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!

topics

- 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	$m_s < \Lambda$	chiral pert. th.	
c	$m_c > \Lambda$	$1/m_c$ expans. (?)	
b	$m_b >> \Lambda$	$1/m_b$ expans. !	
t	$\Gamma_t \sim O(\Lambda)$	perturb. dynamics	$1/m_Q$ exp. / lattice QCD

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

→ ground prepared for fruitful feedback

I.1 Heavy quark expansions

$\gamma(E) \equiv d\Gamma/d\ldots \equiv F\, \Sigma_i c_i\, (\alpha_S)\, (\Lambda_i/m_Q)^i$

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

  $\int_0^\infty dE\, w(E)\gamma(E)|_{quarks} \equiv \int_0^\infty dE\, w(E)\gamma(E)|_{hadrons}$

applied to

- inclusives: lifetimes, SL BR's, lepton spectra

  report card -- later

- exclusives:
  - SL form factors:

    HQET -- no absolute predictions
  - NL two-body modes

    models still only tool available

(new framework for $B \rightarrow M_1 M_2$ hard to justify here -- but should be tried anyhow!)

I.2 Quark-hadron duality (duality)

$< d\sigma(\text{quark\&gluon d.o.f.}) > \equiv < d\sigma(\text{hadr.d.o.f}) >$

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

❶ hard process in femto universe --

time scale $\sim 1/m_Q$

❷ hadronization soft --

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

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

→ gross features determined by 1st step

➡ duality exact at asymptotic scales

corrections at finite scales!

illustration by qm model with potential $V(\mathbf{x})$:

- local properties of V → integrated rates *
- asymptotic " of V → specifics of final state

* unless there are singularities at finite distances

probes:

- OPE → *in*direct lessons
- dispers. relat. → sum rules → *in*direct lessons

- resonance models → direct lessons
- t'Hooft model → direct lessons

  (≡ 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: $\sim \sin(m_Q/\Lambda)/m_Q^k$, $k > 1$
- 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 $\Lambda_i/m_c \leq 1$

since $mc(mc) = 1.25 \pm 0.1$ GeV

- at best: sizeable uncertainties

  at worst: duality inoperative at charm scale

I.3 Lattice QCD

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

$$f(D_s) = \begin{cases} \sout{240 \pm 4 \pm 24,\ 275 \pm 20} \ 255 \pm 30 \text{ MeV, lattice } n_f = 2 \\ 269 \pm 22 \text{ MeV, exp. WA,} \end{cases}$$

probably underestimate!

expectation for the future:

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

analysis with full unquenching that treats charm quarks dynamically not utopian

➥ semileptonic form factors

$$D \to l \nu P$$

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 → 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*

hierarchy

$$\tau(D^+) > \tau(D^0) \sim \tau(D_s^+) \geq \tau(\Xi_c^+) > \tau(\Lambda_c^+) > \tau(\Xi_c^0) > \tau(\Omega_c^+)$$

	$1/m_c$ expect.	comments on expect.	data * PDG '00 ** Osaka '00
$\tau(D^+)/\tau(D^0)$	~ 2	PI in $\tau(D^+)$	2.54 ± 0.03 **
$\tau(D_s)/\tau(D^0)$	1.0 – 1.07 0.9 – 1.3 1.08 ± 0.04	without WA with WA QCD SR	1.125 ± 0.042 PDG '98 1.18 ± 0.02 **
$\tau(\Lambda_c^+)/\tau(D^0)$	~ 0.5	Quark model matrix elem.	0.50 ± 0.03 *
$\tau(\Xi_c^+)/\tau(\Lambda_c)$	~ 1.3	"	1.60 ± 0.30 * 2.14, FOCUS
$\tau(\Xi_c^+)/\tau(\Xi_c^0)$	~ 2.8	"	3.37 ± 0.91 * 3.56, FOCUS
$\tau(\Xi_c^+)/\tau(\Omega_c)$	~ 4	"	5.2 ± 1.8 *

➥ *semilept. BR's*

$BR_{SL}(D^0) =$ 6.7 % vs. ~ 8 %

$BR_{SL}(D^0) =$ 17.2 % vs. ~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 PI, WA, WS etc. which are ~ $O(1/m_Q^3)$
- 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 Ξ_c^0 and Ξ_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*

  $H_c \rightarrow l\nu$ [S=-1,0] 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

  $|V(cs)| = 0.880 \pm 0.096$ from $D \Rightarrow l\nu K$, $\nu N \Rightarrow l^+l^-X$

  $|V(cd)| = 0.226 \pm 0.007$ from $\nu N \Rightarrow l^+l^-X$, $D \Rightarrow l\nu K$

  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

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

$$r_D = \frac{\Gamma\left(D^0 \to l^- X\right)}{\Gamma\left(D^0 \to l^+ X\right)} \approx \frac{x_D^2 + y_D^2}{2} \quad \text{for } x_D, y_D << 1$$

- x_D and y_D Cabibbo suppressed
- $x_D \equiv 0 \equiv y_D$ in the $SU(3)_{Fl}$ limit

