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

Kentaro Inoue

March 1, 2023

Contents

Chapter 1

Introduction

1.1 History of the $\Lambda(1405)$

$\Lambda(1405)$ はストレンジネス $S = -1$、アイソスピン $I = 0$、スピンとスピンパリティ $J^P = (1/2)^-$ を含むハイペロンである。最新の粒子データグループ (PDG) [1] では、後述のいくつかの論文 [5] に基づいて、$\Lambda(105)$ の質量と幅はそれぞれ $1405.1^{+1.3}_{-1.0}$MeV と 50.5 ± 2.0MeV に割り当てられています。

$\Lambda(1405)$ の存在は、1959 年に Dalitz と Taun によって $\bar{K}N$ の準結合状態として初めて予言されました [2]。1961 年、ローレンス放射線研究所において、$K^-p \to \Sigma\pi\pi\pi$ 反応を用いた $\Sigma\pi$ スペクトルで $\Lambda(1405)$ 的過剰状態がバブルチャンバーにより観測された [3]。彼らは、$\pi^-\Sigma^-$ や $\pi^+\Sigma^+$ スペクトルの二重荷電スペクトルに対して、中性 $\pi\Sigma$ スペクトルで $\Lambda(1405)$ 的な過剰状態を報告した。Hemingway は，4.2GeV の K^- ビームを用いた水素バブルチェンバーによる $\Lambda(1405)$) の高統計生成に成功したことを報告した [4]。彼らは、$K^-p \to \pi\Sigma(1660) \to \pi\pi\Lambda(1405) \to \pi\pi(\pi\Sigma)$ の反応レンマの同定が $\Lambda(1405)$ の生成を促進したと主張している。

Dalitz and Deloff evaluated the mass and width of the $\Lambda(1405)$ as 1406.4 ± 4.0MeV and 50 ± 2MeV by adapting an M-matrix/K-matrix analysis to $\pi^-\Sigma^+$ spectrum of this data, which has almost no background come from non-resonant and the $\Lambda(1520)$ [5].

In the 2000's, the chiral unitary model claimed that the $\Lambda(1405)$ is a dynamical molecular state contributed from two poles, $\pi\Sigma$ in the low-mass region and $\bar{K}N$ in the high-mass region. According to the this model, the high-mass pole coupled to $\bar{K}N$ is $1426 + 16$MeV and the low-mass pole coupled to $\pi\Sigma$ is $1390+66i$MeV. That means the $\pi\Sigma$ spectrum is expected to shift high mass region from the conventional 1405MeV by directly accessing to the $\bar{K}N$ pole.

Experimentally, the $\Lambda(1405)$ production was also carried out employing various reaction mechanisms. Niiyama et el. performed photoproduction $\gamma p \to K^+\Lambda(1405)$ employing a γ beam at $E_\gamma = 1.5 - 2.4$GeV at the LEPS beamline in the Spring-8 [8]. They measured the scattering angle in center of mass system of K^+ at $0.8 < \Theta_{K^+} < 1.0$, reported mass spectra of $\pi^-\Sigma^+$ and $\pi^+\Sigma^-$ in the $\Lambda(1405) \to \pi\Sigma$ decay and observed a difference between the two spectra in the $\Lambda(1405)$ region. This fact means existance of the interference term between the isospin $I = 0$ and $I = 1$ channel. The CLAS collaboration employing a 1.61-1.91GeV γ beam for photoproduction at the Jefferson Labolatory and measured the scattering angle in center of mass system of K^+ at $0.6 < \Theta_{K^+} < 0.9$ [9, 10]. They reported all three $\pi^-\Sigma^+$, $\pi^+\Sigma^-$ and $\Sigma^0\pi^0$ spectra. The centroid of those three spectra appear to be at 1405MeV, but their lineshapes are different indicating contribution of $I = 1$ strength in this reaction.

