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New Aspect of Hadron Spectroscopy

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An overview of recent developments in hadron spectroscopy is given with an emphasis on heavy quark dynamics and heavy hadron spectroscopy. Heavy quark spin symmetry and diquark are introduced as important dynamical contents for heavy quark hadrons. We also discuss possibilities of multiquark hadrons with heavy quarks.

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1. Introduction

Hadron spectroscopy has entered a new era. According to the Particle Data Group[1], about 300 mesons and 300 baryons are known in the zoo of hadrons. The quantum chromodynamics (QCD) is the first principle of hadron structures and interactions. The first-principle calculations in QCD, lattice QCD simulations, are well successful in explaining the ground states, while excited (resonance) states are not well reproduced. Recently, we have encountered several "new types" of hadrons, which do not fit in the conventional scheme of the hadron classification.

The most exciting discovery was exotic "quarkonium" states, X, Y and Z's, found at Belle, BaBar and BES-III[2]. Those states cannot be explained as (quark-model) $Q\bar{Q}$ bound states, but require new dynamical contents, such as tetra-quarks, hadronic molecules and their mixings to $Q\bar{Q}$. As an example, recent analyses show that the X(3872) resonance, sitting just at the threshold of $\mathrm{D}+\mathrm{D}^*$ mesons, is likely to be a superposition of the $\mathrm{D}^0\bar{\mathrm{D}}^{*0}$, $\mathrm{D}^+\mathrm{D}^{*-}$molecules and the $c\bar{c}$ states[3].

Such new types of hadrons may not be, in fact, new. In the light meson and baryon spectra, we have a few candidates of hadronic resonances or multi-quarks. One of them is $\Lambda(1405)$, which is likely to be dominated by the $\bar{K}N$ component[4]. Another example of tetra-quarks or meson molecules is seen in the light scalar mesons, f_0, a_0 and so on.

At first glance, tetra-quarks and meson molecules are different and independent. The former contains color-non-singlet qq or $q\bar{q}$ components as ingredients, while the meson molecule is composed only of color-singlet clusters. It is, however, not clear whether they are distinguishable or not. Meson molecules may look just like tetra-quarks when two clusters are close to each other. Furthermore, QCD does not have a conserved charge to distinguish these two kinds of "hadrons". In order to dissolve them we need to clarify the dynamics of quarks and multi-quark (color) correlations inside such multi-quark environments. Recently, some studies to define compositeness of hadrons and resonances were made based on the (wave-function) renormalization factor of hadron operators[5].

Many of these new types of hadrons appear in the heavy hadron spectrum, *i.e.*, they contain heavy quarks. It is interesting to see dynamics of heavy quarks has some new features, represented by the heavy quark symmetry. It is in contrast to light quarks, whose dynamics is dominated by chiral symmetry and its spontaneous breaking. In the spectroscopy, heavy quark spin symmetry is valid in the large quark mass limit, so that spin of the heavy quark is conserved.

In this article, I would like to discuss some topics on heavy quark hadrons. In sect. 2, we discuss distinct dynamical contents of heavy quark systems, comparing strangeness and charm/bottom hadron spectroscopy. Emphases are on diquark structure of baryon excited states and tetra-quark exotic hadron with charm quarks. In sect. 3, we review some theoretical developments in recent years. Lattice QCD calculations have been highly sophisticated and can access hadrons at the physical quark masses. Excited states are also studied. New analyses of QCD sum rules are also presented. In sect. 4, conclusions are presented.

2. Dynamics of Heavy Quarks

The QCD lagrangian is flavor blind, *i.e.*, the color-gauge couplings are common to all the flavors. It is, however, known that the scale dependence arises from the trace anomaly and Λ_{QCD}

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sets the typical momentum of the quark-gluon correlations. As the effective gauge coupling grows at the low energy region, the interaction is weaker for heavier quarks.

The quark flavors can be divided into two categories, depending on their masses: the light flavors (u, d, s), and the heavy flavors (c, b, t). Spectrum of light hadrons has exhibited important roles of chiral symmetry and its spontaneous breaking (SCSB) in low-energy QCD. The SCSB tells us that the QCD vacuum has non-zero quark condensates of light flavors, $\langle \bar{u}u \rangle$, $\langle \bar{d}d \rangle$ and $\langle \bar{s}s \rangle$, and the light pseudo-scalar mesons play roles of the (pseudo-) Nambu-Goldstone bosons. The SCSB induces effective quark masses of order of $\Lambda_{\rm QCD}$, which leads us to the constituent quark picture of hadrons. The ground state mesons and baryons can be explained fairly well as $q\bar{q}$ and qqq with the constituent (valence) quarks, where the hadron masses are roughly given by the sum of quark masses.

