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Hadronic few-body systems in chiral dynamics

Few-body systems in hadron physics

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Abstract Hadronic composite states are introduced as few-body systems in hadron physics. The $\Lambda(1405)$ resonance is a good example of the hadronic few-body systems. It has turned out that $\Lambda(1405)$ can be described by hadronic dynamics in a modern technology which incorporates coupled channel unitarity framework and chiral dynamics. The idea of the hadronic $\bar{K}N$ composite state of $\Lambda(1405)$ is extended to kaonic few-body states. It is concluded that, due to the fact that K and N have similar interaction nature in s-wave $\bar{K}$ couplings, there are few-body quasibound states with kaons systematically just below the break-up thresholds, like $\bar{K}NN$, $\bar{K}KN$ and $\bar{K}KK$, as well as $\Lambda(1405)$ as a $\bar{K}N$ quasibound state and $f_0(980)$ and $a_0(980)$ as $\bar{K}K$.

1 Introduction

Hadrons are composite objects of quarks and gluons governed by quantum chromodynamics, QCD. So far hundreds of hadrons have been experimentally observed in spite of only the five (or six) fundamental pieces, up, down, strange, charm, bottom (and top) quarks. The richness of hadron spectrum is a consequence of highly nontrivial dynamics of quarks and gluons confined in hadron. Precise measurement of hadron spectrum is one of the phenomenological ways to view colored dynamics of quarks and gluons inside hadron, and gives us clues of the confinement mechanism. Especially the systematics of energy excitation is a key issue to understand the hadron structure.

A conventional picture of hadron is the quark model, in which one considers constituent quarks as quasi-particles moving in a one-body mean field created by gluon dynamics, and symmetry of the quasi-particles and (weak) residual interaction characterize the hadron structure. Although quark models work well for lowest-lying states,

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there are a lot of states found which do not match quark model predictions, which are so-called exotic hadrons, and quark models should incorporate hadron dynamics once strong decay channels open. It has been realized that quark models do not give us the universal picture of the hadron structure, and that the constituent quark alone cannot be an effective degree of freedom in hadron. These facts brings us the idea to consider other effective constituents, such as diquark correlation, multiquark component and hadronic composite, which will be the origin of richness of hadron spectrum.

2 Hadronic composite states

Hadron composite state can be one of the existence forms of hadron. Its constituents are hadrons governed by hadronic dynamics not inter-quark colored force. Consequently the spatial size is much larger than the typical hadron size which is characterized by the confining force. The typical examples are atomic nuclei which are bound states of nucleons. Meson also can be a constituent of the hadron composite state. Without meson number conservation, the composite state with mesons has transition modes emitting lighter mesons, mostly pions, and absorptive decay modes. Therefore, most of hadronic composite states are unstable bound states with these decay modes.

Hadron composite state can be a clue to investigate the structure of the exotic hadron. Most of hadron flavors can be explained by a quark-anitquark pair $\bar{q}q$ and three quarks qqq. So far, very few flavor exotic hadrons have been observed. This is an important question to be solved in hadron physics. A clue is multiquark configuration. The multiquark state always has color singlet clusters. Thus, there is dynamical competition between colorful hadron *constituent force* inside confinement range and colorless hadron *interaction force* in a larger ragne than the typical hadron size. For instance, the H-dibaryon composed by $uuddss$ can have a colored three diquark configuration ($[ud][ds][su]$) governed by short range color interaction and a colorless two baryon configuration ($[\Lambda\Lambda]$ and/or $[\Xi N]$) governed by longer range hadronic interaction. These configurations can be mixed in the observed state. Nevertheless, since the former configuration should be a compact object, while the latter can be a larger object, there is a (small) scale gap between two configurations. There are also different systematics in their excitation modes and flavor properties. Thus, it would be very interesting if one could know which systematics is realized in each hadron.

