Spectroscopy of b and c Hadrons at LEP

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This article is a review of the LEP results on bottom and charm spectrocopy from the running period at the Z pole. Some emphasis is put on the most recent updates.

1. Introduction

The Heavy Quark Symmetry (HQS) [1] is a powerful aid to understand the spectrum and decays of mesons and baryons containing a single heavy quark Q. One essential result in the heavy quark limit ($M_Q >> \Lambda_{QCD}$) is the decoupling of the heavy quark spin from the total angular momentum of the light degrees of freedom: $\vec{s}_Q$ and $\vec{j}_q = \vec{s}_q + \vec{L}$ turn out to be conserved independently.

The corrections to the HQS can be calculated in the Heavy Quark Effective Theory (HQET) and give rise to effects of the order Λ_{QCD}/M_Q and $\alpha_s(M_Q)/\pi$, therefore the HQS predictions are expected to work better in B than in D system.

In the case of L=1 orbitally excited B mesons containing either a u or a d quark, the HQS predicts four states indicated with B_J^* (B_{sJ}^* if the light quark is replaced by a s quark). Such states are classified in terms of their spin and parity $J^P = 0^+,\ 1^+,\ 1^+,\ 2^+$, and are expected to respect a relative production rate 1:3:3:5, according to the spin counting rule [2]. They form two doublets characterised by the total angular momentum of the light quark q.

Although all eight $\mathrm{B}_J^* \rightarrow \mathrm{B}^{(*)}\pi\pi$ transitions are theoretically allowed, they are expected to be phase-space suppressed. To conserve parity and angular momentum in two-body $\mathrm{B}_J^* \rightarrow \mathrm{B}^{(*)}\pi$ decays, the restriction shown in Figure 1 apply: the $j_q = 1/2$ states can decay via an S-wave transition and their decay widths are expected to be broad in comparison to those of the $j_q = 3/2$ states which must decay via a D-wave transition.

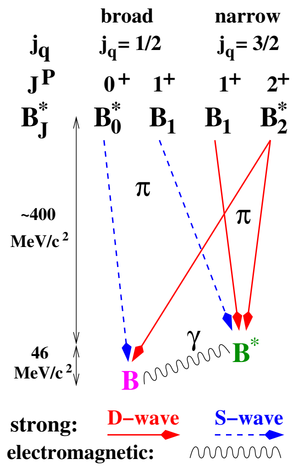

Figure 1. The five allowed two-body decays for B_J^* states.

2. Phenomenology of L=0 B meson states

The mass difference between the pseudo-scalar B mesons and their hyperfine partners, the vector B^* mesons, is less than 50 MeV/c^2, and therefore B^* mesons decay to B via emission of a low energy photon. At LEP, the observation of B^* has been possible using inclusively reconstructed bottom hadron candidates combined with a photon measured in a high resolution crystal calorimeter (L3) [4] or identified by its e^+e^- conversions pair in the material of the beam pipe or detector (ALEPH,DELPHI,OPAL) [5]. Large signals are observed, which are mixtures of B^{*0}, B^{*-} and B^{*0}_s. The LEP averages for the fraction of vector meson production and for the mass splitting $M_{\mathrm{B}^*} - M_{\mathrm{B}}$ are extracted:

$$\begin{aligned} \sigma_{\mathrm{B}^*}/(\sigma_{\mathrm{B}^*} + \sigma_{\mathrm{B}}) &= 0.75 \pm 0.04, \\ M_{\mathrm{B}^*} - M_{\mathrm{B}} &= 45.7\,\mathrm{MeV}/c^2. \end{aligned}$$

Such results are in agreement with simple spin counting and with the HQET prediction $(M_{\mathrm{B}^*} - M_{\mathrm{B}})/(M_{\mathrm{D}^*} - M_{\mathrm{D}}) \simeq M_c/M_b$.

