Knowledge on doubly strange hypernuclei and experimental prospect

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Abstract. Expermiments for doubly strange hypernuclei with nuclear emulsion have been perfomed at KEK and J-PARC for the past 30 years. From detected 47 events, the characteristics were understood for Λ-Λ interaction to be weakly attrative, linear mass number dependence for two Λs binding energy, presence of Ξ hypernucleus, and it can be seen for something like level stracture of ${}^{15}_{\Xi}\mathrm{C}$. Developing scanning method, so calld *overall-scanning method*, probably present more rich information on not only doubly strange hypernuclei but also single-Λ hypernuclei.

1 Introduction

Sixty years have passed since double-Λ hypernucleus was first detected and reported in 1963 [1, 2]. About 30 years later, the second event [3] showing a clear sequential decay topology was detected in the E176 experiment (KEK-PS)[1], in which *hybrid-emulsion method* combining the emulsion and real-time detectors was firstly applied for nuclear physics experiment to study doubly strange hypernuclei. With the development and refinement of *hybrid-emulsion method* in E373 (KEK-PS) and E07 (J-PARC) experiments, about 50 candidate events of doubly strange hypernuclei have now been detected in the emulsion.

Regarding double-Λ hypernuclei, it is possible to measure mass defect, which is the binding energy of two Λ hyperons by ordinal nucleus, denoted as $B_{\Lambda\Lambda}$, given by

$$B_{\Lambda\Lambda}({}^{\mathrm{A}}_{\Lambda\Lambda}\mathrm{Z}) = M({}^{\mathrm{A}-2}\mathrm{Z}) + 2M(\Lambda) - M({}^{\mathrm{A}}_{\Lambda\Lambda}\mathrm{Z}), \tag{1}$$

where M is the mass of the mass of the particles in parentheses. If there is no relationship, interaction, between two Λ hyperons, the $B_{\Lambda\Lambda}$ value will be same as twice of the binding energy of a Λ hyperon, B_{Λ}, in single-Λ hypernuclei. Then the value of $\Delta B_{\Lambda\Lambda}$, so-called $\Lambda\Lambda$ interaction energy, defined by

$$\Delta B_{\Lambda\Lambda}({}^{\mathrm{A}}_{\Lambda\Lambda}\mathrm{Z}) = B_{\Lambda\Lambda}({}^{\mathrm{A}}_{\Lambda\Lambda}\mathrm{Z}) - 2B_{\Lambda}({}^{\mathrm{A}-1}_{\Lambda}\mathrm{Z}), \tag{2}$$

is necessary to be checked. When positive (negative) value for $\Delta B_{\Lambda\Lambda}$ is obtained, Λ-Λ interaction would be considered to be attractive (repulsive).

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[1] A detection of ${}^{6}_{\Lambda\Lambda}\mathrm{He}$ was reported in 1966 [4], however few people accept that result contradicting the data of Nagara event [5] at present.

Binding energy of Ξ^- hyperon, B_{Ξ^-}, is also mesured at captured points by emulsion nuclei, especially ^{12}C, ^{14}N or ^{16}O. B_{Ξ^-} value is obtained as

$$M({}^{\mathrm{A}}\mathrm{Z}) + M(\Xi^-) \ - \ B_{\Xi^-} = M({}^{\mathrm{A}_1}_{\Lambda}\mathrm{Z}_1) + M({}^{\mathrm{A}_2}_{\Lambda}\mathrm{Z}_2) + M'(\sum_{\mathrm{i}=1}^{\mathrm{j}} m_{\mathrm{i}}) + KE, \tag{3}$$

where $M({}^{\mathrm{A}_1}_{\Lambda}\mathrm{Z}_1)$ and $M({}^{\mathrm{A}_2}_{\Lambda}\mathrm{Z}_2)$ are each mass of single-Λ hypernuclei, ${}^{\mathrm{A}_1}_{\Lambda}\mathrm{Z}_1$ and ${}^{\mathrm{A}_2}_{\Lambda}\mathrm{Z}_2$, respectively. If some particles are emitted from Ξ^- captured point, M' is counted as total mass of emitted particles, where each mass is m_{i}. KE is total kinetic energy of emitted particles including neutral ones, which can be known by momentum imbalance.

