REVIEW OF b-FLAVORED HADRON SPECTROSCOPY

G. Eigen

Department of Physics, University of Bergen, Allegaten 55, 5007 Bergen, Norway

The current status of b-flavored hadron spectroscopy is reviewed.

1 Introduction

B-flavored hadrons are the heaviest flavored hadrons, since due to $V_{tb} \sim 1$ the top quark decays long before forming bound states. They are copiously produced in $p\bar{p}$ collisions at the Tevatron and in $Z^0$ decays at LEP. Each LEP experiment has collected $8.8 \times 10^5 b\bar{b}$ events. The formation of B-mesons versus b-baryons at the $Z^0$ is favored by 9:1. The heavy quark ($Q$) also dresses favorably with light quarks produced in soft gluon processes. This leads to production rates of $B_u^+ : B_d^0 : B_s^0 = 1 : 1 : \frac{1}{3}$. $B_c$ production is reduced by $2 - 3$ orders of magnitude, since a hard gluon process is needed.

The properties of heavy-light systems ($Qq$ or $QQq$) are predicted by heavy quark effective theory (HQET), which is based on the observation that in the limit $m_Q \to \infty$ the heavy quark decouples from the light degrees of freedom. The heavy quark symmetry provides a good approximation for b hadrons since $m_b \gg \Lambda_{QCD}$ and corrections obtained from a $\frac{1}{m_b}$ expansion are small. In the heavy quark limit, also the spin of the heavy quark, $s_Q$, decouples from the orbital angular momentum of the system, $l$, and the spin of the light quark(s) $s_q$. Both $s_Q$ and $j = l \oplus s_q$ are separately conserved. Thus, states are grouped into doublets bearing similar properties. The $B$ and $B^*$ belong to the same doublet. The $l = 0$ orbital excitations, frequently called $B^{**}$'s, fall into two doublets. The $j = \frac{3}{2}$ states which include the scalar $B_0^*$ and the axial vector $B_1^*$ are broad decaying dominantly via S-wave to $B\pi$ and $B^*\pi$, respectively. The $j = \frac{1}{2}$ states which include the axial vector $B_1$ and the tensor $B_2^*$ are narrow. Their dominant decays proceed via D-wave to $B^*\pi$ and $B^{(*)}\pi$, respectively. At the $Z^0$ the production of $l = 0$ B-mesons versus $l = 1$ B-mesons is favored by 7:3. According to spin counting 75% of the $l = 0$ B-states are $B^*$'s. The $B^{**}$'s decay strongly to $B^*$'s or $B$'s with a ratio ranging between 1 : 1 and 3 : 1. Thus, B-mesons are the best laboratory to test HQET predictions.

The crucial experimental tool for b-hadron spectroscopy is inclusive b hadron reconstruction. For $b\bar{b}$ events selected via impact parameter tagging or via high $p_t$ muons, energy and momentum of the b-hadron are reconstructed, using either a rapidity algorithm (ALEPH, DELPHI) or secondary vertex...
reconstruction (OPAL). For events consistent with a b-hadron the Q-value defined by $Q_{BX} = m_{BX} - m_B - m_X$ is determined. For the majority of events in the final sample DELPHI e.g. achieves an energy resolution of $\sigma_E/E = 7\%$ and angular resolutions of $\sigma_\phi \simeq \sigma_\theta \simeq 15 \text{ mr.}$

## 2 Status of Pseudoscalar and Vector B Mesons

The $B^+$ and $B^0$ masses have been measured rather precisely by CLEO, ARGUS and CDF. The fits performed by the PDG yield: $m_{B^+} = 5278.9 \pm 1.8 \text{ MeV}$ and $m_{B^0} = 5279.2 \pm 1.8 \text{ MeV}$. The errors are dominated by a systematic uncertainty in determining the $e^+ e^-$ energy scale. The $B^0$ is heavier than the $B^+$ as expected. However, the observed mass difference of $m_{B^0} - m_{B^+} = 0.35 \pm 0.29$ is consistent with zero. The $B^0_s$ mass has been measured rather precisely by CDF in the $B_s^0 \rightarrow J/\psi \phi$ channel (see Figure 1). The present $B^0_s$ mass measurements are depicted in Figure 2. Including the LEP results, the PDG mass fit yields $m_{B^0_s} = 5369.3 \pm 2.0 \text{ MeV}$. This constrains the $B^0_s - B^0_s$ mass splitting to $90 \pm 2.7 \text{ MeV}$ which is consistent with a quenched lattice QCD prediction of $107 \pm 13 \text{ MeV}$. The $B_c$ meson is not yet observed. Searches have been conducted by all four LEP experiments and by CDF. The channels studied include $J/\psi \pi^+$, $J/\psi a_1^+$ and $J/\psi \ell \nu \ell$. Individual candidates are seen but are consistent with the expected background. The most serious candidate is reported by ALEPH in the $J/\psi \mu \nu \ell$ channel and has a mass of $m = 5.96 \pm 0.25 \pm 0.19 \text{ GeV}$.

