Production of excited charmed mesons at LEP

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Abstract

Studies of the production of orbitally excited charmed and charmed strange mesons in $e^+e^-$ collisions, performed by the LEP collaborations are reviewed. Measurements of the production rates of orbitally excited charmed mesons in semileptonic $b$ decays are presented. Searches for charmed meson radial excitations are also briefly discussed.

1. Introduction

In the hadronization of charm quarks into charmed mesons, states with angular momentum $L = 1$ can be produced, generically indicated with $D^{(*)}$, where the subscript applies to charmed strange mesons.

Four such states of the $c\bar{q}$ system are predicted ($q = u, d, s$), one of total spin 0 (usually indicated as $D^0$, $J^P = 0^+$), two of spin 1 ($D_1$, $J^P = 1^+$) and one of spin 2 ($D_2$, $J^P = 2^+$). These excited states decay via strong interactions to $D$ or $D^*$ accompanied by a pion (a kaon in the case of the $D^{**}$ states). Spin-parity conservation implies that the $D^0$ decays to $D\pi$ only, the $D_1$ to $D^*\pi$ only, while the $D_2$ can access both final states.

In the framework of HQET, for $m_Q \rightarrow \infty$, the light quark degrees of freedom decouple from the heavy quark, and new symmetries arise. In this limit the $D^0$ and one of the two $D_1$ mesons are expected to decay in S wave only, and to be broad ($\Gamma$ around 100 MeV), the other $D_1$ and the $D_2$ in D wave only, with narrow widths. No clear evidence for the broad states has been found so far, while the two narrow states have been measured for all of the three systems $D^{**0}$, $D^{**+}$, $D^{**-}$. At LEP $D^{**}$ states can be produced in the fragmentation of charm quarks from $Z$ decays, or in the decay of bottom hadrons.

The production rate of orbitally excited charmed mesons in semileptonic decays of bottom mesons is a major $b$–physics issue. The exclusive decay rates into $D\ell\nu$ and $D^*\ell\nu$ only account for 70–80% of the total inclusive semileptonic rate. The remaining part should be ascribed to narrow or wide $D^{**}$, or non resonant four–body decays. The rates and the nature of final states other than $D\ell\nu$ and $D^*\ell\nu$ is one of the major sources of systematic uncertainty for many $b$–physics measurements which make use of semileptonic final states such as $\tau_B^0$, $\Delta m_d$ or $V_{cb}$. Theoretical predictions exist on the ratio of $D^0_2$ to $D^0_1$ expected in semileptonic $b$ decays.

Radially excited charmed mesons are also predicted to exist, in two states, the $D'$ ($J^P = 0^-$), and the $D''$ ($J^P = 1^-$), with dominant decay modes $D\pi\pi$ and $D^*\pi\pi$, respectively. While the first state is too difficult to reconstruct in present experiments, the $D''$ has been searched for at LEP, with contradictory results.

2. Production of $D^{**}$ mesons in $Z$ decays

2.1. The channels

The cleanest channel to reconstruct $D^{**}$ states is the $D^{**}\pi^-$ final state, which takes advantage of the clear experimental signature of the small mass difference between the $D^{**}$ and the $D^0$ in the $D^{**} \rightarrow D^0\pi^-$ decay. This channel has been used by ALEPH, DELPHI and OPAL, where OPAL reconstructs the $D^0$ via $D^0 \rightarrow K^-\pi^+\pi^-\pi^+$ and ALEPH the previous two plus $D^0 \rightarrow K^-\pi^+\pi^0$. The $D^{**}\pi^-$ final state is accessible for both the $D^0_1$ and the $D^0_2$ mesons, and therefore the reconstructed candidates can be either of the two states.

ALEPH has also studied the $D^{+}\pi^-$ final state, which has a larger background but is accessible only by the $D^0_2$ meson. In this case the tighter kinematic cuts applied make the analysis sensitive to the charm contribution only ($D^{**}$ from charm fragmentation have on average higher momentum than those from $b$ decays).
Finally ALEPH has also studied the channel $D^0\pi^+$, which is a final state for $D_s^+\pi^+$ decays. The $D^0$ is reconstructed in the channels $D^0 \to K^-\pi^+$ and $D^0 \to K^-\pi^+\pi^-\pi^+$, and in this second, again, kinematic cuts imposed to reduce the background damp the contribution of $b$ events.

### 2.2. Fitting methods and results

Samples enriched in $b$ and $c$ events are prepared, by applying lifetime $b$-tagging in the hemisphere opposite to the reconstructed candidate, combined with the information of the measured decay length (longer for $b$ events) and the momentum (larger for $c$ events) of the reconstructed candidate.

ALEPH performs a simple fit to the $D^{**} - D^*$ or $D^{**} - D$ mass difference, using a double Breit–Wigner when both the $D_1$ and the $D_2^*$ are expected to contribute.

DELPHI and OPAL, that did not study the channels where only the $D_2^*$ contributes, use the helicity angle to help disentangling the two states. This is defined in the $D^*$ rest frame as the angle $\Theta_H$ between the $\pi$ from the $D^*$ decay and the $\pi$ from the $D^{**}$ decay. It is expected to be distributed, in the HQET limit, as $1 + 3\cos^2\Theta_H$ in the case of $D_1$ decays and as $\sin^2\Theta_H$ in the case of $D_2^*$ decays.

The fit yields the probability of observing the selected final state in a hadronic $Z$ decay. Folding $Z$ partial widths, decay branching ratios and selection efficiencies, the probability of producing a $D^{**}$ state from the fragmentation of a charm quark or the decay of a bottom hadron can be derived, obtaining the results reported in Table 1.

