Is the fragmentation of charm quarks into D mesons described by heavy quark effective theory?

André David *

CFTP-IST, Lisbon, Portugal and
CERN-PH, Geneva, Switzerland

Abstract

Heavy quark effective theory predicts that produced charm quarks have the same probability to fragment into any of the four D mesons with orbital angular momentum $L=0$: the singlet D state and the triplet D^* states. This would imply $P_V(D^*, D) = 3/4$, where P_V is the ratio between directly produced $L=0$ vector states (D^*) and all $L=0$ (D and D^*) states. Experimental data collected in several different collision systems (e^+e^- , hadro-production, photo-production, etc.) and over a broad range of collision energies, show that $P_V(D^*, D) = 0.594 \pm 0.010$. From this observation, it follows that “naive spin counting” does not apply to charm production, implying a revision of charm production calculations where this assumption is made.

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* Now at LIP, Lisbon, Portugal.

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André David*
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Introduction

Ever since the discovery of the J/ψ meson, the study of charm production has been an important item in the physics agenda of many high-energy experiments. On one hand, the charm quark is relatively heavy, so that charm production can be studied through perturbative QCD calculations. On the other hand, it is light enough so that statistically significant measurements can be made even by experiments using relatively low energy beams.

The measured charged and neutral D mesons account for $\sim 80\%$ of the total production cross section of charm quarks, the remainder ending in D_s mesons (10%), Λ_c hadrons (7.6%) and other charmed hadrons or charmonia [1]. A recent collection of p-A and π -A collision data [2] shows that the collision energy dependence of the measured charged and neutral D meson cross-sections is well reproduced by PYTHIA, a well-known Monte Carlo event generator [3]. However, the normalisations are off by the so-called K -factors, which happen to be around two times higher for the charged than for the neutral mesons [2, 4]. The measured D^+/D^0 ratio from hadro-production experiments is 0.41 ± 0.03 , whereas PYTHIA with default settings yields 0.32.

The best known charmed mesons are the D, D^* , D_1 and D_2^* . All the heavier states finish in a D^+ or D^0 (charge conjugation is implied throughout this article: D^+ also stands for D^- , and D^0 for $\bar{D}^0$) through a decay chain fully symmetric with respect to the light flavour content [5], except for the $D^{*0} \rightarrow D^+$ decay, which is forbidden since $m_{D^{*0}} - m_{D^+} < m_{\pi^-}$. This way, all D^{*0} mesons decay into D^0 mesons, whereas D^{*+} mesons decay into both D^+ and D^0 mesons.

We will focus on the D and D^* mesons, the states with the lowest lying orbital angular momentum, $L=0$, since they are the most abundantly produced. The only difference between these states is their total angular momentum, $J = L + S$: the D^* mesons are a $J=1$ vector spin triplet, while the D mesons are a $J=0$ pseudoscalar spin singlet. When populating the states formed when

fragmenting a charm quark into a charmed $L=0$ meson, it can be argued that the mass of the c quark is much larger than that of the light quark, as done in heavy quark effective theory (HQET) [6, 7, 8]. The result is that all spin states become equivalent and, consequently, D^* mesons should be produced 3 times more often than D mesons. This picture is also commonly called “naive spin counting”. Defining $P_V = V/(V+P)$, the fraction of directly produced $L=0$ vector mesons, HQET then predicts that $P_V = 3/(3+1) = 0.75$.

Extracting P_V from experimental data

To determine P_V we need to consider the production of charmed mesons taking into account the decay structure of D and D^* mesons and sources of feed-down.

The only known feed-down contributions are: B mesons decaying into D and D^* mesons; $L \geq 1$ D mesons (D_1 , D_2^* , etc.) decaying into D and D^* mesons; D_{s1} and D_{s2} mesons decaying into D^* mesons; and the $\psi(3770)$ decays into D mesons. In our study we neglect all these sources of feed-down for the following reasons: feed-down from B decays is tagged experimentally as shown, e.g., by CDF [9]; excited charmed mesons have an effect $< 5\%$ in the measured D meson yields [10, 11, 12, 13, 14, 15] and decay symmetrically into D and D^* states [5]; excited charmed strange mesons have an even smaller effect than excited charmed mesons, since their production cross-sections are lower; and $\psi(3770)$ decays have a negligible contribution, except for the data collected in e^+e^- collisions at $\sqrt{s} \sim m_{\psi(3770)}$.