![Figure 1. The $J/\psi \phi$ invariant mass spectrum observed by CDF.](image1)

![Figure 2. Summary of all $B^0_s$ mass measurements.](image2)
In the heavy quark expansion hyperfine splittings (HFS) are proportional to $1/m_Q$. Thus, the $B$ and $B^*$ are much closer spaced than the $D$ and $D^*$. A quenched lattice calculation e.g. yields $\Delta m_B^{HFS} := m_{B^*_{u,d}} - m_{B_{u,d}} = 34\pm 6$ MeV and $\Delta m_B^{HFS} := m_{B^*_c} - m_{B_c} = 27 \pm 17$ MeV. The small HFS permits only electromagnetic (EM) transitions, of which $B^* \rightarrow \gamma B$ is the dominant one. For $B^*$ reconstruction the low-energy photon needs to be detected. At LEP, however, the photon energy is boosted, maximally up to 800 MeV. L3 detects the photon directly in a crystal calorimeter, whereas the other LEP experiments reconstruct $e^+e^-$ conversions. Typical energy and angular resolutions are $\sigma_E/E = 1-2\%$ and $\sigma_{\theta,\phi} = 1-2$ mr, respectively.

Figure 3 shows the $Q_{B\gamma}$-value distribution measured by OPAL. Since the B-meson flavor is not identified, $\Delta m_B^{HFS}$ includes contributions from $B^{+0}_u$ and $B^{0}_d$. Figure 4 summarizes all $\Delta m_B^{HFS}$ measurements from LEP\cite{18,19,20,21} plus some old results from CLEO II\cite{22} and CUSB\cite{23}. The world average of the $B^* - B$ hyperfine splitting is $\Delta m_B^{HFS} = 45.79 \pm 0.35$ MeV. DELPHI\cite{20} also has set 95% CL limits on $B^* - B^0_d$ and $B^{+0}_{ud} - B^0_s$ HFS differences, yielding: 

|\Delta m^{HFS}_B - \Delta m^{HFS}_{B_d}| < 6$ MeV and $|\Delta m^{HFS}_B - \Delta m^{HFS}_{B_{ud}}| < 6$ MeV.

All LEP experiments have measured the relative $B^*$ production cross sec-
tion in $Z^0$ decays. Ignoring feed-down from $B^{**}$'s the LEP average is 
$$\frac{\sigma_{B^{**}}}{\sigma_{B^{**}} + \sigma_{B}} = 0.748 \pm 0.004.$$ This agrees with expectations from naive spin counting, since the adjustment due to feed-down from $B^{**}$'s is only a few % effect depending on assumptions made for $B^{**}$ decays. ALEPH, DELPHI, and OPAL also have measured the $B^*$ polarization. The observed helicity angle distribution is uniform, indicating that all helicity states are equally populated. The combined LEP result for the longitudinal helicity component is 
$$\frac{\sigma_L}{\sigma_T + \sigma_L} = 0.33 \pm 0.04.
$$

Though the M1 transition is nearly 100%, higher order EM transitions like the $B^*$ Dalitz decays should also occur. The branching fraction independent of a form factor model is expected to be $B(B^* \rightarrow Be^+e^-) \simeq 0.466\%$. Since the $e^+$ and $e^-$ momenta are below 100 MeV, electron identification and tracking in the vertex detector are essential. DELPHI has combined Dalitz pairs originating from the primary vertex with a B candidate. The resulting $Q_{Be^+e^-}$ distribution plotted in Figure 5 shows a peak at the expected $\Delta m_{HFS}$ value.

