CHIRAL DYNAMICS OF THE TWO Λ(1405) STATES

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The Λ(1405) resonance is studied by a chiral unitary approach, in which the resonance is dynamically generated in coupled-channel meson-baryon scattering. Investigating the analytic structure of the scattering amplitudes obtained by the chiral unitary approach, we find two poles around the energies of the Λ(1405) coupling differently to the meson-baryon states. We reach the conclusion that the Λ(1405) resonance seen in experiments is not just one single resonance, but a superposition of these two states.

The Λ(1405) resonance has been a long-standing example of a dynamically generated resonance appearing naturally in scattering theory with coupled meson-baryon channels[1]. Modern chiral formulations of the meson-baryon interaction within unitary frameworks all lead to the generation of this resonance[2,3,4]. Yet, it was shown that in some models one could obtain two poles close to the nominal Λ(1405) resonance, as it was the case within the cloudy bag model[5]. Also, in the investigation of the poles of the scattering matrix within the context of chiral dynamics[3], it was found that there were two poles close to the nominal Λ(1405) resonance both contributing to the $\pi\Sigma$ invariant mass distribution. This was also the case in other works [6]. In this paper, we summarize this important theoretical finding of the two pole structure of Λ(1405) based on Ref. 7.

The Λ(1405) resonance here is described as a dynamically generated object in coupled-channel meson-baryon scattering with $S = -1$ and $I = 0$ within the chiral unitary approach[8]. Respecting the flavor SU(3) symmetry, we consider the octet mesons (π, K, η) and the octet baryons (N, Λ, Σ, Ξ) in the scattering channels. The unitary condition is imposed by summing up a series of relevant diagrams non-perturbatively in a way guided by the well-established procedures in the 60's, such as the N/D method, which are generally expressed in complicated integral equations. The good advantage of our approach is to obtain an analytic solution of the scattering equation under a low energy approximation in which one takes only the s-channel unitarity and limits the model space of the unitary integral to one meson and one baryon states[3]. This is essential to study the resonance structure in detail, since the resonance is expressed as a pole of the scattering amplitude in the second Riemann sheet. The details of the model are given in Refs. 3, 4.

Table 1. Pole positions and couplings to $I = 0$ physical states from Ref. 4.

z_R	$1390 - 66i$		$1426 - 16i$		$1680 - 20i$	
	g_i	$\|g_i\|$	g_i	$\|g_i\|$	g_i	$\|g_i\|$
$\pi\Sigma$	$-2.5 + 1.5i$	2.9	$0.42 + 1.4i$	1.5	$-0.003 + 0.27i$	0.27
$\bar{K}N$	$1.2 - 1.7i$	2.1	$-2.5 - 0.94i$	2.7	$0.30 - 0.71i$	0.77
$\eta\Lambda$	$0.01 - 0.77i$	0.77	$-1.4 - 0.21i$	1.4	$-1.1 + 0.12i$	1.1
$K\Xi$	$-0.45 + 0.41i$	0.61	$0.11 + 0.33i$	0.35	$3.4 - 0.14i$	3.5

Shown in Table 1 are the positions of the poles in the second Riemann sheet of the scattering amplitude with $S = -1$ and $I = 0$ obtained by the chiral unitary approach[4]. The coupling strengths of the resonances to the meson-baryon states are also obtained as the residues of the amplitude at the pole position. We see that there are two poles around the energies of the $\Lambda(1405)$ showing a different nature of the coupling strength: the lower resonance strongly couples to the $\pi\Sigma$ state, while the higher pole dominantly couples to the $\bar{K}N$ state.

Let us see how these two poles appear in the physical observable using a toy model in which amplitudes are described by the sum of two Breit-Wigner formulae corresponding to two resonances, R_1 and R_2, such that:

$$g^{R_1}_{\pi\Sigma}\frac{1}{W - M_{R_1} + i\Gamma_{R_1}/2}g^{R_1}_{\pi\Sigma} + g^{R_2}_{\pi\Sigma}\frac{1}{W - M_{R_2} + i\Gamma_{R_2}/2}g^{R_2}_{\pi\Sigma}\ , \qquad (1)$$

$$g^{R_1}_{\bar{K}N}\frac{1}{W - M_{R_1} + i\Gamma_{R_1}/2}g^{R_1}_{\pi\Sigma} + g^{R_2}_{\bar{K}N}\frac{1}{W - M_{R_2} + i\Gamma_{R_2}/2}g^{R_2}_{\pi\Sigma}\ , \qquad (2)$$

where the resonance parameters have been taken from Table 1. The former amplitude corresponds to the process $\pi\Sigma \to \pi\Sigma$ and the later does to $\bar{K}N \to \pi\Sigma$. Shown in Fig. 1 is the modulus square of these two amplitudes multiplied by the $\pi\Sigma$ momentum as a function of the energy. We also show the contribution of each resonance by itself (dotted and dashed lines). In

