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Status of the J-PARC E07, Systematic Study of Double Strangeness Nuclei with the Hybrid Emulsion Method

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The current status of the J-PARC E07 experiment and two typical events, a ${}_{\Lambda\Lambda}$Be hypernuclear event named "MINO" and ${}^{15}_{\Xi}$C hypernuclear event named "IBUKI", are presented. J-PARC E07 is the most complex emulsion experiment so far to investigate double hypernuclei. The physics run at the K1.8 beam line in the J-PARC hadron facility and photographic development of all emulsion sheets have been completed. The emulsion sheets are presently being analyzed with dedicated optical microscopes. Current statistics are estimated to be about twice that of KEK-PS E373. Quantitative data on $\Delta B_{\Lambda\Lambda}$ of double Λ hypernucleus and B_{Ξ^-} of Ξ hypernucleus are being accumulated successfully.

KEYWORDS: double Lambda hypernuclei, Xi hypernuclei, baryon-baryon interaction, hybrid emulsion method

1. Introduction

Double hypernuclei (DH), such as double Λ hypernuclei (DLH) and Ξ hypernuclei (XH) are valuable sources of information on the $\Lambda\Lambda$ and ΞN interaction. One of the goals of modern physics is to understand the mechanism of matter formation through the hierarchical structure from quarks to nuclei. Thus, study of the baryon-baryon interaction is an active and essential topic of this field. In particular, experimental information in the S=-2 sector, $\Lambda\Lambda$ and ΞN interaction, is urgently required because it is still very scarce due to experimental difficulties. Therefore, DH have been investigated to obtain information on $\Lambda\Lambda$ and ΞN interactions through their mass measurements.

One of the most successful methods to investigate DH is an "emulsion experiment", in which the precise analysis of their production and decay by photographic image with sub-μm spatial resolution [1–3]. Emulsion sheets for E07 are made of very sensitive photographic emulsions which allow tracking minimum ionizing particles. The emulsion sheets have a thickness of nearly 1 mm to record nuclear events with a large solid angle. After the photographic development, tracks are observed under an optical microscope. Computer controlled microscopes and image recognition techniques are used in modern emulsion analysis. With a series of micrographs, we reconstruct production and decay processes of DH and calculate the mass.

J-PARC E07 is expected to detect 10 times higher statistics of DH events compared to past experiments. We completed beam exposure and photographic processing of the all emulsion modules as scheduled. In this article, the current status of the experiment, progress of the data analysis and found DH events, are introduced.

2. The J-PARC E07 Experiment

J-PARC E07 is the most ambitious emulsion experiment with DH thus far. This experiment is designed as an extension of the previous experiment, KEK-PS E373 [3]. The amount of emulsion gel used in the E07 was 2.1 tons (about three times E373). We prepared about 1500 emulsion sheets measuring 35.0 cm × 34.5 cm from Dec. 2013 to May 2014. The purity of the K^- beam provided by the K1.8 beamline in the J-PARC hadron facility [4, 5] was 82%, which is three times better than the previous beam provided by the KEK-PS accelerator. The yield of DH events is designed to be 10 times larger than that in the E373 in order to detect a larger variety of DH nuclides for a systematic validation of the $\Lambda\Lambda$ and ΞN interactions. The effective beam time was less than 30 days, which is a practical period, thanks to the high-intensity beam of J-PARC in spite of the scale-up.

In order to find DH effectively, we employed the so-called "Hybrid emulsion method", which is a combination of electronics detectors and emulsion sheets. The procedure is described as follows:

- The KURAMA spectrometer tags (K^-, K^+) reactions which produce Ξ^- particles.
- A Silicon Strip Detector (SSD) which is located between the target and the emulsion module detects the tracks of the Ξ^-s.
- An emulsion scanning system searches them in the first emulsion sheet faced with the SSD.
- An automated tracking system follows them through several emulsion sheets [6].

Some Ξ^-s travel through the emulsion sheets by losing kinetic energy and stop, where, finally, some Ξ^-s are captured by the surrounding nuclei in the emulsion sheet. A XH is formed if the Ξ^- is bound in a deep enough orbit by the Ξ^--nucleus interaction. Moreover, a DLH is formed if the two Λs converted from Ξ^- + proton are bound on the same nucleus.

