angular resolution between the $B$ meson and the photon. Assumptions for the relative contributions of $B_u$, $B_d$ and $B_s$ mesons in an approximate ratio of 3:3:1 lead to upper limits on the mass splittings between the different $B$ meson species of about 6 MeV. When the fraction $b \rightarrow B_s$ is taken to be $\sim 10 \%$, the $B^*_s-B_s$ mass splitting is determined to be $46.1 \pm 1.5 \pm 1.3 \text{ MeV}$.

The total production rate of $B^*$ mesons per $b\bar{b}$ event is determined using the acceptance from simulation. This is translated into a ratio for the relative production of vector mesons to pseudo-scalar mesons:

$$V/(V+P) = 0.75 \pm 0.10$$

which is in agreement with the spin counting expectation of 3:1, vector mesons having three degrees of freedom and pseudoscalars one. The error includes a possible contribution from $B^{**}$ decays of 30 %.

A second test is done to check if the production is consistent with a spin 1 particle, by studying the helicity distribution of the photon. To obtain the $\cos \theta^*$ distribution the photon is boosted back to the $B^*$ rest frame, and the angle with the $B^*$ flight direction is taken. From the resulting angular distribution it can be concluded that the contribution of longitudinal states to the total is $0.32 \pm 0.04 \pm 0.03$, see figure 1. This is consistent with the expected number of twice as many transverse states as longitudinal states: $\sigma_L/(\sigma_L + \sigma_T) = 1/3$, corresponding to an equal population of the $B^*$ spin states. All results are summarized in table 1.
Figure 1: Photon helicity distribution. The acceptance corrected data are represented by points. The solid line displays the result of a fit to longitudinal and transverse contributions, shown by the dotted and dashed curves respectively. The data are consistent with equal population of the three polarization states of the $B^*$ vector meson.

Table 1: Summary of the $B^* \rightarrow B\gamma$ results. The ratio $\sigma_{B^*}/\sigma_B$ was derived with the assumption of 10 ± 4% beauty baryon production.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>$\Delta M(B^* - B)$</td>
<td>$45.5 \pm 0.3 \pm 0.8 \text{ MeV}/c^2$</td>
</tr>
<tr>
<td>$</td>
<td>\Delta M(B^{\ast\ast} - B^+) - \Delta M(B^{*0} - B^0)</td>
</tr>
<tr>
<td>$\Delta M(B_s^* - B_s)$</td>
<td>$46.1 \pm 1.5 \pm 1.3 \text{ MeV}/c^2$</td>
</tr>
<tr>
<td>$N(B^*)$</td>
<td>$3009 \pm 108 \pm 65$</td>
</tr>
<tr>
<td>$N_{B^*}/Z_{had}$</td>
<td>$0.28 \pm 0.01 \pm 0.03$</td>
</tr>
<tr>
<td>$\sigma_{B^*}/\sigma_B$</td>
<td>$0.72 \pm 0.03 \pm 0.06$</td>
</tr>
<tr>
<td>$V/(V+P)$</td>
<td>$0.75 \pm 0.10$</td>
</tr>
<tr>
<td>$\sigma_l/\sigma_{l+s}$</td>
<td>$0.32 \pm 0.04 \pm 0.03$</td>
</tr>
<tr>
<td>mean fractional $B^*$ energy $&lt;x_E&gt;$</td>
<td>$0.695 \pm 0.009 \pm 0.013$</td>
</tr>
</tbody>
</table>
There are four \( L = 1 \) orbitally excited \( B \) meson states:

\[
\begin{align*}
    j_q &= 3/2: \quad J^P = 1^+, 2^+ = B_1, B_2^* \\
    j_q &= 1/2: \quad J^P = 0^+, 1^+
\end{align*}
\]

The sum \( j_q \) of the light quark spin and the orbital excitation, divides the states into two doublets.

The total meson spin is indicated by \( J \):

\[
\begin{align*}
    \text{Light quark spin:} & \quad j_q = L + s_q = 1 \pm \frac{1}{2} \\
    \text{Total spin:} & \quad J = j_q + s_q
\end{align*}
\]

The \( j_q = 3/2 \) states have been observed as narrow resonances in the charmed meson system, and are named \( D_1 \) and \( D_2^* \). The mass splitting between these states is small. The \( j_q = 1/2 \) resonances have not yet been observed, but are predicted by theory to have much broader widths. The observations in the charmed meson system have led to HQET predictions for the masses and widths of orbitally excited \( j_q = 3/2 \) states in the \( B \) meson system: \( B_1 \) and \( B_2^* \), and broader \( j_q = 1/2 \) resonances [3].