3 The $\Lambda(1405)$ resonance

$\Lambda(1405)$ is a baryon resonance with isospin $I = 0$ and strangeness $S = -1$ sitting between the $\bar{K}N$ (1435 MeV) and $\pi\Sigma$ (1331 MeV) thresholds with mass around 1405 MeV and 50 MeV decay width to $\pi\Sigma$. The flavor of $\Lambda(1405)$ can be expressed by the minimal quark contents of uds, however, simple quark models have failed to reproduce the $\Lambda(1405)$ mass. $\Lambda(1405)$ is a historical example of the hadronic composite state. $\Lambda(1405)$ has been considered as a quasibound state of $\bar{K}N$ [1,2], even before QCD was established. In general, the physically observed state should be given as a mixture of the hadronic composite and quark model type components, it is important to examine the dominant components of hadron resonance states to understand their structure and dynamics, and it would be interesting if one could know the fraction of the components.

For the theoretical description of $\Lambda(1405)$, one needs dynamical study of coupled channels including at least $\bar{K}N$ and $\pi\Sigma$, because the $\Lambda(1405)$ resonance is located in the 100 MeV window of the $\bar{K}N$ and $\pi\Sigma$ thresholds. A complete treatment of Flavor SU(3) coupled channels, by including $\pi\Sigma$, $\bar{K}N$, $\pi\Lambda$, $\eta\Lambda$, $\eta\Sigma$ and $K\Xi$, was already done using a phenomenological vector-meson exchange potential in Ref. [3]. A coupled channels calculation of $\pi\Sigma$ and $\bar{K}N$ based on the cloudy bag model was done in Ref. [4][1]. The modern approach based on chiral dynamics and unitary coupled channels was initiated by Ref. [5], and the $\Lambda(1405)$ resonance is well described as well as the K^-p threshold properties and K^-p scatterings. (See Ref. [6] as a recent review article and Ref. [7,8] for a very recent update including the new SIDDHARTA measurement [9].)

One of the most important consequences of the coupled channels approach based on chiral dynamics is that the $\Lambda(1405)$ resonance is a superposition of two states [10, 11]. These two states have different properties [11]: one of the states is located at 1426 MeV with a 32 MeV width and couples dominantly to $\bar{K}N$, while the other is at 1390 MeV with a broader width and couples strongly to $\pi\Sigma$. All of the recent calculations based on chiral interaction suggest the two pole structure of $\Lambda(1405)$ although the pole positions are model dependent slightly. The reason that there are two states around the $\Lambda(1405)$ energy region is that the chiral interaction indicates two attractions with $I = 0$ in the flavor SU(3) singlet and octet channels group-theoretically [11] or in the $\bar{K}N$ and $\pi\Sigma$ channels physically [12]. The latter fact implies that the $\Lambda(1405)$ is essentially described by two dynamical channels of $\bar{K}N$ and $\pi\Sigma$, and that the higher state is a $\bar{K}N$ quasibound state decaying to $\pi\Sigma$ and the lower is a $\pi\Sigma$ resonant state [12]. As a consequence of the double pole nature, the $\Lambda(1405)$ spectrum depends on the initial channel [11]. Thus, observing that the $\Lambda(1405)$ spectrum in the $\bar{K}N \to \pi\Sigma$ channel is different from that in $\pi\Sigma \to \pi\Sigma$, one can confirm that $\Lambda(1405)$ is a dynamical object of $\bar{K}N$ and $\pi\Sigma$. Since $\Lambda(1405)$ is located below the threshold of $\bar{K}N$, one needs indirect production of $\Lambda(1405)$ from $\bar{K}N$. It has been found in Refs. [13,14] that in the $K^-d \to \Lambda(1405)n$ reaction $\Lambda(1405)$ is selectively produced by $\bar{K}N$, thus this reaction is one of the suitable reactions to investigate the nature of $\Lambda(1405)$. An experiment of this reaction at J-PARC is proposed [15] observing neutrons in the forward direction.