At present, the relation between mass number of A and $B_{\Lambda\Lambda}$ can be seen for double-Λ hypernuclei. The detection of Ξ hypernucleus revealed that an attractive force works between Ξ and nucleus, and furthermore, a level structure can be seen for ${}^{15}_{\Xi}\mathrm{C}$ by B_{Ξ^-} of several samples of Ξ hypernucleus. We are also developing In this report, characteristics as above will be introduced.

2 Experiments for doubly strange hypernuclei with nuclear emulsion

The *hybrid-emulsion method* was firstly developed to effectively detect charmed-particles and measure their masses and life times at the FNAL-E531 experiment [6]. In E531, real-time detectors ware used for tagging neutrino uinteractions in the emulsion via detecttion of charged particles. That policy was carried over to the doubly strange hypernucleus experiment with the emulsion, where the $p(\mathrm{K}^-, \mathrm{K}^+)\Xi^-$ reaction was tagged with K$^+$ meson, in the KEK-E176 experiment, and further developed in the E373 (KEK) and E07 (J-PARC) experiments. In those experiments, K$^-$ beam was irradiated to the emulsion stacks. The beam condition, stack composition and emulsion sheets are summarized in Table 1.

Table 1. The beam condition, stack composition and emulsion sheets for E176, E373 and E07. Nuclear emulsion was coated on both sides of 70-μm-thick polistyrene (PS) film for thick-type sheet. In E373 and E07, one thin-type sheet using 200-μm-thick PS film was set to the upstream of the thick type sheet. Expected numbers of Ξ^- stopping event are also presented.

	E176	E373	E07
K$^-$ momentum (GeV/c)	1.67	1.67	1.81
Beam intencity	3×10^3	1.1×10^3	$\sim 3 \times 10^5$
K$^-$/π^- ratio of the beam	1/3	1/4	6/1
K$^+$ spectrometer magnet	Ushiwaka	Kurama	Kurama
Number of irradiated stack	15	95	118
Number of sheet for one stack	42	11	11
Sheet size (cm^2)	23×23	24.5×25.0	34.5×35.0
Emulsion thickness <thick> (mm)	0.55	0.50	0.50
< thin > (mm)	—	0.10	0.10
Total emulsion gel (t)	0.4	0.8	2.1
Number of Ξ^- stopping	10^2	10^3	10^4

In Figure 1, the setup around the target of the E07 experiment is illustrated. Beam K$^-$ particles reacted with nucleus in diamond (^{12}C) target. When the Kurama spectrometer detected K$^+$ candidate parrticle, energy depoit of secondary particles was recorded at SSDs.

To check Ξ^- particle production, missing mass of $(\mathrm{K}^-,\mathrm{K}^+)$ rections was analized. Finally, the events with K^+ momentum between 0.90 to 1.45 GeV/c were nominated as associating with Ξ^- particle. Ξ^- particle tracks were searched in the upstream SSDs and measered their angle and position. Then the Ξ^- tracks were searched in the top thin type emulsion sheet, automatically. After a human confirmed that the detected track would be real, the Ξ^- candidates were automatically followed through the thick type sheet until it came to stop. If doubly strange light-hypernuclei are produced, three vertices can be seen at the Ξ^- stopping points. This scanning system with information of real-time detectors is called as Emulsion-Counter *Hybrid Method*.

