Charm Physics and the Poor Sleeper’s Impatience

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Disclaimer:
The fascination of charm decays cannot match that of beauty decays anymore than Botticelli can match Michelangelo!

yet:
- test bed for QCD technologies
- charm transitions are a unique portal for obtaining a novel access to the flavour problem with the experimental situation being a priori favourable!
- QCD technologies
- On charm’s promise of New Physics
- Appeal for a comprehensive New Phenomenology
  - $D^0 - \bar{D}^0$ oscillations
  - CP
I. Theoretical Technologies for QCD

- $s$: $m_s < \Lambda$ \hspace{1cm} chiral pert. th.
- $c$: $m_c > \Lambda$ \hspace{1cm} $1/m_c$ expansions (?)
- $b$: $m_b >> \Lambda$ \hspace{1cm} $1/m_b$ expansions !
- $t$: $\Gamma_t \sim O(\Lambda)$ \hspace{1cm} perturb. dynamics

```
1/m_Q exp.
```

- chiral pert. theory
- lattice QCD
- $1/m_Q$ expansions
- quark models (properly used)

```
ground prepared for fruitful feedback
```
I.1 Heavy quark expansions

\[ \gamma(E) \equiv \frac{d\Gamma}{d\ldots} \equiv F \sum c_i (\alpha_s) (\Lambda_i/m_Q)^i \]

- **tools**
  - **effective Lagrangians**
    \[ \mathcal{L}(\Lambda_{UV}) \rightarrow \mathcal{L}(m_Q) \rightarrow \mathcal{L}(\mu) \]
    \[ \Lambda_{UV} \gg m_Q \gg \mu \]
  - **operator product expansion (OPE)**
  - **sum rules**
    \[ \int_0^\infty dE \, w(E) \gamma(E)|_{\text{quarks}} = \int_0^\infty dE \, w(E) \gamma(E)|_{\text{hadrons}} \]
    applied to
    - inclusions: lifetimes, SL BR's, lepton spectra
    - exclusives:
      - SL form factors:
        HQET -- no absolute predictions
      - NL two-body modes
        models still only tool available
        (new framework for $B \rightarrow M_1M_2$ hard to justify here -- but should be tried anyhow!)
1.2 Quark-hadron duality (duality)

\[ \langle d\sigma(\text{quark\&gluon\ d.o.f.}) \rangle = \langle d\sigma(\text{hadr.d.o.f}) \rangle \]

duality

no complete theory yet for duality and its limitations -- but we have moved beyond the folkloric stage in the last few years

we understand physical origins

- hadronic thresholds
- `distant' cuts
- \(1/m_c\) expansions

we have identified mathematical portals

Euclidean \( \exp\{-m_Q/\Lambda\} \)
Minkowskian \( \sin(m_Q/\Lambda) \)
duality -- a very natural concept:

hadronic final state formed in 2 steps

1. hard process in femto universe --
   time scale $\sim 1/m_Q$

2. hadronization soft --

$1/\Lambda$ in restframe of $Q \Rightarrow \sim m_Q/\Lambda^2$ in c.m. frame

$m_Q/\Lambda^2 \gg 1/m_Q$

- gross features determined by 1st step
- duality exact at asymptotic scales
- corrections at finite scales!

illustration by qm model with potential $V(x)$:

- local properties of $V \rightarrow$ integrated rates *
- asymptotic " of $V \rightarrow$ specifics of final state

* unless there are singularities at finite distances
probes:

- OPE
  indirect lessons
- dispers. relat. → sum rules
- resonance models
  direct lessons
- t’Hooft model
  (= QCD in 1+1 dimensions with $N_C \to \infty$)

- over-constraining measurements
  final arbiter!
general findings:

- duality cannot be exact at finite scales
- limitations to duality will depend on the process: \[ \sim \sin(m_Q/\Lambda)/m_Q^k, \quad k \geq 1 \]
- fundamental question:

  is there an OPE -- or not!

