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OPEN QUESTIONS IN CHARM DECAYS DESERVING AN ANSWER ¹

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Abstract

A list is given of those open questions concerning the dynamics of charm decays where there exists a strong need for an answer. Such a need is based on lessons to be learnt about QCD – either in their own right or for a better understanding of B physics – or on searches for New Physics with a small background from the Standard Model. The major items on this list are: lifetimes of the $\Xi_c^{0,+}$ baryons; semileptonic branching ratios of D_s , Λ_c and Ξ_c hadrons and absolute branching ratios for those states; radiative decays $D \rightarrow \gamma K^*$, $\gamma \rho/\omega$, $D_s \rightarrow \gamma \phi/\omega$, $D \rightarrow l^+ l^- K/K^*$; $D^0 - \bar{D}^0$ oscillations down to a sensitivity below 10^{-4} and CP asymmetries in non-leptonic D decays down to 0.1%. Ongoing and already approved experiments will produce important new insights, which are unlikely to provide sufficient answers to all these questions yet. It is discussed how a third-generation fixed-target experiment like CHARM2000 or a τ -charm factory can fill the bill.

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One can always raise further issues about a physical system. Yet the mere fact that some questions still wait for an answer does not mean that there exists any real need for obtaining those answers. My discussion will therefore proceed in three steps: first I will list those open questions concerning the physics of charm decays, which, in my judgement, strongly deserve an answer; next I will try to anticipate which of those will be answered to which degree in ongoing or already approved experiments, including those at the asymmetric B factories; in the final step I will attempt to evaluate to which degree new initiatives, such as a new generation fixed-target experiment – as envisioned by CHARM2000 – or a tau-charm factory, can make significant new contributions.

In passing I would like to note that intriguing open questions remain also concerning charm production, such as the nature of leading particle effects, the size of associated (i.e. $\Lambda_c \bar{D}$) production and of diffractive charm production, the specifics of charm-anticharm correlations etc. However, I will not address these in this note.

1 Worthy Open Questions in Charm Decays

According to the Standard Model (SM) charm decays constitute a decidedly dull affair: the relevant KM parameters $V(cs)$ and $V(cd)$ are well known; for the smallness of $|V(cb)|$ and $|V(ub)|$ constrains $V(cs)$ and $V(cd)$ very tightly through KM unitarity. Slow $D^0 - \bar{D}^0$ oscillations, small CP asymmetries and tiny branching ratios for rare decays are expected.

This is actually the Pessimist's perspective; the Optimist will look at these statements and re-interpret them in a constructive way:

- Because $V(cs)$ and $V(cd)$ are well-known *a priori*, one can employ charm decays to study the workings of QCD in a novel environment under *controlled* laboratory conditions.
- Precisely because the SM promises us no drama in charm decays, one can conduct searches for $D^0 - \bar{D}^0$ oscillations, CP violation and rare charm decays as probes for New Physics (NP) with an almost zero background from the SM.
- In addition it now appears that these phenomena might become observable after all at the new facilities, even if they occur only at the level of the SM expectations.

Let me first summarize our present understanding of charm decays:

1.1 Lifetimes

While most predictions of charm lifetimes have historically turned out to be embarrassing for theory (or at least for the authors involved), postdictions have done much better. While this is not very surprising, it represents a non-trivial success, if it is based on a systematic and self-consistent treatment. Heavy Quark Expansions (HQE) provide us with such a framework. To be sensitive to lifetime differences among charm *mesons*, one has to go to order $1/m_c^3$. In the table below I have juxtaposed the 'Predictions' for the lifetime ratios [1, 2] with present data.

	QCD($1/m_c$ expansion)	Data
$\tau(D^+)/\tau(D^0)$	~ 2 (mainly due to <i>destructive</i> interference)	2.50 ± 0.05
$\tau(D_s)/\tau(D^0)$	$1 \pm \text{few} \times 0.01$	1.13 ± 0.05
$\tau(\Lambda_c)/\tau(D^0)$	~ 0.5	0.51 ± 0.05

In evaluating the theoretical entries in this table one has to keep in mind that the theoretical uncertainty is estimated to be around 30%; the observed value for $\tau(D^+)/\tau(D^0)$ is thus reproduced within the expected errors.

Lifetimes for charm-strange baryons have been measured as well, yet with quite unsatisfactory errors, as listed in the next table.