Finally, we assume that the direct production of D mesons follows isospin symmetry. This implies that the yields of *directly produced* D^0 and D^+ mesons are identical, as well as D^{*0} and D^{*+} , according to experimental evidence [10, 16, 17].

This way we can express the production of D^* mesons as $\sigma^{D^*} = \kappa P_V$, where κ is a constant representing the fraction of the charm quark production cross-section ending in charmed mesons. For D^0 and D^+ we need to in-

clude terms accounting for the feed-down from D^* decays:

$$\begin{aligned}
 \sigma^{D^0} &= \sigma_{\text{direct}}^{D^0} + \sigma_{\text{feed-down}}^{D^0} \\
 &= \sigma_{\text{direct}}^{D^0} + \sigma^{D^*} [\text{Br}(D^{*+} \rightarrow D^0) + \text{Br}(D^{*0} \rightarrow D^0)] \\
 &= \kappa (1 - P_V) + \kappa P_V (\text{Br}^* + 100\%) \\
 &= \kappa (1 + P_V \text{Br}^*),
 \end{aligned}$$

where Br^* is $\text{Br}(D^{*+} \rightarrow D^0) = (67.7 \pm 0.5)\%$ [5]. Similarly, it follows that $\sigma^{D^+} = \kappa (1 - P_V \text{Br}^*)$. Given the present accuracy of the measurements of Br^* , the only factor that can significantly affect the ratio of measured D^0 and D^+ mesons is the proportion of directly produced vector states, P_V .

The value of P_V can be determined from any simultaneous measurement of at least two of the production cross-sections of D^0 , D^+ , D^{*+} or D^{*0} mesons. The latter is not commonly measured, since among its decay products there is always a γ or a π^0 .

The first P_V estimate for charmed mesons is due to the CLEO Collaboration, which published the value $0.85 \pm 0.11 \pm 0.17$ in 1988 [18]. This result, consistent with 0.75, persuaded the community that “naive spin counting” worked for charm. However, starting from the product $P_V \text{Br}^* = 0.44 \pm 0.04 \pm 0.05$ from the same publication, and using the present value of Br^* , we obtain $P_V = 0.65 \pm 0.09$. In fact, correcting all the cross-section measurements of [18] for the “time evolution” of branching fractions we obtain $P_V = 0.52 \pm 0.05$, substantially lower than the value given in 1988.

In the 1990’s, several experiments published P_V values close to 0.75 from D^* polarisation analyses [19, 20, 21, 22]. These values averaged to 0.764 ± 0.012 , apparently confirming HQET expectations. However, what these experiments really measured were the relative abundances of D^* ($J=1$) mesons in their different spin states, $j_z = -1, 0$ and 1 , which were seen to be very similar. To determine P_V , these experiments then *assumed* that the amount of D and D^* mesons with $j_z=0$ was the same, using Ref. [23] as their basis. In a subsequent D^* polarisation analysis, the CLEO Collaboration abandoned this practice understanding that this assumption strongly biased the P_V values previously published [24].

In our study we have collected many and varied measurements of charmed meson production that can lead to an estimate of P_V . All measured cross-sections in the original publications were corrected for the most recent knowledge of branching fractions from Ref. [5]. When propagating uncertainties we have combined all quoted errors (statistical and systematic) in quadrature.

For each experiment we evaluate P_V by performing a simultaneous fit of the updated measurements to the equations

$$\sigma^{D^0} = \kappa (1 + P_V \text{Br}^*)$$

FIG. 1: P_V values as a function of the collision energy. Dashed vertical lines signal the successive meson pair production thresholds, while the horizontal lines indicate the band 0.594 ± 0.010 and the HQET expectation of 0.75.

