BLED WORKSHOPS
IN PHYSICS
VOL. 3, NO. 3

Proceedins of the Mini-Workshop
Quarks and hadrons *(p. 63)*
Bled, Slovenia, July 7-14, 2002

Production and detection of $bb\bar{u}\bar{d}$ tetraquarks at LHC? *

M. Rosina[a,b], D. Janc[b], D. Treleani[c], and A. Del Fabbro[c]

[a] Faculty of Mathematics and Physics, University of Ljubljana, Jadranska 19, P.O. Box 2964, 1001 Ljubljana, Slovenia
[b] J. Stefan Institute, 1000 Ljubljana, Slovenia
[c] Dipartimento di Fisica Teorica, Università di Trieste, Strada Costiera 11, Miramare-Grignano, and INFN, Sezione di Trieste, I-34014 Trieste, Italy

Abstract. The bound state of two B mesons (the "tetraquark" $bb\bar{u}\bar{d}$) has been shown to be bound by 100 MeV. Therefore it is stable against strong and electromagnetic decay and can decay only weakly. It represents a very interesting four-body problem to test our ideas about the effective quark-quark interactions and about the formation of the bb diquark (which later gets dressed by two light antiquarks into the tetraquark). It represents also a challenge to experimentalists. We shall discuss possible models of its formation, possible characteristic decays and the possibility of detecting it in LHC.

1 Introduction

Different versions of the nonrelativistic constituent quark model agree that the only long-living tetraquark should be $bb\bar{u}\bar{d}$ with the I=0, J=1 quantum numbers [1–3]. The predictions of its energy are about 100 MeV below the threshold of BB^* and about 60 MeV below the threshold of B^0B^- (into which it cannot decay anyway due to its quantum numbers). Therefore it can decay only weakly with a lifetime of picoseconds which corresponds to a width of meV. It would be very rewarding to confirm these predictions experimentally.

The estimates of the production and detection rate of the $bb\bar{u}\bar{d}$ tetraquark in the present machines are very pessimistic and have for this reason not been published. Therefore we consider the possibility of the production and detection of such a heavy dimeson (tetraquark) in LHC . For production we assume a three-step model.
(i) First, two b-quarks are formed in the process $pp \to b\bar{b}b\bar{b}$ by a double parton interaction fusion ($g + g \to b + \bar{b}$, (twice)) which is the leading production mechanism [4]. One might wonder why we need a TeV machine to produce GeV particles. The answer is simple. The two colliding protons can be considered as two packages of virtual gluons whose number is huge for low Bjorken-x. Only the number of gluons with $x \sim 0.001$ turns out to be sufficient to make tetraquarks

* Talk delivered by M. Rosina

detectable.
(ii) In the second step, the two b-quarks join into a diquark.
(iii) In the third step, the diquark gets dressed either with one light quark into the doubly-heavy baryon bbu, bbd or bbs, or with two light antiquarks to become a tetraquark. We shall show that the rates are comparable and that the comparison of the branching ratios may test our understanding of the process.

For the decay we consider two competitive processes, the independent decay of the two B-mesons (for example $B \to D +$ anything), and the direct formation of Υ with its characteristic energy and decay modes. While the former decay is difficult to distinguish from the decay of two completely independent b-quarks, the latter would require some kind of $b \to \bar{b}$ oscillation which is not easily feasible for bound B mesons.

2 Production

2.1 Double $b\bar{b}$ production

The multiple bottom production in a double parton collision was first studied as a possible contamination of the signal for the Higgs boson [4]. Such a double b production is, however, also a promising source of doubly heavy baryons and tetraquarks.

The forward detector LHCb will cover the pseudorapidity region $1.8 < \eta < 4.9$ and will detect the B and $\bar{B}$ hadrons in the low p_T region. By requiring that the two b are produced with $|p_1(j) - p_2(j)| < \Delta,\ j = x, y, z$, we get the cross section $\sigma \approx 0.4(\Delta/\mathrm{GeV})^3$ nb. The cross section is approximately proportional to the momentum volume up to 2 GeV: $d\sigma/d^3p \approx 0.4\mathrm{nb/GeV}^3$.

We are interested in double-b production in which the two b-quarks are close enough in phase space to synthesize a diquark. In our rough estimate we use wave functions approximated by Gaussians and denote the oscillator parameter of nucleon by B and of diquark by β. The quark model calculation of the diquark gives an effective momentum of each quark 1.04 GeV which correspond to a momentum range $\Delta^3 \approx 10\,\mathrm{GeV}^3$ (see next subsection) and therefore to a cross section of 4 nb. At the expected luminosity L=0.1 events/(second nb) this corresponds to 1440 interesting bb pairs per hour.

2.2 Formation of the diquark

We assume simultaneous production of two independent b-quarks with momenta $\mathbf{p}_1, \mathbf{p}_2$, modulated with a Gaussian profile of the nucleon size $B = \sqrt{2/3}\sqrt{< r^2 >} = 0.69$ fm:

$$\begin{aligned} &\mathcal{N}_B \exp(-\mathbf{r}_1^2/2B^2 + i\mathbf{p}_1\mathbf{r}_1)\mathcal{N}_B \exp(-\mathbf{r}_2^2/2B^2 + i\mathbf{p}_2\mathbf{r}_2) \\ \equiv\ &\mathcal{N}_{B/\sqrt{2}} \exp(-\mathbf{R}^2/2(B/\sqrt{2})^2 + i\mathbf{P}\mathbf{R})\mathcal{N}_{B\sqrt{2}} \exp(-\mathbf{r}^2/2(B\sqrt{2})^2 + i\mathbf{p}\mathbf{r}) \end{aligned}$$

where the normalization factor $\mathcal{N}_\beta = \pi^{-3/4}\beta^{-3/2}$.