DELPHI preliminary results on B* Dalitz decays [6] turn out to be consistent with QED expectations, the measured branching ratio being

$$\frac{\Gamma(\mathrm{B}^* \to \mathrm{B}e^+e^-)}{\Gamma(\mathrm{B}^* \to \mathrm{B}\gamma)} = (4.8 \pm 0.9 \pm 0.9) \times 10^{-3}.$$

3. Inclusive studies of the B_J^* resonance

All the 4 LEP collaborations perform inclusive studies of the B_J^* resonance, applying common experimental methods which may differ just in minor details:

- a beauty-enhanced sample of hadronic events is selected applying a lifetime based event tag;
- the B meson candidates are reconstructed in an inclusive way: their 4-momentum is estimated using the kinematical informations from the secondary vertex and from the tracks with large rapidity with respect to the B-jet axis;
- the pion candidate from the strong B_J^* decay is identified as the primary vertex charged track with the largest component of momentum along the B direction.

Evidence for production of L=1 orbitally excited B mesons has been reported in 1995 by OPAL, DELPHI and ALEPH collaborations [7]. The B_J^* signal is observed as a peak in the Bπ invariant mass distribution, with a typical mass resolution of 50 MeV. No attempt is made to disentangle the structure of the B_J^* resonance. After background subtraction, single bump fits are applied which give the following results:

$$\begin{aligned} \text{OPAL} \quad M_{\mathrm{B}_J^*} &= 5681 \pm 11\,\mathrm{MeV}, \\ f_{\mathrm{B}_J^*} &= 0.270 \pm 0.056. \\ \text{DELPHI} \quad M_{\mathrm{B}_J^*} &= 5734 \pm 5 \pm 17\,\mathrm{MeV}, \\ f_{\mathrm{B}_J^*} &= 0.32 \pm 0.018 \pm 0.06. \\ \text{ALEPH} \quad M_{\mathrm{B}_J^*} &= 5703 \pm 4 \pm 10\,\mathrm{MeV}, \\ f_{\mathrm{B}_J^*} &= 0.279 \pm 0.016 \pm 0.059. \end{aligned}$$

Where isospin symmetry is assumed to account for B_J^* decays via neutral pions.

Applying some experimental methods very similar with respect to those described above, OPAL gets a clear evidence for B_{sJ}^* production, observed as a peak in the B$K^\pm$ invariant mass distribution: $M_{\mathrm{B}_{sJ}^*} = 5853 \pm 15$.

3.1. The B_J^* structure

In the analysis published by L3 [8], the Bπ mass spectrum peak in the region $5.6 - 5.8$ GeV (Figure 2) is interpreted as the result of $\mathrm{B}_J^* \to \mathrm{B}^{(*)}\pi$ decays, where B_J^* denotes a mixture of $L = 1$ spin states. According to spin-parity conservation, one expects mass peaks from the five possible channels sketched in the Figure 1. No attempt is made to tag subsequent $\mathrm{B}^* \to \mathrm{B}\gamma$ decays, as the efficiency for selecting the soft photon is low. As a consequence, the Bπ mass distribution is fitted with five Voigt functions, accounting for effects due to detector resolution. The background is

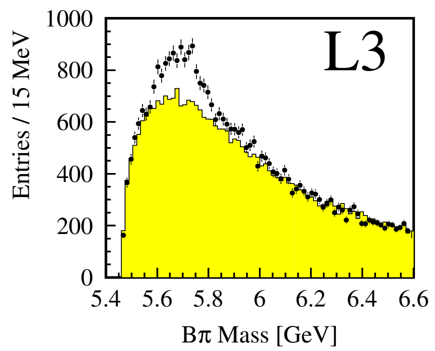

Figure 2. Mass spectrum for selected Bπ pairs. The dots are the L3 data and the histogram represents the expected background.