The $B^*$ Dalitz decay rate normalized to that of the M1 transition is measured to be: 
$$\Gamma(B^* \rightarrow Be^+e^-)/\Gamma(B^* \rightarrow B\gamma) = (4.7 \pm 1.1 \pm 0.9) \times 10^{-3}.$$

3 Status of Orbitally-Excited B-Mesons

HQET predicts two narrow and two broad $B^{**}$ states similarly as in the $D^{**}$ system. Using the heavy quark expansion Eichten, Hill and Quigg determine the masses and total widths of the two $j = \frac{3}{2}$ $B^{**}$ states to be 
$m_{B_{1}} = 5759$ MeV, $m_{B_{2}} = 5771$ MeV, $\Gamma_{B_{1}} = 21$ MeV and $\Gamma_{B_{2}} = 25$ MeV, respectively. A recent calculation by Falk and Mehen based on the heavy flavor expansion yields masses of $m_{B_{1}} = 5780$ MeV and $m_{B_{2}} = 5794$ MeV. The masses of the $j = \frac{1}{2}$ states are expected to lie about 100 MeV lower than those of the $j = \frac{3}{2}$ states.

ALEPH, DELPHI, and OPAL have analyzed single $\pi^+$ transitions using inclusive B reconstruction methods. The Q-value distribution measured by DELPHI is plotted in Figure 6. A broad structure is observed at $m = 5734 \pm 5 \pm 17$ MeV. A decomposition into individual $j = \frac{1}{2}$ and $j = \frac{3}{2}$ states is presently not conclusive. Similar observations have been found by the other LEP experiments. A summary of all mass measurements is shown in Figure 7. Note that the masses from OPAL and ALEPH shown here have been shifted up by 31 MeV to account for dominant contributions from $B^*\pi$ transitions. The combined LEP result for the $B_{u,d}^{**}$ mass is $m(B_{u,d}^{**}) = 5722 \pm 8$ MeV. This is lower than the mass predictions for $j = \frac{3}{2}$ states, thus leaving room for various scenarios for $B^{**}$ production and decay.

\textsuperscript{a}We have assumed that $B^*\pi$ versus $B\pi$ transitions are enhanced by $2 \pm 1 : 1$, by considering various scenarios for $B^{**}$ production and decay.\textsuperscript{a}
for contributions from the $j = \frac{3}{2}$ states. ALEPH, in addition, has performed an exclusive analysis in the $B\pi$ channel. A significant narrow structure is seen at $m = 5703 \pm 14$ MeV. The resolution of $\sigma = 28\pm18$ MeV would permit contributions from both $j = \frac{3}{2}$ states. However, even after the +31 MeV shift, the mass is still too low to agree with a DELPHI measurement obtained in the $B^{(*)}\pi\pi$ final state (see below).

The decay angle distribution of the $\pi$ in the $B^{(*)}$ rest frame provides information on the helicity distribution of the light quark system. DELPHI has observed a uniform decay angle distribution, which implies that the maximally allowed helicity components of the light quark system are not suppressed. This is surprising since ARGUS has observed the opposite for $D_2^*$ decays. Assuming that the contribution of decays from the $j = \frac{3}{2}$ states, which produce a non-uniform decay angle distribution, is small, a fraction of $w_\frac{3}{2} = 0.53 \pm 0.07 \pm 0.10$ is measured for the helicity $j = \pm \frac{3}{2}$ components.

The masses predicted by Eichten, Hill and Quigg for the narrow $B_s^{(*)}$ states are $m_{B_{s1}} = 5849$ MeV and $m_{B_{s2}} = 5861$ MeV. Predictions by Falk and Mehen

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$b$ The S-wave decays $B_0^{*+} \to B\pi$ and $B_1^{*+} \to B^{*}\pi$ are expected to be dominant.
are again higher, yielding $m_{B_{s1}} = 5886 \text{ MeV}$ and $m_{B_{s2}^{*}} = 5899 \text{ MeV}$. Since the $B_{s}^{**} - B_{u,d}$ mass difference is larger than the kaon mass, the dominant transitions are $B_{s}^{**} \rightarrow KB_{u,d}$.

