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Hybridized tetraquarks

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ABSTRACT

We propose a new interpretation of the neutral and charged X, Z exotic hadron resonances. *Hybridized*-tetraquarks are neither purely compact tetraquark states nor bound or loosely bound molecules but rather a manifestation of the interplay between the two. While meson molecules need a negative or zero binding energy, its counterpart for h-tetraquarks is required to be positive. The formation mechanism of this new class of hadrons is inspired by that of Feshbach metastable states in atomic physics. The recent claim of an exotic resonance in the $B_s^0\pi^\pm$ channel by the D0 Collaboration and the negative result presented subsequently by the LHCb Collaboration are understood in this scheme, together with a considerable portion of available data on X, Z particles. Considerations on a state with the same quantum numbers as the $X(5568)$ are also made.

1. Introduction

The two most popular phenomenological models introduced to describe the XYZ resonances are the compact tetraquark [1–4] and the loosely bound meson molecule [5]. While in the first description the exotic mesons are four-quark objects tightly bound by color forces, in the second one they are real bound states in a shallow inter-hadron potential (for a review, see [6]).

In this Letter we propose a new interpretation of these states: h-tetraquarks[1] result from an hybridization between the discrete levels of the tetraquark potential and continuous spectrum levels of the two-meson potential.

The guiding principle to identify h-tetraquarks is to write first the diquark composition of would-be-compact tetraquarks along the lines described in [1,2]. This gives an estimate of the energy of the discrete level of interest. The strongly bound diquark–antidiquark state can be Fierz rearranged in a number of color singlet pairs which can be of the form hidden-flavor + light meson or two open flavor mesons, having quantum numbers compatible with the initial tetraquark state. The spin of the light quark component is allowed to flip, whereas the spin of the heavy quark pair has to be the same in both the compact tetraquark and the meson pair description.

The mass of the would-be-compact tetraquark is computed with the methods of [1,2]. The masses of the corresponding different would-be-hadron molecules are computed as sums of the masses of the components in the pair with no interaction energy. A reference molecule is taken in our analysis: the one having the closest possible mass, *from below*, to the tetraquark (diquark–antidiquark) discrete level.

The meson pair is allowed to interact in the continuous spectrum of some unknown shallow meson–meson potential which is assumed not to have (negative-energy) bound states. A level in the continuous spectrum of the two-body system and the near discrete level of the compact tetraquark can match as illustrated below. If this matching is realized, a sort of *'hybridization'* of the hadron molecule into the compact structure occurs.

The hybridized state is unstable as it can dissociate back into its free components — this is expected to be the major contribution to the width of the ground state tetraquarks. Other, less frequent, dissociation channels are also possible and partly contribute to the total width.

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[1] Note that our states do not have any relation to the gluonic hybrids [7]. The term 'hybridization' here is taken from the physics of Feshbach resonances in cold atom systems, with the meaning explained in the text.

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The scattering in the continuous spectrum is assumed to be essentially inelastic because of the hybridization of the tetraquark final state, which produces a temporary rearrangement of the internal structure of the system.

What is important is that the *detuning* δ, *i.e.* the distance in energy between the expected tetraquark discrete level (which we can estimate) and the onset of the continuous spectrum starting from the closest molecular threshold is *positive* and *small* with respect to the coupling $|\varkappa|$ responsible of the hybridization process.

The case in which $\delta < 0$ suggests a repulsion in the meson–meson channel, which is incompatible with hybridization. This might be the reason which forbids the charged partners of the $X(3872)$ and provides isospin violation (the charged threshold happens to be 4 MeV above the tetraquark level).

2. 'Hybridization'

For any given threshold, the scattering length a in the open channel P of the meson pair gets enhanced if a discrete level of the closed channel Q of compact diquarkonia happens to be *above* and close to the onset of the continuous spectrum of the pair, according to

$$a \simeq a_P - C \sum_n \frac{\langle \Psi_\alpha | H_{PQ} | \Psi_n \rangle \langle \Psi_n | H_{QP} | \Psi_\alpha \rangle}{E_n - E_\alpha}$$

$$\simeq \left(1 - \frac{\varkappa}{\delta - E + i\epsilon}\right) a_P, \tag{1a}$$

$$\mathrm{Im}\, a \sim \delta(E - \delta)\, \varkappa\, a_P, \tag{1b}$$

where $|\Psi_n\rangle$ is the discrete level in the closed channel and $|\Psi_\alpha\rangle$ is a continuous spectrum state above one of the thresholds $\psi^{(\prime)}\pi$, $\eta_c\,\rho$, $\bar{D}^*D^*$, $\bar{D}^*D$, taking the Z_c resonance as an example. The energy associated with $|\Psi_\alpha\rangle$ is $E_\alpha = E$ for brevity. a_P represents the small scattering length at zero coupling between open and closed channels. C is a positive numerical constant, H_{QP} is the non-hermitian Hamiltonian which couples the closed and open channels. In (1a), $\delta = E_n - E_{\rm thr}$ is the small 'detuning' between the discrete level and the closest threshold (onset of the continuous spectrum). The effective coupling $\varkappa$ is real and depends on the overlap integrals in (1a). It contributes to the inelastic channel in which a compact tetraquark is formed as a metastable state (the inverse process also occurs).

