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Origin of Dynamically Generated Baryon Rsonances*

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Abstract: We study the origin of baryon resonances which are dynamically generated in the chiral unitary approach. We propose a *natural renormalization scheme* for the dynamical generation of resonances using the low energy chiral interaction and a general feature of the scattering theory. A deviation of a phenomenological scattering amplitude from the natural one is interpreted by an effective pole term interaction of genuine nature which can not be described by the meson-baryon dynamics, reminiscent of the CDD pole. Applying the present method to physical meson-baryon scatterings, we find that the Λ(1405) resonance is dominated by a meson-baryon component forming a $\bar{K}N$-$\pi\Sigma$ molecular-like structure, while the N(1535) resonance requires some pole contribution.

Key words: baryon resonances; dynamical generation; chiral unitary approach

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1 Introduction

A great amount of recent research activities in hadron physics is stimulated by the success of chiral theory for hadrons. It has turned out that the range of its applicability is not limited to the low energy region[1－4], but can be wider as extended to the first resonance region by unitarizing the low energy chiral amplitude[5－9]. Since the method is based on the scattering of hadrons, it is suited for comparison with the experimental data from which resonance properties are extracted. In this method, the scattering amplitude is obtained by solving the Bethe-Salpeter (or Lippmann-Schwinger) equation with a suitable hadron interaction, and therefore, the resulting resonances, if there are, may naturally be regarded as dynamically generated resonances.

Historically, the constituent quark model has been also widely used for the description of hadron resonances as excited states of constituent quarks[10,11]. The constituent quark model is useful particularly for the classification of hadrons in terms of the empirical $SU(6)$ spin-flavor symmetry and orbital excitations. A large part of observed hadron states are then identified with the quark model states. Although the origin of the constituent quarks are not yet explained by the first principle of QCD, it reflects at least a part of the nature of the strong interaction dynamics.

Yet if we look at dynamical properties of hadrons such as masses, decay properties and so on, there are cases which can not be explained easily by the quark model. Strong couplings to two (or more) hadron states may modify substantially properties of the quark model states. We expect this particularly for the case when S-wave channels

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near in energy can couple to the expected state. Such a coupling can be estimated for the case of a two-body coupling by

$$\int d^3x j_l(qr)\rho(\bar{\boldsymbol{x}}) \ , \qquad (1)$$

where l and q are the orbital angular momentum and three momentum of the two-body system, and $\rho(\bar{\boldsymbol{x}})$ is a transition density. For small q the S-wave channel has a dominant coupling.

In view of the above two major ingredients of meson-baryon and quark originated dynamics, in this report, we discuss the origin of baryon resonances in the following two steps. First we define the resonance which emerges as a pole of the amplitude constructed in the *natural renormalization scheme*. This is demonstrated by the chiral unitary approach based on the meson-baryon dynamics of chiral symmetry. A possible resonance, if exists, is then dominated by a molecular-like structure of a meson and baryon. In the next step, we compare the phenomenological amplitude with the natural one. The difference between the two amplitudes then introduces an effective interaction of a pole structure which may have an origin not dictated by the meson-baryon dynamics but instead be conveniently described by the quark oriented dynamics. We apply the analysis to S-wave baryons of $J^P=1/2^-$, Λ(1405) and N(1535), and investigate their properties. Complete discussions on the materials of this report are given in our recent publication[12, 13].

2 Natural Renormalization for Dynamical Generation

Let us consider a two-body scattering of a meson and a baryon. The central object we investigate is the scattering amplitude T which is a solution to the Lippmann-Schwinger(LS) equation

$$T(\sqrt{s}) = V + VG(\sqrt{s})T(\sqrt{s}) \ . \qquad (2)$$

Here we indicate explicitly the energy ($\sqrt{s}$) dependence of T and of the two-body propagator $G(\sqrt{s})$. The interaction V can also have energy dependence, which, however, is not shown explicitly here.

In the chiral unitary approach, the interaction V is taken as the lowest order chiral interaction [6, 7, 9] extracted from the Weinberg-Tomozawa term of the chiral Lagrangian[14, 15]

$$L_{\mathrm{WT}} = \frac{1}{4f^2}\mathrm{tr}\bar{B}i\gamma_\mu[\phi\partial_\mu\phi - \partial_\mu\phi\phi, B] \ , \qquad (3)$$

where f is the pion decay constant, and B and ϕ are the standard $SU(3)$ matrices for baryon octet and meson octet fields. To the leading order of non-relativistic expansion, the interaction has the energy dependence

$$V_{\mathrm{WT}}(\sqrt{s}) = -\frac{C}{2f^2}[\sqrt{s} - M_{\mathrm{T}}] \sim -\frac{C}{2f^2}\omega \ , \qquad (4)$$

where M_{T} is the mass of the target baryon, ω the energy of the meson, and C a group theoretical factor which is given in Ref. [16].

