

STUDY OF D^{**} AND $D^{*'}$ PRODUCTION IN B AND C JETS, WITH THE DELPHI DETECTOR

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Using D^{*+} mesons exclusively reconstructed in the DELPHI detector at LEP, orbital and radial excitations of non strange charmed mesons are studied. The multiplicities of the two narrow D_1^0 and D_2^{*0} orbital excitations are measured in $Z^0 \rightarrow c\bar{c}$ and $Z^0 \rightarrow b\bar{b}$ decays. Preliminary results are obtained on the production of broad D^{**} states, using B meson semi-leptonic decays. A narrow signal of 66 ± 14 events is observed in the $(D^{*+}\pi^+\pi^-)$ final state, interpreted as the first evidence of the predicted $D^{*'}$ radial excitation.

1 Introduction

For mesons containing heavy and light quarks ($Q\bar{q}$), and in the limit where the heavy quark mass is much larger than the typical QCD scale, the spin \vec{s}_Q of the heavy quark decouples from other degrees of freedom. Thus, for strong decays, the total (spin+orbital) angular momentum $\vec{j}_q = \vec{s}_q + \vec{L}$ of the light component is conserved. This heavy quark symmetry, together with quark potential models used for lower mass mesons, allows the masses and decay widths of heavy mesons to be predicted¹.

els of the ($L=0, j_q = 1/2$) state. The two ($L=1, j_q = 3/2$) states have been clearly observed², because they have narrow decay widths of about $20 \text{ MeV}/c^2$. The measured masses of the $D_1^0(2420)$ and $D_2^{*0}(2460)$ agree within $20 \text{ MeV}/c^2$ with the prediction of the models. Section 3 presents a measurement of their production rate in $c\bar{c}$ and $b\bar{b}$ jets.

The ($L=1, j_q = 1/2$) states decay through a S wave and are expected to have large decay widths. Up to now, they have not been observed directly, but their total production rate is measured using B meson semi-leptonic decays (section 4).

In addition to these orbital excitations, radial excitations of heavy mesons are foreseen. The D' and $D^{*'}$ are expected to have masses of $2.58 \text{ GeV}/c^2$ and $2.64 \text{ GeV}/c^2$ respectively, with a $10\text{-}25 \text{ MeV}/c^2$ uncertainty on the mass predictions³. They are expected to decay, in S wave, into $D^{(*)}\pi\pi$. Section 5 presents the first evidence for the $D^{*'}$ meson, observed in the decay mode $(D^*\pi\pi)$.

2 D^{**} and $D^{*'}$ reconstruction

DELPHI⁴ is a multipurpose LEP detector, with special emphasis on precise vertex and charged tracks momentum reconstruction, and particle identification. The micro-vertex detector provides 3 R ϕ and 2 Z hits per track, with intrinsic resolutions of 7.6 and 9 μm . For muons of 45 GeV/c momentum, a resolution of $\sigma(p)/p$ of $\pm 3\%$ is obtained, and the precision of the track extrapolation to the beam collision point is $26 \pm 2 \mu\text{m}$. Kaon and pion identification is performed using a Ring Imaging Cherenkov detector, and the ionisation loss in the TPC, which is the main tracking device. A total of 3.4 million hadronic events is obtained from the 1992-1995 data, at center-of-mass energies close to the Z^0 mass.

2.1 D^* reconstruction

All the decay channels considered here involve the $D^{*+} \rightarrow D^0\pi^+$ decay, followed by $D^0 \rightarrow (K^-\pi^+)$ or

