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B MESON SPECTROSCOPY* **

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A review of recent experimental progress in the B meson spectroscopy is given. The results concerning the masses, production rates at Z^0 energy and helicity of beauty mesons are presented and compared with theoretical predictions.

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1. Introduction

The mass of the beauty quark which is of the order of 5 GeV is much bigger than the typical scale of strong interactions Λ_{QCD} at which quarks are bound into hadrons. Thus inside the hadron the b-quark decouples from the light degrees of freedom of quarks and gluons. This gives rise to the symmetry in the flavour and spin of heavy quarks predicted by the Heavy Quark Effective Theory [1] (HQET). In particular the B mesons are expected to group into several doublets of similar quantum numbers with some analogy to the spectrum of hydrogen atom. The HQET gives numerical predictions concerning *e.g.* meson masses and rates of spectroscopic transitions between them.

In the last decade the beauty hadrons were studied in $p\bar{p}$ collisions and in e^+e^- annihilation. The b production in $p\bar{p}$ interactions is very copious but plagued by huge background. This was partially overcomed by silicon detector of the CDF collaboration allowing best result for B_s and B_c. In e^+e^- annihilation the B mesons were studied in two regions of the centre-of-mass energy. The lower one around 10 GeV corresponds to the mass of the family of Υ resonances where the B mesons are produced almost at rest. In this

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region lifetimes cannot be measured but due to high purity the measurements dominate the branching fraction of B_u and B_d mesons. In the second region covered by experiments working at LEP storage-ring, the centre-of-mass energy is very close to the mass of the intermediate boson Z^0 and energetic pairs of beauty quarks are produced every fifth hadronic collision to form well-collimated jets of observed particles. Under these conditions the samples enriched with $b\bar{b}$ quarks are obtained via impact parameter tagging [2, 3]. Four-momenta of b-hadrons are reconstructed with the help of either a rapidity algorithm (particles with rapidities above certain value, typically around 1.5, are considered to be the products of b-hadron's decay) developed by ALEPH [2] and DELPHI [4] or by the secondary vertex reconstruction as chosen by OPAL [5].

2. Pseudoscalar B mesons

The pseudoscalars B_d and B_u are the lightest B mesons[1]. The precise measurements of their masses were performed by the experiments CLEO [6], ARGUS [7] and CDF [8] making use of fully reconstructed B decays in modes with good signal to background ratios. For example CDF has found (147 ± 14) $B_u^- \to J/\psi K^-$ and (51 ± 8) $\bar{B}_d^0 \to J/\psi K^{*0}$ decays. The analysis of CLEO yielded 362 B_u^- decays (in the channels $J/\psi K^-$, $D^0\pi^-$, $D^0\rho^-$, $D^{*0}\pi^-$ and $D^{*0}\rho^-$) and 340 $\bar{B}_d^0$ (channels: $J/\psi K^{*0}$, $D^+\pi^-$, $D^+\rho^-$, $D^{*+}\pi^-$ and $D^{*+}\rho^-$). The average masses as given by the PDG [9] are $m_{B_d^0} = (5279.8 \pm 1.6)$ MeV and $m_{B_u^-} = (5278.9 \pm 1.5)$ MeV. The B_d^0 is heavier than $B_u^\pm$ as expected. The mass difference, however, measured precisely as $m_{B_d^0} - m_{B_u^\pm} = (0.35 \pm 0.29)$ MeV is consistent with zero. The precision of mass measurement is at present limited by an uncertainty in the overall energy scale. For CLEO and ARGUS the B mass is constrained to the beam energy while CDF uses for calibration the mass of the J/ψ reconstructed through its decay into muon pairs.

Another well established pseudoscalar state is the meson B_s^0 (quark content $(\bar{b}s)$). The most precise measurement of its mass comes from the CDF collaboration [8] and is based on the observation of (32 ± 6) events of the decay $B_s^0 \to J/\psi\phi$ with the subsequent decays $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$. At LEP only single events of B_s decays to $D_s\pi$, $D_s a_1$ and $J/\psi\phi$ were reported by ALEPH [10], DELPHI [11] and OPAL [12]. The average mass of the B_s^0 is (5369.6 ± 2.4) MeV. The mass difference between the B_s^0 and B_d^0 determined by CDF [8] to be $(89.7 \pm 2.7 \pm 1.2)$ MeV is in agreement with lattice QCD calculations [13] yielding the value $(87 \pm 12^{+7}_{-9})$ MeV.

