

Information and perspective for doubly-strange hypernuclei with nuclear emulsion detector

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Abstract. The study on doubly-strange hypernuclei has been performed with nuclear emulsion detector at KEK-PS and J-PARC for 30 years. Detected 47 candidate events of doubly-strange hypernuclei show characteristics for the Λ - Λ and Ξ - N interactions. The Λ - Λ interaction is weakly at-tractive and the binding energy of two Λ hyperons to nuclei shows linear dependence on the mass number of a nucleus. The Ξ^- hyperon is found to be bound by the ^{14}N nucleus, forming the ^{15}C hypernucleus, with larger energy than that given by Coulomb force. Also, the level scheme of the Ξ^- hyperon in the ^{15}C hypernucleus can be seen. With the light source of hard X-ray instead of an optical microscope, since it will enable to count grains constituting tracks in the emulsion, charge recognitions of light nuclei, especially H^+ and He^{2+} , can be possible. This would work effectively in determining the nuclides of doubly-strange hypernuclei. The ‘*overall-scanning method*’ to scan whole volume of the emulsion sheets will allow to detect nearly 1×10^3 events of doubly-strange hypernuclei, which is the expected number recorded in the emulsion of the E07 experiment, with machine learning in the near future.

1 Introduction

The detections of double- Λ hypernucleus were reported for more than 50 years ago [1-3]. The interaction energy, $\Delta B_{\Lambda\Lambda}$, between two Λ hyperons was presented to be about 3 – 5 MeV. After that, no doubly-strange hypernuclei were detected, because detection by skilled personnel had reached its limits. Doubly-strange hypernuclei have been very useful for unified understanding of the baryon(B)- B interaction under $\text{SU}(3)_f$ symmetry, and for the study of the nuclear equation of state of neutron stars because of likely appearance of hyperons in them.

In the E176 experiment at KEK-PS, four candidates of doubly-strange hypernuclei in about 52 at-rest events of Ξ^- hyperon were successfully detected via $p(\text{K}^-, \text{K}^+)\Xi^-$ reactions with Emulsion-Counter ‘*hybrid-method*’ [4-7], with which electric detectors predict the highly possible positions of production of doubly-strange hypernuclei in the emulsion sheet.

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However, the nuclide of double- Λ hypernucleus was not identified uniquely, and the case close to the $\Delta B_{\Lambda\Lambda}$ in the past was preferred. Other two events were candidates of Ξ hypernucleus formed via at-rest absorption of Ξ^- hyperon in ^{12}C nucleus.

Among nearly 4×10^2 events of Ξ^- hyperon captured at rest by nuclei in the emulsion with the *hybrid-method*, the detection of the Nagara event, ${}_{\Lambda\Lambda}^6\text{He}$ (${}^4\text{He} + 2\Lambda$) in the E373 experiment at KEK-PS requested change of the $\Delta B_{\Lambda\Lambda}$ to about 1 MeV, then the Λ - Λ interaction was confirmed to be weakly attractive [8, 9]. The past three double- Λ hypernuclei showing the range of $\Delta B_{\Lambda\Lambda}$ to be 3 – 5 MeV were also re-examined. The $\Delta B_{\Lambda\Lambda}$ reported in Ref. [3] had a large discrepancy with the one given by the Nagara event, even if both events were composed by the same nuclide, so that the authenticity of one event of Ref. [3] was lost. Among 10 candidate events of doubly-strange hypernucleus, the Kiso event was the first demonstration of the presence of deeply bound Ξ hypernucleus, ${}_{\Xi}^{15}\text{C}$, where the event was detected in the development of ‘*overall-scanning method*’ to search for typical-topology event of doubly-strange hypernuclei in whole volume of the emulsion sheets [10]. Later analysis showed that the Kinka event gave even deeper binding [11].

In the E07 experiment at J-PARC, 33 candidate events of doubly-strange hypernuclei have been detected among 2×10^3 at-rest captured events of Ξ^- hyperon with the *hybrid-method*. One double- Λ hypernucleus, the Mino event, has presented the $\Delta B_{\Lambda\Lambda}$ of ${}_{\Lambda\Lambda}\text{Be}$ nucleus, where $\Delta B_{\Lambda\Lambda}$ value was not consistent with the one by the Nagara event in the most likely case as a ${}_{\Lambda\Lambda}^{11}\text{Be}$ [12]. Regarding Ξ hypernuclei, the Ibuki event showed a Coulomb-assisted nuclear bound state of ${}_{\Xi}^{13}\text{C}$ uniquely [13]. The Irrawaddy event was understood to be unique detection of a nuclear s -state of ${}_{\Xi}^{15}\text{C}$ [11]. The accumulation of Ξ hypernuclei has revealed the level structure of the Ξ hypernucleus of ${}_{\Xi}^{15}\text{C}$.