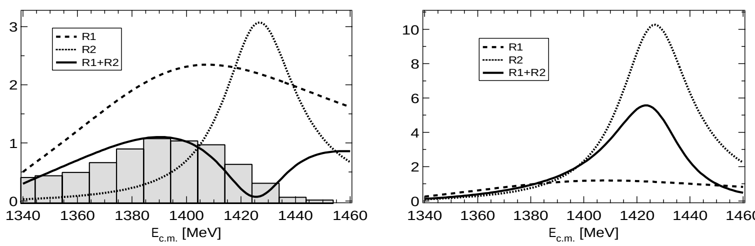

Figure 1. The $\pi\Sigma$ mass distributions calculated from the toy model in Eq. (1) for $\pi\Sigma \to \pi\Sigma$ (left panel) and Eq. (2) for $\bar{K}N \to \pi\Sigma$ (right panel). The dashed, dotted and solid lines denote the contributions from the first term, the second term and the coherent sum of the two terms, respectively. The histogram in the left panel shows experimental data[9]. Units are arbitrary.

both cases only one resonant shape (solid line) is seen, but the simulated $T_{\pi\Sigma\to\pi\Sigma}$ amplitude in the left panel of Fig. 1 produces a resonance at a lower energy and with a larger width. This case reproduces very well the nominal experimental $\Lambda(1405)$. However, if the invariant mass distribution of the $\pi\Sigma$ states were dominated by the $\bar{K}N \to \pi\Sigma$ amplitude, then the second resonance R_2 would be weighted more, since it has a stronger coupling to the $\bar{K}N$ state, resulting into an apparent narrower resonance peaking at higher energies as shown in the right panel of Fig. 1.

The existence of the two pole is strongly related to the flavor symmetry. The underlying SU(3) structure of the chiral Lagrangians implies that a singlet and two octets of dynamically generated resonances should appear, to which the $\Lambda(1670)$ and the $\Sigma(1620)$ would belong[4], and that the two octets get degenerate in the case of exact SU(3) symmetry. In the physical limit, the SU(3) breaking resolves the degeneracy of the octets, and, as a consequence, one of them appears quite close to the singlet pole around energies of the $\Lambda(1405)$ resonance.

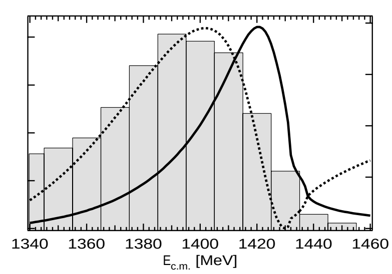

Figure 2. The $\pi\Sigma$ mass distributions with $I = 0$ constructed from the $\pi\Sigma \to \pi\Sigma$ (dotted lile) and $\bar{K}N \to \pi\Sigma$ (solid line) amplitudes obtained by the chiral unitary approach. The histogram shows experimental data[9]. Units are arbitrary.

The double pole structure of $\Lambda(1405)$ found here should be confirmed by new experiments. Clearly a reaction which forces the initial channel to be $\bar{K}N$ produces a different distribution with a narrower peak at higher energy than the original distribution observed in the $\pi\Sigma \to \pi\Sigma$ channel, since the former reaction gives more weight to the second resonance as shown in Fig. 2, where we show the $\pi\Sigma$ mass distributions with $I = 0$ initiated by the $\pi\Sigma$ (dotted line) and $\bar{K}N$ (solid line) states in the chiral unitary approach[4]. One problem here is that one cannot access the second resonance directly from the $\bar{K}N$ scattering, since the resonance lies below the threshold of the $\bar{K}N$ state. Therefore one has to lose energy of the $\bar{K}N$ state before the creation of the resonance. One possibility is to have the $\bar{K}$ lose some energy by emitting a photon, as done in Ref. 10 in the study of the $K^- p \to \gamma\Lambda(1405)$ reaction. Another possibility is provided in Ref. 11, where the photo-induced K^* production on proton has been discussed, and this process has been found suitable to isolate the second resonance.

In conclusion, the chiral unitary approach suggests that two resonances are dynamically generated around energies of the nominal $\Lambda(1405)$. Since they are located very close to each other, what one sees in experiments is a superposition of these two states. The existence of the two poles can be found out by performing different experiments of the creation of the $\Lambda(1405)$ initiated by the $\bar{K}N$ state. If one could confirm the double pole structure, it would be one of the strong indications that the structure of the $\Lambda(1405)$ is largely dominated by a quasibound meson-baryon component.

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