Eur. Phys. J. C 50, 81–83 (2007)
DOI 10.1140/epjc/s10052-006-0207-1

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article – Theoretical Physics

Tetraquarks and pentaquarks in string models

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Received: 2 October 2006 /
Published online: 3 February 2007 – © Springer-Verlag / Società Italiana di Fisica 2007

Abstract. We consider the production and decay of multiquark systems in the framework of string models where the hadron structure is determined by valence quarks together with string junctions. We show that the low mass multiquark resonances can be very narrow.

PACS. 25.75.Dw

1 Structure of multiquark systems

In the string models baryons are considered as configurations consisting of three strings (related to three valence quarks) connected at the point called the "string junction" (SJ) [1–6]. The string junction has a nonperturbative origin in QCD. Many phenomenological results (some of them will be discussed below) were obtained in this approach 25 years ago [2–4, 7–10].

In QCD hadrons are composite bound state configurations built up from quark $\psi_i(x)$, $i = 1, \dots, N_c$ and gluon $G^\mu_a(x)$, $a = 1, \dots, N_c^2 - 1$ fields. In string models, the meson wave function has the form of an "open string" [1, 4], as it is shown in Fig. 1a.

The meson wave function (here and below we present only its colour structure) reads

$$M = \bar{\psi}^i(x_1)\Phi_i^{i'}(x_1, x_2)\psi_{i'}(x_2)\,. \tag{1}$$

$$\Phi_i^{i'}(x_1, x_2) = \left[T \exp\left(g \int_{P(x_1,x_2)} A_\mu(z)\,\mathrm{d}z^\mu\right)\right]_i^{i'}, \tag{2}$$

where the field A_μ is the following matrix in colour space:

$$A_\mu = \sum_a t_a A^a_\mu\,. \tag{3}$$

In (2), $P(x_1, x_2)$ represents a path from x_1 to x_2 which looks like an open string with ends at x_1 and x_2.

For the baryons there exist two possibilities, the "triangle", or Δ, connection shown in Fig. 1b, and the "star", or Y, connection shown in Fig. 1c. The last variant is considered as the most interesting one. Here a baryon is considered as a configuration consisting of three strings attached to three valence quarks and connected in a point called the "string junction" (SJ) [1, 4]. Such a picture is confirmed by lattice calculations [11]. The corresponding wave function can be written as

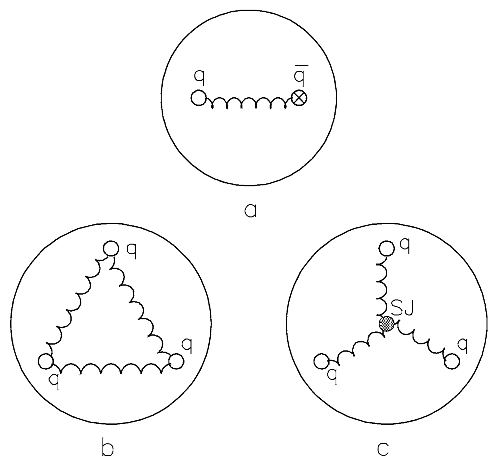

Fig. 1. Composite structure of a meson (**a**) and a baryon (**b** and **c**) in string models. Quarks are shown by *open points* and antiquarks by *crossed points*

$$B = \psi_i(x_1)\psi_j(x_2)\psi_k(x_3)J^{ijk}, \tag{4}$$

$$J^{ijk} = \Phi^i_{i'}(x_1, x)\Phi^j_{j'}(x_2, x)\Phi^k_{k'}(x_3, x)\epsilon^{i'j'k'}\,. \tag{5}$$

Such a baryon wave function can be defined as a "star" or "Y" shape, and it is preferable [1, 4] in comparison with the "triangle" ("ring") or "Δ" shape.[1]

[1] Strictly speaking we cannot build up the "Δ" configuration with the help of a string as in (2). In this ("Δ") case the colour flux produced by the quark is divided between two strings. That is, we need a fractional colour factor (like $g/2$) in the power of the exponent in (2).

