DOUBLE CHARM PHYSICS

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Abstract
We review the weak-decay and spectroscopy properties of baryons with two charmed quarks. We also present the convergent speculations on exotic mesons $(QQ\bar{q}\bar{q})$ with two heavy quarks and two light antiquarks.

1 INTRODUCTION

The discovery of the $(b\bar{c})$ ground state [1], and that of the (ccd) baryon [2–4] demonstrates that new sectors of hadron physics are becoming accessible to experiments.

There are several good reasons to study hadron systems with two c quarks:

- Double charm baryons provide tests of mechanisms proposed to describe the weak decays of charmed mesons and single-charm baryons.
- The dynamics of confinement in (QQq) baryons combine the slow relative motion of two heavy quarks with the fast motion of a light quark.
- $(QQ\bar{q}\bar{q})$ multiquark states have been predicted, whose stability results from the flavour-independent character of quark forces at short distances and from pion-exchange between two heavy mesons at large distances.

These aspects will be reviewed in the next sections. Details will be skipped. Many references will be provided for further reading.

2 WEAK DECAY OF CHARM

2.1 General considerations

It was a surprise in our community when the ratio of lifetimes $r = \tau(D^{\pm})/\tau(D^0)$ was announced to significantly differ from unity. The preliminary value $r \simeq 4$ even amplified the shock. Still, the stabilised value $r \simeq 2.5$ [1] is impressive. With only spectator diagrams such as those of Fig. 1, all lifetimes would be equal (up to minor phase-space effects) and all semileptonic widths comparable. $r \neq 1$ reveals

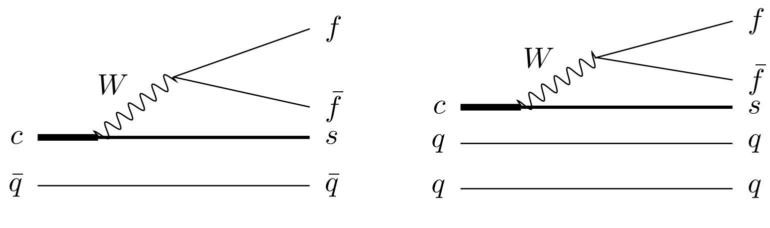

Fig. 1: Spectator diagram, for charmed mesons (left) and single-charm baryons (right).

important non-spectator effects: interferences between a constituent quark or antiquark, and another coming from c or W decay; W exchange between c and d or s; to a lesser extent, W formation in the s-channel. Further refinements such as penguin diagrams might also be included.

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2.2 Charmed mesons

There are many data on charmed mesons. In particular, the semileptonic widths are comparable [1]

$$\Gamma_{\rm SL}(D^{\pm}) \sim \Gamma_{\rm SL}(D^0) \sim \Gamma_{\rm SL}(D_s) \sim 0.3\,{\rm ps}^{-1}\ . \tag{1}$$

There is no major interference effect. So the mechanism of Fig. 1 (left) with $(f, \bar{f}) = (e^+, \nu_e)$ or (μ^+, ν_μ) provides all mesons with a similar semi-leptonic rate. The differences in lifetimes come from the hadronic part. The results [1]

$$\tau(D^0) \sim 400\,{\rm fs}\ , \quad \tau(D_s) \sim 500\,{\rm fs}\ , \quad \tau(D^+) \sim 1000\,{\rm fs}\ , \tag{2}$$

indicate that the light antiquark is not a mere spectator. When $\bar{f} = \bar{d}$ in $W \to f\bar{f}$ decay, this $\bar{d}$ interferes with the $\bar{d}$ of D^+. For D^0 and D_s, a W boson can be exchanged. For D_s, there is a small contribution of W formation. Some effects are pictured in Fig. 2.