The interactions derived from the chiral Lagrangian are in general contact (delta-function) type. This introduces a well-known problem of divergence, specifically in the propagator $G(\sqrt{s})$. This can be treated either by a cut-off or by a subtraction constant (a-parameter). An important point is that this renormalization procedure introduces an arbitrariness in the construction of the scattering amplitude T, which can be determined by a suitable renormalization condition. Usually, a condition is chosen such that the amplitude reproduces experimental data at a certain energy. This defines a phenomenological amplitude, which will be discussed later. Here we first propose an alternative condition, which we shall call the *natural renormalization scheme*.

For the natural renomalization, we introduce the following two requirements:

(1) the full scattering amplitude satisfies the low energy theorem at a certain low energy $\sqrt{s}=\mu$:

$$T(\mu) = V \rightarrow G(\mu) = 0 , \qquad (5)$$

since the interaction V is derived from the chiral Lagrangian;

(2) the two-body propagator satisfies the inequality

$$G(\sqrt{s}) < 0 \qquad (6)$$

below the threshold of the meson-baryon scattering, $\sqrt{s} < m + M_{\mathrm{T}}$, where m and M_{T} are the masses of the meson and baryon, respectively.

The first requirement is to ensure the consistency of the amplitude with the low energy theorem at $\sqrt{s} = \mu$. The LS-equation then determines the $\sqrt{s}$ dependence of the amplitude $T(\sqrt{s})$ at all $\sqrt{s}$. There is still an arbitrariness in the choice of μ. In the spirit of the chiral perturbation theory, Eq. (5) should hold for small momenta of light Nambu-Golstone bosons. In the interaction of the form (4), this corresponds to $\sqrt{s} \approx M_{\mathrm{T}}$. Therefore, we consider it reasonable to set $\mu = M_{\mathrm{T}}$.

The requirement (2) is a consistency with familiar problems in quantum mechanics, where a finite range potential $V(\bar{\boldsymbol{x}})$ is given and the LS-equation can be solved without the divergence problem. In general the propagator can be formally written as

$$G(\sqrt{s}) \approx \sum_n \frac{1}{\sqrt{s} - E_n} , \qquad (7)$$

where E_n are intermediate energies of the two-body channel. Since $E_n > m + M_{\mathrm{T}}$, $G(\sqrt{s}) < 0$ for $\sqrt{s} < m + M_{\mathrm{T}}$. Here we have implicitly assumed that there are not isolated poles, and consequently the sum over E_n is smoothly performed.

Now let us look at the propagator $G(\sqrt{s})$ in more detail. In the dimensional regularization scheme, after subtracting the divergent terms and introducing a subtraction constant a, it can be written analytically as

$$G(\sqrt{s}, a) = \frac{2M_{\mathrm{T}}}{(4\pi)^2}\Big\{a + \frac{m^2 - M_{\mathrm{T}}^2 + s}{2s}\ln\frac{m^2}{M_{\mathrm{T}}^2} + \frac{\bar{q}}{\sqrt{s}}[\ln(s - (M_{\mathrm{T}}^2 - m^2) + 2\sqrt{s}\bar{q}) + \ln(s + (M_{\mathrm{T}}^2 - m^2) + 2\sqrt{s}\bar{q}) - \ln(-s + (M_{\mathrm{T}}^2 - m^2) + 2\sqrt{s}\bar{q}) - \ln(-s - (M_{\mathrm{T}}^2 - m^2) + 2\sqrt{s}\bar{q})]\Big\} , \qquad (8)$$

where on the left hand side, the a dependence is shown explicitly. The resulting real part of $G(\sqrt{s}, a)$ is plotted in Fig. 1 as a function of $\sqrt{s}$ for the case of kaon and nucleon scattering, $m = 495$ MeV and $M_T = 940$ MeV. Below the threshold $\sqrt{s} = m + M_T$, there is no imaginary part, while the kink