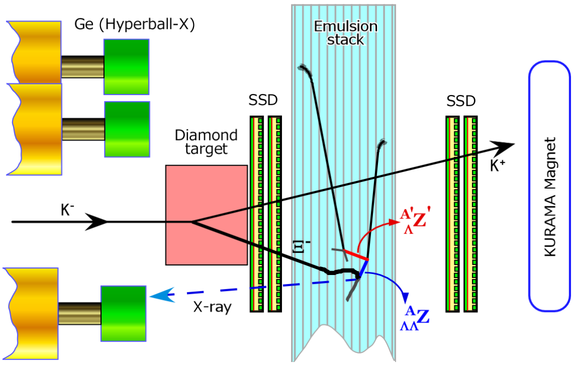

Figure 1. The setup around the target of the E07 experiment. Germanium (Ge) detectors, Hyperball-X, were located to measure X-ray from Ξ^- capture reaction for checking formation of Ξ hypernucleus via energy of of X-ray [7].

3 Experimental results on doubly strange hypernuclei

In the E176, the E373 and the E07 experiments, we dected events with squential weak decay of double-Λ hypernuclei and with two single-Λ hypernuclei, so-called twin hypernuclei, emitted from Ξ^- captured points. The number of those events is summarized in Table 2.

Table 2. Numbers of detected doubley strange hypernuclei from three experiments (E176, E373 and E07). The Kiso event is counted in Twin of E373, although it was detected at the development of the *overall-scanning method* to search for the events in whole volume of the emulsion without help of real-time detectors.

	double-Λ	Twin	double-Λ or Twin	total
E176	1	2	1	4
E373	4	3	3	10
E07	14	13	6	33
total	19	18	10	47

3.1 Double-Λ hypernuclei

The value of $\Delta B_{\Lambda\Lambda}$ is the key for Λ-Λ interaction as mentioned in Sect. 1. In that point of view, the Nagara event uniquely presented to work weakly attractive force as 0.67 ± 0.17 MeV between two Λ particles [5, 8]. Reinterpretations of the earlier detected events of [1, 2] and of[3] in E176 were made to be consistent with the result of the Nagara event. In E07, we removed the constraint of being consistent with the Nagara event and nominated the cases for events with $\Delta B_{\Lambda\Lambda}$ within ± 5 MeV. The Mino event showed $\Delta B_{\Lambda\Lambda} = 1.87 \pm 0.37$ MeV, which was not consistent with that of the Nagara event, as the most probable case [9].

In Figure 2, $B_{\Lambda\Lambda}$ values for several double-Λ hypernuclei are polotted against mass number A. It can be seen for a linear A dependence for $B_{\Lambda\Lambda}$ values.

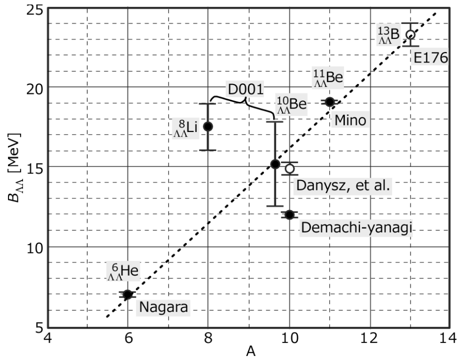

Figure 2. The relation of $B_{\Lambda\Lambda}$ values and mass number A. The numerical values of Nagara [8], D001 [10], Mino [9], and E176, Demachi-Yanagi, and Danysz et al. [11] are summarized in [7] with this figure.

3.2 Ξ hypernuclei - twin hypernuclei

In the E176 experiment, two events showed a topology which emitted two single-Λ hypernuclei at Ξ^- captured point. They said that two units of strangeness were surely transferred to nucleus. In most probable case for both of them, Ξ^- were provably captured by ^{12}C nuclei. Those events ware interpreted to decay into (1) ${}^{4}_{\Lambda}\mathrm{H}+{}^{9}_{\Lambda}\mathrm{Be}$ and (2) ${}^{4}_{\Lambda}\mathrm{H}+{}^{9}_{\Lambda}\mathrm{Be}^*$. The papers for each events introduced B_{Ξ^-} to be 0.54 MeV (1) [12] and 0.62 MeV (2) [13] with ~ 0.2 MeV errors. Although we and some theorists discussed a presence of a Coulomb assisted nuclear $2p$ state in Ξ hypernucleus, someones claimed that they were consistent with atomic 3D level (0.13 MeV) due to large errors. After the mass change of the Ξ^- hyperon by 0.4 MeV, the B_{Ξ^-} values for both events were recalculated with kinetatical fitting. We obtained B_{Ξ^-} to be 0.82 MeV for both with errors 0.17 MeV (1) and 0.14 MeV (2) [11], which were inconsistent with 3D level, however, we had to wait for detection of more highly reliable Ξ hypernucleus.

