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B, D SPECTROSCOPY AND $\overline{B} \to D/D^*/D^{**}\ell\overline{\nu}$

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Abstract

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1 Introduction

At LEP and Fermilab, the energy of charm and beauty hadrons and their relatively long lifetimes allow the measurement of secondary decay vertices or impact parameters by using efficient silicon microstrip devices. B-tagging algorithms have been tuned at LEP and provide high purity $b\bar{b}$ events with high efficiency. Z^0 decays and $p\bar{p}$ collisions can thus contribute to charm physics and extend b-hadron spectroscopy in a mass range which is not accessible at Υ_{4S} energies.

2 D** spectroscopy

For $(Q\bar{q})$ mesons containing heavy and light quarks and in the limit where the heavy quark mass is much larger than the typical QCD scale ($m_Q >> \Lambda_{QCD}$), the spin $\vec{s}_Q$ of the heavy quark and the the total (spin+orbital) angular momentum $\vec{j_q} = \vec{s}_q + \vec{L}$ of the light component are separately conserved. Heavy quark symmetry, together with the knowledge of lower mass mesons, allow to predict the mass and decay widths of heavy mesons[1] of total spin $\vec{J} = \vec{s}_Q + \vec{j}_q$.

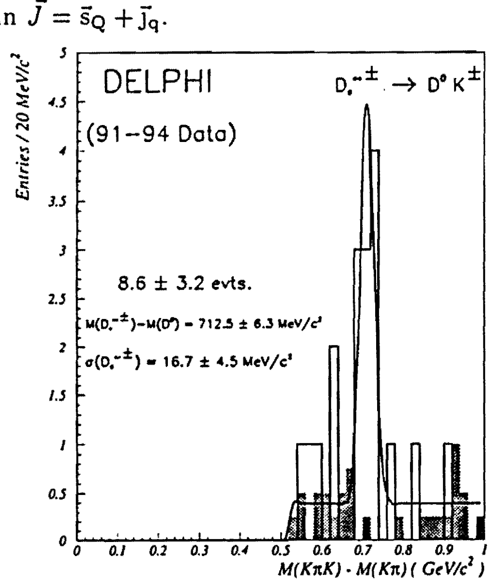

Figure 1: $M(D^0K^+)$-$M(D^0)$ with $D^0 \to K^-\pi^+$ in DELPHI (all tracks are identified in the RICH).

The L=0 states of D and D* and of $B_{u,d,s}$ mesons are well identified. For ($c\bar{s}$) charmed mesons, the isospin-violating decay $D_s^{*+} \to D_s^+\pi^0$ is observed by CLEO[2]: its rate relative to the dominant radiative decay mode $\Gamma(D_s^{*+} \to D_s^+\pi^0)/\Gamma(D_s^{*+} \to D_s^+\gamma) = 0.062^{+0.020}_{-0.018} \pm 0.022$ favours a 1^- spin-parity assignment for the D_s^{*+}.

Table 1: L=1 D mesons ($j_q = 1/2$ states are estimated[3], 3/2 states are measured[4−7]) and predictions for B mesons[1,9].

	J^P j_q	Mass (MeV/c^2)	Width (MeV/c^2)	Main decay modes
D_0^*	0^+ 1/2	~ 2360	≥ 170	$D\pi$
D_1^*	1^+ 1/2	~ 2420	≥ 250	$D^*\pi$
D_1^0	1^+ 3/2	2422 ± 2	18 ± 4	$D^*\pi$ ($D\rho$)
D_1^+	1^+ 3/2	2425 ± 3	26 ± 9	$D^*\pi$ ($D\rho$)
D_2^{*0}	2^+ 3/2	2458 ± 2	23 ± 4	$D\pi$, $D^*\pi$
D_2^{*+}	2^+ 3/2	2457 ± 2	24 ± 6	$D\pi$, $D^*\pi$
D_{s1}^+	1^+ 3/2	2535	< 2.3	D^*K
D_{s2}^{*+}	2^+ 3/2	2573 ± 2	14 ± 5	DK
B_0^*	0^+ 1/2	~ 5650	broad	$B\pi$
B_1^*	1^+ 1/2	~ 5650	broad	$B^*\pi$
B_1	1^+ 3/2	~ 5759	~ 21	$B^*\pi$
B_2^*	2^+ 3/2	~ 5771	~ 25	$B\pi$, $B^*\pi$
B_{s1}^0	1^+ 3/2	~ 5849	~ 1	B^*K
B_{s2}^{*0}	2^+ 3/2	~ 5861	~ 4	BK, B^*K

