Direct measurement of the $\bar{K}N \to \pi\Sigma$ scattering amplitude below the $\bar{K}N$ threshold employing the $d(K^-, N)$"$\pi\Sigma$" reaction

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November 2, 2022

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Chapter 1

Introduction

1.1 Discovery of the $\Lambda(1405)$

The $\Lambda(1405)$ is a hyperon resonance state with strangeness $S = -1$, isospin $I = 0$ spin-parity $J^P = \frac{1}{2}^-$. This resonance state was first predicted by Dalitz and Tuan [1] in 1959. They analyzed the $\bar{K}N$ scattering data and found that the $I = 0$ $\bar{K}N$ scattering amplitude has a resonance pole below the $\bar{K}N$ mass threshold. They suggested that this resonance pole is a bound state of $\bar{K}N$ [3]. Later, $\Lambda(1405)$ was first reported in a hydrogen bubble chamber experiment at the Lawrence Radiation Laboratory: the $K^-p \rightarrow \Sigma\pi\pi\pi$ reaction with a K^- beam of 1.15GeV/c.

A high-statistics generation experiment of $\Lambda(1405)$ was performed at CERN [4]. In this experiment, $K^-p \rightarrow \Sigma^+(1660)\pi^- \rightarrow \Lambda(1405)\pi^+\pi^-$ reaction was measured using a 4.2GeV/c K^- beam. Dalitz and Deloff deduced mass $M = 1406.5 \pm 4.0$ MeV/c^2 and width $\Gamma = 50 \pm 2.0$ MeV/c^2 of $\Lambda(1405)$ from fitting of this data. In the latest Particle Data Group, the mass of $Lambda(1405)$ was determined to be $M = 1405.1^{+1.3}_{-1.0}$MeV/c^2 and $Gamma = 50$GeV/c^2 from these analyses. This method of analysis is called the phenomenological method.

1.2 Recent situation of $\Lambda(1405)$

Wise et al. confirmed that the $\Lambda(1405)$ resonance pole is located below the $\bar{K}N$ threshold using a chiral Lagrangian with a strangeness $S = -1$ sector [6]. In the 2000's, the chiral unitary model proposed that $\Lambda(1405)$ is a dynamical generated molecular state consisting of two poles [7]. The higher pole is coupled to the $\bar{K}N$ channel, while the lower pole is coupled to the $\pi\sigma$ channel. Therefore, they claim that the pole coupled to $\bar{K}N$ shifts to a higher position than the previously mentioned 1405 MeV/c. This approach is called the chiral unitary approach.

Photoproduction of $\Lambda(1405)$ was performed at LEPS in Spring-8 [8]. In that experiment, the $\gamma p \to K^+\Lambda(1405)$ reaction at $E_\gamma = 1.5 - 2.4$GeV was used to measure the K^+ scattered at $0.8 < \cos\theta_{K^+} < 1.0$. They reported $\pi^+\Sigma^-$ and $\pi^-\Sigma^+$ and ovserved a difference between the two spectra. This fact implies the existence of an interference term between $I = 0$ and $I = 1$, suggesting that $\Lambda(1405)$ is a dynamically generated state.

The CLAS Collaboration reported highly-statistical photoproduction of $\Lambda(1405)$. The spectra of $\pi^-\Sigma^+$, $\pi^0\Sigma^0$, and $\pi^-\Sigma^+$ are measured for total energies $2.55 < W < 2.85$GeV and K^+ scattering angles of $0.6 < \cos\theta_{K^+} < 0.9$ in the center-of-mass frame [9,10]. T. Nakamura et al. reproduced those spectra finely well using the chiral unitary model, although the reaction mechanism is not simple [11]. L. Roca et al. constructed a model with two poles using photonuclear reactions with a potential with free parameters based on the chiral unitary model [12]. They deduced a high pole is located above 1405 MeV/c^2, albeit with many parameters.

