

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

Revised June 2021 by T. Hyodo (Tokyo Metropolitan U.) and U.-G. Meißner (Bonn U.; Jülich).

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

References

- [1] R. Dalitz and S. Tuan, *Phys. Rev. Lett.* **2**, 425 (1959).
- [2] V. Bernard, N. Kaiser and U.-G. Meißner, *Int. J. Mod. Phys. E* **4**, 193 (1995), [[hep-ph/9501384](#)].
- [3] N. Kaiser, P. Siegel and W. Weise, *Nucl. Phys. A* **594**, 325 (1995), [[arXiv:nucl-th/9505043](#)].
- [4] T. Hyodo and D. Jido, *Prog. Part. Nucl. Phys.* **67**, 55 (2012), [[arXiv:1104.4474](#)].
- [5] U.-G. Meißner, *Symmetry* **12**, 6, 981 (2020), [[arXiv:2005.06909](#)].
- [6] M. Mai, *Eur. Phys. J. ST* **230**, 6, 1593 (2021), [[arXiv:2010.00056](#)].
- [7] T. Hyodo and M. Niiyama, *Prog. Part. Nucl. Phys.* **120**, 103868 (2021), [[arXiv:2010.07592](#)].
- [8] J. Oller and U.-G. Meißner, *Phys. Lett. B* **500**, 263 (2001), [[hep-ph/0011146](#)].
- [9] D. Jido *et al.*, *Nucl. Phys. A* **725**, 181 (2003), [[arXiv:nucl-th/0303062](#)].
- [10] T. Hyodo and W. Weise, *Phys. Rev. C* **77**, 035204 (2008), [[arXiv:0712.1613](#)].
- [11] M. Bazzi *et al.* (SIDDHARTA), *Phys. Lett. B* **704**, 113 (2011), [[arXiv:1105.3090](#)].
- [12] M. Bazzi *et al.* (SIDDHARTA), *Nucl. Phys. A* **881**, 88 (2012), [[arXiv:1201.4635](#)].
- [13] U.-G. Meißner, U. Raha and A. Rusetsky, *Eur. Phys. J. C* **35**, 349 (2004), [[hep-ph/0402261](#)].
- [14] Y. Ikeda, T. Hyodo and W. Weise, *Phys. Lett. B* **706**, 63 (2011), [[arXiv:1109.3005](#)].
- [15] Y. Ikeda, T. Hyodo and W. Weise, *Nucl. Phys. A* **881**, 98 (2012), [[arXiv:1201.6549](#)].
- [16] M. Mai and U.-G. Meißner, *Nucl. Phys. A* **900**, 51 (2013), [[arXiv:1202.2030](#)].
- [17] Z.-H. Guo and J. Oller, *Phys. Rev. C* **87**, 3, 035202 (2013), [[arXiv:1210.3485](#)].
- [18] M. Mai and U.-G. Meißner, *Eur. Phys. J. A* **51**, 3, 30 (2015), [[arXiv:1411.7884](#)].

- [19] A. Cieplý *et al.*, Nucl. Phys. A **954**, 17 (2016), [arXiv:1603.02531].
- [20] D. Sadasivan, M. Mai and M. Döring, Phys. Lett. B **789**, 329 (2019), [arXiv:1805.04534].
- [21] M. Niiyama *et al.*, Phys. Rev. C **78**, 035202 (2008), [arXiv:0805.4051].
- [22] K. Moriya *et al.* (CLAS), Phys. Rev. C **87**, 3, 035206 (2013), [arXiv:1301.5000].
- [23] K. Moriya *et al.* (CLAS), Phys. Rev. Lett. **112**, 8, 082004 (2014), [arXiv:1402.2296].
- [24] H. Lu *et al.* (CLAS), Phys. Rev. C **88**, 045202 (2013), [arXiv:1307.4411].
- [25] I. Zychor *et al.*, Phys. Lett. B **660**, 167 (2008), [arXiv:0705.1039].
- [26] G. Agakishiev *et al.* (HADES), Phys. Rev. C **87**, 025201 (2013), [arXiv:1208.0205].
- [27] L. Roca and E. Oset, Phys. Rev. C **87**, 5, 055201 (2013), [arXiv:1301.5741].
- [28] M. Hassanvand *et al.*, Phys. Rev. C **87**, 5, 055202 (2013), [Addendum: Phys.Rev.C 88, 019905 (2013)], [arXiv:1210.7725].
- [29] M. Bayar *et al.*, Phys. Rev. C **97**, 3, 035203 (2018), [arXiv:1710.03964].