LABORATORI NAZIONALI DI FRASCATI
SIS – Pubblicazioni

LNF–95/061 (P)
4 Dicembre 1995

Charm Lifetimes and Semileptonic Decays

S. Bianco

INFN – Laboratori Nazionali di Frascati, P.O. Box 13, I 00044–Frascati (Roma) Italy

PACS.: 13.20.Fc; 13.20.-v; 13.30.Ce

Invited mini–review talk given at the
1995 International Europhysics Conference on High Energy Physics
Brussel, Belgium, July 27 – August 2, 1995

1 Introduction

The study of lifetimes and semileptonic (SL) decays of charmed mesons and baryons is currently the goal of several experiments all around the world.

$$\tau = \frac{\hbar}{\Gamma_{leptonic} + \Gamma_{SL} + \Gamma_{nonleptonic}} \quad (1)$$

This paper is focussed on giving an overview of current status and open questions, and on reviewing new results by E687 and CLEO presented as contributed papers at this Conference. A wealth of detailed reviews exists on both charm lifetimes[5]-[2] and SL decays [3]-[4]-[1], some very up-to-date, which the reader can refer to for details.

2 Lifetimes

In the case of charmed hadrons, the picture of states being made of a heavy quark Q and a cloud of light quarks q and gluons, with essentially a unique lifetime independent of both the number of light partners and their flavor, is grossly contradicted by experiment: the lifetimes differ widely both between mesons and baryons ($D^+/\Xi_c^0 \sim 10$), and among mesons ($D_s^+/D^0 = 1.125 \pm 0.042$, $D^+/D^0 = 2.547 \pm 0.043$). Since the SL partial widths are compatible:

$$B(D^+ \to e^+X) = (17.2 \pm 1.9)\% \, (PDG94) \quad (2)$$

$$B(D^0 \to e^+X) = (6.97 \pm 0.18 \pm 0.30)\% \, (CLEO) \quad (3)$$

$$\frac{\Gamma(D^0 \to e^+X)}{\Gamma(D^+ \to e^+X)} = \frac{B(D^0 \to e^+X)}{B(D^+ \to e^+X)} \frac{\tau(D^+)}{\tau(D^0)} \quad (4)$$

$$= 1.03 \pm .12 \quad (5)$$

while the leptonic partial widths are negligible:

$$\Gamma_{leptonic} \sim 10^{-3} - 10^{-4} \quad (6)$$

as shown in eq.1 the extra rate is in the nonleptonic width. W-exchange diagrams (partially helicity- and color-suppressed), W-annihilation diagrams, Pauli interference of the decay and the spectator quarks, all conspire in increasing the D^+ lifetime with respect to the other charmed mesons. Theoretical consensus does exist on the prediction

$$\tau(D^+) > \tau(D^0) \sim \tau(D_s^+) \quad (7)$$

while the extent of the $\sim$ sign is not clear. In the charmed baryon sector, on the other hand, the presence of a second light quark makes W-exchange neither helicity- nor color-suppressed, thus increasing the spread in lifetimes. Predictions span quite widely[6]-[7]:

$$\tau(\Omega_c^0) < \tau(\Xi_c^0) < \tau(\Lambda_c^+) \sim \tau(\Xi_c^+) \quad (8)$$

Table 1: Measurements of the Ω_c^0 lifetime (ps), beams, and decay channels.

E687 [8]	WA89 [9]
$0.086^{+0.027}_{-0.020} \pm 0.028$	$0.055\,^{+0.013}_{-0.011}\,^{+0.018}_{-0.023}$
γ, 220 GeV	Σ^-, 340 GeV/c
$\Sigma^+(p\pi^0, n\pi^+)K^-K^+\pi^+$	$\Xi^- K^-\pi^+\pi^+, \Omega^-\pi^+\pi^-\pi^+$

$$\tau(\Omega_c^0) \sim \tau(\Xi_c^0) < \tau(\Lambda_c^+) < \tau(\Xi_c^+) \tag{9}$$

$$\tau(\Omega_c^0) < \tau(\Xi_c^0) \quad OR \quad \tau(\Omega_c^0) > \tau(\Xi_c^+) \tag{10}$$

Charm lifetimes are therefore a probe for hadronic dynamics; they also are a tool for b-physics items such as tagging, $B^0 - \bar{B}^0$ mixing, and CP violation.