HADES Collaboration reported the spectra of $\Lambda(1405) \to \pi^\mp\Sigma^\pm$ using the $pp \to K^+\Lambda(1405)$ reaction with a 1405GeV/c p beam [13]. The peak position of the spectra was located below 1400GeV/c. M. Hassanvand et al. obtained the mass and width of $\Lambda(1405)$ with $M = 1405.1^{+11}_{-9}$MeV/c^2 and $\Gamma = 62 \pm 10$MeV/c^2 by adapting phenomenological analysis [14]. On the other hand, J. Siebenson et al. argue that the data can be reproduced in a two pole structure such as the chiral unitary model [15].

1.3 $\bar{K}N$ interaction and $\Lambda(1405)$

As mentioned before, $\Lambda(1405)$ is closely related to the KN interaction. One way to measure the $\bar{K}N$ interaction on the $\bar{K}N$ threshold is to measure X-rays from Kaonic hydrogen. In this method, the $\bar{K}N$ interaction is determined by measuring the shift of the X-ray emitted from the Kaonic hydrogen from the electromagnetic interaction. The results of this measurement were previously thought to be repulsive, but the E228 experiment performed at KEK-PS by Iwasaki et al. concluded that the interaction is attractive [16].

Then, the SIDDHARTA collaboration performed experiments with higher precision [17]. The results of this experiment were used as a constraint for analyzing $\bar{K}N$ scattering, and the pole position of $\Lambda(1405)$ was deduced by several theorists [18].

1.4 J-PARC E31 experiment and $d(K^-, n)$ reaction

In this situation, direct measurement of $\bar{K}N \to \pi\Sigma$ scattering is desired. But the reaction can not happen in free space due to energy conservation. This reaction using a K^- beam of 644-844MeV/c has been measured at CERN using a bubble chamber and a $K^-d \to n\pi^+\Sigma^-$spectrum has been reported [19]. This spectrum was calculated using the chiral unitary model

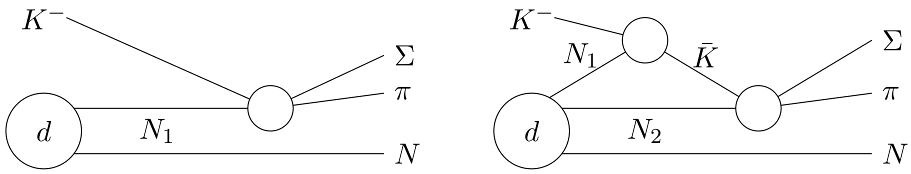

Figure 1.1: Fynman diagrams about $d(K^-, N)$"$\pi\Sigma$" reaction. The left and right figures indicate about 1-step and 2-step reactions, respectively.

and reproduced reasonably well [20, 21]. However, since only the $\pi^+\Sigma^-$ spectrum is reported in this experiment, interference cannot be discussed.

For the reason, we performed the J-PARC E31 experiment [28]. The experimental setup is described in detail in the next chapter.**??**. In this experiment, a 1.0GeV/c K^- beam is irradiated to the deuterium target and the forward scattered nucleons are measured. The final state is then identified as the $\pi\Sigma$ state to confirm that a reaction has occurred in which the backward-scattered $\bar{K}$ mesons have scattered with the remaining nucleons to become $\pi\Sigma$. In this reaction, The momentum transfer near the $\pi\Sigma$ invariant mass near the $\bar{K}N$ threshold is as low as 0.25GeV/c, so the angular momentum transfer becomes small and S-wave scattering is expected to be dominant in the 2-step $\bar{K}N \to \pi\Sigma$ scattering.

In the final state of $\pi\Sigma n$, the 1-step reaction is also considered in which $\pi\Sigma$ is produced by direct scattering with a nucleon. In this case, the emitted nucleon has a Fermi momentum in deuterium < 0.2GeV/c, and all the momentum of the K^- beam is given to $\pi\Sigma$, and its invariant mass appears in the high 1.9GeV/c^2 region. Therefore, the contribution from the 1-step reaction in the region of interest near the $\bar{K}N$ threshold is negligible.

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