On the other hand, the heavy quarks are subjected to heavy-quark symmetry. In particular, the heavy quark spin symmetry plays a key role to classify and describe the heavy hadron spectra. The dynamics behind the heavy quark symmetry is that for a large heavy quark mass m_Q, the soft QCD dynamics is independent from m_Q and depends on the velocity v of the heavy quark, which is a constant of motion[6]. This symmetry gives simple relations among the transition amplitudes of heavy quark decays. Furthermore, $1/m_Q$ expansion of the QCD Hamiltonian leads to the conservation of the heavy quark spin, as is shown in the next subsection.

2.1 Heavy Quark Spin Symmetry (HQSS)

The heavy-quark gluon interaction can be expanded by $1/m_Q$, where m_Q is the heavy quark mass, giving

$$\bar{Q}\gamma^{\mu}\frac{\lambda^a}{2}QA^a_{\mu} \sim Q^{\dagger}\frac{\lambda^a}{2}QA^a_0 - \frac{1}{m_Q}Q^{\dagger}\boldsymbol{\sigma}_Q\frac{\lambda^a}{2}Q\cdot(\boldsymbol{\nabla}\times\mathbf{A}^a) \tag{2.1}$$

The first term is the color-electric Coulomb coupling and the second term denotes the coupling of the quark spin to the color-magnetic field. One sees that the spin-dependent coupling is suppressed by $1/m_Q$. Thus in the heavy quark limit, the spin of the heavy quark disappears from the interaction. Namely, the heavy quark spin $\boldsymbol{\sigma}/2$ is conserved in the limit, $[\boldsymbol{\sigma}_Q, H_{\rm QCD}] = O(1/m_Q)$. This is called the heavy quark spin symmetry (HQSS).

This symmetry is important in the heavy hadron spectroscopy. For instance, the pseudoscalar (0^-) meson and the vector (1^-) meson are degenerate in the limit. This is indeed the tendency for the charm and bottom meson masses, $\Delta m(\mathrm{K}^* - \mathrm{K}) = 397$ MeV $\to \Delta m(\mathrm{D}^* - \mathrm{D}) = 142$ MeV $\to \Delta m(\mathrm{B}^* - \mathrm{B}) = 46$ MeV. At each flavor step ($s \to c \to b$), the splitting is reduced by a factor $\sim 1/3$.

A similar degeneracy is seen in the baryon spectrum (Fig.1). The ud quarks in Σ_Q and Σ_Q^* have the total spin 1. Then the splittings of Σ_Q^* and Σ_Q come from the interaction between the heavy-quark spin and the light-quark spin. The observed mass splittings are 194 MeV for the strange Σ and Λ, 65 MeV for charm, and 21 MeV for bottom. Again the ratios are about 1/3 for each step.

In the heavy quark picture, the classification of the baryons are different from the familiar SU(3) scheme used in the light hadron sector. In SU(3), Σ and Σ^* belong to the octet (**8**) and the decuplet (**10**), respectively. Now in the heavy baryon spectrum, the HQSS combines Σ_Q and Σ_Q^* (**6** in SU(3)) into the same “multiplet” and Λ_Q ($\bar{\mathbf{3}}$) becomes independent from Σ_Q.

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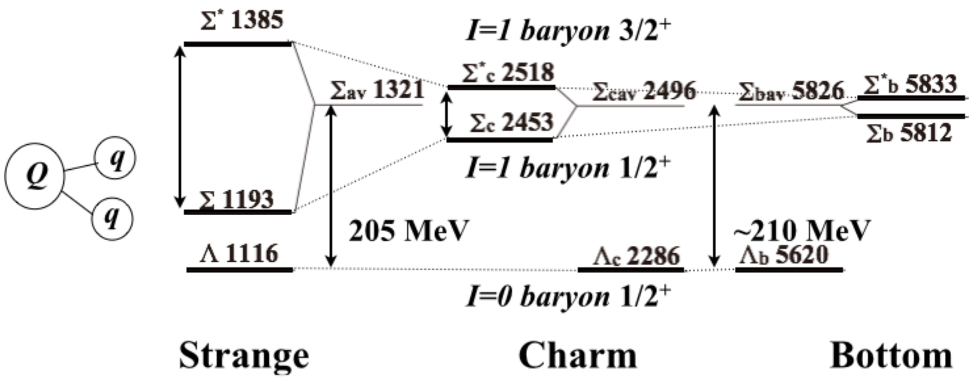

Figure 1: Heavy baryon spectrum for strange, charm and bottom sectors.

