EPJ Web of Conferences **291**, 01015 (2024)
MESON 2023
https://doi.org/10.1051/epjconf/202429101015

Knowledge of doubly strange hypernuclei and experimental prospect

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Abstract. Experiments for doubly strange hypernuclei with nuclear emulsion have been performed at KEK and J-PARC for the past 30 years. From detected 47 events, the characteristics were understood for - interaction to be weakly attractive, linear mass number dependence for two s binding energy, presence of hypernucleus, and it can be seen for something like the level structure of ^{15} C. Developing scanning method, so-called *overall-scanning method*, probably presents more rich information on not only doubly strange hypernuclei but also single- hypernuclei.

1 Introduction

Sixty years have passed since double- 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 the *hybrid-emulsion method* combining the emulsion and real-time detectors was first applied to nuclear physics experiment to study doubly strange hypernuclei. With the development and refinement of the *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- hypernuclei, it is possible to measure mass defect, which is the binding energy of two particles by ordinal nucleus, denoted as B , given by

$$B\quad(^{A}Z) = M(^{A\ \ 2}Z) + 2M(\ )\quad M(^{A}Z), \tag{1}$$

where M is the mass of the particle enclosed in parentheses. If the interaction between two particles is very weak, the B value will be the same as twice the binding energy of the particle, B , in single- hypernuclei. Then the value of B , so-called interaction energy, defined by

$$B\quad(^{A}Z) = B\quad(^{A}Z)\quad 2B\ (^{A\ \ 1}Z), \tag{2}$$

is necessary to be checked. When the positive (negative) value for B is obtained, - interaction would be attractive (repulsive).

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

Binding energy of the particle, B , is also measured at captured points by emulsion nuclei, especially ^{12}C, ^{14}N, or ^{16}O. B value is obtained as

$$M(^{A}Z) + M(\quad) \quad B \quad = M(^{A_1}Z_1) + M(^{A_2}Z_2) + M\,(\ _{i=1}^{j}\ m_i) + KE, \tag{3}$$

where $M(^{A_1}Z_1)$ and $M(^{A_2}Z_2)$ are each mass of single- hypernuclei, $^{A_1}Z_1$ and $^{A_2}Z_2$, respectively. If some particles are emitted from the captured point, M is counted as the total mass of emitted particles, where each mass is m_i. KE is the total kinetic energy of emitted particles including neutral ones, which can be known by momentum imbalance.

At present, the relation between the mass number of A and B can be seen for double-hypernuclei. The detection of hypernucleus revealed that an attractive force works between and the nucleus, and a level structure can be seen for ^{15} C by B of several samples of hypernucleus. In this report, the characteristics above will be introduced with the development of a detection method for doubly strange hypernuclei.

2 Experiments for doubly strange hypernuclei with nuclear emulsion

The *hybrid-emulsion method* was first developed to effectively detect charmed particles and measure their masses and lifetimes at the FNAL-E531 experiment [6]. In E531, real-time detectors were used for tagging neutrino interactions in the emulsion via the detection of charged particles. That policy was carried over to the doubly strange hypernucleus experiment with the emulsion, where the p(K ,K$^+$) 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, the K beam was irradiated to the emulsion stacks. The beam condition, stack composition, and emulsion sheets are summarized in Tab. 1.

Table 1. The beam condition, stack composition, and emulsion sheets for E176, E373, and E07. The nuclear emulsion was coated on both sides of 70- m-thick polystyrene (PS) film for a thick-type sheet. In E373 and E07, one thin-type sheet using 200- m-thick PS film was set upstream of the thick-type sheet. Expected numbers of stopping events are also presented.

	E176	E373	E07
K momentum (GeV/c)	1.67	1.67	1.81
Beam intensity	3 10^3	1.1 10^3	3 10^5
K / ratio of the beam	1 / 3	1 / 4	6 / 1
K$^+$ spectrometer magnet	Ushiwaka	Kurama	Kurama
Number of irradiated stacks	15	95	118
Number of sheets 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 stopping	10^2	10^3	10^4

In Fig. 1, the setup around the target of the E07 experiment is illustrated. Beam K particles reacted with the nucleus in the diamond (^{12}C) target. When the Kurama spectrometer detected the K$^+$ candidate particle, the energy deposit of secondary particles was recorded at SSDs. To check the Ξ^- particle production, the missing mass of $(K^-\ K^+)$ reactions was analyzed. Finally, the events with the K^+ momentum between 0.90 to 1.45 GeV/c were nominated as associating with the Ξ^- particle. The Ξ^- particle tracks were searched in the upstream SSDs and measured their angle and position. Then the Ξ^- tracks were searched in the top thin type of emulsion sheet, automatically. After a human confirmed that the detected track would be real, the Ξ^- candidates were automatically followed through the thick type of sheet until it came to a stop. If doubly strange light-hypernuclei are produced, three vertices can be seen at the Ξ^- stopping points. This scanning system with information from real-time detectors is called as Emulsion-Counter *Hybrid Method*.