	QCD($1/m_c$ expansion)+ quark models [2]	Data
$\tau(\Xi_c^+)/\tau(\Lambda_c)$	~ 1.3	1.68 ± 0.5
$\tau(\Xi_c^+)/\tau(\Xi_c^0)$	~ 2.8	2.46 ± 0.75

Considering that m_c represents at best a moderately large expansion parameter, the agreement between theoretical expectations and present data is better than could have been anticipated. I can identify a need for improved experimental accuracy only in two respects: (i) Present data on the lifetimes of $\Xi_c^{0,+}$ baryons clearly leave something to be desired. A 10% accuracy on $\tau(\Xi_c^{0,+})$ represents an appropriate goal; a similar measurement of $\tau(\Lambda_c)$ would be neat. Such data would provide us with valuable cross checks of the $1/m_c$ expansion for baryon decays, yield indirect information on terms of higher order in $1/m_c$ not yet computed, and allow us to make numerically meaningful extrapolations to beauty baryon lifetimes. (ii) Measuring the ratio $\tau(D_s)/\tau(D^0)$ with $\sim 1\%$ precision would provide us with a rather sensitive gauge for the impact of ‘weak annihilation’ (WA) in charm decays and for the weight of $SU(3)_{Fl}$ breaking.

1.2 Semileptonic Decays of Charm Hadrons

Somewhat dated measurements read

$$b_{SL}(D^+) \equiv BR(D^+ \rightarrow e^+ X) = 17.2 \pm 1.9\% \quad (1)$$

$$b_{SL}(D^0) \equiv BR(D^0 \rightarrow e^+ X) = 7.7 \pm 1.2\% . \quad (2)$$

whereas a very recent CLEO analysis has yielded:

$$b_{SL}(D^0) = 6.97 \pm 0.18 \pm 0.30\% . \quad (3)$$

Their ratio is consistent with the observed $D^+ - D^0$ lifetime ratio. The absolute numbers are also reproduced reasonably well in the $1/m_c$ expansion [3].

$BR(D_s \rightarrow lX)$ has not been measured yet (only constrained), nor have $BR(\Xi_c^{0,+} \rightarrow lX)$; I also remain unconvinced that $BR(\Lambda_c \rightarrow lX)$ has truly been measured. It should be noted that while $\Gamma(D^+ \rightarrow lX_s) = \Gamma(D^0 \rightarrow lX_s)$ holds, due to isospin invariance, no symmetry argument can be invoked for $\Gamma(\Lambda_c \rightarrow lX_s)$ vs. $\Gamma(D^0 \rightarrow lX_s)$; in the $1/m_c$ expansion one actually finds $\Gamma_{SL}(\Lambda_c) \sim (0.85 - 0.9) \times \Gamma_{SL}(D)$ through order $1/m_c^2$.

The lepton energy spectra have been measured in inclusive D decays, but not with a high degree of accuracy; the Cabibbo-suppressed $c \rightarrow d$ transitions have not been identified there yet. Exclusive decays such as $D \rightarrow l\nu K/K^*$ have been studied and $D^0 \rightarrow l\nu\pi$ have been seen.

Yet the overall data base is highly unsatisfactory and calls for a significant improvement. The insights to be gained from it concerning the workings of QCD would be valuable not only in their own right, but would be a great asset in understanding the weak decays of beauty hadrons in general and in extracting $|V(cb)|$ and $|V(ub)|$ in particular. To be more specific: (i) The semileptonic widths of D , D_s , Λ_c and preferably Ξ_c should be measured with at least 5% accuracy. Comparing them with each other and the corresponding non-leptonic widths will illuminate the impact of WA. (ii) The observed value of $\Gamma_{SL}(D)$ yields an important calibration point for understanding the semileptonic width of B mesons as a function of $|V(cb)|$. (iii) Analysing the lepton *spectra* in inclusive semileptonic decays separately of D^0 , D^+ and D_s mesons, in particular in the endpoint region, will provide us with rather direct information on the weight of WA and other hadronization effects.

1.3 Absolute Branching Ratios

Absolute branching ratios for D^0 and D^+ decays have been determined with 5-10% accuracy. Nothing is known in this respect about Ξ_c and precious little about Λ_c decays. Reviewing events over the last two years I feel little confident that the absolute branching ratios for D_s decays are known to better than 30% – if even that.

