PRODUCTION OF C AND B FLAVORED MESONS AND THEIR DECAYS AT LEP*

Eric Rohne

Institut für Physik, Johannes Gutenberg-Universität Mainz
55099 Mainz, Germany

For ALEPH Collaboration

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The production rates of D^0, D^+, D_s^+, Λ_c, D^{*+}, D^{*0}, D_s^{*+}, D^{**} and D_s^{**} hadrons in $Z^0 \to c\bar{c}$ and $Z^0 \to b\bar{b}$ measured by the LEP collaborations are presented. The measurements of the number of produced charm quarks in b-hadron decays and the partial width of the Z^0 going into a charm quark pair $\Gamma_{c\bar{c}}/\Gamma_{\rm had}$ derived from charm production rates are discussed. The LEP measurements of the semileptonic branching ratio Br(B$\to l$) are compared with results from CLEO and with recent theoretical calculations. From the production rates of pseudoscalar and vector mesons the ratio V/(V+P) in the D and the D_s sectors are determined and the results are compared with simple spin counting predictions. Finally the first observation of the radially excited $D^{*'}$ meson is discussed.

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1. Introduction

In the years 1989–1995 each of the 4 LEP collaborations ALEPH, DELPHI, L3 and OPAL have collected approximately 4 Million hadronic Z^0 decays. Whereas b-hadrons are only produced in the fragmentation of primary b quarks, charmed hadrons are not only produced from c quark fragmentation, but also in cascade decays of b-hadrons. From the large statistics collected at LEP the production rates of charmed hadrons from the two different sources are determined. From summing the production rates of the weakly decaying charmed hadrons D^0, D^+, D_s^+ and Λ_c the partial width of the Z^0 to decay into a charm quark pair $\Gamma_{c\bar{c}}/\Gamma_{\rm had}$ and the average number of

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produced charm quarks in b-hadron decays can be determined and compared to theoretical expectations. Measurements of the semileptonic branching ratio Br(B$\rightarrow$ l) have previously shown a significant difference to theoretical expectations. However there is now a better agreement with newer calculations from higher order QCD corrections which have increased the rate for the process $b \rightarrow c\bar{c}s$ and therefore lowered the semileptonic branching ratio. From the production rates of the vector and pseudoscalar mesons the ratio V/(V+P) in the D and the D_s sector are determined and compared to simple spin counting expectations. Finally the latest results from the observation of exited states D^{**}, D_s^{**}, and $D^{*'}$ are discussed.

2. Production of charmed hadrons in $Z^0 \rightarrow b\bar{b}$ and $Z^0 \rightarrow c\bar{c}$ events

To measure the production rates of charmed hadrons produced in the fragmentation of c quarks their harder energy spectrum compared to charmed hadrons produced in b-hadron decays is exploited (see Fig. 1).

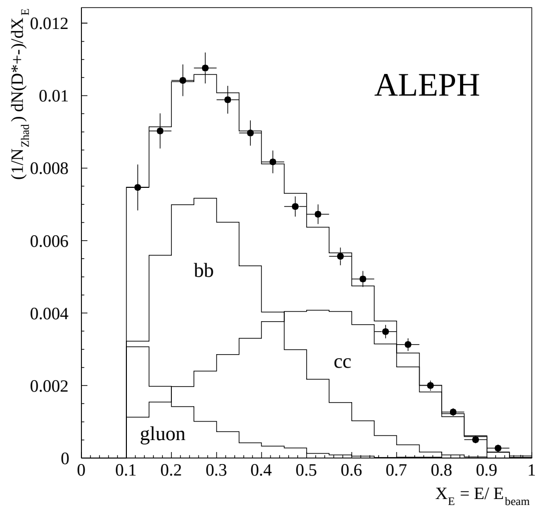

Fig. 1. Energy spectrum of charmed hadrons in Z^0 decays.