Only the narrow orbital excitations (L=1, $j_q = 1/2$) of charmed mesons (hereafter named D_J) have been clearly observed. Wide states are expected but not seen yet (see Table 1). Orbitally excited (B^{**}) beauty mesons are foreseen to present a similar scheme.

Evidence for D_{s2}^{*+} in its decay into D^0K^+ was first published by CLEO[6]. It is now confirmed by ARGUS[7] ($M(\Gamma) = 2574.5 \pm 3.3 \pm 1.6$ ($10.4 \pm 8.3 \pm 3.0$) MeV/c^2) and also observed by DELPHI[8] in Z^0 decays (see Fig.1).

3 Semileptonic B decays with D* and D**

New measurements of the branching fraction $Br(\bar{B} \to D^*\ell^-\bar{\nu}$ are obtained in CLEO and LEP experiments[10−12] (for LEP data, the probability for a b quark to fragment into a $\bar{B}^0$ is estimated here to be $f_d = 0.39 \pm 0.02$). According to Table 2, it is clear that the contribution of direct D and D* explains only $(60 \pm 5)\%$ of all semileptonic B decays. The remaining part may be due to orbitally excited (L=1) D** production, higher (L> 1) resonant states or non-resonant $D^{(*)}\pi(\pi)$. The understanding

Table 2: Measured $Br(\bar{B} \to X/D/D^{*}\ell^{-}\bar{\nu})$ (averaging $\bar{B}^0$ and B^-).

$Br(B \to X\ell^{-}\bar{\nu})$ (%)[4]	10.43 ± 0.24
$Br(B \to D\ell^{-}\bar{\nu})$ (%)[4]	1.80 ± 0.41
$Br(B \to D^{*}\ell^{-}\bar{\nu})$ (%)	
PDG94[4]	4.47 ± 0.39
CLEO[10]	4.66 ± 0.43
ALEPH[11]	$5.08 \pm 0.29 \pm 0.57$
DELPHI[12]	$3.51 \pm 0.18 \pm 0.50$
LEP Average	4.34 ± 0.52
All Average	4.50 ± 0.25

Table 3: B semileptonic branching fractions into $D^{(*)}\pi X$ (%).

narrow D^{**}	ALEPH[14]	OPAL[13]
$B^- \to D_J^0(\to D^{*+}\pi^-)\ell^-\bar{\nu}$	0.60 ± 0.19	1.56 ± 0.47
$B^- \to D_2^{*0}(\to D^{+}\pi^-)\ell^-\bar{\nu}$	—	0.41 ± 0.20
$\bar{B}^0 \to D_J^+(\to D^{*0}\pi^+)\ell^-\bar{\nu}$	0.53 ± 0.19	1.79 ± 0.58
$\bar{B}^0 \to D_2^{*+}(\to D^{0}\pi^+)\ell^-\bar{\nu}$	< 0.20	1.08 ± 0.41
all D^{**}	ALEPH[14]	DELPHI[12]
$B^- \to D^{*+}\pi^-\ell^-\bar{\nu}X$	0.95 ± 0.31	0.96 ± 0.58
$\bar{B}^0 \to D^{(*)0}\pi^+\ell^-\bar{\nu}X$	1.66 ± 0.45	—

of semileptonic B decays is thus closely related to the knowledge of charmed meson excited states.