4 Compositeness of hadron

Compositeness of hadron had been discussed before QCD was established in order to find fundamental or elementary hadrons. But this trial was certainly failed, since all of the hadrons are composite objects of quarks and gluons. Here we discuss the compositeness of hadron resonances in terms of quark originated state and hadronic composite state. To discuss the compositeness of the hadron resonances, first of all, we need to define elementary hadrons. The elementary hadrons may be the ground state hadrons stable against strong interactions, or one may take hadrons which survive in the large N_c limit. Once one defines the elementary hadrons, one can discuss the compositeness of hadron quantitatively. The elementary components are expressed in the free Hamiltonian H_0 and the composite states are dynamically generated as a consequence of the interaction of the elementary components V out of the full Hamiltonian of the system $H = H_0 + V$. The compositeness index can be written as $1 - Z$ where $Z = \sum_n |\langle n|d\rangle|^2$

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[1] In this model, a bare pole term for the $\Lambda(1405)$ resonance was explicitly introduced around 1650 MeV.

with the eigenstates $|n\rangle$ of H_0 and the dynamically generated state $|d\rangle$ as an eigenstate of H [16]. This definition of the compositeness can be extended in field theory by introduction the Lagrangian of the system as $L = L_0 + L_{\text{int}}$ in which L_0 is the free Lagrangian of the elementary component and L_{int} represents their interaction. The field renormalization constant Z appears as the reside of the full propagator Δ at the pole position. The full propagator satisfies Dyson equation and its normalization is given by the free propagator $\Delta_0(E) = 1/(E - M_0)$ with the bare mass M_0 [17]. An application for chiral dynamics is discussed in Ref. [18]. For the resonance state, the compositeness index can be a complex number. Thus, one needs its appropriate interpretation, which is an open issue yet.

Here we would like to discuss the compositeness of $\Lambda(1405)$ in a different way within the chiral unitary approach [19]. In the chiral unitary approach, one solves Lippmann-Schwinger equation $T = V + VGT$, in which V is the interaction kernel, while G is the loop function which guarantees unitarity and specifies the model space. Thus, in the chiral unitary approach, the elementary components are specified in the loop function. In the present case for $\Lambda(1405)$, they are the lowest lying octet baryons and mesons. The interactions among the elementary components are given by the chiral effective theory. In the context of the discussion of compositeness, one has to take care of the interaction kernel, since the source of the resonances can be hidden in the interaction kernel. It is well-known that the s-channel resonance contributions are involved in the contact interactions of the elementary component [20]. Nevertheless, the Weinberg-Tomozawa interaction may be free from the s-wave resonance contributions since it comes from the t-channel vector meson exchange. For the discussion of the compositeness of the resonance, let us take only the Weinberg-Tomozawa interaction as the interaction kernel. Since the Weinberg-Tomozawa interaction is a short range contact force, one needs to regularize the loop integral. In the regularization procedure, one fixes high-momentum behavior which is not controlled in the present model space. Therefore, even though one takes only hadronic interaction in theinteraction kernel, some contributions coming from outside of the model space can be hidden in the regularization parameters [19]. In the chiral unitary model, this parameter is fixed phenomenologically so as to reproduce observed scattering cross section. Thus, if necessary, nature will request the components which come from the outside of the model space, such as a quark originated component.

We have a choice of the parameter in which the hidden contribution can be excluded from formulation by theoretical requirement on the renormalization constant (natural renormalization scheme) [19]. If resonances can be reproduced by the chiral unitary approach with the Weinberg-Tomozawa interaction in the natural renormalization scheme, the resonances can be regarded as composite objects of meson and baryon constituents. In Ref. [19] it has been found that the pole positions of $\Lambda(1405)$ is well reproduced by the natural renormalization scheme, while $N(1535)$ is not. This suggests that $\Lambda(1405)$ is mostly a composite state of the ground state mesons and baryons. In contrast, for $N(1535)$ one needs some components other than hadronic composites, such as quark originated states. This twofold character of $N(1535)$, meson cloud and valense quark, can be seen also in the transition form factors of $\gamma^* N \rightarrow N(1535)$ (helicity amplitudes) [21]. In Ref. [21], the $N(1535)$ transition form factors obtained by two different approaches, the chiral unitary approach [22] and the spectator quark model [23, 24], are compared. The quark model calculation of the transition form factors tells that the F_1^* form factor is produced well, while the F_2^* amplitude is overestimated in higher Q^2, where the quark model may be applicable. It is very interesting that
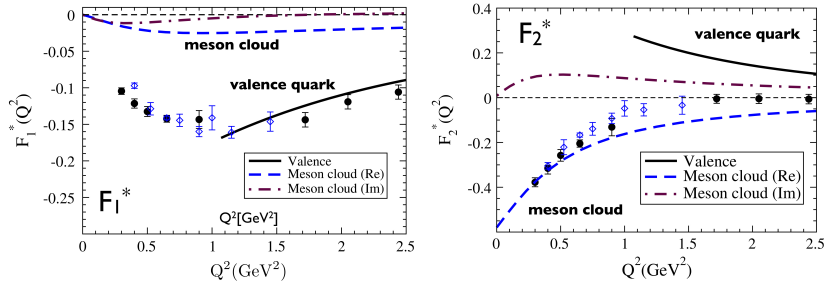
Fig. 1 Transition form factors of $\gamma^* p \to N(1535)$ calculated by the chiral unitary model (meson cloud) [22] and spectator quark model (valence quark) [23,24]. The plots are taken from Ref. [21].

