# TETRAQUARKS, WHY IT IS SO DIFFICULT TO MODEL THEM\*

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We review the difficulties in searching for exotic tetraquarks both in experiments, in numerical lattice QCD computations and in analytic quark models. We propose to address  $qq\bar{Q}\bar{Q}$  exotic tetraquark boundstates and resonances with a fully unitarized and microscopic quark model.

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### 1. Introduction

A long standing problem of QCD is the search for localized exotic states [1] and the corresponding decay to the hadron-hadron continuum. There is no QCD theorem preventing the existence of exotic hadrons, say two-gluon glueballs, hybrids, tetraquarks, pentaquarks, three-gluon glueballs, hexaquarks, *etc.*, and the scientific community continues to search for clear exotic candidates. However, this problem turned out to be much harder than expected.

#### 2. The experimental search for tetraquarks

This is a very difficult problem experimentally, since exotic candidates are resonances immersed in the excited hadron spectra, and moreover, they usually decay to several hadrons.

Recently, an experimental article [2] was published indicating that the  $\pi_1(1600)$  observation of a resonance with mass M = 1660(74) MeV, and width  $\Gamma = 269(85)$  MeV, in diffractive dissociation of 190 GeV/ $c \pi^-$  into  $\pi^- \pi^- \pi^+$ , has exotic  $J^{PC} = 1^{-+}$  quantum numbers, consistent with an hybrid meson or a tetraquark.

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Moreover, the existence of tetraquarks has been advanced by the experimental collaborations at the charm and bottom factories to interpret the new X, Y, Z hidden charm or bottom mesons [3]. Their mass and decay products mark them as charmonia-like resonances but their masses do not fit into the quark model spectrum of quark–antiquark mesons [4]. In particular, the charged  $Z_c^{\pm}$  and  $Z_b^{\pm}$  are crypto-exotic, but technically they can be regarded as essentially exotic tetraquarks if we neglect  $c\bar{c}$  or  $b\bar{b}$  annihilation. There are two  $Z_b^{\pm}$  observed by the BELLE Collaboration at KEK [5], slightly below  $BB^*$  and  $B^*B^*$  thresholds, the  $Z_b(10610)^+$  and  $Z_b(10650)^+$ . Their nature is possibly different from the two  $Z_c(3940)^{\pm}$  and  $Z_c(4430)^{\pm}$ , which mass is well above the DD threshold. The LHCb Collaboration at CERN [6] recently confirmed  $Z_c(4430)^-$  with a resonance mass of 4475 MeV and width of 172 MeV.

Using very approximate Resonant Group Method calculations, in 2008, we predicted [7] a partial decay width to  $\pi J/\psi$  of the  $Z_c(4430)^-$  consistent with the experimental value.

However, to establish a new resonance, it is necessary to study with an accurate level of confidence all its properties, including its mass and width as determined by its S-matrix pole and all relevant partial decay widths. Possibly, we need more data and more extensive data analysis to be able to absolutely confirm exotics [8].

#### 3. The lattice QCD search for tetraquarks

In lattice QCD, the study of exotics is presently even harder than in the laboratory, since the techniques and computer facilities necessary to study resonances with many decay channels remain under development.

Lattice QCD already searched for evidence of a large tetraquark component in the  $Z_c(3940)^-$  candidate [9]. The difficulty of the study of the  $Z_c^-$ , a resonance well above threshold, is due to its many two-meson coupled channels. The authors considered 22 two-meson channels, corresponding to lattice QCD interpolators  $O^{M_1 M_2}$ . In addition, they considered 4 tetraquarks channels, corresponding to diquark–antidiquark interpolators with flavour and colour  $[\bar{c}\bar{u}]_3$   $[cd]_{\bar{3}}$ . An evidence for the tetraquark resonance candidate was investigated in the full coupled correlator matrix of hadron operators.

Finally, after switching on and off the 4 tetraquark-like channels, the authors [9, 10] found no significant deviation in the 13 lowest channels, who span the energy range from the lowest threshold to the  $Z_c(3940)^-$  candidate. Thus, the authors concluded there is no robust evidence of a  $Z_c^{\pm}$  tetraquark resonance.

However, the direct proof for, or against, a tetraquark resonance in lattice QCD would require the study of the S-matrix. The technique to perform phase shift analysis in lattice QCD exists [11]. From the phase shift analysis, inasmuch as with experimental data, the poles of the S-matrix can be extracted. But phase shift analysis of the tetraquark  $Z_c^+$  was not done yet with lattice QCD data. For an absolute evidence, the different partial decay widths should be computed as well in lattice QCD.

With present computers only resonances with just ~ 1 open decay channel have been studied in lattice QCD, with sufficient detail. The method of extracting the phase shifts from the spectrum of harmonic waves in a box has been extended to inelastic (more than one open channel) coupled channels [12]. However, tetraquarks are excited resonances, decaying into many channels, ~ 30 for the last experimental  $Z_c^-$  candidates. This is presently unattainable by present computers and codes, but we expect lattice QCD to be on the way to, in the future, reach the level of experimental data analysis.

These difficulties can be approximately relaxed when one uses a hybrid numerical-model approach. Recently, the light-antistatic potentials have been computed in lattice QCD [13, 14]. A static antiquark constitutes a good approximation to a spin-averaged  $\bar{b}$  bottom antiquark. The light-antistatic potential is a good approximation to the B-B potential, where we neglect higher order  $1/m_b$  terms including the spin-tensor terms. According to the quantum numbers of the two dynamical light quarks, either attraction or repulsion is found. In the most attractive channel, the potential is strong enough to produce a bound  $ll\bar{b}\bar{b}$  tetraquark.