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The wave function of an antibaryon has the form

$$\bar{B} = \psi^i(x_1)\psi^j(x_2)\psi^k(x_3)J_{ijk}\,. \tag{6}$$

The operators J^{ijk} and J_{ijk} differ by the position of the colour indices, which gives the possibility of annihilation of a $B\bar{B}$ pair into mesons.

The presented picture leads to several phenomenological predictions [12–14]. In particular, there is room for exotic states, such as the glueball, or gluonium ("closed string"); see Fig. 2a [4, 15]. We have

$$\text{Glueball} = \text{Tr}\left[T\exp\left(g\int_{P(\text{closed})} A_\mu(z)\,\mathrm{d}z^\mu\right)\right]. \tag{7}$$

Multiquark bound states, such as the 4-quark meson, Fig. 2b, the pentaquark, Fig. 2c, etc. also can exist. Without specified model it is impossible to say anything about the sign of the correspondent binding energy, i.e. whether they are bound states or not. However, we can expect that part of the particle momentum carried away by gluons in the case of multiquark states should be larger than for usual particles, see Figs. 1a,c, due to the larger number of string junctions.

Similarly to (4) and (5), the wave function of the M_4 meson (tetraquark) can be written

$$M_4 = \psi_i(x_1)\psi_j(x_2)J^{ijm} \times \bar{\psi}^k(x_3)\bar{\psi}^l(x_4)J_{kln} \times \Phi^n_m\left(x_0^{(1)}, x_0^{(2)}\right), \tag{8}$$

and the pentaquark wave function

$$B_5 = \psi_i(x_1)\psi_j(x_2)J^{ijn} \times \psi_l(x_4)\psi_m(x_5)J^{lmq} \times \bar{\psi}^k(x_3)\Phi^{k'}_k\left(x_3, x_0^{(2)}\right)\epsilon_{nqk'}\,, \tag{9}$$

The specified form of the colour wave functions of M_4 and B_5 presented above should result in weak mixing of them with $qq\bar{q}\bar{q}$ and $qqqq\bar{q}$ states produced radiatively from usual mesons and baryons.

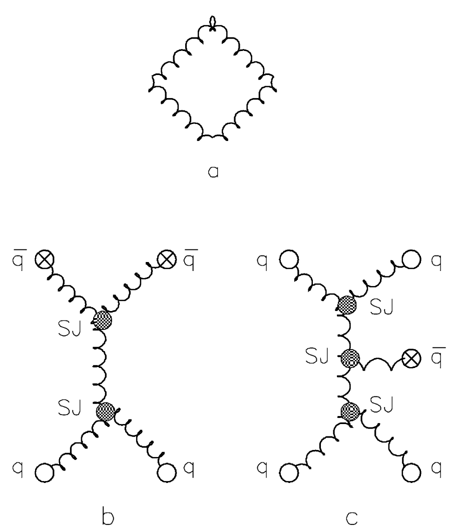

Fig. 2. Exotic states: glueball (**a**), 4-quark meson (tetraquark) $M_4 = qq\bar{q}\bar{q}$ (**b**) and 5-quark baryon (pentaquark) $B_5 = qqqq\bar{q}$ (**c**) in string models. Quarks are shown by *open points* and antiquarks by *crossed points*

2 Tetraquark and pentaquark production

The probability of SJ pair production in a small space-time region is rather small. In the case of pentaquark production an estimation can be taken from the ratio of the $\pi^- p \to \bar{p}d$ reaction cross section to the total inelastic one. Experimentally [16] it is of the order of 10^{-3}–10^{-4} at $\sqrt{s} = 2.9$–3.2 GeV. Note that these energies are rather close to the $\bar{p}d$ threshold. The momenta of the final nucleons are about 200–300 MeV. So the expected suppression (~ 0.01) due to the low probability to form a deuteron is not too strong, and it looks reasonable to assume that an additional factor of (0.01–0.1) is caused by the SJ pair production.

One way to avoid the smallness is to use the initially prepared SJ. So we can produce a tetraquark in $\bar{p}p$ collisions and a pentaquark in $\bar{p}d$ collisions at rather small energy. In the first case we can expect the annihilation of one $q\bar{q}$ pair that corresponds to the planar dual topological unitarization diagram which is of leading order in a $1/N_c$ expansion. In this case we expect the annihilation of two $q\bar{q}$ pairs and an additional smallness of about 10^{-2}, which is connected with the probability to find a proton and a neutron in the deuteron at small distances.

