101. Pole Structure of the $\Lambda(1405)$ Region

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The $\Lambda(1405)$ resonance emerges in the meson-baryon scattering amplitude with the strangeness $S = -1$ and isospin $I = 0$. It is the archetype of what is called a dynamically generated resonance, as pioneered by Dalitz and Tuan [1]. The most powerful and systematic approach for the low-energy regime of the strong interactions is chiral perturbation theory (ChPT), see e.g. Ref. 2. A perturbative calculation is, however, not applicable to this sector because of the existence of the $\Lambda(1405)$ just below the $\bar{K}N$ threshold. In this case, ChPT has to be combined with a non-perturbative resummation technique, just as in the case of the nuclear forces. By solving the Lippmann-Schwinger equation with the interaction kernel determined by ChPT and using a particular regularization, in Ref. 3 a successful description of the low-energy K^-p scattering data as well as the mass distribution of the $\Lambda(1405)$ was achieved (for further developments, see Ref. 4 and references therein).

The study of the pole structure was initiated by Ref. 5, which finds two poles of the scattering amplitude in the complex energy plane between the $\bar{K}N$ and $\pi\Sigma$ thresholds. The spectrum in experiments exhibits one effective resonance shape, while the existence of two poles results in the reaction-dependent lineshape [6]. The origin of this two-pole structure is attributed to the two attractive channels of the leading order interaction in the SU(3) basis (singlet and octet) [6] and in the isospin basis ($\bar{K}N$ and $\pi\Sigma$) [7]. It is remarkable that the sign and the strength of the leading order interaction is determined by a low-energy theorem of chiral symmetry, i.e. the so-called Weinberg-Tomozawa term. The two-pole nature of the $\Lambda(1405)$ is qualitatively different from the case of the N(1440) resonance. Two poles of the N(1440) appear on different Riemann sheets of the complex energy plane separated by the $\pi\Delta$ branch point. These poles reflect a single state, with a nearby pole and a more distant shadow pole. In contrast, the two poles in the $\Lambda(1405)$ region on the same Riemann sheet (where $\pi\Sigma$ channels are unphysical and all other channels physical, correspondingly to the one, connected to the real axis beween the $\pi\Sigma$ and $\bar{K}N$ thresholds) are generated from two attractive forces mentioned above [6,7].

Recently, various new experimental results on the $\Lambda(1405)$ have become available [4]. Among these, the most striking measurement is the precise determination of the energy shift and width of kaonic hydrogen by the SIDDHARTA collaboration [8,9], which provides a quantitative and stringent constraint on the K^-p amplitude at threshold through the improved Deser formula [10]. Systematic studies with error analyses based on the next-to-leading order ChPT interaction including the SIDDHARTA constraint have been performed by various groups [11–15]. . All these studies confirm that the new kaonic hydrogen data are compatible with the scattering data above threshold.

The results of the pole positions of $\Lambda(1405)$ in the various approaches are summarized in Table 101.1. We may regard the difference among the calculations as a systematic error, which stems from the various approximations of the Bethe-Salpeter equation, the fitting procedure, and also the inclusion of SU(3) breaking effects such as the choice of the various meson decay constants, and so on. A detailed comparison of the various approaches that enter the table is given in Ref. 16. A recent analysis including also the

$J^P = 1/2^+$ P-wave contribution (and also an explicit $\Sigma(1385)$ $3/2^+$ state) gives results consistent with the findings reported above, with the pole positions at $(1364 - i43)$ MeV and $(1430 - i15)$ MeV, respectively [17].

The main component for the $\Lambda(1405)$ is the pole 1, whose position converges within a relatively small region near the $\bar{K}N$ threshold. On the other hand, the position of the pole 2 shows a sizeable scatter. Detailed studies of the $\pi\Sigma$ spectrum in various reaction processes, together with the precise experimental lineshape (see e.g. the recent precise photoproduction data from the LEPS collaboration [18] and from the CLAS collaboration [19,20], electroproduction data from the CLAS collaboration [21], and proton-proton collision data from COSY [22] and the HADES collaboration [23]) , will shed light on the position of the second pole. The $\pi\Sigma$ spectra from the CLAS data are analyzed in Ref. 24 and Ref. 15. It was shown in Ref. 15 that several solutions, which agree with the scattering data, are ruled out if confronted with the recent CLAS data. The remaining solutions are collected as solution #2 and solution #4 in Table 101.1. The HADES data are analyzed in Ref. 25 and Ref. 26. Although the result of the pole found in Ref. 25 is not compatible with other results, the authors of Ref. 26 invoke the anomalous triangle singularity mechanism to argue that the invariant mass distribution of the $\pi\Sigma$ system is found at lower masses than in other reactions. It is thus desirable to perform more comprehensive analyses of $\pi\Sigma$ spectra together with the systematic error analysis of the scattering data.

Table 101.1: Comparison of the pole positions of $\Lambda(1405)$ in the complex energy plane from next-to-leading order chiral unitary coupled-channel approaches including the SIDDHARTA constraint. The lower two results also include the CLAS photoproduction data.

approach	pole 1 [MeV]	pole 2 [MeV]
Refs. 11,12, NLO	$1424^{+7}_{-23} - i\ 26^{+3}_{-14}$	$1381^{+18}_{-6} - i\ 81^{+19}_{-8}$
Ref. 14, Fit II	$1421^{+3}_{-2} - i\ 19^{+8}_{-5}$	$1388^{+9}_{-9} - i\ 114^{+24}_{-25}$
Ref. 15, solution #2	$1434^{+2}_{-2} - i\ 10^{+2}_{-1}$	$1330^{+4}_{-5} - i\ 56^{+17}_{-11}$
Ref. 15, solution #4	$1429^{+8}_{-7} - i\ 12^{+2}_{-3}$	$1325^{+15}_{-15} - i\ 90^{+12}_{-18}$

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