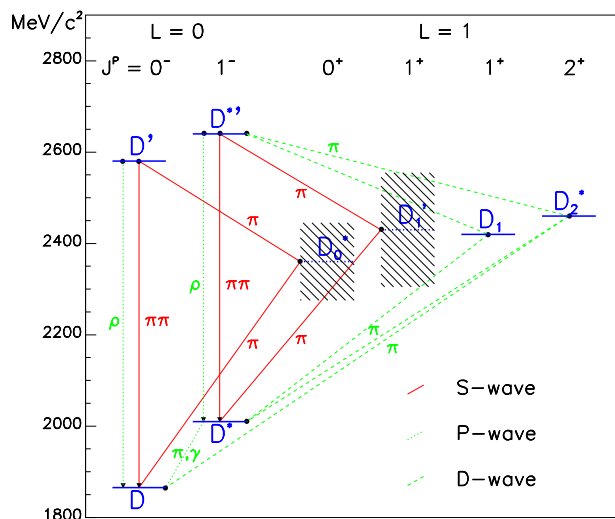


Figure 1: Spectroscopy of non-strange D mesons. The shaded areas show predicted widths for these states. For clarity the expected D_1 and D_2^* decays involving a ρ meson or $\pi\pi$ pairs are not shown.

The present knowledge of charmed meson spectroscopy is summarized in Figure 1. The well established D and D^* mesons² correspond to the two degenerate lev-

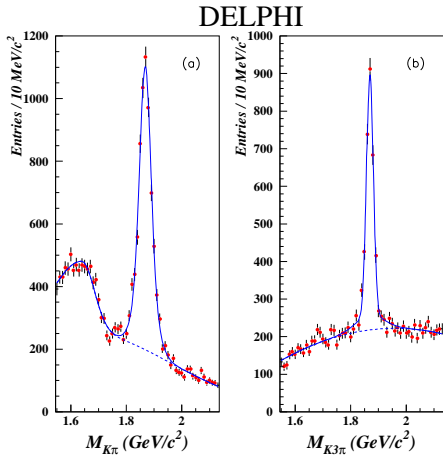


Figure 2: $K\pi$ and $K3\pi$ invariant mass distributions in (a) the $D^{*+} \rightarrow (K^-\pi^+)\pi_*^+$ and (b) the $D^{*+} \rightarrow (K^-\pi^+\pi^-\pi^+)\pi_*^+$ decay channels.

$D^0 \rightarrow (K^-\pi^+\pi^-\pi^+)$.^a

To reconstruct the D^0 decay final state, all $(K^-\pi^+)$ and $(K^-\pi^+\pi^-\pi^+)$ combinations are tried to fit a secondary vertex in space. Kinematical and track selection cuts are described in detail in⁵. Kaon candidates are considered if they have a momentum larger than 1 GeV/c and, in the $K3\pi$ channel, a loose kaon identification is required. The D^0 momentum and invariant mass are computed from the momenta of the decay products. Then, all charged particles with momentum between 0.4 GeV/c and 4.5 GeV/c and charge opposite to that of the kaon candidate are used as pion candidates for the $D^{*+} \rightarrow D^0\pi_*^+$ decay. In the $K\pi$ ($K3\pi$) channel, events are selected if the mass difference ($M_{K\pi\pi_*} - M_{K\pi}$) (resp. $(M_{K3\pi\pi_*} - M_{K3\pi})$) is within ± 2 (± 1) MeV/c² of the nominal value ($M_{D^*} - M_{D^0}$). The D^* candidates must have an energy fraction $X_E(D^*) = E(D^*)/E_{beam}$ greater than 0.25. Figure 2 shows the distribution of the $M(K\pi)$ and $M(K3\pi)$ invariant masses for the selected events. The fitted D^0 masses and widths are 1868 ± 1 (1869 ± 1) and 19 ± 1 (12 ± 2) MeV/c². The reconstructed D^0 mass is required to lie within ± 40 (± 30) MeV/c² of the nominal D^0 mass: 4661 ± 88 (2164 ± 65) MeV/c². D^* candidates are selected in the $K\pi$ ($K3\pi$) channels. The selection efficiency is estimated, using the simulation, to be 21% (8%).

2.2 D_1^0 , D_2^{*0} and $D^{*'} reconstruction$

Similar selection criteria and vertex reconstruction are used to reconstruct narrow orbitally and radially excited states.

^aThroughout this paper, charge-conjugate states are always implied, and the π from D^* decay is denoted as π_* .

In the case of D_1^0 and D_2^{*0} decaying into $D^{*+}\pi^-$, a pion with a charge opposite that of the D^{*+} is added, and the $D^0\pi_*^+\pi^-$ vertex is fitted. All combinations are tried, provided the pion candidate has a momentum larger than 1.0 (1.5) GeV/c in the $K\pi$ ($K3\pi$) channel. The reconstruction efficiency is 14% (6%) in the $K\pi$ ($K3\pi$) channels.