At LEP, the $\bar{B} \to D^{**}\ell^-\bar{\nu}$ decay vertex can be evaluated from the lepton, pion from $D^{**} \to D^{(*)}\pi$ (and pion from $D^{*+} \to D^0\pi$) and the reconstructed $D \to K^-(n)\pi$ meson. Lepton (and kaon) identification, kinematical cuts and vertex or impact parameter constraints allow D^{**} candidates to be selected.

The mass difference distribution $M(D^{(*)}\pi)$-$M(D^{(*)})$ measured in OPAL[13] indicates the production of both D_1 and D_2^* states. However only the D_1 resonance is observed in ALEPH in the $D^{*+}\pi^-$ or $D^{*0}\pi^+$ decay modes[14]. Assuming as above that $f_d = 0.39$, the measured branching fractions are given in Table 3. Further assumptions are necessary in order to correct for the unknown D_J branching fractions[13]. One can then infer that only about (31 ± 8)% of the missing semileptonic B decays are explained by the observed narrow D_J excited states.

In order to evaluate the contribution of all (narrow + wide + non-resonant) D^{**}, the impact parameter distributions of the pion from D^{**} relative to the primary interaction vertex or B decay vertex are considered. From Table 3, one infers that (33 ± 10)% of B^- and (59 ± 17)% of B^0 unidentified semileptonic decays are due to $D^{**} \to D^{(*)}\pi X$ transitions. These results agree with the ARGUS[4] value of $Br(\bar{B} \to D^{**}\ell^-\bar{\nu}) = (2.7 \pm 0.7)$% using $D^{*+}\ell^- X$ final states.

More data are needed in order to conclude if the D_2^* narrow state is present in semileptonic B decays, and if the wide (or non-resonant) states are necessary to understand the overall semileptonic B branching fraction.

4 B_s mass, B_c search and b-baryons

Based on the full 1992-1993 statistics (19.3 pb^{-1}), a significant improvement in the B_s mass determination has been achieved by CDF at Fermilab[18] (see Fig.2 and Table 4). Systematics in the tracking are reduced by using about 80000 reconstructed J/ψ. Signals from $B^- \to J/\psi K^-$ ($M(B^-) = 5279.1 \pm 1.7 \pm 1.4$ MeV/c^2) and $B^0 \to J/\psi K^*$ ($M(B^0) = 5281.3 \pm 2.2 \pm 1.4$ MeV/c^2) are in good agreement with CLEO[4].

The B_c meson is the last L=0 beauty meson to be discovered. Its mass should range around 6250 ± 50 MeV/c^2 with lifetime $\sim 0.5 - 1.4$ ps and 100 to 700 B_c / 10^6 Z^0_{had} are expected[19]. A search is performed by ALEPH in the decay channels $B_c^+ \to J/\psi\ \pi^+$ ($Br = (0.2 - 0.4)$%) and $J/\psi\ \ell^+\nu$ ($Br = (1-3)$%, ℓ =e or μ). No $J/\psi\pi^+$ but 2 $J/\psi\ell^+\nu$ candidates are observed, leading to the following 90% *c.l.* upper limits[19] : $Br(Z^0_{had} \to B_c X)\ Br(B_c \to J/\psi\ \pi^+) < 4.\ 10^{-5}$, $Br(Z^0_{had} \to B_c X)\ Br(B_c \to J/\psi\ \ell^+\nu) < 7.\ 10^{-5}$ which are a factor 14 and 4, respectively, above the most optimistic theoretical expectation.

Exclusive Λ_b decays into $\Lambda_c^+\pi^-$ allow to measure its mass[20] : preliminary results give 4 candidates in ALEPH ($M(\Lambda_b) = 5621 \pm 17 \pm 15$ MeV/c^2) and 3 in DELPHI ($M(\Lambda_b) = 5656 \pm 22 \pm 6$ MeV/c^2). The quoted values improve the PDG one[4] and agrees with the 5547-5660 MeV/c^2 expected mass range[21].

