On the nature of the $\Lambda(1405)$ as a superposition of two states.

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Abstract

We use recent data on the $K^- p \rightarrow \pi^0\pi^0\Sigma^0$ reaction with the $\pi^0\Sigma^0$ mass distribution of forming the $\Lambda(1405)$ with a peak at 1420 MeV and a relatively narrow width of $\Gamma = 38$ MeV, together with those of the $\pi^- p \rightarrow K^0\pi\Sigma$ reaction to show that there are two $\Lambda(1405)$ states instead of one as so far assumed.

The $\Lambda(1405)$ has been described as a dynamical resonance generated from the interaction of meson baryon components in coupled channels by means of unitary extensions of chiral perturbation theory ($U\chi PT$) [1, 2, 3, 4, 5]. The surprise, however, came with the realization that there are two poles in the neighborhood of the $\Lambda(1405)$ both contributing to the final experimental invariant mass distribution [3, 4, 5, 6, 7, 8, 9]. The properties of these two states are quite different, one has a mass around 1390 MeV, a large width of about 130 MeV and couples mostly to $\pi\Sigma$, while the second one has a mass around 1425 MeV, a narrow
width of about 30 MeV and couples mostly to $\bar{K}N$. The two states are populated with different weights in different reactions and, hence, their superposition can lead to different distribution shapes. Since the $\Lambda(1405)$ resonance is always seen from the invariant mass of its only strong decay channel, the $\pi\Sigma$, hopes to see the second pole are tied to having a reaction where the $\Lambda(1405)$ is formed from the $\bar{K}N$ channel. This is accomplished by the recently measured reaction $K^-p \rightarrow \pi^0\pi^0\Sigma^0$ which allows us to test already the two-pole nature of the $\Lambda(1405)$.

![Diagram of nucleon pole term for the $K^-p \rightarrow \pi^0\pi^0\Sigma$ reaction.](image)

Figure 1: Nucleon pole term for the $K^-p \rightarrow \pi^0\pi^0\Sigma$ reaction.

Our model for the reaction $K^-p \rightarrow \pi^0\pi^0\Sigma^0$ in the energy region of $p_{K^-} = 514$ to 750 MeV/c, as in the experiment [10], considers those mechanisms in which a $\pi^0$ loses the necessary energy to allow the remaining $\pi^0\Sigma^0$ pair to be on top of the $\Lambda(1405)$ resonance. The first of such mechanisms is given by the diagram of Fig. 1. Other mechanisms that involve the meson meson interaction and baryon-baryon-three meson vertices were found negligible in the detailed study of [11].

![Invariant mass distribution plots for three different initial kaon momenta.](image)

Figure 2: The $\pi^0\Sigma^0$ invariant mass distribution for three different initial kaon momenta.

The indistinguishability of the two emitted pions requires the implementation of symmetrization. This is achieved by summing two amplitudes evaluated with the two pion mo-
menta exchanged. In addition, a factor of 1/2 for indistinguishable particles is also included in the total cross section.

Our calculations show that the process is largely dominated by the nucleon pole term shown in Fig. 1. As a consequence, the Λ(1405) thus obtained comes mainly from the $K^- p \to \pi^0 \Sigma^0$ amplitude which, as mentioned above, gives the largest possible weight to the second (narrower) state.

![Figure 3](image-url)

**Figure 3:** Two experimental shapes of Λ(1405) resonance. See text for more details.

In Fig. 2 our results for the invariant mass distribution for three different energies of the incoming $K^-$ are compared to the experimental data. Symmetrization of the amplitudes produces a sizable amount of background. At a kaon laboratory momentum of $p_K = 581$ MeV/c this background distorts the Λ(1405) shape producing cross section in the lower part of $M_I$, while at $p_K = 714$ MeV/c the strength of this background is shifted toward the higher $M_I$ region. An ideal situation is found for momenta around 687 MeV/c, where the background sits below the Λ(1405) peak distorting its shape minimally. The peak of the resonance shows up at $M_I^2 = 2.02$ GeV$^2$ which corresponds to $M_I = 1420$ MeV, larger than the nominal Λ(1405), and in agreement with the predictions of Ref. [6] for the location of the peak when the process is dominated by the $t_{KN} \to \pi \Sigma$ amplitude. The apparent width from experiment is about 40 – 45 MeV, but a theoretical analysis permits extracting the pure resonant part by not symmetrizing the amplitude [11] and one finds $\Gamma = 38$ MeV. This is smaller than the nominal Λ(1405) width of $50 \pm 2$ MeV [13], obtained from the average of several experiments, and much narrower than the apparent width of about 60 MeV that
one sees in the $\pi^- p \rightarrow K^0 \pi \Sigma$ experiment \cite{14}, which also produces a distribution peaked at 1395 MeV. In order to illustrate the difference between the $\Lambda(1405)$ resonance seen in this latter reaction and in the present one, the two experimental distributions are compared in Fig. 3. We recall that the shape of the $\Lambda(1405)$ in the $\pi^- p \rightarrow K^0 \pi \Sigma$ reaction was shown in Ref. \cite{12} to be largely built from the $\pi \Sigma \rightarrow \pi \Sigma$ amplitude, which is dominated by the wider lower energy state.

The invariant mass distributions shown here are not normalized, as in experiment. But we can also compare our absolute values of the total cross sections with those in Ref. \cite{10}. This is done in Ref. \cite{11} and the agreement is good.

The study of the present reaction, complementary to the one of Ref. \cite{12} for the $\pi^- p \rightarrow K^0 \pi \Sigma$ reaction, has shown that the quite different shapes of the $\Lambda(1405)$ resonance seen in these experiments can be interpreted in favour of the existence of two poles with the characteristics predicted by the chiral theoretical calculations. Besides demonstrating once more the great predictive power of the chiral unitary theories, this combined study of the two reactions gives the first clear evidence of the two-pole nature of the $\Lambda(1405)$.

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