The beam exposure of J-PARC E07 was performed at the K1.8 beamline in the J-PARC hadron facility in two periods, Jun. 2016 and Apr.-Jun. 2017. A total of 118 modules, containing one thousand five hundred emulsion sheets, were used. The target was irradiated by 1.13×10^{11} K^- beam particles. Photographic development of all emulsion sheets has been completed at Gifu Univ. in Feb. 2018. The developed emulsion sheets are presently being analyzed with the tracking systems at JAEA and Gifu Univ.

Thus far, we have analyzed approximately 20% of the total statistics collected by E07, which is almost twice the statistic achieved in the E373. The time to scan one emulsion module is about one week with a microscope system. Based on these analyses, we observed 7 DLH events and 6 twin single Λ hypernuclear (TH) events as special events. We analyzed all of them in detail, that is, we measured the angle and length of the tracks with sub-µm spatial resolution. Then we finally evaluated conservation laws and kinematic consistency to identify their production and decay process of DLH or TH events. Among them, we have succeeded in the identification of the nuclide for several events.

3. Detected Special Events

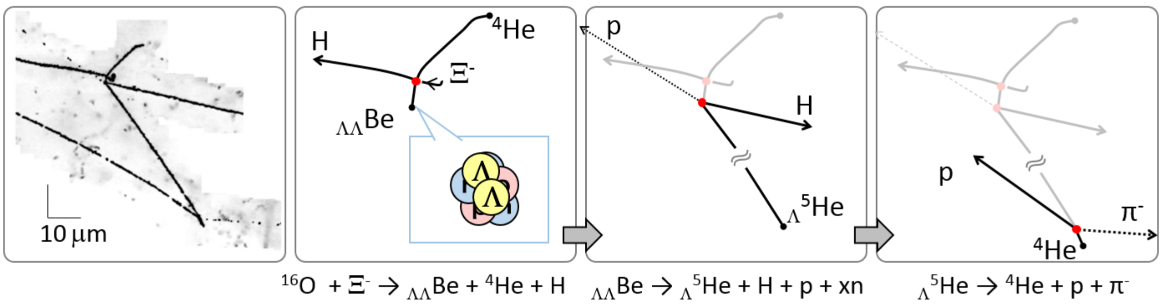

Fig. 1. A micrograph of the MINO event and its schematic drawing of production and sequential decay.

Figure 1 shows a DLH event found in Jul. 2018 named “ MINO ” [7]. A DLH was produced at the stop point of Ξ^- and it decayed twice sequentially. The nuclide of the DLH was interpreted as one of the following candidates: ${}^{10}_{\Lambda\Lambda}$Be, ${}^{11}_{\Lambda\Lambda}$Be, or ${}^{12}_{\Lambda\Lambda}$Be*. Among them, the most probable interpretation was found to be ${}^{11}_{\Lambda\Lambda}$Be from a kinematic analysis.

$B_{\Lambda\Lambda}$ and $\Delta B_{\Lambda\Lambda}$ of these interpretations are summarized in Table I. $\Delta B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z)$, defined as $B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z) - 2B_{\Lambda}({}^{A-1}_{\Lambda}Z)$, is the interaction energy between two Λs in the nucleus. The two error components described in the table are the residuals of kinematic fitting and systematic errors, respectively. In the calculation of $\Delta B_{\Lambda\Lambda}$, B_{Ξ^-} is assumed to be 0.23 MeV as the Ξ^- captured in the atomic 3D state of ^{16}O [8]. In the case of ${}^{12}_{\Lambda\Lambda}$Be, if the DLH was produced in an excited state, the excitation energy should be added to $\Delta B_{\Lambda\Lambda}$ calculated in the case of the ground state. The excitation energy shall be about 3.4-6.3 MeV by assuming $^{10}\mathrm{Be}^{*}$, and the core nucleus of $^{12}_{\Lambda\Lambda}\mathrm{Be}^{*}$. Furthermore, B_{Λ} of $^{11}_{\Lambda}\mathrm{Be}$ is an extrapolated value by that of several isotopes of $_{\Lambda}\mathrm{Be}$ [9, 10], because no experimental data has been reported yet.

