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Hadrons in "Hypernuclei"

Tomofumi Nagae[*†]
Kyoto University
E-mail: nagae@scphys.kyoto-u.ac.jp

"Hypernuclei" are the hadron many-body systems with strangeness degree of freedom. Not only ordinary nuclear force, nucleon-nucleon interaction, but also hyperon-nucleon and hyperon-hyperon interactions can be investigated through the spectroscopy of "hypernuclei". The present understanding on the baryon-baryon interactions in $SU(3)_F$ including $\bar{K}N$ interaction is overviewed.

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1. Introduction

When we embed hadrons with strangeness (S) into a nucleus, formation of "hypernuclei" is expected if the hadron-nucleus interaction has attraction strong enough to form a bound state. From spectroscopic studies on such hypernuclear bound states, the information on hadron-nucleon interaction has been extracted. This gives us a unique way to investigate the interaction, in some cases, because hadron-nucleon scattering measurements at low energies are usually difficult due to the short lifetimes of the hadron. Our current view of "hypernuclei" has been extended from the traditional Λ hypernuclei to Σ hypernuclei, double-Λ hypernuclei including Ξ hypernuclei and Kaonic nuclei.

In this talk, I will review the present status of understandings on the baryon-baryon interactions in $SU(3)_F$ as well as $\bar{K}N$ interaction. As for the recent theoretical progress, these baryon-baryon interactions are now calculable with a Lattice QCD technique [1]. It is very interesting to compare the calculations in high precision with the experimental data in near future.

2. S=-1 Baryon Systems

2.1 Λ in nuclei

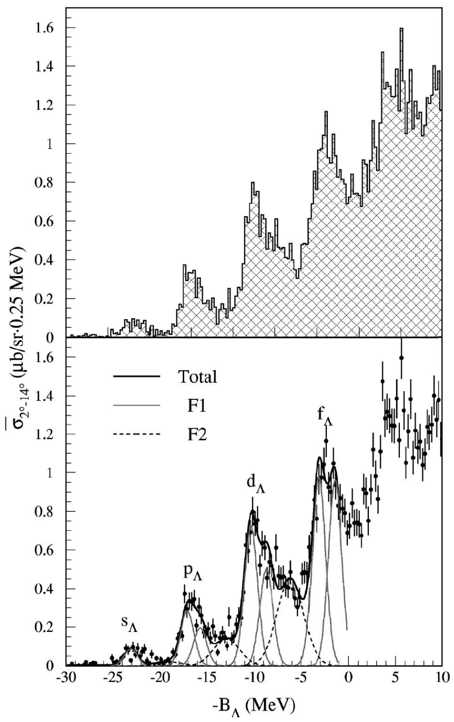

Figure 1: Hypernuclear mass spectra of ${}^{89}_{\Lambda}$Y [3] measured with the SKS spectrometer.

The production of Λ hypernuclei with (π^+, K^+) reactions in a wide mass-number range of ${}^{7}_{\Lambda}$Li, ${}^{9}_{\Lambda}$Be, ${}^{10}_{\Lambda}$B, ${}^{12}_{\Lambda}$C, ${}^{13}_{\Lambda}$C, ${}^{16}_{\Lambda}$O, ${}^{28}_{\Lambda}$Si, ${}^{51}_{\Lambda}$V, ${}^{89}_{\Lambda}$Y (see Fig. 1), ${}^{139}_{\Lambda}$La, and ${}^{208}_{\Lambda}$Pb has been successfully carried out [2, 3, 4] at 12-GeV proton synchrotron (PS) of High Energy Accelerator Research Organization (KEK) by using the Superconducting Kaon Spectrometer (SKS) [5]. From the systematic measurement of Λ single-particle energies, the potential depth in nuclear matter is estimated to be 28 ± 1 MeV.

In the *p*-shell Λ hypernuclei from $^{7}_{\Lambda}$Li to $^{16}_{\Lambda}$O, the fine structures due to Λ spin-dependent interactions have been measured at KEK and Brookhaven National Laboratory (BNL). As for a recent summary, please refer to Ref. [6].

These high precision data have been theoretically analyzed by D.J. Millener [7] based on shell-model calculations taking account of $\Lambda N - \Sigma N$ mixing effects. The spin-orbit interaction, in particular, in the ΛN interaction is found to be very small compared to the nucleon-nucleon case.