FIG. 2: P_V values per collision system, for measurements with $\sqrt{s} > 2m_{D^{**}}$.

$$\begin{aligned}
 \sigma^{D^+} &= \kappa (1 - P_V \text{Br}^*) \\
 \sigma^{D^*} &= \kappa P_V
 \end{aligned}$$

if all three cross-sections have been measured. If only two measurements (or their ratio) are available, we perform the ratio of the corresponding equations and solve it for P_V . If an experiment quotes a value of P_V that was obtained with current branching fractions, we use it directly. To obtain the final value we perform a weighted average of all values of P_V for $\sqrt{s}$ above the $D^{**}D^{**}$ production threshold, $2m_{D^{**}} = 4.92$ GeV.

Table I summarises the values of P_V for each experiment, while Figs. 1 and 2 show them as a function of centre-of-mass energy and production process, respectively.

Figure 1 shows that there is no strong dependence on $\sqrt{s}$. The measurements performed at the lowest energies are either not relevant (if below the D^* production threshold) or not robust, since none of the experiments at these low $\sqrt{s}$ values measured D^* mesons. When we average all P_V values for $\sqrt{s} > 2m_{D^{**}}$, we obtain

System	$\sqrt{s}$ (GeV)	Experiment	Ref.	P_V
Electro-production $\sqrt{s} < 2m_{D^*}$				
e^+e^-	3.771	MARK-II	[25]	<i>0.36 ± 0.11</i>
e^+e^-	3.773	BES	[25]	<i>0.26 ± 0.08</i>
e^+e^-	3.774	MARK-I	[25]	<i>0.29 ± 0.17</i>
Electro-production $2m_{D^*} < \sqrt{s} < 2m_{D^{**}}$				
e^+e^-	4.03	BES	[26]	<i>0.78 ± 0.09</i>
e^+e^-	4.14	BES	[26]	<i>1.00 ± 0.22</i>
e^+e^-	3.88-5.20	MARK-II	[27]	<i>0.76 ± 0.06</i>
Electro-production $\sqrt{s} > 2m_{D^{**}}$				
e^+e^-	5.20-6.70	MARK-II	[27]	<i>0.69 ± 0.14</i>
e^+e^-	10.55	CLEO	[18]	<i>0.52 ± 0.05</i>
e^+e^-	10.6	ARGUS	[28]	<i>0.61 ± 0.07</i>
e^+e^-	91.2	ALEPH	[29]	<i>0.595 ± 0.045</i>
e^+e^-	91.2	DELPHI	[17]	<i>0.620 ± 0.032</i>
e^+e^-	91.2	OPAL	[10]	<i>0.57 ± 0.05</i>
e^+e^-	91.2	SLD	[30]	<i>0.65 ± 0.10</i>
Photo-production				
γ -Be	13.73	NA14/2	[31]	<i>0.64 ± 0.16</i>
γ -Be	16.52	E691	[32]	<i>0.608 ± 0.045</i>
γ -p	215	ZEUS	[16]	<i>0.566 ± 0.037</i>
Hadro-production				
π^- -Si	19.39	NA32	[33]	<i>0.60 ± 0.13</i>
K^- -Si	19.40	NA32	[33]	<i>0.42 ± 0.18</i>
π^- -Cu	20.79	NA32	[34]	<i>0.58 ± 0.09</i>
$\pi^\pm$ -A	21.68	E769	[35]	<i>0.59 ± 0.05</i>
$K^\pm$ -A	21.68	E769	[35]	<i>0.46 ± 0.09</i>
p-A	21.70	E769	[35]	<i>0.43 ± 0.11</i>
π^- -A	25.64	WA92	[36]	<i>0.597 ± 0.018</i>
p-A	41.56	HERA-B	[37]	<i>0.57 ± 0.12</i>
d-Au	200	STAR	[38]	<i>0.55 ± 0.29</i>
p- $\bar{p}$	1960	CDF	[39]	<i>0.641 ± 0.035</i>
Other				
ν_μ -A	45.3	NOMAD+CHORUS[40]		<i>0.48 ± 0.18</i>
DIS	319	H1	[41]	<i>0.61 ± 0.07</i>
All $\sqrt{s} > 2m_{D^{**}}$				0.594 ± 0.010

TABLE I: P_V values determined from different sources of experimental data. Values in italic signal experiments that did not measure D^* mesons.