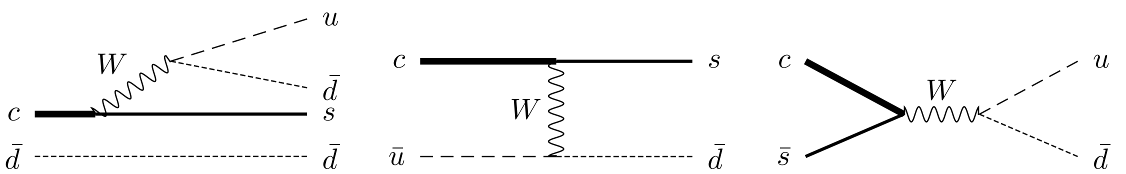

Fig. 2: Some mechanisms contributing to differences among the lifetimes of charmed mesons: interferences (left), W exchange (centre), fusion into W (right).

2.3 Baryons with single charm

The above mechanisms have been applied to charmed baryons: $\Lambda_c^+(cud)$, $\Xi_c^+(csu)$, $\Xi_c^0(csd)$ and $\Omega_c(css)$. A new interference appears with respect to the meson case: the s-quark coming from the decaying c might "feel" the presence of another s. The W-exchange contribution receives a larger strength. Annihilation becomes negligible, since requiring an antiquark from the sea. Some typical contributions are shown in Fig. 3. The mechanisms can be tested in subclasses of decays, once the statistics becomes sufficient for such filtering. An example is the last diagram of Fig. 3 showing a W-exchange contribution to doubly-Cabbibo-suppressed decay.

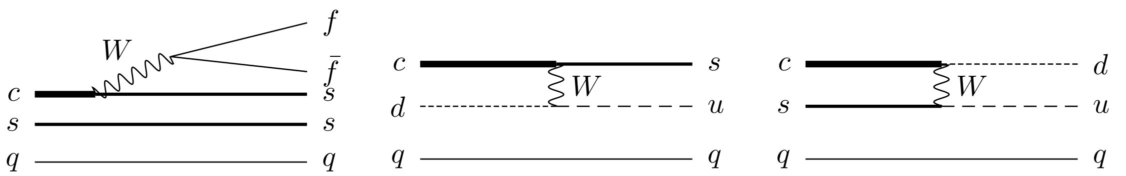

Fig. 3: Some diagrams differentiating the weak decay properties of various single-charm baryons: ss interferences, W exchange for ordinary hadronic decay, W exchange for suppressed decay.

The main *predictions* [5, 6] are that

- there are differences in the semileptonic partial widths $\Gamma_{\rm SL}$, namely

$$\Gamma_{\rm SL}(\Lambda_c^+) < \Gamma_{\rm SL}(\Xi_c^+) < \Gamma_{\rm SL}(\Xi_c^0) < \Gamma_{\rm SL}(\Omega_c^0)\ , \tag{3}$$

- the lifetimes are ordered as

$$\tau(\Omega_c) < \tau(\Xi_c^0) < \tau(\Lambda_c^+) < \tau(\Xi_c^+)\ . \tag{4}$$

Present data do not enable one to check the prediction (3). The ordering (4) of lifetimes is remarkably verified by the data, but the spread of values seems always underestimated in theoretical calculations, at least to my knowledge. This is hopefully just a matter of using more realistic values of some model-dependent parameters, such as the probability to find two quarks at the same location, which enters the contribution of W exchange.

There are many predictions for exclusive rates, at least for their relative values. See, for example, Ref. [7] for a flavour of this rich physics.

2.4 Weak decays of baryons with double charm

The same mechanisms have been further applied to baryons with double charm. Examples are drawn in Fig. 4. There is an overall agreement that the hierarchy of lifetimes is [6, 8]

$$\tau(\Xi_{cc}^{+}) \lesssim \tau(\Omega_{cc}^{+}) \ll \tau(\Xi_{cc}^{++}) \,, \tag{5}$$

with, perhaps, an underestimate of the magnitude of the effect. For instance, Kiselev *et al.* [9, 10] predicted $\tau(\Xi_{cc}^{+}) \sim 400\,\mathrm{fs}$, as compared to the value $\tau \lesssim 30\,\mathrm{fs}$ suggested by SELEX data [2, 4]. This is one of the reasons leading Kiselev *et al.* [11] to cast some doubt about the Fermilab result. See, also, Ref. [12]. But, again, the lifetime of other charmed baryons was also overestimated by theorists. In the plot of lifetimes, Fig. 5, a value as low as $30\,\mathrm{fs}$ does not look too extravagant an extrapolation.

