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Strangeness Nuclear Physics

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The present status and the future prospect of strangeness nuclear physics are summarized, mainly based on our experimental activities at J-PARC. Recent results on γ-ray spectroscopy of Λ hypernuclei at J-PARC on ${}^{4}_{\Lambda}$He and ${}^{19}_{\Lambda}$F are presented, and the charge symmetry breaking in A=4 Λ hypernuclei is discussed together with a recent ${}^{4}_{\Lambda}$H data at Mainz. Recent progress at J-PARC on double strange systems ($\Lambda\Lambda$ hypernuclei, Ξ hypernuclei and Ξ atoms) is also reported. In addition, future plans to study three-body YNN force necessary to understand the core of neutron stars are also discussed.

KEYWORDS: strangeness, strange quark, hyperon, hypernuclei, baryon-baryon interaction, charge symmetry breaking, neutron star, hyperon puzzle, γ-ray spectroscopy, $(e, e'K^+)$ spectroscopy, (π^+, K^+) spectroscopy, J-PARC, JLab.

1. Introduction – Why strangeness?

The most important goal of the nuclear physics today is to elucidate the origin and the evolution of matter in the universe based on QCD, by answering basic questions how the quarks are combined to form hadrons (nucleons), and how the hadrons are combined to form various atomic nuclei and also neutron stars. Although ordinary nuclei forming the matter in the universe are made of up and down quarks, strange quarks play particularly important roles to approach these problems.

The nuclear force, a particular type of strong interaction between colorless baryons, has complicated features completely different from those of the gluon exchange force between quarks. The long range part of the nuclear force (> 2 fm) is well described by one pion exchange, and the mid-range (1–2 fm) part is believed to be described by a picture based on exchange of various mesons. On the other hand, the short range part characterized by the repulsive core may be understood via quark-gluon dynamics. When the nuclear force is extended to the octet baryon-baryon (BB) interactions including hyperon-nucleon (YN) and hyperon-hyperon (YY) interactions, different features are expected to appear; the BB interactions are classified as $8 \otimes 8 = 27 \oplus 10 \oplus 10^* \oplus 8 \oplus 8^* \oplus 1$, where the NN nuclear force belongs to the 27 (S=0) and the 10* (S=1) multiplets. According to the quark cluster model [1], the 10 and 8 multiplets have a repulsive core much stronger than the NN case due to Pauli principle between quarks, while the singlet is expected to have an attractive core due to attractive color magnetic interaction as well as a lack of the Pauli effect. Those characteristic features are reproduced by recent lattice QCD calculations [2]. Thus, study of YN and YY interactions provides essential information to understand the mechanism of the BB interactions. It is one of the most important motivations in strangeness nuclear physics.

Strangeness nuclear physics has to be also explored in order to understand the core of neutron stars, in which a part of neutrons with a large Fermi energy are naively expected to convert to hyperons via weak interaction. However, the existence of hyperons makes the Equation Of State of the nuclear matter too soft to support neutron stars heavier than $\sim 1.5 M_\odot$. The recent reliable observations of two massive neutrons stars with $2.0 M_\odot$ mass clearly contradict the existence of hyperons in neutron stars.

This problem called “hyperon puzzle” suggests that our current understanding of the *BB* interactions is quite limited and further theoretical and experimental efforts should be made to reveal the properties of the *BB* interactions in high density nuclear matter.

2. γ-ray spectroscopy of Λ hypernuclei at J-PARC

Structure of Λ hypernuclei have been investigated via the missing mass spectroscopy using (K^-, π^-), (π^+, K^+) and $(e, e'K^+)$ reactions, and via γ-ray spectroscopy [3]. High precision γ-ray spectroscopy experiments with germanium (Ge) detectors started in 1998 and investigated most of the experimentally accessible *p*-shell Λ hypernuclei [4]. Recently at J-PARC, we extended the studies into lighter (*s*-shell) and heavier (*sd*-shell) hypernuclei. By employing the newly-developed Ge detector array (Hyperball-J), our group has measured γ-rays from ${}^{4}_{\Lambda}$He and ${}^{19}_{\Lambda}$F produced by the (K^-, π^-) reaction using high-intensity K^- beams at K1.8 beam line in J-PARC.

The beam K^- (1.5 GeV/c for ${}^{4}_{\Lambda}$He and 1.8 GeV/c for ${}^{19}_{\Lambda}$F) was momentum analyzed by the K1.8 beam spectrometer, and the scattered π^- was identified and analyzed by the SKS spectrometer. Surrounding the target, Hyperball-J was installed to detect γ rays from hypernuclei. Details are described in Ref. [5].