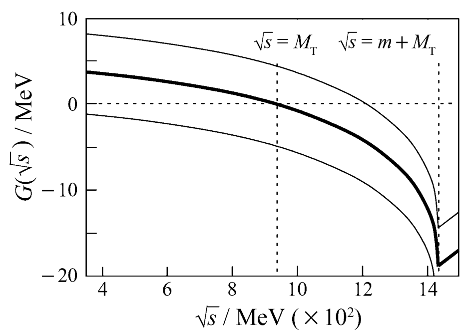

Fig. 1 The real part of the propagator $G(\sqrt{s})$ as a function of $\sqrt{s}$.

at the threshold $\sqrt{s} = m + M_{\mathrm{T}}$ indicates the appearance of the imaginary part at and above the threshold. Different curves in Fig. 1 correspond to $G(\sqrt{s}, a)$'s with different values of a. As shown explicitly in the figure, the real part of $G(\sqrt{s}, a)$ function is a monotonically decreasing function in the region of $M_{\mathrm{T}} \leqslant \sqrt{s} \leqslant m + M_{\mathrm{T}}$. This behavior guarantees that if we impose $G(\sqrt{s} = M_{\mathrm{T}}, a) = 0$, then $G(\sqrt{s}, a)$ becomes negative in the region $M_{\mathrm{T}} \leqslant \sqrt{s} \leqslant m + M_{\mathrm{T}}$. This condition determines the natural amplitude T with the natural subtraction constant a_{natural},

$$a_{\mathrm{natural}} = -\Big\{+\frac{m\sqrt{m^2 - 4M_{\mathrm{T}}^2}}{2M_{\mathrm{T}}^2} \times [\ln(m^2 + m\sqrt{m^2 - 4M_{\mathrm{T}}^2}) + \ln(2M_T^2 - m^2 + m\sqrt{m^2 - 4M_{\mathrm{T}}^2}) - \ln(-m^2 + m\sqrt{m^2 - 4M_{\mathrm{T}}^2}) -$$

$$\ln(-2M_T^2 + m^2 + m\sqrt{m^2 - 4M_T^2})]\} . \tag{9}$$

3 Phenomenological Amplitude and an Effective Pole Interaction

If the amplitude constructed in the natural renormalization scheme develops a pole in the resonance region, its structure is dominated by a molecular-like component of a meson and baryon. we consider it as a dynamically generated resonance. Its properties, however, do not necessarily agree with experimental data. In this case, to reproduce the data we need to fix phenomenologically the a parameter, which is in general different from the natural one, $a_{\rm pheno} \neq a_{\rm natural}$. The difference $\Delta a = a_{\rm pheno} - a_{\rm natural}$ is an indication that the resonance has a component which can not be described by the meson-baryon dynamics of chiral symmetry but rather has an origin of quark dynamics nature. This is similar to the CDD pole in the N/D construction[17, 18].

The difference Δa can now be translated into an additional term of pole structure in the interaction V. This is seen by rewriting the formal solution to the T-matrix as

$$T(\sqrt{s}) = \frac{1}{V_{\rm WT}^{-1} - G(\sqrt{s}, a_{\rm pheno})},$$

$$G(\sqrt{s}, a_{\rm pheno}) = G(\sqrt{s}, a_{\rm natural}) + \frac{2M_T}{(4\pi)^2}\Delta a \tag{10}$$

and by introducing the effective interaction through

$$\widetilde{V}^{-1} = V_{\rm WT}^{-1} + \frac{2M_T}{(4\pi)^2}\Delta a,$$

or

$$\widetilde{V} = V_{\rm WT} + \frac{C}{2f^2}\frac{(\sqrt{s} - M_T)^2}{\sqrt{s} - M_{\rm eff}} , \tag{11}$$

where the effective mass $M_{\rm eff}$ is given by

$$M_{\rm eff} = M_T - \frac{16\pi^2 f^2}{CM_T \Delta a} . \tag{12}$$

From this equation we observe: (i) as anticipated the new pole term is added for a finite Δa, (ii) the strength of the pole term is inversely proportional to Δa, and (iii) the pole term is of higher order with respect to the chiral expansion $\sim O((\sqrt{s} - M_T)^2)$. From the property (2), if the natural renormalization scheme can produce the properties of a physical resonance, Δa is small and $M_{\rm eff}$ is large, which means that the role of the pole term is irrelevant.