The Kiso event commented at Table 2 confirmed the presence of the Ξ hypernucleus for ${}^{15}_{\Xi}$C (Ξ^-+^{14}N) with the B_{Ξ^-} to be 4.38 ± 0.25 MeV or 1.11 ± 0.25 MeV [14]. There were two interpritations (ground or the 1st excited states) for one of two single-Λ hypernuclei emitted from the Ξ^- captured point, the both B_{Ξ^-} values were clearely over the atomic 3D level (0.17 MeV) of Ξ^--^{14}N system with errors of 3 standard deviations. (Later, the B_{Λ} value of ${}^{10}_{\Lambda}$Be was precisely measured [15], and B_{Ξ^-} values of the Kiso event have been revised as 3.87 ± 0.21 MeV or 1.03 ± 0.18 MeV [16]). In the E07 experiment, the Ibukli event gave a unique value of B_{Ξ^-} for ${}^{15}_{\Xi}$C as 1.27 ± 0.27 MeV [17], then the value of 1.03 ± 0.18 MeV would be more appropriate for one of lebels of ${}^{15}_{\Xi}$C nucleus. The attrcative nuclear force between Ξ^- and nucleus (^{14}N) surely work and the preasence of the Coulomb assisted nuclear $2p$ state was confirmed around $B_{\Xi^-} = 1$ MeV.

The Irrawaddy event by E07 uniquely presented more deeper bound (6.27 ± 0.27 MeV) of Ξ^- in ^{14}N [18]. In the E373 experiment, since we had detected such deeper bound event, the Kinka event, reanalisys for Kinka has been performed, and obtained $B_{\Xi^-} = 8.00 \pm 0.77$ MeV or 4.96 ± 0.77 MeV [18].

B_{Ξ^-} values of detected twin hypernuclei for Ξ^- captured in ^{14}N are plotted with theoretical predictions in Figure 3. Theoretical calculations predicted that $2p$ and $1s$ atates will be ~ 1.0 MeV and ~ 6 MeV, respectively. Detail discussion with this figure is given in Ref. [7]. By the observation of the level structure of ${}^{15}_{\Xi}$C, two events of E176 seem to be reseen on discussion about $2p$ state of Ξ^--^{12}C system.

4 Current status to search for doubly strange hypernuclei

As we can see figures 2 and 3, information from experiments is still limited at present. When we started experiment on hypernuclear physics with nuclear emulsion, the *hybrid method* was

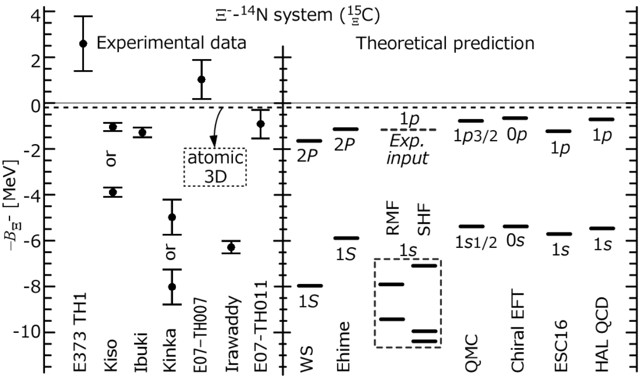

Figure 3. B_{Ξ^-} values of detected twin hypernuclei. All of them are the cases of Ξ^- captured in ^{14}N. References and this figure are presented in Ref [7].

