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Why static bound-state calculations of tetraquarks should be met with scepticism

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Abstract: Recent experimental signals have led to a revival of tetraquarks, the hypothetical $q^2\bar{q}^2$ hadronic states proposed by Jaffe in 1976 to explain the light scalar mesons. Mesonic structures with exotic quantum numbers have indeed been observed recently, though a controversy persists as to whether these are true resonances and not merely kinematical threshold enhancements, or otherwise states not of a true $q^2\bar{q}^2$ nature. Moreover, puzzling non-exotic mesons are also often claimed to have a tetraquark configuration. However, the corresponding model calculations are practically always carried out in pure and static bound-state approaches, ignoring completely the coupling to asymptotic two-meson states and unitarity, especially the dynamical effects thereof. In this short paper we argue that these static predictions of real tetraquark masses are highly unreliable and provide little evidence of the very existence of such states.

Keywords: tetraquarks, unitarisation and coupled channels, mass shifts, bound-state approaches, light scalar mesons, unrestrained disintegration, meson-meson molecules

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1 Introduction

In 1976 R. L. Jaffe proposed [1] an ingenious construct to explain the low masses of the light scalar mesons, in the context of the MIT bag model [2]. His solution amounted to introducing "crypto-exotic" colourless $qq\bar{q}\bar{q}$ configurations instead of the usual $q\bar{q}$ ones for ordinary mesons. Due to the very large and attractive colour-magnetic spin-spin interaction for the ground-state $q^2\bar{q}^2$ systems, an enormous negative mass shift could be obtained and so reasonable masses could be found for the lightest scalar mesons [1], viz. 650 MeV for the ϵ (now called $f_0(500)$ [3, 4] or σ), 900 MeV for the κ ($K_0^\star(800)$ [3]), and 1100 MeV for both the $S^\star$ ($f_0(980)$ [3]) and the δ ($a_0(980)$ [3]). Although Jaffe's proposal was received with general approbation, interest rapidly faded owing to the poor status of the light scalars in those days and the lack of experimental indications of truly exotic (necessarily non-$q\bar{q}$) states.

Renewed interest in the $q^2\bar{q}^2$ or "tetraquark" [5] model resulted primarily from the experimental discovery of a number of mesons that did not seem to fit in the traditional static quark model (SQM), which treats hadrons as manifestly bound states of quarks and antiquarks. Indeed, the most widely used SQM, viz. the relativised quark model of mesons by Godfrey and Isgur [6], predicted considerably higher masses for enigmatic mesons such as e.g. the scalar charmed-strange $D_{s0}^\star(2317)$ [3] and the axial-vector charmonium X(3872) [3]. Over the following years, a large number of puzzling mesonic enhancements were observed, most of these in the hidden-charm sector and some with hidden bottom, a few of them even electrically charged. The latter ones would of course exclude simple $c\bar{c}/b\bar{b}$ assignments, if indeed confirmed as genuine resonances, justifying speculations that they may be tetraquarks. For some time these states were labelled — quite arbitrarily — "X", "Y", or "Z", but the PDG now calls them all Xs [3]. For very recent reviews, see Ref. [7] on hidden-charm pentaquark and tetraquark states, and Ref. [8] on exotic hadrons in general.

Despite these exciting observations, figuring out the true nature of all these unusual states is an enormous challenge. First of all, the experimental identification

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of several X structures as bona-fide resonances is anything but undisputed. In a recent lattice calculation [9], with many two-meson interpolating fields included, no evidence was found of isovector hidden-charm tetraquark states up to 4.2 GeV. Moreover, several authors [10–14] interpret charged hidden-charm or hidden-bottom signals rather as non-resonant cusp-like structures, resulting from kinematical triangle singularities in intermediate-state diagrams. On the other hand, even when four-quark states are predicted in model calculations, these are often described as (quasi-)bound states of two mesons [15, 16], with binding due to t-channel meson exchange instead of colour forces among two quarks and two antiquarks. Finally, there are also models suggesting that the observed charged hidden-charm and/or hidden-bottom peaks may be highly excited D_s ($\mathrm{c\bar{s}}$) states [17, 18] or light-quark axial-vectors [19].

