Hadrons in "Hypernuclei"

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"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 $\Lambda$ hypernuclei to $\Sigma$ hypernuclei, double-$\Lambda$ hypernuclei including $\Xi$ 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 $\Lambda$ in nuclei

The production of $\Lambda$ hypernuclei with ($\pi^+, K^+$) 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

![Figure 1: Hypernuclear mass spectra of $^{89}\Lambda Y$ measured with the SKS spectrometer.](image-url)
measurement of a single-particle energies, the potential depth in nuclear matter is estimated to be $28 \pm 1$ MeV.

In the $p$-shell $\Lambda$ hypernuclei from $^5\Lambda Li$ to $^{16}\Lambda O$, the fine structures due to $\Lambda$ 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 $\Lambda N$ interaction is found to be very small compared to the nucleon-nucleon case.

2.2 $\Sigma$ in nuclei

Since there is a strong conversion process of $\Sigma N \rightarrow \Lambda N$ in $\Sigma$ hypernuclei, formation of narrow bound states in $\Sigma$ hypernuclei would not be easy. In fact, there is only one bound state, $^4\Sigma He$, first reported in the $^4\Sigma He(K^-,\pi^-) \rightarrow ^4\Sigma He(K^+,\pi^+)$ reaction at KEK [8] and later confirmed in the in-flight $(K^-,\pi^-)$ 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 $^4\Sigma He(K^-,\pi^-)$ and $^4\Sigma He(K^+,\pi^+)$ at 600 MeV/c $K^-$ momentum [9].

Up to now, there have been no other measurements claiming other bound states of $\Sigma$ hyperon. On the other hand, it is believed that $\Sigma^-$-nucleus potential would be strongly repulsive [11] in the medium to heavy nuclear systems based on a measurement of the $(\pi^-,K^+)$ spectra at 1.2 GeV/c near the $\Sigma^-$ 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 $\Lambda$ hypernuclei. The $\Lambda N - \Sigma N$ coupling has been an issue on the systematics of the binding energies in $s$-shell $\Lambda$ hypernuclei among $^3\Lambda H$, $^4\Lambda H$, $^3\Lambda He$, 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 \( \Lambda \) hypernuclei. Production of such a hypernucleus with the double-charge-exchange reaction of \( ^{10}\text{B}(\pi^{-}, K^{+}) \) reaction was first demonstrated with the SKS \([13]\). Recently, the FINUDA experiment at the \( \phi \)-factory DA\( \Phi \)NE reported three candidate events of \( ^{6}\text{Li}(K^{-}, \pi^{+}) \) reaction \([14]\). In Japan Proton Accelerator Research Complex (J-PARC), the E10 experiment has just completed the data taking on the \( ^{6}\text{Li}(p, K^{+}) \) reaction at 1.2 GeV/c using a high-intensity \( p \) beam. Unfortunately, there were no peaks for \( ^{6}\Lambda\text{H} \) around the \( ^{4}\Lambda\text{H} + 2\text{n} \) 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 \( \Lambda \) hypernuclei and \( \Xi \) hypernuclei. A \( \Xi^{-} \) hyperon is produced through the \( K^{-} + p \rightarrow K^{+} + \Xi^{-} \) reaction.

3.1 Double-\( \Lambda \) hypernuclei

Up to now, several double-\( \Lambda \) 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 \( ^{6}\Lambda\text{He} \) \([16]\). The binding energy was measured with the unique event interpretation. The \( \Lambda-\Lambda \) bonding energy (\( \Delta B_{\Lambda\Lambda} \)) was extracted to be \( 1.01 \pm 0.20^{+0.18}_{-0.11} \) MeV, for the first time, which has been updated to be \( 0.67 \pm 0.17 \) MeV \([17]\) because of an update of \( \Xi^{-} \) mass. This value of \( \Delta B_{\Lambda\Lambda} \) is smaller than the previously believed value of about 4.7 MeV.

3.2 \( \Xi \) hypernuclei

There are almost no experimental information on \( \Xi N \) interaction. It is still ambiguous if \( \Xi \) 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 \( \Xi \)-nucleus potential is another important issue to be explored. In a naive quark model, the \( \Xi N \) spin-orbit interaction is expected to be as large as that in the nucleon case.

\( \Xi \) hypernuclei can be directly produced via the \( (K^{-}, K^{+}) \) reaction. Such measurements were carried out at KEK \([18]\) and BNL \([19]\) for the \( ^{12}\text{C}(K^{-}, K^{+}) \) reaction (Fig. 3). However, the energy resolution of the spectrometers and statistics were not enough to observe the bound-state peaks of \( \Xi \) 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 \( ^{12}\text{C}(K^{-}, K^{+})^{12}\text{Be} \) reaction with the energy resolution 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.
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 $K^- p p$ 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
back to back showed a significant shift suggesting the binding energy of $115^{+6}_{-5} \text{(stat)}^{+3}_{-4} \text{(syst)}$ MeV and the width of $67^{+14}_{-11} \text{(stat)}^{+3}_{-3} \text{(syst)}$ MeV. Later, the DISTO collaboration reanalyzed their data on the $p + p \rightarrow K^+ + \Lambda + p$ reaction at 2.85 GeV \cite{24}, and found the binding energy of $103^{+3}_{-5} \text{MeV}$ and the width of $118^{+8}_{-10} \text{MeV}$.

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 $^3\text{He}(K^-,n)$ reaction at 1 GeV/c. A neutron is knocked out in the forward direction from a $^3\text{He}$, and the $K^-$ scattered backward is expected to form the $K^-pp$ with two protons in the $^3\text{He}$. A neutron hodoscope with a flight distance of about 15 m has been installed for the missing-mass measurement. Also, surrounding the $^3\text{He}$ target, a cylindrical detector system was constructed for the invariant-mass measurement of the decay products coming from the $K^-pp$; for example, $K^-pp \rightarrow \Lambda + p$. 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 \cite{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 $\Lambda$ and $\Sigma$ 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 ($\Lambda^+p \rightarrow (K^-pp) \rightarrow \Lambda + p$). 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 \cite{26} in this conference. A proton coincidence rate plot as a function of the $(\pi^+,K^+)$ missing-mass (Fig. 4) shows a broad bump around 2.3 GeV/c$^2$ suggesting the $K^-pp$-like structure.

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**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 \cite{24}. A broad bump is observed around 2.3 GeV/c$^2$. 

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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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References

[26] Y. Ichikawa, a talk in a parallel session of this conference.