2.1 ${}^{4}_{\Lambda}$He result

Figure 1 (a) shows the measured missing mass spectrum of the ^{4}He(K^-, π^-) reaction with a liquid helium target, showing a peak for the ${}^{4}_{\Lambda}$He (0^+ and 1^+) production. When this peak region is gated, the γ-ray spectrum exhibits a peak at 1.4 MeV, after event-by-event Doppler shift correction is applied, as shown in Fig. 1 (b). Since the ground state of ${}^{4}_{\Lambda}$He is known to be 0^+, this peak is assigned as the ${}^{4}_{\Lambda}$He$(1^+ \rightarrow 0^+)$ transition, and its energy gives the ${}^{4}_{\Lambda}$He$(1^+,0^+)$ spacing energy of $1406 \pm 2(stat) \pm 2(syst)$ keV. As described later in detail, this spacing energy confirmed the existence of a large charge symmetry breaking effect in the *A*=4 Λ hypernuclei. See Ref. [5] for details.

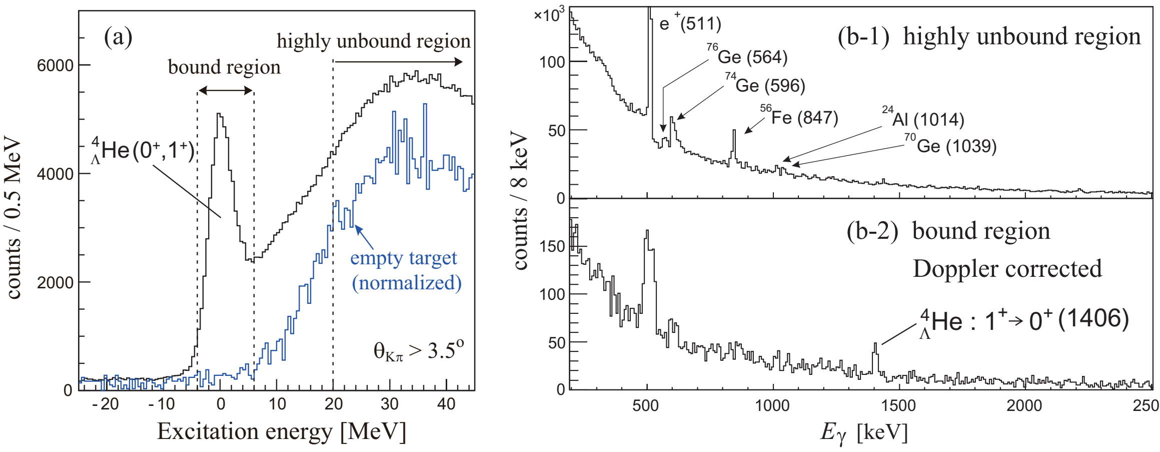

Fig. 1. Result of the J-PARC E13 experiment for ${}^{4}_{\Lambda}$He γ-ray spectroscopy [5]. (a) Missing mass spectrum of ^{4}He(K^-, π^-) reaction, showing a peak of ${}^{4}_{\Lambda}$He$(1^+,0^+)$ production just below the Λ binding threshold. (b) γ-ray spectra after gating the peak region in the mass spectrum (a). (b-1) shows a spectrum for the highly unbound region indicated in (a), and (b-2) for the ${}^{4}_{\Lambda}$He bound region in (a) with event-by-event Doppler shift correction applied.

2.2 ${}^{19}_{\Lambda}$*F result*

The ${}^{19}_{\Lambda}$F γ-ray spectrum obtained with a liquid CF$_4$ target is shown in Fig. 2 [6]. By comparing it with the background spectrum obtained by gating the highly unbound mass region of the ^{19}F$(K^-,\pi^-){}^{19}_{\Lambda}$F missing mass spectrum, four γ-rays were assigned as the transitions in ${}^{19}_{\Lambda}$F. The energies, yields, and widths (lifetimes of the transitions) of the four peaks are compared with the expected values by a shell model calculation by Umeya and Motoba [7], and the four transitions were uniquely assigned and the level scheme of ${}^{19}_{\Lambda}$F was reconstructed as shown in Fig. 3. Details are described in Ref. [6].