[1] Unless explicitely stated, any symbol of particle refers at the same time to its antiparticle.

The quest for the $B_c^{\pm}$ meson (quark content $(\bar{b}c)$) has finally succeded in finding of $(20.4^{+6.2}_{-5.5})$ decays $B_c \rightarrow J/\psi l X$ reported in March 1998 by CDF [14] (*cf* Fig. 1). The mass of the $B_c^{\pm}$ was measured to be $(6.40 \pm 0.39 \pm 0.13)$ GeV. One year before ALEPH [15] has presented a single candidate of the same decay channel with the mass estimate of $(5.96^{+0.25}_{-0.19})$ GeV. As the $B_c^{\pm}$ is composed of two non-relativistic heavy quarks of different flavours its mass can be predicted to be between 6.2 and 6.3 GeV from the extrapolation of results of potential models [16] from the charmonium and bottomonium spectroscopy.

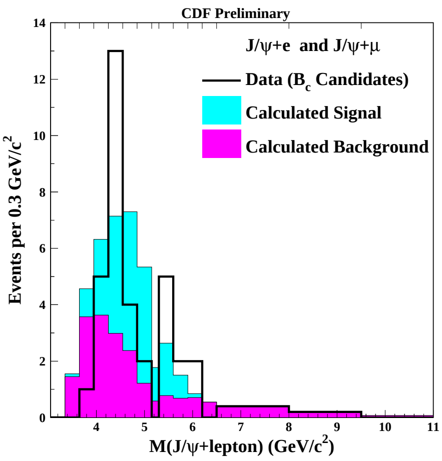

Fig. 1. The distributions of the invariant mass of the $J/\psi l$ pairs.

3. Vector meson B^*

The mass difference between the vector and pseudoscalar mesons (the hyperfine splitting) is inversely proportional to the mass of heavy quark. This indicates in particular that B^* and B mesons are much closer in mass than the D^* and D. The mass difference $\Delta M(B^* - B) = m_{B^*} - m_B$ is predicted by lattice QCD [17] to be of (34 ± 6) MeV. Due to such a small difference (less than pion mass) only electromagnetic decays (dominated by $M1$ transitions) $B^* \rightarrow B\gamma$ are allowed. At LEP the resulting photon spectrum peaks at around 300 MeV and extends up to 800 MeV. Among the LEP experiments only L3 is able to reconstruct directly such photons in its electromagnetic calorimeter. The other three collaborations reconstruct $\gamma \rightarrow e^+e^-$ conversions. The average of results obtained at LEP ([4],[18–20]) and given by the CLEO [21] and CUSB [22] collaborations yields: $\Delta M(B^* - B) = (45.7 \pm 0.4)$ MeV (*cf* Fig. 2).

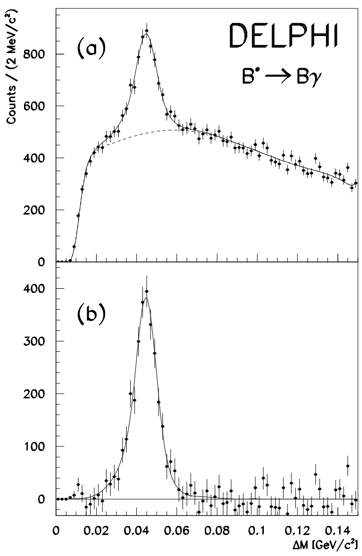

Fig. 2. The distribution of the mass difference $\Delta M(B^* - B)$ before (a) and after (b) background subtraction. The data are represented by points; the line shows the fit using background and signal shapes predicted by simulation.

The B^* and B yields have been measured by all LEP collaborations ([4], [18]- [20]) and found to be consistent with the statistical spin composition: $\frac{\sigma_{B^*}}{\sigma_B+\sigma_{B^*}} = 0.748 \pm 0.004$ (after subtracting the constribution from orbitally excited B^{**} mesons). The angular distribution of photons in the B^* rest frame was studied by ALEPH [18], DELPHI [4] and OPAL [20] and found to be isotropic: $\frac{\sigma_L}{\sigma_T+\sigma_L} = 0.33 \pm 0.04$, where the indices L (T) correspond to the longitudinal (transverse) helicity states, respectively. This result means that all helicity states are equally populated.