I regard this situation as truly embarrassing, since the absolute charm branching ratios constitute an important ‘engineering input’ in beauty physics. The uncertainties in the charm branching ratios are emerging as the limiting factor in determining the branching ratios of beauty decays such as $B \rightarrow l\nu D^{(*)}$, $B_s \rightarrow l\nu D_s^{(*)}$ and $\Lambda_b \rightarrow l\nu \Lambda_c$, with obvious consequences for extracting a numerical value for $|V(cb)|$. Any analysis of the charm content in B decays depends on the absolute branching ratios of charm hadrons, and any claim of a ‘charm deficit’ is therefore severely compromised by our ignorance in that respect.

1.4 Rare Decays

An observation of D^+ , $D_s^+ \rightarrow \mu^+\nu, \tau^+\nu$ will allow a reliable extraction of the values for the decay constants f_D and f_{D_s} . A battery of theoretical estimates cluster around [4]

$$f_D \sim 200 \pm 30 \text{ MeV}, f_{D_s} \sim 200 \pm 30 \text{ MeV}, f_{D_s}/f_D \simeq 1.15 - 1.2 \quad (4)$$

The Mark III upper bound on $D^+ \rightarrow \mu^+\nu$ yields $f_D \leq 290 \text{ MeV}$ at 90% C.L. Recent studies by CLEO and WA75 on $D_s \rightarrow \mu^+\nu$ yield $f_{D_s} = 344 \pm 37 \pm 52 \pm 42 \text{ MeV}$ [5] (for $BR(D_s \rightarrow \phi\pi) = 3.7\%$) and $f_{D_s} = 232 \pm 45 \pm 20 \pm 48 \text{ MeV}$ [6], respectively. I view these as pilot studies, establishing in principle that such decays can be observed and measured not only at $D\bar{D}$ threshold.

The occurrence of radiative decays such as $D \rightarrow \gamma K^*$, $\gamma\rho/\omega$ or $D_s \rightarrow \gamma\phi, \gamma\rho/\omega$ *per se* would not be remarkable theoretically, since they can proceed via WA coupled with photon emission off the initial light antiquark line. Yet their observation would serve an important ulterior motive. For it has been suggested [7] that the KM parameter $|V(td)|$ can be extracted from exclusive radiative B decays: $BR(B \rightarrow \gamma\rho/\omega)/BR(B \rightarrow \gamma K^*) \simeq |V(td)|^2/|V(ts)|^2$. This is based on the assumption that both radiative transitions are dominated by the electromagnetic penguin operator. There is however a fly in the ointment of this interesting suggestion: WA coupled with photon emission also generates $B \rightarrow \gamma\rho/\omega$ transitions and this WA contribution is independent of $|V(td)|$ and estimated to be roughly comparable in size to the penguin contribution¹! Ignoring such a contribution would lead to the extraction of an incorrect number for $|V(td)|$. Radiative charm decays on the other hand do not receive any significant contributions from penguin operators, only from WA. Measuring $BR(D \rightarrow \gamma K^*)$ and $BR(D \rightarrow \gamma\rho/\omega)$ will provide us with an important calibration for gauging the impact of WA on $B \rightarrow \gamma\rho/\omega$. As a rough estimate one expects $BR(D \rightarrow \gamma K^*) \sim 10^{-5} - 10^{-4}$ and $BR(D \rightarrow \gamma\rho/\omega) \sim 10^{-6} - 10^{-5}$ [8].

There is actually a nice bonus to be found in measuring these charm decays: New Physics can generate $c \rightarrow u\gamma$ transitions leading to $D \rightarrow \gamma\rho/\omega$, but not to $D \rightarrow \gamma K^*$. Observing

$$\frac{BR(D \rightarrow \gamma\rho/\omega)}{BR(D \rightarrow \gamma K^*)} \neq \tan^2 \theta_c \quad (5)$$

would then signal the intervention of NP, of which non-minimal SUSY is one relevant example [9]!

¹WA also contributes to $B^- \rightarrow \gamma K^{*-}$, but that can be neglected.