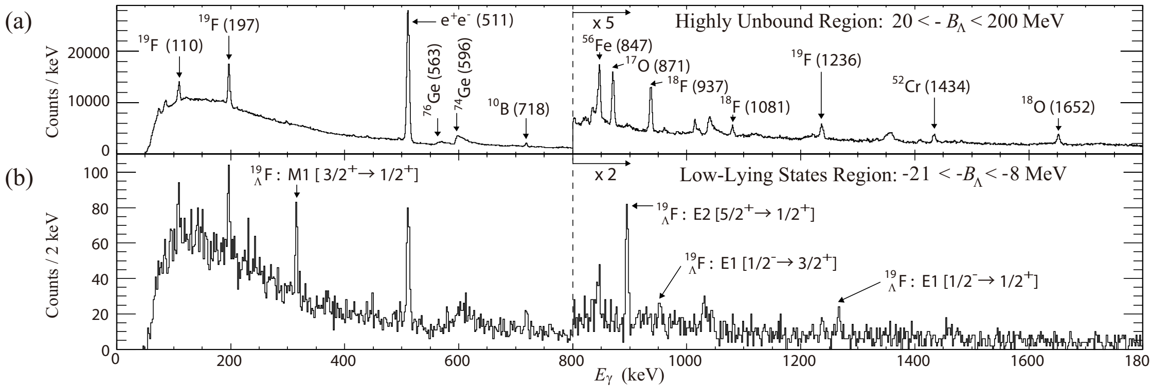

Fig. 2. Result of the J-PARC E13 experiment for ${}^{19}_{\Lambda}$F γ-ray spectroscopy [6]. (a) γ-ray spectrum after gating the highly unbound region of ${}^{19}_{\Lambda}$F in the missing mass spectrum of ^{19}F(K^-,π^-). (b) γ-ray spectrum after gating the ${}^{19}_{\Lambda}$F low-lying bound state region in the missing mass spectrum of ^{19}F(K^-,π^-). Four peaks are assigned as transitions in ${}^{19}_{\Lambda}$F.

The most intense 315 keV γ-ray was assigned as the spin-flip M1 transition between the ground state doublet ($3/2^+ \rightarrow 1/2^+$), of which spacing is determined by the ΛN spin-spin interaction between the Λ in the 0*s* orbit and the deuteron-like *pn* pair with spin 1 in the *sd* shell orbit as illustrated in Fig. 3. Such ground-state spin doublet spacings determined by the ΛN spin-spin interaction were also measured for an *s*-shell hypernucleus, ${}^{4}_{\Lambda}$He (by the same E13 experiment) [5], and for a *p*-shell hypernucleus, ${}^{7}_{\Lambda}$Li [10]. Their energies reflect the ΛN spin-spin effective interaction strength, which is expected to rapidly decrease for heavier hypernuclei due to a less overlap between the $\Lambda(0s)$ and the nucleon (0*s*, 0*p*, and 1*s*0*d*) wave functions. It is found that the observed doublet energy spacing is reproduced quite well by the ΛN spin-dependent interactions consistently with the *s*- and *p*-shell hypernuclear doublet spacing data, suggesting our knowledge of the interaction and the theoretical frameworks are valid for a wide range of hypernuclei. Thus we hope that precise spectroscopic data of heavier Λ hypernuclei would allow us to investigate the nuclear density dependence of the ΛN interactions in nuclear matter, which will provide valuable information to solve the hyperon puzzle.

3. Charge symmetry breaking in ΛN interaction

Since the charge symmetry breaking (CSB) in nuclear (baryonic) systems stems from the up and down quark mass difference as well as Coulomb effects, it would provide a stringent test of our understanding of the hadron-hadron interaction from QCD.

Old emulsion experiments in 1960s suggested that the Λ binding energies of the A=4 mirror hypernuclei, ${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$He, are different by 350 keV (see Fig. 4), much larger than the ^{3}H and ^{3}He binding energy difference (after the electromagnetic effects subtracted) of ~70 keV [11]. Since systematic

