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How can we solve the hyperon puzzle?

—Introduction to "topical session on ΛNN three-body force"

Hirokazu Tamura[1,2,*]

[1]Department of Physics, Tohoku University, Sendai 980-8578, Japan
[2]Advanced Science Research Center, Japan Atomic Energy Agency, Tokai 319-1195, Japan

Abstract. As an introduction to the "topical session on ΛNN three-body force" in HYP2022, a scenario to solve the hyperon puzzle and to elucidate high density matter in neutron stars is proposed. It is related to the J-PARC Hadron Facility extension project, in which experimental studies of ΛNN three-body force (3BF) via high precision spectroscopy of Λ hypernuclei and high quality ΛN scattering are one of the flagship subjects in the project. Development of theoretical methods to extract 3BF effects from experimental data and to reliably extrapolate them to higher density is challenging but extremely important.

1 Introduction

Microscopic understanding of the high density matter in the core of neutron stars (NS's) is one of the most challenging subjects in hadron/nuclear physics. In particular, there is a serious contradiction called "hyperon puzzle" between observational data of massive NS's and our knowledge and frameworks of nuclear physics; huge fermi energies of neutrons in the NS core provoke their conversion to hyperons, particularly to Λ's which undergo considerable attraction in nuclear matter as demonstrated by hypernuclear data. Such hyperon appearance drastically softens the Equation-Of-State (EOS) of nuclear matter, leading to the conclusion that the three reliable observational data of NS's with twice the solar mass cannot be supported at all.

Most probably, the contradiction is caused by our naive assumption that the Λ's in-medium attraction experimentally confirmed only at the normal nuclear density (ρ_0) can be also applied to higher density nuclear matter. It is well known that microscopic calculations based on the realistic NN interaction models, which describe all the NN scattering data and light nuclei (by adding attractive NNN 3BF from pion exchange), fail to reproduce the nuclear saturation density ρ_0, indicating that a repulsive, short-range 3BF is at work. It is natural to imagine a similar repulsive ΛNN (and $\Lambda\Lambda N$, $\Lambda\Lambda\Lambda$) interaction. However, we have no experimental evidence so far [1] to support this idea.

2 How to see the ΛNN 3BF effects in experiments

Yamamoto *et al.* used the Nijmegen ESC08c models for YN interaction and phenomenologically introduced a "universal" baryon-baryon-baryon (BBB) 3BF common to all the baryon channels, of which strength was determined from the NNN 3BF strength necessary to reproduce the ^{16}O-^{16}O scattering cross sections at 70 MeV/A [2]. Using this model, they calculated

*e-mail: tamura@lambda.phys.tohoku.ac.jp

[1]In this topical session, Friedman and Gal suggested a hint of ΛNN 3BF in the B_Λ data of Λ hypernuclei [1].

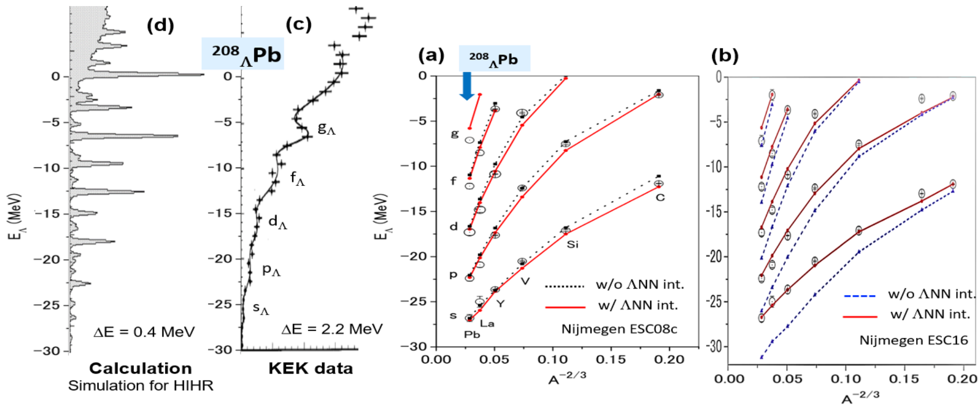

Figure 1. (a) B_Λ values of various Λ's single particle states for a wide range of hypernuclear mass number A calculated using the ESC08 interaction [2], without and with the universal 3BF for ΛNN. Experimental data are shown in inside circles. (b) The same as (a) but the ESC16 interaction is used [3]. (c) $^{208}_{\Lambda}$Pb spectrum measured at KEK [4] shown together with the figures (a) and (b). (d) Simulated $^{208}_{\Lambda}$Pb spectrum expected in the proposed experiment at HIHR [5] based on a theoretical calculation.