In the case of, say, pentaquark production in $\pi^- p$ collisions the ratio of signal to background should be worse in comparison with $\bar{p}d$ interactions.

3 Tetraquark and pentaquark decay

Let us start from the case when the mass of a meson M_4 (tetraquark), see Fig. 2b, is large enough. In the considered case the simplest mode of M_4 meson decay is breaking of the string between the points $x_0^{(1)}$ and $x_0^{(2)}$ with production of a light $q\bar{q}$ pair, which should result in the decay of M_4 into a $B\bar{B}$ state. The decay into two mesons should be less preferable; this is supported also by a triality analysis [7]. Similarly a B_5 baryon (pentaquark), see Fig. 2c, with high enough mass should decay preferably into a $BB\bar{B}$ state via breaking of two strings and production of two $q\bar{q}$ pairs.[2]

The situation becomes more complicated in the case of low mass multiquark states [19, 20]. Due to the completeness condition we can consider only real hadrons in the intermediate states. So we can imagine that now a tetraquark decays firstly into a virtual $B\bar{B}$ pair with their subsequent annihilation into mesons. Similarly, in the case of pentaquark decay the intermediate $BB\bar{B}$ system will result in a system of a baryon together with several

[2] The probability of two SJ annihilation (or production) is assumed to be small [7–9, 17]. It was argued in [18] that the smallness of SJ annihilation may be caused by the small size (~ 0.2–0.4 fm) of the "junction".

mesons. The important point is the suppression factor coming from every virtual baryon with 4-momentum k. In comparison with the normal width of the N^* resonances ($\Gamma \sim 150$–$200\,\mathrm{MeV}$) here we have suppression due to the loop which provides the annihilation of the virtual $B\bar{B}$ pair into mesons. Besides the numerically small factor $1/4\pi$, the loop contains the baryons far off the mass-shell. This leads to a suppression of the order of $(2m_\pi)^2/(m_B^2 - k^2) \sim 1/10$. That is, we expect suppression of the decay amplitude $\sim 1/100$, i.e. we expect a width of about $10^{-4} \times 200\,\mathrm{MeV} = 20\,\mathrm{keV}$ or even smaller, since the $B\bar{B}$ pair mainly annihilates into rather high multiplicity pion states and there should be an additional suppression due to the limited phase space available for the final pions. The small width of pentaquarks was also obtained [21, 22] in the framework of QCD sum rules approach.

The possibility exists to search tetraquarks and pentaquarks in the decay modes with strange particles, for example $K_s^0 + \Lambda + X$, where $s\bar{s}$ pair can be produced in the process of string breaking. The constituent mass of a strange quark is not much larger than that of light (u, d) quarks. The correspondent decay mode should be suppressed by the factor 10^{-1}, but the background should be suppressed more significantly.

Moreover, since the events with the K_s^0 or Λ decay are easy to select experimentally, the decay modes with strange particles and/or the reactions of strange pentaquark (the one which contains a strange quark) production look like an attractive way to search for such multiquark states.

The small width of the pentaquark (tetraquark) can explain the problems of their search, see, e.g. the reviews in [23, 24]. Indeed, it is hard to find a very narrow state performing the usual partial wave analysis. On the other hand the cross section of the inclusive pentaquark (or tetraquark) production is expected to be very small in the processes where there are no three SJ in the initial state and one needs to create two new SJ.

Therefore, it looks like it that there is more perspective in searching for the pentaquark in $\bar{p}d$ annihilation.

We conclude that the existence of tetraquarks and pentaquarks is natural in the string models. The production probability can be enhanced in special combinations of beam and target. The light multiquark systems can have a rather large mean life time (on the scale of the strong interactions) that can produce additional problems for the experimental search for them.

Acknowledgements. We are grateful to A.K. Likhoded, L.N. Lipatov and V.Y. Petrov for useful discussions. This paper was supported by DFG grant GZ: 436 RUS 113/771/1-2 and, in part, by grants RSGSS-1124.2003.2 and PDD (CP) PST.CLG980287.

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