Although no compelling discrepancy can be claimed, several differences, at the level of twice the estimated errors, are observed. In particular ALEPH reports a significantly higher rate of $D_2^*$ from $c$ hadronization than the two other experiments, DELPHI has a lower $D_1$ rate from $b$ decays, and ALEPH finds no $D_2^*$ production in $b$ decays while the other collaborations find a signal of about 2σ significance. ALEPH and DELPHI results are still preliminary.

### 3. $D^{**}$ mesons in semileptonic $b$ decays

Two strategies have been adopted to study $D^{**}$ production and generic four–body final states in semileptonic $b$ decays. In both cases the first step is to select $(D^+\ell^-)$, $(D^0\ell^-)$, $(D^{**}\ell^-)$ pairs. Then one possibility is to look for a charged pion that forms a heavier resonance with the $D^{(*)}$ candidate, and extract the individual $B \to D^{(*)}$ rates. The other strategy is to search for pions incompatible with the primary vertex and compatible with the reconstructed $b$ vertex, using inclusive discriminants. This yields an estimate of the total four–body decay rate, including narrow resonant, wide resonant and non resonant final state hadronic systems.

The most recent results from ALEPH and DELPHI are reported in Table 1.

The inclusive four–body decay rate observed by DELPHI would account for the difference between the total semileptonic rate and the sum of $D$ and $D^*$ rates. The corresponding ALEPH results is lower by 1.8σ. No significant production of $D_2^*$ is observed, in contrast with what is given by all available theoretical predictions.

### 4. Production of $D_s^{**}$ mesons in $Z$ decays

$D_s^{**}$ mesons are reconstructed in the channels $D^*K$ and $DK$. The $D_s^{++}$ is searched for in the $D^{*0}K^+$ and $D^{**}K^0_S$ final states. The second has a cleaner experimental signature but lower efficiency due to the $K_S^0$ reconstruction, and lower branching ratio both due to phase space (the $Q$-value of the decay is very small) and to the factor 1/2 because of the $K_S^0$. The $D^{**}$ is reconstructed in the $D^0\pi^+$ final state, with $D^0 \to K^-\pi^+$ in the case of OPAL, while ALEPH uses also $D^0 \to K^-\pi^+\pi^-\pi^+$ and $D^0 \to K^-\pi^+\pi^-\pi^+$. For the $D^{*0}K^+$ final state, the $D^{*0}$ decays to $D^0\pi^0$ or $D^0\pi^+$, where the photon or the pion are not detected. The $D^0$ is reconstructed in the channel $D^0 \to K^-\pi^+$, and the resolution in the $D_s^{**} - D^0$ mass difference only marginally

### Table 1. Results on $D^{**}$ production probabilities in $Z$ hadronic decays.

|       | ALEPH (preliminary) | DELPHI (preliminary) | OPAL (published) |
|-------|----------------------|----------------------|------------------|
| $f(c \to D_1)$ | 0.032 ± 0.009        | 0.019 ± 0.004        | 0.021 ± 0.008    |
| $f(c \to D_2^*)$ | 0.094 ± 0.019        | 0.047 ± 0.013        | 0.052 ± 0.026    |
| $f(b \to D_1)$ | 0.046 ± 0.014        | 0.020 ± 0.006        | 0.050 ± 0.015    |
| $f(b \to D_2^*)$ | < 0.039 @ 95% CL     | 0.048 ± 0.020        | 0.047 ± 0.027    |
efficiency also for loose enough to have significant reconstruction observe this state. and efficiency are estimated to be insufficient to similar to that used in Db and Ds 5. Production of D∗+ mesons in Z decays

Relativistic quark models predict the masses of the D′ and D∗+ mesons to be around 2.6 GeV/c². Although no firm prediction is given for their widths, it is considered likely that these states could be narrow. The reconstruction of D∗+ states has been attempted by DELPHI 8 and OPAL 9, in the final state D∗+π⁺π⁻, with D∗+ → D0π⁺. The D⁰ is reconstructed in the channel D⁰ → K⁻π⁺ in the case of OPAL, while DELPHI uses the channel D⁰ → K⁻π⁺π⁻π⁻ as well.

A clear excess of events is found by the DELPHI collaboration, with a reconstructed mass of 2637 ± 2 ± 6 MeV/c² (see Fig. 1). The signal events in the peak are estimated to be 66 ± 14 which gives a significance of 4.7σ. The width of the peak is compatible with the experimental resolution, therefore no value is given, but the limit Γ < 15 MeV is set at 95% CL.

Given the signal observed by DELPHI, OPAL would be expected to see a significant signal as well, despite the somewhat worse mass resolution and the use of the D⁰ → K⁻π⁺ channel only. Instead, no evidence for a resonance is found. In order to quantify in a conservative way the level of incompatibility of the two observations, the ratio has been calculated, between the number of D∗+ candidates reconstructed in the D∗+π⁺π⁻...
channel, and the number of $D^0, D_s^0$ candidates reconstructed in the $D^{*+}\pi^-$ final state. In the ratio most of the experimental effects cancel out, so that the values obtained by the DELPHI and the OPAL experiments can be directly compared, although, on the other hand, the significance of the incompatibility between the two results is substantially washed out by the small statistics of the sample used for the normalization.

The results obtained are $R = 0.49 \pm 0.18 \pm 0.10$ for DELPHI and $R < 0.21 @ 95\%$ CL for OPAL.

6. Conclusions

Narrow orbital excitations of charmed and charmed strange mesons have been observed at LEP in $Z$ decays. The contributions of direct $c$ quark hadronization and $b$ hadron decays have been separated on a statistical basis. Some differences are observed between the rates measured by different experiments.

The production rates of $D^{**}$ states and the inclusive four–body rate have been measured in semileptonic $b$ decays.

The observation of a charmed meson radial excitation by DELPHI has not been confirmed by OPAL.

References

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