No exclusive candidate is observed yet in Ξ_b decay, but its semileptonic branching fraction is measured[22].

Table 4: Measurements of the B_s mass (MeV/c^2).

PDG94[4]	5375 ± 6	
ALEPH[15]	$5368.6 \pm 5.6 \pm 1.5$	1 $J/\psi\ \phi$, 1 $D_s^+\pi^-$
DELPHI[16]	$5374 \pm 16 \pm 2$	1 $\psi'\phi$, 2 $D_s(n)\pi$
OPAL[17]	$5367 \pm 15 \pm 7$	2 $J/\psi\ \phi$
CDF[18]	$5369.9 \pm 2.3 \pm 1.3$	32 ± 6 $J/\psi\ \phi$
New Average	5370 ± 2	

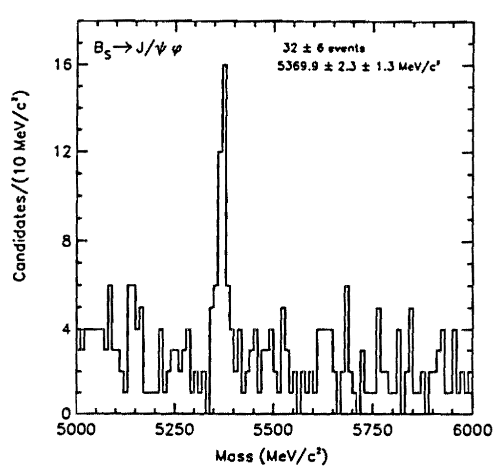

Figure 2: $J/\psi\ K^+K^-$ mass distribution from CDF.

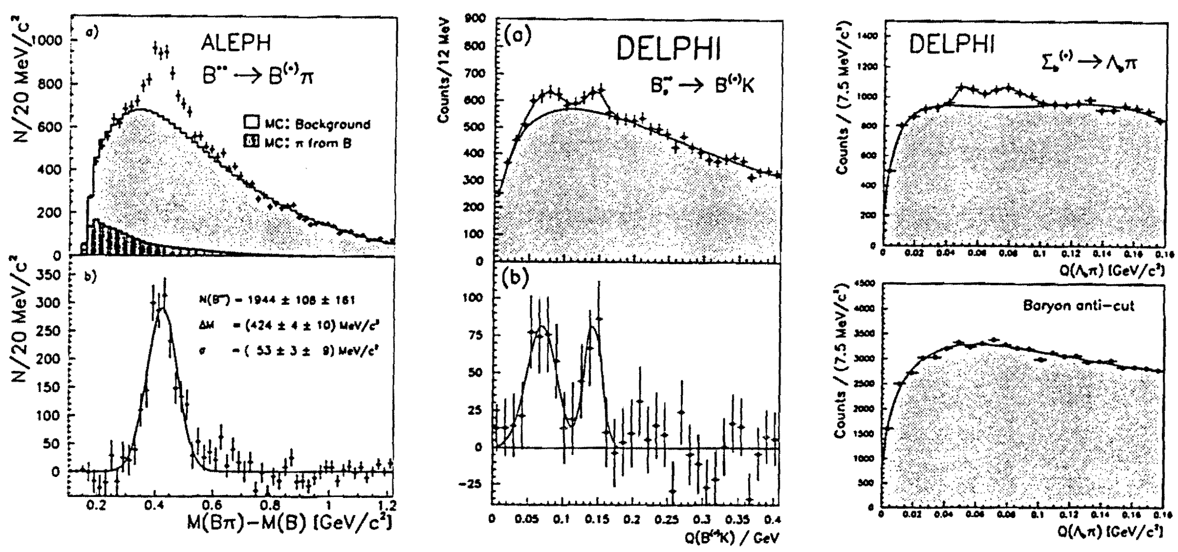

Figure 3: (left) $B^{(*)}\pi$-$B^{(*)}$, (middle) $B^{(*)}K$-$B^{(*)}$ mass differences and (right) Q value of $\Lambda_b\pi$ candidates.