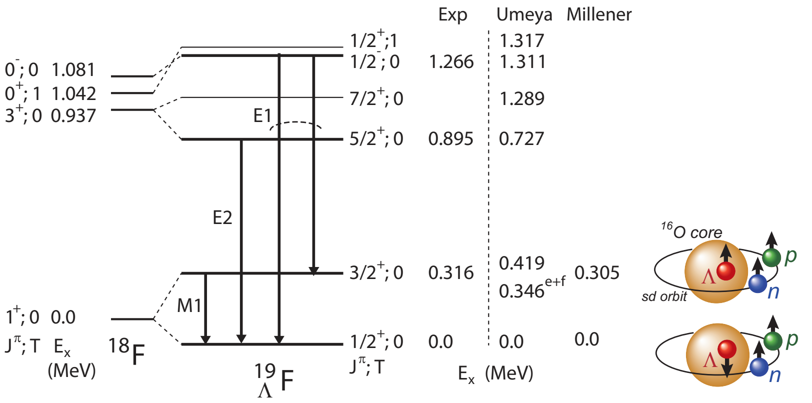

Fig. 3. Level scheme of $^{19}_{\Lambda}$F reconstructed from the observed γ rays [6]. Level energies measured from the γ rays are compared with theoretical predictions by Umeya-Motoba [7] and by Millener [8]. Umeya and Motoba performed a shell model calculation with the YN interaction from the NSC97e model, and the $3/2^+$ energy value marked with "e + f" is the same calculation with the NSC97e + NSC97f models adjusted to reproduce the $^{7}_{\Lambda}$Li$(3/2^+,1/2^+)$ spacing [9]. Millener's calculation uses the phonomenological ΛN spin-spin interaction strength which reproduced the $^{7}_{\Lambda}$Li$(3/2^+,1/2^+)$ spacing.

errors are not given in literatures of the old emulsion experiments, independent measurements, hopefully with other methods than the emulsion method, are long awaited.

As shown in Fig. 4, the $^{4}_{\Lambda}$He$(1^+,0^+)$ spacing recently determined from γ-ray data as $1.406 \pm 0.002 \pm 0.002$ MeV is much larger than that of the mirror hypernuclei, the $^{4}_{\Lambda}$H$(1^+,0^+)$ spacing of 1.09 ± 0.02 MeV. It unambiguously confirmed the existence of a large CSB effect in the A=4 hypernuclei.

In order to investigate the origin of the large CSB effect, precise and reliable measurements of the absolute values of B_Λ (the Λ binding energy) for $^{4}_{\Lambda}$He and $^{4}_{\Lambda}$H are necessary. Employing the MAMI accelerator in Mainz, the momentum of π^- emitted in the $^{4}_{\Lambda}\mathrm{H} \to {}^{4}\mathrm{He} + \pi^-$ decay was precisely measured and the B_Λ value of $^{4}_{\Lambda}$H was determined to be $2.12 \pm 0.01(stat) \pm 0.09(syst)$ MeV [12]. This B_Λ value is consistent with the old emulsion value (2.04 ± 0.04 MeV), significantly away from the old emulsion value for $^{4}_{\Lambda}$He (2.39 ± 0.03 MeV). This experiment supports reliability of the B_Λ values in the old emulsion experiments. Combined with the $^{4}_{\Lambda}$He γ-ray data, the binding energy difference,

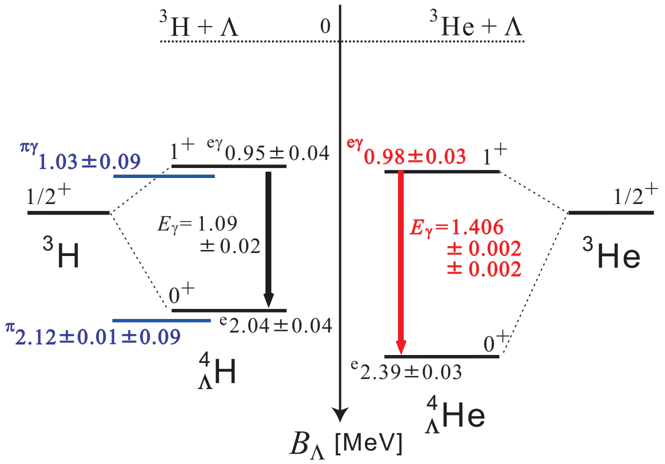

Fig. 4. Level schemes of the A=4 mirror hypernuclei, $^{4}_{\Lambda}$He and $^{4}_{\Lambda}$H, updated from recent data of the $^{4}_{\Lambda}$He$(1^+ \to 0^+)$ γ-ray energy [5] and the $B_\Lambda(^{4}_{\Lambda}\mathrm{H}(0^+))$ energy from $^{4}_{\Lambda}\mathrm{H} \to {}^{4}\mathrm{He} + \pi^-$ decay measurement [12], together with old emulsion values for B_Λ. The suprescript given in the B_Λ values means the experimental source of the value; "e", "γ", and "π" stand for emulsion, γ-ray, and decay π^- experiments, respectively.