estimated from a large Monte Carlo sample of B meson candidates. Additional physical constraints are applied (see Table 1), relying on predictions common to existing HQET models which are based on the phenomenology of orbitally excited D mesons states. The resulting fits give:

State	Frac.	Mass	Width
B_0^*	1/12	$M_{B_1(\frac{1}{2})} - 12$ MeV	$\Gamma_{B_1(\frac{1}{2})}$
$B_1(\frac{1}{2})$	3/12	free	free
$B_1(\frac{3}{2})$	3/12	$M_{B_2^*} - 12$ MeV	$\Gamma_{B_2^*}$
B_2^*	5/12	free	free

Table 1
Constraints used in the L3 fit.

$$
\begin{aligned}
M_{B_1(\frac{1}{2})} &= (5670 \pm 10 \pm 13)\ \text{MeV}, \\
\Gamma_{B_1(\frac{1}{2})} &= (70 \pm 21 \pm 25)\ \text{MeV}, \\
M_{B_2^*} &= (5768 \pm 5 \pm 6)\ \text{MeV}, \\
\Gamma_{B_2^*} &= (24 \pm 19 \pm 24)\ \text{MeV}.
\end{aligned}
$$

The number of events in the signal region corresponds to a branching fraction $f_{B_J^*} = \text{BR}(b \rightarrow B_J^*)/\text{BR}(b \rightarrow B) = 0.32 \pm 0.03 \pm 0.06$.

3.2. An indirect evidence of radially excited B meson states

Quark models based on Quantum Chromodynamics predict the existence of radially excited 2S $B^{'}$ and $B^{*'}$ states in the region $5.9 - 6.0$ GeV. In the L3 $B\pi$ mass spectrum, a slight excess of events is observed in this mass region, which could be the result of the decay $B^{'} \rightarrow B^{(*)}\pi$. To account for the possible existence of these states in the mass spectrum, the data have been refitted including a Gaussian function in the region of interest. The $B^{'}$ mass, Gaussian width and branching fraction are found to be

$$
\begin{aligned}
M_{B^{'}} &= (5937 \pm 21 \pm 4)\ \text{MeV}, \\
\sigma_{B^{'}} &= (50 \pm 22 \pm 5)\ \text{MeV}, \\
f_{B^{'}} &= 0.034 \pm 0.011 \pm 0.008.
\end{aligned}
$$

3.3. The B_J^* decays

In order to disentangle $B_J^* \rightarrow B^*\pi$ from $B_J^* \rightarrow B\pi$, OPAL[9] uses the information of the photon in the decay $B^* \rightarrow B\gamma$. For each B meson candidate, a probability weight is assigned to come from a B^* decay. The selected B^* candidates are used to obtain complementary subsamples enriched or depleted in the inclusive decay $B_J^* \rightarrow B^*\pi X$. Where X refere to decay modes with or without additional accompanying decay particles. From the multiplicities of such subsamples, the model-independent result for the inclusive B_J^* decays into $B^*\pi$ is found to be $\text{BR}(B_J^* \rightarrow B^*\pi X) = 0.85^{+0.26}_{-0.27} \pm 0.12$, in agreement with theoretical predictions [10].

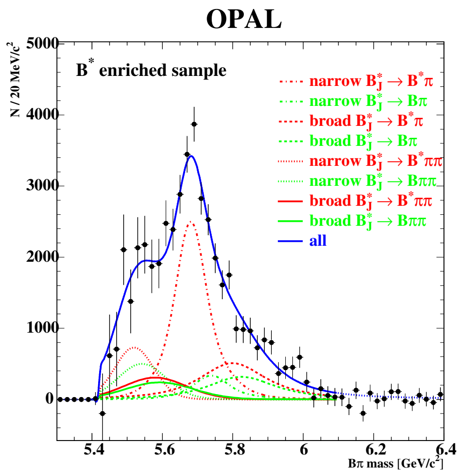

Figure 3. $B\pi$ mass distribution after background subtraction and efficiency correction for OPAL $B_J^* \rightarrow B^*\pi X$ enriched data. The fit results of the decays of the broad and narrow resonances for transitions via one and two pions are presented separately.