1.5 $D^0 - \bar{D}^0$ Oscillations

According to the SM the rate for $D^0 - \bar{D}^0$ oscillations is quite slow, namely

$$r_D \equiv \frac{\Gamma(D^0 \rightarrow l^- X)}{\Gamma(D^0 \rightarrow l^+ X)} \sim \mathcal{O}(10^{-4}). \quad (6)$$

The $D^0 - \bar{D}^0$ transitions are driven by long-distance dynamics within the SM; the prediction stated in Eq.(6) therefore suffers from considerable numerical uncertainties. The best available experimental bound comes from E691:

$$r_D \leq 3.7 \times 10^{-3} \text{ (90\% C.L.)}. \quad (7)$$

There is intrinsically nothing to prevent NP to intervene at this level; i.e. a measurement with improved sensitivity could reveal a positive signal. Observing a non-vanishing value for r_D between 10^{-4} and 10^{-3} would at present not constitute irrefutable evidence for NP, considering the uncertainties in the SM prediction. There is some hope that those can be reduced in the future, partly through theoretical efforts and partly through more precise and comprehensive data on $D^0 \rightarrow K^+ K^-, \pi^+ \pi^-, K^0 \bar{K}^0, \pi^0 \pi^0, \pi^- K^+, K \bar{K} \pi, 3\pi, K \bar{K} \pi \pi, 4\pi$ modes. For a more reliable estimate of $\Gamma(D^0 \rightarrow \bar{D}^0)$ can be obtained from a dispersion relation involving the measured branching ratios for the channels common to D^0 and \bar{D}^0 decays.

1.6 CP Violation in Charm Decays

CP asymmetries of very different forms and shapes can arise in charm decays: they can involve $D^0 - \bar{D}^0$ oscillations or represent direct CP violation; in the latter case they can refer to decay widths or to final-state distributions like T -odd correlations in $D \rightarrow K \bar{K} \pi \pi$ modes.

1.6.1 Direct CP Violation

Since direct CP asymmetries require the interference of two different weak amplitudes with different strong phases, one has the best (and within the SM the only) chance to observe such an effect in Cabibbo-suppressed charm decays like $D^0 \rightarrow K^+ K^-, \pi^+ \pi^-; D^+ \rightarrow K^+ K^- \pi^+, \phi \pi^+$. No CP asymmetry has been observed yet, with the best bounds so far coming from E687 and CLEO:

Decay mode	Measured asymmetry	90% C.L. limit
$D^0 \rightarrow K^+ K^-$	0.024 ± 0.084 [10]	$-11\% < A_{CP} < 16\%$
	0.071 ± 0.065 [11]	$-3.6\% < A_{CP} < 17.8\%$
$D^+ \rightarrow K^- K^+ \pi^+$	-0.031 ± 0.068 [10]	$-14\% < A_{CP} < 8.1\%$
$D^+ \rightarrow K^{*0} K^+$	-0.12 ± 0.13 [10]	$-33\% < A_{CP} < 9.4\%$
$D^+ \rightarrow \phi \pi^+$	0.066 ± 0.086 [10]	$-7.5\% < A_{CP} < 21\%$
$D^0 \rightarrow K_S \phi$	-0.005 ± 0.067 [11]	$-11.5\% < A_{CP} < 10.5\%$
$D^0 \rightarrow K_S \pi^0$	-0.011 ± 0.030 [11]	$-6\% < A_{CP} < 3.8\%$

The requirement to encounter strong final-state interactions does not pose any problem in principle, since charm decays proceed in the resonance region below 2 GeV; yet at the same time it introduces an element of considerable numerical uncertainty into the predictions. A rough estimate suggests that within the SM direct CP asymmetries could be as ‘large’ as $\mathcal{O}(10^{-3})$ [12, 13]. Fitting a set of quark diagrams to describe a host of non-leptonic two-body modes of D mesons leads to quite a similar conclusion [14]. It is not inconceivable that NP could enhance these asymmetries somewhat, say to the 1% level.

Larger effects could surface in the Dalitz plots for $D \rightarrow K \bar{K} \pi, 3\pi$ or in T -odd correlations, like for example $\langle \vec{p}_{\pi^\pm} \cdot (\vec{p}_{K^+} \times \vec{p}_{K^-}) \rangle$ in $D^\pm \rightarrow K^+ K^- \pi^\pm \pi^0$.