$\Delta B_\Lambda = B_\Lambda(^4\mathrm{He}) - B_\Lambda(^4\mathrm{H})$, is large for the 0^+ state ($\Delta B_\Lambda(0^+)$ ∼0.3 MeV) but almost vanishing for the 1^+ state. This spin dependence of the CSB effect would be a hint to understand the origin of this phenomenon.

p-shell hypernuclear data are also helpful to investigate the origin of the hypernuclear CSB. Recent B_Λ data for *p*-shell hypernuclei taken by the $(e, e'K^+)$ reaction at JLab and by the (K^-_{stop},π^-) reaction at DAΦNE, together with the (π^+, K^+) data at KEK and the old emulsion data, the B_Λ differences between *p*-shell mirror hypernuclei are less than ∼100 keV but with large errors of a few 100 keV, as complied in Ref. [13]. The accuracy of the B_Λ values for *p*-shell hypernuclei should be further improved.

4. S = -2 systems at J-PARC

As the beam intensity increases at J-PARC, experimental data for double strange nuclear systems have recently started to be accumulated employing the (K^-, K^+) reaction with intense K^- beams.

4.1 Counter-emulsion hybrid experiment at J-PARC

The J-PARC E07 experiment “Systematic Study of Double Strangeness System with an Emulsion-Counter Hybrid Method” successfully finished data taking (beam exposure to emulsion) and analysis of the emulsion image is going on [14]. Ξ^- hyperons were produced by the (K^-, K^+) reaction on ^{12}C (diamond) target and injected into an emulsion stack placed downstream of the target. Ξ^- production events were identified by missing mass of the (K^-, K^+) reaction employing magnetic spectrometers, and information on each Ξ^- track measured with silicon strip detectors (SSDs) was recorded. In the emulsion analysis, emulsion image around the Ξ^- injection point predicted from the SSDs was automatically examined with a microscope and the Ξ^- track in the emulsion was traced down to the Ξ^- absorption point. In this analysis hypernuclear events are efficiently searched for and their kinematic information on the production and decay of hypernuclei is obtained. As of November 2018, about 30% of the total exposed emulsion stacks have been analyzed, and 16 events of doubly strange events have been observed.

4.2 ΛΛ hypernuclei

Although several ΛΛ hypernuclear events were observed in emulsion so far, only the “NAGARA event” gives a precise binding energy of a ΛΛ hypernucleus; the binding energy of $^{6}_{\Lambda\Lambda}$He was obtained and the Λ-Λ bond energy was determined to be $\Delta B_{\Lambda\Lambda} = 0.67 \pm 0.17$ MeV [15]. Since the $\Delta B_{\Lambda\Lambda}$ values may differ by nuclear structure due to ΛΛ-Ξ*N* mixing, systematic data of $\Delta B_{\Lambda\Lambda}$ from several different ΛΛ hypernuclei are necessary to extract the strength of the ΛΛ interaction.

In the present emulsion analysis, more than ten ΛΛ hypernuclear events have been observed. Among them an event called “MINO event” (see Fig. 5) has been identified as a Be double Λ hypernucleus, $^{10}_{\Lambda\Lambda}$Be, $^{11}_{\Lambda\Lambda}$Be, or $^{12}_{\Lambda\Lambda}$Be* [16]. From kinematical fitting, $^{11}_{\Lambda\Lambda}$Be is found to be the most probable interpretation. In this case the ΛΛ binding energy and the ΛΛ bond energy are obtained as $B_{\Lambda\Lambda} = 19.07 \pm 0.11$ MeV and $\Delta B_{\Lambda\Lambda} = 1.87 \pm 0.37$ MeV. We expect that more ΛΛ hypernuclear events will be identified and $\Delta B_{\Lambda\Lambda}$ values will be obtained for several different nuclear species.

4.3 Ξ hypernuclei

In emulsion experiments, Ξ hypernuclei are studied with “twin hypernuclei” events, in which two single Λ hypernuclei are emitted at the Ξ^- absorption point. From kinetic energies and Λ binding energies of the two Λ hypernuclei we can determine the target nuclide, the energy of the initial state (the Ξ^- nuclear bound system when the Ξ^- is absorbed), and consequently the Ξ^- binding energy B_Ξ to the target nucleus. If the B_Ξ value is larger than that expected from Ξ^--nuclear Coulomb energy ($<$ 0.1 MeV), it is an evidence for a bound system of a Ξ^- and a nucleus via strong interaction.