In the framework of HQS, a simultaneous fit to the Bπ background-subtracted and efficiency-corrected mass spectra of the $B_J^* \to B^*\pi X$ enriched (Figure 3) and $B_J^* \to B^*\pi X$ depleted subsamples yields the mass and the width of the $B_1(\frac{1}{2})$ and B_2^* mesons as well as the branching ratio of B_J^* mesons decaying into $B^*\pi$ and $B^{(*)}\pi\pi$:

$$\begin{aligned}
M_{B_1(\frac{1}{2})} &= (5851 \pm 40)\ \text{MeV}, \\
\Gamma_{B_1(\frac{1}{2})} &= (129 \pm 68)\ \text{MeV}, \\
M_{B_2^*} &= (5758 \pm 9)\ \text{MeV}, \\
\Gamma_{B_2^*} &= (18 \pm 30)\ \text{MeV}, \\
\text{BR}(B_J^* \to B^*\pi) &= 0.74 \pm 0.21, \\
\text{BR}(B_J^* \to B^{(*)}\pi\pi) &= 0.33 \pm 0.15.
\end{aligned}$$

The constraints applied in this fit are similar to those of the L3 analysis (Table 1), apart from the hyperfine split of the narrow resonances which is assumed to be 20 MeV.

4. An exclusive study of the B_J^* resonance

Only ALEPH collaboration performs an exclusive study of the B_J^* resonance [11], based on samples of B mesons reconstructed in the following decay modes:

- $B \to D^{(*)}\ \pi^\pm(\rho^\pm, a_1^\pm)$
- $B \to J/\psi(\psi')\ K^\pm(K^0)$

The selection gives 238 charged and 166 neutral B meson candidates. In order to reconstruct the B_J^* states, the B mesons are combined with a charged pion coming from the primary vertex. The achieved mass resolution is better than 5 MeV. An excess of 45±13 events in the right-sign combinations is observed above the expected background estimated from wrong sign combinations. Figure 4 shows a fit to the right-sign mass spectrum where the signal shape consists of five Breit-Wigner functions. However, because of the limited statistics only the mass of the B_2^* state and the relative production rate of the B_J^* system are left free in the fit, the fine and hyperfine splittings being fixed to their theoretical values

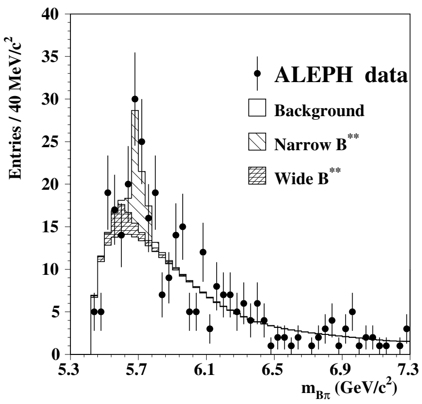

Figure 4. Bπ mass distribution after background subtraction with fit results for ALEPH.

predicted by HQS. The results of the fit are:

$$\begin{aligned}
M_{B_2^*} &= 5739\ ^{+8}_{-11}\ ^{+6}_{-4}\,\text{MeV}, \\
f_{B_J^*} &= 0.31 \pm 0.09\ ^{+0.06}_{-0.05}.
\end{aligned}$$

5. Conclusions on B_J^*

The four LEP experiments have provided clear evidence for the existence of orbitally excited B mesons.