Orbitally excited \( B \) mesons are reconstructed through their decays into a \( B \) or \( B^* \) meson and a charged pion: \( B^{**} \rightarrow B^{(*)}\pi \). The \( B \) or \( B^* \) mesons are inclusively reconstructed following the same algorithm as used in the \( B^* \rightarrow B\gamma \) analysis described in the previous section. No distinction is made between a decay to \( B \) or \( B^* \). Because the \( B^{**} \) decay strongly, the pions must come from the primary vertex. This fact is used to reduce combinatoric background. The accurate reconstruction of hits in the vertex detector allows an iterative algorithm to assign the charged tracks in an event to a primary vertex and two secondary \( B \) vertices. These vertices being determined, the pion is required to belong to the primary vertex, and in addition the separation between \( B \) vertex and primary vertex must exceed 1.5 \( mm \).

The quantity \( Q_{B^{**}} \) indicates the mass difference between the \( B^{**} \) and its decay products and is experimentally directly accessible:

\[
Q_{B^{**}} = m(B^{(*)}\pi) - m(B^{(*)}) - m(\pi)
\]

Figure 2(b) shows the \( B^{**} \) peak in the mass difference distribution at \( 284 \pm 5 \pm 15 \ MeV/c^2 \) [5].

The peak has a Gaussian spread of \( 79 \pm 5 \pm 8 \ MeV/c^2 \) and contains \( 2157 \pm 120 \pm 323 \) events. The results are summarized in table 2. Decays to a \( B^* \) meson produce 45 \( MeV/c^2 \) lower \( Q_{B^{**}} \) values than decays to a \( B \) meson. To obtain a value of the \( B^{**} \) mass from the measured \( Q \) value, a ratio between decays to \( B^* \) and \( B \) mesons of 2 \pm 1 is assumed. The \( B^{**} \) mass is then determined to be \( 5732 \pm 5 \pm 20 \ MeV/c^2 \), which agrees well with the predicted masses for \( B_1 \) and \( B_2^* \).
Figure 2: (a) Q-value distributions for $B\gamma$ (left) and $B^{(*)}\pi$ pairs (right), with the Monte Carlo expectations without $B^*$ or $B^{**}$ production superimposed. (b) The background subtracted distributions.

The observed signal width of 145 $MeV/c^2$ is significantly broader than the experimental resolution in $Q_{B^{**}}$ of 38 $MeV/c^2$. This allows a qualitative distinction between the different contributions. The observed shape of the signal is consistent with the theoretical prediction of four excited $B$ meson states, with narrow and broad contributions, and small mass splittings. Any explanation using only narrow resonances is ruled out by the data.

The observed decay $B^{***} \rightarrow B^{(*)0}\pi^+$ provides a new way to tag the flavor of a $B^0$ meson, since a positively charged pion indicates the presence of a $\bar{b}$ quark at production time. Traditional methods use the flavor of the co-produced beauty quark in the opposite hemisphere to determine the flavor of the neutral $B$ meson at its production time. Adding the self-tagging method to the traditional tagging methods could lead to an increase in statistics for future measurements of time-dependent mixing and CP violation in the $B^0$ system. A positively charged pion does not *always* signal a $\bar{b}$ quark in the same hemisphere, since also the $\bar{B}\rightarrow B^{(*)}-\pi^+$ decay can produce a positively charged pion. However, these decays result in a charged $B$ meson, and have no effect on exclusive measurements in the neutral $B$ system.
Table 2: Absolute value, width and experimental resolution, of the measured mass difference \( Q_{B^{**}} \). Also shown are the derived production rate, the derived \( B_{ud}^{**} \) mass difference and the predicted theoretical values.

| \( Q_{B^{**}} \) & \( \Delta M(B^{**} - B^{(*)} - \pi) \) & \( 284 \pm 5 \pm 15 \ MeV/c^2 \)  \\
| & \( \sigma(Q_{B^{**}}) \) & \( 79 \pm 5 \pm 8 \ MeV/c^2 \)  \\
| & full width \( \Gamma \) & \( 145 \pm 28 \ MeV/c^2 \)  \\
| & experimental resolution in \( Q \) & \( 38 \ MeV/c^2 \)  \\
| & number of events & \( 2157 \pm 120 \pm 323 \)  \\

