

Double charm hadrons revisited¹

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Abstract

The dynamics of two heavy quarks inside the same hadron is probed against the double charm baryon results of SELEX. This can be seen as a part of the mechanism to bind tetraquarks with two heavy quarks and two light antiquarks. In the framework of potential models, it is possible to test the role of different effects: relativistic corrections, confinement, hyperfine forces, etc. It is conjectured that an additional interaction rescaled from the nucleon–nucleon system and acting between light quarks only, can help in bringing extra, possibly required, binding in tetraquarks.

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1 Introduction

The observation of double charmed baryons, (ccq) , by the SELEX collaboration [1, 2] has brought new incentive to study hadrons containing heavy quarks. The discovery by Belle and BaBar of the $D_{s,J}$ states [3], of the anomalously narrow $X(3872)$ meson [4], and of the other hidden-charm states $X(3940)$ [5] and $Y(4260)$ [6] also stimulated much activity in this field. Some of these states might be interpreted as meson–meson molecules or as multiquark states.

Regarding double-charm baryons, several uncertainties are left in the SELEX results: only the $(ccd)^+(3520)$ is confirmed, as being seen in two different weak-decay modes. Unfortunately, other peaks, which are candidates for isospin partner, spin or orbital excitation, are far from being established [7]. There is hope that the final analysis of SELEX data and future experiments could clarify the situation. In particular, the double charm production seen in B-factories to detect charmonium states recoiling against other charmonium states, could possibly lead to final states with double charm hadrons recoiling against double anticharm systems.

The purpose of the present study is to investigate whether or not charmonium ($c\bar{c}$), charmed mesons ($c\bar{q}$) and baryons (cqq) can be described in a simple unified picture and lead to predictions for double-charm baryons (ccq) and for hidden-charm ($cq\bar{c}\bar{q}$) and double-charm ($cc\bar{q}\bar{q}$) tetraquarks.

We believe that mixing heavy and light quarks or antiquarks in the same system sometimes favours multiquark binding below the threshold for spontaneous dissociation into simpler hadrons. Some attractive effects between two heavy quarks, or between two light quarks, might lower the mass of a multiquark system without acting on the threshold energy.

The structure of this paper is as follows. In the next section, we present the main dynamical ingredients that play a role in multiquark binding. In Secs. 3 and 4, we briefly review some of the theoretical approaches to double charm baryons. Section 5 is devoted to an analysis of the latest results on open charm tetraquarks. The last section raises several questions on the role of various dynamical effects and, in particular, of the light quark dynamics in the binding of tetraquarks.

2 Aspects of quark dynamics

2.1 The heavy–heavy effect

Flavour independence is one of the appealing features of quark models, directly linked to QCD. Potentials have been designed, for instance, to describe simultaneously the ($c\bar{c}$) and ($b\bar{b}$) spectra. In a flavour-independent potential used in the context of the Schrödinger, or an improved equation, with relativistic kinematics, one automatically gets a *heavy–heavy* effect: a subsystem with large reduced mass takes better benefit of the attraction. This is

illustrated by the following inequalities [8].

$$(Q\bar{Q}) + (q\bar{q}) \leq 2(Q\bar{q}) , \quad (1)$$

$$(QQq) + (qqq) \leq 2(Qqq) , \quad (2)$$

$$(QQ\bar{q}\bar{q}) \leq 2(Q\bar{q}) . \quad (3)$$

While (1) and (2) are valid for any value of the heavy-to-light mass ratio $x = M/m$, (3) requires a minimal value of x for a bound state to occur. In atomic physics, a sort of flavour independence is also present, inasmuch as the same Coulomb potential acts on light and heavy charges. There the inequality (1) means that a system of a protonium and a positronium is lighter than the hydrogen plus the antihydrogen. The inequality (3) is also observed: while the positronium molecule is marginally bound, the hydrogen molecule lies well below the threshold of dissociation into two hydrogen atoms.

2.2 The light–light effect

In quark physics, one also encounters a *light–light* effect, which is not explicitly included in simple potential models and thus should be added by hand. Two hadrons, containing at least one light quark each, have a long-range strong interaction which is sometimes attractive and might contribute to binding. The best known example is the deuteron. The $(D\bar{D}^* + \text{c.c.})$ is another possibility, which has perhaps been seen in the Belle data [4]. This light–light effect also contributes to the inner dynamics of hadrons with two or more light quarks.

In Sec. 5, we shall speculate about the role of an additional meson exchange interaction at the quark level, as in Ref. [9, 10]. Only the residual interaction between light-flavour quarks is admitted to be significant. Accordingly, such an interaction, rescaled from the nucleon–nucleon interaction can increase the binding the two interacting mesons.

3 Phenomenological models

Several attempts have been made to build potentials that describe simultaneously meson and baryon masses, with a suitable ansatz for going from the quark–antiquark to the quark–quark case [11]. Some models were even extended from the heavy to the light quark sector [12] and can be applied to systems such as charmed mesons and double charm baryons and tetraquarks.