The L3 results [8] provide the first measurements of the masses and decay widths of the $B_1(\frac{1}{2})$ and B_2^* mesons. They disfavour recent theoretical models proposing spin-orbit inversion [12,13], but agree well with earlier models [10,14]. Indirect evidence is obtained for the existence of an excited B meson state (or mixture of states) in the region $5.9 - 6.0\,\text{GeV}$

The OPAL results [9] provide the first measurement of the branching ratio for the decay $B_J^* \to B^{(*)}\pi X$. The broad resonances are found to be heavier with respect to the narrow ones, confirming spin-orbit inversion, in agreement with recent theoretical models and in contrast with L3 results. B_J^* transitions containing two pions are observed, while no B' state is seen. However, also ALEPH [11] result on B_2^* is in agreement with recent theoretical models [12,13].

LEP results on B_J^* provide support for HQS, nevertheless further cross checks would be needed in order to clarify the controversial phenomenological results on spin orbit inversion, $B^{'}$ production and $B_J^* \to B^{(*)}\pi\pi$ decays.

6. Search for radially excited D meson states

The 2S pseudo-scalar and vector D meson states are referred to as the $D^{'}$ and $D^{*'}$ respectively and their masses are predicted to be $M_{D'} = 2579\,\mathrm{MeV}/c^2$ and $M_{D^{*'}} = 2629\,\mathrm{MeV}/c^2$ [13], with an uncertainty of the order of $20\,\mathrm{MeV}/c^2$.

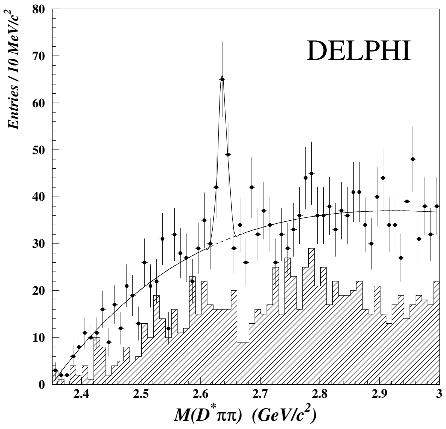

Figure 5. Invariant mass distributions for $D^{*+}\pi^+\pi^-$ (dots) and $D^{*+}\pi^-\pi^-$ (hatched histogram). The full curve is a fit which includes a background parameterisation (dashed curve alone) and a Gaussian function.

An excess of $N = 66 \pm 14$ events in the $D^{*+}\pi^-\pi^+$ mass spectrum (Figure 5) has been reported by DELPHI [15], which is compatible with the production of a narrow resonance with mass $M = 2637 \pm 2 \pm 6\,\mathrm{MeV}$, identified as the $D^{*'}$ state. The corresponding production rate is

$$
\begin{aligned}
R &= \frac{N_{D^{*'+} \to D^{*+}\pi^+\pi^-}}{N_{D_1^0 \to D^{*+}\pi^-} + N_{D_2^{*0} \to D^{*+}\pi^-}} \\
&= 0.49 \pm 0.18(\mathrm{stat.}) \pm 0.10(\mathrm{syst.})
\end{aligned}
$$

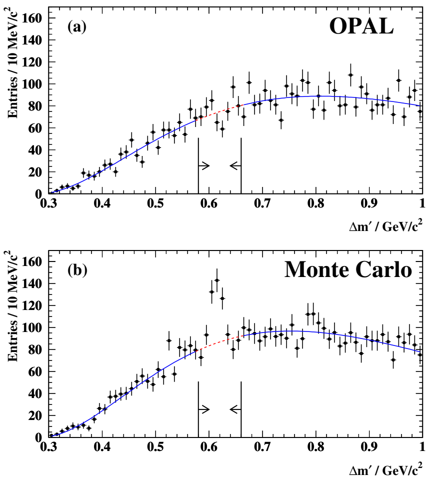

Figure 6. Distribution of the mass difference $\Delta_{m'} = M_{D^{*'}} - M_{D^*}$ of $D^{*'}$ candidates for (a) OPAL data and (b) Monte Carlo, where the $D^{*'}$ production rate has been fixed at the value published by DELPHI. The arrows indicate the mass window defined as the signal region. The line represents the result of the background fit. The line is dashed in regions that have been excluded from the fit.