Total number of candidates of doubly-strange hypernuclei is 47, and information on Λ - Λ and Ξ - N interactions was obtained in less than 20 events. This is because, in many events, the daughter particles emitted from production and decay of doubly-strange hypernuclei cannot be identified. To identify charges of the daughter particles, e.g. H^+ , H^{2+} , Li^{3+} , Be^{4+} or B^{5+} , the development has been made for the measurement of track thickness in the emulsion [14]. A more promising approach is the use of X-rays as a light source for microscopy [15]. By using X-ray microscopy, developed grains consisting tracks can be counted, then the discrepancy of the grain densities of tracks allows for the identification of the charge.

In the E07 emulsion, the *hybrid-method* was applied to effectively get information of at-rest stopping Ξ^- hyperons. However, many events were lost due to mis-detection of electric detectors, especially no-detection of $n(\text{K}^-, \text{K}^0)\Xi^-$ events. If it is possible to detect the production and decay of doubly-strange hypernuclei with the *overall-scanning method*, the detectable number of doubly-strange hypernuclei is estimated to reach one thousand. The R&D of the *overall-scanning method* with a machine learning method is on-going.

2 Information for doubly-strange hypernuclei

Regarding double- Λ hypernuclei, two physical values are defined as

$$B_{\Lambda\Lambda} = M(^{\Lambda-2}\text{Z}) + 2M(\Lambda) - M({}_{\Lambda\Lambda}^{\Lambda}\text{Z}), \quad (1)$$

$$\Delta B_{\Lambda\Lambda} = B_{\Lambda\Lambda} - 2B_{\Lambda}({}_{\Lambda}^{\Lambda-1}\text{Z}), \quad (2)$$

where M is the symbol for the mass of the particles in brackets. The $B_{\Lambda\Lambda}$ is the binding energy of two Λ hyperons by a double- Λ hypernucleus with the mass of $M({}_{\Lambda\Lambda}^{\Lambda}\text{Z})$. The Λ binding energy by a single- Λ hypernucleus of ${}_{\Lambda}^{\Lambda-1}\text{Z}$ is denoted as $B_{\Lambda}({}_{\Lambda}^{\Lambda-1}\text{Z})$.

The Nagara event presented the $B_{\Lambda\Lambda}$ and $\Delta B_{\Lambda\Lambda}$ values to be 7.25 ± 0.19 MeV and 1.01 ± 0.20 MeV, respectively [8]. As mentioned above, the oldest double- Λ hypernucleus event [1, 2] was then revised for the values of $B_{\Lambda\Lambda}$ and $\Delta B_{\Lambda\Lambda}$ to be 14.7 ± 0.4 MeV and 1.3 ± 0.4 MeV

as the formation of ${}_{\Lambda\Lambda}^{10}\text{Be}$, respectively [9]. The $B_{\Lambda\Lambda}$ and $\Delta B_{\Lambda\Lambda}$ values of E176 double- Λ hypernucleus were also revised as 23.3 ± 0.7 MeV and 0.6 ± 0.8 MeV, respectively [9]. From the E373 and E07 experiments, three and two events have been published as double- Λ hypernuclei, respectively [9, 10, 16]. Published data for $B_{\Lambda\Lambda}$ and $\Delta B_{\Lambda\Lambda}$ of double- Λ hypernuclei are listed in Table 1. The relationship between $B_{\Lambda\Lambda}$ and mass number A for most probable case with small errors is plotted in Figure 1, where a linear dependence between them can be seen.

Table 1. Published data of $B_{\Lambda\Lambda}$ and $\Delta B_{\Lambda\Lambda}$ under assumption of Ξ^- hyperon captured in atomic 3D state in ${}^{12}\text{C}$, ${}^{14}\text{N}$ or ${}^{16}\text{O}$. Regarding the Nagara event, the values of the $B_{\Lambda\Lambda}$ and $\Delta B_{\Lambda\Lambda}$ have been revised in Ref. [9] as in this table due to change of the mass of Ξ^- hyperon in Ref. [17].