Experimentally, the field is mature for charm mesons. Over the past 10 years fixed-target photoproduction experiments E691 and, recently, E687 [10] have provided precision measurements well beyond the prediction power of theory. They both employed a microstrip silicon detector for the detection of production and decay vertices, and the measurement of decay lengths.

The scenario for baryons is less statistically satisfactory. Still, a definite hierarchy has emerged

$$\begin{aligned} \tau(\Omega_c^0) \le \tau(\Xi_c^0) < \tau(\Lambda_c^+) < \tau(\Xi_c^+) < \\ < \tau(D^0) < \tau(D_s^+) < \tau(D^+) \end{aligned} \tag{11}$$

with the E687 measurement of the Ω_c lifetime [8] being confirmed at this Conference by the new WA89 value [9] (Table 1).

Table 2 shows the most precise measurements compared to the PDG94 average.

3 Semileptonic decays

Semileptonic decays are relatively simple to handle theoretically, since the decay matrix decouples into a weak current (describing the $W\ell\nu_\ell$ vertex), and a strong current (for the $Wc\bar{q}$ vertex) that is parameterized through functions - form factors (f.f.) - of the invariant mass (q^2) of the W exchanged. Measuring the f.f. and their q^2 evolution provides useful insights into quark dynamics, model-dependent information on absolute branching ratios, and is a playground for theories on interpolation to the beauty-related CKM elements V_{ub} and V_{cb}. Experimentally, rates are not too small, but the undetected neutrino forbids us to close the event kinematically, and we are left with demonstrating that the final state is indeed exclusive.

Table 2: Lifetimes of D^+, D^0, D_s^+, Λ_c^+, Ξ_c^0, Ξ_c^+ (ps)

	E687	PDG94
D^+	$1.048 \pm 0.015 \pm 0.011$	1.057 ± 0.015
D^0	$0.413 \pm 0.004 \pm 0.003$	0.415 ± 0.004
D_s^+	$0.475 \pm 0.020 \pm 0.007$	0.467 ± 0.017
Λ_c^+	$0.215 \pm 0.016 \pm 0.008$	$0.200^{+0.011}_{-0.010}$
Ξ_c^0	$0.101^{+0.025}_{-0.017} \pm 0.005$	$0.098^{+0.023}_{-0.015}$
Ξ_c^+	$0.41^{+0.11}_{-0.08} \pm 0.02$	$0.35^{+0.07}_{-0.04}$

Experiments studying SL in e^+e^- annihilations exploit the favorable charm-to-background ratio, while having to cope with the relatively small cross section; they also usually enjoy excellent γ and π^0 reconstruction capabilities.

In fixed-target hadroproduction the charm cross section is higher, with the background of light quarks also larger. Fixed-target photoproduction is somehow midway, with more favorable signal-to-noise. Crucial is the possibility of exploiting excellent primary and secondary vertexing.

Common techniques to both e^+e^- and fixed-target are D^*-tagging (i.e., selecting D's coming from the $D^* \to D\pi$ decay), wrong-sign subtraction, kinematic cuts, and particle identification [1].

3.1 $D \to$ (*Pseudoscalar*) $\ell\nu$

The differential decay rate for the decay of a charmed meson to a pseudoscalar meson, a lepton, and a neutrino has the dependence

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2 |V_{cq}|^2 P^3}{24\pi^3} \left\{ |f_+(q^2)|^2 + |f_-(q^2)|^2 \mathcal{O}(m_\ell^2) + ... \right\} \tag{12}$$

where P is the momentum of the pseudoscalar meson in the reference frame of the charmed meson, and the $Wc\bar{q}$ vertex is described by only two f.f., $f_\pm(q^2)$.

The $f_\pm(q^2)$ form factors [note that $f_-(q^2)$ becomes unimportant in the limit of zero lepton mass] are usually parameterized as

$$F_\pm(q^2) = \frac{f_\pm(0)}{(1 - q^2/M_{pole}^2)} \tag{13}$$

or

$$F_\pm(q^2) = f_\pm(0) e^{\alpha q^2}. \tag{14}$$

Table 3: $B(D_s^+ \to \phi e^+\nu)/B(D_s^+ \to (\eta+\eta')e^+\nu)$ (the ISGW2 predictions are for -10° and -20° $\eta-\eta'$ mixing angles respectively)