binding energies (B_Λ) of Λ's single-particle orbits ($0s$, $0p$, $0d$, $0f$) for a wide range of hypernuclear mass number ($A = 12 - 208$) and compared them with the data, as shown in Fig. 1 (a). When the universal 3BF is turned on, the A-dependence of the B_Λ values became slightly weaker, reflecting the density-dependent repulsive force. Thus, it was found that those B_Λ values contain a density dependent effect of the ΛN interaction, although the effect is only less than 1 MeV for $A = 12-208$. They also found that the EOS calculated with the universal 3BF successfully supports the two solar-mass NS's.

It is noted that in the NN case the density dependence cannot be studied in this method, because most of the single-particle nucleon hole states are too broad to be observed. On the contrary, a Λ hyperon is free from Pauli principle from nucleons and behaves as a distinguishable particle in a nucleus. For each of the single-particle Λ states, we know the local nuclear density where the Λ stays, since the spatial distribution of the Λ wave function in the hypernucleus can be theoretically calculated rather well. Thus, the A-dependence and the orbital dependence of the B_Λ values in Λ hypernuclei can be unique probes to extract the strength of the ΛNN force, if the B_Λ values are measured in ~0.1 MeV accuracy.

In order to reliably extract the ΛNN force strength, the ΛN interaction in the free space should be accurately known. Actually, as shown in Fig. 1 (b), another version of the ESC models (ESC16) gives a drastically different A-dependence between the cases without and with the universal 3BF [3]. This change between Fig. 1 (a) and (b) is caused by a difference of the p-wave component of the ΛN interaction between ESC08c and ESC16. Our present knowledge of the ΛN interaction is based on sparce Λp scattering data supplemented by Λ hypernuclear data. However, the hypernuclear data cannot be used for the present purpose, and accurate Λp scattering data are absolutely necessary.

3 Experimental prospects to solve the hyperon puzzle at J-PARC

Aiming at solving the hyperon puzzle, new experiments are proposed at J-PARC. In order to study ΛNN 3BF, we plan to perform a series of high precision Λ hypernuclear spectroscopy study via the (π^+, K^+) reaction [6], combined with high quality Λp scattering experiments [7]. It is one of the flagship programs in the J-PARC Hadron Facility extension project [5]. In this extension project, the primary proton beam line is extended and a new production target is installed, and then several new secondary beam lines are constructed. With the momentum dispersion matching technique, the High Intensity High Resolution beam line (HIHR) delivers an intense ($\sim 2.5 \times 10^8$/spill) pion beam with a high resolution of ~0.4 MeV (FWHM) for the (π^+, K^+) hypernuclear spectroscopy [6]. The K1.1 beam line is a high-purity mass-separated line for low momentum （$\leq$1.1 GeV/c） kaon beams, which will be used for Λ production in the ΛN scattering experiment [7].

4 Theoretical prospects

In our plan, the property and the strength of the ΛNN 3BF will be extracted from the high-resolution Λ hypernuclear spectroscopy and ΛN scattering experiments and then applied to higher density matter in NS's. However, how to extrapolate them to densities higher than ρ_0, strongly depends on the theoretical framework. Discussing how to develop appropriate theoretical frameworks is an important motivation of this topical session.

The chiral effective field theory (chEFT) approach for NN interaction has a great potential to describe higher density matter via systematic treatment of the NNN 3BF appearing at N^{2}LO and higher order calculations. The low energy constants (LECs) are determined from the rich NN scattering data. However, determination of the two contact terms (c_D, c_E) responsible for the NNN 3BF is not straightforward. Studies are in progress using various data of light nuclei (^{3}H, ^{4}He *etc.*), pd scattering, or the nuclear saturation density [8].

The chEFT approach is extended to BB interactions including hyperons and the NLO calculation has been made [9]. In order to determine the LECs, high quality YN scattering data are essential, even though the flavor SU(3) symmetry is helpful. Then, in a similar way as the NNN case, the LEC's for the ΛNN 3BF could be determined from light Λ hypernuclear data as well as Λd scattering data to be available in the future. Here, unlike the case of NNN 3BF, precise B_Λ data of single-particle Λ states of various Λ hypernuclei are expected to play significant roles particularly in determining the 3BF contact terms. Here, theoretical development for precise calculations of light to heavy hypernuclear structure is quite important.