#### 4. Quark model approaches to exotic tetraquarks

A detailed theoretical understanding of the properties of exotic hadrons is important to support the experimental and lattice QCD searches of exotics. Several theoretical problems need to be solved before addressing exotics hadrons.

Already at the onset of QCD, the bag model predicted many tetraquarks [1]. However, as soon as lattice QCD was able to compute static quark potentials and colour electromagnetic fields, it was realized that quark confinement was not bag-like, but string-like, due to colour flux tubes. Inspired in lattice QCD linear confining potentials, the relativized quark model potential was developed [4], after the authors fitted the spectra of all known hadrons in the 80s. Notice that a correctly calibrated quark model needs many terms and many parameters, say of the order of  $\sim 20$  parameters. Nevertheless, the relativized quark model still lacks two crucial effects, leading with up to 400 MeV deviations, chiral symmetry breaking, now included, say in the Dyson–Schwinger approach [15], coupled channels/unquenching, now included, say in effective meson or baryon models [16].

Moreover, since tetraquarks are always open to decays into a mesonmeson pair, tetraquark resonances or boundstates may only exist if a mechanism exists to provide binding specific to tetraquarks. Here, we explore a mechanism observed in lattice QCD static potentials: the confining four body potential [17, 18], produced by double Y or butterfly shaped flux tubes or strings [19], depicted in Fig. 1. This mechanism is related to the Jaffe-Wilczek model [20, 21] who proposed the tetraquark would form a diquarkantidiquark system. We acknowledge other mechanisms may exist to support binding. For instance, attraction may also be due to quark–antiquark annihilation, however it turned out to be insufficient to bind a proposed pentaguark [22, 23]. Another mechanism is the hyperfine spin-dependent potential utilized in the original bag model [1], however the spin-tensor potentials have only been computed in lattice QCD for mesons. For baryons, they are model dependent, while for multiquarks the details of the spin-tensor potentials remain speculative. To avoid the complexity of quark-antiquark annihilation, spin tensor quark–quark interactions and chiral symmetry breaking, we specialize in a family of tetraquarks where they can be neglected. Here, we consider purely exotic tetraquarks only, where quark-antiquark annihilation does not occur directly. And, as a first study, we neglect spin-tensor interactions and chiral symmetry breaking effects.



Fig. 1. Surface plot of the static tetraquark flux tube computed in lattice QCD [19].

Clearly, tetraquarks are always coupled to meson-meson systems, and we must be able to address correctly the meson-meson interactions. Confining two-body potentials with the SU(3) colour Casimir invariant  $\vec{\lambda}_i \cdot \vec{\lambda}_j$  suggested by the One-Gluon-Exchange potential, and possibly compatible with lattice QCD, lead to a van der Waals potential,

$$V_{\text{van der Waals}} = \frac{V'(r)}{r} \times T$$
, (1)

where T is a polarization tensor. This would lead to an extremely large van der Waals [24, 25] force between mesons, or baryons which clearly is not observed experimentally. Thus, two-body confinement dominance is ruled out for multiquark systems. The string flip-flop potential for the meson–meson interaction was developed [26, 27], to solve this problem. Traditionally, it considers that the potential is the one that minimizes the energy of the possible two different meson–meson configurations, say  $M_{13} M_{24}$  or  $M_{14} M_{23}$ . This removes the inter-meson potential, and thus solves the problem of the van der Waals force.

Thus, we upgrade the string flip-flop potential, considering a third possible configuration, the tetraquark one, say  $T_{12,34}$ , where the four constituents are linked by a connected string [28]. The three configurations differ in the strings linking the quarks and antiquarks, see Fig. 2. When the diquarks qq and  $\bar{q}\bar{q}$  have small distances, the tetraquark configuration minimizes the string energy. When the quark–antiquark pairs  $q\bar{q}$  and  $q\bar{q}$  have small distances, the meson–meson configuration minimizes the string energy.



Fig. 2. Triple string flip-flop potential. While the previous string flip-flop potentials choose the minimum of two different meson pair potentials, we consider as well the tetraquark potential.

With a triple string flip-flop potential, the scientific community has already found bound states below the threshold for hadronic coupled channels [28, 29]. This avoids the computation of decay widths, however it does not access resonances.

On the other hand, the string flip-flop potentials allow fully unitarized studies of resonances [26, 27, 30]. Utilizing analytical calculations with a double flip-flop harmonic oscillator potential [30], and using the resonating group method again with a double flip-flop confining harmonic oscillator potential [26, 27], resonances and boundstates have already been predicted.

Moreover, using the perturbative approximation of the resonating group method, a preliminary estimation of the partial decay width of the  $Z(4430)^-$  resonance was similar to the one measured by LHCb [7].

These studies suggest that tetraquark boundstates or resonances are plausible. We are presently developing fully unitarized techniques, adapted to state of the art potentials, necessary to achieve a quantitative theoretical study of tetraquark resonances and boundstates.

#### 5. Conclusion

We address systems where the quantum numbers, or the S-matrix pole and decay amplitudes clearly correspond to tetraquarks. We review problems in observing tetraquarks experimentally and in simulating them in lattice QCD. We develop techniques to solve some of the theoretical problems of multiquarks, and to predict multiquark boundstates and resonances.

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