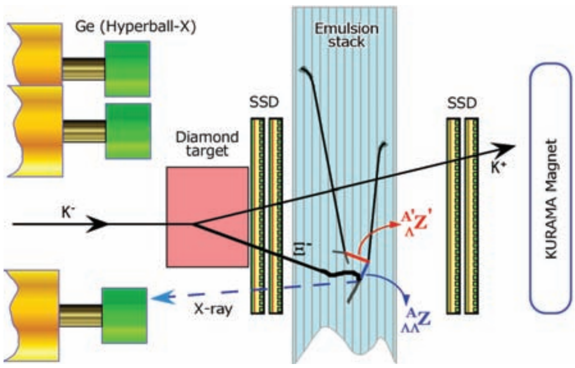

Figure 1. The setup around the target of the E07 experiment. Hyperball-X germanium detectors (Ge) were located to measure X-rays from Ξ^- capture reaction for checking the formation of Ξ hypernucleus via the energy of X-ray [7].

3 Experimental results on doubly strange hypernuclei

In the E176, the E373, and the E07 experiments, we detected events with sequential 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 Tab. 2.

Table 2. Numbers of detected doubly strange hypernuclei from three experiments (E176, E373 and E07). The Kiso event is counted in the Twin of E373, although it was detected at the development of the *overall-scanning method* to search for the events in the whole volume of the emulsion without the 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 Sec. 1. From 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 Ref. [1, 2] and of Ref. [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 Fig. 2, $B_{\Lambda\Lambda}$ values for several double-Λ hypernuclei are plotted against the mass number A. It can be seen for a linear A dependence for $B_{\Lambda\Lambda}$ values.

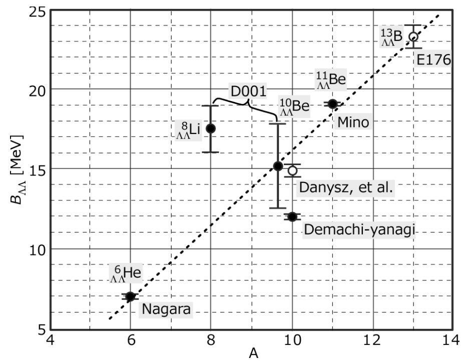

Figure 2. The relation of B values and mass number A. The numerical values of Nagara [8], D001 [10], Mino [9], and E176, Demachi-Yanagi, and Danysz et al. [11] are summarized in [7] with this figure.

3.2 hypernuclei - twin hypernuclei

In the E176 experiment, two events showed a topology that emitted two single- hypernuclei at captured point. They said that two units of strangeness were surely transferred to the nucleus. In most probable cases for both of them, the particles were probably captured by ^{12}C nuclei. Those events were interpreted to decay into (1) ^{4} H$+^9$ Be and (2) ^{4} H$+^9$ Be . The papers for each event introduced B to be 0.54 MeV (1) [12] and 0.62 MeV (2) [13] with 0.2 MeV errors. Although we and some theorists discussed the presence of a Coulomb-assisted nuclear $2p$ state in hypernucleus, some claimed that they were consistent with atomic 3D level (0.13 MeV) [14]. After the mass change of the particle by 0.4 MeV, the B values for both events were recalculated with kinematical fitting. We obtained B to be 0.82 MeV for both with errors 0.17 MeV (1) and 0.14 MeV (2) [11], which were inconsistent with the 3D level, however, we had to wait for the detection of more highly reliable hypernucleus.

The Kiso event commented at Tab. 2 confirmed the presence of the hypernucleus for ^{15}C ($+^{14}$N) with the B to be 4.38 0.25 MeV or 1.11 0.25 MeV [15]. There were two interpretations (ground or the 1st excited states) for one of two single- hypernuclei emitted from the captured point, the both B values were clearly over the atomic 3D level (0.17 MeV) of -^{14}N system with errors of 3 standard deviations. (Later, the B value of ^{10}Be was precisely measured [16], and B values of the Kiso event have been revised as 3.87 0.21 MeV or 1.03 0.18 MeV [17]). In the E07 experiment, the Ibukli event gave a unique value of B for ^{15}C as 1.27 0.27 MeV [18], then the value of 1.03 0.18 MeV would be more appropriate for one of the levels of ^{15}C nucleus. The attractive nuclear force between and nucleus (^{14}N) surely works, and the presence of the Coulomb-assisted nuclear $2p$ state was confirmed around B $= 1$ MeV.

The Irrawaddy event by E07 uniquely presented more deeper bound (6.27 0.27 MeV) of in ^{14}N [19]. In the E373 experiment, since we had detected such a deeper bound event, the Kinka event, reanalysis for Kinka has been performed and obtained B $= 8.00$ 0.77 MeV or 4.96 0.77 MeV [19].

