Meson-baryon nature of \( \Lambda(1405) \) in chiral dynamics

Tetsuo Hyodo\textsuperscript{a}, Daisuke Jido\textsuperscript{b}, Atsushi Hosaka\textsuperscript{c}

\textsuperscript{a}Department of Physics, Tokyo Institute of Technology, Meguro 152-8551, Japan
\textsuperscript{b}Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan
\textsuperscript{c}Research Center for Nuclear Physics (RCNP), Ibaraki, Osaka 567-0047, Japan

Abstract

We present the recent progress in the study on the origin of baryon resonances in chiral dynamics. It is shown that in the chiral coupled-channel approach, the form of the interaction cannot be specified due to the cutoff of the loop integral. To avoid this ambiguity, we propose a natural renormalization scheme, which affords a clue to the origin of the resonance, together with the phenomenological fitting to experimental data. We study the structure of the \( \Lambda(1405) \) resonance in comparison with the \( N(1535) \).

Key words: Chiral dynamics, structure of the \( \Lambda(1405) \), the CDD pole

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1. Introduction

The structure of the \( \Lambda(1405) \) resonance has been extensively discussed in strangeness nuclear/hadron physics \cite{1,2}. From the viewpoint of hadron spectroscopy, the \( \Lambda(1405) \) is considered to be a meson-baryon molecule, since the coupled-channel scattering framework \cite{3} seems to be favored over a simple three-quark picture, while possible multi-quark structure is also discussed. On the other hand, the \( \Lambda(1405) \) is of particular importance for the behavior of the kaon in nucleus \cite{4}, since this resonance strongly dictates the subthreshold \( \bar{K}N \) interaction \cite{5}. Clarification of the structure of the \( \Lambda(1405) \) resonance as well as the study of \( \bar{K} \) in nucleus are within the scope of current/future experiments in facilities such as SPring-8, Jefferson Lab., and J-PARC.

It is our aim here to study the structure of the \( \Lambda(1405) \) resonance from the viewpoint of scattering theory. We utilize the theoretical framework of chiral coupled-channel approach \cite{6,7,8,9}, where the excited baryons are described as resonances in the meson-baryon scattering amplitude, generated by the chiral low energy interaction. In this framework, any components other than dynamical two-body state (meson-baryon molecule) are expressed by the Castillejo-Dalitz-Dyson (CDD) pole contribution \cite{10}. Thus, the magnitude of the CDD pole contribution in the amplitude tells us about the origin of resonances. We present the method to extract such an information within the chiral coupled-channel framework \cite{11}.

2. Formulation

We start with the general form of the amplitude based on the N/D method \cite{8}, for \( s \)-wave single-channel meson-baryon scattering at total energy \( \sqrt{s} \):

\[
T(\sqrt{s},a) = \left[ V^{-1}(\sqrt{s}) - G(\sqrt{s},a) \right]^{-1},
\]

(1)
where $V(\sqrt{s})$ is the kernel interaction constrained by chiral low energy theorem. The once subtracted dispersion integral $G(\sqrt{s}; a)$ can be identified as the meson-baryon loop function with dimensional regularization, and the subtraction constant $a$ plays the role of the cutoff of the loop function. In this way, Eq. (1) is regarded as the solution of the algebraic Bethe-Salpeter equation. The interaction kernel $V(\sqrt{s})$ is determined by the order by order matching with chiral perturbation theory [8]. At the leading order, $V(\sqrt{s})$ is given by the $s$-wave interaction of the Weinberg-Tomozawa (WT) term $V(\sqrt{s}) = V_{\text{WT}}(\sqrt{s}) = -(\sqrt{s} - M_T)/(2f^2)$ where $C, M_T$ and $f$ are the group theoretical factor, the baryon mass, and the meson decay constant, respectively.

In the framework of N/D method, the CDD pole contribution should be included in the kernel interaction $V(\sqrt{s})$. The CDD pole contribution has been manifested in chiral dynamics by the introduction of an explicit resonance propagator, or the contracted resonance contribution from the higher order chiral Lagrangian. We however show that the loop function $G(\sqrt{s}, a)$ can also have the CDD pole contribution [11]. This can be understood from the viewpoint of the renormalization group; Once the amplitude $T$ is determined by experiments, then the change of the interaction $V$ can be absorbed by the change of the cutoff parameter $a$ in the loop function $G$. In this case, the CDD pole contribution in the kernel $V$ may be effectively transferred to the loop function $G$. Thus, in order to study the origin of resonances in this approach, we should make the CDD pole contribution in the model under control.

For this purpose, we propose the “natural renormalization scheme,” in which the CDD pole contribution is excluded from the loop function $G(\sqrt{s}, a)$. This can be achieved by requiring (i) no state exists below the meson-baryon threshold, and (ii) the amplitude $T$ matches with the interaction kernel $V$ at certain low energy scale, based on the validity of chiral expansion. These conditions uniquely determine the subtraction constant $a_{\text{natural}}$ such that $G(\sqrt{s}; a_{\text{natural}}) = 0$ at $\sqrt{s} = M_T$ [11]. The similar condition was proposed in different contexts, but our point is to regard this condition as the exclusion of the CDD pole in the loop function, based on the consistency with the negativeness of the loop function.

