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Multiquark hadrons

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Abstract. The possible production of multiquark systems is very important for our understanding of hadrons. A considerable interest in such states started with Jaffe's work in 1977, demonstrating the role of the chromomagnetic interaction in the stability of light multiquarks. Since then, heavy quarks have also been included. A brief survey is presented regarding the evolution of the problem. Some of the recently observed resonances, named X,Y or Z, are discussed as possible candidates for tetraquarks.

1 Introduction

The multiquark hadrons studied so far are compact objects of type:

- Tetraquarks: $q^2\bar{q}^2$, $Q^2\bar{q}^2$, $Q\bar{Q}q\bar{q}$
- Pentaquarks: $q^4\bar{Q}$, $q^4\bar{q}$
- Hexaquarks: q^6 (the H-particle), q^5Q

where $q = u, d, s$ and $Q = c, b$. They are all color singlet objects described by the representation $[222]_c$. The possible existence of exotics has been mentioned in the literature [1,2] before the advent of QCD. Later on, their existence appeared natural in QCD inspired models. The interest started in 1977 with the work of Jaffe [3] who explained the stability of tetraquarks and hexaquarks (the H-particle) as due to the chromomagnetic interaction. Ten years later, independently, Gignoux et al. [4] and Lipkin [5] applied the same mechanism to charmed strange pentaquarks P, with explicit SU(3) breaking, finding more binding than for the H-particle. The status of the H-dibaryon is reviewed, for example, in Ref. [6]. In a review of the experimental searches for both H and P, Ashery [7] explained that the failure in observing the H-particle was the lack of sensitive measurements to small bindings. He also mentioned that the P search in charm hadroproduction at the Fermilab E791 experiment did not give a convincing evidence.

The criterion for stability was

$$\Delta E = E(q^m\bar{q}^n) - E_{threshold} < 0\ , \tag{1}$$

with q light or heavy.

The above theoretical studies were based on the OGE model which has a color-spin hyperfine interaction. Later on, the stability was also studied within the GBE (Goldstone boson exchange) model, which has a flavour-spin hyperfine interaction [8]. A comparison of the stability results in the two models was given in Ref. [9]. In most cases, when the OGE interaction stabilizes a system, the GBE interaction destabilizes it and vice versa. For example, in Jaffe's calculations the H-particle is a bound $\Lambda\Lambda$ system, while the GBE interaction induces a strong short range repulsion in $\Lambda\Lambda$ [10], like in the NN system. The GBE model indicates that q^5Q is also highly unstable, despite the presence of a heavy quark [11]. Moreover the GBE interaction does not require strangeness in pentaquarks to better stabilize the system. The variational calculations of Ref. [12] predict a mass of about 2900 MeV for the $uudd\bar{c}$ system in its lowest state and the system is stable, the threshold energy being $M_N + M_{\bar{D}}$ = 2970 MeV. Moreover the lowest state has a positive parity in contradistinction to the OGE model. The H1 Collaboration [13] observed a narrow resonance of mass M = 3099 MeV and width Γ = 12 MeV, which was interpreted as a $uudd\bar{c}$ pentaquark. This resonance was not confirmed by the CDF Collaboration.

2 Multiquark hadrons after 2002

After Jaffe's work there were several occasional waves of interest, some of them mentioned above. An impressive renaissance started in 2002, with the first observation by the LEPS Collaboration of a narrow baryon-like resonance in the nK^+ invariant mass spectrum produced in $\gamma n \to K^+K^-n$ reactions [14]. This was interpreted as a $uudd\bar{s}$ pentaquark. These results were supported by several experiments and contradicted by others, leading to a controversial situation. The LEPS Collaboration did however pursued its search to clarify the situation and some plausible explanations of the controversy together with new high statistics measurements can be found in Ref. [15].

Almost simultaneously several open charm D_s mesons with rather small widths were observed. The existing quark model calculations, based on the OGE interaction, failed to explain them as $c\bar{s}$ or $s\bar{c}$ pairs. For this reason, among others, a tetraquark interpretation has been proposed for $D_s(2317)$ [16]. The molecular picture [17] is more popular. Alternative explanations are: chiral partners of the ground state multiplet [18] or, simply, ordinary mesons with a proper spin-orbit interaction for unequal quark-antiquark masses [19], or $c\bar{s}$ states coupled to D^*K channels (for a review see $e.g.$ [20]).

3 The hidden charm X,Y,Z resonances

The discovery of the charmonium-like resonances X,Y,Z starting with the first observation of X(3872) by the Belle Collaboration triggered a considerable interest in their interpretation as exotics, for example, $D\bar{D}$ molecules, tetraquarks, hybrids, etc. At the same time conventional options as $c\bar{c}$ pairs, threshold effects, etc., are being considered. A partial list of the newly observed hidden charm resonances is shown in Table 1. (For a more extensive list see [21].)