CLEO first measurement [20]	$0.60 \pm 0.06 \pm 0.06$
ISGW2 [22]	0.60, 0.69

The form in eq.13 relies [11]-[12] on the coupling of the $c\bar{q}$ quarks to the virtual $W^\pm$ being dominated by bound states of the $c\bar{q}$ system; in the case of $D \to K\ell\nu$ decay, one expects that M_{pole} should be set to the mass of the vector $D_S^*(2110)$ since it has the same spin-parity as the $c\bar{s}$ current. Equation 14 is suggested by the ISGW model [13]. However, the two forms are not distinguishable in the range probed by $K\ell\nu$ decays ($q^2 < 2\,GeV^2/c^4$), while sensitivity exists for $\pi\ell\nu$ decays ($2 < q^2 < 3\,GeV^2/c^4$) (ref.[3]).

E687 has recently reported[14] on the analysis of 1897±62 events in the decay mode $D^0 \to K^-\mu^+\nu_\mu$. The strategy followed was to increase the event statistics by relaxing the D^*-tag requirement[15]. Results are shown in Table 4, including the first measurement of the f.f. ratio at $q^2 = 0$, which is consistent with the theoretical estimates, which range from -1.2 to -0.4. The M_{pole} is now 2.2σ away from the $D_s^*(2110)$. Finally, the ratio

$$\frac{B(D^0 \to K^{*-}\mu^+\nu_\mu)}{B(D^0 \to K^-\mu^+\nu_\mu)} \tag{15}$$

in agreement with previous measurements and different from unity as so far predicted by theory, confirms the so-called vector-to-pseudoscalar puzzle.

The CLEO group has submitted to this Conference [20] the first measurement of the branching ratios of the decays $D_s^+ \to \eta\ell^+\nu_\ell$ and $D_s^+ \to \eta'\ell^+\nu_\ell$ [where $\ell = \mu(mostly), e$], relative to $B(D_s^+ \to \phi\ell^+\nu_\ell)$. This measurement constitutes a real steeplechase for their new CsI calorimeter [21]. The calorimeter is used for detecting many-photon final states, such as $\eta \to \gamma\gamma$, $\eta' \to \eta(\to \gamma\gamma)\pi^+\pi^-$, and also for the tagging mode $D_s^{*+} \to D_s^+\gamma$ used to clean up the high statistics mode. Their first measurement (Table 3) is consistent with the 0.56±0.06 world average of the ratio (eq.15), and confirm the existence of a vector-to-pseudoscalar puzzle. A recent paper [22] is also quoted, in which a prediction of 0.6 is derived for the vector-to-pseudoscalar ratio, in good agreement with their result.

The importance of the Cabibbo-suppressed decays $D \to \pi\ell\nu$ deserves to be stressed, since they allow one to probe f.f. models over an extended q^2 range. CLEO has measured $|f_+^\pi(0)/f_+^K(0)|$ in both $D^+ \to \pi^0\ell^+\nu_\ell$ [23] and $D^0 \to \pi^-\ell^+\nu_\ell$[24] channels. Results are consistent with theoretical predictions ranging from 0.7 to 1.4. The challenging π^0 channel does not suffer from the $\pi^\pm/K^\pm$ misidentification background.

3.2 $D \to$ (*Vector*) $\ell\nu$

The decay of a charm meson to a vector meson involves a hadronic current described by two axial $A_{1,2}(q^2)$ and one vector $V(q^2)$ f.f. (neglecting m_ℓ^2 terms). Traditionally[25]-[26] one measures the ratios $R_V \equiv V(0)/A_1(0)$, $R_2 \equiv A_2(0)/A_1(0)$, and assumes a pole form for the f.f.'s with $M_A = M_{D_s^{**}} = 2.5\,GeV/c^2$ and $M_V = M_{D_s^*} = 2.1\,GeV/c^2$.

The decay $D^+ \to \bar{K}^{*0}\ell^+\nu_\ell$ has been studied by E691, E653, and E687. No new measurements are available, and the latest results on R_V, R_2 and polarizations are quite consistent and agree with lattice calculations.