Due to the relatively long lifetime of b-hadrons the decay vertex of cascade charmed hadrons from B decays in general is further displaced from the primary vertex than for prompt charmed hadrons. To determine the production rates of D^0, D^+, D_s^+ and Λ_c from the different sources a two dimensional fit to the scaled energy and the decay length distributions is performed by OPAL [1]. In the measurement of prompt charm production from ALEPH [2] the charm content is enriched by the requirement that the scaled energy x_E of the charmed hadron has to be greater than 0.5. The remaining background from b-hadron decays determined from Monte Carlo is subtracted. In order to measure the charm production in $Z^0 \to b\bar{b}$ events ALEPH [3] selects a high b-purity sample with the help of a b-tag algorithm which is a combination of a lifetime tag and a mass tag which relies on the high invariant mass in b-jets. To avoid any bias the b-tag is applied to the opposite hemisphere of the charmed hadron candidate. In the measurements of charmed hadron production rates from DELPHI [4–6] the contributions from the different sources are determined with a fit to the measured x_E spectrum of the hadrons. The results obtained are listed in Table I. The values are calculated with the standard model values of $R_c = 17.2\%$ and $R_b = 21.6\%$.

TABLE I

Production of charmed hadrons in $Z^0 \to c\bar{c}$ and $Z^0 \to b\bar{b}$ events.

	$f(c \to D^0)$	$f(c \to D^+)$
ALEPH	$(56.2 \pm 1.7 \pm 3.2)\%$	$(23.5 \pm 0.8 \pm 1.3)\%$
DELPHI	$(54.2 \pm 5.2 \pm 3.3)\%$	$(20.2 \pm 2.0 \pm 1.4)\%$
OPAL	$(58.9 \pm 4.1^{+3.9}_{-3.8})\%$	$(22.8 \pm 2.9^{+1.6}_{-2.0})\%$
	$f(c \to D_s^+)$	$f(c \to \Lambda_c^+)$
ALEPH	$(11.6 \pm 1.9 \pm 0.7)\%$	$(8.9 \pm 0.9 \pm 0.3)\%$
DELPHI	$(11.8 \pm 1.8 \pm 1.8)\%$	$(10.0 \pm 2.0 \pm 2.0)\%$
OPAL	$(9.4 \pm 2.4^{+1.2}_{-1.2})\%$	$(6.2 \pm 2.9^{+1.0}_{-1.1})\%$
	$f(b \to D^0, \overline{D}^0)$	$f(b \to D^\pm)$
ALEPH	$(60.5 \pm 2.4 \pm 1.6)\%$	$(23.4 \pm 1.3 \pm 1.0)\%$
DELPHI	$(59.4 \pm 3.7 \pm 2.9)\%$	$(22.2 \pm 1.9 \pm 1.4)\%$
OPAL	$(53.4 \pm 2.7 \pm 3.1)\%$	$(18.8 \pm 1.5 \pm 1.3)\%$
	$f(b \to D_s^\pm)$	$f(b \to \Lambda_c^\pm)$
ALEPH	$(18.3 \pm 1.9 \pm 0.9)\%$	$(11.0 \pm 1.4 \pm 0.6)\%$
DELPHI	$(16.1 \pm 1.9 \pm 1.9)\%$	$(13.8 \pm 2.7 \pm 3.1)\%$
OPAL	$(21.4 \pm 2.3 \pm 2.1)\%$	$(12.5 \pm 2.4 \pm 1.0)\%$

3. Determination of R_c from charm production rates

The partial width of a Z^0 to decay into a charm quark pair $R_c = \Gamma_{c\bar{c}}/\Gamma_{\mathrm{had}}$ can be obtained by summing over the production rates of the weakly decaying charmed hadrons D^0, D^+, D_s^+ and Λ_c. One has to correct for the production of other weakly decaying charmed baryons as Ξ_c and Ω_c. Whereas ALEPH uses an absolute correction for the production of Ξ_c and Ω_c baryons of $f(c \to \Xi_c, \Omega_c) = (2.0 \pm 1.0)\%$, DELPHI and OPAL both multiply the measured Λ_c production rate with factor of (1.15 ± 0.05) to take this effect into account. The production of J/ψ mesons from primary c-quarks can be neglected (OPAL [7]). The values of R_c obtained with this method by ALEPH, DELPHI and OPAL are listed in Table II and agree within errors with the standard model value of 17.2%.