Now, if tetraquarks nonetheless exist in nature as genuine $\mathrm{q}^2\mathrm{\bar{q}}^2$ bound states or resonances, the question remains how to describe them in a realistic way, besides resorting to the lattice. This brings us inexorably to the issue of mass shifts from unitarisation, sometimes called “unquenching” [20], which we shall discuss in the next section. But let us first quote the warning of Jaffe himself [1] about describing the light scalar mesons as stable tetraquarks:

> “First, we are confronted with mesons whose width is a substantial fraction of their mass. A calculation of their masses which ignores decay processes (as does ours) must not be taken too literally. We should not expect the accuracy we demanded in our treatment of $\mathrm{Q\bar{Q}}$ mesons and Q^3 baryons.”

2 Unquenching the quark model

A fundamental difference between strong interactions and e.g. electromagnetism is that in the former case mass splittings and decay widths can be of similar magnitude. Picking just one typical example from the PDG [3] Meson Summary Table, we see that the mass difference between the tensor meson $\mathrm{f}'_2(1525)$ and its first radial excitation $\mathrm{f}_2(1950)$ is about 420 MeV, while the full width of the latter resonance is (472 ± 18) MeV. This has tremendous implications for spectroscopy, as was recognised almost four decades ago by the Cornell [21], Helsinki [22], and Nijmegen [23] hadronic-physics groups. Namely, most mesons/baryons are not merely bound $\mathrm{q\bar{q}}$/qqq states, but rather resonances in meson-meson or meson-baryon scattering, respectively. Now, arguments based on S-matrix analyticity imply that imaginary parts of resonance poles are in principle of the same order as the corresponding real shifts with respect to the corresponding bound states from quark confinement only. This may give rise to huge distortions of hadron spectra as predicted by the SQM. To make life worse, relatively stable hadrons, with widths of roughly 1 MeV or even less, can still be subject to real mass shifts at least two orders of magnitude larger, due to virtual decay. A famous example is the enigmatic scalar charmed-strange meson $\mathrm{D}^{\star}_{s0}(2317)$ [3], predicted to be 170–180 MeV heavier by the SQM, but ending up at a much lower mass owing to the closed yet strongly coupling S-wave DK decay channel [24]. The latter model result was recently confirmed on the lattice [25], thus enfeebling claims [26] of a tetraquark interpretation of this meson.

In order to illustrate the possible effects of unquenching on meson spectra in general, we collect in Table 1 several model calculations of mass shifts owing to strong decay. Note that not all of these approaches amount to full-fledged S-matrix unitarisations of the SQM, in fact only those in Refs. [21, 23, 28, 29, 34, 35] (for further details, see Ref. [20]). But even among the latter there can be sizable differences, as we can see in Table 1 by comparing the predictions of Refs. [21] and [23] for charmonium. These disagreements not only originate in different confinement forces, but also in the employed decay mechanisms, which are in their turn influenced by the nodal structure of the $\mathrm{q\bar{q}}$ wave functions. Nevertheless, Table 1 shows potentially huge mass shifts, some of which are even larger than typical radial spacings in meson spectra. Also note that S-matrix calculations generally produce complex shifts, whenever at least one decay channel is open. Particularly interesting in this respect is the case of the charmed-light axial-vector meson $\mathrm{D}_1(2430)$, whose imaginary mass shift in Ref. [35] came out an order of magnitude larger than its real shift, with the corresponding resonance pole position being in good agreement with experiment [3]. Note that this is a highly non-perturbative effect and not a consequence of the usual perturbative calculation of the width.

Table 1. Negative real mass shifts from unquenching. Abbreviations: P, V, S=pseudoscalar, vector, scalar mesons, respectively; q=light quark. See text and Ref. [20] for further details.

Refs.	mesons	$-\Delta M$/MeV
[21]	charmonium	48–180
[22, 27]	light P, V	530–780, 320–500
[23, 28]	$\mathrm{q\bar{q}}$, $\mathrm{c\bar{q}}$, $\mathrm{c\bar{s}}$, $\mathrm{c\bar{c}}$, $\mathrm{b\bar{b}}$; P, V	$\approx$ 30–350
[29]	σ, κ, $\mathrm{f}_0(980)$, $\mathrm{a}_0(980)$	510–830
[29]	standard S (1.3–1.5 GeV)	~ 0
[30]	$\rho(770)$, $\phi(1020)$	328, 94
[24]	$\mathrm{D}^{\star}_{s0}(2317)$, $\mathrm{D}^{\star}_{0}(2400)$	260, 410
[31]	$\mathrm{D}^{\star}_{s0}(2317)$, $\mathrm{D}^{\star}_{s}(2632)$	173, 51
[32]	charmonium	165–228
[33]	charmonium	416–521
[34]	X(3872)	$\approx$100
[35]	$\mathrm{c\bar{q}}$, $\mathrm{c\bar{s}}$; $J^P=1^+$	4–13, 5–93

