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Exotic molecules of heavy quark hadrons

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Abstract. We discuss hadronic molecules containing both heavy and light quarks. The interactions are provided by meson exchanges between light quarks in the constituent hadrons. The tensor force in the one-pion exchange potential mixes states of different spins and angular momenta. This provides attraction and generates rich structure in exotic channels in the heavy quark sectors. The method has been applied to exotic baryons with a $\bar{c}$ or $\bar{b}$ quark, and exotic mesons containing $b\bar{b}$ including the recently found Z_b's.

Recent interest in hadron physics has been largely motivated by the observations of candidates for exotic multi-quark states which are not (easily) explained by the conventional quark model [1–4]. Many of them appear near the threshold region of their possible decay channels. The finding of the twin Z_b's is perhaps the most striking in that they appear very close to the BB^* and B^*B^* thresholds [4–6].

Strictly, multiquarks does not make much sense for light flavors especially for u and d quarks when the quark number is not a conserved quantity. In fact, they interact strongly at the energy scale of Λ_{QCD}, creating $q\bar{q}$ pairs and generating massive constituent quarks. It is known that it is a consequence of spontaneous breaking of chiral symmetry. In the low energy region we expect that such constituent quarks become active degrees of freedom as almost on-shell particles, forming exotic multi-quark states. Contrary to the light flavor sector heavy quarks such as c and b with mass $M \gg \Lambda_{QCD}$ conserve their quark number. Thus we can treat them as almost on shell particles with non-relativistic kinematics at low energies of typical hadron resonances.

Starting from the conventional quark model picture for orbitally excited states, multiquark configurations can mix with them because the typical excitation energy of about 0.5-1 GeV is sufficient to create a (constituent) $q\bar{q}$ pair. A color singlet multiquark system of more than the minimal number ($\bar{q}q$ or qqq) may form color singlet sub-systems (clusters) of hadrons. Clustering phenomena of multiparticle systems have been extensively studied in nuclear physics for many years [7]. Alpha particles saturate the dominant component of spin and isospin dependent nuclear force. The spin-isospin neutral alpha particles interact rather weakly and can form loosely bound states near the threshold regions of alpha decay.

In QCD, the state corresponding to alpha particle is a hadron which saturates the strong color dependent force. If these hadrons have sufficient amount of attraction (but weak as compared to the color force), they may form a bound or resonant state, which is the hadronic molecule. it must be a rather loosely bound state having an extending spatial structure to retain the identity of hadronic constituents. We expect that the relevant energy scale of binding and resonant states should be sufficiently small as compared to Λ_{QCD} of some hundreds MeV.

To establish exotic states is interesting not only for its own sake, but also because it is expected to reveal important aspects of non-perturbative dynamics of QCD. In this respect, as experimental observations imply, hadrons of light and heavy quarks are interesting, where more candidates of exotic states are observed. There, heavy quark symmetry and chiral symmetry play simultaneously. The former suppresses the spin dependent interactions, leading to degeneracy of different spin states. On the other hand, the latter is responsible for the pion coupling to the light quarks, which provides the source of the strong one pion exchange potential between heavy flavor hadrons. When these two conditions are satisfied, we expect the formation of exotic hadronic molecules. The spin and isospin dependent nature of the pion exchange potential as well as its orientation dependence of the tensor structure are the cause of the rich structure of hadron spectrum.

Based on these ideas, we have studied hadronic molecular states for exotic heavy baryons in Refs. [8–10], and for exotic heavy mesons in Ref. [11–13]. They are exotic not only due to hadronic molecular structure but also due to their exotic quantum numbers which are not accessible by the minimal number of quarks. In forming the hadronic molecular state, the following three points are important; (1) heavy mass which suppresses kinetic energy of constituent hadrons, (2) one pion exchange force of tensor nature which mixes the 0^- and 1^- states (DD^* and BB^*), and (3) degeneracy of 0^- and 1^- states which makes the wider space of coupled channels more effective to gain more attraction.

Hadronic molecules have been also studied for DN systems of ordinary quantum numbers [14,15]. These channels allow even more attraction leading to deeply bound states of a binding energy of order a few hundred MeV with much spatially compact configuration. Here $q\bar{q}$ annihilation is also possible, the treatment of which is more difficult than in the case of exotic channel without $q\bar{q}$ annihilation.

Turning to the exotic channels, employing an interactions between heavy flavor hadrons in a boson exchange model including one pion exchange potential, we find several bound and resonant states near the threshold regions. Many of them with small binding energy of order ten MeV or less have a rather extended size compatible to hadronic molecules. For baryons, we have found bound states of $J^P = 1/2^-$ states of exotic quark content $\bar{c}q$-qqq and $\bar{b}q$-qqq just below the threshold of $\bar{D}N$ and BN, respectively. Other resonant sates are also found for $J^P = 3/2^-, 1/2^+, 3/2^+, 5/2^+$ with similar structure of mass spectrum for c and b quark sectors [9, 10].

For mesons, in the hidden bottom sector, we have found ten $B\bar{B}, B\bar{B}^*, B^*\bar{B}^*$ molecules for low lying spin $J \leq 2$. In particular, the hidden bottom exotic mesons Z_b's are well predicted [11]. Further exotic states of double heavy flavor (charm and bottom) mesons are also found [12]. In Ref. [13], we have estimated the decay and production rates of various states in the limit of heavy quarks which are characteristic to the hadronic molecular structure. These theoretical predictions for rich structure of hadronic molecules can be studied in the facilities such as Belle, JPARC and LHC.

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