2.2 Σ in nuclei

Since there is a strong conversion process of $\Sigma N \to \Lambda N$ in Σ hypernuclei, formation of narrow bound states in Σ hypernuclei would not be easy. In fact, there is only one bound state, $^{4}_{\Sigma}$He, first reported in the ^{4}He(K^{-}_{stop}, π^{-}) reaction at KEK [8] and later confirmed in the in-flight (K^{-}, π^{-}) reaction at 600 MeV/*c* at BNL as shown in Fig. 2 [9]. Large isospin dependence plays an important role to form this bound state [10].

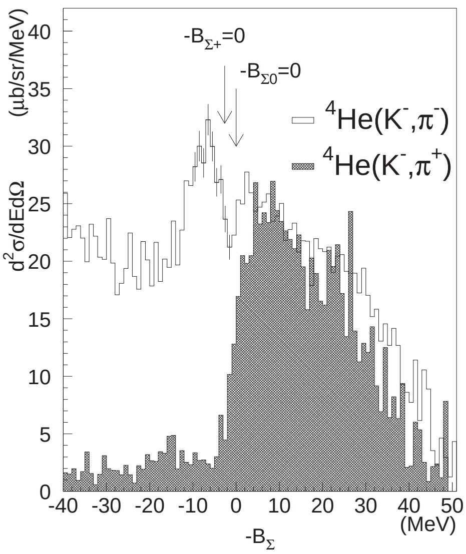

Figure 2: Excitation energy spectra of ^{4}He(K^{-}, π^{-}) and ^{4}He(K^{-}, π^{+}) at 600 MeV/*c* K^{-} momentum [9].

Up to now, there have been no other measurements claiming other bound states of Σ hyperon. On the other hand, it is believed that Σ^{-}-nucleus potential would be strongly repulsive [11] in the medium to heavy nuclear systems based on a measurement of the (π^{-}, K^{+}) spectra at 1.2 GeV/*c* near the Σ^{-} production threshold in KEK E438 [12].

2.3 $\Lambda N - \Sigma N$ coupling

One important subject to be explored is a role of the $\Lambda N - \Sigma N$ coupling in Λ hypernuclei. The $\Lambda N - \Sigma N$ coupling has been an issue on the systematics of the binding energies in *s*-shell Λ hypernuclei among $^{3}_{\Lambda}$H, $^{4}_{\Lambda}$H, $^{4}_{\Lambda}$He, and $^{5}_{\Lambda}$He, and a possible source of charge-symmetry breaking between $^{4}_{\Lambda}$H and $^{4}_{\Lambda}$He. These aspects can be investigated with the future high-precision spectroscopy.

It is also expected that the $\Lambda N - \Sigma N$ coupling effect might be enhanced in high-isospin environments such as neutron-rich Λ hypernuclei. Production of such a hypernucleus with the double-charge-exchange reaction of ^{10}B(π^-, K^+) reaction was first demonstrated with the SKS [13]. Recently, the FINUDA experiment at the ϕ-factory DAΦNE reported three candidate events of $^{6}_{\Lambda}$H production in the ^{6}Li(K^-_{stop}, π^+) reaction [14]. In Japan Proton Accelerator Research Complex (J-PARC), the E10 experiment has just completed the data taking on the ^{6}Li(π^-, K^+) reaction at 1.2 GeV/c using a high-intensity π^- beam. Unfortunately, there were no peaks for $^{6}_{\Lambda}$H around the $^{4}_{\Lambda}$H+2n threshold. The upper limit of the production cross section of 1.2 nb/sr at 90% confidence level was estimated [15].

3. S=-2 Baryon Systems

The reaction, (K^-, K^+), at the K^- incident momentum of around 1.8 GeV/c has been used for the production of $S = -2$ systems: double Λ hypernuclei and Ξ hypernuclei. A Ξ^- hyperon is produced through the $K^- + p \rightarrow K^+ + \Xi^-$ reaction.

3.1 Double-Λ hypernuclei

Up to now, several double-Λ hypernuclei events were observed in nuclear emulsions by observing sequential weak decay patterns. Among them, one event called "Nagara Event" detected in a hybrid-emulsion experiment, KEK E373, gave a clear identification of $^{6}_{\Lambda\Lambda}$He [16]. The binding energy was measured with the unique event interpretation. The Λ-Λ bonding energy ($\Delta B_{\Lambda\Lambda}$) was extracted to be $1.01\pm0.20^{+0.18}_{-0.11}$ MeV, for the first time, which has been updated to be 0.67$\pm$0.17 MeV [17] because of an update of Ξ^- mass. This value of $\Delta B_{\Lambda\Lambda}$ is smaller than the previously believed value of about 4.7 MeV.