- duality violations larger in NL than SL decays, but no fundamental difference!
- difference between local and other versions of duality quantitative rather than qualitative

one particular and obvious problem in charm sector:

expansion parameter \( \Lambda_f/m_c \leq 1 \)

since \( m_c(m_c) = 1.25 \pm 0.1 \text{ GeV} \)

- at best: sizeable uncertainties
- at worst: duality inoperative at charm scale
originally introduced
- to prove confinement and
- bring spectroscopy under theoret. control
now making major contributions to heavy flavour physics... with partially unquenched results

- decay constants
  \[ f(D^0) = \begin{cases} 
  240_{-44}^{+44} & 275_{-20}^{+20} \text{ MeV, lattice } n_f=2 \\
  269_{-22}^{+22} \text{ MeV, exp. WA.} 
  \end{cases} \]

\[ \Delta f(D^0), \Delta f(D^-) \sim \begin{cases} 
  6 - 10 \% \text{, BABAR/BELLE using CLEO method} \\
  2 - 3 \% \text{, } \tau \text{-charm factory} 
  \end{cases} \]

analysis with full unquenching that treats charm quarks dynamically not utopian
semileptonic form factors

\[ D \rightarrow l \nu P \]

in the future:
analysis with full unquenching that treats charm quarks dynamically required and not utopian

my expectation:
charm decays provide rich lab for quantitative tests of lattice QCD
I.4 Synergies

natural feedback between the two technologies

- both defined in Euclidean space
- both “mature”
- similar as well as different expansion parameters
- lattice QCD provides input to $1/m_Q$ expansion

(high sensitivity $\rightarrow$ high accuracy probe for NP!

* charm scale ~ bridge between

$1/m_Q$ expansion and lattice QCD)
II. Present Profile of Weak Dynamics of Charm

- lifetimes

\[ \tau(D^+) > \tau(D^0) \approx \tau(D_s^+) \geq \tau(E_s^+) > \tau(\Lambda_c^+) > \tau(E_c^0) > \tau(\Omega_c^+) \]

| \( \tau(D^+)/\tau(D^0) \) | 2 | Pl in \( \tau(D^+) \) | 2.54 ± 0.03 **
|-----------------|---|----------------|------------------|
| \( \tau(D_s^+)/\tau(D^0) \) | 1.0 – 1.07 | without WA | 1.125 ± 0.042 PDG '98
| | 0.9 – 1.3 | with WA | 1.18 ± 0.02 **
| | 1.08 ± 0.04 | QCD SR | |
| \( \tau(\Lambda_c^+)/\tau(D^0) \) | 0.5 | Quark model matrix elem. | 0.50 ± 0.03 *
| \( \tau(E_c^+)/\tau(\Lambda_c^+) \) | 1.3 | ** | 1.60 ± 0.30 *
| \( \tau(E_c^+)/\tau(E_c^0) \) | 2.8 | ** | 3.37 ± 0.91 *
| \( \tau(\Omega_c^+)/\tau(\Omega_c^+) \) | 4 | ** | 3.56, FOCUS

- semilept. BR's

\[ \text{BR}_{\text{SL}}(D^0) = 6.7\% \quad \text{vs.} \quad \sim 8\% \]
\[ \text{BR}_{\text{SL}}(D^0) = 17.2\% \quad \text{vs.} \quad \sim 16\% \]

OPE term \( \sim 1/m_c^2 \)
Score card:

- predictions better than could have been counted on.
- $1/m_Q$ expansions provide an after the fact rationale for most phenomenological concepts like $\text{PL, WA, WS}$ etc. which are $\sim O(1/m_Q^3)$
- they are more definite about those concepts; e.g., WA has to be nonleading, though still significant.
- predictions for baryon lifetimes are based on QM calculations of expectation values
- need more precise data on $\Xi_c^0$ and $\Xi_c^-$ lifetimes
- the absolute $D^0$ & $D^+$ SL BR's are understood now due to an $O(1/m_Q^2)$ effect
- ratios of SL BR's of baryons do not reflect their lifetime ratios
• **Cabibbo Hierarchy**

\[ H_c \rightarrow l\nu \quad [S=1,0] \quad \text{observed} \]

\[ H_c \rightarrow [S=1,0, +1] \]