2.2 Diquarks

The structure of these baryons can be viewed based on the diquark picture in the quark model. For the $Q-q-q$ heavy baryons, the light quarks form a diquark state. It is straightforward to see that the ud quarks in Λ_Q forms a spin 0 and isospin 0 (or flavor $\bar{\mathbf{3}}$) pair of light quarks. This is the scalar (0^+) diquark. The $q-q$ interaction via a gluon exchange or the instanton-light-quark coupling gives strong attraction in this channel. According to the color Casimir factor, its strength is a half of that for the $q-\bar{q}$ in the pseudoscalar (0^-) channel.

In contrast, the light quarks in Σ_Q and Σ_Q^* form a spin 1, isospin 1 (or flavor **6**) diquark, called the axial-vector (1^+) diquark. The $q-q$ attraction is weaker in this channel compared to the scalar diquark. Some quenched lattice calculations are available for the diquark spectrum. Different approaches give consistent results on the mass splitting of the scalar and axial vector diquarks, ranging about 100-200 MeV[7].

Extending these observations to excited states of baryons is very interesting. Consider the P-wave baryons with spin-parity $1/2^-$, $3/2^-$ and $5/2^-$. In the SU(6) scheme of the quark model for the u, d and s quarks, they are identified as 70-dimensional representation.

When one of the quarks is heavy, then they can be classified into two distinct excitation modes: λ and ρ modes. They correspond to excitations of the individual Jacobi coordinates, λ and ρ, of the three-quark system, defined (non-relativistically) by

$$\boldsymbol{\rho} = \boldsymbol{r}_1 - \boldsymbol{r}_2, \qquad \boldsymbol{\lambda} = \boldsymbol{r}_Q - \frac{m_1 \boldsymbol{r}_1 + m_2 \boldsymbol{r}_2}{m_1 + m_2} \tag{2.2}$$

Here we assign the heavy quark to the particle 3, $m_3 = m_Q$. The λ-mode is the excitation from $L = 0 \to 1$ of the heavy quark relative to the light diquark, while the internal diquark state is excited in the ρ-mode.

If m_Q is equal to $m_q = m_1 = m_2$ (the SU(3) limit), then the λ and ρ modes are degenerate, and mix with each other. On the other hand, in the large m_Q limit, they split so that the λ excited states come lower than the ρ excited states. The ratio of the excitation energies can be roughly estimated from the harmonic oscillator model of confinement,

$$\frac{E_\lambda}{E_\rho} = \frac{\omega_\lambda}{\omega_\rho} = \frac{\sqrt{m_Q + 2m_q}}{\sqrt{3m_Q}} \quad \xrightarrow{m_Q \to \infty} \quad \frac{1}{\sqrt{3}} \tag{2.3}$$

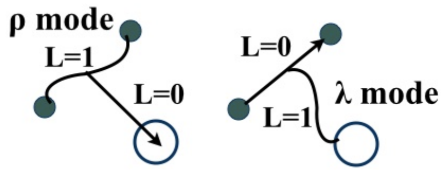

Figure 2: The ρ and λ mode excitations for the Qqq baryons.

where ω denotes the harmonic oscillator constant for the relevant mode. This ratio reaches 1 in the SU(3) limit and $1/\sqrt{3}$ in the large m_Q limit. In reality, the ρ and λ modes may mix at intermediate m_Q. In a recent quark model calculation[8], it is shown that the mixing is reduced rapidly when m_Q increases from $m_q \to m_s \to m_c, m_b$. These two kinds of excitation modes can be generalized to higher excitations and their separation is advantageous in studying the effective mass and dynamics of the light diquarks, as well as the interaction between the heavy quark and the light quarks.

Experimental studies of charm baryon spectroscopy are on-going or planned at several facilities. Among them, J-PARC has a plan to utilize the new high-momentum beam line in the hadron experimental hall to explore charm baryon excitations up to 3 GeV or higher[9].

3. Multi-quark hadrons with heavy quarks

QCD does not restrict hadrons to $q\bar{q}$ and qqq. Exotic hadrons are the ones with quantum numbers that are not realized by $q\bar{q}$ or qqq. Possible low-lying exotic (multi-quark) hadrons can be found by considering the attraction of the scalar diquark.