Using the inclusive analysis techniques DELPHI has studied $B^{(*)}K^{\pm}$ final states. DELPHI is rather suited for analyzing such channels because of their excellent kaon identification over a wide momentum range. The resulting $Q$-value distribution depicted in Figure 8 shows two narrow structures at $70 \pm 4 \pm 8 \text{ MeV}$ and $142 \pm 4 \pm 8 \text{ MeV}$. Their widths are slightly smaller than the observed resolution. Assuming that the upper peak stems from the transition $B_{s1} \rightarrow B^{*}K$ and the lower peak stems from $B_{s2}^{*} \rightarrow BK$, masses of $m_{B_{s1}} = 5888 \pm 4 \pm 8 \text{ MeV}$ and $m_{B_{s2}^{*}} = 5914 \pm 4 \pm 8 \text{ MeV}$ have been obtained. The mass splitting is $m_{B_{s2}^{*}} - m_{B_{s1}} = 26 \pm 6 \pm 8 \text{ MeV}$. Both the masses and the splitting are higher than the HQET predictions. In addition, upper limits have been set on the widths, yielding $\Gamma_{B_{s1}} < 60 \text{ MeV}$ and $\Gamma_{B_{s2}^{*}} < 50 \text{ MeV}$ at 95% CL, respectively. The production cross sections for $B_{s1}$ and $B_{s2}^{*}$ states with respect to that of $B_{u,d}^{**}$ has been measured to be: $(\sigma_{B_{s1}} + \sigma_{B_{s2}^{*}})/\sigma_{B_{u,d}^{**}} = 0.142 \pm 0.028 \pm 0.047$. OPAL has also studied this channel, observing a $\Gamma = 47 \text{ MeV}$ broad structure at $m = 5853 \pm 15 \text{ MeV}$, which again needs to be shifted upward by $\sim 31 \text{ MeV}$ to account for dominant $B^{*}K$ transitions.

**B^{**} Mass Measurements**

|        | Mass (MeV) |
|--------|------------|
| OPAL   | 5712 \pm 11 |
| DELPHI | 5734 \pm 5 \pm 17 |
| ALEPH  | 5734 \pm 3 \pm 16 |
| World average | 5722 \pm 8 |

*Figure 7. Summary of all inclusive $B^{**}$ mass measurements.*

**Figure 8. The $Q$-value distribution for $BK^{\pm}$ final states.*
4 First Observation of Radially Excited B Mesons

Radial excitations of D mesons and B mesons should exist similarly as those of $cc$ and $bb$ states. A QCD inspired relativistic quark model predicts the masses of the 2S pseudoscalar and vector states to lie at 5900 MeV and 5930 MeV, respectively. DELPHI has extended the inclusive analysis to $\pi^+\pi^-$ transitions to look for such states. For $bb$ events with a $\pi^+\pi^-$ pair from the primary vertex where both pions have large rapidities ($\eta > 2.5$) and are in the same hemisphere as the B candidate, the variable, $Q_{B\pi\pi} = m_{B(\pi^+)\pi^-} - m_{B(\pi)} - 2m_{\pi^\pm}$, was determined. This selection is 52 ± 3% efficient and has a purity of 80 ± 4%. The resulting Q-value distribution displayed in Figure 9 shows two narrow structures, one at $Q_{B(\pi^+)\pi^-} = 301 \pm 4 \pm 10$ MeV containing 56 ± 13 events and a second at $Q_{B(\pi^+)\pi^-} = 220 \pm 4 \pm 10$ MeV containing 60 ± 12 events. The corresponding measured resolutions, $\sigma = 12 \pm 3$ MeV and $\sigma = 15 \pm 3$ MeV, are compatible with the detector resolution, implying that their natural widths must be narrow. Thus, the two broad states, $j = \frac{3}{2}$ orbital excitations cannot contribute significantly here.

Figure 10 shows all allowed transitions for the 2S states and 1P states. The non-suppressed $\pi$ and $\pi\pi$ transitions of the narrow $j = \frac{3}{2}$ P states are: $B_1 \to B^* \pi$ (D-wave), $B_1 \to B \pi\pi$ & $B_1 \to B^*\pi\pi$ (P-wave); $B_2^* \to B\pi$ & $B_2^* \to B^*\pi$ (D-wave), and $B_2^* \to B^*\pi\pi$ (P-wave). The corresponding transitions of the 2S states are: $B' \to B^*\pi$ (P-wave), $B' \to B_b^*\pi$ & $B' \to B\pi\pi$ (S-wave); $B'' \to B\pi$ & $B'' \to B^*\pi$ (P-wave), and $B'' \to B_b\pi$ & $B'' \to B^*\pi\pi$ (S-wave). $\rho$ transitions are suppressed by phase space. Since the mass resolution is smaller than $\Delta m_B^HFS$, we can exclude that a single excited state decays to $B\pi\pi$ and $B^*\pi\pi$ simultaneously. In that case two peaks separated by $\Delta m_B^HFS$ should have been visible. It is, however, possible that the two peaks originate from two closely spaced excited states, where the heavier decays to $B^*\pi\pi$ and the lighter to $B\pi\pi$.