• **\( V(cs), V(cd) \)**

**imposing 3-family unitarity**

\[ |V(cs)| = 0.9742 \pm 0.0008 \]

\[ |V(cd)| = 0.222 \pm 0.003 \]

**without imposing 3-family unitarity**

\[ |V(cs)| = 0.880 \pm 0.096 \quad \text{from} \quad D \rightarrow l\nu K \]

\[ \nu N \rightarrow l^+l^- X \]

\[ |V(cd)| = 0.226 \pm 0.007 \quad \text{from} \quad \nu N \rightarrow l^+l^- X \]

\[ D \rightarrow l\nu K \]

**new OPAL analysis of** \( W \rightarrow H_c \ X \)

\[ |V(cs)| = 0.969 \pm 0.058 \]
loop processes...

**general expectations:**

- slow $D^0 - \bar{D}^0$ oscillations
- tiny CP asymmetries
- extremely rare decays
- ~ zero background search for New Physics

**$D^0 - \bar{D}^0$ oscillations**

controlled by two quantities

\[
x_D = \frac{\Delta m_D}{\Gamma_D} \quad y_D = \frac{\Delta \Gamma_D}{2 \Gamma_D}
\]

\[
\Gamma_D = \frac{\Gamma(D^0 \rightarrow l^- X)}{\Gamma(D^0 \rightarrow l^+ X)} \approx \frac{x_D^2 + y_D^2}{2} \quad \text{for } x_D, y_D \ll 1
\]

- $x_D$ and $y_D$ Cabibbo suppressed
- $x_D = 0 = y_D$ in the $SU(3)_F$ limit
- $x_D, y_D < 0.05$

a conservative estimate

\[
x_D, y_D \sim O(0.01)
\]
\[
\begin{align*}
\gamma_D' &= -2.5^{+1.4}_{-1.6} \pm 0.3\% & \text{CLEO, } D \rightarrow K\pi \\
\gamma_D &= 0.8 \pm 2.9 \pm 1.0\% & \text{E 791, } D \rightarrow l\nu K \\
\gamma_D &= 1.0^{+3.8}_{-3.5}^{+1.1}_{-2.1}\% & \text{Belle} \\
\gamma_D &= 3.42 \pm 1.39 \pm 0.74\% & \text{FOCUS, } D \rightarrow KK \\
\gamma_D &= -1.1 \pm 2.5 \pm 1.4\% & \text{CLEO, } D \rightarrow KK, \pi\pi
\end{align*}
\]

i.e., data consistent with zero -- on the \% level
\[ \begin{align*}
\mathcal{CP} \\
\text{time integrated partial widths} \\
\text{possible with SM \& KM in singly Cabibbo suppressed modes} \\
\text{benchmark estimate:} \\
\text{asymmetry } \sim \mathcal{O}(\lambda^4) \sim \mathcal{O}(0.001) \\
data, \text{ WA Osaka '00} \\
A_{\mathcal{CP}}(D^0 \to K^+K^-) &= 0.5 \pm 1.6 \% \\
A_{\mathcal{CP}}(D^0 \to \pi^+\pi^-) &= 2.2 \pm 2.6 \% \\
A_{\mathcal{CP}}(D^\pm \to K^\pm K^-\pi^+) &= 0.2 \pm 1.1 \% \\
\text{CLEO '01} \\
A_{\mathcal{CP}}(D^0 \to K^+K^-) &= 0.05 \pm 2.18 \pm 0.84 \% \\
A_{\mathcal{CP}}(D^0 \to \pi^+\pi^-) &= 2.0 \pm 3.2 \pm 0.8 \% \\
A_{\mathcal{CP}}(D^0 \to K_S\pi^0) &= 0.1 \pm 1.3 \% \\
A_{\mathcal{CP}}(D^0 \to \pi^0\pi^0) &= 0.1 \pm 4.8 \% \\
i.e., data consistent with zero -- on the \% level
\end{align*} \]
unfinished business

- **absolute** BR’s, in particular for $D_s$ and charm baryons
- $\Xi_c$ and $\Omega_c$ lifetimes
- **SL** BR’s of charm baryons
- more precise data on $D_s \rightarrow 1\nu$ and measurements of $D^+ \rightarrow 1\nu$
- **post-MARK III** data on lepton spectra in inclusive **SL** charm decays

all important engineering inputs to beauty studies and some provide interesting lessons on QCD, but ...

is it more than dotting the “i”s and crossing the “t”s?
III. Charm Decays -- Novel Portals to New Physics

III.1 General remarks

SM incomplete!

where to look for New Physics?