It is noted that lattice QCD calculations also play important roles. The HAL QCD approach has succeeded in deriving the BB interaction potentials [10]. Calculations for various BB channels will be checked by correlation measurements with high energy nuclear collisions ("femtoscopy") and used to supplement the ΛN, ΣN scattering data in the construction of the SU(3)$_f$ extended chEFT interactions. In addition, efforts are being made to apply the HAL QCD method to the BBB 3BF [11]. In the future, lattice-calculated ΛNN 3BF will be directly compared with the hypernuclear data.

5 Scenario to solve the hyperon puzzle

Figure 2 summarizes our scenario to solve the hyperon puzzle. We plan to collect high-quality Λp and Σp scattering data from the K1.1 (and High-p) beam lines at J-PARC and provide YN scattering database to theorists. YN scattering data from JLab(CLAS) are also useful particularly for momenta higher than 1 GeV/c. In addition, YN/YY interaction data of other channels are also required to construct BB interaction models with a help of SU(3)$_f$ symmetry. $\Xi/\Lambda\Lambda$ hypernuclei and Ξ^- atom data from the K1.8 line in the present J-PARC Hadron Facility provide ΞN and $\Lambda\Lambda$ interactions, and femtoscopy data for various channels ($\Lambda\Lambda$, ΞN, $\Xi\Xi$, ΩN *etc.*) will be also accumulated in high energy experiments. It is to be also mentioned that $\bar{K}N$ interaction data from kaonic nuclei/atoms from J-PARC K1.8BR and DAΦNE are also necessary for constructing EOS.

Employing all these data, "realistic BB interaction" models will be constructed, for example, by upgrading the Nijmegen ESC models. In parallel, the SU(3)$_f$-extended chEFT model

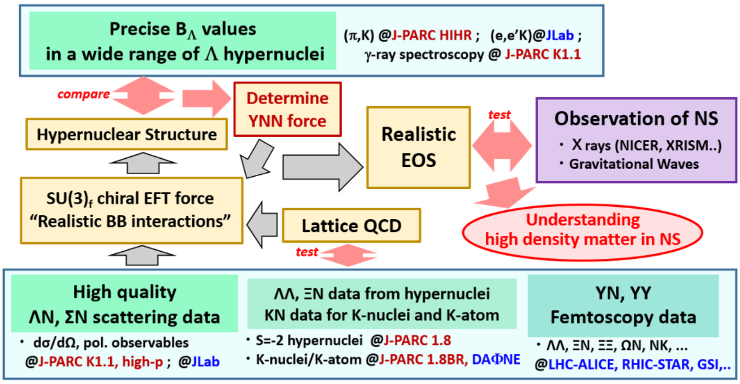

Figure 2. Scenario to solve the hyperon puzzle in the J-PARC Hadron Facility extension project.

will proceed to the N^{2}LO calculation and the LEC's, including those for the ΛNN 3BF, will be hopefully determined. The lattice QCD calculations confirmed by experiments will be employed to improve the realistic BB interactions. Then, Λ hypernuclei will be precisely calculated from the realistic BB interactions.

Precise hypernuclear B_Λ data to be measured at HIHR as described above, as well as $(e, e'K^+)$ spectroscopy data at JLab, will be compared with the precise calculations. To separate and assign closely-located peaks in the spectra, γ-ray spectroscopy will be applied at K1.1 for low-lying s_Λ states of the same hypernucleus. Thus, the property and strength of the ΛNN 3BF will be extracted. If the 3BF is found to be not very repulsive and cannot reproduce the observed massive NS's, it could suggest that deconfined quark matter begins to appear in NS's at rather low densities of 2–3ρ_0. If not, the 3BF should be properly incorporated into the extended chEFT interaction by determining the LEC's from those hypernuclear data, so that the chEFT interaction can be reliably applied to higher density for calculation of EOS. This would be a theoretical challenge.

Finally, the calculated EOS will be tested by mass and radius data of NS's. Such data are being accumulated via X-ray observation by NICER and then by XRISM satellite. Gravitational wave (GW) data will also provide additional information on the stiffness of NS mergers. When the BB interaction is reliably determined by our studies, more realistic calculations of GW templates will be possible and unique information will be extracted from GW data.

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