B values of detected twin hypernuclei for captured in ^{14}N are plotted with theoretical predictions in Fig. 3. Theoretical calculations predicted that $2p$ and $1s$ states will be 1.0 MeV and 6 MeV, respectively. A detailed discussion with Fig. 3 is given in Ref. [7]. By the observation of the level structure of ^{15}C, two events of E176 seem to be reseen on the discussion about $2p$ state of -^{12}C system.

4 Current status to search for doubly strange hypernuclei

As we can see in Figs. 2 and 3, information from experiments is still limited at present. When we started experimenting with hypernuclear physics with nuclear emulsion, the *hybrid*

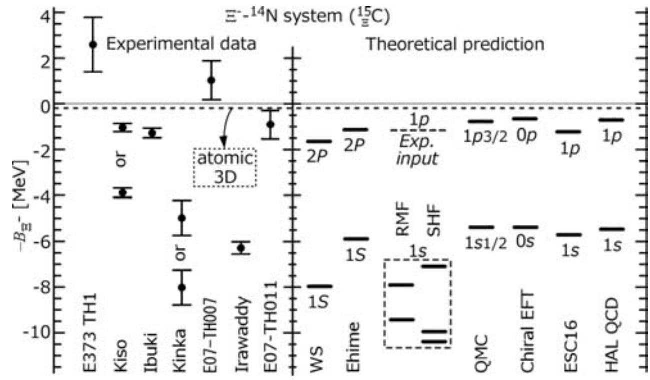

Figure 3. B values of detected twin hypernuclei. All of them are the cases of captured in ^{14}N. References and this figure are presented in Ref [7].

method was very helpful in searching for very rare events such as doubly strange hypernuclei in the emulsion by getting free of very hard human activity. However, nobody can detect all the events even if we use very clever real-time detectors. In the E07 experiment, about 70% of (K , K$^+$) events were not tagged due to the limitation of spectrometer acceptance and tracking. In addition to K$^+$ tagging, the particle will be produced via n(K , K^0) reaction, where neutrons (n) are in the target diamond and emulsion nuclei. Such a reaction shall be expected at a much higher rate. Thus, we have started to develop *overall-scanning method* to search for typical topologies of production and decay of doubly strange hypernuclei with three vertices.

The *overall-scanning method* consists of a 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 decay with four or five prongs, then we achieved 80% efficiency with S/N 0.17 [20]. Next, this method was applied for the measurement of B on ^{3}H, precisely. In Fig. 4, a detected ^{3}H event was shown with the *overall-scanning method* [21].

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

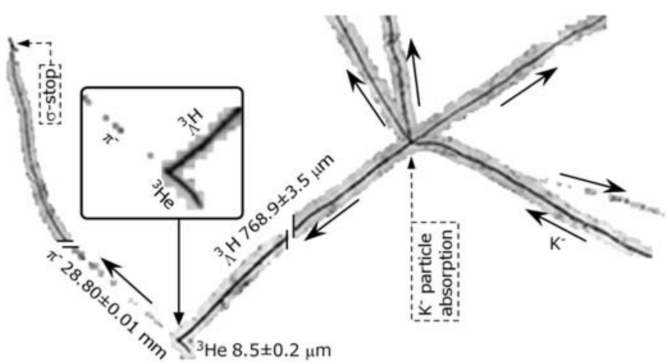

Figure 4. Firstly, detected scheme of production and decay of ^{3}H with *overall-scanning method* in Ref [7]. The original figure is presented in Ref. [21].

5 Concluding remarks and prospect

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

- - interaction is weakly attractive.

. The values of B have a linear dependence on mass number A.
. hypernuclei surely exist and the interaction between and ^{14}N is attractive.
. The level structure of ^{15}C will be seen for the $2p$ state to be B 1.0 MeV, and the $1s$ state may be around 6 MeV.

With the development of the *overall-scanning method*, we shall detect one thousand samples of doubly strange hypernuclei in the future. Then, by using the E07 emulsion, it will be sure that knowledge on doubly strange hypernuclei becomes much richer on, for example, - interaction for not only two s in the ground state but one in an excited state, and more precise measurement of level scheme for ^{13}B and ^{17}N as well as ^{15}C. In addition to them, precise measurement of B of single- hypernuclei, which is expected for 1 million events, shall be performed and hypernuclei can be studied with a p-bar beam which was exposed in the emulsion for position calibration for emulsion sheet by sheet.

In J-PARC, the E70 experiment is ready for beam exposure to search for ^{12}Be by measuring missing mass spectrum of ^{12}C(K ,K^{+})^{12}Be reaction [22]. The extension of the Hadron Experimental Facility at J-PARC must open the nuclear physics with $S =$ 3.

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