83. 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. [4–7] and references therein).

The study of the pole structure was initiated by Ref. [8], 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 [9]. 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) [9] and in the isospin basis ($\bar{K}N$ and $\pi\Sigma$) [10]. 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 [9, 10].

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 [11, 12], which provides a quantitative and stringent constraint on the K^-p amplitude at threshold through the improved Deser formula [13]. Systematic studies with error analyses based on the next-to-leading order ChPT interaction including the SIDDHARTA constraint have been performed by various groups [14–18] 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 83.1. 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. [19]. 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 [20].

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 [21] and from the CLAS collaboration [22, 23], electroproduction data from the CLAS collaboration [24], and proton-proton collision data from COSY [25] and the HADES collaboration [26]), will shed light on the position of the second pole. The $\pi\Sigma$ spectra from the CLAS data are analyzed in Ref. [27] and Ref. [18]. It was shown in Ref. [18] 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 83.1. The HADES data are analyzed in Ref. [28] and Ref [29]. Although the result of the pole found in Ref. [28] is not compatible with other results, the authors of Ref. [29] 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 83.1: 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. [14, 15], NLO	$1424^{+7}_{-23} - i\ 26^{+3}_{-14}$	$1381^{+18}_{-6} - i\ 81^{+19}_{-8}$
Ref. [17], Fit II	$1421^{+3}_{-2} - i\ 19^{+8}_{-5}$	$1388^{+9}_{-9} - i\ 114^{+24}_{-25}$
Ref. [18], solution #2	$1434^{+2}_{-2} - i\ 10^{+2}_{-1}$	$1330^{+4}_{-5} - i\ 56^{+17}_{-11}$
Ref. [18], solution #4	$1429^{+8}_{-7} - i\ 12^{+2}_{-3}$	$1325^{+15}_{-15} - i\ 90^{+12}_{-18}$

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