Event	Ξ^- captured by nuclide	$B_{\Lambda\Lambda}$ (MeV)	$\Delta B_{\Lambda\Lambda}$ (MeV)	Comments [reference(s)]
Nagara	${}^{12}\text{C}$ ${}_{\Lambda\Lambda}^6\text{He}$	6.91 ± 0.16	0.67 ± 0.17	Uniquely identified [9]
Danysz, et al.	${}^{12}\text{C}$ ${}_{\Lambda\Lambda}^{10}\text{Be}$	14.7 ± 0.4	1.3 ± 0.4	${}_{\Lambda\Lambda}^{10}\text{Be} \rightarrow {}_{\Lambda}^9\text{Be}^*$ ($E_x = 3.0$ MeV) [9, 18]
E176	${}^{14}\text{N}$ ${}_{\Lambda\Lambda}^{13}\text{B}$	23.3 ± 0.7	0.6 ± 0.8	${}_{\Lambda\Lambda}^{13}\text{B} \rightarrow {}_{\Lambda}^{13}\text{C}^*$ ($E_x = 4.9$ MeV) [7]
Demachi-yanagi	${}^{14}\text{N}$ ${}_{\Lambda\Lambda}^{10}\text{Be}^*$	11.90 ± 0.13	-1.52 ± 0.15	most probable (topology) [9] $E_x \sim 2.8$ MeV for ${}_{\Lambda\Lambda}^{10}\text{Be}^*$
Mikage	${}^{12}\text{C}$ ${}_{\Lambda\Lambda}^6\text{He}$	10.01 ± 1.71	3.77 ± 1.71	most probable (mesonic decay) [9]
	${}^{12}\text{C}$ ${}_{\Lambda\Lambda}^{11}\text{Be}$	22.15 ± 2.94	3.95 ± 3.00	
	${}^{14}\text{N}$ ${}_{\Lambda\Lambda}^{11}\text{Be}$	23.05 ± 2.59	4.85 ± 2.63	
Hida	${}^{12}\text{C}$ ${}_{\Lambda\Lambda}^{11}\text{Be}$	20.83 ± 1.27	2.61 ± 1.34	Assumed 10.24 MeV for $B_{\Lambda}({}_{\Lambda}^{11}\text{Be})$ [9]
	${}^{14}\text{N}$ ${}_{\Lambda\Lambda}^{12}\text{Be}$	20.48 ± 1.21	2.00 ± 1.21	
Mino	${}^{16}\text{O}$ ${}_{\Lambda\Lambda}^{10}\text{Be}$	15.05 ± 0.11	1.63 ± 0.14	most probable (χ^2 minimum) [12]
	${}^{16}\text{O}$ ${}_{\Lambda\Lambda}^{11}\text{Be}$	19.07 ± 0.11	1.87 ± 0.37	
	${}^{16}\text{O}$ ${}_{\Lambda\Lambda}^{12}\text{Be}$	13.68 ± 0.11	-2.7 ± 1.0	
D001	${}^{12}\text{C}$ ${}_{\Lambda\Lambda}^8\text{Li}$	17.50 ± 1.46	6.34 ± 1.46	likely by $B_{\Lambda\Lambda}$ [16]
	${}^{14}\text{N}$ ${}_{\Lambda\Lambda}^{11}\text{Be}$	15.05 ± 2.78	1.63 ± 2.78	

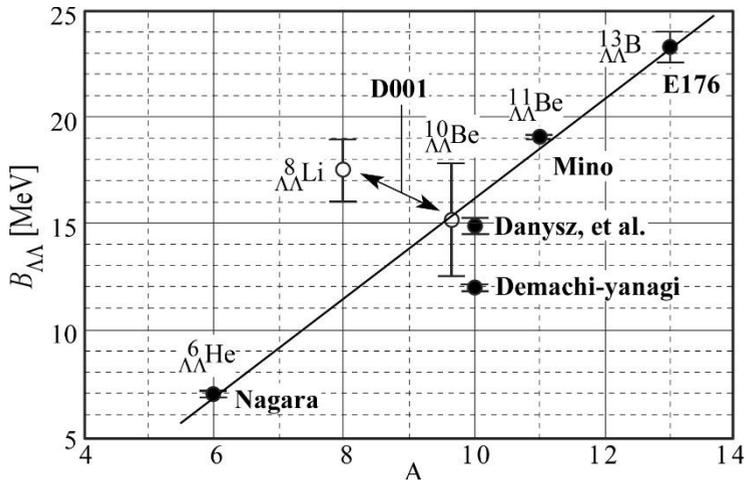


Fig. 1. Relationship between the mass number A and $B_{\Lambda\Lambda}$ for the most probable cases with small errors form Table 1.

