Eur Phys J C **33**, s01, s554–s556 (2004)
Digital Object Identifier (DOI) 10.1140/epjcd/s2004-03-1682-9

EPJ C direct
electronic only

Spectroscopy and charm quark fragmentation

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Received: 30 October 2003 / Accepted: 9 January 2004 /
Published Online: 18 February 2004 –

Abstract. The large data sample accumulated at the KEKB storage ring allows for dedicated analysis in charm spectroscopy. This made the first observations of e.g. the broad D^{**} resonances in B decays as well as other processes possible. The observation of the $D_{sJ}(2317)$ resonances are confirmed and indications of their quantum numbers are given. The fragmentation function for D^{*+} has been measured with unprecedented accuracy.

PACS. 13.25.Hw 13.66.Bc 14.40.Lb

1 Introduction

Although known as B-factories, the asymmetric storage rings PEP-II and KEKB enable the BaBar and Belle detectors to explore the charm sector. Charmed hadrons are not only the dominant decay product of b flavoured mesons, but, in addition, the decay kinematics give valuable constraints allowing the detection of previously unobserved particles and the determination of their quantum numbers. The cross section of e^+e^- into charm is similar to the $B\bar{B}$ production cross section, opening a second door to the charm section via e^+e^-annihilation.

Due to the excellent performance of the accelerators, the data sample available for charm studies at Belle is unprecedented. KEKB recently reached its design luminosity of $\mathcal{L} = 10^{-34}/\mathrm{cm}^2/\mathrm{s}$. Belle accumulated a total integrated luminosity of about 159 fb^{-1}. About 143 fb^{-1} was recorded at the $\Upsilon(4S)$ resonance, with the largest part of the remaining 16 fb^{-1} about 60 MeV below the resonance. In the following a few recent results from the Belle collaboration are presented, see [1] and references therein for more details on the analyses.

2 Spectroscopy

2.1 Charmonium: $\eta_c(2S)$

Recently, Belle has observed the $\eta_c(2S)$ in B decays at a mass of $(3656 \pm 6 \pm 8)$ MeV/c^2 about 60 MeV/c^2 higher than the only previous observation, due to Crystal Ball. A second process where it was seen is in double $c\bar{c}$ production in Belle. It describes the production of a J/Ψ produced in conjunction with another $c\bar{c}$ pair in e^+e^- annihilation. From non-relativistic QCD (NRQCD), it is believed that at $\sqrt{s} \approx 10.6$GeV this process contributes about 10% to the total $e^+e^- \to J/\Psi X$ cross section. Recently, it was found that double $c\bar{c}$ production is the dominant contribution [2] and [3].

Here, a data sample of $\mathcal{L} = 101.8\mathrm{fb}^{-1}$ has been used. The J/Ψ's are inclusively reconstructed, a minimum momentum cut effectively removes decay products from b decays. In the mass spectrum of the system recoiling against the J/Ψ, clear signals of the η_c (175 ± 23 events) and the χ_{c0} (61 ± 21 events) are found. Their fitted masses are in very good agreement with the world averages. A third peak at a mass of (3630 ± 8) MeV/c^2 containing 107 ± 24 events (4.4 σ) is found, identifying it as the $\eta_c(2S)$. The mass determined here is lower than the other determination from Belle by about 2σ, but again significantly higher than the one by Crystal Ball.

This analysis also confirms the surprising large double charm cross section in comparison with the single charmonium cross section in e^+e^- annihilation. More details about this topic can be found in [2] and [3].

Now, the $\eta_c(2S)$ has also been seen in two photon events in BaBar and CLEO.

2.2 Charmed baryons: Ω_C^0

The production of baryons in general and of those containing charm in particular are not well understood. Exact determination of their properties can help improve understanding these particles. For example, the mass of the Ω_C^0, a css state and the heaviest weakly decaying hadron containing single charm, is known only on the permille level, with a spread of about 2.5σ between the only two different measurements by CLEO and E687. In a data sample of $\mathcal{L} = 87.1\mathrm{fb}^{-1}$, the Ω_C^0 has been reconstructed in the $\Omega^-(\Lambda^0 K-)\pi^+$ channel. A momentum cut has been applied to reduce combinatorial background. The fit to the reconstructed mass spectrum of candidate events gives 80.5 ± 10.8 observed Ω_C^0 candidates. From this fit, the mass has been determined to be $M_{\Omega_C^0} = (2.693.9 \pm 1.1 \pm 1.4)$ MeV/c^2. This is in good agreement with the CLEO measurement, but disfavours the E687 measurement.