1.6.2 CP Asymmetries involving $D^0 - \bar{D}^0$ Oscillations

In the presence of $D^0 - \bar{D}^0$ oscillations and for a channel f common to D^0 and \bar{D}^0 decays, the required interference can occur between the amplitudes for $D^0 \rightarrow f$ and $\bar{D}^0 \rightarrow f$. Examples for such final states are $f = K^+K^-$, $\pi^+\pi^-$, $K_s\pi^0$, $K_S\omega$, $K_S\eta$. Ignoring the possibility of direct CP violation one writes down:

$$\begin{aligned}\Gamma(D^0 \rightarrow f; t) &= e^{-\Gamma_D t} |T(D^0 \rightarrow f)|^2 \left(1 - \text{Im} \frac{q}{p} \bar{\rho}_f \sin \Delta m_D t\right) \\ \Gamma(\bar{D}^0 \rightarrow f; t) &= e^{-\Gamma_D t} |T(\bar{D}^0 \rightarrow f)|^2 \left(1 + \text{Im} \frac{q}{p} \bar{\rho}_f \sin \Delta m_D t\right)\end{aligned}\quad (8)$$

with $\bar{\rho}_f = T(\bar{D}^0 \rightarrow f)/T(D^0 \rightarrow f)$, denoting the ratio of decay amplitudes and q/p reflecting $D^0 - \bar{D}^0$ oscillations. Three observations should be noted here [15]:

(i) While this CP asymmetry becomes unobservable for $\Delta m_D = 0$, it actually is proportional to $\Delta m_D/\Gamma_D$ for small values of Δm_D . The quantity r_D , introduced in eq.(6), on the other hand is given by $\frac{1}{2}(\Delta m_D/\Gamma_D)^2$. (For simplicity I ignore $\Delta\Gamma_D$ effects although, within the SM, one expects very roughly $\Delta\Gamma \sim \mathcal{O}(\Delta m_D)$.) Thus the experimental bound on r_D translates into $\Delta m_D \leq 0.09 \cdot \Gamma_D$ and the CP asymmetry

$$A_{CP}^f \equiv \frac{\Gamma(\bar{D}^0 \rightarrow f; t) - \Gamma(D^0 \rightarrow f; t)}{\Gamma(\bar{D}^0 \rightarrow f; t) + \Gamma(D^0 \rightarrow f; t)} \simeq \frac{\Delta m_D}{\Gamma_D} \frac{t}{\tau_D} \text{Im} \frac{q}{p} \bar{\rho}_f \quad (9)$$

could still reach values of several per cent!

(ii) No such luck arises in the SM: for reasons that are quite specific to it, one finds $\Delta m_D \sim \mathcal{O}(0.01)\Gamma_D$ and $\text{Im}(q/p)\bar{\rho} \sim \mathcal{O}(10^{-3})$; i.e. the size predicted by the SM for these kinds of asymmetry is presumably too small to be observable.

(iii) Accordingly one should vigorously search for CP asymmetries involving $D^0 - \bar{D}^0$ oscillations: their dependance on the (proper) time of decay provides a striking experimental signature; observing them – as defined in eq.(9) – with a size of 10^{-3} or above constitutes a clear sign for the intervention of NP.

Hence we arrive at the following benchmarks concerning future studies of CP violation: one should aim for achieving a 10^{-3} sensitivity for CP asymmetries involving $D^0 - \bar{D}^0$ oscillations as well as for direct CP violation. Observation of an effect unequivocally signals the presence of NP in the former case, but not necessarily in the latter.

2 Answers Expected To Be Obtained by Existing or Approved Experiments

Over the next four years I expect important new data to come from experiments at FNAL, CERN, Beijing and Cornell. In five years from now the asymmetric B factories at KEK and SLAC will start to contribute. I anticipate the most significant new information in the following areas:

- (i) A more precise determination of $\tau(D_s)$, and the first fully quantitative measurement of $\tau(\Xi_c^{+,0})$.
- (ii) The first measurement of $BR(D_s \rightarrow l + X)$ and studies of the *inclusive* lepton spectrum in semileptonic D_s decays; the first *direct* determination of $BR(D_s \rightarrow \phi\pi)$.
- (iii) Extracting the *absolute* values of $BR(D \rightarrow K\pi, K\pi\pi)$ to better than 5%.
- (iv) Possibly a measurement of *absolute* Λ_c branching ratios via a $\Sigma_c \rightarrow \Lambda_c\pi$ tag.
- (v) The first quantitative extraction of f_D and f_{D_s} from $D, D_s \rightarrow \mu\nu$.
- (vi) Mapping out the doubly-Cabibbo-suppressed D and D_s decays.