➡ $x_D, y_D < 0.05$

a conservative estimate

$$x_D, y_D \sim O\,(0.01)$$

data

$y'_D \equiv -2.5^{+1.4}_{-1.6} \pm 0.3\ \%$	CLEO, $D \to K\pi$
$y_D \equiv 0.8 \pm 2.9 \pm 1.0\ \%$	E 791, $D \to l\nu K$
$y_D \equiv 1.0^{+3.8}_{-3.5}{}^{+1.1}_{-2.1}\ \%$	BELLE
$y_D \equiv 3.42 \pm 1.39 \pm 0.74\ \%$	FOCUS, $D \to KK$ vs. $D \to K\pi$
$y_D \equiv -1.1 \pm 2.5 \pm 1.4\ \%$	CLEO, $D \to KK, \pi\pi$ vs. $D \to K\pi$

i.e., data consistent with zero -- on the % level

- $\not{CP}$

time integrated partial widths

possible with SM & KM in singly Cabibbo suppressed modes

benchmark estimate:

asymmetry ~ $O(\lambda^4)$ ~ $O(0.001)$

data, WA Osaka '00

$A_{CP}(D^0 \to K^+K^-) = 0.5 \pm 1.6$ %

$A_{CP}(D^0 \to \pi^+\pi^-) = 2.2 \pm 2.6$ %

$A_{CP}(D^\pm \to K^\pm K^- \pi^+) = 0.2 \pm 1.1$ %

CLEO '01

$A_{CP}(D^0 \to K^+K^-) = 0.05 \pm 2.18 \pm 0.84$ %

$A_{CP}(D^0 \to \pi^+\pi^-) = 2.0 \pm 3.2 \pm 0.8$ %

$A_{CP}(D^0 \to K_S\pi^0) = 0.1 \pm 1.3$ %

$A_{CP}(D^0 \to \pi^0\pi^0) = 0.1 \pm 4.8$ %

i.e., data consistent with zero -- on the % level

Interlude -- Info on Charm as Engineering Input

- unfinished business
  - absolute BR's, in particular for D_s and charm baryons
  - Ξ_c and Ω_c lifetimes
  - SL BR's of charm baryons
  - more precise data on $D_s \rightarrow l\, \nu$ and measurements of $D^+ \rightarrow l\, \nu$
  - 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.]
  - $\not{CP}$ with D^0-D^0 oscill. — cannot occur
  - direct $\not{CP}$ 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
  - $D^* \to D\pi$ 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!

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

general bound: $x_D, y_D < 0.05$

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

$y'_D = -2.5^{+1.4}_{-1.6} \pm 0.3\ \%$	CLEO, $D \to K\pi$
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$y_D = 3.42 \pm 1.39 \pm 0.74\ \%$	FOCUS, $D \to KK$ vs. $D \to K\pi$
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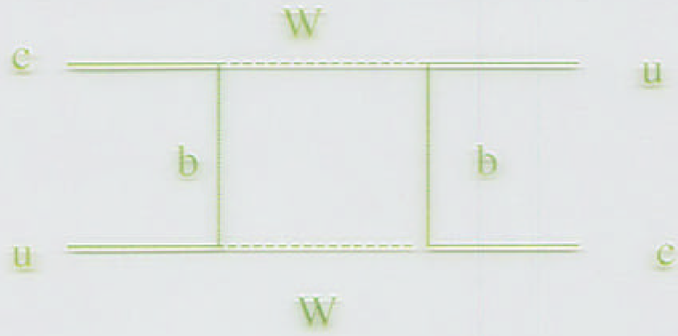
the game has just begun!

considerable previous literature

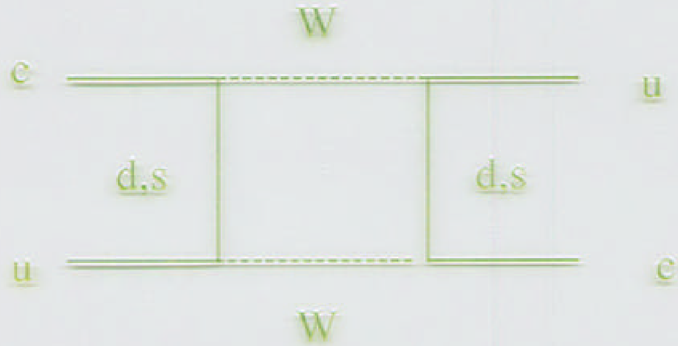
- quark box diagram
  - local operator: ~ $m_b > M_D$



$(m_b/M_W)^2$

$x_D(bb)$ ~ few × 10^{-7}

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



$(m_c/M_W)^2 \times (m_s/m_c)^4$

$x_D(box)$ ~ few × 10^{-5}

- long distance contributions:

  use various schemes to describe selected hadronic states:

  ➡ $x_D(LD)$, $y_D(LD)$ ~ 10^{-4} - 10^{-3}

systematic analysis based on O$_{\text{perator}}$ P$_{\text{roduct}}$ E$_{\text{xpansion}}$

$$T(\Delta C=2, \omega) = \int d^4x\, e^{-i\omega t} \langle D| \{ \mathcal{L}(x)\, \mathcal{L}(0) \}_T |D\rangle / 4M_D$$

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

$$A(\omega) \equiv -\, \Delta\overline{M}_D(\omega) + i\, \Delta\overline{\Gamma}_D(\omega)/2$$

$$\Delta M_D \equiv \Delta\overline{M}_D(0)\,,\ \Delta\Gamma_D = \Delta\overline{\Gamma}_D(\omega)$$

$$\Delta M_D = (1/2\pi)\ \text{P.V.} \int d\omega\, [\Delta\overline{\Gamma}_D(\omega)/\, \omega]$$

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

OPE (→ $1/m_c$) GIM (→ m_s)

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

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