After extrapolation to the full kinematic momentum range, the production cross section times branching ratio has been determined to be (19.1 ± 9.0) fb. Here, the largest uncertainty comes from the shape of the fragmentation function used for the extrapolation.

In addition, the Ω_C^0 has been reconstructed in the semi-leptonic decay channel to $\Omega^- \ell^+ \nu$. Interference between the s quarks from the original quark content and from the decay of the charm quark can significantly enhance the semi-leptonic branching ratio. Here an Ω is combined with a lepton (e or μ) of the correct charge to form a Ω_C^0 candidate. Similar yields are observed in both channels. The ratio of branching ratios of the above mentioned hadronic decay to this semi-leptonic channel has been measured to be (0.8 ± 0.2) and is higher than the previous CLEO measurement of (0.4 ± 0.2), but still consistent given the large uncertainties.

2.3 D mesons: D^{**}

In the $c\bar{u}$ system, the large mass of the c quark allows the application of heavy quark effective theory (HQET). Assuming an infinite mass for the c quark, its spin decouples and the total angular momentum j_q of the light quark becomes a good quantum number. Therefore, four different P-wave excitations in the $c\bar{u}$ system exist. The two states with momentum $j_q = 3/2$ have already been established. The other two with momentum $j_q = 1/2$ have not been observed yet; a possible observation by CLEO was never published. They are expected to be broad, making their observation difficult.

In a sample of 65 million $B\bar{B}$ mesons, Belle searched for these two broad states. Decays of charged B^- to $D^{(*)}(D^{(+)}) + \pi^-\pi^-$ have been fully reconstructed. In both channels, signal yields of 1101 ± 46 (D^+) and 578 ± 30 (D^{*+}) candidate events were obtained from a fit to the ΔE distributions over very low background due to the two pions of negative charge. ΔE describes the difference of the beam energy and the energy of the reconstructed B candidate.

The decay $B^- \to D^+\pi^-\pi^-$ has previously not been observed. Here, its branching ratio has been determined to be $\mathcal{B}(B^- \to D^+\pi^-\pi^-) = (1.02 \pm 0.04 \pm 0.15) \times 10^{-3}$. The branching ratio of the other decay has been measured to be $\mathcal{B}(B^- \to D^{*+}\pi^-\pi^-) = (1.25 \pm 0.08 \pm 0.22) \times 10^{-3}$. It is lower than, but within uncertainties compatible with the world average.

An unbinned fit to the Dalitz plot has been performed to disentangle the different contributions from various intermediate resonances. The background has been estimated from a fit to sidebands in ΔE. Apart from the narrow D_2^{*0} resonance, a significant contribution of a broad resonance is necessary in order describe the data. The narrow resonance shows a clear structure of a tensor particle in the Dalitz plot as expected from the D_2^{*0}. The broad resonance has never been observed before and is identified with the D_0^{*0}. Its mass has been determined to $M_{D_0^{*0}} = (2308 \pm 17 \pm 15 \pm 28)$ MeV/c^2. The third uncertainty is due to model dependence and is estimated using the differences in fitted masses when neglecting certain particles in the fit to the Dalitz plot. The reduced χ^2 of the fit improved when including two virtual particles, a D_v^* and a B_v^*, parametrising contributions from higher resonances. The same fit gives product branching ratios of the decays of $B^- \to D^+\pi^-\pi^-$ via a D_2^{*0} of $\mathcal{B} = (3.4 \pm 0.3 \pm 0.6 \pm 0.4) \times 10^{-4}$ and via a D_0^{*0} of $\mathcal{B} = (6.1 \pm 0.6 \pm 0.9 \pm 1.6) \times 10^{-4}$, dominating this decay.

For the decay channel into $D^{*+}\pi^-\pi^-$, two broad resonances can contribute to the decay in addition to the narrow resonance D_1^0. One is the newly-observed D_0^{*0}. In the fit to the Dalitz plot, its mass and width has been set to the values obtained in the fit to $B^- \to D^+\pi^-\pi^-$, described above. The second broad resonance contributing was identified with the D_1^0. Its mass has been measured to be $M_{D_1'^0} = (2427 \pm 26 \pm 20 \pm 15)$ MeV/c^2. This is the first observation of this resonance.

