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Exotic hadrons with heavy flavour or hidden flavour*

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Abstract

The molecular picture and the constituent-quark model of exotic hadrons are reviewed, with application to the states recently discovered in the hidden-charm and hidden beauty sectors, and to other configurations.

Keywords: exotic hadrons, quark model

1. Introduction

Since the discovery of the $X(3872)$ [1, 2], there has been a lot of experimental activity in the field of XYZ mesons, and a flurry of theoretical papers. The literature benefits from valuable reviews, for instance and several talks at this Conference have given interesting updates of the experimental and theoretical studies. In this contribution, I shall make a few comments about the molecular model and the constituent-quark pictures. The field of mesons with hidden or naked heavy flavour will be slightly extended, as to include some remarks on multi-baryons with strangeness (i.e., light hypernuclei), and the pentaquarks which have been announced [3] in between this QCD15 conference and the deadline for its Proceedings.

It has been early noticed that states with a variety of quarks, such as $(uuddss)$, can benefit from a coherent chromomagnetic attraction without offending the Pauli principle. Introducing charm or beauty is not just a variant. The mass of the c or b quarks gives more binding, and call for a subtle interplay of spin-independent and spin-dependent interactions, or, say, chromoelectric and chromomagnetic effects.

The possibilities offered by mixing light and heavy flavours was noticed rather early, for instance in [4] for multi-baryons, in [5] for double-charm mesons, in [6][1]for anticharmed baryons, etc., at a time where the experimental search was not easy. The new experimental facilities offer a considerable improvement and should give access to many configurations, even beyond hidden-charm and hidden-beauty.

Already for double-charm or double-beauty baryons, there is a subtle interplay between the slow relative motion of the heavy quarks, and the interaction of the flavoured core with the relativistic light quark [7].

2. Molecules

The idea is rather old that the Yukawa interaction is not restricted to nucleons. The physics of hyperons linked to nuclei is now very well documented. There remains, however, some uncertainty about configurations which are at the edge of binding. For years, the main guidance was provided by models based on meson exchanges and SU(3) flavour symmetry, carefully tuned

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[1] It is pleasure to thank Harry Lipkin for several enjoyable discussions and to renew the best wishes of the community at the occasion of his 94th birthday which occurred shortly before this Conference. Note that the two papers [6] were elaborated independently and are always cited together, except, surprisingly, in a recent paper by the LHCb collaboration [3].

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to accommodate the sparse amount of date on hyperon-nucleon and hyperon-hyperon interaction. See, e.g., [8], and refs. there to the earlier literature. This approach is, however, challenged by models based on chiral effective field theory [9] which give comparable scattering lengths but appreciably smaller effective range, and thus favours the binding of Borromean[2] states, as shown recently [10].

In the case of charm, besides hypernuclei [4], there has been early speculations about the possibility of $D^{(*)}\bar{D}^{(*)}$ molecules [11], in particular to account for some anomalies in the decay pattern of high-lying Ψ states [12], but this picture was abandoned and the anomalies eventually explained by the nodes in the wavefunction of the radially excited $(\bar{c}c)$ states [13].

More recently, the possibility of molecules was revisited by Ericson and Karl [14], Manohar and Wise [15], and especially Törnqvist [16], and the discovery of the $X(3872)$ [1] was considered as a success for this approach. Now, a more moderate point of view tends to prevail, where the $X(3872)$ is mainly a $(\bar{c}c)$ state, in which the higher Fock components play a more important role than in other quarkonium states [17].

The scenario of the $X(3872)$ as a molecule, though very appealing, call for some warnings. The degeneracy or near degeneracy of isospin $I = 0$ and $I = 1$ is badly broken, as some of the leading terms of the interaction, such as π- or ρ-exchange are strongly isospin dependent. Historically, this isospin-dependence of nuclear forces made it difficult to describe the mesons as baryon-antibaryon molecules [18].

Another problem is the risk of proliferation. Binding D and $\bar{D}^*$ suggests the existence of similar meson-meson bound states with hidden beauty, and also of meson-baryon bound states, baryon-baryon bound states [19], etc. In ordinary nuclear physics, the existence of repulsive forces at short distances restricts the number of bound states. For instance, the spin-singlet proton-proton and neutron-neutron systems are unbound though the pion-exchange is attractive, and the spin-triplet proton-neutron is rescued by the interplay of the s- and d-wave components [20]. In most other hadron-hadron systems, there is no reason to believe that there is a repulsive core in the interaction, and thus attractive long-range forces lead more easily to bound states.

3. Chromomagnetism

Let us now consider a direct quark picture of tentative multiquark states. Jaffe [21] and many authors after him stressed the role of the short-range chromomagnetic interaction. Very schematically, once the other degrees of freedom are integrated out, the chromomagnetic Hamiltonian reads

$$H_{\mathrm{CM}} = \sum_i m_i - \sum_{i,j} C_{ij}\, \tilde{\lambda}_i.\tilde{\lambda}_j\, \boldsymbol{\sigma}_i.\boldsymbol{\sigma}_j\,, \tag{1}$$

where C_{ij} is the expectation value of a short-range operator.

In the sector of ordinary mesons and baryons, this Hamiltonian explains most of the observed hyperfine splittings, such as $J/\psi - \eta_c$.

If applied to the the dibaryon configuration $H = (uuddss)$ with the assumption that the $C_{i,j}$ are the same for all pairs, and taken equal to their value for ordinary baryons, a binding of about $-150\,\mathrm{MeV}$ is obtained, below the $\Lambda\Lambda$ threshold.

Note that this excess of attraction is rather remarkable. For instance, to describe the positronium molecule Ps_2 in terms of the Coulomb interaction $\sum a_{ij}/r_{ij}$, the same cumulated strength $\sum a_{ij} = -2$ is found for both Ps_2 and its threshold made of two isolated atoms, and the binding of Ps_2 is due to a subtle deformation of its constituents, to favour the attractive terms.

In subsequent studies of the H dibaryon, it was shown that breaking SU(3) flavour symmetry and computing the C_{ij} self-consistently from 6-body wavefunctions considerably reduce the attraction and suggest that the H is unbound [22].

More recently, the model (1) has been applied to the $X(3872)$ described as $(c\bar{c}q\bar{q})$ with $J^P = 1^+$ and $I = 0$ [23]. The parameters C_{ij}, and the effective quark masses m_i (which include the chromoelectric energy) were taken from a fit of heavy hadrons. A remarkable state was found near 3872 MeV which is a pure octet-octet of colour in the $(c\bar{c}) + (q\bar{q})$ channel and thus is refrained from falling apart into a charmonium and an ordinary meson. The decay into a charmed and an anticharmed mesons is suppressed by the lack of phase space. This model predicts an isospin $I = 1$ partner slightly above, with the same quantum numbers. Unfortunately, the data [2] suggests that the $X(3872)$ and the neutral $X(3900)$ have opposite charge conjugations, and thus different structures.

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[2] A Borromean three-body system is bound while its two-body subsystems are unbound. For a Borromean n-body system with $n > 3$, there is no path to build the system by adding the constituents one by one through a series of bound states.