The HADES collaboration performed $\Lambda(1405)$ production in p-p collisions using the 3.5GeV/c proton beam [11]. They reported $\pi^-\Sigma^+$, $\pi^+\Sigma^-$ and these average spectra, which clearly show a peak below 1405MeV.

1.2 $\Lambda(1405)$ and the $\bar{K}N$ interaction

As mentionted as before section, the $\Lambda(1405)$ has been predicted as a quasi-bound state of the $\bar{K}N$ state and has been discussed as such. In order words, it is necessaray the information of the $\bar{K}N$ interaction in order to understand the structure of the $\Lambda(1405)$. In the 1960-70's, various $\bar{K}N$ scattering data from K^- beam were measured with the bubble chamber at the CERN [12–16]. These data were included up to 2.1GeV in the center-of-mass frame and were fitted by partial wave analysis. The $\bar{K}N$ scattering amplitudes are well analysed, especially in the high energy region.

Also, one method of measuring the $\bar{K}N$ scattering length at the $\bar{K}N$ threshold is X-ray from kaonic nuclei. In this method, the X-ray shift emitted by the capture of K^- meson by the nuclei is compared with that of the electromagnetic force alone to assess the effect of the strong force. In 1970-80's, some groups reported $\bar{K}N$ interaction is repulsive by X-ray from the kaonic hydrogen at the CERN, which is inconsistent with the scattering experiment. In 1997, Iwasaki et al. reported this negative shift from a high-resolution experiment at KEK-PS E228 and concluded that the $\bar{K}N$ interaction was an attractive force [17]. This result was verified and updated by the DAϕNE collaboration in 2005 and the SIDDAHARTA collaboration in 2011 [18]. The $\bar{K}N$ scattering lengths and effective range obtained by these experiments provide strong constraints on the $\bar{K}N$ scattering amplitude at the $\bar{K}N$ threshold.

Some theoretical groups consistently reproduced the KN scattering amplitude on this constraint and scattering data above the $\bar{K}N$ threshold using various approch based on low energy scattering therm [19–24]. Although, there are large uncertainty due to shortage of the data in low energy region.

1.3 J-PARC E31 experiment

As the situation is described in the previous section, it is desirable to measure $\bar{K}N$ directly scattering amplitudes, especially below the $\bar{K}N$ threshold. However, due to energy conservation laws, kaon and nucleon cannot be directly scattered in free space. Therefore, an experiment using the $d(K^-n)$ reaction was planned and carried out at J-PARC E31 [25]. A similar experiment was carried out at CERN in 1977 using a bubble chamber and reported a spectrum with a peak position shifted to the high mass side above 1405 MeV,albeit only in $\Sigma^-\pi^+$ [26]. This spectrum shape was successfully reproduced by theoretical calculations using the chiral unitary model [28]. It is known that $P-$wave scattering $\Sigma(1385)$ of isospin $I = 1$ exists in the near region. The $\pi\Lambda$ spectrum of $I = 1$ in the same experiment was successfully reproduced by a similar theoretical calculation including $P-$waves scattering [32]. These theoretical calculations assume a 2-step reaction, $K^-p \to \bar{K}N$ scattering in 1 step and $\bar{K}N \to \pi\Sigma$ in 2 step.

In this experiment, due to the low momentum of the K^- beam and the unknown angle of the nucleon knocked out in the first step, some argued that there was a contribution from a reaction in which the K^- beam and nucleon in deuteron were directly converted to $\pi\Sigma$ in the first step reaction and the $\Lambda(1405)$ contribution was unknown.