A similar analysis brings no confirmation of the narrow $D^{*'}$ resonance in the OPAL data [16]. In order to improve the mass resolution, the mass difference $\Delta_{m'} = M_{D^{*'}} - M_{D^*}$ is calculated for the $D^{*'} \to D^{*+}\pi^-\pi^+$ candidates. No narrow resonance is observed anywhere in the $\Delta_{m'}$ distribution between 0.3 and 1.0 GeV/c^2 (Figure 6a), although the Monte Carlo simulation with a $D^{*'}$ production rate fixed at the value published by DELPHI shows a clear signal (Figure 6b). A limit on the production of a narrow $D^{*'}$ resonance is derived: $R < 0.22$ @ 95 C.L.

7. Spectroscopy of orbitally excited D meson states

Several studies on D orbitally excited states have been published by the LEP collaborations [3]. Here only the most recent ALEPH results on D_{s1}^{+} and D_{s2}^{+} production [17] are reported. The narrow states are fully reconstructed in the following decay modes: $D_{s1}^{+} \rightarrow D^{*+}K_s^0$, $D_{s1}^{+} \rightarrow D^{*0}K^{+}$, $D_{s2}^{*+} \rightarrow D^0K^{+}$. The corresponding mass difference distributions for like-sign and wrong-sign combinations are shown in Figure 7. The background shapes are extracted from wrong-sign combinations. The signal is fitted with a Breit-Wigner function convoluted with the Gaussian detector resolution.

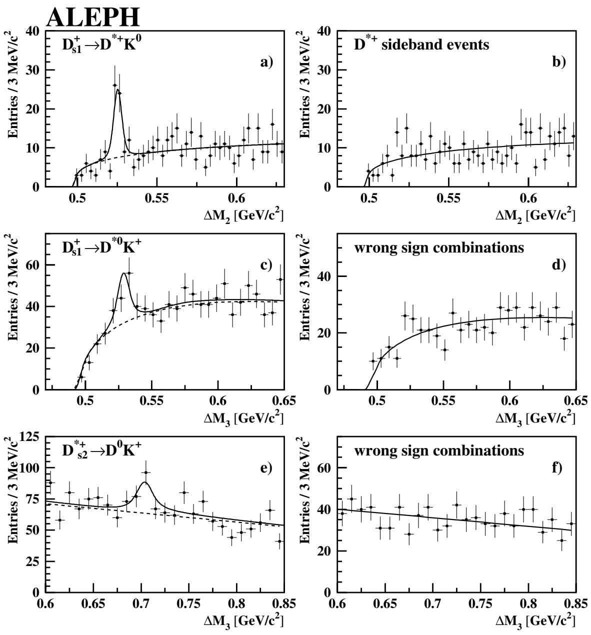

Figure 7. Reconstructed mass difference distribution for the decays $D_{s1}^{+} \rightarrow D^{*+}K_s^0$ (a and b), $D_{s1}^{+} \rightarrow D^{*0}K^{+}$ (c and d), $D_{s2}^{*+} \rightarrow D^0K^{+}$ (e and f). The solid lines show the results of the fit and the dashed lines show the combinatorial background.

The production rate of the $D_{s1}^{\pm}$ is measured to be $BR(Z \rightarrow D_{s1}^{\pm}X) = (0.49 \pm 0.09 \pm 0.06) \times 10^{-2}$, assuming that the two considered decay modes of the D_{s1}^{+} saturate the branching ratio. The production rate of the $D_{s2}^{\pm}$ is determined to be $BR(Z \rightarrow D_{s2}^{\pm}X) = (0.77 \pm 0.26 \ ^{+0.07}_{-0.13}) \times 10^{-2}$, assuming that the partial width of the decay $D_{s2}^{*+} \rightarrow D^0K^{+}$ is 45%.

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