3.2 Ξ hypernuclei

There are almost no experimental information on ΞN interaction. It is still ambiguous if Ξ hypernuclei exist or not. Even if the potential depth is deep enough to form several bound levels, there is a possibility that the bound state peaks could not be resolved because of a large conversion width due to $\Xi^- p \rightarrow \Lambda\Lambda$. Further, spin and isospin dependence of the Ξ-nucleus potential is another important issue to be explored. In a naive quark model, the ΞN spin-orbit interaction is expected to be as large as that in the nucleon case.

Ξ hypernuclei can be directly produced via the (K^-, K^+) reaction. Such measurements were carried out at KEK [18] and BNL [19] for the ^{12}C(K^-, K^+) reaction (Fig. 3). However, the energy resolution of the spectrometers and statistics were not enough to observe the bound-state peaks of Ξ hypernuclei. Assuming the Woods-Saxon type potential, a potential depth was obtained to be -14 MeV for A=12 from a spectrum shape analysis near the binding threshold.

The J-PARC E05 experiment aims to observe a bound-state peak in the ^{12}C$(K^-, K^+)^{12}_{\Xi}$Be reaction with the energy resolution of better than 2 MeV(FWHM). A new spectrometer named as "S-2S" [20] is under construction at the K1.8 beam line in the hadron experimental hall of J-PARC.

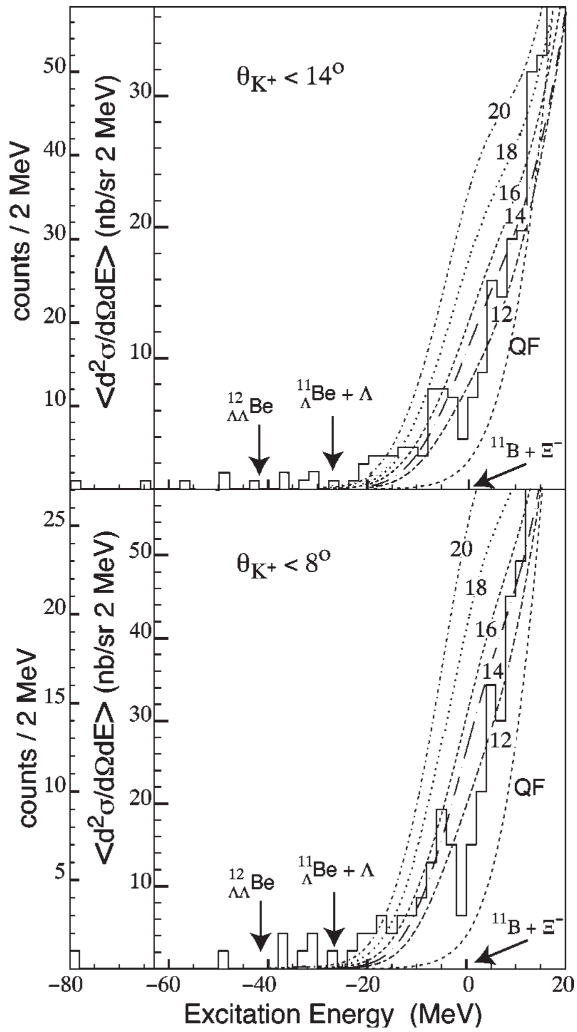

Figure 3: Excitation-energy spectra from E885 for ^{12}C(K^-,K^+) for θ_{K^+} $\leq$14° (top figure) and θ_{K^+} $\leq$8° (bottom figure) along with $^{12}_{\Xi}$Be production theoretical curves for $V_{0\Xi}$ equal to 20, 18, 16, 14, and 12 MeV [19].

4. S=-1 Meson System

In elementary $\bar{K}N$ interactions, there was a conflict between low-energy KN scattering analyses and energy shifts observed in kaonic hydrogen x-rays. This puzzle was solved with a clean measurement of the kaonic hydrogen x-ray at KEK [21], and the recent measurement at DAΦNE by the SIDDHARTA group has achieved a better precision [22].