Therefore, we measured the nucleon knocked out at super-forward angle employing the $d(K^-, n)$ reaction with 1GeV/c K^- beam by the forward detector systems. In the case of a direct reaction between the K^- beam and the nucleon to $\pi\Sigma$, the $\pi\Sigma$ mass is distributed near the kinematic limit ($\sim$ 1.9GeV/c) due to the small Fermi momentum of the nucleon in the deuteron and the energy given by the K^- beam. This means that the contribution from a direct 1-step reaction is negligible. In the case of 2-step reaction, the $\bar{K}N \to \pi\Sigma$ scattering of the second step can be accessed to below the $\bar{K}N$ threshold due to the virtual particle of recoiled $\bar{K}$ between the first and second steps. In addition, the momentum transfer is small due to the small momentum of the recoiled $\bar{K}$, and the second scattering is expected to enhance $S-$wave scattering against $P-$wave, $D-$waves and so on.

Also, previous experiment reported about $\pi^+\Sigma^-$ and $\pi^-\Lambda$ spectra for $I = 0$ and $I = 1$, respectively. Hence, it was not possible to decompose the isospin for these spectra and discuss the contribution of each isospin, in particular the contribution of the $I = 0$ and $I = 1$ interference term. We identified the final state and decay modes by measuring decay particles from produced hyperons by the cryndrical detectors system srounding the liquid deuterium target and performed isospin decomposition on the obtained spectra.

Since the J-PARC E31 experiment was proposed, theoretical $\pi\Sigma$ spectra were reported using various KN interactions and kinematics. Onishi et al.

reported the $\pi^-\Sigma^+, \pi^0\Sigma^0$ and $\pi^+\Sigma^-$ spectrum from a full three-body calculation using two types of$\bar{K}N$N interactions, whose one is an effective theory of $\mathbf{SU}(3)$ fields, called the energy-dependent model, and the other is a phenomenological potential, called the energy-independent model [29]. Miyagawa et al. reported spectra contracted from two subsystems, $\bar{K}N \to \bar{K}N$ and KN $\bar{K}N \to \pi\Sigma$. The first step $\bar{K}N \to \bar{K}N$ interaction was used on the basis of recent partial wave analysis as it has a large K^- beam momentum. On the other hand, the second step $\bar{K}N \to \pi\Sigma$ interaction was used based on various results from the chiral unitary model, a low-energy scattering theory.

Chapter 2

Experimental setup

Chapter 3

Analysis

Chapter 4

Discussion and conclusion

Appendix A

Appendix Title.1

Appendix B

Appendix Title.2

Bibliography

[1] R.L. Workman et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01 (2022)
"Review of Particle Physics"

[2] R. H. Dalitz and S. F. Tuan, Phys. Rev. Lett. 2 (1959).
"Possible Resonant State in Pion-Hyperon Scattering"

[3] M. H. Alston, L. W. Alvarez, P. Eberhard and M. L. Good, Phys. Rev. Lett. 6, 698 (1961).
"Study of Resonances of the $\Sigma - \pi$ System"

[4] R. J. Hemingway, Nucl Phys B **253**, 742 (1985).
"Production of $\Lambda(1405)$ in $K^{-}p$ Reactions at 4.2GeV/c"

[5] R. H. Dalitz and A. Deloff, J. Phys. G17, 281 (1991).
"The Shape and Parameters of the $\Lambda(1405)$ Resonance"

[6] N.KaiserP.B.Siegel and W.Weise, Nucl Phys A **594**, 325 (1995).
"Chiral Dynamics and the Low-Energy Kaon-Nucleon Interaction"

[7] D. Jido et el., Nucl. Phys. A **725**, 181 (2003).
"Chiral Dynamics of the Two $\Lambda(1405)$ States"

[8] M. Niiyama et el., Phys. Rev. C **78**, 035202 (2008).
"Photoproduction of $\Lambda(1405)$ and $\Sigma(1385)$ on the proton at $E_{\gamma} = 1.5$-2.4GeV/c"

[9] K. Moria for the CLAS Collaboration, Phys. Rev. C **87**, 035206 (2013).
"Measurement of the $\pi\Sigma$ photoproduction line shapes near the $\Lambda(1405)$"

[10] K. Moria for the CLAS Collaboration, Phys. Rev. Lett. **112**, 082004 (2014).
"Spin and parity measurement of the $\Lambda(1405)$ baryon"

[11] G. Agakishiev for the HADES Collaboration, Phys. Rev C **87**, 025201 (2013).