The decay $D^+ \to \phi\ell^+\nu_\ell$ is also important, since it can be used to obtain a model-dependent estimate of the absolute branching ratio for $D_s^+ \to \phi\pi^+$:

$$\begin{aligned} B(D_s^+ \to \phi\pi^+) &= \tau(D_s) \times \\ model \to \quad & \frac{\Gamma(D_s^+ \to \phi\ell^+\nu_\ell)}{\Gamma(D \to \overline{K}^*\ell^+\nu_\ell)} \times \\ & \Gamma(D \to \overline{K}^*\ell^+\nu_\ell) \times \\ & \frac{\Gamma(D_s^+ \to \phi\pi^+)}{\Gamma(D_s^+ \to \phi\ell^+\nu_\ell)} \end{aligned} \qquad (16)$$

This decay has been studied by E653[27], E687[28], and CLEO-II[29]. No new results are available, errors are large, and no clear agreement is found either among experiments, or with the K^{*0} channel.

3.3 Semileptonic Baryon Decays

Both CLEO[30]-[33] and ARGUS[31] have data on the decay $\Lambda_c \to \Lambda\ell^+\nu$, while data on $\Xi_c \to \Xi\ell^+\nu$ only come from CLEO[32]. Particularly interesting is the measurement of the polarization of the Λ in the final state, for which an explicit prediction is made by HQET [34]. Finally, CLEO evidence for $\Omega_c \to \Omega e^+\nu$ was shown recently [4], new results with improved statistics are expected soon [35].

4 Conclusions

Charm lifetimes are a stage for precision physics: E687 has measured meson lifetimes at a level of precision beyond that presently predictable by theory, while measuring the lifetimes of all known charm baryons, including the first measurement of the Ω_c^0. The new measurement presented by WA89 at this Conference confirms that the Ω_c^0 has the shortest lifetimes of all known charm particles. New data are expected by CERN WA89, and Fermilab E791, E831, SELEX .

Precise, consistent data is available for the SL decays of charm mesons to pseudoscalar light mesons. New E687 results have been presented on $K\mu\nu$ decay, including the first measurement of the f.f. ratio at $q^2 = 0$. Due to the limited q^2 range accessible, one cannot

Table 4: Preliminary results for the E687 new measurement of $D^0 \to K^- \mu^+ \nu_\mu$.

Reference	$\frac{B(D^0 \to K^- \mu^+ \nu_\ell)}{B(D^0 \to K^- \pi^+)}$	$M_{pole}(GeV/c^2)$	$\frac{B(D^0 \to K^{*-} \mu^+ \nu_\mu)}{B(D^0 \to K^- \mu^+ \nu_\mu)}$
[14] (E687 95)	0.852± 0.034±0.028	$1.87^{+0.11+0.07}_{-0.08-0.06}$	0.62±0.07±0.09
[17] (CLEO 93)	0.978± 0.027±0.044	2.00± 0.12±0.18	0.62± 0.08
[18] (CLEO 91)	0.79± 0.08±0.09 (μ *only*)	$2.0^{+0.4+0.3}_{-0.2-0.2}$	0.51± 0.18±0.06
[16]-[19] (E691)	0.91± 0.07±0.11	$2.1^{+0.4}_{-0.2} \pm 0.2$	0.55± 0.14
Reference	$\Gamma(D^0 \to K^- \ell^+ \nu_\mu) 10^{10} s^{-1}$	$f_+(0)$	$f_-(0)/f_+(0)$
[14] (E687 95)	8.07±0.37 ± 0.44	0.71±0.03±0.02	$-1.3^{+3.6}_{-3.4} \pm 0.6$
[17] (CLEO 93)	9.1±0.3 ± 0.6	0.77±0.01±0.04	
[18] (CLEO 91)		0.81±0.03±0.06	
[16] (E691)	9.1±1.1 ± 1.4	0.79±0.05±0.06	

tell the pole form from the exponential: new data in the Cabibbo-suppressed channel $\pi \ell \nu$ would be welcome, to extend the q^2 range. CLEO has presented the first measurement of the $D \to (\eta, \eta') \ell \nu$ branching ratios, which confirms the so-called vector-to-pseudoscalar puzzle. Data on SL decays to vector light mesons are still confused, partially in disagreement with theory, with large errors. New results should be expected from Fermilab E831, E791 and Beijing BES.

Acknowledgements

I would like to thank all my E687 fellow collaborators for their efforts, continuous discussions and information. Particular thanks go to G.Bellini, J.Cumalat, S.Malvezzi, L.Perasso and S.Ratti (E687), S.Paul and L.Rossi (WA89), S.Menary (CLEO). I finally thank the Organizers for a perfectly enjoyable Conference.

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