- (vii) A rather comprehensive analysis of Cabibbo-favoured and once-Cabibbo-suppressed D , D_s and possibly Λ_c decays.
- (viii) Detailed studies of exclusive semileptonic decays $D \rightarrow l\nu K/K^*/\pi/\rho$, $D_s \rightarrow l\nu\eta/\phi/K/K^*$ and $\Lambda_c \rightarrow l\nu\Lambda/\Sigma$, with the dependance of the form factors on the momentum transfers measured rather than assumed.
- (ix) A probe of $D^0 - \bar{D}^0$ oscillations down to $r_D \sim 10^{-4}$ and CP asymmetries down to a few per cent.

All these anticipated data will certainly deepen our understanding of the hadrodynamics driving charm decays:

- (a) Applying a comprehensive BSW-type analysis of the two-body modes of D and D_s mesons (and preferably of Λ_c baryons as well) *separately* to Cabibbo-allowed, once- and twice-suppressed decays will undoubtedly reveal clear deviations from the predictions based on factorization, presumably with a definite pattern. It will also help us to arrive at better estimates of $\Delta m_D|_{SM}$, and it will sharpen our understanding of where we can expect the largest direct CP asymmetries, and what size they can reach within the SM.
- (b) It will be immensely instructive to compare detailed data on exclusive semileptonic D , D_s and Λ_c decays with predictions obtained in particular through simulations of QCD on the lattice.
- (c) The improved accuracy in the measurements of $\tau(D_s)$ and $\tau(\Xi_c^{0,+})$ will provide us with a handle to arrive at a quantitative understanding of charm lifetimes and at the same time with a gauge from which to extrapolate to $\bar{\tau}(B_s)$, $\tau(\Lambda_b)$ and $\tau(\Xi_b)$.
- (d) Observing $D^0 - \bar{D}^0$ oscillations and/or CP violation would represent a major discovery; its ramifications would of course depend on the numerical size of the effect.

Yet, despite all this progress, major tasks will remain unaddressed or at least unfinished:

- (i) A $\sim 5\%$ measurement of $\tau(\Omega_c)$ would be quite helpful, although this is not the major item among the unfulfilled tasks.
- (ii) I find it doubtful that the *absolute* branching ratios for D_s , Λ_c or Ξ_c decays will have been determined within even 10%.
- (iii) Likewise, f_D and f_{D_s} will not have been measured to better than 20% or so.
- (iv) Nothing useful will be known about the radiative decays $D \rightarrow \gamma K^*/\rho/\omega$, $D_s \rightarrow \gamma\phi/\rho/\omega$.
- (v) The accuracy will still be unsatisfactory, with which the total semileptonic widths will be known for D , D_s and Λ_c , let alone for Ξ_c ; likewise for the *inclusive* lepton spectra.

At first sight, this list might appear like a rather pitiful collection of small morsels having fallen off the main table. In particular, I have already implied that I expect all two-body channels of D and D_s mesons to have been measured with sufficient accuracy and detail, i.e. including modes with one or two neutrals. Yet I would like to state quite emphatically that the above list represents very major unresolved problems using the criteria given in the introduction:

- Weak decays of charm hadrons constitute a microscope to study the strong interaction effects crucial for a full understanding and thus exploitation of beauty decays.
- Charm decays provide a rather clean lab to search for manifestations of NP in rare D decays, $D^0 - \bar{D}^0$ oscillations and CP violation.

These two aspects will not have been treated with the ‘ultimate’ sensitivity. I therefore conclude: in all likelihood there will remain a strong and identifiable need for another major new initiative for studies of charm decays to understand hadronization effects down to the level of the QCD ‘noise’ and to probe for NP down to the SM ‘noise’ – or to better understand a signal that has emerged!

3 New Initiatives for the Next Millenium

I will attempt to evaluate the potential of two complementary facilities to provide the ‘final’ answers in the physics of charm decays, namely CHARM2000 on the one hand and a τ -charm

factory on the other.

3.1 CHARM2000

A next-generation experiment based on fixed-target production of charm will be able to do a superb job in measuring the *relative* branching ratios of a host of exclusive non-leptonic channels in D , D_s , Λ_c and Ξ_c accurately. I am however not convinced at all that our understanding of charm decays would improve in proportion, since I am sceptical that the theoretical ‘noise’, i.e. the irreducible uncertainties, will drop to the per cent level. I should add one caveat, though: I could see a meaningful progress emanate from CHARM2000 measurements of (quasi-)two-body modes if previous experiments – contrary to my expectations stated above – had failed to measure channels containing two neutrals in the final state with decent accuracy.