Assuming \( N(B^*\pi^+)/N(B\pi^0) = 2 \):

\[
BR(b \to B^{**}X) = 0.27 \pm 0.02 \pm 0.06
\]

Assuming \( N(B^*\pi)/N(B\pi) = 2 \pm 1 \):

\[
m(B^{**}) = 5732 \pm 5 \pm 20 \ MeV/c^2
\]

measured:

\[
M(B_{ud}^{**}) - M(B_{ud}) = 453 \pm 5 \pm 20 \ MeV/c^2
\]

predicted [3]:

\[
M(B_2^*) - M(B) = 488
\]

\[
M(B_4) - M(B) = 476
\]

4 \( B_s \) mesons

Only recently have experiments at LEP and at the Tevatron reconstructed \( B_s \) mesons exclusively through decays such as \( B_s \to J/\psi \phi \). Unfortunately only a handful of events can be reconstructed in such a way. To obtain more statistics the DELPHI analyses are concentrating on several inclusive decay modes [6,7].

The inclusive decay \( B_s \to D_sX \) is a logical candidate, since more than 80% of the \( B_s \) mesons are expected to decay into a \( D_s \) meson. The \( D_s \) mesons are reconstructed through their decays into \( \phi \pi \) or \( K^{0*}K \). This results in a high statistics sample, with relatively high combinatoric background that contains almost equal amounts of \( B_s \) and other \( B \) meson decays into \( D_sX \). Unfortunately, only the \( D_s \) vertex position is determined and the \( B_s \) vertex remains to be estimated. Another reconstruction mode offering high statistics is the semileptonic decay into a \( \phi \)–lepton pair, which has similar combinatoric background and purity. The purest sample is selected through the semi–leptonic decay of the \( B_s \) meson into \( D_s l \nu \), where the high \( p_T \)–lepton and the \( D_s \) must have opposite sign.

The results on the \( B_s \) lifetime are summarized in table 3. All three channels use the 1991, 1992 and 1993 data except for the \( \phi \)–lepton signal where only the 1991 data are used.

Statistics in the \( B_s \to D_s l \nu \) channel is still too low to allow for a time–dependent oscillation measurement. Current studies therefore investigate the possibility of dropping the requirement of an identified lepton. In that case decays into \( D_s \pi X \) and \( D_s K X \) are added which would increase statistics by a factor four, while keeping the
Table 3: Measurement of the average $B_s$ lifetime, using three inclusive reconstruction modes.

<table>
<thead>
<tr>
<th>decay channel</th>
<th>lifetime (ps)</th>
<th>number of signal events</th>
<th>S/B ratio</th>
<th>$B_s$ purity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s \to D_s^{*}X$</td>
<td>$1.56^{+0.38}_{-0.32} \pm 0.23$</td>
<td>206 ± 26</td>
<td>0.5</td>
<td>60 %</td>
</tr>
<tr>
<td>$B_s \to \phi l X$</td>
<td>$1.18^{+0.44}_{-0.36} \pm 0.15$</td>
<td>31 ± 8</td>
<td>0.5</td>
<td>60 %</td>
</tr>
<tr>
<td>$B_s \to D_s l X$</td>
<td>$1.32^{+0.41}_{-0.32} \pm 0.18$</td>
<td>37 ± 8</td>
<td>1.5</td>
<td>90 %</td>
</tr>
<tr>
<td>combined result</td>
<td>$1.42^{+0.25}_{-0.23} \pm 0.14$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The combinatoric background at a low level. The same kinematic cuts can be used as for the lepton, and the exact $B_s$ vertex can be determined. This is called the $D_s^*T$ reconstruction mode, where the $T$ track is chosen to be the highest momentum track of opposite charge to the $D_s$ forming a $D_s^*T$ invariant mass of more than 3 GeV/c$^2$, and having a momentum of at least 2 GeV/c. The $D_s^*T$ reconstruction mode includes both semileptonic $B_s$ decays and exclusive decays such as $B_s \to D_s \pi$.