the meson cloud components calculated by the chiral unitary model compensates the disagreement of the quark model calculation as seen Fig. 1.

In the chiral unitary approach, one can calculate the diagonal component of the electromagnetic form factor, and in Ref. [25] the first moment of the $\Lambda(1405)$ form factor, which corresponds to the spatial radius if the particle is stable, and it has been found that $\Lambda(1405)$ has a substantially large size compared to the typical hadron. The "radius" of unstable particles are obtained as a complex number and its interpretation should be done carefully.

5 Kaonic few-body systems

Let us consider hadronic composite states with kaon and nucleon constituents as an extension of the $\Lambda(1405)$ resonance of a quasibound state of $\bar{K}N$. For hadronic composite states, pion has a too light mass to form bound states with other hadrons by hadronic interaction, since the pion kinetic energy in a hadronic composite system overcomes attractive potential energy. In contrast, kaon has a unique feature in

Fig. 2 Family of kaonic few-body states.

the hadronic composite state. The mass of kaon is so moderately heavy that the kaon kinetic energy in a hadronic bound system can be smaller. In kaonic few-body systems, hadronic molecular states are unavoidably resonances decaying into pionic channels. The interaction of kaon as a Nambu-Goldstone boson is described well by the chiral effective theory at low energy. It suggests that the Tomozawa-Weinberg s-wave interactions in the $\bar{K}N$ and $\bar{K}K$ channels are attractive enough to form two-body quasibound states, and thus are driving forces of the hadronic molecular systems. It is very interesting that the strength of the Tomozawa-Weinberg interaction is fixed by SU(3) flavor symmetry and K and N are classified into the same state vector in the SU(3) octet representation. Therefore, considering also that K and N are a similar mass, one finds that the fundamental interactions in s-wave are very similar in the $\bar{K}K$ and $\bar{K}N$ channel. Consequently these channels with $I = 0$ have quasibound states of $\bar{K}K$ and $\bar{K}N$ similarly with a dozen MeV binding energy. This similarity between K and N is
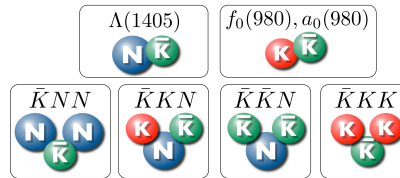
responsible for systematics of three-body kaonic systems, $\bar{K}NN$, $\bar{K}KN$, $\bar{K}\bar{K}N$ and $\bar{K}KK$, as shown Fig. 2. Further few-body systems with kaons and nucleons have been studied, for instance, in $\bar{K}NNN$ and $\bar{K}\bar{K}NN$ systems [26, 27].