For the sake of the discussion, we consider explicitly the potential of Bhaduri et al. [12] and the AL1 potential [13], the parameters of which include constituent-quark masses, the string tension of a linear confinement, the strength of the Coulomb interaction, and the strength and size parameters of the hyperfine interaction which is a smeared contact term. The Hamiltonian reads

$$H = \sum_i m_i + \sum_i \frac{\vec{p}_i^2}{2m_i} - \frac{(\sum_i \vec{p}_i)^2}{2 \sum_i m_i} + \sum_{i < j} [V_\ell(r_{ij}) + V_c(r_{ij}) + V_h(r_{ij})] ,$$

$$\begin{aligned}
V_\ell(r_{ij}) &= -\frac{3}{16} \lambda_i^c \cdot \lambda_j^c (ar_{ij} - b), & V_c(r_{ij}) &= -\frac{3}{16} \lambda_i^c \cdot \lambda_j^c \frac{\kappa}{r_{ij}}, \\
V_h(r_{ij}) &= -\frac{3}{16} \frac{\kappa}{m_i m_j r_0^2} \frac{\exp(-r_{ij}/r_0)}{r_{ij}} \lambda_i^c \cdot \lambda_j^c \vec{\sigma}_i \cdot \vec{\sigma}_j.
\end{aligned}
\tag{4}$$

In the case of AL1, the smearing parameter r_0 depends on the reduced mass of the quark pair.

4 Double charm baryons

An extensive study of the double-charm baryons has been performed by Fleck and Richard [14] and a review of the situation at that time can be found in Refs. [15, 16]. This has been followed by other potential model studies, as for example, Ref. [13]. These studies suggest that the ground state $\Xi_{cc}^{++}(ccu)$ and $\Xi_{cc}^+(ccd)$ have a mass around 3.6 GeV (for more examples, see Ref. [17]). In a more recent work [18] an effective scale-dependent strong-coupling constant which distinguishes between qq , cq and cc pairs has been used to calculate the spectrum of double charmed baryons, but the ground state of $\Xi_{cc}^+(ccd)$ was fitted to the SELEX data [1, 2] at 3520 MeV. Double-charm baryons have also been investigated in lattice QCD. Predictions for masses and spin splittings were made in lattice nonrelativistic quenched QCD calculations [19, 20] prior to the SELEX experiment. Recently, quenched lattice calculations with exact chiral symmetry [21] showed an agreement with the published SELEX data [1, 2]. There are also studies based on an effective field theory Lagrangian approach adequate for heavy quarks [22].

Table 1: The baryon masses (in MeV) obtained from the Bhaduri et al. [12] model, without and with hyperfine interaction V_h , compared to the experimental values, from PDG [23] for single charm and from SELEX data [1] for double charm baryons.

Content	without V_h	with V_h	Exp.
cqq	2500	2332 (1/2 ⁺)	$\Lambda_c(2285)$
		2500 (1/2 ⁺)	$\Sigma_c(2455)$
		2568 (3/2 ⁺)	$\Sigma_c(2520)$
ccq	3693	3643 (1/2 ⁺)	$\Xi_{cc}^+(3520)$
		3724 (3/2 ⁺)	?

In Table 1, preliminary estimates of the masses from the Bhaduri et al. potential [12] are compared with the experimentally known masses. The results are shown without and with hyperfine interaction. For single charm baryons we use PDG data [23] and for the confirmed double charm baryon the SELEX data [1]. Note that the spin and parity are quark model predictions, not determined experimentally so far, even for single charm

baryons. Our estimate is made with the powerful method of Kamimura et al. [24]. So far, we have used a small number of terms in the Gaussian expansion. A better calculation with a larger basis will be presented elsewhere.

The mass of $(ccd)(1/2^+)$ is found around 3.6 GeV, consistent with several previous constituent quark model calculations [17] and lattice results [19, 20]. Note that the hyperfine splitting of $(1/2)^+$ and $(3/2)^+$ states is about 80 MeV, similar to most quark model studies and lattice calculation results, but at variance with the 24 MeV splitting of Ref. [18], which seems to be anomalously small.

5 Tetraquarks

An understanding of baryons with two heavy quarks could make it possible to better extrapolate towards tetraquarks with double heavy flavour [25, 26]. Let us consider the tetraquarks with open charm $cc\bar{q}\bar{q}$ which have been extensively studied in the framework of the Bhaduri et al. potential [12] or in some of its improved versions [13].

Table 2 displays the binding energy $\Delta E = M(cc\bar{q}\bar{q}) - M_{th}$ of the lowest state having spin $S = 1$ and isospin $I = 0$ calculated with the Bhaduri et al. potential and with the AL1 potential. The masses were obtained with two different numerical methods. The threshold mass is $M_{th} = M(D) + M(D^*)$.