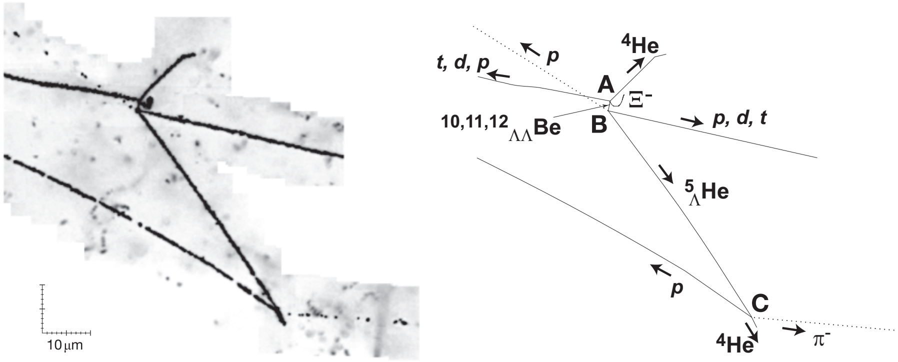

Fig. 5. Left: Elumsion image of a new $\Lambda\Lambda$ hypernuclear event "MINO"observed in the E07 experiment [16]. Right: Schematic drawing of the MINO event with the assigned particles. A Ξ^- is absorbed by ^{16}O at the vertex A. The track between the vertices A and B is assigned as a $_{\Lambda\Lambda}$Be, most probably as a $^{11}_{\Lambda\Lambda}$Be.

The first clear event of a Ξ-nuclear bound state was reported from reanalysis of the previous emulsion experiment performed at KEK-PS [17]. They observed a twin hypernuclear event of $\Xi^- + {}^{14}$N $\rightarrow {}^{10}_{\Lambda}$Be $+ {}^{5}_{\Lambda}$He, where the initial state ($^{15}_{\Xi}$C) is found to be a Ξ hypernucleus with $B_{\Xi^-} = 1.1$–4.38 MeV. This event (called "KISO event") suggests an attractive Ξ-nucleus potential, and observations of more events are awaited to confirm it. In the E07 experiment, several twin hypernuclear events have been observed, and among them a new event of the same reaction as Kiso event ($\Xi^- + {}^{14}$N $\rightarrow {}^{10}_{\Lambda}$Be $+ {}^{5}_{\Lambda}$He) has been found, giving a similar value of $B_{\Xi^-} \sim 1$ MeV. By accumulating such Ξ hypernuclear events, we will be able to determine the depth of the Ξ nuclear potential.

4.4 Ξ atomic X rays

In the E07 experiment, the emulsion target was surrounded by six Ge detectors to detect X-ray photons emitted from Ξ^- atoms before Ξ^- absorption by the nucleus. The last transition before the Ξ^- absorption contains information on the strong interaction between the Ξ^- and the nucleus; the shift of the transition energy from the one calculated purely from electromagnetic interaction provides strength of the real part of the Ξ nuclear potential, and the width of the X ray peak gives strength of the imaginary part of the potential. In the E07 case, by analyzing the emulsion image and selecting only Ξ^- nuclear absorption events, background in the X-ray spectrum is expected to be drastically reduced. This is the first attempt of the "hybrid emulsion X-ray measurement". The data analysis to pick up Ξ^- absorption events is in progress. When Ξ^- is absorbed by heavy nuclei in emulsion, Ag and Br, X rays from Ξ^- Ag and Br atoms are emitted with energies around 200–400 keV for the last transitions. The experiment aims at the first observation of Ξ^- atomic X rays.

It should be also noted that at J-PARC another experiment for Ξ-atomic X-ray measurement (E03) is also scheduled to run soon.

4.5 Ξ hypernuclear spectroscopy via (K^-, K^+) reaction at J-PARC

Another important approach to study Ξ hypernuclei is to measure the excitation spectrum via the direct (K^-, K^+) reaction. The J-PARC E05/E70 experiment aims at measurement of the ^{12}C$(K^-,K^+)^{12}_{\Xi}$Be spectrum. A preliminary spectrum which was already taken in a pilot run (E05) with ~5 MeV (FWHM) resolution exhibits a significant number of events below the Ξ^- binding threshold, suggesting existence of bound Ξ hypernuclear states [18].

A full-scale experiment (E70) is under preparation. It employs a dedicated large-acceptance magnetic spectrometer (S-2S), which realizes much better mass resolution and higher statistics than E05.

By introducing a newly-developed active fiber target, an energy resolution of ~2 MeV (FWHM) is expected to be achieved, and bound state peaks are hopefully observed.

