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Double heavy baryons and dimesons

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Abstract. We critically examine the question whether the $cc\bar{q}\bar{q}$ dimeson is bound or not.

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1 Introduction

There is a revived interest to study double heavy baryons and dimesons, both due to the theoretical urge of understanding better the quark-quark effective interaction, as well as due to new experimental opportunities in Fermilab and LHC.

The effective interaction between heavy quarks (and antiquarks) is expected to be cleaner than between light quarks. For heavy particles the nonrelativistic constituent quark model is more acceptable, the perturbative QCD contributions (such as one-gluon-exchange) are more adequate and chiral fields are less important. The effective interaction between a heavy quark and a heavy antiquark has been reasonably well studied and fitted by the charmonium and bottomium spectra. There is, however, no free diquark to study the effective interaction between two heavy quarks; one has to dress the diquark in order to obtain a colour singlet object QQq or $QQ\bar{q}\bar{q}$ (Q=c or b, q=u,d, or s).

It is straightforward to extrapolate the one-gluon-exchange (OGE) interaction from $Q\bar{Q}$ to QQ (Q= any quark). The charge conjugation changes the $\bar{Q}$ antitriplet to Q triplet. Then the colour factor $\lambda \cdot \lambda/4 = -4/3$ for the $Q\bar{Q}$ singlet changes to $-2/3$ for the QQ antitriplet (the "$V_{QQ} = \frac{1}{2} V_{Q\bar{Q}}$ *rule*"). On the other hand, it is questionable whether the (linear) confining potential should also possess such a colour factor and obey the $V_{QQ} = \frac{1}{2} V_{Q\bar{Q}}$ rule. The fact that the ground state energies and some excited states of light and heavy baryons are reasonably well reproduced with such a "universal" OGE + confining effective interaction is encouraging [1] but not conclusive. There may be other mechanisms for the $V_{QQ} = \frac{1}{2} V_{Q\bar{Q}}$ rule. For example, the flux tubes in a Y configuration can be mimicked by twice weaker two-body flux lines since the length of the arms of the Y is approximately half the length of the circumference of the triangle. The colour singlet 3-quark system is insensitive to the features of the *colour · colour* operator since it is just a constant in the 3-body singlet representation. To explore the colour structure of the effective interaction one has to go beyond mesons and baryons to dimesons and other exotics.

The study of double-heavy baryons and of double-heavy dimesons are complementary. The double-heavy baryons help to study the QQ interaction, while the dimesons also test the pion exchange between light quarks [2] and are more sensitive to three-body forces.

Our constituent quark model calculation [3] has shown the bb-dimeson to be bound by more than 100 MeV and the cc-dimeson to be unbound, which is consistent with some other calculations, for example [4]. We have proposed to look for the bb-dimesons at LHC assuming a mechanism of double $b\bar{b}$ production by double gluon gluon fusion $(g+g)+(g+g) \to (b+\bar{b})+(b+\bar{b})$ which has been described at this Conference by Danielle Treleani [5]. The two b-quarks then join into a diquark which gets dressed with a light quark or two light antiquarks to become a double heavy baryon or a dimeson. However, the production rate bb-dimesons has been estimated to be rather low [6,7], about 5 events/hour, and there seem to be no characteristic decays.

Therefore it is of utmost importance to look also for the cc-dimesons since their production rate might be as much as 10^4 events/hour if the same mechanism applies. They would also be easier to detect, for example by $cc\bar{u}\bar{d} \to D^+ + K^- + \pi^+$. There is, of course, a grat risk that they do not exist. If they, however, do exist they would be very exciting – we would have to revise our ideas about the effective quark-quark interaction, and/or introduce many-quark forces.

2 Can the $cc\bar{u}\bar{d}$ dimeson be bound?

We have obtained a phenomenological estimate for the binding energy of the cc-dimeson $(ISP = 01+)$ with respect to the DD* by assuming a compact structure like in the $\bar{\Lambda}_\mathrm{c}$ or $\bar{\Lambda}_\mathrm{b}$ baryon with the cc-diquark playing the role of the heavy antiquark. For the cc binding in the diquark we assumed the $V_\mathrm{QQ} = \frac{1}{2} V_{\mathrm{Q\bar{Q}}}$ rule and no 3-body forces. We compared the following hadrons [3]