TABLE II

R_c measurements from charm counting.

ALEPH [2]	$R_c = (17.56 \pm 0.48_{\mathrm{stat}} \pm 0.85_{\mathrm{syst}} \pm 0.68_{br})\%$
DELPHI [4]	$R_c = (16.8 \pm 1.1_{\mathrm{stat}} \pm 1.3_{\mathrm{syst}})\%$
OPAL [1]	$R_c = (16.7 \pm 1.1_{\mathrm{stat}} \pm 1.1_{\mathrm{syst}} \pm 0.5_{br})\%$

The measurements of R_c from charm counting are used together with other measurements in the calculation of the averaged R_c value for LEP and SLD which is found to be $(17.31 \pm 0.44)\%$ [8].

4. Charm production in b-hadron decays and the semileptonic B branching ratio Br(B$\to l$)

In most b-hadron decays one charmed hadron is produced because the Cabibbo-Kobayashi-Maskawa mixing matrix element $|V_{cb}|$ is much bigger than $|V_{ub}|$ or in other words charmless B decays are suppressed. It is also possible to produce two charmed hadrons if the W decays for example into a $\bar{c}s$ quark pair (see Fig. 2).

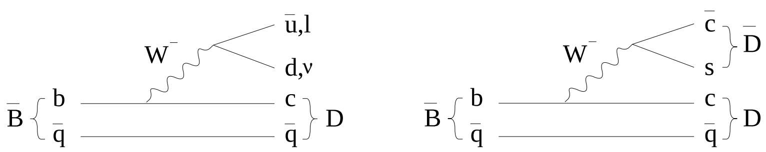

Fig. 2. Charm production in weak decays of b-hadrons.

Therefore one expects n_c which is defined as the number of produced charm quarks in b-hadron decays to be greater than one. To measure n_c the production rates of D^0, D^+, D_s^+ and Λ_c hadrons in $Z^0 \to b\bar{b}$ events are added. One has to take into account the production of charmonia states f($b \to$ charmonia)=$(1.7 \pm 0.5)\%$ (ALEPH) and $(1.95 \pm 0.1 \pm 0.2)\%$ (OPAL). The values for charmonia production are based on measurements on J/ψ production in $Z^0 \to b\bar{b}$ events and extrapolated to include also other charmonia states. ALEPH is also taking into account the production of Ξ_c baryons $f(b \to \Xi_c) = (6.3 \pm 2.1)\%$. The values of n_c measured by ALEPH and OPAL are listed in Table III. Part of the differences of the ALEPH and the OPAL measurements is explained by the missing correction for Ξ_c production. Adding the Ξ_c production value from ALEPH the obtained values of n_c are in agreement with the most recent theoretical calculations of Neubert and Sachrajda [9] ($n_c = 1.20 \pm 0.06$).

TABLE III

Charm production in b-hadron decays.

ALEPH [3]	$n_c = (1.230 \pm 0.036_{\rm stat} \pm 0.038_{\rm syst} \pm 0.053_{br})\%$
OPAL [1]	$n_c = (1.10 \pm 0.045_{\rm stat} \pm 0.060_{\rm syst} \pm 0.037_{br})\%$

Related to the charm production in b-hadron decays is the semileptonic B branching ratio which is defined in the following way.

$$\mathrm{Br}(\mathrm{B}\to l) = \frac{\Gamma(\overline{B} \to Xe\overline{\nu})}{\Gamma_{\rm tot}(\overline{B})}\,.$$

The measurements of the semileptonic branching ratio from CLEO, LEP and SLD cannot be compared directly because of the different b-hadron composition produced at the $\Upsilon(4S)$ and the Z^0 resonance. However one expects the semileptonic branching ratio measured at LEP and SLD to be smaller than at CLEO due to the larger hadronic width of the Λ_b baryon which is only produced at LEP and SLD. However the measurements listed in Table IV show the opposite, but due to the large systematic uncertainties of

TABLE IV

Semileptonic B branching ratios Br(B$\to l$).