The $B_s$ oscillation frequency is expected to be much higher than the $B_b$ oscillation frequency. It is therefore much more difficult to observe, and has so far not been measured. Lower limits on the $B_s$ oscillation frequency are important because an unexpectedly low mass difference between the $B_s$ mass eigenstates would signal physics beyond the Standard Model. Statistics is the main limitation for measurements of faster oscillation frequencies when using the semi–exclusive reconstruction modes described in this section.

5 Beauty baryons

Within the quark model there are four possible combinations for beauty baryons, if the contribution from charm quarks is neglected. The electroweakly decaying ground states of these beauty baryons are:

the $\Lambda_b^0$ (bud), the $\Xi_b^0$ (bsu), the $\Xi_b^-$ (bsd), and the $\Omega_b^-$ (bss)

Until now, only the $\Lambda_b^0$ has been observed directly. The $\Xi_b$ baryons are produced by an order of magnitude less, the $\Omega_b$ are even more rare.

Recently, DELPHI has added the analysis of two new decay channels to the inclusive study of $b$ baryon production [9], and has shown evidence for the production of $\Xi_b$ baryons, including a lifetime measurement [10]. The results are summarized in table 4. The first three channels are expected to be dominated by $\Lambda_b$ decays, the fourth channel by $\Xi_b$ decays. A schematic of the $\Lambda_b$ decay chain is shown in figure 3. All channels make use of a high $p_T$ lepton, this primary lepton is oppositely charged to the proton charge. Electrons are included in the first two channels to determine the $b$–baryon production rate, but are left out in lifetime measurements. The second column of the table gives the production frequency per $b$-jet of the specific
Table 4: Measurement of the average beauty baryon lifetimes. The first three inclusive reconstruction modes are expected to be dominated by $\Lambda_b$ decays. The fourth reconstruction mode has allowed the first observation, and an initial lifetime measurement of the $\Xi_b$ baryon.

<table>
<thead>
<tr>
<th>decay channel</th>
<th>production rate per $b$-jet (%)</th>
<th>$b$ baryon lifetime (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda_b \rightarrow \Lambda l^- X$</td>
<td>$0.29 \pm 0.06^{+0.05}_{-0.04}$</td>
<td>$1.13^{+0.30}_{-0.23} \pm 0.05$</td>
</tr>
<tr>
<td>$\Lambda_b \rightarrow \Lambda_c l^- X$</td>
<td>$1.09 \pm 0.26^{+0.35}_{-0.17}$</td>
<td>$1.32^{+0.71}_{-0.42} \pm 0.08$</td>
</tr>
<tr>
<td>$\Lambda_b \rightarrow \mu^- p^+ X$</td>
<td>$0.42^{+0.10+0.17}_{-0.09-0.07}$</td>
<td>$1.13^{+0.35}_{-0.29} \pm 0.09$</td>
</tr>
<tr>
<td>all three channels combined</td>
<td></td>
<td>$1.21^{+0.21}_{-0.18} \pm 0.04$</td>
</tr>
<tr>
<td>$\Xi_b \rightarrow \Xi^- l^- X$</td>
<td>$0.059 \pm 0.021 \pm 0.010$</td>
<td>$1.5^{+0.7}_{-0.4} \pm 0.3$</td>
</tr>
</tbody>
</table>

Figure 3: Schematic of the $\Lambda_b$ decay chain, illustrating the concept used in analyses (1) and (2) of the table.
decay signatures for one lepton channel, assuming equal contributions of muons and electrons.

The first channel studies the inclusive semi-leptonic decay to a $\Lambda$–lepton pair where the $\Lambda$ baryons are reconstructed through their decay into an oppositely charged proton–pion pair. This decay channel has been used in an earlier analysis [8]. Since the $\Lambda$ baryons decay in the tracking chambers after travelling a considerable distance, the event signature of the first decay channel is quite different to the other channels. This feature makes the signal relatively easy to identify, but complicates the reconstruction of the $b$–baryon vertex. To solve this problem an extra pion (oppositely charged to the lepton) is used to reconstruct the $b$–baryon vertex for the lifetime measurement.

In the second channel the $\Lambda_c$ is reconstructed exclusively through the most abundant decay mode $\Lambda_c \rightarrow pK\pi$, which unfortunately does not profit from favorable kinematical features. Particle identification provided by the Ring Imaging Cherenkov detector and supported by the dE/dx measurement is therefore of prime importance. Exclusive reconstruction of the $\Lambda_c$ represents a step up in the $\Lambda_b$ decay chain. Such a step can only be made when enough statistics is available, because the reconstruction efficiency is low. However, this loss is repaid by a very pure sample of $b$–baryon decays.