The most surprising result in Table 1 is, though, for the light scalar mesons, which emerged as a complete nonet of dynamical resonances in the 30-year-old model calculation of Ref. [29], without any parameter fitting. The scalar-meson mass shifts of 510–830 MeV from unitarisation reported in Table 1 correspond to the differences between the bare ("quenched") $1\,^3\mathrm{P}_0$ quark-antiquark energy levels and the real parts of the lowest scalar resonance poles. However, the latter appear as extra, dynamically generated poles, besides an also complete nonet of scalar resonances that shift much less (cf. $\mathrm{D}_1(2430)$ above) and remain in the range 1.3–1.5 GeV [29]. This allows description of both the light scalar nonet $\mathrm{f}_0(500)$ (σ), $\mathrm{K}_0^\star(800)$ (κ), $\mathrm{f}_0(980)$, $\mathrm{a}_0(980)$ [3] and the standard ground-state scalar nonet $\mathrm{f}_0(1370)$, $\mathrm{K}_0^\star(1430)$, $\mathrm{f}_0(1500)$, $\mathrm{a}_0(1450)$ [3] as unitarised $\mathrm{q\bar{q}}$ states. Recent work [36] supports this phenomenon of generating extra resonances in the light scalar sector (also see Ref. [37] and references therein).

In the next section we shall focus on the light scalar mesons in other approaches, keeping in mind the importance of unitarisation.

3 Light scalar meson nonet

As described above, the observation of many mysterious mesonic signals over the past decade has led to a revival of Jaffe's [1] tetraquark model, also for the light scalars (see e.g. Ref. [38]). The problem is that practically all these works simply ignore unitarisation. This is all the more serious in the scalar-meson case, as any postulated tetraquark wave function will inevitably contain components of two colourless $\mathrm{q\bar{q}}$ subsystems in a relative S-wave. So if phase space allows, such a hypothetical tetraquark can simply fall apart into two mesons, like e.g. $\mathrm{f}_0(500) \to \pi\pi$ or $\mathrm{K}_0^\star(800) \to \mathrm{K}\pi$, which was recognised by Jaffe already 40 years ago (see Ref. [1] for the figures mentioned):

> "If it is heavy enough an S-wave $\mathrm{Q}^2\overline{\mathrm{Q}}^2$ meson will be unstable against decay into two S-wave $\mathrm{Q}\overline{\mathrm{Q}}$ wave mesons. The $\mathrm{Q}^2\overline{\mathrm{Q}}^2$ state simply falls apart, or dissociates, as illustrated in Fig. 4(a). In contrast, decay of a $\mathrm{Q}\overline{\mathrm{Q}}$ meson into two $\mathrm{Q}\overline{\mathrm{Q}}$ mesons (for example $\rho \to \pi\pi$ or $\mathrm{f} \to \pi\pi$) requires creation of a $\mathrm{Q}\overline{\mathrm{Q}}$ pair [Fig. 4(b)]."

In face of this physical reality, Jaffe and Low developed [39] the so-called P-matrix formalism, which should relate S-matrix observables, with boundary conditions at infinity, to solutions of a relativistic wave equation with boundary conditions at an arbitrary finite distance and the corresponding discrete energy levels. They then applied it to S-wave meson-meson scattering, extracting real energies corresponding to P-matrix poles from experimental scattering data and comparing these to the MIT-bag-model mass predictions [1] for light scalar tetraquarks. However, it remains unclear how to justify a direct link, in a single-channel approach, between asymptotic two-meson states and a wave function for 4 coloured quarks confined to a bag. Also, no quark-antiquark annihilation is considered in this formalism, which the authors themselves expected [39] to occur in mixing of heavier $\mathrm{q^2\bar{q}^2}$ and $\mathrm{q\bar{q}}$ states. Moreover, the P-matrix method does not allow conclusions on resonance widths to be drawn from the data. Finally, the experimental data do not support the existence of exotic or crypto-exotic states between 1 and 2 GeV that should correspond to the P-matrix poles of heavier scalar tetraquark bag states predicted in Ref. [1].