The lower peak most likely stems from the P-wave transitions, $B_1 \to B\pi^+\pi^-$ with a possible contribution from $B_2^* \to \pi^+\pi^- B^*$. Denoting the mass splitting of the $j = \frac{3}{2}$ states by $\Delta m_{B_{3/2}} := m_{B_2^*} - m_{B_1}$ and the fraction of $B_2^*$ decays by $f$, we can parametrize the masses of the narrow states by: $m_{B_1} = 5778 + f \cdot (\Delta m_B^HFS - \Delta m_{B_{3/2}}) \pm 11$ MeV and $m_{B_2^*} = 5824 - (1 - f) \cdot (\Delta m_B^HFS - \Delta m_{B_{3/2}}) \pm 11$ MeV. These mass estimates are consistent with the heavy quark predictions for $j = \frac{3}{2}$ states, but they are higher than the mass of the broad structure observed in Figure 6. This implies that $j = \frac{1}{2}$ states contribute significantly there. Assuming that $0 \leq \Delta m_{B_{1/2}} \leq \Delta m_B^HFS$ as in the D-system, we can set bounds of $m_{B_1} > 5756$ MeV and $m_{B_2^*} < 5846$ MeV @95% CL, which are in conflict with the exclusive $B(\pi)\pi$ ALEPH result.
The upper peak has to originate from states which lie ≥ 80 MeV above the $B_1$. The most likely interpretation is that this peak stems from $\pi\pi$ transitions of the 2S radial excitations: $B' \rightarrow B\pi\pi$ and $B^{*'} \rightarrow B^*\pi\pi$. The S-wave $\pi\pi$ transitions are expected to be dominant, though two successive $\pi$ transition via the broad $j = \frac{1}{2}$ orbital excitations are kinematically allowed. However, more detailed studies are needed to clarify this issue. Though single $\pi$ transitions $B^{(*)'} \rightarrow B^{(*)}\pi$ are allowed, they should be suppressed because of nodes in the radial wave functions, which lead to cancelations in the overlap integral. Such cancelations have been observed in $\rho \rightarrow \pi\pi$ and $\psi(4040) \rightarrow D\bar{D}$ decays. Nevertheless, the observed Q-value distribution for $B^{(*)}\pi$ final states actually has room for such transitions. Assuming that the production of $B^{*'}$ to $B'$ is similar to that of $B^*$ to $B$, we obtain the following mass estimates for the 2S states: $m_{B'} = 5859 + \frac{2}{3}(\Delta m_{B}^{HFS} - \Delta m_{B'}^{HFS}) \pm 12$ MeV and $m_{B^{*'}} = 5905 - \frac{1}{3}(\Delta m_{B}^{HFS} - \Delta m_{B'}^{HFS}) \pm 12$ MeV. Here $\Delta m_{B}^{HFS}$ denotes the HFS of the radially excited states. These values are consistent with predictions from a QCD inspired relativistic quark model, thus supporting the interpretation of observing 2S radial excitations. A preliminary estimate of the production cross sections from the observed signal yield is: $\sigma(b \rightarrow B' + B^{*'})/\sigma(b \rightarrow all) = 0.5\% - 4\%$. The branching ratio for $B_1 \rightarrow B\pi\pi$ is of the order of $2\% - 10\%$.
5 Status of b Baryons

The Λ_b is clearly established since a recent CDF measurement in the Λ_J/ψ channel. The Λ_J/ψ invariant mass peaks at \( m_{Λ_b} = 5621 \pm 4 \pm 3 \) MeV. Previously, ALEPH and DELPHI had observed a few candidates in the Λ_b±π∓ channel. All mass measurements are summarized in Figure 11. The present world average for the Λ_b mass is \( m_{Λ_b} = 5624 \pm 9 \) MeV.

| Λ_b | Mass Measurements |
|-----|-------------------|
| ALEPH | 5614±21±4 |
| DELPHI | 5668±16±8 |
| CDF | 5621±4±3 |
| World average | 5624±9 |

Figure 11. Summary of Λ_b mass measurements.