"Baryonic Resonances to the $\bar{K}N$ threshold: The case of $\Lambda(1405)$ in pp collisions"

[12] B. Conforto et el., Nucl. Phys. B **34**, 41 (1971).
"New experimental results on the Reactions $K^-p \to \bar{K}N$ and $K^-p \to \Sigma\pi$ a partial-wave analysis between 430 and 800MeV/c"

[13] A. J. Van Horn, Nucl. Phys. B **87**, 145 (1975).
"Energy dependent partial-wave analysis of $K^-p \to \Lambda\pi^0$ between1540 and 2215MeV"

[14] R. J. Hemingway et el., Nucl. Phys. B **91**, 12 (1975).
"New data on $K^-p \to K^-p$ and K^0n and a partial-wave analysis between 1840 and 2234MeV center of mass energy"

[15] P. Baillon and P. J. Litchfield, Nucl. Phys. B **94**, 39 (1975).
"Energy-independent partial-wave analysis of $\bar{K}N \to \Lambda\pi$ between 1540 and 2150 MeV"

[16] G. P. Gopal et al., Nucl. Phys. B **119**, 362 (1977).
"Partial-wave analyses of KN two-body reactions between 1480 and 2170 MeV"

[17] M. Iwasaki et el., Phys. Rev. Lett. **78**, 3067 (1997).
"Observation of Kaonic Hydrogen K_α X Rays"

[18] M. Bazzi et el., Phys. Lett. B **704**, 113 (2011).
"A New Measuerment of Kaonic Hydrogen X-Rays"

[19] Y. Ikeda, T. Hyodo and W. Weise, Phys. Lett. B **706**, 63 (2011)
"Improved constraints on chiral $\mathbf{SU}(3)$ dynamics from kaonic hydrogen"

[20] Y. Ikeda, T. Hyodo and W. Weise, Nucl. Phys. A **881**, 98 (2012)
"Chiral $\mathbf{SU}(3)$ theory of antikaon–nucleon interactions with improved threshold constraints"

[21] M. Mai and U.-G. Meiβner, Nucl. Phys. A **900**, 51 (2013)
"New insights into antikaon–nucleon scattering and the structure of the $\Lambda(1405)$"

[22] Z.-H. Guo and J. Oller, Phys. Rev. C **87**, 3, 035202 (2013),
"Meson-baryon reactions with strangeness -1 within a chiral framework"

[23] M. Mai and U.-G. Meiβner, Eur. Phys. J. A **51**, 3, 30 (2015),
"Constraints on the chiral unitary $\bar{K}N$ amplitude from $\pi\Sigma K^*$ photoproduction data"

[24] A. Cieplý et al., Nucl. Phys. A 954, 17 (2016),
"On the pole content of coupled channels chiral approaches used for the $\bar{K}N$ system"

[25] H. Noumi et el., Proposals for the 15th PAC meeting
"Spectroscopic study of hyperon resonances below $\bar{K}N$ threshold via the (K^{-}, n) reaction on Deuteron"

[26] O. Braun et el., Nucl. Phys. B **129**, 1 (1977).
"New Information About the Kaon-Nucleon-Hyperon Coupling Constants $g(KN\Sigma(1197)), g(KN\Sigma(1385))$ and $g(KN\Lambda(1405))$"

[27] T. Hyodo and U.-G. Meiβner, PDG Review, Tables and Plots, Section.83
"Pole Structure of the $\Lambda(1405)$ Region"

[28] D. Jido, E. Oset and T. Sekihara, Eur. Phys. J. A **42**, 257 (2009).
"Kaonic Production of $\Lambda(1405)$ off deuteron target in chiral dynamics"