The fit also gives the product branching ratios of the final state $B^- \to D^{*+}\pi^-\pi^-$ decaying via $D_1^{'0}$, $\mathcal{B} = (6.8 \pm 0.7 \pm 1.3 \pm 0.3) \times 10^{-4}$, via a D_2^{*0}, $\mathcal{B} = (1.8 \pm 0.3 \pm 0.3 \pm 0.2) \times 10^{-4}$ and via the newly observed $D_1^{'0}$, $\mathcal{B} = (5.0 \pm 0.4 \pm 1.0 \pm 0.4) \times 10^{-4}$.

Though the new particles give a large contribution to the total decay width in the decay modes used here, their large widths made it difficult to observe them.

2.4 D mesons: D_{sJ}

BaBar and CLEO observed two narrow resonances in the mass spectrum of $D_s^{(*)+}\pi^0$. Their masses have been determined to 2317 MeV/c^2 and 2460 MeV/c^2, respectively. In the following they will be referred to as $D_{sJ}(2317)$ and $D_{sJ}(2457)$.

Belle has confirmed both peaks in e^+e^- annihilation, using the above mentioned decay channels, and determined their masses to $M_{D_{sJ}(2317)} = (2317.2 \pm 0.5 \pm 0.9)$ MeV/c^2 and for the other state $M_{D_{sJ}(2457)} = (2456.5 \pm 1.3 \pm 1.1)$ MeV/c^2. No information about their quantum numbers was available so far.

In order to determine quantum numbers and branching ratios, the additional constraints in decays of B mesons are indispensable. An angular analysis of $B \to \overline{D}D_{sJ}$ can help determine branching ratios and will reveal the quantum numbers.

In a sample containing 123×10^6 $B\bar{B}$ events, Belle searched for the decays of B mesons to the new states D_{sJ} accompanied by a $\overline{D}$ meson. Consistent signal yields are found from fits to the distributions of ΔE, M_{bc} and in the invariant mass of the ${D_s}^{(*)}$ and the π^0, the significances are above 6σ.

A clear signal (7.4σ) in another channel was found, $D_{sJ}(2457) \to D_s\gamma$, with a mass of $M_{D_{sJ}(2457)} = (2458.8 \pm 2.7 \pm 2.0)$ MeV/c^2 consistent with the other channel. The large signal in this channel already rules out the $0^\pm$ assignment for the $D_{sJ}(2457)$. In other channels no signal was found, Table 1 lists the different decay modes of the $D_{sJ}(2317)$ and $D_{sJ}(2457)$.

Table 1. The upper two rows describe results for the decay $B \to \overline{D}D_{sJ}(2317)$, the lower five describe the results for $B \to \overline{D}D_{sJ}(2457)$

decay channel	$\mathcal{B},\ 10^{-4}$	significance
$D_{sJ}(2317) \to D_s\pi^0$	$8.5^{+2.1}_{-1.9} \pm 2.6$	6.1σ
$D_{sJ}(2317) \to D_s^*\gamma$	$< 5.8\ (2.5^{+2.0}_{-1.8})$	1.8σ
$D_{sJ}(2457) \to D_s^*\pi^0$	$17.8^{+4.5}_{-3.9} \pm 5.3$	6.4σ
$D_{sJ}(2457) \to D_s\gamma$	$6.7^{+1.3}_{-1.2} \pm 2.0$	7.4σ
$D_{sJ}(2457) \to D_s^*\gamma$	$< 5.6\ (2.7^{+1.8}_{-1.5})$	2.1σ
$D_{sJ}(2457) \to D_s\pi^+\pi^-$	< 1.2	
$D_{sJ}(2457) \to D_s\pi^0$	< 1.2	

Since in the latter decay, the quantum numbers of all other particles except for the $D_{sJ}(2457)$ are well known, an angular analysis can be performed to narrow down further possible spin and parity assignments to this particle. The helicity angle distribution of the $D_{sJ}(2457)$ strongly favours a $\sin^2\theta_{hel}$ distribution, which supports the 1^+ assignment to this particle. Here, the helicity angle θ_{hel} is defined as the angle between $D_{sJ}(2457)$ momentum in the B meson rest frame and the D_s momentum in the $D_{sJ}(2457)$ rest frame.