Table 2: The $I = 0$, $S = 1$ tetraquark binding energy (in MeV) $\Delta E = M(cc\bar{q}\bar{q}) - M_{th}$, where the threshold mass M_{th} is calculated with the same model.

Potential	Bhaduri et al.	AL1
Silvestre-Brac & Semay [27]	19	11
Janc & Rosina [28]	-0.6	-2.7

The tetraquark with spin $S = 1$ and isospin $I = 0$ appears unbound in Ref. [27], where the four-body problem is solved by an expansion in a harmonic-oscillator basis up to $N = 8$ quanta. However, it is bound in the calculations by Janc and Rosina [28], who used a multi-channel variational basis, as presented in Ref. [29], by including, in particular, meson–meson type of asymptotic channels. It was already noted in Ref. [30] that the meson–meson configurations are important when the stability limit is approached. On the other hand, using the mass of 3520 MeV for ccu/ccd from SELEX the mass of the tetraquark $cc\bar{u}\bar{d}$ becomes about 3905 MeV i. e. some 35 MeV above the $D + D^*$ threshold [26], consistent with earlier estimates [25].

The picture of a “two-meson” state in tetraquarks also emerges from recent SU(3) lattice QCD calculations [31]. There it is seen as a flux-tube recombination, known as “flip-flop”, when a quark and antiquark are near each other. The extension to pentaquarks has been considered in a more recent calculation [32].

There are several ways to increase the binding, all related to long-range forces. One concerns the confinement potential. The common assumption is that the confinement is two-body, although this is too a simplified picture in the light of lattice calculations [31]. It has been suggested that a three-body confinement interaction can be introduced as a colour operator via the cubic invariant of SU(3) [33]. This is a pure algebraic approach, without an underlying physical picture, so far. It can produce an increase of the binding, depending on the sign and strength of the three-body interaction [28].

6 Perspectives

It is remarkable that stable tetraquarks are predicted from Hamiltonians adjusted to 2- and 3-body systems and applied to 4-body systems. If the $(cc\bar{q}\bar{q})$ state exists, it will be accessible to ongoing and future experiments.

The prediction deserves further investigation and the natural question is whether or not the stability survives changes in the basic assumptions. This is the aim of our present and future study. Several questions can be raised, for instance:

- are the relativistic effects important, are they more important in tetraquarks than in mesons and baryons?
- is the interaction between quarks pairwise?
- in the case of a two-body interaction is the $\lambda_i^c \cdot \lambda_j^c$ operator appropriate to describe the colour dependence?
- is the linear parametrisation of the confinement adequate?
- do we need to introduce asymptotic-freedom type of correction to the strength κ of the Coulomb term?
- is the chromomagnetic interaction $V_h \propto \lambda_i^c \cdot \lambda_j^c \vec{\sigma}_i \cdot \vec{\sigma}_j$ realistic enough to describe hyperfine effects?
- do results on stability depend strongly on the assumed regularisation of the hyperfine interaction?
- does a tensor type interaction increase the binding in tetraquarks?

In addition to these questions, it seems crucial to us to investigate the role of the light–light effect mentioned in the introduction. This is required by chiral dynamics as well as by empirical evidence. An observation is that in simple quark models, it is difficult to accommodate simultaneously light and heavy hadrons. Also a long-range hadron–hadron exists, if both hadrons contain light quarks. This suggests to introduce a residual interaction of meson-exchange type, admitted to be significant only between light quarks. This pedestrian way of implementing chiral symmetry at the quark level leads to interesting

predictions. According to Refs. [9, 10], the contribution of light pairs represents a fraction of the nucleon-nucleon interaction, so it can be obtained by rescaling the nucleon-nucleon interaction to the corresponding hadron-hadron system. In particular, the $\Xi_{cc} - \Xi_{cc}$ interaction includes a pion exchange component. Although its strength is only a fraction of the nucleon-nucleon interaction,⁴ a deuteron-like bound state is likely to exist between double charm baryons because the kinetic energy has a less repulsive effect in $\Xi_{cc} - \Xi_{cc}$ than in NN , as a consequence of the large mass of Ξ_{cc} .

By analogy, we expect that in a $(cc\bar{q}\bar{q})$ system the $\bar{q}\bar{q}$ pair should bring an extra attraction like in $\Xi_{cc} - \Xi_{cc}$, and possibly lead to stable tetraquarks against strong decays.

In the future we plan to estimate the contribution of the light pairs of quarks to the mass of $cc\bar{q}\bar{q}$ from a realistic nucleon-nucleon interaction, as for example the Paris potential [34].

The $(cc\bar{q}\bar{q})$ state has the unique feature to combine the heavy-heavy and light-light effects which are absent in its dissociation products, and hence offers the best possibility for multi-quark binding.

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⁴For example, the light quark fraction of the central part and of the spin-isospin part of the long range interaction are 1/9 and 1/25 respectively [10].

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