In the case of $D^{*'} decaying into $D^{*+}\pi^+\pi^-$, all pairs of oppositely charged pions are used to fit a $D^0\pi^+\pi^-$ vertex. The pion candidates are required to have a momentum larger than 0.6(1.0) GeV/c, and those compatible with a kaon according to particle identification are rejected. For a signal of mass 2640 MeV/c², the reconstruction efficiency is 4% (2%) in the $K\pi$ ($K3\pi$) channels.$

In both cases, the precision on the invariant mass reconstruction is improved by correcting for a 4 MeV/c² shift observed in the D^0 mass, by using:

$$\begin{aligned} M(D^*\pi) &= M_{(D^0\pi_*\pi)} - M_{(D^0\pi_*)} + m_{D^*} \\ M(D^*\pi\pi) &= M_{(D^0\pi_*\pi\pi)} - M_{(D^0\pi_*)} + m_{D^*} \end{aligned} \quad (1)$$

where m_{D^*} is the nominal D^{*+} mass. The simulation predicts a resolution of about 6 MeV/c² on the mass reconstruction, for both radial and orbital excitations.

2.3 Selection of $b\bar{b}$ and $c\bar{c}$ samples

Due to the relatively long lifetimes of charmed and bottomed particles, heavy flavour events are characterized by the presence of secondary vertices. The probability \mathcal{P} that all tracks detected in the event come from the primary vertex is small: for $b\bar{b}$ events, a purity of 90% is achieved, with an efficiency of 60%, by requiring $\mathcal{P} \leq 10^{-2}$.

Charmed mesons from $Z^0 \rightarrow b\bar{b}$ events are distinguished from those in $c\bar{c}$ events by considering both their energy and lifetime informations. Bottom quarks fragment into a B hadron, which subsequently decays into a D^{*+} meson, whereas in $c\bar{c}$ events charmed mesons are directly produced in the fragmentation process. This difference in the hadronization leads to a smaller energy fraction of $X_E(D^*)$ for $b\bar{b}$ events. Also, due to the b quark lifetime, the apparent flight of the D^0 meson is greater than the true decay length. Its measured proper time distribution is larger than the mean B meson lifetime, 1.6 ps, compared to a true D^0 lifetime of 0.4 ps.

By combining these variables, $b\bar{b}$ and $c\bar{c}$ samples are selected, with high purities: 92 % for $b\bar{b}$, 89 % for $c\bar{c}$.

In the $b\bar{b}$ sample, the combinatorial background is higher, but is reduced by 50% using the kaon identification, and also by asking that the impact parameter of the additional pion is positive, i.e. that the intersection of the pion and D^* directions is on the same side of the primary vertex as the D^* vertex. As a consequence, the

ratio of efficiencies $\epsilon(D^*\pi)/\epsilon(D^*)$ is 52% for $b\bar{b}$, compared to 62% for $c\bar{c}$.

3 Study of narrow orbital excitations

Figure 3 shows the $M(D^*\pi)$ invariant mass distribution obtained for the sum of the $b\bar{b}$ and $c\bar{c}$ samples⁶. A clear excess of $(D^{*+}\pi^-)$ pairs is observed between 2.4 and 2.5 GeV/c^2 , corresponding to the two overlapping contributions of the D_1^0 and D_2^{*0} . They are fitted by two Breit-Wigner functions, whose widths are fixed to the measured world average², convoluted with the experimental resolution. A total signal of (361 ± 58) $D_1^0 + D_2^{*0}$ events is fitted, out of which (65 ± 10) % is assigned to D_1^0 . The masses are left free in the fit, and the result is $M_{D_1^0} = 2425 \pm 3(\text{stat}) \text{ MeV}/c^2$ and $M_{D_2^{*0}} = 2461 \pm 6(\text{stat}) \text{ MeV}/c^2$, i.e. consistent with the world averages². The helicity distributions are consistent with the production of a $J^P = 1^+$ and $J^P = 2^+$ states.