An interesting possibility is a double charm meson T_{cc} ($cc\bar{u}\bar{d}$, $J^\pi = 1^+$, $I = 0$) state[10]. This state is formed by cc ($C = \bar{\mathbf{3}}, J = 1$) and the scalar diquark $\bar{u}\bar{d}$ ($C = \bar{\mathbf{3}}, J = 0, I = 0$). The lowest strong-decay threshold is $D(0^-) + D^*(1^-)$. If the scalar diquark is light enough to make a bound state below the DD^* threshold, T_{cc} will be a stable tetra-quark resonance. Recently, we have estimated production cross sections of T_{cc} in e^+e^- reactions using the NRQCD approach[11]. We have also investigated production of another possible exotic state of the same quantum number, $T^*_{cc} \sim T_{cc}(\mathbf{6})$,[1] where $T_{cc}(\mathbf{6})$ consists of diquarks with the color **6** representation, cc ($C = \mathbf{6}, J = 0$) and $\bar{u}\bar{d}$ ($C = \mathbf{6}, J = 1, I = 0$). It is extremely interesting to identify $T^*_{cc} = T_{cc}(\mathbf{6})$ separately from the ground state T_{cc}, because such an "exotic" color configuration is not allowed inside ordinary hadrons of color-singlet $q\bar{q}$ or qqq. It is pointed out that the T_{cc} and T^*_{cc} can be distinguished from shapes of the momentum distribution.

Another interesting suggestion of an exotic heavy hadron was made by Diakonov in the chiral quark model[13]. It is a pentaquark state made of $uudc\bar{s}$ ($J^\pi = 1/2^-$), whose strong decay is forbidden if its mass is lower than the $\Lambda_c + K$ threshold. The predicted mass is 2420 MeV and the main decay modes are into the Cabibbo allowed $\Lambda(\Sigma) + K$ final states.

[1] $T_{cc}(\mathbf{6})$ and $T_{cc}(\bar{\mathbf{3}})$ may mix as they have the same overall quantum numbers. However, the mixing of $T_{cc}(\bar{\mathbf{3}})$ in T^*_{cc} will be suppressed due to the suppression of the spin-flip interaction of heavy quarks[12].

4. QCD analyses

The quantum numbers and masses of the ground state hadrons are well reproduced by the quark model as well as the lattice QCD calculations[14].[2] On the other hand, the theoretical approaches on the excited states are quite limited. There are some attempts of first principle calculations of the heavy mesons in lattice QCD, which give excitations spectra of the charmonium states[16]. They reproduce $1P$, $2S$, $1D$ states fairly well, although $X(3827)$ or the other non-standard excited states are not given. A conjecture is that those non-standard states do not couple to $\bar{q}q$ operators strongly and we need to introduce 4-quark operators to generate them.

Another powerful method to obtain the hadron spectrum based on QCD is the QCD sum rules[17]. Recent developments include application of the maximum entropy method (MEM) to analyses of the QCD sum rules[18]. By using MEM, we have succeeded in obtaining the spectral functions from the sum rule without making the pole+continuum assumption for its functional form. So far the method has been applied to the ordinary mesons, nucleon, D mesons and the charmonium at finite temperature[19, 20, 21]. For J/ψ and the other charmonium states, analyses show that the temperature dependences of the gluon condensates modify the spectral functions strongly. It is found that sharp peaks of the spectral functions disappear quickly at around $T > 1.2T_c$, where T_c is the critical temperature for the quark-gluon plasma phase[20]. The situation is different in the bottomonium spectrum[21], where we find that the Upsilon peaks remain above T_c, and will dissociate at a higher temperature.

5. Conclusion – Goals and Issues –

Hadrons are elementary excitation modes of the QCD vacuum. Their spectrum is the most important clue of the dynamics of confined quarks and gluons. It gives the key degrees of freedom and symmetries of low energy QCD, such as SU$(3)_f$ symmetry, spontaneous chiral symmetry breaking, U$_A(1)$ anomaly, heavy quark symmetry and so on. Color confinement does not easily allow multi-quark, or multi-gluon "exotic" hadrons, but our list of abnormal hadrons, such as X, and Z, is growing. We need more than zoology and must construct a unified picture of all the hadrons.

I pose a question: Are "exotic" hadrons well defined? Indeed, it is not clear how the various structures, such as tetra-quark, hadron molecule, diquark molecule, etc., are different? We do not know how to quantify and determine experimentally the "exotic-ness" of hadrons in QCD. A caution is that number of quarks in a hadron, *i.e.*, #(quark)+#(antiquark), is not a conserved quantity, nor an observable, while #(quark)−#(antiquark)$= 3\times$ (baryon number) is conserved. Nonetheless, the reason is not known why the constituent quark model works extremely well for describing the ground-state hadrons. A hint would be that the number of heavy quarks are approximately conserved, because $Q\bar{Q}$ creation and annihilation are suppressed. Conservation of the heavy-quark spin in productions and decays may be a key to solve the structure problem.