The phenomenon described induces a resonant enhancement in the production of h-tetraquarks and is compatible with their production in high energy and high transverse momentum proton–(anti)proton collisions, as opposed to what expected for real loosely bound molecules, as discussed in the literature [8,9].

The inelastic cross section at low energy in the continuous spectrum of the open channel is (neglecting numerical constants)

$$\sigma_{\rm in} \sim \frac{|\mathrm{Im}\, a|}{p}, \tag{2}$$

where p is the relative momentum in the center-of-mass of the pair. Therefore, the rate at which the h-tetraquark is formed is

$$d\Gamma \sim \rho\, v\, \sigma_{\rm in} \sim \delta(E - \delta)\ |\varkappa\, a_P|\, \frac{\rho}{m}, \tag{3}$$

where ρ is the density of initial states

$$\rho \sim d^3p = (2m)^{3/2}\sqrt{E}\, dE, \tag{4}$$

and the integral in E is extended over some $[0, E_{\rm max}]$ range. The Dirac-delta in (3) gives an integral different from zero only if the detuning δ falls within the integration range, $\delta < E_{\rm max}$. In that case the level matching condition $E \sim \delta$ enhances the hybridization of the would-be-molecule with the corresponding diquarkonium. Inserting (4) into (3) gives [2]

$$\Gamma \sim (2m)^{1/2}\ |\varkappa\, a_P|\ \sqrt{\delta} \sim A\,\sqrt{\delta}. \tag{5}$$

It is difficult to estimate $E_{\rm max}$, the maximum relative energy in a would-be-molecule (tens of MeVs). In our view the hadronization state is a superposition of a diquarkonium state plus all possible molecular states allowed by quark flavors and quantum numbers. We might reasonably expect that being the color force screened between the color singlets components of the molecule, the relative energy must be smaller that what one would find in a compact system.

The total width of the state can be expressed as a sum on all available open-channels

$$\Gamma \sim \sum_i \Gamma_i. \tag{6}$$

It is essential here to note that if only pure phase space were to be considered [10], then the open channel with the largest detuning would be the dominant one. On the contrary, the considerations made above show how the enhancement in Eq. (1) leads to select the *closest* threshold (from below): all partial widths will be negligible, exception made for the one relative to a δ within the $[0, E_{\rm max}]$ integration range. This mechanism is inspired by the formation of metastable Feshbach states in atomic physics [11] (in XYZ context see [12,9], and in general in the strong interaction [13]).

Therefore we now only consider the closest molecular channel, and for practical purposes use $\Gamma = A\sqrt{\delta}$ in place of Eq. (5). We observe that the widths and detunings in a broad class of observed resonances strictly obey this law with a common value for the A parameter — this can be appreciated by the very good fit in Fig. 1. The fact that all data can be fitted with the same proportionality constant A, strongly supports for the described states to share the same nature. It also shows that this is not just a phase space effect. It is worth noting that Fig. 1 implies that the $\varkappa$ coupling in (5) has to nearly cancel (within the errors of the fit) the $\sqrt{m}$ dependency on the reduced mass of the molecule.

We might expect small variations among different a_P's. For example, open charm meson pairs have scattering lengths, a_P, likely larger than the ones for charmonium + light meson pairs. This might explain why the $Y(4140)$, which matches a $J/\psi\,\phi$ threshold, is slightly off in the description of Fig. 1, even though by merely a 1σ deviation.

The above arguments do not straightforwardly generalize to excited tetraquarks. In that case the closed channel is itself not stable against a de-excitation into its allowed tetraquark ground state. It then follows that the width predicted with the approach explained will for sure underestimate the actual width of the state. For example, we consider the $Z(4430)$ which, in the tetraquark model, is the radial excitation of the $Z_c(3900)$ [2]. The closest threshold from below would be $\eta_c(2S)\,\rho$ with a detuning $\delta \simeq 65$ MeV. The latter one is probably rather large to consider Eq. (1) without including other discrete levels. Nevertheless the width obtained would be $\Gamma \simeq 80$ MeV which naturally underestimates the experimental one, $\Gamma = 181 \pm 31$ MeV. Similarly, for the moment we do not extend the analysis to pentaquarks, being the experimental information not sufficient. In this case, not only one of the two observed resonances would be an excited state, but we do not have any hint about A. We indeed expect substantial differences from the present case since the baryon-meson scattering is different.

[2] Compare with the discussion in [11].