If Ξ^- hyperon is bound by a nucleus with a much strong force than Coulomb one, a Ξ hypernucleus is formed, and it is desirable to measure the binding energy of the Ξ^- hyperon, B_{Ξ^-} , in the nucleus. This is equivalent to measuring the mass of the nucleus containing the Ξ^- hyperon by measuring the total energy obtained from all decay products. For this

measurement, an event, twin hypernucleus, in which two single- Λ hypernuclei of known mass are emitted from the Ξ^- absorption point is preferred. Therefore B_{Ξ^-} is obtained as

$$M(^A Z) + M(\Xi^-) - B_{\Xi^-} = M(^{A_1}_{\Lambda} Z_1) + M(^{A_2}_{\Lambda} Z_2) + M(\sum_{i=1}^k m_i) + KE, \quad (3)$$

where the $^{A_1}_{\Lambda} Z_1$, $^{A_2}_{\Lambda} Z_2$ and m_i are two single- Λ hypernuclei and other emitted particles, respectively. KE is the total kinetic energy of every emitted particle from the absorption point.

There have been 18 events of twin hypernuclei detected in the past three experiments. The nuclides that could be identified as absorbing Ξ^- hyperons were ^{12}C , ^{14}N and ^{16}O , with the number of events, 4, 7 and 1, although the molar ratio are 0.55 : 0.15 : 0.30, respectively. In the case of ^{14}N , the core nucleus after absorbing Ξ^- hyperon becomes carbon. It may be easy to identify the absorbing nuclide because decay daughters of the Ξ^- - ^{14}N system tend to be α clusters. Among the events that have not been identified, there may be events absorbed by ^{12}C and ^{16}O . However, the number of ^{14}N absorption of 7 is large compared to $18 \times 0.15 = 2.7$.

The experimental values of B_{Ξ^-} in the case of the ^{14}N absorption are plotted with several theoretical calculations in Figure 2. The nuclear $2p$ state is clearly seen at about -1 MeV. There should be the nuclear $1s$ state at $-5 \sim -8$ MeV. Theoretical calculations are in good agreement with experimental data. Detail discussion is given in Ref. [11] and experimental values can be found therein.

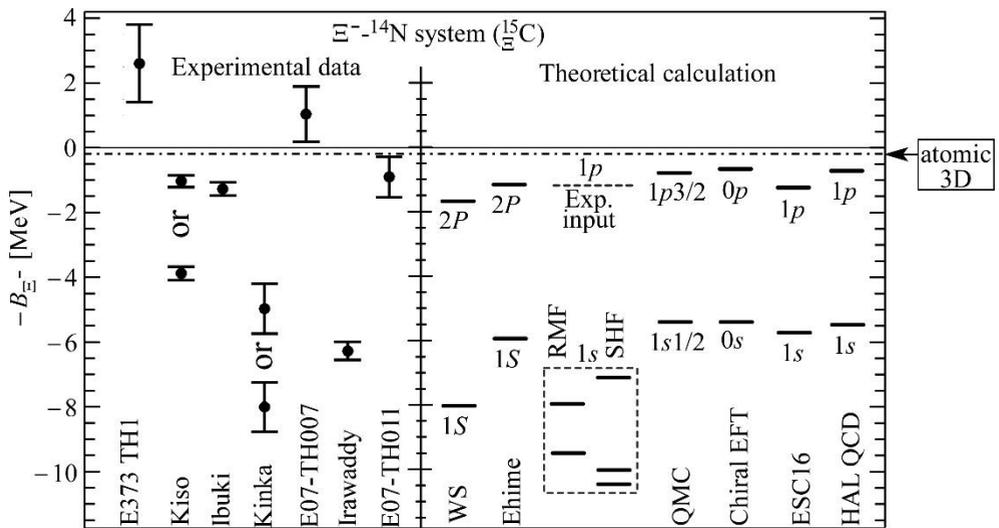


Fig. 2. Experimental data of B_{Ξ^-} and various theoretical calculations. Relevant references of both ones are given in Ref. [11] except for Chiral-EFT [19], ESC16 [20] and HAL-QCD [21].