Furthermore, we make an impulse approximation that such a two quarks sate is instantaneously transformed in any of the eigenstates of the two-quark Hamiltonian. Then the probability of the formation of the lowest energy diquark is equal to the square of the overlap $\mathcal{M}$ between the two free quarks and the diquark (with the same centre-of-mass motion). If we approximate the diquark wavefunction with a Gaussian with the oscillator parameter $\beta = 0.23$ fm, we get the overlap

$$\begin{aligned} M &= \int d^3r\, \mathcal{N}_{B\sqrt{2}} \exp(-\mathbf{r}^2/2(B\sqrt{2})^2 - i\mathbf{pr})\mathcal{N}_\beta \exp(-\mathbf{r}^2/2\beta^2) \\ &= \sqrt{\frac{2\sqrt{2}B\beta}{2B^2+\beta^2}}^{\,3} \exp\left[-(k^2/2)(2B^2\beta^2/(2B^2+\beta^2))\right] \end{aligned}$$

and the production cross section

$$\begin{aligned} \sigma &= \int d^3p\, \frac{d\sigma}{d^3p} M^2(k) = \frac{d\sigma}{d^3p}\left(\frac{4\pi\hbar^2}{2B^2+\beta^2}\right)^{3/2} \\ &\approx \frac{d\sigma}{d^3p}\left(\frac{\sqrt{2\pi}\hbar}{B}\right)^3 = 0.15\text{nb}. \end{aligned}$$

This expression can be interpreted as

$$\sigma = \frac{d\sigma}{d^3p} \times \Delta^3 \times f_{vol}$$

where $\Delta^3 = (\sqrt{2\pi}/\beta)^3 \approx 10\,\text{GeV}^3$ is the effective momentum range of the diquark and $f_{vol} = (\beta/B)^3 = (0.23\,\text{fm}/0.69\,\text{fm})^3 = 0.04$ is the volume ratio between the diquark and nucleon. This cross section corresponds to 54 dibaryons/hour.

2.3 Dressing of the diquark into tetraquark

Since the diquark will soon get dressed by two antiquarks or more probably by a single u, d or s quark, we guess a probability f_{dress} to synthesize our tetraquark smaller than 1/4, possibly $f_{dress} \sim 0.1$. This yields a production rate $L\sigma f_{vol} f_{dress}$ $\sim 5-6$ events/hour.

The estimate $f_{dress} \sim 0.1$ is supported by the comparison with the dressing of a single quark in the Fermilab experiment [5]:

$$b \to B^-, B^0, B_s, \Lambda_b = 0.375 \pm 0.015, 0.375 \pm 0.015, 0.160 \pm 0.025, 0.090 \pm 0.028.$$

Since a heavy diquark acts similarly as a heavy quark, we expect similar branching ratios:

$$bb \to bbd, bbu, bbs, bb\bar{d}\bar{u} \approx 0.37, 0.37, 0.16, 0.09.$$

3 Decay and detection

The independent decay of the two B-mesons (for example $B \rightarrow D +$ anything) is difficult to distinguish from the decay of two unbound b-quarks and is therefore not characteristic. Anyway, there are no good two-body decay channels of B mesons to allow the reconstruction of the total energy of the tetraquark; moreover, each separate exclusive decay channel has a low branching ratio of up to a few percent.

We are looking for more characteristic decay channels of the tetraquark – the direct formation of Υ with its characteristic energy and decay mode. This would be a simple two-body channel $\Upsilon + \pi$ with c.m. energy of the tetraquark which means a kinetic energy 876 MeV for both mesons (in the c.m. system). Of course there would be a crowd of other Υ mesons, but few at this energy. The inspiration comes from the $B^0 \rightarrow \bar{B}^0$ oscillation which unfortunately is not feasible for bound B mesons because the BB and $B\bar{B}$ states are not degenerate. The weak transition $b\bar{u} \rightarrow u\bar{b}$ is negligible because of the low CKM amplitudes. New ideas are needed!

The reader may wonder why are we so keen about the $bb\bar{u}\bar{d}$ tetraquark rather than the $cc\bar{u}\bar{d}$ tetraquark which would be easier to produce and detect. The answer is that in all reasonable models so far the cc-tetraquark is unbound. However, a recent measurement at SELEX in Fermilab [6] hints at three ccu (ccd) candidates with masses at 3519 , 3783 (and 3460) MeV. The 3519 MeV ground state can be accomodated into present quark models and does not change the conclusion that the cc-tetraquark is unbound. If the 3460 MeV state is confirmed, it would require a major revision of our quark model calculations (3-body forces ?) and by further stretching parameters T_{cc} might even be bound [7]. But we do not believe it since the 60 MeV isospin splitting is not believable and we rather wait for futher experiments.

References

1. D. Janc and M. Rosina, Few-Body Systems **31**, 1 (2001)
2. B. Silvestre-Brac and C. Semay, Z. Phys. **C57**, 273 (1993)
3. D. M. Brink and Fl. Stancu, Phys. Rev. **D57**, 6778 (1998)
4. A. Del Fabbro and D. Treleani, Phys. Rev. **D61**, 077502 (2000) Phys. Rev. **D63**, 057901 (2001) Nucl. Phys. B **92**, 130 (2001)
5. T. Affolder et al. (CDF Collaboration), Phys. Rev. Lett. **84**, 1663 (2000)
6. M. Mattson et al. (SELEX Collaboration), Phys. Rev. Lett. **89**, 112001 (2002); J. S. Russ (on behalf of the SELEX Collaboration), hep-ex/0209075
7. B. A. Gelman and S. Nussinov, hep-ph/0209095