Another hint comes from special roles of color singlet clusters, *i.e.*, hadrons[5]. Scattering states of color singlet clusters are well defined in the asymptotic region, and bases in hadronic languages may help to avoid the ambiguity.

[2] One possible exception is the double charm baryon Ξ_{cc}, whose predicted masses are not completely consistent with the observed one at SELEX[15].

I have mainly discussed the heavy hadron spectroscopy in this report. It is also interesting to see charm hadron bound states in ordinary matter[22, 23, 24, 25]. Their properties may reveal differences of the QCD dynamics between light and heavy quark sectors. New experimental facilities of hadron and lepton beams, such as Super KEKB, PANDA and J-PARC, have possibilities of exploring the charmed hadrons, their production and interactions, as well as various exotic heavy hadron physics.

References

[1] http://pdg.lbl.gov.

[2] J. Brodzicka et al. (Belle Coll.), Prog. Theor. Exp. Phys. **2012** (2012) 04D001; N. Brambilla et al., Eur. Phys. J. **C71** (2011) 1534; J. Messchendorp et al. (BESIII Coll.), PoS **Bormio2013** (2013) 043.

[3] M. Takizawa, S. Takeuchi, PTEP **2013** (2013) 0903D01.

[4] T. Hyodo, D. Jido, Prog. Part. Nucl. Phys. **67** (2012) 55.

[5] T. Hyodo, Int. J. Mod. Phys. A **28** (2013) 1330045.

[6] H. Georgi, Phys. Lett. **B240** (1990) 447.

[7] M. Hess, et al., Phys. Rev. **D58** (1998) 111502; C. Alexandrou, et al., Phys. Rev. Lett. **97** (2006) 222002; R. Babich, et al., Phys. Rev. **D76** (2007) 074021; T. DeGrand, et al., Phys. Rev. bf D77 (2008) 034505.

[8] T. Yoshida et al., in preparation.

[9] H. Noumi, Few-Body Syst., **54** (2013) 813.

[10] S. Zouzou, et al., Z. Phys. **C30** (1986) 457; H. J. Lipkin, Phys. Lett. **B172** (1986) 242.

[11] T. Hyodo, Y.R. Liu, M. Oka, K. Sudoh, S. Yasui, Phys. Lett. **B721** (2013) 56.

[12] J. Vijande, A. Valcarce, Phys. Rev. **C80** (2009) 035204.

[13] D. Diakonov, ArXiv: 1003.2157 and Prog. Theor. Phys. **S186** (2010) 99.

[14] Y. Namekawa et al. (PACS-CS Coll.), Phys. Rev. **D87** (2013) 094512.

[15] M. Mattson et al. (SELEX Collaboration), Phys. Rev. Lett. **89** (2002) 112001.

[16] L. Liu, et al. (Hadron Spectrum Collaboration), JHEP **07** (2012) 126.

[17] M.A. Shifman, A.I. Vainshtein, V.I. Zakharov, Nucl. Phys. **B147** (1979) 385; **B147** (1979) 448.

[18] P. Gubler, M. Oka, Prog. Theor. Phys. **124** (2010) 995.

[19] K. Ohtani, P. Gubler, M. Oka, Eur. Phys. J. A **47** (2011) 114; Phys. Rev. **D87** (2013) 034027.

[20] P. Gubler, K. Morita, M. Oka, Phys. Rev. Lett. **107** (2011) 092003.

[21] K. Suzuki, P. Gubler, K. Morita, M. Oka, Nucl. Phys. **A897** (2013) 28.

[22] Y.R. Liu and M. Oka, Phys. Rev. **D85** (2012) 014015; S. Maeda, et al., in preparation.

[23] C.B. Dover and S.H. Kahana, Phys. Rev. Lett. **39** (1977) 1506; H. Bando and S. Nagata, Prog. Theor. Phys. **69** (1983) 557; H. Bando, Prog. Theor. Phys. **S81** (1985) 197.

[24] W. Meguro, Y.R. Liu, M. Oka, Phys. Lett. **B704** (2011) 547.

[25] A. Yokota, E. Hiyama and M. Oka, PTEP **2013** (2013) 11, 113D01.