The DELPHI collaboration [23] has reported the observation of (74 ± 17) decays of $B^* \to Be^+e^-$ Dalitz decays and measured its rate as $\Gamma(B^* \to Be^+e^-)/\Gamma(B^* \to B\gamma) = 0.479 \pm 0.093 \pm 0.091)$ %. Such electromagnetic transition occurs in the second order of fine structure constant and its branching ratio is predicted to be of $(0.466 \pm 0.002$ %) [24]. The electrons emitted in Dalitz transition are rather slow (typical momentum of 160 MeV). Their strongly curved tracks were reconstructed using the dedicated algorithm exploiting the information given by the silicon tracker alone.

4. Orbitally excited B mesons

Four orbitally excited ($l = 1$) beauty meson states, commonly denoted by B^{**}, are expected. In HQET [25] they are groupped into two doublets differing in the value of the total angular momentum of the light quark $\vec{j_q} = \vec{l} + \vec{s_q}$ ($s_q = 1/2$ denotes the light-quark spin). The doublet with $j_q = 3/2$ is composed of the states B_1 and B_2^* (with spins 1 and 2, respectively). Due to the conservation of angular momentum and parity these two states can decay to $B^{(*)}\pi$ only via D-wave and, as a result, are expected to be narrow (decay width $\Gamma \sim 20$ MeV). Their masses are predicted as $(5.77 \div 5.80)$ GeV ([16, 26]). The states B_0 and B_1^* (with spins 0 and 1, respectively) form the second doublet with $j_q = 1/2$ and should be broad ($\Gamma \sim 150$ MeV) as for them S-wave transitions are not forbidden. The mass splittings inside a doublet are predicted to be small (~ 10 MeV) while the masses of $j_q = 1/2$ states should be about 100 MeV lower than those of the $j_q = 3/2$ doublet.

The first experimental evidence for orbitally excited B mesons was given by ALEPH [27], DELPHI [28] and OPAL [5] by combining single charged pions with B mesons reconstructed inclusively. All three collaborations reported the observation of broad maximum in the spectrum of the Q-value of $B^{(*)}\pi$ pairs corresponding to the average mass of (5698 ± 12) MeV and the production rate $\sigma_{B^{**}_{u,d}}/\sigma_b = 0.25 \pm 0.02$ [9]. The best description of its shape is given by the mixture of broad and narrow states but the detailed decomposition into individual resonances is not possible yet.

In a separate approach ALEPH [27] has used the sample of 404 fully reconstructed charged and neutral B mesons to analyse the $B\pi$ system. A resonant structure with the mass of (5695^{+17}_{-19}) MeV and width of (53^{+26}_{-19}) MeV was observed. The detailed analysis in the framework of HQET resulted in the estimate of the rate $BR(b \to B^{**} \to B^{(*)}\pi)/BR(b \to B_{u,d}) = (31 \pm 9(\text{stat})^{+6}_{-5}(\text{syst}))$ % and the mass of the B_2^* of $(5739^{+\ 8}_{-11}(\text{stat})^{+6}_{-4}(\text{syst}))$ MeV.

The angular distribution of the decay pions in the B^{**} helicity frame was found by DELPHI [28] to be flat. This would indicate that none of the B^{**} states is produced in a preferred helicity state. which differs from that for the D^{**} where the ARGUS [29] experiment reported the evidence that the helicity state ± 2 is suppressed for D_2^*.

The set of four orbitally excited states B_s^{**} is expected in full analogy with its non-strange counterparts. They are expected to decay into $B^{(*)}$ with the kaon's emission. Contrary to $B^{**} \to B\pi$ where a signal is expected for both pion's charges independently of the presence of the b or $\bar{b}$ as initial quark's flavour the $\bar{B}_s^{**}$ can decay into $B_u^- K^+$ but not into $B_u^- K^-$. As a result information of the initial quark's flavour given by the hemisphere's charge may be used to suppress the background. The DELPHI collaboration [28], using kaon identification over a wide momentum range, has reported two structures in the spectrum of Q-value of $B^{(*)}K$ pairs (*cf* Fig. 3). They have been interpreted as follows: the upper maximum comes from the decay $B_{s1} \to B^*K$ while the lower one stems from $B^*_{s2} \to BK$. The masses of parent states were obtained to be: $m_{B_{s1}} = (5888 \pm 4 \pm 8)$ MeV and $m_{B^*_{s2}} = (5914 \pm 4 \pm 8)$ MeV (the respective preditions: 5886 MeV and 5899 MeV [26]) and their widths found to be smaller than the detector's resolution. Similar study performed by OPAL [5] gave a broad maximum at the mass of (5853 ± 15) MeV. The production ratio of B^{**}_s to B^{**} was estimated by DELPHI [28] to be : $\frac{\sigma_{B_{s1}}+\sigma_{B^*_{s2}}}{\sigma_{B^{**}_{u,d}}} = 0.142 \pm 0.028(\mathrm{stat}) \pm 0.047(\mathrm{syst})$.