Belle also searched in e^+e^- annihilation for these particles. The existence of the decay modes $D_{sJ} \to D_s^{(*)}\gamma$ is confirmed, with a signal of 152 ± 18 events. The ratio $\mathcal{B}(D_{sJ}(2457) \to D_s\gamma)$ over $\mathcal{B}(D_{sJ}(2457) \to D_s^*\pi^0)$ has been determined to $0.63 \pm 0.15 \pm 0.15$, to be compared to $0.38 \pm 0.11 \pm 0.04$ determined in B decays. For the $D_{sJ}(2317)$, no signal is seen in the γ channel and an upper limit on the branching ratio of this decay of less than 5% of the branching ratio of $D_{sJ}(2317) \to D_s^{(*)+}\pi^0$ is set at the 90% confidence level.

It is worthwhile to notice that the masses as well as mass differences between the 0^+ and the 1^+ states in the $c\bar{u}$ system and the $c\bar{s}$ system are almost degenerate, i.e. within uncertainties the same.

3 Charm fragmentation

The fragmentation of heavy quarks differs from that of light quarks due to their higher masses. Many different model predictions exist, the model of Peterson et al. being one of the most well known.

The data sample for this analysis consists of 3.65 fb^{-1} taken 60 MeV below and 25.53 fb^{-1} at the $\Upsilon(4S)$ resonance. In the latter sample, a momentum cut removes contributions from B decays. For now, only the fragmentation of c into D^{*+} has been measured; the analysis will be extended to include other charmed hadrons in the future. The D^{*+} has been reconstructed in the fully charged decay channel $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$. Various binnings in the scaled momentum of the D^{*+} candidate have been used, 10 bins for comparison with other measurements, 50 bins for the comparison between different models and 100 bins for the determination of the mean scaled momentum. The scaled momentum x_P is defined as the momentum of the D^{*+} candidate in the $\Upsilon(4S)$ rest frame, scaled to its maximum allowed value of about 4.89 GeV/c^2.

Table 2. Different fragmentation functions compared to the data. The free parameters of each fragmentation functions has been tuned for best agreement with data, regardless of their influence on other distributions

fragment'n fct	$\chi^2_{\min}$	value at minimum	sample
Bowler et al.	59.2/49	$a = 0.23,\ b = 0.568$	off-res
	166.8/24	$a = 0.21,\ b = 0.532$	on-res
Lund	110.6/49	$a = 0.68,\ b = 0.58$	off-res
	517.0/24	$a = 0.61,\ b = 0.58$	on-res
Kartvelishvili	122.2/49	$\alpha_c = 3.6$	off-res
et al.	1050.7/24	$\alpha_c = 3.5$	on-res
Collins-Spiller	185.44/49	$\varepsilon_c = 0.089$	off-res
	736.9/24	$\varepsilon_c = 0.093$	on-res
Peterson et al.	300.6/49	$\varepsilon_c = 0.054$	off-res
	1613.1/24	$\varepsilon_c = 0.052$	on-res

This determination has been compared to two other measurements of ARGUS and CLEO, which were based on a much smaller data set about 1/30 the size of the present analysis. The data agree very well.

The data has been compared to various models: the above-mentioned Peterson et al, Kartvelishvili et al, Bowler, Collins and Spiller and the Lund model. Table 2 lists the value of the model parameters in the minimum. The Bowler models agrees best with the data.

The mean value for the scaled momentum of the D^* has been determined with the off-resonance sample to $\langle x_P(D^{*\pm})\rangle = 0.610 \pm 0.003(\text{stat.}) \pm 0.004(\text{syst.})$.

4 Conclusion

Although being a dedicated B factory, the Belle detector at the KEKB storage ring has been proven to give valuable contribution to the charm physics sector. In Belle, the $\eta_c(2S)$ has been seen in both B decays and double $c\bar{c}$ production. The broad P-wave D^{**} states have been observed for the first time. The new particles observed by BaBar and CLEO have been confirmed, and their possible quantum numbers have been narrowed. Last, but not least, the charm quark fragmentation into D^{*+} has been measured with a much larger data sample.

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