The $\bar{K}KN$ and $\bar{K}\bar{K}N$ states with $I = 1/2$ and $J^p = 1/2^+$, which are N^* and Ξ^* resonances, respectively, were studied first in Refs. [28, 29] with a single-channel non-relativistic potential model. The $\bar{K}KN$ system was found to be bound with 20 MeV binding energy [28], and later was investigated in a more sophisticate calculation [30, 31] based on a coupled-channels Faddeev method developed in Refs. [32], in which a very similar state to one obtained in the potential model was found. It was found also in a fixed center approximation of three-body Faddeev calculation [33]. The $\bar{K}KN$ state is essentially described by a coexistence of $K\Lambda(1405)$ and $a_0(980)N$ [28]. An experimental search for $\bar{K}KN$ was discussed in Ref. [34]. The $\bar{K}KK$ state with $I = 1/2$ and $J^p = 0^-$, being an excited state of kaon, was studied in a two-body f_0K and a_0K dynamics [35], in the three-body Faddeev calculation [36] and in the non-relativistic potential model [36]. The three-body Faddeev calculation was done in coupled-channels of $\bar{K}KK$, $K\pi\pi$ and $K\pi\eta$ and a resonance state was found at 1420 MeV, while the potential model suggested a quasi bound state with a binding energy 20 MeV. This state is essentially described by the $\bar{K}KK$ single channel and its configuration is found to be mostly f_0K. Experimentally, Particle Data Group tells that there is a excited kaon around 1460 MeV observed in $K\pi\pi$ partial-wave analysis, although it is omitted from the summary table.

In the potential model calculations of the $\bar{K}KN$ and $\bar{K}KK$ states, it was found that the root mean-squared radii of these systems are as large as 1.7 fm, which are similar to the radius of ^{4}He. The inter-hadron distances are comparable with an average nucleon-nucleon distance in nuclei. It was also found that the two-body subsystems inside the three-body bound state keep their properties in isolated two-body systems. These features are caused by weakly binding of the three hadrons.

6 Conclusion

There should be hadronic composite states in which hadrons including mesons are constituents of the state in the hadron spectrum as one of the existence forms of hadron. These states have spatially larger sizes than the typical confinement range, because the driving force of the hadronic composite state is inter-hadron interaction which is out of the confinement range.

The $\Lambda(1405)$ resonance is one of the strong candidates of the hadronic composite states. The peculiarity of the $\Lambda(1405)$ resonance is not only being a hadronic composite object but also being composed of two resonance states. These two states stem from the presence of two attractive channels in fundamental meson-baryon interactions. Eventually the observed $\Lambda(1405)$ resonance is composed by two pole states. One of the states is a quasi-bound state of $\bar{K}N$ located at around 1420 MeV and dominantly couples to the $\bar{K}N$ channel. Thus, this is the relevant resonance for the kaon-nucleus interaction. The double pole structure of $\Lambda(1405)$ can be confirmed experimentally by observing $K^-d \to \Lambda(1405)n$, in which $\Lambda(1405)$ is produced selectively by the $\bar{K}N$ channel and the peak position appears around 1420 MeV.

The idea that $\Lambda(1405)$ is a quasibound state of $\bar{K}N$ can be extended systematically to further few-body states with kaons like $\bar{K}NN$, $\bar{K}KN$ and $\bar{K}KK$ having dozens MeV binding energy. In these states, a unique role of kaon is responsible for the systematics

of the few-body kaonic states. Kaon has a half mass of nucleon and its coupling strength to $\bar{K}$ is very similar to the $\bar{K}N$ coupling in the s-wave chiral interaction. This leads to weakly bound systems within the hadronic interaction range. The hadronic composite state is a concept of weakly binding systems of hadron constituents. If a resonance state has a large binding energy measured from the break-up threshold, coupled-channel effects, like $\pi\Sigma$ against $\bar{K}N$, and/or shorter range quark dynamics should be important for the resonance state. In such a case the hadronic composite picture is broken down, and one should take into account coupled channels contributions and quark dynamics.

The hadronic composite configuration is a complementary picture of hadron structure to constituent quarks, which successfully describe the structure of the low-lying baryons in a simple way. Strong diquark configurations inside hadrons can be effective constituents [37], and mixture of hadronic molecular and quark originated states is also probable in some hadronic resonances [38]. The hadronic molecular state has a larger spatial size than the typical low-lying hadrons. In heavy ion collision, coalescence of hadrons to produce loosely bound hadronic molecular systems is more probable than quark coalescence for compact multi-quark systems [39, 40]. Thus, one could extract the structure of hadrons by observing the production rate in heavy ion collisions.

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