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 $K$ 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 $KN$ quasi-bound 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 $\bar{K}N$ 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 $\bar{K}N$ 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 $\bar{K}N$ 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 Λ(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,

\[ T_{ij}(\sqrt{s}) = V_{ij}(\sqrt{s}) + \sum_{k} V_{ik}(\sqrt{s}) G_{k}(\sqrt{s}) T_{kj}(\sqrt{s}), \]

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 $T_{\gamma ij}^{\mu}$ in a charge conserved way, considering current couplings to the constituent hadrons as \cite{[12,14]}:

\[ T_{\gamma ij}^{\mu}(\sqrt{s'}, \sqrt{s}; Q^{2}) = T_{\gamma(1)ij}^{\mu} + T_{\gamma(2)ij}^{\mu} + T_{\gamma(3)ij}^{\mu}, \]

with the squared current momentum $Q^{2}$ and

\[ T_{\gamma(1)ij}^{\mu} = \sum_{k} T_{ik} D_{M_{k}}^{\mu} T_{kj}, \quad T_{\gamma(2)ij}^{\mu} = \sum_{k} T_{ik} D_{B_{k}}^{\mu} T_{kj}, \quad T_{\gamma(3)ij}^{\mu} = \sum_{k,l} T_{ik} G_{k} \Gamma_{kl} G_{l} T_{lj}, \]

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

\[ F^{\mu}(Q^{2}) = - \left( \frac{(\sqrt{s'} - Z_{R}) T_{\gamma ij}^{\mu}(\sqrt{s'}, \sqrt{s}; Q^{2})}{T_{ij}(\sqrt{s})} \right) \bigg|_{\sqrt{s} \rightarrow Z_{R}}, \]

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

\[ \hat{Q} \frac{dG_{k}}{d\sqrt{s}} = (D_{M_{k}}^{0} + D_{B_{k}}^{0})|_{Q^{2}=0}, \quad \hat{Q} \frac{dV_{ij}}{d\sqrt{s}} = \Gamma_{ij}|_{Q^{2}=0}, \]

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 [$F_{B}(Q^{2})$] and strangeness [$F_{S}(Q^{2})$] form factors of $\Lambda(1405)$ proved in Ref. \cite{[12]},

\[ F_{B}(Q^{2}) = -F_{S}(Q^{2}) = - \sum_{i,j} g_{i} g_{j} \left( \frac{dG_{i}}{d\sqrt{s}} \delta_{ij} + G_{i} \frac{dV_{ij}}{d\sqrt{s}} G_{j} \right) \bigg|_{\sqrt{s} \rightarrow Z_{R}} = 1, \]

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 $D_{M_{i}}^{0} + D_{B_{i}}^{0}$ ($\Gamma_{ij}^{0}$) at $Q^{2} = 0$. This relation corresponds to the Ward identity for
the vertex 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 ($= -g_{\overline{K}N}^2 dG_{\overline{K}N}/d\sqrt{s}$) is $0.994 \pm 0.048i$ whereas contributions from other channels and the vertex term ($= -\sum_{ij} g_{ij} G_{ij} dV_{ij}/d\sqrt{s} G_{ij} g_{ij}$) 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 $\bar{K}N$ 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 $\bar{K}$ component has longer tail than the $N$ component and $\bar{K}$ distribution largely exceeds typical hadronic size $\lesssim 1$ fm.

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