5. Future prospect –challenge to the hyperon puzzle

In order to solve the hyperon puzzle, we need to understand YN and YY interactions in dense nuclear matter, where the three-body BBB interactions including hyperons play essential roles. In ordinary nuclei made of nucleons, *ab initio* calculations of various nuclei using realistic NN potentials based on rich pp and pn scattering data revealed the existence of three-body NNN force, which gives attractive effects to light nuclei but strongly repulsive effects to heavy nuclei. Thus the properties of the NNN force have been clarified with both of the precise NN data and a variety of precise nuclear data. Similarly, Quantum Monte Carlo calculations for Λ hypernuclei suggest a strongly repulsive ΛNN force, which supports massive neutron stars heavier than $2.0M_\odot$ [19]. However, in order to obtain quantitative information on the YNN force, rich and precise experimental data on the two-body YN forces in free space, together with a variety of precise hypernuclear data, are indispensable.

Until now we have investigated structure of hypernuclei to extract information on the YN and YY interactions, but this strategy has to be changed. Rich and precise YN/YY data in free space would determine low energy constants in the chiral effective field theory extended to the BB interactions [20], which will be then applied to *ab initio* or precise calculations of hypernuclei [21].

5.1 *YN, YY interactions in free space*

Due to experimental difficulty from short hyperon lifetimes, YN scattering data have been extremely limited in statistics and energy ranges. The scattering data have not been updated from sparse ones taken in 1970s using bubble chambers and in 1990s with scintillating fiber images.

Very recently, $\Sigma^\pm p$ scattering experiment has started running at J-PARC (E40), aiming at 100 times improvement in statistics than the previous data [22]. This type of YN scattering experiments will be further carried out at a new beam line (K1.1 line) at J-PARC. At the CLAS experiment in JLab, data analysis for high statistics Λp scattering events is in progress [23].

On the other hand, momentum correlation between two particles emitted from a small hot volume produced in high energy proton-nucleus or nucleus-nucleus collisions contains information on the interaction between the two particles. Λ-Λ and Ξ^--p correlations have been studied with ALICE data [24]. The $\Xi^- p$ correlation data clearly showed that the strong interaction between Ξ^- and p is attractive. This method is applicable to studies of YY interactions, not only $\Lambda\Lambda$ but also $\Lambda\Sigma$, $\Sigma\Sigma$, $\Lambda\Xi$, *etc.*, which cannot be studied via scattering experiments nor hypernuclei.

5.2 *YN interaction in nuclear medium*

Comparing high-precision experimental data on light to heavy Λ hypernuclei with high-precision calculations based on the realistic and precise YN interactions would reveal the properties and the strength of the ΛNN interaction. For example, Nijmegen BB interaction models (ESC models) based on meson exchange picture have been recently updated to include three-body NNN repulsive force of which strength is determined to reproduce the ^{16}O-^{16}O scattering cross sections at large angles where the nuclear density is expected to reach more than $2\rho_0$ in the middle of the collision [25]. By assuming that the YNN, YYN, and YYY channels also have the same three-body repulsion as NNN (so called "universal three-body force"), they found that the maximum mass of neutron stars calculated with the degree of freedom for hyperons exceeds the observed mass of $2M_\odot$. In this assumption, the calculated B_Λ values of Λ single-particle states in light to heavy (A=13–208) Λ hypernuclei change by ~1 MeV or less as shown in Fig. 6. Reflecting the averaged nuclear density where the Λ wave function distributes, a density dependent effect of the three-body repulsion is seen as difference of the slope of the B_Λ value as a function of A as well as slight change of the behavior of the B_Λ

difference among the s, p, d, f single-particle states. In order to experimentally extract information on the repulsive three-body force strength, however, the B_Λ values should be measured in ~0.1 MeV accuracy for hypernuclei in a wide range of A.

Most of the present experimental data for B_Λ values of medium and heavy Λ hypernuclei were obtained via the (π^+, K^+) reaction at KEK-PS with the accuracy of ~1 MeV [3, 26]. To improve the accuracy to ~0.1 MeV, high resolution spectroscopy is planned at JLab and J-PARC. At JLab, the $(e, e'K^+)$ spectroscopy with ~0.5 MeV (FWHM) resolution will be extended to medium and heavy hypernuclei. While the $(e, e'K^+)$ spectroscopy may suffer from severe electromagnetic background for heavy (large Z) nuclear targets, the (π^+, K^+) spectroscopy can be used for heavy hypernuclei such as ${}^{208}_{\Lambda}$Pb with almost no background as demonstrated in Ref. [26].