LEP-SLD [8]	Br(B$\to l$)=$(11.06 \pm 0.19)\%$
CLEO [10]	Br(B$\to l$)=$(10.49 \pm 0.17_{\rm stat} \pm 0.43_{\rm syst})\%$

the CLEO measurement the difference is not very significant. The LEP-SLD average is obtained from a simultaneous fit to 17 electroweak parameters.

Historically most theoretical predictions of the semileptonic branching ratio have been larger than the measured values. For example Bigi *et al.* [12] have concluded that it is difficult to obtain values for the semileptonic branching ratio of lower than 12.5%. However newer calculation from Bagan *et al.* [13, 14] which are taking higher order QCD corrections into account have increased the rate for the process $b \rightarrow c\bar{c}s$ and therefore lowered the the semileptonic branching ratio. There is no difference of the experimental values and most recent calculations of the semileptonic branching ratio from Neubert and Sachrajda [9], who predict the following values depending on the renormalization scale and the ratio of the quark masses m_c/m_b.

$$\mathrm{Br}(\mathrm{B}\rightarrow l) = \begin{cases} 12.0 \pm 1.0\% & \text{for } \mu = m_b \\ 10.9 \pm 1.0\% & \text{for } \mu = m_b/2 \end{cases} .$$

5. Production of the vector mesons D^{*0}, D^{*+} and D_s^{*+}

The production of D^{*+} mesons is measured at LEP in the decay channel $\mathrm{D}^{*+}\rightarrow\mathrm{D}^0\pi^+$ followed by the decay $\mathrm{D}^0\rightarrow\mathrm{K}^-\pi^+$. Because of the good momentum resolution of charged tracks inside the tracking chambers of the LEP detectors the reconstruction efficiency and the mass resolution in the reconstruction of these decays is very good. D^{*0} mesons decay into a D^0 by emitting a photon or a π^0 meson and D_s^{*+} mesons decay mainly via photon emission into the D_s^+, since π^0 emission is suppressed due to isospin conservation. In the reconstruction of these decays calorimetric photons are used and therefore the mass resolution is much worse. To improve the mass resolution events in which the photon undergoes a photoconversion inside the detector are used but this suffers from low statistics. The vector meson production rates are listed in Table V.

TABLE V

Vector meson production rates.

OPAL [15]	$f(c \rightarrow D^{*+})$=$(22.2 \pm 1.4 \pm 1.4)\%$
	$f(b \rightarrow D^{*+})$=$(17.3 \pm 1.6 \pm 1.2)\%$
	$f(c \rightarrow D^{*0})$=$(21.8 \pm 5.4 \pm 4.5)\%$
ALEPH [2]	$f(c \rightarrow D_s^{*+}) = (7.5 \pm 2.2 \pm 0.5)\%$
	$f(b \rightarrow D_s^{*+}) = (10.2 \pm 3.1 \pm 0.5)\%$

The production rates of D^{*0} and D^{*+} are approximately equal due to isospin invariance, whereas D_s^{*+} production is suppressed by a factor of approximately 0.3 due to strange quark suppression:

$$\frac{f(c \to D^{*0})}{f(c \to D^{*+})} = 0.94 \pm 0.31 \quad \text{and} \quad \frac{f(c \to D_s^{*+})}{f(c \to D^{*+})} = 0.34 \pm 0.11\,.$$

The production ratio of vector and pseudoscalar mesons V/(V+P) is predicted by simple spin counting to be 0.75. However feed down decays from excited states like D^{**} and D_s^{**} reduce this ratio, but this should only affect the D sector since D_s^{**} mesons also decay mainly into D and D^* meson states. Also thermodynamical models which take into account mass effects predict lower values for V/(V+P). Experimentally the ratio V/(V+P) is determined under the assumption of equal production of D^{*0} and D^{*+} mesons. The values obtained by ALEPH and OPAL are listed in Table VI.