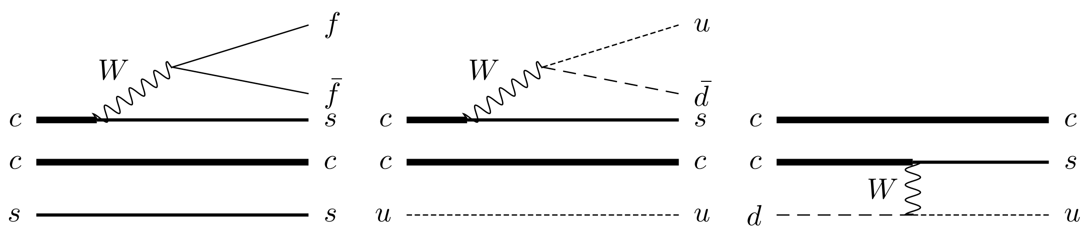

Fig. 4: Some diagrams leading to differences among the lifetimes of baryons with double charm.

3 SPECTROSCOPY OF DOUBLE-CHARM BARYONS

In the 1960s, the flavour group SU(3)$_{\mathrm{F}}$ was immediately extrapolated to SU(4) or higher. A better motivation for a fourth quark came from the GIM mechanism [13]. At the time where charm was discovered, in the hidden form of $(c\bar{c})$, some classic papers were written on hadrons with charm, including a section on (ccq) states [14, 15].

More detailed studies of (QQq) baryons came in the 1980s and later [6, 16–23]. No doubt the recent discovery at SELEX will stimulate further works.

(QQq) baryons are perhaps the most interesting of ordinary hadrons, as they combine in a single bag two extreme regimes:

1. the slow relative motion of two heavy quarks, as in charmonium,
2. the fast motion of a light quark. Remember that the electron moves faster in hydrogen than in positronium. Similarly, a light quark is likely more relativistic in heavy-light hadrons than in light mesons.

Hence, (QQq) baryons offer a very interesting laboratory to study confinement.

3.1 Diquark clustering and excitations

In the (QQq) wave function, the average QQ separation is smaller than the Qq one. This leads to envisage approximations, such as a quark–diquark picture, to be discussed shortly. The diquark is,

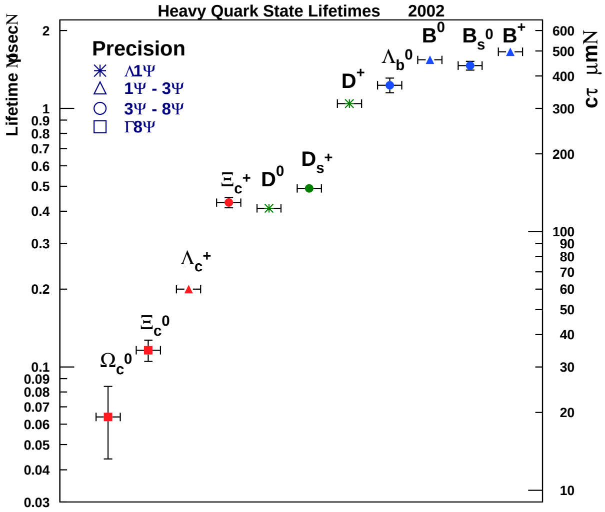

Fig. 5: Lifetimes of heavy baryons, borrowed from the slides of P. Cooper at the last Hyperon Conference [3].

however, not frozen. The first excitations arise in the QQ relative motion, i.e., the (QQq) ground state, and its first orbital excitation $(QQq)^*$ are built out of different diquarks.