$$\begin{aligned} m_{\mathrm{cc\bar{u}\bar{d}}} &= 2m_\mathrm{c} + m_\mathrm{u} + m_\mathrm{d} + E_{cc} + E_{\mathrm{\bar{u}\bar{d}[cc]}} \\ m_{\mathrm{J}/\psi} &= 2m_\mathrm{c} + E_{\mathrm{c\bar{c}}} \\ m_{\bar{\Lambda}_\mathrm{c}} &= m_\mathrm{c} + m_\mathrm{u} + m_\mathrm{d} + E_{\mathrm{\bar{u}\bar{d}\bar{c}}} \end{aligned}$$

where $E_{\mathrm{\bar{u}\bar{d}[cc]}} \approx E_{\mathrm{\bar{u}\bar{d}\bar{c}}}$ is the potential plus kinetic energy contribution of the two light antiquarks in the field of a heavy diquark or antiquark, respectively, and it cancels in the difference in the limit where the mass of the b quark goes to infinity and the heavy diquark is point-like so that we can neglect the size of the heavy diquark in the dimeson.

We estimated the diquark binding energy by using the theorem [3] $V_\mathrm{cc} = \frac{1}{2} V_{\mathrm{c\bar{c}}} \quad \Rightarrow \quad E_\mathrm{cc}(m_\mathrm{red}) = \frac{1}{2} E_{\mathrm{c\bar{c}}}(\frac{1}{2} m_\mathrm{red})$. Since meson binding energies lie on a smooth curve as a function of their reduced masses, it is easy to interpolate for the "fictitious meson" with $m_\mathrm{red}/2$ and we get [3]
$E_\mathrm{cc} - \frac{1}{2} E_{\mathrm{c\bar{c}}} = 134 \pm 20\,\mathrm{MeV}$ yielding

$$\begin{aligned} \Delta E_{\mathrm{cc\bar{u}\bar{d}}} &= m_{\Lambda_\mathrm{c}} + m_{J/\psi}/2 + E_\mathrm{cc} - E_{\mathrm{c\bar{c}}}/2 - m_\mathrm{D} - m_{\mathrm{D}^*} \\ &= (-42 + 134)\,\mathrm{MeV} = +92\,\mathrm{MeV}. \end{aligned}$$

This means that such a compact structure is not bound with respect to the DD* threshold. Also detailed four-body calculations with OGE+linear potential with Bhaduri or Grenoble parameters [4] did not yield a bound state.

An alternative estimate lies considerably lower but is still unbound:

$$\begin{aligned} \Delta E_{\mathrm{cc\bar{u}\bar{d}}} &= m_{\Lambda_\mathrm{b}} - m_\mathrm{b} + m_\mathrm{c} + m_{J/\psi}/2 + E_\mathrm{cc} - E_{\mathrm{c\bar{c}}}/2 \\ &\quad - m_\mathrm{D} - m_{\mathrm{D}^*} = (-94 + 134)\,\mathrm{MeV} = +40\,\mathrm{MeV}. \end{aligned}$$

The actual cc-diquark mass lies midway between the masses of the c and b quark (appearing in the center of Λ_c and Λ_b, respectively), therefore the answer is inbetween the two estimates which still means no binding.

The question arises whether the parameters in the OGE+linear confinement model could be stretched so as to bind cc-dimeson without spoiling the fit to mesons and baryons. If the $V_\mathrm{QQ} = \frac{1}{2} V_{\mathrm{Q\bar{Q}}}$ rule applies smaller quark masses could do the job. For Bhaduri masses, half of reduced mass od the cc diquark ($m_\mathrm{c}/4 = 467\,\mathrm{MeV}$) coincides with the reduced mass of D$_\mathrm{s}$, $m_\mathrm{c} m_\mathrm{s}/(m_\mathrm{c} + m_\mathrm{s}) = 454\,\mathrm{MeV}$ so that $E_\mathrm{cc} = \frac{1}{2} E_{\mathrm{c\bar{s}}}$. If we decrease all quark masses by 200 MeV, the reduced mass of D$_\mathrm{s}$, would decrease by 132 MeV and $m_\mathrm{c}/4$ only by 50 MeV. Higher reduced mass of cc compared to D$_\mathrm{s}$ means better binding of cc (by about 40 MeV). This is still not quite enough but might work in cooperation with additional effects.

A three-body interaction of the type

$$V_{ijk} = -\frac{U_0}{8} d^{abc} \lambda_i^a \lambda_j^b \lambda_k^c \, \exp(-(r_i^2 + r_j^2 + r_k^2)/a^2) \qquad (1)$$

with at most $U_0 = 20$ MeV and $a = 2.3$ fm would bind. The choice of $a < 1$ fm gives small effect, and above 2.3 fm the effect saturates. Due to the combinatorics, a three-body interaction is more effective for tetraquarks than for baryons and the proposed one spoils baryons only by few MeV.