TABLE VI

Measurements of V/(V+P) in the D and D_s sector.

	$\frac{2\cdot f(c\to D^{*+})}{f(c\to D^{+})+f(c\to D^{0})}$	$\frac{f(c\to D_s^{*+})}{f(c\to D_s^{+})}$
ALEPH [2]	0.595 ± 0.045	0.64 ± 0.22
OPAL [15]	0.57 ± 0.05	

6. Production of excited states D^{**}, D_s^{**} and $D^{*'}$

In addition to pseudoscalar and vector mesons also higher excited states with angular momentum L=1, so called D^{**} or D_s^{**} mesons, are produced. In the framework of HQET the spin of the light quark couples with the angular momentum to ($j = 1/2$) and ($j = 3/2$). Due to the coupling of the spin of the heavy quark 4 different states grouped in two doublets are formed. The two states of the ($j = 1/2$) doublet D_0^* and D_1 undergo S-wave decays into the ground states and are therefore expected to be broad resonances with a decay width over 100 MeV/c^2. Experimentally these wide states have not yet been observed. The two states of the ($j = 3/2$) doublet D_1^* and D_2^* can only decay via D-wave decays and therefore have a smaller decay width of only a few MeV/c^2. At LEP the narrow D^{**} states are observed in the decay channels ($D_1^{*0}(2420) \to D^{*+}\pi^-$) and ($D_2^{*0}(2460) \to D^{*+}\pi^-$). The two narrow D_s^{**} resonances are observed in the three decay channels ($D_{s1}^{+}(2536) \to D^{*+}K^0$), ($D_{s1}^{+}(2536) \to D^{*0}K^+$) and ($D_{s2}^{*+}(2573) \to D^0K^+$). The production rates of these states in $Z^0 \to b\bar{b}$ and $Z^0 \to c\bar{c}$ events obtained by ALEPH and OPAL are listed in Table VII.

TABLE VII

Production rates of D** and D$_s^{**}$ mesons.

OPAL [16]	$f(c \to D_1^0) = (2.1 \pm 0.7 \pm 0.2)\%$
	$f(b \to D_1^0) = (5.0 \pm 1.4 \pm 0.6)\%$
	$f(c \to D_2^{*0}) = (5.2 \pm 2.2 \pm 1.3)\%$
	$f(b \to D_2^{*0}) = (4.7 \pm 2.4 \pm 1.3)\%$
ALEPH [17]	$f(c \to D_{s1}^+) = (0.77 \pm 0.20 \pm 0.08)\%$
	$f(b \to D_{s1}^+) = (1.1 \pm 0.3 \pm 0.2)\%$
	$f(c \to D_{s2}^{*+}) = (1.3 \pm 0.5 \pm 0.2)\%$
	$f(b \to D_{s2}^{*+}) = (2.2 \pm 0.8 \pm 0.5)\%$

DELPHI [18] now has published evidence for the first observation of the radially excited D$^{*'}$ meson which was observed in the (D$^{*+}\pi^-\pi^+$) final state with a mass of ($2637 \pm 2_{\rm stat} \pm 6_{\rm syst}$) MeV/$c^2$. Whereas the mass of the D$^{*'}$ meson is in the expected range, the production rate is about a factor of two higher than one would expect from thermodynamical models which calculate the production rates from the mass and the spin of the meson state. It would therefore be desirable if this observation could also be confirmed by the other LEP Collaborations.

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