vey helpful to serach for very rare event such as doubly strange hypernuclei in the emulsion by getting free of very hard human activity. However, nobody can detect all of the events even if we use very clever real-time detecors. In the E07 experiment, about 70% for $(\mathrm{K}^-,\mathrm{K}^+)$ event were not tagged due to the limitation of spectorometer acceptance and tracking. In addition to K^+ tagging, Ξ^- hyperon will be prodeuced via 'n'(K^-, K^0)Ξ^- reaction. Such reaction shall be expected in more higher rate. Thus we have started to develop *overall-scanning method* to serach for typical topologies of production and decay of doubly strange hypernuclei with three vertices.

The *overall-scanning method* consists of microscope with high speed image taking in the emulsion and image-recognition with machine learning for object detection, which is educated by simulated images. Firstly we applied this method for detecting α decay with four or five prongs, then we achived 80% efficiency with S/N $\sim$ 0.17 [19]. Next this method was applied for measurement of B_{Λ} on ${}^{3}_{\Lambda}$H, precisely. In Figure 4, a detected ${}^{3}_{\Lambda}$H event was shown with the *overall-scanning method* [20].

At present, we apply the current machine learning to doubly strange hypernuclei and several event have been detected. In addition to object detection, we are going to build detection method of segement and edge of tracks for machine learning.

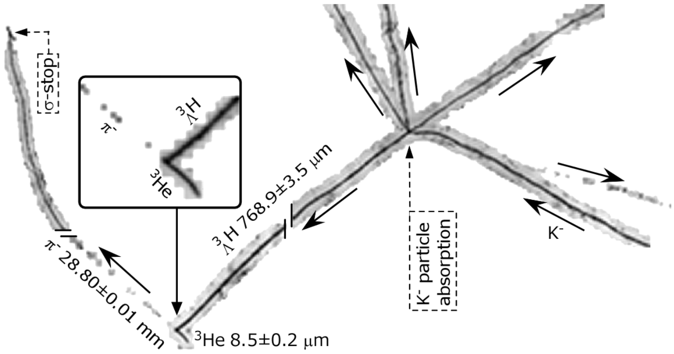

Figure 4. Firstly detected scheme of production and decay of ${}^{3}_{\Lambda}$H with *overall-scanning method* in Ref [7]. The original figure is presented in Ref. [20].

5 Concluding remarks and prospect

By detection of 47 doubly strange hypernuclei, beginning with E176 and continuing through E373, E07 experiments, we understood as follows;

. Λ-Λ interaaction is weakly attractive,
. the values of $B_{\Lambda\Lambda}$ has linear dependence on mass number A,

. Ξ hypernuclus surely exisiti and the interacion between Ξ^- and ^{14}N is attractive,
. the level structure of $^{15}_{\Xi}$C will be seen for $2p$ state to be $B_{\Xi^-} \sim 1.0$ MeV and $1s$ state may be around 6 MeV.

With the development of *overall- scanning method*, we shall detect one thousand samples of doubly strange hypernuclei in the not-too-far future. Then, by using E07 emulsion, it will be sure that knowledge on doubly strange hyernuclei becomes more rich on, for examples, Λ-Λ interaction for not only two Λs in ground state but one Λ in excited state, and more precise mesureament of level scheme for $^{13}_{\Xi}$B and $^{17}_{\Xi}$N as well as $^{15}_{\Xi}$C. In addition to them, precise measurement of B_Λ of single-Λ hypernuclei, which is expected for 1 million events, shall be performed and hypernuclei can be studied with p-bar beam which was exposed in the emulsion for position callibration for emulsion sheet by sheet.

In J-PARC, the E70 experiment is ready for beam exposure to search for $^{12}_{\Xi}$Be by measuring missing mass spectrum of $^{12}\mathrm{C}(\mathrm{K}^-,\mathrm{K}^+)^{12}_{\Xi}\mathrm{Be}$ reaction [21]. The extenion of the Hadron Experimental Facility at J-PARC must open the nuclear physics with $S = -3$.

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