Figure 4 shows the same mass distribution, but for the $b\bar{b}$ and $c\bar{c}$ samples separately. The same fit is performed, but both D_1^0 and D_2^{*0} masses and widths are fixed to the world average. The result of the fit is (97 ± 26) D_1^0 and (69 ± 27) D_2^{*0} in the $b\bar{b}$ sample, (141 ± 26) D_1^0 and (104 ± 26) D_2^{*0} in the $c\bar{c}$ sample. In order to measure the D_1^0 and D_2^{*0} production rates, these results are unfolded from the reconstruction efficiencies, signal purities, D_1^0 and D_2^{*0} decay widths into $D^{*+}\pi^-$. The errors quoted below are statistical only. Systematic errors are still under study, but smaller than the statistical errors.

The $c\bar{c}$ sample provides direct information on the charm fragmentation. Results are:

$$\begin{aligned} f(c \rightarrow D_1^0) &= 1.9 \pm 0.4 (\text{stat}) \% \\ f(c \rightarrow D_2^{*0}) &= 4.3 \pm 1.3 (\text{stat}) \% \end{aligned} \quad (2)$$

Both results are in agreement with previous LEP and CLEO measurements. For the D_1^0 , the result is also in agreement with theoretical calculations⁷, which predicted 1.7%. For the D_2^{*0} , the result is high compared to the expectation (2.4 %), but has large errors. A more precise measurement would need to use the $D_2^{*0} \rightarrow D^+\pi^-$ channel, which is forbidden for the D_1^0 .

For the $b\bar{b}$ sample, results are:

$$\begin{aligned} f(b \rightarrow D_1^0) &= 2.2 \pm 0.6 (\text{stat}) \% \\ f(b \rightarrow D_2^{*0}) &= 4.8 \pm 2.0 (\text{stat}) \% \end{aligned} \quad (3)$$

This shows that the charm fragmentation properties are similar, although in a different environment.

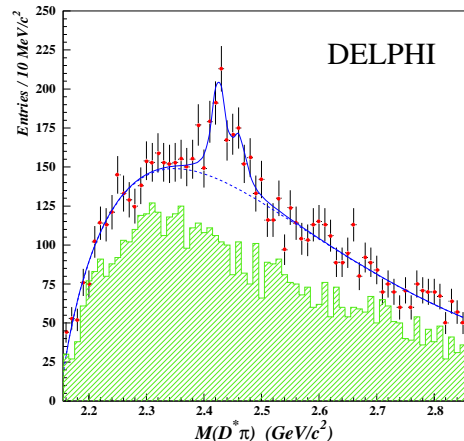


Figure 3: Invariant mass distributions ($D^{*+}\pi^-$) (dots) and ($D^{*+}\pi^+$) (hatched histogram). The mass computation and the fit are explained in the text.

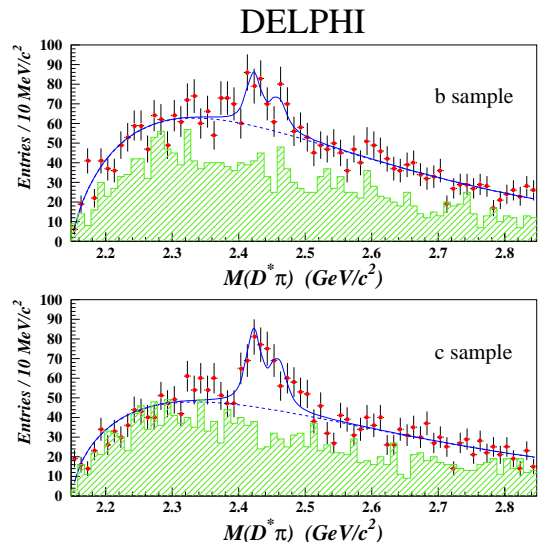


Figure 4: Invariant mass distributions ($D^{*+}\pi^-$) (dots) and ($D^{*+}\pi^+$) (hatched histogram) for the separate $b\bar{b}$ and $c\bar{c}$ samples. The mass computation and the fit are explained in the text.