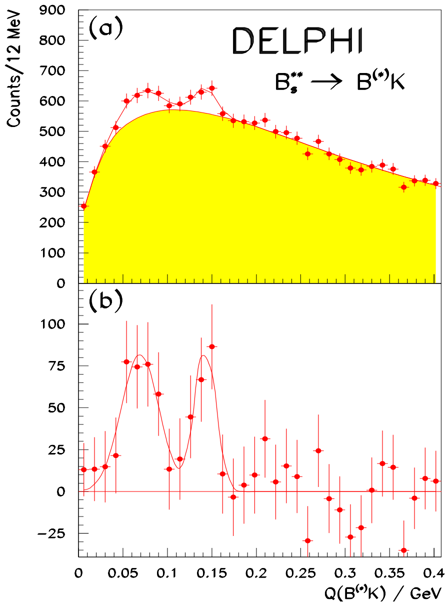

Fig. 3. (a) The Q-value distribution of $B^{(*)}K$ pairs (data points) along with the Monte Carlo expectation without B^{**}_s production. (b) shows the background subtracted spectrum with the fit to two Gaussian distributions.

5. Radially excited B mesons

According to the models inspired by QCD the masses of radially excited $(2S)$ B mesons should be in the range between 5.9 and 5.93 GeV [30]. The DELPHI collaboration in 1996 has reported the observation of the transition from radially excited $B^{(*)\prime}$ mesons to the $B^{(*)}$ with the emission of the pair of opposite charged and high-rapidity pions [31] (*cf* Fig. 4). The distribution

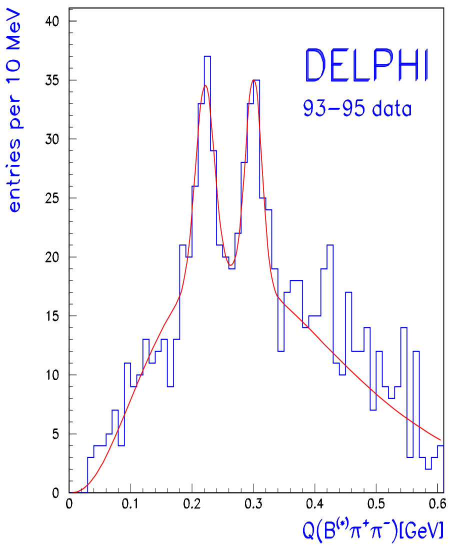

Figure 1: $M(B^{(*)}\pi^+\pi^-) - M(B^{(*)} - 2M(\pi))$ Q-value spectrum

Fig. 4. The Q-value distribution of $B^{(*)}\pi\pi$ pairs (solid histogram along with the fit to two Gaussian maxima on top of the background estimated from the Monte Carlo simulation.

of the Q-value showed two narrow maxima at $(220 \pm 4 \pm 10)$ MeV and $(301 \pm 4 \pm 10)$ MeV. They contain (56 ± 13) and (60 ± 12) events, respectively and their widths are compatible with the detector resolution. The upper peak is interpreted as corresponding to the S-wave $\pi\pi$ transitions of radially excited B mesons: $B^{'} \to B\pi\pi$ and $B^{*'} \to B^*\pi\pi$. The lower one most probably stems from the P-wave transition $B_1 \to B\pi\pi$ with a possible admixture from $B_2^* \to B^*\pi\pi$. The $B^{'}$ production was estimated to be: $\sigma(b \to B^{'})/\sigma(b) = (0.5 \div 4)$ %.

6. Summary

In the last few years the knowledge of spectroscopic features of the B meson family has improved significantly. With the recent observation of the B_c state and the precise measurement of the B_s's and B^*'s masses the sector of pseudoscalar and vector ground states in now quite well measured. First evidences for orbitally excited $l = 1$ $B_{u,d}^{**}$ and B_s^{**} states and radially excited $(2S)$ $B^{'}$ mesons were reported although the isolation of contributions from individual resonances is ambiguous. Among the topics which are missing in the sector of B mesons one should underline the lack of any direct measurement of spin-parity, poor knowledge about exclusive decays (even for the B_u and B_d known decays give rise to only a few % of the overall production) and the non-observation of B_s^*.

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