3 R&D for systematic study of doubly-strange hypernuclei

Much research and development has been done to identify as many doubly-strange hypernuclei as possible. However, for more than 50% of the candidates, no detailed information is available at the moment, because the nuclide of decay daughters cannot be determined as introduced in Section 1.

Very recently, the use of X-rays reveals the possibility to identify the decay daughter particles by measuring the relation between the energy loss, developed grain density (G.D. : grains/0.1mm), and the length of the track with X-ray microscopy. Figure 3 shows track

images of a ${}^1\text{H}^+$ and a ${}^4\text{He}^{2+}$ near their stopping points. The G.D. was measured for 3 and 10 tracks of ${}^1\text{H}^+$ and ${}^4\text{He}^{2+}$, respectively, on the range $10 \sim 80 \mu\text{m}$ from the stopping point. Very preliminary results show 231 ± 11 and 267 ± 6 [grains/0.1mm] for ${}^1\text{H}^+$ and ${}^4\text{He}^{2+}$, respectively. It thus seems to be possible to recognize the charge of both nuclei. The number of samples is currently small and should be increased, and then the possibility of identification would be confirmed for other nuclides of Li, Be and B.

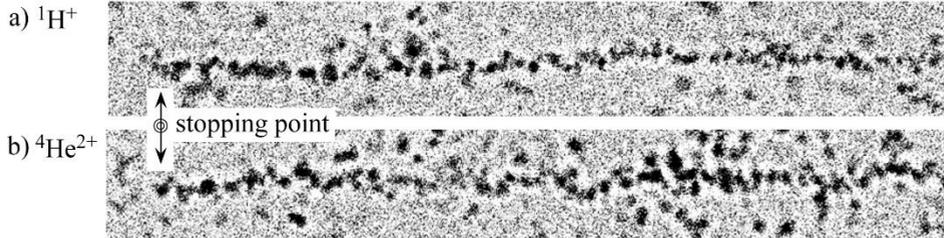


Fig. 3. Images taken by X-ray microscopy for tracks of a) ${}^1\text{H}^+$ and b) ${}^4\text{He}^{2+}$ around their stopping point.

As mentioned in Section 1, about 1×10^3 candidate events might be recorded in the emulsion sheets. Although it would be sufficient to search the whole volume of the emulsion sheets, it would take 560 years if people have to search for them. Therefore, the development of the *overall-scanning method* has been started for more than 10 years ago. Initially, line-segment detection in microscope images of tracks was attempted by means of the Hough transform. It was applied to the detection of α particle groups associated with the decay of natural radioisotopes with some success [22], but was not put into practical use.

Recently, machine learning models have been developed to detect rare events recorded in the emulsion sheets, with positive results. Track information of rare events was generated by Monte Carlo simulation and its image style was transformed into mimetic image in the emulsion. They are employed to train a machine learning model for event detection, and the model can obtain the position and topology of events in actual microscopic images. These models were applied to search for ${}^3_{\Lambda}\text{H}$ to precisely measure the Λ binding energy, and the decay of ${}^3_{\Lambda}\text{H}$ was successfully detected [23-25]. During the search for the decay of ${}^3_{\Lambda}\text{H}$, an event with a topology of production and decay of double- Λ hypernucleus was successfully detected, although the nuclide could not be determined uniquely. The development of machine learning models has been started for selective detection of doubly-strange hypernuclei [25]. Now, a model successfully detects the Nagara event. No doubt further development will lead to the detection of numerous doubly-strange hypernuclei in the near future.

4 Summary and perspective

The *hybrid-method* with nuclear emulsion detector has opened a doorway for the study of doubly-strange hypernuclei. By the detection of double- Λ hypernuclei, the Λ - Λ interaction was found to be weakly attractive and two Λ hyperons' binding energies, $B_{\Lambda\Lambda}$, seem to linearly depend on the mass number of core nuclei. The presence of a Ξ hypernucleus being deeper bound than by Coulomb force shows the Ξ - N interaction to be attractive. By dedicated technics analysing the events in the emulsion and the *overall-scanning method* with machine Learning models, an order of magnitude more doubly-strange hypernuclei will be detected. Much detailed understanding will then be obtained of the interaction relevant to double strangeness sector using doubly-strange hypernuclei. By the Hadron-Hall extension at J-PARC, we will be able to step out of the doubly-strange hypernuclei and study the triple strangeness world.

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