This natural renormalization scheme enables us to extract the CDD pole contribution hidden in the loop function in the phenomenological amplitude. In the following, we demonstrate it in a single-channel model. First, with the leading order WT term $V_{\text{WT}}$ for the interaction kernel, we fit the experimental data by adjusting the subtraction constant $a_{\text{pheno}}$ for the conventional phenomenological approaches. We then try to construct an equivalent amplitude in the natural renormalization scheme with the subtraction constant $a_{\text{natural}}$ and the effective interaction $V_{\text{natural}}$. The equivalence of the amplitude is achieved by

$$V_{\text{natural}}^{-1}(\sqrt{s}) - G(\sqrt{s}; a_{\text{natural}}) = V_{\text{WT}}^{-1}(\sqrt{s}) - G(\sqrt{s}; a_{\text{pheno}}).$$

This equation gives us the effective interaction $V_{\text{natural}}$ as

$$V_{\text{natural}}(\sqrt{s}) = -\frac{C}{2f^2}(\sqrt{s} - M_T) + \frac{C}{2f^2} \frac{(\sqrt{s} - M_T)^2}{\sqrt{s} - M_{\text{eff}}},$$

with an effective mass $M_{\text{eff}} \equiv M_T - (16\pi^2 f^2)/CM_T\Delta a$ and $\Delta a = a_{\text{pheno}} - a_{\text{natural}}$. The expression [11] indicates that the interaction kernel $V_{\text{natural}}(\sqrt{s})$ can have a pole, whose relevance depends on the scale of the effective mass $M_{\text{eff}}$. This pole can be the source of a resonance in the amplitude, and so it is interpreted as the CDD pole contribution. If $\Delta a$ is small, the effective pole mass $M_{\text{eff}}$ becomes large and the second term of Eq. (3) can be neglected in the resonance energy region $\sqrt{s} \sim M_T + m \ll M_{\text{eff}}$. If the difference $\Delta a$ is large, the effective mass $M_{\text{eff}}$ gets closer to the threshold and the pole contribution is no longer negligible. Thus, we can estimate the effect of the CDD pole contribution from the values of the effective mass $M_{\text{eff}}$. 

2
3. Numerical results

We analyze the meson-baryon scattering and the $\Lambda(1405)$ in $S = -1$ and $I = 0$ channel and the $N(1535)$ in $S = 0$ and $I = 1/2$ channel, using the method explained above. We use the phenomenological models [12, 13] to determine the phenomenological subtraction constants $a_{\text{pheno},i}$. These models are based on the results in Refs. [14, 15], and the scattering observables are well reproduced by the interaction kernel of the WT term. The natural values of the subtraction constants $a_{\text{natural},i}$ are obtained by setting $G(M_N) = 0$ for all channels.

We first evaluate the effective interaction in the natural renormalization scheme and extract the pole positions in the kernel. The nearest pole in each channel is given by $z_{\text{eff}}^{\Lambda} \sim 7.9$ GeV and $z_{\text{eff}}^{N} = 1693 \pm 37$ MeV. It is observed that the pole for the $N(1535)$ lies in the energy region of interest, while the pole for the $\Lambda(1405)$ is obviously out of the scale of the physics of the resonance. This result indicates that the $N(1535)$ may require some CDD pole contribution, whereas the $\Lambda(1405)$ does not.

Next we consider the idealized situation of purely dynamical components, which can be obtained by adopting the WT term with the natural subtraction constant. The pole positions in this model are shown by crosses in Fig. 1. Note that in chiral dynamics the $\Lambda(1405)$ is described as the two poles in the complex energy plane [16, 17]. These poles can be compared with the those in the phenomenological amplitude shown by the triangles in Fig. 1 which corresponds to the physical resonances. The phenomenologically extracted poles for the $\Lambda(1405)$ (triangles) appear near the dynamical ones (crosses). This indicates the dominance of the meson-baryon component in the $\Lambda(1405)$. On the other hand, the pole for the $N(1535)$ moves to the higher energy when we use the natural values. Although the dynamical component generates a state by itself, the physical $N(1535)$ requires some more contributions, which is expressed as the pole in the effective interaction at 1.7 GeV. Thus, the comparison in Fig. 1 also indicates the dynamical nature of the $\Lambda(1405)$ and the sizable CDD pole contribution for the $N(1535)$.

\[1\] With $n$-coupled channels, the effective interaction has $n$ poles, and a pair of complex poles can also appear [11].
4. Summary

We have studied the structure of baryon resonances in chiral dynamics. It is shown that the CDD pole contribution can be excluded from the loop function in the natural renormalization scheme. A methodology to study the origin of the resonance is discussed using the effective interaction kernel in the natural renormalization scheme, which is obtained in comparison with the phenomenological amplitude. We analyze the origin of the $\Lambda(1405)$ and the $N(1535)$ in meson-baryon scattering. In the natural renormalization scheme, the physical $\Lambda(1405)$ can be well reproduced with the WT interaction for the kernel of the scattering equation, while the $N(1535)$ requires a substantial contribution in addition to the WT term, especially a pole singularity at around 1.7 GeV. These facts indicate that the $N(1535)$ may not be a pure dynamical state and it requires substantial CDD pole contribution in its structure. On the other hand, the $\Lambda(1405)$ can be mainly described by a dynamical state of the meson-baryon scattering. This conclusion is qualitatively consistent with the analysis of the $N_c$ scaling [17, 18] and the estimation of the electromagnetic size [19].

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