0.594 ± 0.010 .

Figure 2 shows (for $\sqrt{s} > 2m_{D^{**}}$) the values in groups related to the production process, confirming the universality of P_V .

Remarks related to the use of Pythia

In PYTHIA there are three parameters in the PARJ array that allow the user to set the P_V values. PARJ(13)

E791 data [43]		Default PYTHIA PARJ(13) = 0.75	Tuned PYTHIA PARJ(13) = 0.6
$D^0\bar{D}^0$	$0.50 \pm 0.04 \pm 0.01$	0.57	0.47
D^0D^-	$0.20 \pm 0.02 \pm 0.01$	0.20	0.21
$D^+\bar{D}^0$	$0.18 \pm 0.02 \pm 0.01$	0.17	0.21
D^+D^-	$0.12 \pm 0.02 \pm 0.01$	0.06	0.09
χ^2/ndf		2.6	1.1

TABLE II: Comparison between measured charmed meson pair production fractions and PYTHIA values obtained using two different PARJ(13) settings. The agreement with the data is substantially improved using the P_V value determined in this study.

controls both charmed and beauty mesons. Its default value is 0.75, the “naive spin counting” expectation of HQET which, as we have shown, does not apply to charmed mesons. For light mesons PARJ(11) = 0.5, whereas for strange mesons PARJ(12) = 0.6, following evidence and ideas expressed by Field and Feynman already in 1978 [42].

Table II shows a comparison of PYTHIA simulations with D meson pair production data from E791 [43], which was not used in our “world average” of P_V . It can be clearly seen that the description of the data improves significantly when using PARJ(13) = 0.6.

Furthermore, PYTHIA with PARJ(13) = 0.6 also a D^+/D^0 ratio of 0.44, in very good agreement with the measured average of p-A and π -A data: 0.41 ± 0.03 [2].

We finish with a remark concerning experiments which extract charm production cross-sections from the yields of (high- p_T) single leptons. The total electron yield from D^+ and D^0 meson decays depends on the proportions of each of these mesons in the final state. Changing P_V from 0.75 to 0.6 leads to 20% more D^+ and 7% less D^0 for the same total charm production cross-section. Since $\text{Br}(D^+ \rightarrow e^+X) = 2.5 \text{ Br}(D^0 \rightarrow e^+X)$, it follows that if $P_V = 0.6$ instead of $P_V = 0.75$ we have a 13% higher electron yield for the same amount of produced charm quarks. Therefore, charm production cross-sections derived from high- p_T electrons using models where $P_V = 0.75$ should be down-scaled by a factor 0.89.

Summary and conclusions

In the last 20 years, measurements of the production of charmed mesons have reached a precision level that allows to confront theoretical predictions made in the framework of HQET with the data.

We have collected many measurements from which a P_V value for charmed mesons can be estimated. Averaging measurements with $\sqrt{s} > 2m_{D^{**}}$ leads to $P_V(D^*, D) = 0.594 \pm 0.010$ as the fraction of directly

produced D^* mesons, far below 0.75, the value expected in HQET.

Using this value of P_V in PYTHIA, instead of the default 0.75, leads to a much better description of available data, including the E791 measurements of charm pair production yields.

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* Present address: LIP, Lisbon, Portugal; Electronic address: Andre.David@cern.ch