3.2 The two-step approximation

It is rather legitimate to replace the full three-body calculation by a two-step procedure where one

1. calculates the QQ mass, by solving a two-body problem,
2. calculates the $QQ - q$ mass by solving another two-body problem.

The second step is rather safe. The finite-size corrections are small. For instance, they cancel out exactly for the harmonic oscillator.

As for the first step, one should be aware that the QQ potential is *effective*, since it contains both the direct QQ interaction and a contribution from the light quark. For instance, in the harmonic oscillator model, the identity

$$r_{12}^2 + r_{23}^2 + r_{31}^2 = \frac{3}{2} r_{12}^2 + 2\, r_{12-3}^2 \,, \tag{6}$$

demonstrates that 1/3 of the QQ interaction comes from the light quark. Replacing 3/2 by 1 results in an underestimate of energies and spacings by a factor $\sqrt{3/2}$.

3.3 The Born–Oppenheimer approximation

It was used, for example, by Fleck and Richard [16]. For a given QQ separation r_{12}, the two-centre problem is solved for the light quark, with proper reduced mass. The ground-state energy $E_0(r_{12})$, supplemented by the direct QQ interaction, provides the adiabatic potential V_{QQ}. Solving the 2-body problem with this potential gives the first levels. The adiabatic potential built out of the second “electronic” energy $E_1(r_{12})$ leads to a second series of levels. This is very similar to the spectroscopy of H_2^+ in atomic physics.

Within explicit potential models, the Born–Oppenheimer approximation can be checked against an accurate solution of the 3-body problem, using for instance a systematic hyperspherical expansion. The approximation is excellent for (bbq) and (ccq), with $q = u$, d or s, or even for (ssu) or (ssd).

3.4 Typical results

In Ref. [16], (ccq) masses were estimated from a specific variant of the bag model, already used for charmed mesons. The results turn out to be rather sensitive to details such as centre-of-mass corrections, value of the bag constant, etc. Other bag-model calculations have been performed [24].

Potential models, on the other hand, tend to give very stable results, when the parameters are varied while maintaining a reasonable fit of lighter hadrons. Typically

- a ground state near or slightly above $3.6\,\text{GeV}$ for the (ccu) or (ccd) ground state,
- a hyperfine splitting of about $80\,\text{MeV}$ between the spin 3/2 and spin 1/2 states,
- the first orbital excitation about $300\,\text{MeV}$ above the ground state,
- the first (ccs) state near $3.7\,\text{GeV}$.

Note that models tuned to (cqq) or lighter baryons might underestimate the short-range QQ attraction. If models are adjusted to $(c\bar{c})$ spectroscopy, there is an ambiguity on how to translate it to cc. The usual recipe stating that

$$V_{QQ} = \frac{1}{2} V_{Q\overline{Q}} \,, \tag{7}$$

implies pairwise forces mediated by colour-octet exchanges. Small, non-confining, colour-singlet exchanges, as well as three-body forces might complicate the issue.

3.5 Towards better estimates

Most existing calculations are of a rather exploratory nature, since made when double charm was considered as science fiction, or far future. Meanwhile, the art of QCD has made significant progress.

One could retain from simple potential models that the Born–Oppenheimer approximation provides an adequate framework. The effective QQ potential could be estimated from relativistic models or from lattice calculations, similar to those of the $Q\overline{Q}$ potential or the effective QQ potential in exotic $(QQ\bar{q}\bar{q})$ mesons, on which more shortly. It is hoped that the new experimental results will stimulate such calculations.

The literature already contains approaches somewhat more ambitious than simple bag or potential models: QCD sum rules [19], string picture [25, 26], etc.