[29] S. Ohnishi et el, Phys. Rev. C **93**, 025207 (2016).
"Strcture of the $\Lambda(1405)$ and the $K^{-}d \to \pi\Sigma n$ reaction"

[30] M. Hassanvand et el., Phys. Rev. C **87**, 055202 (2013)
"Theoretical analysis of $\Lambda(1405) \to (\pi\Sigma)^{0}$ mass spectra produced in $p + p \to p + \Lambda(1405) + p$ reactions"

[31] J. Siebenson and L. Fabbietti, Phys. Rev. C **88**, 055201 (2013)
"Investigation of the $\Lambda(1405)$ line shape observed in pp collisions"

[32] J. Yamagata-Sekihara, T. Sekihara, and D. Jido, Prog. Theor. Exp. Phys.**2013**, 043D02 (2013).
"Production of hyperon resonances induced by kaons on a deuteron target"

[33] A. D. Martin, Nucl. Phys. B **179**, 33 (1981).
"Kaon-Nucleon Parameters"

[34] J. D. Davies et el., Phys. Lett. B **83**, 55 (1979).
"Obserbation of Kaonic Hydrogen Atom X-rays"

[35] M. Izychi et el., Z. Phys. A **297**, 11 (1980).
"Results of the Search for K-series X-rays from Kaonic Hydrogen"

[36] H. Zhang et el., Phys. Rev. C **88**, 035204 (2013).
"Partial-wave analysis of $\bar{K}N$ scattering reactions"

[37] H. Zhang et el., Phys. Rev. C **88**, 035205 (2013).
"Multichannel parametrization of $\bar{K}N$ scattering amplitudes and extraction of resonance parameters"

[38] P. M. Bird et el., Nucl. Phys. A **404**, 482 (1983).
"Kaonic Hydrogen Atom X-rays"

[39] Y. Ikeda, T. Hyodo, and W. Weise, Nucl. Phys. A **881**, 98 (2012)
"Chiral SU(3) theory of antikaon–nucleon interactions with improved threshold constraints"

[40] T. Hashimoto et el., Phys. Rev. Lett. **128**, 112503 (2022).
"Measurements of Strong-Interaction Effects in Kaonic-Helium Isotopes at Sub-eV Precision with X-Ray Microcalorimeters"

[41] J. Zmeskal et el., J-PARC P57 Proposal
"Measurement of the Strong Interaction Induced Shift and Width of the 1s State of Kaonic Deuterium at J-PARC"

[42] Jonathan M. M. Hall et el, Phys. Rev. Lett. **114**, 132002 (2016).
"Lattice QCD Evidence that the $\Lambda(1405)$) Resonance is an Antikaon-Nucleon Molecule"

[43] H. Kamano et el., Phys. Rev. C **90**, 065202 (2014).
"Dynamical Coupled-Channels Model of K^-p Reactions: Determination ofPpartialWwaveAamplitudes"
Phys. Rev. C**92**, 025205 (2015).
"Dynamical Coupled-Channels Model of K^-p Reactions. II Extraction of Λ^* and Σ^* Hyperon Resonances"
Phys. ReV. C**95**, 044903(E) (2015).

[44] J. Esmaili, Y. Akaishi, and T. Yamazaki, Phys. Lett. B **686**, 23 (2010)
"Experimental confirmation of the $\Lambda(1405)$ ansatz from resonant formation of a K^-p quasi-bound state in K^- absorption by ^{3}He and ^{4}He"

[45] M. Niiyama et el., Phys. Rev. C **78**, 035202 (2008).
"Photoproduction of $\Lambda(1405)$ and $\Sigma(1385)$ on the proton at $E_\gamma = 1.5$-$2.4\text{GeV}/c$"

J. K. Ahn, Nucl. Phys. A **721**, 715c (2002).
"$\Lambda(1405)$ photoproduction at Spring-8/LEPS"

[46] J.C.Nacher et el., Phys. Lett. B **455**, 55 (1999).
"Photoproduction of the $\Lambda(1405)$ on the proton and nuclei"

[47] A. Cieplý and J. Smejkal, Nucl. Phys. A **881**, 115 (2012).
"Chirally motivated $\bar{K}N$ amplitudes for in-medium applications"

[48] L.Fabbietti et el., Nucl. Phys. A **914**, 60 (2013).