The pion exchange between D and D* leads to a coulomb-like long-range force because the exchanged pion is almost on the mass shell [8]: (D$^* \rightarrow$ D$+\pi$), (D$+\pi \rightarrow$ D*). (Note that $m_{\mathrm{D}^{*+}} - m_{\mathrm{D}^+} - m_{\pi^0} = 5.6\,\mathrm{MeV}$, $\quad m_{\mathrm{D}^{*0}} - m_{\mathrm{D}^0} - m_{\pi^0} = 7.1\,\mathrm{MeV}$, $\quad m_{\mathrm{D}^{*+}} - m_{\mathrm{D}^0} - m_{\pi^+} = 5.8\,\mathrm{MeV}$.) This should in principle give a (weak) binding. We are studying the conflicting effects of short-range QQ interaction and this long-range DD* interaction.

3 A speculation using the ccu and ccd signals

Recent SELEX experiments and analysises [9] gave some more and some less convincing signals about the ccu(3460 and 3541) and ccd(3443 and 3520) baryons. If confirmed, they would have a dramatic effect on our estimates about the binding of the cc$\mathrm{\bar{u}\bar{d}}$ dimeson. If refuted, the present section remains a piece of science fiction.

Our expectations about the ccq baryon are consistent with the $\sim$ 3530 MeV isodoublet but would need a lot of stretching to accommodate the $\sim$ 3450 isodoublet (if this one is confirmed as the spin=1/2 ground state). A phenomenological estimate similar as in the previous section gives for s=1/2 (assuming an S=1 cc-diquark) the value inbetween

$$m_\mathrm{ccq} = \frac{1}{2} m_{\mathrm{J}/\psi} + E_\mathrm{cc} - \frac{1}{2} E_{\mathrm{c\bar{c}}} + \frac{3}{4} m_\mathrm{D} + \frac{1}{4} m_{\mathrm{D}^*} = 3584\,\mathrm{MeV}$$

and

$$\begin{aligned} m_\mathrm{ccq} &= \frac{1}{2} m_{\mathrm{J}/\psi} + E_\mathrm{cc} - \frac{1}{2} E_{\mathrm{c\bar{c}}} + m_\mathrm{c} - m_\mathrm{b} \\ &\quad + \frac{1}{4} m_\mathrm{B} + \frac{3}{4} m_{\mathrm{B}^*} - \frac{1}{2}(m_{\mathrm{D}^*} - m_\mathrm{D}) = 3535\,\mathrm{MeV} \end{aligned}$$

The predicted spin 3/2 state lies higher by
$\frac{3}{4}(m_{\mathrm{D}^*} - m_\mathrm{D}) = 106$ MeV Such spin-spin splitting is noticeably larger than the difference 80 MeV between the 3530 and 3450 MeV SELEX levels and it will be some surprise if the 3450 level is confirmed as a ground state and the 3530 level gets an 3/2 assignment.

Then follows a phenomenological estimate for the cc-dimeson

$$\begin{aligned} \Delta E_{\mathrm{cc\bar{u}\bar{d}}} &= m_\mathrm{ccu} - (\frac{3}{4} m_\mathrm{D} + \frac{1}{4} m_{\mathrm{D}^*}) \\ &\quad + m_{\Lambda_\mathrm{c}} - m_\mathrm{D} - m_{\mathrm{D}^*} \\ &= -42 \quad \text{or} \quad +38\,\mathrm{MeV} \end{aligned}$$

assuming the 3450 or 3530 MeV level, respectively, to be the ccu ground state

The alternative estimate is very similar.

$$\begin{aligned}\varDelta E_{\mathrm{cc\bar{u}\bar{d}}} &= m_{\mathrm{ccu}} - (\frac{1}{4}m_{\mathrm{B}} + \frac{3}{4}m_{\mathrm{B}^*}) \\ &+ \frac{1}{2}(m_{\mathrm{D}^*} - m_{\mathrm{D}}) + m_{\varLambda_{\mathrm{b}}} - m_{\mathrm{D}} - m_{\mathrm{D}^*} \\ &= -45 \quad \text{or} \quad +35\,\mathrm{MeV}\end{aligned}$$

4 Conclusion

There are several subtle effects each of which separately is not likely to bind the $\mathrm{cc\bar{u}\bar{d}}$ dimeson with respect to the DD* threshold. However, their cooperative effect might just bind it or just fail to bind it. Therefore we join and support those researchers who propose the detection of the $\mathrm{cc\bar{u}\bar{d}}$ dimeson as a crucial experiment.

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