Table 1. Charmonium-like resonances

Resonance	Mass (MeV)	Width (MeV)	J^{PC}	Decay modes	Ref.
X(3872)	3871.4 ± 0.6	< 2.3	1^{++}	$\pi^+\pi^- J/\Psi, \gamma J/\Psi$	[22]
X(3940)	3942 ± 9	37^{+27}_{-17}	J^{P+}	$D\bar{D}^*$	[23]
Y(3940)	$3915\ ^{+4.3}_{-3.9}$	$34\ ^{+13}_{-9}$	J^{P+}	$\omega J/\Psi$	[24]
Z(3930)	3929 ± 5	29 ± 10	2^{++}	$D\bar{D}$	[25]
X(4160)	4156^{+29}_{-25}	139^{+113}_{-65}	J^{P+}	$D^*\bar{D}^*$	[23]
Y(4260)	4259 ± 8	88 ± 23	1^{--}	$\pi^+\pi^- J/\Psi$	[26]
Z^+(4430)	4433 ± 5	45^{+35}_{-18}	?	$\pi^+\Psi'$	[27]
Z_1^+(4051)	$4051 \pm 14^{+20}_{-41}$	82^{+21+47}_{-17-22}	?	$\pi^+\chi_{c1}$	[28]
Z_2^+(4248)	$4248\ ^{+44+180}_{-29-35}$	$177^{+54+316}_{-39-61}$	?	$\pi^+\chi_{c1}$	[28]
Y(4660)	4664 ± 12	48 ± 15	1^{--}	$\pi^+\pi^-\Psi'$	[29]
Y(4140)	4143 ± 3.14	$11.7^{+8.3}_{-5.0} \pm 3.7$	J^{P+}	$\phi J/\Psi$	[30]

After Belle, X(3782) has been confirmed by three other different collaborations [22]. The status of Y(3940), seen by BaBar [24], with M = 3915 ± 4 MeV, $\Gamma \approx 34$ MeV and that of X(3940), seen by Belle, with M = 3943 ± 17 MeV, $\Gamma = 87$ MeV ± 34 MeV [31], is being clarified. The Belle collaboration recently confirmed BaBar's results, as described in the recent overview by Olsen [32]. All the other resonances need confirmation.

Most of these resonances do not match well any of the unassigned charmonium levels. They can be candidates for exotics. In particular, a considerable amount of work has been devoted to the tetraquark or the molecular picture. In particular the best established and the narrowest resonance, X(3872), has been interpreted as a diquark-antidiquark state in a chromomagnetic model. The width was explained to be narrow due to its unnatural 1^{++} spin-parity, which forbids $D\bar{D}$ decay and estimated in a rearrangement of quarks and antiquarks process by Maiani et al. [33]. The mass was finally fitted. The diquark-antidiquark picture is useful in a relativistic framework [34]. In the tetraquark option, also with a chromomagnetic interaction, but without any correlated quark or antiquark pairs, it was found that the ground state $c\bar{c}q\bar{q}$ system has a mass of 3910 MeV, close to experiment and contains a tiny $J/\Psi + \rho$ or $J/\Psi + \omega$ component in the wave function, which can well explain the narrowness of its width [35]. The full spectrum of $c\bar{c}q\bar{q}$ was calculated within the same model in Ref. [36]. It contains twice more states than that of Maiani et al., because a complete color space was taken into account.

The X(3872) is also naturally interpreted as a loosely bound hadronic molecule, since its mass is close to $D^0\bar{D}^{*0}$ threshold, *e.* g. [37] or [38]. But this picture contradicts some experimental data. An ambiversion interpretation was recently proposed [39].

The spectrum of the $c\bar{c}s\bar{s}$ system was calculated [40] within the model of Ref. [35]. The structure of the states 1^{++} and 0^{++} suggests that they can decay into $\phi J/\Psi$ with narrow widths. Thus they are good candidates for the resonance Y(4140), if this exists.

The charged Z^+ resonances from Table 1 are natural candidates for exotics because they have non-zero electric charge. In particular the $Z^+(4430)$ was interpreted as a $D^*(2010)\overline{D}_1(2420)$ molecule, for example in Ref. [41] or as a tetraquark [42].

4 Perspectives

Another type of tetraquarks, which have more chance to be bound are $QQ\bar{q}\bar{q}$. They have only one threshold $Q\bar{q} + Q\bar{q}$, while $Q\bar{Q} + q\bar{q}$, has two: $Q\bar{q} + Q\bar{q}$ and $Q\bar{Q} + q\bar{q}$. They are free of annihilation effects. Their study amounts to solve a four-body problem with a specific Hamiltonian. The interest started about two decades ago. Different variational methods have been proposed along the years as, for example, in Refs. [43–46]. A more complete list can be found in Ref. [47] where elaborate calculations are presented, both for S and P states. In the latter work as well as in Ref. [46], both $cc\bar{q}\bar{q}$ and $bb\bar{q}\bar{q}$ turn out to be bound, at least in the ground state. The possible experimental observation of $cc\bar{q}\bar{q}$ with present and future facilities is discussed in [47], complementing earlier studies [48]. There is hope that future generation experiments can lead to their observation.

5 Conclusion

The basic question is whether or not multiquark hadrons exist. The thoroughly searched H-particle, has not been seen so far. The evidence for heavy charmed pentaquarks $uuds\bar{c}$, $udds\bar{c}$ and $uudd\bar{c}$, is not convincing. The LEPS Collaboration still stubbornly searches for the pentaquark $uudd\bar{s}$ [15].

The number of X,Y,Z resonances is increasing every year and still more experimental work is necessary to confirm their existence, their quantum numbers, charged partners to neutral one, etc. It is plausible to believe that some of them, at least X(3872) or the Z^+ resonances, are exotics, in particular, they could have a tetraquark component at short range and behave as hadronic molecules at medium-longer range. Their theoretical interpretation is still a serious challenge. Less hastily studies are desired.

There is hope that future experiments will give evidence for $QQ\bar{q}\bar{q}$ states, found to be stable tetraquarks in quark model studies.

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