[49] K. Miyagawa, J. Haidenbauer, and H. Kamada Phys. Rev. C **97**, 055209 (2018)
"Faddev approach to the reaction $K-d \rightarrow \pi\Sigma n$ at $p_K = 1.0GeV/c$"

[50] S. Kawasaki et al., JPS Conf. Proc. **13**, 020018 (2017).
"Spectroscopic Experiment of $\Lambda(1405)$ via the In-flight $d(K^{-},n)$n) Reaction at J-PARC K1BR.8"

[51] E. Oset, A. Ramos, and C. Bennhold, Phys. Lett. B **527**, 99 (2002); **530**, 260(E) (2002).
"Low lying $S = -1$ excited baryons and chiral symmetry"

[52] H. Zhang, et el., Phys. Rev. C **88**, 035204 (2013). "Partial-wave analysis of $\bar{K}N$ scattering reactions"

[53] H. Kamano et el., Phys. ReV. C**94**, 065205 (2016).
"Toward Establishing Low-Lying Λ and Σ Hyperon Resonances with the $\bar{K}+d \rightarrow \pi+Y+N$ Reaction"

[54] T. Hyodo and D. Jido, Prog. Part. Nucl. Phys. **67**, 55 (2012).
"The Nature of the $\Lambda(1405)$ Resonance in Chiral Dynamics"

[55] K. Agari et el, Prog. Theor. Exp. Phys., 02B009 (2012)

[56] K. Agari et el, Prog. Theor. Exp. Phys., 02B011 (2012)

[57] TRANSPORT http://linac96.web.cern.ch/Linac96/Proceedings/Thursday/THP72/Paper.p

[58] T. K. Ohska et al., Nuclear Science, IEEE Transactions on 33, 98 (1986).

[59] M. Shiozawa and et el., A new TKO system manager board for a dead-time-free data acquisition system, in 1994 IEEE Nuclear Science Symposium-NSS'94, pages 632–635, (1994)

[60] M. Iio et al., Nucl. Instrum. Methods Phys. Res., Sect. **A** 687, 1 (2012).

[61] S. Agostinelli et al., Nucl. Instrum. Methods Phys. Res., Sect. **A** 506, 250 (2003)
J. Allison et el., IEEE Transactions on Phys. Sci. 53, 207 (2006)
J.Allison et al., Nucl. Instrum. Methods Phys. Res., Sect. **A** 835, 186 (2016)

[62] K. Fuji, `https://www-jlc.kek.jp/subg/offl/lib/docs/helix_manip/node3.html` (1968).

[63] Opera Electromagnetic FEA Solution Software

[64] V. Flaminio et al., CERN-HARA-87-01, 121 (1983).

[65] M.Jones et el, Nucl. Phys. B **90**, 349 (1975)

[66] R. Barlow and C. Beeston, Comp. Phys. Comm. **77**, 219 (1993).

[67] A. Nappi, Comp. Phys. Comm. **180**, 269 (2009).

[68] M. jones, R. Levi, Setti, D. Merrill and R. D. Tripp, Phys. Rev. B**90**, 349 (1975).

[69] M. Bernheim and et. el., Nucl. Phys. A**365**, 349, (1981).

[70] R. Machleidt, Phys. Rev. C**63**, 024001 (2001).

[71] S. Agostinelli et al., Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **506**, 250 (2003).
J.Allison et el., Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **835**, 186 (2016).