4 Study of broad orbital excitations in B meson semileptonic decays

In B meson semileptonic decays, only 60% to 70% of the final states are described by $D\ell\bar{\nu}_\ell$ and $D^*\ell\bar{\nu}_\ell$. The remaining contribution is attributed to D^{**} . The total production rate, including broad orbital excitations, can be measured using the impact parameter of the pion, denoted π_{**} , emitted in the decay chain $B \rightarrow D^{**}X \rightarrow (D^*\pi_{**})X'$.

Events are selected if a lepton with momentum larger than $3 \text{ GeV}/c^2$ is identified, and if its transverse momentum relative to the D^{*+} is larger than $0.5 \text{ GeV}/c^2$. The kaon candidates in the D^0 decay must have the same charge as the lepton. 459 ± 25 (288 ± 19) events are selected in the $K\pi(K3\pi)$ channel. All remaining tracks, of charge opposite to that of the D^{*+} , are π_{**} candidates. Kinematical and selection cuts are described in ⁸. The background due to fake D^{*+} associated to a true lepton ℓ^- is subtracted by using events in the tail of the D^* invariant mass distribution. The contribution of true D^{*+} associated to a fake lepton is subtracted using $D^*\ell$ pairs with the wrong sign combination. The remaining 111 ± 16 events are due to true b semileptonic decays into $D^{*+}\ell^-X$ final state, associated with a π_{**} candidate either from D^{**} decay, or from jet fragmentation. The shape of the two contributions are shown in figure 5. They are used to fit the π_{**} impact parameter distribution shown in figure 6. From the result of the fit, the following branching ratio is obtained:

$$\begin{aligned} BR(B^- \rightarrow (D^{*+}\pi^-)\ell^-\bar{\nu}X) \\ = 1.15 \pm 0.17(stat) \pm 0.14(syst) \% \end{aligned} \quad (4)$$

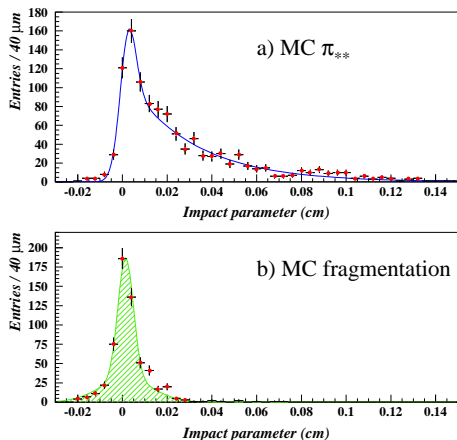


Figure 5: Impact parameter relative to the primary interaction vertex in simulated B semileptonic decays for a) π_{**} from D^{**} decay and b) charged particles from jet fragmentation.

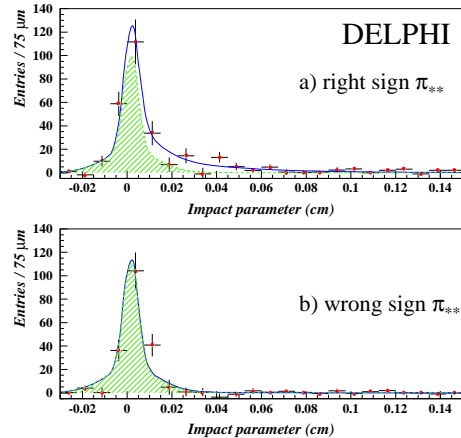


Figure 6: Impact parameter relative to the primary interaction vertex in real data for a) right charge π_{**}^- and b) wrong charge π_{**}^+ candidates. The hatched area is the contribution from jet fragmentation.

This result significantly improves a previous DELPHI measurement, and is in agreement with other LEP measurements.

The $(D^{*+}\pi_{**})$ invariant mass is also reconstructed and used to fit, in the way described in the previous section, the D_1^0 and D_2^0 narrow resonances. A signal of $26.7 \pm 8.2 D_1^0$ is fitted, and the corresponding production rate is:

$$\begin{aligned} BR(B^- \rightarrow D_1^0\ell^-\bar{\nu}X) \\ = 0.72 \pm 0.22(stat) \pm 0.13(syst) \% \end{aligned} \quad (5)$$

For the D_2^0 state, 14.8 ± 7.7 events are fitted, i.e. a signal significance smaller than 2σ . More data would be necessary to estimate the corresponding branching ratio.