4 EXOTIC MESONS WITH DOUBLE CHARM?

4.1 Minireview on advertised exotics

The famous H dibaryon proposed by Jaffe [27], and the less notorious pentaquark P proposed independently by Lipkin [28] and the Grenoble group [29], owe their tentative stability to *chromomagnetic* forces. Other mechanisms might lead to stable multiquarks: *chromoelectric* forces and long-range *Yukawa* interaction. These mechanisms were first proposed with crude approximations for the overall dynamics. It is important to examine to which extent multiquark binding survives all refinements brought in model calculations.

4.1.1 Hexaquark

The chromomagnetic interaction [15]

$$H_{cm} = -C \sum_{i<j} \frac{\vec{\sigma}_i.\vec{\sigma}_j \,\tilde{\lambda}_i.\tilde{\lambda}_j}{m_i m_j} \delta^{(3)}(\vec{r}_{ij}) \,, \tag{8}$$

or its bag model analogue [30], successfully describes the observed hyperfine splittings such as $\Delta - N$ or $J/\Psi - \eta_c$. The astute observation by Jaffe [27] is that this operator provides a binding

$$(ssuudd) - 2(sud) \sim -150\,\text{MeV} \tag{9}$$

to the $H = (ssuudd)$ dibaryon with spin and isospin $J = I = 0$. This estimates, however, relies on:

1. SU(3)$_\mathrm{F}$ flavour symmetry,
2. $\langle\delta^{(3)}(\vec{r}_{ij})\rangle$ independent of (i, j) pair and borrowed from the wave function of ordinary baryons.

Relaxing these hypotheses, and introducing kinetic energy and spin-independent forces in the 6-body Hamiltonian usually spoils the stability of H [31–33]. The existence of H is nowadays controversial. It has been searched for in many experiments, without success so far. For instance, the doubly-strange hypernucleus ${}^{6}_{\Lambda\Lambda}\mathrm{He}$ is not observed to decay into $H + \alpha$ [34].

4.1.2 Pentaquark

If the calculation made for the H is repeated in the limit where $m(Q) \to \infty$, the same binding

$$(\overline{Q}qqqq) - (\overline{Q}q) - (qqq) \sim -150\,\mathrm{MeV} \tag{10}$$

is obtained for the pentaquark $(\overline{Q}qqqq)$, $qqqq$ being in a SU(3)$_\mathrm{F}$ triplet [28, 29]. All corrections, again, tend to weaken this binding [33, 35] so it is not completely sure that the actual pentaquark is stable. See, also, Ref. [36].

For the case where the chromomagnetic term (8) is replaced by Goldstone-boson exchange, see, for example, the review by Stancu [37] and references therein.

4.2 Tetraquark

Twenty years ago, it was pointed out that current confining potentials bind $(QQ\bar{q}\bar{q})$ below its dissociation threshold into $(Q\bar{q})+(Q\bar{q})$, provided the mass ratio $m(Q)/m(q)$ is large enough [38]. This *chromoelectric* binding was studied by several authors, in the context of flavour-independent potentials [39–47] or with lattice QCD [48, 49] (see, also, [50, 51]), with a remarkable convergence towards the same conclusion. This somewhat contrasts with the confusion in other sectors of multiquark spectroscopy.

4.2.1 Favourable symmetry breaking

Let us consider the limit of a purely flavour-independent potential V for $(QQ\bar{q}\bar{q})$. The situation becomes similar to that of exotic four-body molecules (M^+, M^+, m^-, m^-), which all use the very same Coulomb potential. The hydrogen molecule with $M \gg m$ is much more stable than the positronium molecule Ps_2 with $M = m$. If one decomposes the 4-body Hamiltonian as

$$\mathcal{H}_4 = \left[\frac{M^{-1}+m^{-1}}{4}\left(\vec{p}_1^{\,2}+\vec{p}_2^{\,2}+\vec{p}_3^{\,2}+\vec{p}_4^{\,2}\right)+V\right]+\frac{M^{-1}-m^{-1}}{4}\left(\vec{p}_1^{\,2}+\vec{p}_2^{\,2}-\vec{p}_3^{\,2}-\vec{p}_4^{\,2}\right)\ , \tag{11}$$