4 Λ(1405) and N(1535)

In this section, we briefly discuss the application of the previous section to the physical resonances of Λ(1405) and N(1535). There are very intensive discussions on Λ(1405) in relation with its two pole nature as generated by the meson-baryon dynamics in the chiral unitary approach[19—21]. The confirmation of such a structure is extremely important not only to the understanding of hadron dynamics but also to kaon nuclear interactions which has a wide range of applications including hyper nuclear physics and high density matter. The nucleon resonance N(1535) is also an interesting object, particularly due to its relevance to chiral nature of baryons[22—24].

In order to analyze these states, we need to consider coupled channel effects of various meson-baryon pairs, $\bar{K}N$, $\pi\Sigma$, $\eta\Lambda$ for Λ(1405), $K\Xi$, and πN, $\bar{K}\Sigma$, $K\Lambda$, ηN for N(1535). In Refs. [12, 25, 26], full coupled channel analysis was performed. Here we discuss only some important results.

Shown in Table 1 are the subtraction constants for various channels; the values in the two rows are those phenomenologically fitted values and those determined in the natural renormalization scheme. From the table we observe that for Λ(1405), the two kinds of subtraction constants are similar, while those for N(1535) are not so. As a consequence, we conclude that Λ(1405) is largely dominated by the dynamically generated components governed by the chiral dynamics, while N(1535) requires a significant amount of a genuine component although the strength of the dynamically generated part is also important. Concerning the effective pole interaction, the effective mass $M_{\rm eff}$ takes a value around 7 GeV for Λ(1405) while 1.6 GeV for N(1535). These values also indicate the irrelevance of the genuine resonance component for Λ(1405), while it has some relevance for N(1535).

Table 1 Natural values and phenomenological values for the subtraction constants with the regularization scale $\mu = M_i$

$S=-1$	$\bar{K}N$	$\pi\Sigma$	$\eta\Lambda$	$K\Xi$
$a_{\rm pheno,\,i}$	−1.042	−0.722 8	−1.107	−1.194
$a_{\rm natural,\,i}$	−1.150	−0.699 5	−1.212	−1.138
$S=0$	πN	ηN	$K\Lambda$	$K\Sigma$
$a_{\rm pheno,\,i}$	1.509 0	−0.292 0	1.454	−2.813
$a_{\rm natural,\,i}$	−0.397 6	−1.239 0	−1.143	−1.138

It is interesting to investigate various coupling properties of the resonances. In Ref. [12], meson-baryon couplings of the resonances N(1535) and Λ(1405) were investigated. In Ref. [27], photon couplings were also studied for N(1535). It turned out that for N(1535), the coupling properties were well describe by the meson-baryon component of the resonance wave function in a way consistent with experimental data. Meson-baryon couplings were also extracted for the genuine components, which turned out to be very much different from the observed ones[12]. Therefore, though the N(1535) wave function contains genuine components substantially, it plays only minor role for coupling properties of the resonance.

5 Conclusions

The recent research activities based on the chiral theory with its extensive application to resonance dynamics have strongly suggested that some resonances could have a molecular-like structure of ground state hadrons. Recent experimental data in the heavy flavor sector including charm quarks also suggest such a structure. The confirmation of that structure as well as of exotic states will provide further development of hadron physics, as it would require a reconsideration of our conventional understanding of hadrons based on the constituent quark model. From the theory side, it had been rather unclear how we could differentiate the molecular-like structure from the genuine quark dominated structure. In this report, we have shown our proposal for how to differentiate the one from the other. To establish the framework in a reliable manner, it is important to have a good theory for hadron interactions, which is indeed the case with the chiral theory.

Within the framework of the chiral unitary approach, we have proposed a natural renormalization scheme, where dynamically generated resonance are defined without explicitly referring to a genuine component of the resonance. This has been performed by imposing theoretical requirements which are consistent with the low energy theorems and some basic properties of scattering amplitudes. When the scattering amplitude is fitted to reproduce experimental data, the resulting phenomenological amplitude can be constructed by introducing a pole term interaction in addition to the low energy interaction (Weinberg-Tomozawa term).

The application of the present framework suggests that the two resonances for Λ(1405) are dominated by the meson-baryon dynamics and the genuine component is almost negligible. Contrarily, N(1535) requires both the meson-baryon originated component and the genuine one. What is interesting here is that the coupling properties are mostly described by the meson-baryon component.

The present method can be applicable to various resonance states. It would be interesting to study systematically the structure of resonances for further understanding of hadron dynamics.

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