In principle, the dynamical consequences of uninhibited decay may be dramatic. Suffice it to recall the enormous mass shifts for the light scalar mesons in the unitarised $\mathrm{q\bar{q}}$ model of Ref. [29], despite the necessity of creating a new $\mathrm{q\bar{q}}$ pair. An important hint may come from Ref. [40], in which a unitarised toy model of tetraquarks was formulated via a two-variable Schrödinger equation for the two spatial configurations $(\mathrm{qq})(\mathrm{\bar{q}\bar{q}})$ and $(\mathrm{q\bar{q}})(\mathrm{q\bar{q}})$. In spite of the implemented simplifications, a very striking conclusion emerges from this study, namely that no tetraquark bound state or observable resonance is found for zero orbital angular momentum, i.e., precisely in the case of scalar mesons. What may happen here is that a bound-state pole corresponding to a static scalar tetraquark state moves very far away or even disappears completely in the scattering continuum once decay into two mesons is allowed. In order to better investigate such a scenario, a more realistic version of the referred toy model would be highly desirable, perhaps along the lines of Ref. [41], but applied to a light scalar tetraquark instead of the studied $\mathrm{qq\bar{Q}\bar{Q}}$ systems, where Q stands for heavy quark (c or b).

To conclude our discussion, we turn to a very recent [42], alternative description of light scalar tetraquarks, which amounts to the numerical solution of a four-body Bethe-Salpeter (BS) equation with pairwise rainbow-ladder gluonic interactions. The authors formally write down a scattering equation for the $\mathrm{qq\bar{q}\bar{q}}$ T-matrix, i.e.,

$$T = K + K\,G_0\,T, \tag{1}$$

where K is the $\mathrm{qq\bar{q}\bar{q}}$ interaction kernel and G_0 the product of four dressed (anti-)quark propagators. However, in order to search for poles, Eq. (1) is immediately replaced by a homogeneous equation for the BS amplitude (or vertex function) Γ:

$$\Gamma = K\,G_0\,\Gamma. \tag{2}$$

The latter equation allows bound-state solutions to be found, but in principle it can also be used to describe a resonance for complex energy, provided that a proper analytic continuation into the second Riemann sheet is carried out, so as to include the corresponding pole contribution. This was done in Ref. [43] for a three-dimensional relativistic two-body equation, using contour-rotation techniques. However, doing something similar in the four-dimensional four-body BS case must be a gargantuan enterprise, as the authors of Ref. [42] themselves admit:

> "This is, however, a rather formidable task which has not even been accomplished in simpler systems so far."

Yet, the implications of this understandable restriction to pure bound states could be much more far-reaching than the truncation of the kernel to pairwise interactions only. So let us see what the lattice has to say. Quite ideal would be to have full-fledged lattice simulations of S-wave $\pi\pi$, Kπ, and $\eta\pi$ scattering, with meson-meson and either $q\bar{q}$ or $qq\bar{q}\bar{q}$ interpolators included. Very recent lattice work has tried to describe these systems with quark-antiquark and two-meson degrees of freedom included, viz. the $f_0(500)/\sigma$ [44], $K_0^\star(800)/\kappa$ [45], and $a_0(980)$ [46], though with still unphysically large pion masses. Nevertheless, the results suggest that no tetraquark configurations are required in the description of the light scalars. On the other hand, there are lattice indications of the importance to account for scattering solutions, albeit for a different system. In Ref. [47] several excited meson and baryon spectra were presented, resulting from unquenched lattice calculations with fully dynamical quarks, but without considering meson-meson scattering solutions. Among these was a mass prediction above 1.6 GeV for the first radial excitation of the $K^\star(892)$ resonance. But almost simultaneously, the same lattice group published [48] results on P-wave Kπ scattering, employing both $q\bar{q}$ and meson-meson interpolators. This allowed reasonable reproduction of the mass and Kπ decay coupling of $K^\star(892)$, besides extracting a tentative mass for its first radial recurrence at (1.33 ± 0.02) GeV, more or less compatible with the observed [3] Breit-Wigner mass of the broad $K^\star(1410)$ resonance. Apart from being much closer to the experimental value than the predictions of mainstream quark models, the value of 1.33 GeV is about 300 MeV lower than the above lattice bound-state result [47]. So open meson-meson channels can yield a huge mass shift, even for a radially excited meson decaying in a P-wave, for which unitarisation is usually supposed to be of limited importance. One can only guess how large such effects might be for a ground-state tetraquark that can freely fall apart into an S-wave $\pi\pi$ or Kπ state.