5 Excited b-hadrons

Pure samples of $b\bar{b}$ events are provided by b-tagging techniques. The b-hadron direction and momentum is estimated from the jet axis and energy, optimized in DELPHI and ALEPH by selecting particles at large rapidity ($|y| > 1.6$) and in OPAL by using a secondary vertex algorithm. Above about 25 GeV, the B energy can be parameterized from the jet energy and mass according to the simulation with a typical resolution of 7-9% for 70% of the candidates. These partially reconstructed b-hadrons are then associated with another photon, pion or kaon candidate from the primary interaction point in order to search for b-excited states.

The B^* meson was first observed by CUSB and CLEO in e^+e^- collisions near the Υ_{4S} center-of-mass energy[4]. Due to the small mass difference of 46 MeV/c^2, all B^* decay into $B\gamma$. In $Z^0 \to b\bar{b}$ events, due to the hard b quark fragmentation, the photon energy is boosted up to 800 MeV with a mean value of 300 MeV. At LEP, the photon can thus be directly detected in the BGO calorimeter of L3 or after conversion in DELPHI and ALEPH down to 100-200 MeV energy. The LEP results on the $B^* - B$ mass difference are in good agreement with CUSB and CLEO (see Table 5). The isospin splitting is found to be[23] $|\Delta M(B^{*+} - B^+) - \Delta M(B^{*0} - B^0)| < 6.0$ MeV/c^2 (95% *c.l.*). The hyperfine splitting[23] $|\Delta M(B_s^* - B_s) - \Delta M(B_{u,d}^* - B_{u,d})| < 6.0$ MeV/c^2 (95% *c.l.*) agrees with CUSB[4]. The production ratio $B^*/(B^* + B)$ and the helicity components $\sigma_L/(\sigma_L + \sigma_T)$ agree with the simple spin counting expectations of 3/4 and 1/3, respectively.

Evidence for B^{**} decays into $B\pi$ has been clearly established at LEP. OPAL[26] tags the charge of the partially reconstructed B mesons. An excess of events is obtained when comparing opposite charge $B^\pm\pi^\mp$ and same charge $B^\pm\pi^\pm$ pairs. The mass difference distributions of OPAL, DELPHI[27,28] and ALEPH[25] (see Fig.3-left) reveal a broad enhancement of full width $\Gamma \simeq 120$ MeV/c^2. The estimated mass resolution is 35-40 MeV/c^2 in the B^{**} mass region, larger than the expected narrow states width (see Table 1). The signal can be explained by two narrow resonances or by a mixture of broad and narrow ones, a distinction is not yet possible. A better understanding of the combinatorial background behaviour below the peak is necessary before any further interpretation. Another way to look for B^{**} is to associate a primary pion with a fully reconstructed B meson. ALEPH[29] uses 470 exclusive B mesons, with an expected $B\pi$ mass resolution of only 4 MeV/c^2 : a narrow signal is indeed observed. Such an analysis may establish the viability of B-flavor tagging for the *CP* violation search at future colliders. Results are summarized in Table 6.

Replacing a pion with an identified kaon reveals $B_s^{**} \to B^{(*)}K$ decays. The OPAL[26] signal is inter-

Table 5: Results on $B^* \to B\gamma$.