- charm only up-type quark allowing full range of indirect searches for New Physics
  - $D^0 - D^0$ oscillations
    - no $T^0 - T^0$ oscill.
      - [no top hadroniz.]
  - CP with $D^0 - D^0$ oscill.
    - cannot occur
  - direct CP in excl. modes with decent BR's
    - tiny BR's, lost coherence
  - charm decays proceed in resonance region
    ⇒ FSI of great vitality:
    - optimal for getting signals
      - (not for interpreting them)
practical advantages and opportunities
  - large rates
  - long lifetimes
  - $D^* \rightarrow D\pi$ flavour tagging

**basic contention:**

charm transitions are a unique portal for obtaining a novel access to the flavour problem with the experimental situation being a priori favourable!
III.2 $D^0 - \bar{D}^0$ oscillations

A tough challenge for theoret. technologies as well!

$$x_D = \frac{\Delta m_D}{\Gamma_D} \quad y_D = \frac{\Delta \Gamma_D}{2\Gamma_D}$$

General bound: $x_D, y_D < 0.05$

A conservative estimate: $x_D, y_D \sim O(0.01)$

<table>
<thead>
<tr>
<th>$y_D'$</th>
<th>CLEO, $D \to K\pi$</th>
<th>$y_D$</th>
<th>E 791, $D \to l\nu K$</th>
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<th>BELLE</th>
</tr>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

The game has just begun!
considerable previous literature

- quark box diagram
  - local operator: $\sim m_b > M_D$
  
  \[
  \begin{array}{c}
  \text{c} \\
  \text{b} \\
  \text{u} \\
  \text{w} \\
  \text{b} \\
  \text{d,s} \\
  \text{d,s} \\
  \text{u} \\
  \text{c} \\
  \end{array}
  \]
  
  \[
  (m_b/M_W)^2
  \]

  $x_D(bb) \sim \text{few} \times 10^{-7}$

- short distance operator: $\sim m_c > \overline{\Lambda}$

  \[
  \begin{array}{c}
  \text{c} \\
  \text{d,s} \\
  \text{u} \\
  \text{w} \\
  \text{d,s} \\
  \text{u} \\
  \text{c} \\
  \end{array}
  \]
  
  \[
  (m_c/M_W)^2 \times \frac{(m_s/m_c)^4}{(m_s/m_c)^4}
  \]

  $x_D(\text{box}) \sim \text{few} \times 10^{-5}$

- long distance contributions:
  use various schemes to describe selected hadronic states:

  $x_D(\text{LD}), y_D(\text{LD}) \sim 10^{-4} - 10^{-3}$
\[ T(\Delta C=2, \omega) = \int d^4x \ e^{-i\omega t} \langle D|\{ \mathcal{L}(x) \mathcal{L}(0) \}_T|D\rangle/4M_D \]

\[ 4 \ T(\Delta C=2, \omega) = A(\omega) + A(-\omega) \]

\[ A(\omega) = -\Delta M_D(\omega) + i\Delta \Gamma_D(\omega)/2 \]

\[ \Delta M_D = \Delta M_D(0), \ \Delta \Gamma_D = \Delta \Gamma_D(\omega) \]

\[ \Delta M_D = (1/2\pi) \text{ P.V. } \int d\omega \ [\Delta \Gamma_D(\omega)/\omega] \]

- expansion in powers of $1/m_c, m_s, KM$

- **OPE**

- **GIM**

\textbf{GIM suppression} $(m_s/m_c)^4$ of usual quark box diagram \textbf{untypically severe}!

\exists \text{ contributions from higher-dimensional operators with a very gentle GIM factor $\sim m_s/\mu_{\text{had}}$ ... due to condensates in the OPE}