Some final words are due concerning the results of Ref. [42], which may be very relevant for QCD even if having little bearing upon experiment. The most important conclusion seems to be:

> "... these tetraquarks are not diquark-antidiquark states but predominantly 'meson molecules' ..."

In other words, two colourless $q\bar{q}$ systems constitute by far the most important component of the computed bound-state wave function, so that the designation "meson-meson molecule" appears much more appropriate for such a system than "tetraquark". Moreover, this microscopic modelling of the light scalar mesons is not so different from the effective approach in Ref. [43], where only meson-meson interactions were considered, though in a fully unitary formalism. Curiously, the latter paper reported a very light σ-like pole in the $\pi\pi$ S-wave, with a real part of 387 MeV and an enormous imaginary part of 305 MeV. This former value of 387 MeV is not very far from the bound-state "σ" mass of 348 MeV found in Ref. [42]. Of course, this may be just a coincidence, in view of the strong unitarisation effects leading to a width of more than 600 MeV in Ref. [43].

4 Conclusions

The hypothetical tetraquark system is a hotly disputed topic in hadronic physics nowadays. Many are led to take recent experimental signals, especially in the charmonium sector, as proof of their existence. However, several alternative explanations exist, such as non-resonant structures due to kinematical singularities, meson-meson molecules bound by t-channel exchanges, and highly excited regular $q\bar{q}$ mesons. The experimental challenge is not only to provide high-statistics data with unambiguous resonance characteristics, but also to find unmistakable partner states as predicted by the tetraquark model, either in the same isomultiplet or the same flavour multiplet.

On the theoretical side, things are by no means easier. As we hope to have made clear, predictions of tetraquark models that ignore the effects of decay should not be trusted. And this applies not only to states above two-meson thresholds but also to seemingly genuine $qq\bar{q}\bar{q}$ bound states, since the virtual meson loops corresponding to closed yet nearby thresholds will inevitably have a significant influence, especially in the case of S-waves.

As for the light scalar resonances, of which $f_0(500)$ (σ) and $K_0^\star(800)$ (κ) are very broad, a pure bound-state tetraquark description cannot be realistic, although the 4-body BS calculation of Ref. [42] appears to approximately account for some meson-meson contributions. Unitarising such an approach would be a huge step foreward, but does not seem feasible for the time being. An alternative is the unitarised tetraquark potential model of Ref. [41], but applied to the crypto-exotic light scalars instead of exotic $qq\bar{Q}\bar{Q}$ systems. However, quark-antiquark annihilation would then have to be considered too, making an already very difficult problem even more cumbersome. Finally, the lattice will probably be able at some point to settle the tetraquark issue for the light scalar mesons, perhaps quite soon, in view of the progress made recently (see Refs. [44–46]), also on describing vector-meson resonances (see e.g. Ref. [48]). Still, the complication of flavour mixing and coupled $\pi\pi$-$K\bar{K}$ channels in the isosinglet $f_0(500)$ case suggests that the first scalar to reproduce in full glory is $K_0^\star(800)$. This would also help to finally convince the Particle Data Group to include the latter resonance in the Meson Summary Table [3], which we believe is overdue [49]. We are also convinced that such a lattice calculation will lend support to the decades-old [29] picture of the light scalars as dynamical resonances generated by the strong coupling of much heavier bare $^3P_0$ $q\bar{q}$ states to low-mass S-wave meson-meson decay channels. The "tetraquark" interpretation of these solutions then essentially boils down to the dominant meson-meson components apparently observed in Ref. [42], with a subdominant $q\bar{q}$ component constituting the missing ingredient, besides the restriction to real energies only. The absence of a $q\bar{q}$ component also in Ref. [43] may explain the too low σ mass and much too large σ width obtained in this pure meson-meson model.

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