Quantity	Experiment	Measurement
$\lvert\Delta M(B^* - B)\rvert$ (MeV/c^2)	L3[24]	$46.3 \pm 1.9(stat)$
	DELPHI[23]	$45.5 \pm 0.3 \pm 0.8$
	ALEPH[25]	$45.3 \pm 0.4 \pm 0.9$
	PDG94[4]	46.0 ± 0.6
	Average	45.8 ± 0.4
production ratio $B^*/(B^* + B)$	L3[24]	$0.74 \pm 0.04 \pm 0.06$
	DELPHI[23]	$0.72 \pm 0.03 \pm 0.06$
	ALEPH[25]	$0.77 \pm 0.03 \pm 0.07$
	Average	0.74 ± 0.04
helicity analysis $\sigma_L/(\sigma_L + \sigma_T)$	DELPHI[23]	$0.32 \pm 0.04 \pm 0.03$
	ALEPH[25]	$0.33 \pm 0.06 \pm 0.05$
	Average	0.32 ± 0.04

Table 6: Results on $B^{**} \to B\pi$. Masses are recalculated from mass differences or Q values using an upward shift by 31 MeV/c^2 in order to account for the average $B^{**} \to B^*$ contribution. Errors do not contain the uncertainty on this procedure (except DELPHI).

Quantity	Experiment	Measurement
$M(B^{**})$ (MeV/c^2)	OPAL[26]	$5712 \pm 11(stat)$
	DELPHI[27,28]	$5734 \pm 5 \pm 17$
	ALEPH[25]	$5734 \pm 4 \pm 10$
	ALEPH excl.[29]	$5734 \pm 14(stat)$
	Average	5732 ± 17
width σ (MeV/c^2)	DELPHI[27,28]	$72 \pm 5 \pm 8$
	ALEPH[25]	$53 \pm 3 \pm 9$
	ALEPH excl.[29]	$28^{+18}_{-14}(stat)$
ratio B^{**}_{ud}/B_{ud}	OPAL[26]	$(27 \pm 2 \pm 5)\%$
	DELPHI[27,28]	$(33 \pm 2 \pm 7)\%$
	ALEPH[25]	$(28 \pm 2 \pm 8)\%$
	ALEPH excl.[29]	$(30 \pm 8(stat))\%$

preted as a single resonance of mass (Γ width) 5884 ± 15 (47 ± 22) MeV/c^2, whereas DELPHI[28] fits two contributions (see Fig.3-middle), likely assigned to B_{s1} with mass (Γ) of $5888 \pm 4 \pm 8$ (< 60 at 95% *c.l.*) MeV/c^2 and B^*_{s2} with mass (Γ) of $5914 \pm 4 \pm 8$ (< 50 at 95% *c.l.*) MeV/c^2. Production rates are $\sigma(B_{sJ}) \cdot Br(B_{sJ} \to B^{(*)}K)/\sigma(b-\text{jet}) = (2.1 \pm 0.5 \pm 0.7)\%$ and $(1.6 \pm 0.5 \pm 0.7)\%$ ($J = 1, 2$), in agreement with OPAL. The masses are 40-50 MeV/c^2 above prediction (see Table 1).

Finally asking for an identified Λ or proton inside the b-jet gives the first evidence for $\Sigma_b^{(*)}$ (Fig.3-right from DELPHI preliminary[30]). About 900 $\Sigma_b^{(*)} \to \Lambda_b \pi$ are fitted with two enhancements interpreted as $M(\Sigma_b) - M(\Lambda_b) = 173 \pm 3 \pm 8$ MeV/c^2 and $M(\Sigma_b^*) - M(\Lambda_b) = 229 \pm 3 \pm 8$ MeV/c^2, in agreement with expectations[31]. The full widths are compatible with detector resolution, suggesting the intrinsic widths to be small. The multiplicity $\left\langle N(\Sigma_b + \Sigma_b^{(*)})\right\rangle_{b-\text{jet}} = (4.8 \pm 0.6 \pm 1.5)\%$ describes a large fraction of Λ_b produced in Z^0 decays.

6 Conclusion

Semileptonic B decays are still not completely explained by D^{**} transitions. A preliminary Λ_b mass and evidence for B^{**}_{ud}, B^{**}_s and (preliminary) $\Sigma_b^{(*)}$ were obtained at LEP. 1995 was a fruitful year for spectroscopy !

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