the first term, even under charge conjugation, corresponds to a rescaled equal-mass system with *the same threshold* as $\mathcal{H}_4$. The second term, which breaks charge conjugation, improves the energy of $\mathcal{H}_4$ (one can applies the variational principle to $\mathcal{H}_4$ using the symmetric ground state of the first term as a trial wave function). In the molecular case, the second term changes the marginally bound Ps_2 (or rescaled copy) into the deeply bound H_2. In quark models, an unbound $(qq\bar{q}\bar{q})$ becomes a stable $(QQ\bar{q}\bar{q})$.

The effective QQ potential has been estimated by Rosina *et al.* [46] in the framework of empirical potential models, and by Mihaly *et al.* [48] and Michael *et al.* (UKQCD) [49], who used lattice simulations of QCD.

The question is obviously: is the c quark heavy enough to make $(cc\bar{q}\bar{q})$ bound when $q = u$ or d? At this point, the answer is usually negative, most authors stating that b is required to bind $(QQ\bar{q}\bar{q})$ below its $(Q\bar{q}) + (Q\bar{q})$ threshold.

4.3 Deuterium-like binding

There is, however, another mechanism: pion-exchange or, more generally, nuclear-like forces between hadrons containing light quarks or antiquarks. This effect was studied by several authors, in particular Törnqvist [52], Manohar and Wise [53], and Ericson and Karl [54]. In particular a D and D^* can exchange a pion, thus inducing an attractive potential. It is weaker than in the nucleon–nucleon case, but what matters for a potential $gV(r)$ to bind, is the product gm of the strength g and reduced mass m.

It is found that (DD^*) is close to being bound, while binding is better established for (BB^*). The result depends on how sharply the long-range potential is empirically regularised at short distances.

4.4 Combining long- and short-range forces

A lattice calculation such as those of Refs. [48, 49] contains in principle all effects. In practice, space is truncated, so long-range forces are perhaps not entirely included. Explicit quark models such as [46] make specific assumptions about interquark forces, but do not account for pion exchange.

In our opinion, a proper combination of long- and short-range forces should lead to bind (DD^*), since each component is almost sufficient by itself. This is presently under active study.

4.5 Borromean binding

There is a further possibility to build exotic, multicharmed systems. If the interaction between two charmed mesons cannot lead to a bound state (this is presumably the case for (DD), since pion exchange does not contribute here), it is likely that the very same meson–meson interaction binds three or more mesons. This is known as the phenomenon of 'Borromean' binding.

For instance, in atomic physics, neither two ^{3}He atoms nor a ^{3}He atom and a ^{4}He atom can form a binary molecule, even at vanishing temperature, but it is found that $^3\mathrm{He}^3\mathrm{He}^4\mathrm{He}$ is bound [55]. Similarly, in nuclear physics, the isotope ^{6}He is stable against evaporating two neutrons, or any other dissociation process, while ^{5}He is unstable. In a 3-body picture, this means that (α, n, n) is stable, while neither (α, n) nor (n, n) have a stable bound state. In short, binding three constituents is easier than two.

5 CONCLUSIONS AND OUTLOOK

The results by the SELEX [2] and BELLE [56] groups show that we are now able to produce and identify two units of charm in hadron or electron collisions.

Double charm opens unique perspectives for studying new aspects of weak decays and confining forces, and for producing heavy exotic states.

A step further is triple-charm. The Ω_{ccc} family was named by Bjorken [57] the "ultimate goal of baryon spectroscopy". It will reveals a 'pure' baryon spectrum, without light quark complications. Comparing $(c\bar{c})$ and (ccc) ordering and spacing pattern will be crucial to check current ideas on the gluon strings picture leading to linear confinement.

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