Figure 12. The Q-value distribution for Λ_b±π± final states.

Using the heavy quark expansion in combination with the observed Σ_b±π± HFS provides a prediction for the Σ_b±π± HFS of \( \Delta m^HFS_{Σ_b} = 22 \) MeV. DELPHI has looked for b-flavored baryons using the inclusive analysis techniques. Baryon enrichment is obtained by selecting fast p's, n's and Λ's. For events consistent with a Λ_b, a pion from the primary vertex is added to determine the variable \( Q_{Λ_bπ} = m_{Λ_bπ} - m_{Λ_b} - m_π \). The resulting distribution depicted in Figure 12 reveals two structures at \( Q_{Λ_bπ} = 33 \pm 3 \pm 8 \) MeV and \( Q_{Λ_bπ} = 89 \pm 3 \pm 8 \) MeV. Interpreting these as transitions from the Σ_b and Σ_b±, mass differences of \( m_{Σ_b} - m_{Λ_b} = 173 \pm 3 \pm 8 \) MeV and \( m_{Σ_b±} - m_{Λ_b} = 229 \pm 3 \pm 8 \) MeV are determined. Within errors they are consistent with quark model predictions yielding \( m_{Σ_b} - m_{Λ_b} = 200 \pm 20 \) MeV and \( m_{Σ_b±} - m_{Λ_b} = 230 \pm 20 \) MeV,
respectively. The measured HFS of $\Delta m_{HFS}^{\Sigma_b} = 56 \pm 15$ MeV is in conflict with HQET predictions\cite{14}. This measurement needs to be checked, since presently it cannot be ruled out that either a transition from a different state is seen or that for one of the structures the observed mass is shifted due to contributions from another transition. It is worthwhile to note that the lower peak is narrower than the higher peak. This is supportive for a more complex interpretation. To clarify this issue DELPHI plans to redo the analysis with reprocessed data, which show significant improvements in track reconstructions and thus achieve improved efficiencies and momentum resolutions.

Assuming that the two peaks stem from $\pi$ transitions of the $\Sigma_b$ and $\Sigma_b^*$, DELPHI measures a relative production cross section of $(\sigma_{\Sigma_b} + \sigma_{\Sigma_b^*})/\sigma(b \to all) = 4.8 \pm 0.6 \pm 1.5\%$. The fraction originating from $\Sigma$ baryons is $24 \pm 6 \pm 10\%$.

DELPHI has also measured the helicity angle distribution of the $\pi$ in the $\Sigma_b^*$ rest frame. A fit to the Falk Peskin model\cite{15} yields $w_1 = 0.36 \pm 0.30 \pm 0.030$ for the helicity $h = \pm 1$ component of the light quark system, indicating that these states are suppressed. According to Falk and Peskin\cite{15} large $\Sigma_b$ and $\Sigma_b^*$ rates in combination with a suppression of helicity $\pm 1$ states lead to a substantial reduction of the $\Lambda_b$ polarization in $Z^0$ decays. This has in fact been observed by ALEPH\cite{16} measuring $P(\Lambda_b) = -0.26^{+0.25}_{-0.18}$.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig13}
\caption{Observed B-mesons masses and transitions.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig14}
\caption{b-baryon states and transitions. Observed states are shown by solid lines.}
\end{figure}
6 Summary

The knowledge of the B meson sector has improved over the past few years. The present status is summarized in Figure 13. Precisely measured masses exist for all pseudoscalar and vector B meson ground states except for those in the $B_c$ system, which has not been detected yet. Evidence is found for orbital excitations, but only in the $B_0^s$ system it was possible to isolate two separate narrow states. Cross section measurements agree with expectations and decay angle distributions indicate that helicity $j = \pm \frac{3}{2}$ states are not suppressed. While presently there is no evidence for orbital excitations with $L > 1$, first evidence is found for the $2S$ $B_{u,d}$ radial excitations.

States and transitions in the b-baryon sector are summarized in Figure 14. The knowledge is still rather poor here. Only the $\Lambda_b$ is well-established. The $\Sigma_b$ and $\Sigma^*_b$ may be observed but the HFS is in conflict with HQET predictions. Thus, these measurements need confirmation. The mass of the $\Xi_b$ is unknown, though its lifetime has been measured. So far no other b-flavored baryon has been identified.

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