Internal structure of the $\Lambda(1405)$ resonance probed in chiral unitary amplitude

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The internal structure of the resonant $\Lambda(1405)$ state is investigated based on meson-baryon coupled-channels chiral dynamics. We evaluate $\Lambda(1405)$ form factors which are extracted from current-coupled scattering amplitudes in meson-baryon degrees of freedom. Using several probe currents and channel decomposition, we find that the resonant $\Lambda(1405)$ state is dominantly composed of widely spread $\overline{K}$ around N, with escaping $\pi\Sigma$ component.

1 Introduction

There are hadrons which are expected to have exotic structures, *e.g.*, hadronic molecules, and it is one of the important issues in hadron physics to clarify their structures. A classical example is the excited baryon $\Lambda(1405)$, which has been considered as an s-wave $\overline{K}N$ quasibound state [1]. It is also suggested by the modern theoretical approach based on the chiral dynamics within the unitary framework (the chiral unitary approach) [2–7] that $\Lambda(1405)$ is dynamically generated in the meson-baryon scattering, in addition to the good reproduction of the low-energy K^-p cross sections and the $\Lambda(1405)$ peak in $\pi\Sigma$ mass spectrum. Moreover, the chiral unitary approach predicts double-pole structure for $\Lambda(1405)$ [4, 6] and one of the poles is expected to originate from the $\overline{K}N$ bound state [8, 9]. Some approaches for the survey on the $\Lambda(1405)$ structure in experiments have been proposed, e.g., in Refs. [10, 11].

If $\Lambda(1405)$ is dominated by the $\overline{K}N$ quasibound state with a small binding energy, one can expect that $\Lambda(1405)$ has a larger size than typical ground state baryons dominated by genuine qqq components. Motivated by this expectation, in Ref. [12] we have investigated the internal structure of the resonant $\Lambda(1405)$ state by evaluating density distributions obtained from the form factors on the $\Lambda(1405)$ pole originating from the $\overline{K}N$ bound state. In our study the $\Lambda(1405)$ form factors are directly extracted from the current-coupled scattering amplitude, which involves a response of $\Lambda(1405)$ to the external current. The current-coupled scattering amplitude is evaluated in a charge conserved way by considering current couplings to the constituent hadrons inside $\Lambda(1405)$. Here we note that the wave functions and form factors of $\Lambda(1405)$ were studied also in Ref. [13] in a cut-off scheme within chiral unitary approach, which results were not significantly different from ours, except for the high momentum region compared to the cut-off.

2 Internal structure of $\Lambda(1405)$

In the chiral unitary approach, the meson-baryon scattering amplitude T_{ij} with channel indices i and j is obtained by a coupled-channels equation,

$$T_{ij}(\sqrt{s}) = V_{ij}(\sqrt{s}) + \sum_{k} V_{ik}(\sqrt{s}) G_{k}(\sqrt{s}) T_{kj}(\sqrt{s}), \tag{1}$$

with the interaction kernel V_{ij} given by chiral perturbation theory, a meson-baryon loop integral G_k, and the center-of-mass energy $\sqrt{s}$. The obtained amplitude contains dynamically generated $\Lambda(1405)$ in s wave. Next, in order to observe response of $\Lambda(1405)$ to the conserved probe current in the chiral unitary approach, we evaluate current-coupled scattering amplitude $T^{\mu}_{\gamma ij}$ in a charge conserved way, considering current couplings to the constituent hadrons as [12, 14]:

$$T^{\mu}_{\gamma ij}(\sqrt{s'}, \sqrt{s}; Q^2) = T^{\mu}_{\gamma(1)ij} + T^{\mu}_{\gamma(2)ij} + T^{\mu}_{\gamma(3)ij}, \tag{2}$$

with the squared current momentum Q^2 and

$$T^{\mu}_{\gamma(1)ij} = \sum_{k} T_{ik} D^{\mu}_{\mathrm{M}_k} T_{kj}, \quad T^{\mu}_{\gamma(2)ij} = \sum_{k} T_{ik} D^{\mu}_{\mathrm{B}_k} T_{kj}, \quad T^{\mu}_{\gamma(3)ij} = \sum_{k,l} T_{ik} G_k \Gamma^{\mu}_{kl} G_l T_{lj}, \tag{3}$$

where D_{M_k} and D_{B_k} are respectively loop integrals with the current couplings to the meson and baryon and Γ_{ij} represents $MBM'B'\gamma$ vertex. Then the $\Lambda(1405)$ form factor, $F^{\mu}(Q^2)$, can be extracted by [12, 15],

$$F^{\mu}(Q^2) = - \left. \left. \frac{(\sqrt{s'} - Z_{\mathrm{R}}) T^{\mu}_{\gamma ij}(\sqrt{s'}, \sqrt{s}; Q^2)}{T_{ij}(\sqrt{s})} \right|_{\sqrt{s} \to Z_{\mathrm{R}}} \right|_{\sqrt{s'} \to Z_{\mathrm{R}}}, \tag{4}$$

where Z_{R} is the $\Lambda(1405)$ pole position. Here we note that we have following relations:

$$\hat{Q} \frac{dG_k}{d\sqrt{s}} = (D^{0}_{\mathrm{M}_k} + D^{0}_{\mathrm{B}_k})|_{Q^2=0}, \quad \hat{Q} \frac{dV_{ij}}{d\sqrt{s}} = \Gamma^{0}_{ij}|_{Q^2=0}, \tag{5}$$

with $\hat{Q}$ being the charge of $\Lambda(1405)$ with respect to the probe current. These are the Ward-Takahashi identity for the two-body free propagator G_k and the elementary vertex V_{ij}.