Particle identification becomes even more crucial in the inclusive proton–muon decay channel, where the high-momentum proton must be positively identified by the RICH. This reconstruction mode aims to detect decays such as $\Lambda_b \rightarrow pD\mu\nu$, where both muon and proton come directly from the $\Lambda_b$ decay vertex. Proton/kaon separation is essential for this channel. The RICH provides this separation in the relevant momentum region from 8.5 to 30 GeV/c, making this analysis unique for the DELPHI detector.

The $b$–baryon lifetime measurements of the first three channels use data samples of respectively 63, 28 and 47 events. The resulting combined lifetime of $1.21^{+0.21}_{-0.18} \pm 0.04$, as shown in the table, is 1.5 sigma below the average $B$ lifetime of 1.52 ps. This is in qualitative agreement with theory, which predicts the beauty baryon lifetime to be approximately 1.35 ps. The production rates for each individual channel have also been calculated, but it remains difficult to extrapolate to the production rate of $\Lambda_b$ baryons per $b$–jet since the intervening branching ratio’s are largely unknown. As a result the error on the production rate remains large: $b \rightarrow \Lambda_b = 10 \pm 4 \%$.

The fourth channel shows evidence for the production of $\Xi_b$ baryons from an excess in the number of same-sign $\Xi$–lepton pairs, see figure 4. This is checked against Monte Carlo data containing no $b$–baryon production at all. In this data $\Xi$ – lepton pairs can only be produced through various fragmentation processes, charm and $B$ meson decays. These processes contribute approximately equally to the number of same-sign and opposite-sign pairs. Note that a small contribution to the number of same-sign pairs is also expected from $\Lambda_b \rightarrow \Lambda_c l \rightarrow \Xi l$ decays.

The $\Xi$ baryons are reconstructed through their decays into $\Lambda\pi$ where the $\Lambda$ decays
into a proton-pion pair. In most cases only the decay products are reconstructed. In addition to this method an extra, pure sample is obtained by using a new technique called Hyperon Tracking. This technique identifies unassociated track fragments in the vertex detector as $\Xi$ tracks. Ten candidates selected by this new method were used to measure the $\Xi_b$ lifetime, resulting in $\tau = 1.5^{+0.7}_{-0.4} \pm 0.3 \, \text{ps}$. Currently, the systematic error is dominated by Monte Carlo statistics.

The $b \to \Xi^- l^-$ production rate is measured to be $(5.9 \pm 2.1 \pm 1.0) \times 10^{-4}$. Again, the intervening branching ratios are largely unknown. However, reasonable assumptions lead to a production rate $b \to \Xi_b$ of $3.3 \pm 1.2 \pm 0.6 \%$, which is a factor three higher than the predicted Monte Carlo rate of $1 \%$.

Conclusions

The production of $B^*$ vector mesons was found to be in agreement with spin counting and has provided an accurate measurement of the $B^*-B$ mass difference. A considerable production of orbitally excited $B^{**}$ mesons is observed with mass splittings that are in agreement with Heavy Quark Effective Theory and the prediction of four $L=1$ states with narrow and broad resonances.

The large number of collected events has yielded significant measurements of the $B_s$ meson and beauty baryon lifetimes, including a first measurement of the $\Xi_b$ lifetime. More precise measurements of the beauty baryon lifetime are considered very important, since the current world average is much lower than the expected theoretical value. Theory predicts the beauty baryon lifetime to be approximately ten percent lower than the $B$ meson lifetime and the $B_s$ meson lifetime to be almost equal to the $B_d$ lifetime. Although the beauty baryon lifetime is still low, the new DELPHI measurements are in agreement with the theoretical predictions.

As statistics and detector performance increase there is a general trend towards more and more exclusive reconstruction. Particle identification plays an important
role in this process. The recent large data sample taken with the RICH in 1994 and in the current year promise to deliver even more precise beauty hadron results in the near future.

Acknowledgements

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9. The DELPHI Collaboration, P. Abreu et al., "Lifetime and production rate of beauty baryons from Z^0 decays", to be submitted to Z. Phys. C.
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