In my opinion there are then five main challenges against which the significance and the merits of CHARM2000 can be judged:

- (1) The lifetimes of Ξ_c and preferably also of Ω_c baryons should be measured with an accuracy of at least 5%.
- (2) The decay constants f_D and f_{D_s} should be extracted from $D, D_s \rightarrow \mu\nu$ to within 10%.
- (3) CHARM2000 would again have the statistical muscle to observe the radiative decays $D \rightarrow \gamma K^*/\rho/\omega$, $D_s \rightarrow \gamma\phi/\rho/\omega$ (and also $D \rightarrow l^+l^-K/K^*/\rho/\omega$, etc.) at the transition rate expected for them. The question is whether backgrounds like $D \rightarrow \pi^0 K^* \rightarrow \gamma[\gamma]K^*$ can be controlled.
- (4) Can *absolute* branching ratios be determined to within $\sim 1-2\%$ for D , within $\sim 5\%$ for D_s and within $\sim 10\%$ for Λ_c decays? The strong decay $D^* \rightarrow D\pi$ can be used for calibrating the D branching ratios; for the other charm hadrons new calibration methods have to be pioneered, like $\Sigma_c \rightarrow \Lambda_c\pi$.
- (5) Can $D^0 - \bar{D}^0$ oscillations be probed down to $r_d \sim 10^{-5}$, which almost certainly should reveal a positive signal? Even more crucially, can systematics be controlled to such a degree that a comprehensive search for CP asymmetries involving $D^0 - \bar{D}^0$ oscillations and direct CP violation can be undertaken with a sensitivity of 10^{-3} or even smaller?

There is another aspect to be briefly mentioned, not – in all fairness – as a formal challenge, but rather as a potential bonus of quite significant weight: (i) Can the inclusive semileptonic widths of the different charm hadrons be measured with, say, 5% accuracy?

(ii) Can the lepton energy spectra in inclusive semileptonic charm hadron decays be measured with an accuracy that allows the extraction of the value of $|V(cd)|$ from the endpoint region?

3.2 τ -Charm Factory

The capabilities of a τ -charm factory are quite complementary to those of CHARM2000. Clearly charm lifetimes cannot be measured directly. What can be done – and can be done quite well – is to measure semileptonic branching ratios. For the isospin partner D^+ and D^0 one has: $\tau(D^+)/\tau(D^0) \simeq BR_{SL}(D^+)/BR_{SL}(D^0)$. Yet such a relation does not hold in general for all hadrons; in particular one expects $\tau(\Lambda_c)/\tau(D^0) \neq BR_{SL}(\Lambda_c)/BR_{SL}(D^0)$. Using tagged decays one can determine the *absolute* branching ratios of the various charm hadrons in a clean way. The lepton energy *spectra* in inclusive semileptonic decays both of mesons and of baryons can be studied quite well. Employing beam energy constraints should allow one to measure radiative charm decays such as $D \rightarrow \gamma K^*/\rho/\omega$ rather reliably. Relying on quantum mechanical EPR-like correlations, one can probe for $D^0 - \bar{D}^0$ oscillations, CP asymmetries involving them and direct CP violation [12].

While all this appears feasible in principle, I see two challenges on a practical level:

- (1) Can r_D be probed down to values $\sim 10^{-5}$? Even more importantly, can one acquire the sensitivity to search for $\sim 10^{-3}$ CP asymmetries?

(2) The clean environment at a τ -charm factory has its price: very little charm physics can be done ‘parasitically’; i.e., D , D_s , Λ_c and Ξ_c decays have to be studied at different beam energies corresponding to $D\bar{D}$, $D^*\bar{D}/D\bar{D}^*$, $D_s\bar{D}_s$, $\Lambda_c\bar{\Lambda}_c$ and $\Xi_c\bar{\Xi}_c$ final states. The required statistics has then to be accumulated in the rather limited amount of time available at each beam energy – and these beam energies have to span, merely for charm physics, the region from the $D\bar{D}$ threshold up to at least the Λ_c and very preferably the Ξ_c threshold!

4 Summary

There is a strong and well-defined need for another new generation of charm decay experiments, like CHARM2000 and a τ -charm factory. Very specific challenges can be formulated, which these projects have to overcome. Since their approaches, strengths and drawbacks are quite complementary, it would be wonderful if both could be realized.

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