Now let us show our results for the internal structure of the resonant $\Lambda(1405)$. First, we write a normalization relation for the baryonic [$F_{\mathrm{B}}(Q^2)$] and strangeness [$F_{\mathrm{S}}(Q^2)$] form factors of $\Lambda(1405)$ proved in Ref. [12],

$$F_{\mathrm{B}}(Q^2 = 0) = -F_{\mathrm{S}}(Q^2 = 0) = - \sum_{i,j} g_i g_j \left. \left(\frac{dG_i}{d\sqrt{s}} \delta_{ij} + G_i \frac{dV_{ij}}{d\sqrt{s}} G_j \right) \right|_{\sqrt{s} \to Z_{\mathrm{R}}} = 1, \tag{6}$$

where $g_i g_j$ is a residue of T_{ij} at the $\Lambda(1405)$ pole position and $dG_i/d\sqrt{s}$ ($dV_{ij}/d\sqrt{s}$) term comes from $D^{0}_{\mathrm{M}_i} + D^{0}_{\mathrm{B}_i}$ (Γ^{0}_{ij}) at $Q^2 = 0$. This relation corresponds to the Ward identity for the vertex

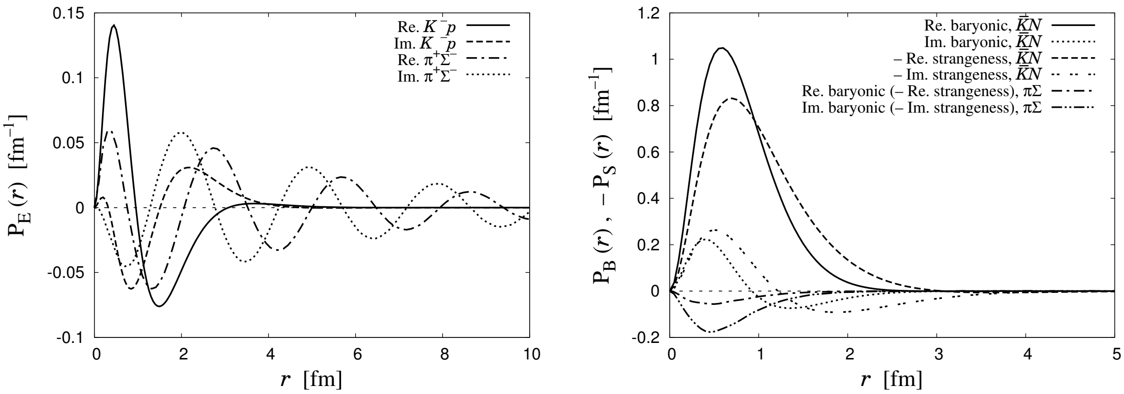

Figure 1: Electric (P_E, left), baryonic and strangeness (P_B and P_S, right) density distributions of $\Lambda(1405)$ in each component. Here P_E is shown in particle basis whereas P_B and P_S are in isospin basis [12].

and wave-function renormalization factors, and this originates from that we evaluate $T^{\mu}_{\gamma ij}$ in a charge conserved way with current couplings satisfying Ward-Takahashi identity (5). With this relation, we can pin down the dominant component of the $\Lambda(1405)$ structure by decomposing the summation in Eq. (6). As a result, we find that contribution from the $\overline{K}N(I=0)$ channel $(= -g^2_{\overline{K}N} dG_{\overline{K}N}/d\sqrt{s})$ is $0.994 + 0.048i$ whereas contributions from other channels and the vertex term $(= -\sum_{i,j} g_i G_i dV_{ij}/d\sqrt{s} G_j g_j)$ are negligibly small [12]. Therefore, this result indicates that the $\overline{K}N(I=0)$ channel generates more than 99% of the $\Lambda(1405)$ charge, which is consistent with the $\overline{K}N$ quasibound state picture for $\Lambda(1405)$.

Next we show the electric, baryonic, and opposite-sign strangeness density distributions (P_E, P_B, and $-P_S$, respectively) of $\Lambda(1405)$ in each component in Fig. 1. From P_E, we can see that the negative (positive) charge distribution appears in $\Lambda(1405)$ due to the existence of lighter K^- (heavier p) in the outside (inside) region, bearing in mind the $\overline{K}N$ dominance for $\Lambda(1405)$. Also it is interesting to see the dumping oscillation in $\pi^+\Sigma^-$ (equivalently $\pi^-\Sigma^+$ with the opposite sign) component in P_E as the decay of the system, although this is not observed in the total P_E due to the cancellation of $\pi^+\Sigma^-$ and $\pi^-\Sigma^+$ components. On the other hand, P_B and P_S indicate that inside $\Lambda(1405)$ the $\overline{K}$ component has longer tail than the N component and $\overline{K}$ distribution largely exceeds typical hadronic size $\lesssim 1$ fm, bearing in mind that the baryonic (strangeness) current probes the N ($\overline{K}$) distribution inside $\Lambda(1405)$.

3 Summary

We have investigated the internal structure of the resonant $\Lambda(1405)$ state in the chiral unitary approach, in which $\Lambda(1405)$ is dynamically generated in meson-baryon coupled-channels chiral dynamics. Probing $\Lambda(1405)$ with conserved current in a charge conserved way, we have observed that $\overline{K}N$ component gives more than 99% of the total $\Lambda(1405)$ charge. The electric density distribution indicates that inside $\Lambda(1405)$ lighter K^- (heavier p) exists in the outside (inside) region and the escaping $\pi\Sigma$ component appears as the decay mode of $\Lambda(1405)$. Also from the baryonic and strangeness density distributions we have found that inside $\Lambda(1405)$ the $\overline{K}$ component has longer tail than the N component and $\overline{K}$ distribution largely exceeds typical hadronic size $\lesssim 1$ fm.

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