It turned out that there was a strong attraction in the $\bar{K}N$ interaction in the isospin (I) = 0 channel. A possibility to have deeply-bound kaonic nuclei due to this strong attraction was suggested by several authors.

A lot of search experiments for kaonic nuclei have been carried out. Among them, the FINUDA group first claimed the evidence for a K^-pp bound state [23] in the K^- absorption reactions on ^{6}Li, ^{7}Li, and ^{12}C targets at rest. The invariant mass distribution of the $\Lambda-p$ pairs emitted in

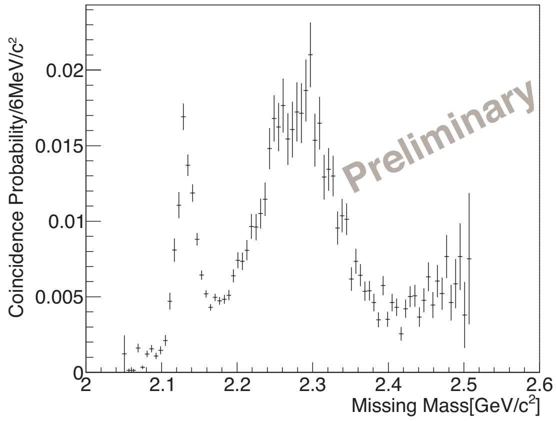

Figure 4: A preliminary spectrum of the proton coincidence rate in the $d(\pi^+,K^+)$ reaction at 1.7 GeV/c as a function of the missing-mass [26]. A broad bump is observed around 2.3 GeV/c^2.

back to back showed a significant shift suggesting the binding energy of 115^{+6}_{-5}(stat)$^{+3}_{-4}$(syst) MeV and the width of 67^{+14}_{-11}(stat)$^{+2}_{-3}$(syst) MeV. Later, the DISTO collaboration reanalyzed their data on the $p+p \to K^+ + \Lambda + p$ reaction at 2.85 GeV [24], and found the binding energy of 103±3±5 MeV and the width of 118±8±10 MeV.

At this stage, it would be too early to say that the existence of the K^-pp bound state is experimentally established. It is needed to confirm the existence in different reactions with much simpler reaction mechanisms.

In J-PARC, there are two experiments searching for the K^-pp bound state. One is the E15 experiment by using the ^{3}He(K^-,n) reaction at 1 GeV/c. A neutron is knocked out in the forward direction from a ^{3}He, and the K^- scattered backward is expected to form the K^-pp with two protons in the ^{3}He. A neutron hodoscope with a flight distance of about 15 m has been installed for the missing-mass measurement. Also, surrounding the ^{3}He target, a cylindrical detector system was constructed for the invariant-mass measurement of the decay products coming from the K^-pp; for example, $K^-pp \to \Lambda + p$. We took a preliminary data during the short beam times in March and May, 2013, with a limited statistics. Preliminary results will be presented by S. Enomoto [25] in this conference.

Another experiment is the E27 experiment by using the $d(\pi^+,K^+)$ reaction at 1.7 GeV/c. At this incident energy, we can produce not only Λ and Σ hyperons but also $\Sigma(1385)$ and $\Lambda(1405)$ hyperon resonances. Here we can expect the K^-pp bound state would be formed through the $\Lambda(1405)$ doorway state ($\Lambda^* p \to (K^-pp) \to \Lambda + p$). However, the sticking probability of $\Lambda(1405)$ in deuteron would be as small as 1% or less. So that the signal would be in the huge backgrounds of quasi-free hyperon and hyperon resonance productions. We, therefore, installed a range counter system surrounding a liquid deuterium target from ±39 degrees to ±122 degrees from the beam direction. By requiring one or two high-momentum (>250 MeV/c) proton(s), we could suppress most of the quasi-free backgrounds. A pilot data taking was performed in June, 2012. A preliminary result will be presented by Y. Ichikawa [26] in this conference. A proton coincidence rate plot as a function of the (π^+,K^+) missing-mass (Fig. 4) shows a broad bump around 2.3 GeV/c^2 suggesting the K^-pp-like structure.

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5. Summary

The world of "hypernuclei" are expanding. A variety of experimental facilities including J-PARC are producing new experimental data. New information on baryon-baryon and meson-baryon interactions will establish a modern picture of these interactions and reveal a role of strangeness in high-density nuclear matter.

Acknowledgments

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