Probing internal structure of $\Lambda(1405)$ in meson-baryon dynamics with chiral symmetry

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Abstract. The internal structure of the resonant $\Lambda(1405)$ state is investigated based on meson-baryon coupled-channels chiral dynamics, by evaluating density distributions obtained from the form factors of the $\Lambda(1405)$ state. The form factors are extracted from current-coupled scattering amplitudes in which the current is coupled to the constituent hadrons inside $\Lambda(1405)$. Using several probe interactions and channel decomposition, we find that the resonant $\Lambda(1405)$ state is dominantly composed of widely spread $\bar{K}$ around $N$, with a small fraction of the escaping $\pi\Sigma$ component.

Keywords: $\Lambda(1405)$ structure, meson-baryon chiral dynamics, current couplings to resonances

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1. INTRODUCTION

It is one of the important issues in hadron physics to clarify properties of the resonant $\Lambda(1405)$ state, which is an excited baryon with spin-parity $J^P = 1/2^-$, isospin $I = 0$, and strangeness $S = -1$, and is located just below the threshold of antikaon ($\bar{K}$) and nucleon ($N$). The $\Lambda(1405)$ state has been considered as a $\bar{K}N$ quasi-bound state [1]. Recent theoretical studies have also suggested that the $\Lambda(1405)$ is dynamically generated in meson-baryon coupled-channels chiral dynamics, or so-called chiral unitary approach [2, 3, 4, 5, 6], reproducing well the low-energy $K^-\rho$ cross sections as well as the $\Lambda(1405)$ peak in $\pi\Sigma$ mass spectrum. Moreover, the chiral unitary approach predicts double-pole structure for $\Lambda(1405)$ [6] and one of the poles is expected to originate from the $\bar{K}N$ bound state [7, 8]. Some approaches for the survey on the $\Lambda(1405)$ structure in experiments have been proposed, e.g., in Refs. [9, 10].

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. [11] we investigate 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 we extract the form factors of $\Lambda(1405)$ directly 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 microscopic way, that is, by considering current couplings to the constituent hadrons inside $\Lambda(1405)$. The wave functions and form factors of $\Lambda(1405)$ were studied also in Ref. [12] in a cut-off scheme within chiral unitary approach. Their results would not show much difference with respect to our results, except for the high momentum region compared to the cut-off
scale introduced in the cut-off scheme.

2. INTERNAL STRUCTURE OF $\Lambda(1405)$

In chiral unitary approach, $\Lambda(1405)$ is dynamically generated in the meson-baryon coupled-channels amplitude $T_{ij}$ with the channel indices $i$ and $j$. In order to observe response of the $\Lambda(1405)$ state with respect to the conserved probe current, we evaluate current-coupled scattering amplitude $T^\mu_{ij}$ in a charge conserved way, considering current couplings to the constituent hadrons [13]. Then the form factor, $F^\mu (Q^2)$, can be extracted by [11, 14],

$$F^\mu (Q^2) = -\frac{(z' - Z_R)T^\mu_{ij}(z', z; Q^2)}{T_{ij}(z)} \Bigg|_{z \to Z_R, z' \to Z_R},$$

where $Q^2$ is squared current momentum, $z^{(i)}$ center-of-mass energy in complex plane, and $Z_R$ the $\Lambda(1405)$ pole position. The details of the calculation are given in Ref. [11].

Now let us show numerical results for the internal structure of the resonant $\Lambda(1405)$. First, in order to pin down the dominant component of the $\Lambda(1405)$ structure we evaluate the values of the baryonic and strangeness form factors at $Q^2 = 0$ with various components of $\Lambda(1405)$, which correspond to individual contributions from meson-baryon channels and contact term to the baryon number and strangeness of the system. As a result, we find that the $\bar{K}N(I = 0)$ channel generates $0.994 + 0.048i$ of the baryonic and (opposite sign of) strangeness charges of $\Lambda(1405)$, which is unity, whereas the other components such as $\pi\Sigma(I = 0)$ channel are negligibly small [11]. This result indicates that the $\bar{K}N(I = 0)$ channel dominates the total baryonic and strangeness charges of $\Lambda(1405)$, giving more than 99% of the charges. The $\bar{K}N$ channel dominance for the $\Lambda(1405)$ structure is caused by the large coupling strength of $\Lambda(1405)$ to $\bar{K}N$, $g_{\bar{K}N}$.

Next we show the meson-baryon components of the electric, baryonic, and strangeness density distributions ($P_E$, $P_B$, and $P_S$, respectively) in Fig. 1. Here $P_S$ is presented with opposite sign for comparison. From $P_E$, we can see that the negative...
(positive) charge distribution appears in Λ(1405) due to the existence of lighter K− (heavier p) in the outside (inside) region, bearing in mind the ¯KNN dominance for Λ(1405). Also it is interesting to see the dumping oscillation in π−Σ− (equivalently π−Σ+ with the opposite sign) component in PE, which can be interpreted as the decay of the system into the πΣ channels through the photon coupling to the intermediate π, as discussed in Ref. [11]. This oscillation behavior is, however, not observed in the total electric density distribution due to the cancellation of π+Σ− and π−Σ+ components. From PB and PS, on the other hand, we can separately observe the ¯K and N components inside Λ(1405), because the baryonic (strangeness) current probes the N (¯K) distribution. These distributions indicate that inside Λ(1405) the ¯K component has longer tail than the N component and ¯K distribution largely exceeds typical hadronic size ≲ 1 fm.

3. SUMMARY
We have investigated the internal structure of the resonant Λ(1405) state in the chiral unitary approach, in which Λ(1405) is dynamically generated in meson-baryon coupled-channels chiral dynamics. Making conserved probe current couple to Λ(1405) in a charge conserved way, we have observed that ¯KN component gives more than 99% of the total baryon number and strangeness of Λ(1405). The electric density distribution has shown that in Λ(1405) lighter K− (heavier p) exists in the outside (inside) region and the escaping πΣ component appears. Also from the baryonic and strangeness density distributions we have found that inside Λ(1405) the ¯K component has longer tail than the N component and ¯K distribution largely exceeds typical hadronic size ≲ 1 fm.

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