BLED WORKSHOPS
IN PHYSICS
VOL. 4, NO. 1

Proceedings of the Mini-Workshop
Effective q-q Interaction *(p. 103)*
Bled, Slovenia, July 7-14, 2003

Is the $cc\bar{u}\bar{d}$ tetraquark bound? ⋆

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Abstract. The lightest $cc\bar{u}\bar{d}$ tetraquark (IJP=01+) is supposed to be above the DD^* threshold. We show, however, that it is possible to stretch the quark model parameters so that it might get bound.

1 Introduction

In previous Bled Workshop we were very enthusiastic about the $bb\bar{u}\bar{d}$ tetraquark which according to our [1–4] and other [5,6] estimates should be bound by about - 100 MeV with respect to the BB^* threshold. We strongly advertized to preparation for its search, possibly at LHC. However, our estimate of its production rate at LHC [3,4] is only about 5 events/hour, and its decay is not very characteristic.

This year, we turned our attention to the $cc\bar{u}\bar{d}$ tetraquark, in spite of our pessimistic estimates [1,2] that it is not bound. The motivation is threefold.

- It would be *more abundant*, possibly 10^4 events/hour if the same mechanism applies as for the bb-tetraquark [3,4,7], namely a double gluon fusion in two $c\bar{c}$ pairs so that the two charm quarks join in a cc-diquark which gets later dressed with two light antiquarks.
- It might be *easier to detect*, for example by $cc\bar{u}\bar{d} \to D^+ + K^- + \pi^+$ (in analogy with the SELEX ccd signal [8] $ccd \to \Lambda_c^+ + K^- + \pi^+$).
- If it exists its discovery would be *more revolutionary*. We would have to modify the effective quark-quark interaction, and/or introduce many-quark forces.

2 Mechanisms for stronger binding

It is difficult to stretch the parameters in the OGE+linear confinement so as to bind cc-dimeson without spoiling the fit to mesons and baryons. At first sight it seems that smaller quark masses could do the job if the $V_{QQ} = \frac{1}{2}V_{Q\bar{Q}}$ rule applies. In this case it has been shown [1] that the diquark binding energy is $E_{cc}(m_{red}) = \frac{1}{2}E_{c\bar{c}}(m_{red}/2)$. For Bhaduri masses, half of reduced mass of the cc diquark ($m_c/4 = 467$ MeV) coincides with the reduced mass of D_s, $m_c m_s/(m_c + m_s) = 454$ MeV so

⋆ Talk delivered by M. Rosina

that $E_{cc} = \frac{1}{2} E_{c\bar{s}}$. If we decrease all quark masses by 200 MeV, the reduced mass of D_s would decrease by 132 MeV and $m_c/4$ only by 50 MeV. Higher reduced mass of cc compared to D_s means better binding of cc (by about 40 MeV). However, this would spoil the spectra of single mesons.

A three-body interaction of the type

$$V_{qq\bar{q}}(\mathbf{r}_i, \mathbf{r}_j, \mathbf{r}_k) = -\frac{1}{8} d^{abc} \lambda_i^a \lambda_j^b \lambda_k^{c*} U_0 \exp(-(r_i^2 + r_j^2 + r_k^2)/a^2)$$

with $U_0 < 20$ MeV and $a > 2.3$ fm would bind. Due to the combinatorics, a three-body interaction is more effective for tetraquarks than for baryons and the proposed one spoils baryons only by about 10 MeV. Details are presented it the talk of Damijan Janc (these Proceedings).

The $cc\bar{u}\bar{d} = DD^*$ offers a coulomb-like long-range force because the exchanged pion is almost on the mass shell [9]: $(D^* \to D + \pi)$, $(D + \pi \to D^*)$. (Note that $m_{D^{*+}} - m_{D^+} - m_{\pi^0} = 5.6\,\text{MeV}$, $m_{D^{*0}} - m_{D^0} - m_{\pi^0} = 7.1\,\text{MeV}$, $m_{D^{*+}} - m_{D^0} - m_{\pi^+} = 5.8\,\text{MeV}$.)

Assuming Coulomb binding similar to that in the hydrogen atom, but with $g \approx 0.6$, ("α" $= g^2/4\pi \approx 1/35$) we get a loose system bound by only $E = -\frac{1}{2} \frac{m}{2} \frac{1}{35^2} = -0.4\,\text{MeV}$. However, this effect might help in the asymptotic channel.

3 Important information will come from double-charm baryons

Recent SELEX experiments and analysises [8] gave some more and some less convincing signals about the ccu(3460 and 3541) and ccd(3443 and 3520) baryons.

We first show that the more established ccd resonance at 3520 MeV is consistent with our phenomenological expectations if it is the ground state. Then we discuss the dramatic deviation from our expectations if the other three resonances are confirmed so that the ground state is at 3450 MeV (the isodoublet average) and the isodoublet average 3530 would then be the excited state of the double-charm baryon.

A phenomenological estimate following the same lines as we have used for the $cc\bar{u}\bar{d}$ tetraquark [1–3] gives for s=1/2 (assuming an S=1 cc-diquark) the value

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

Here we have immitated the ccq baryon by a $\bar{c}q$ meson and estimated the cc binding energy to be [1] $E_{cc} - \frac{1}{2} E_{c\bar{c}} = 134\,\text{MeV}$. We also took the appropriate averages of the spin-spin interaction. Actually, the cc-dimeson has a mass inbetween the $\bar{c}$ and $\bar{b}$ masses and the ccq mass could be as low as

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

or inbetween both values.

The predicted spin 3/2 state lies higher by $m_{ccq(3/2)} - m_{ccq(1/2)} = \frac{3}{4}(m_{D^*} - m_D) = 106\,\text{MeV}$. 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 assignement. The surprise would be even more evident in the need for a major revision of quark model parameters in order to obtain the ccq ground state as low as 3450 MeV.

Then follows a phenomenological estimate for the cc-dimeson. If the 3530 level is the ground state

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

or, alternatively

$$\begin{aligned} \Delta E_{cc\bar{u}\bar{d}} &= m_{ccu} - (\frac{1}{4}m_B + \frac{3}{4}m_{B^*}) \\ &+ \frac{1}{2}(m_{D^*} - m_D) + m_{\Lambda_b} - m_D - m_{D^*} = +35\,\text{MeV} \end{aligned}$$

If, however, the 3450 level is confirmed as the ground state, the corresponding estimates would give -42 (or - 45) MeV binding ! Such confirmation would strongly encourage the search for the cc-tetraquark.

4 Conclusion

There are several subtle effects each of which separately is not likely to bind the $cc\bar{u}\bar{d}$ tetraquark with respect to the DD* threshold. However, their cooperative effect might just bind it or just fail to bind it. We emphasise the importance of the search for the $cc\bar{u}\bar{d}$ tetraquark as a crucial experiment.

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