- [1] L. Gladilin (1999), hep-ex/9912064.
- [2] H. K. Wöhri and C. Lourenço (2006), Phys. Rep. in print, CERN/PH-EP/2006-013.
- [3] T. Sjöstrand, S. Mrenna, and P. Skands, JHEP **05**, 026 (2006), hep-ph/0603175.
- [4] P. Braun-Munzinger, D. Miskowiec, A. Drees, and C. Lourenço, Eur. Phys. J. **C1**, 123 (1998), nucl-ex/9704011.
- [5] W.-M. Yao et al. (PDG), J. Phys. **G33**, 1 (2006).
- [6] E. Eichten, Nucl. Phys. Proc. Suppl. **4**, 170 (1988).
- [7] E. Eichten and B. Hill, Phys. Lett. **B243**, 427 (1990).
- [8] E. Eichten and B. Hill, Phys. Lett. **B234**, 511 (1990).
- [9] D. Acosta et al. (CDF), Phys. Rev. Lett. **91**, 241804 (2003), hep-ex/0307080.
- [10] K. Ackerstaff et al. (OPAL), Eur. Phys. J. **C5**, 1 (1998), hep-ex/9802008.
- [11] K. Ackerstaff et al. (OPAL), Z. Phys. **C76**, 425 (1997).
- [12] C. Bourdarios (1998), hep-ex/9811014.
- [13] P. Avery et al. (CLEO), Phys. Lett. **B331**, 236 (1994), hep-ph/9403359.
- [14] T. Bergfeld et al. (CLEO), Phys. Lett. **B340**, 194 (1994).
- [15] J. C. Anjos et al. (Tagged Photon Spectrometer), Phys. Rev. Lett. **62**, 1717 (1989).
- [16] S. Chekanov et al. (ZEUS), Eur. Phys. J. **C44**, 351 (2005), hep-ex/0508019.
- [17] P. Abreu et al. (DELPHI), Eur. Phys. J. **C12**, 225 (2000).
- [18] D. Bortoletto et al. (CLEO), Phys. Rev. **D37**, 1719 (1988).
- [19] H. Aihara et al. (TPC/Two-Gamma), Phys. Rev. **D43**, 29 (1991).
- [20] Y. Kubota et al. (CLEO), Phys. Rev. **D44**, 593 (1991).
- [21] S. Abachi et al. (HRS), Phys. Lett. **B199**, 585 (1987).
- [22] H. Albrecht et al. (ARGUS), Phys. Rept. **276**, 223 (1996).
- [23] J. F. Donoghue, Phys. Rev. **D19**, 2806 (1979).
- [24] G. Brandenburg et al. (CLEO), Phys. Rev. **D58**, 052003 (1998), hep-ex/9802022.
- [25] M. Ablikim et al. (BES), Phys. Lett. **B603**, 130 (2004), hep-ex/0411013.
- [26] J. Z. Bai et al. (BES), Phys. Rev. **D62**, 012002 (2000), hep-ex/9910016.
- [27] M. W. Coles et al., Phys. Rev. **D26**, 2190 (1982).
- [28] H. Albrecht et al. (ARGUS), Z. Phys. **C52**, 353 (1991).
- [29] R. Barate et al. (ALEPH), Eur. Phys. J. **C16**, 597 (2000), hep-ex/9909032.
- [30] K. Abe et al. (SLD) (1997), SLAC-PUB-7574.
- [31] M. P. Alvarez et al. (NA14/2), Z. Phys. **C60**, 53 (1993).
- [32] J. C. Anjos et al. (Tagged Photon Spectrometer), Phys. Rev. Lett. **62**, 513 (1989).
- [33] S. Barlag et al. (ACCMOR), Z. Phys. **C39**, 451 (1988).
- [34] S. Barlag et al. (ACCMOR), Z. Phys. **C49**, 555 (1991).
- [35] G. A. Alves et al. (E769), Phys. Rev. Lett. **77**, 2388 (1996).
- [36] M. Adinolfi et al. (BEATRICE), Nucl. Phys. **B547**, 3 (1999).
- [37] A. Zoccoli et al. (HERA-B), Eur. Phys. J. **C43**, 179 (2005).
- [38] M. Calderon de la Barca Sanchez et al. (STAR), Eur. Phys. J. **C43**, 187 (2005).
- [39] CDF (2003), CDF Note 6623, URL http://www-cdf.fnal.gov/physics/new/bottom/030403_blessed-dxsec/.
- [40] G. De Lellis, F. Di Capua, and P. Migliozi, Phys. Lett. **B550**, 16 (2002), hep-ph/0210383.
- [41] A. Aktas et al. (H1), Eur. Phys. J. **C38**, 447 (2005), hep-ex/0408149.
- [42] R. D. Field and R. P. Feynman, Nucl. Phys. **B136**, 1 (1978).
- [43] E. M. Aitala et al. (E791), Eur. Phys. J. direct **C1**, 4 (1999), hep-ex/9809029.