5 Evidence for a narrow radial excitation

Figure 7 shows the invariant mass distribution obtained when two pions of opposite charges are added to the D^* candidate, and using the sum of the two $b\bar{b}$ and $c\bar{c}$ samples. An excess of 66 ± 14 (stat) events is observed in the $(D^{*+}\pi^+\pi^-)$ combination. The signal is fitted by a Gaussian distribution of free parameters: the χ^2 per degree of freedom is 60/59, and would be 91/62 if the Gaussian was removed. About $(57 \pm 10)\%$ of the signal is selected in the $c\bar{c}$ sample.

The fitted mass is 2637 ± 2 (stat) ± 6 (syst) MeV/c^2 . It is thus consistent with the predictions for the D^{*} radial excitation³: $2640 \text{ MeV}/c^2$. Other L=2 states are predicted, but with masses higher by at least $50 \text{ MeV}/c^2$.

The width of the fitted Gaussian is $7 \pm 2 \text{ MeV}/c^2$, i.e. compatible with the detector resolution. Therefore, only an upper limit is derived: the full width of the signal is smaller than $15 \text{ MeV}/c^2$ at 95 % C.L. There is no natural explanation of such a small value, neither for the $D^{*'}$ nor for higher orbital excitations⁹.

Various checks were performed. Varying the background shape and the kinematical cuts has no effect within statistics. No peculiar double counting was noticed, and the signal is stable when the π^* is added to the $D^0\pi^+\pi^-$ tracks in the vertex fit. As explained above, mass shifts are studied using D_1^0 and D_2^{*0} narrow states, and a conservative systematic error of $6 \text{ MeV}/c^2$ is attached to the mass measurement.

The production rate of this signal can be compared with that of the D_1^0 and D_2^{*0} narrow states:

$$\frac{\langle N_{D^{*'}} \rangle \times Br(D^{*' } \rightarrow D^* \pi^+ \pi^-)}{\sum_{J=1,2} \langle N_{D_J^{(*)}} \rangle \times Br(D_J^{(*)} \rightarrow D^* \pi)} \quad (6)$$

$$= 0.49 \pm 0.18(stat) \pm 0.10(syst)$$

Most of the systematic uncertainties cancel in this ratio. The quoted systematics is due to the Monte-Carlo statistics, and to the uncertainties on widths and on the kaon rejection. This result is compatible, within its large errors, with the value obtained using the thermodynamical models already mentioned for orbital states^{5,7}.

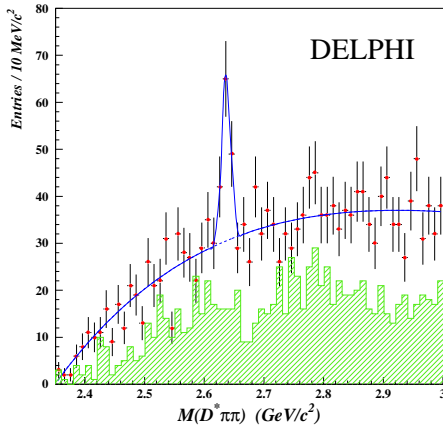


Figure 7: Invariant mass distributions ($D^{*+}\pi^+\pi^-$) (dots) and ($D^{*+}\pi^-\pi^-$) (hatched histogram). The mass computation and the fit are explained in the text.

6 Conclusion

Using about 7000 exclusively reconstructed D^* mesons, the D_1^0 and D_2^{*0} multiplicities are measured in $c\bar{c}$ events, and found to be consistent with theoretical calculations.

The measured multiplicities in $b\bar{b}$ events are consistent with the ones in $c\bar{c}$ events, both for the D_1^0 and D_2^{*0} .

The total D^{**} production rate, involving a D^{*+} in the final state, is measured in B meson semileptonic decays.

A narrow signal is observed in the ($D^{*+}\pi^+\pi^-$) final state, at the mass $M = 2637 \pm 2 (stat) \pm 6 (syst) \text{ MeV}/c^2$, interpreted as the first evidence of the predicted $D^{*'}$ meson.

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