At J-PARC, we are planning an extension of the hadron facility in order to add more production targets and install several new secondary beam lines [27]. One of the most unique apparatus there will be the high-intensity high-resolution (HIHR) beam line (see Fig. 7). At present pion beam intensity is limited by counting rate of the tracking detectors inserted in the beam. On the other hand, the HIHR line is designed to determine the beam momentum with accuracy of ~0.2 MeV/c using the momentum dispersion matching method without inserting detectors in the beam, and the full intensity of pions (~$2.8\times10^8\pi^+$/spill at 1.2 GeV/c for 25-kW beam loss on a primary target) will be utilized for the (π^+, K^+) spectroscopy experiments with 0.2 MeV (FWHM) resolution.

Although a Λ hyperon has no isospin, the ΛN interaction in nuclear matter may be different between in symmetric matter and in pure neutron matter, because ΛNN three-body force for isospin $T = 0$ and 1 channels may differ. Thus the T=1 ΛNN force (Λnn interaction) has to be investigated to describe neutron star matter. At JLab Hall A, an experiment to measure the ^{40}Ca,^{48}Ca $(e, e'K^+)$ ${}^{40}_{\Lambda}$K,${}^{48}_{\Lambda}$K spectra precisely is being prepared to reveal the strength of the T=1 ΛNN force [28].

6. Summary

Strangeness nuclear physics has made significant progress, experimentally at J-PARC, JLab, Mainz, *etc.* and via various theoretical developments. At J-PARC, a γ-ray spectroscopy experiment

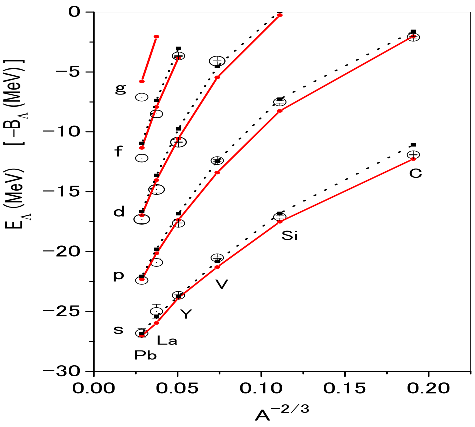

Fig. 6. Λ binding energies (B_Λ) of the Λ's s, p, d, f and g single-particle states in light to heavy (A=13–208) hypernuclei calculated using the Nijmegen ESC model with the universal three-body repulsion (MPa) (solid lines) and without it (dotted lines) [25]. Experimental values are shown with open circles.

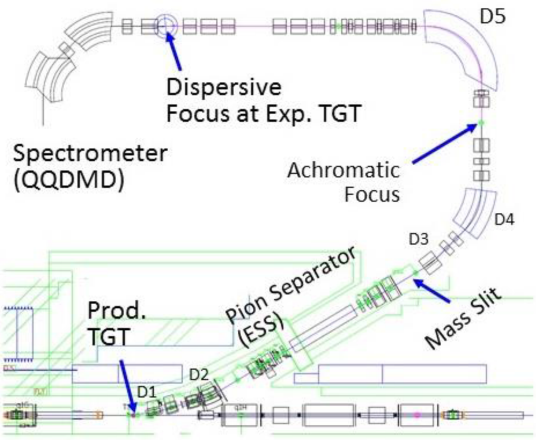

Fig. 7. HIHR beam line planned at the extended hadron facility at J-PARC [27].

was performed for ${}^{4}_{\Lambda}$He and ${}^{19}_{\Lambda}$F and revealed their level schemes. The energy of the ${}^{4}_{\Lambda}$He($1^+ \to 0^+$) transition clearly confirmed the existence of a large charge symmetry breaking (CBS) effect in A=4 Λ hypernuclei. Together with the Mainz data for the ${}^{4}_{\Lambda}$H weak decay pion energy, it was found that the large CSB effect appears only in the ground state 0^+ but not in the excited 1^+ state. At J-PARC, double strange hypernuclei have been recently studied and new ΛΛ hypernuclear events and a new Ξ^- nuclear deeply bound state have been observed. In future, high statistics data for YN and YY scattering and correlation will be obtained, and high precision spectra for light to heavy Λ hypernuclei are planned to be measured at JLab and with the new HIHR line at J-PARC. Both of these studies would allow us to reveal the properties of ΛNN three-body force and to solve the hyperon puzzle.

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