Table I. $B_{\Lambda\Lambda}$ and $\Delta B_{\Lambda\Lambda}$ of each candidate for the MINO event.

Nuclide	$B_{\Lambda\Lambda}$ [MeV]	$\Delta B_{\Lambda\Lambda}$ [MeV]	$B_{\Lambda}(^{A-1}_{\Lambda}Z)$ [MeV]
$^{10}_{\Lambda\Lambda}\mathrm{Be}$	15.05 ± 0.09 ± 0.07	1.63 ± 0.09 ± 0.11	6.71 ± 0.04 [9]
$^{11}_{\Lambda\Lambda}\mathrm{Be}$	19.07 ± 0.08 ± 0.07	1.87 ± 0.08 ± 0.36	8.60 ± 0.07 ± 0.16 [10]
$^{12}_{\Lambda\Lambda}\mathrm{Be}^{*}$	13.68 ± 0.08 ± 0.07	$(-2.7 + E_{excite} \pm 0.08 \pm 1.0)$	8.2 ± 0.5 (extrapolation)

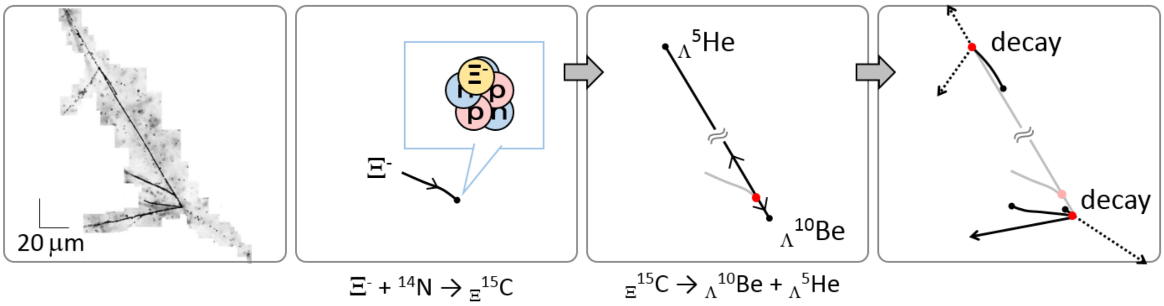

Fig. 2. A micrograph of the IBUKI event and its schematic drawing of production and decay.

Figure 2 shows a TH event found in Sep. 2018 named "IBUKI". From kinematic analysis, it is identified a production and decay event of $^{15}_{\Xi}\mathrm{C}$ via Ξ^{-} capture by a $^{14}\mathrm{N}$ nucleus. Two tracks of $^{10}_{\Lambda}\mathrm{Be}$ and $^{5}_{\Lambda}\mathrm{He}$ are emitted from the decay point of $^{15}_{\Xi}\mathrm{C}$. Both daughter nuclei were identified to be in the ground state according to an energy calculation. Therefore, this event seems to be the first observation of an unequivocal XH event even the B_{Ξ^-}. B_{Ξ^-}, and its uncertainty were measured as little more than 1 MeV and about 0.2 MeV, respectively. As this event is an additional candidate of $^{15}_{\Xi}\mathrm{C}$ following the KISO event [11, 12], one may discuss the width of B_{Ξ^-}. The detail of the analysis will be reported in the near future.

4. Conclusion and Perspectives

J-PARC E07 is the most ambitious emulsion experiment so far to investigate DH with hybrid emulsion method. Beam exposure and photographic processing of the emulsion sheets have been completed successfully and the event hunting is ongoing. Current statistics of E07 is more than twice that of E373.

Several interesting events are identified among the found seven DLH and six TH events and quantitative data on B_{Ξ^-} and $\Delta B_{\Lambda\Lambda}$ are being accumulated. A DLH event named "MINO" was identified as a $^{10}_{\Lambda\Lambda}\mathrm{Be}$, $^{11}_{\Lambda\Lambda}\mathrm{Be}$, or $^{12}_{\Lambda\Lambda}\mathrm{Be}$. From a kinematic calculation, the most probable interpretation is $^{11}_{\Lambda\Lambda}\mathrm{Be}$. A TH event named "IBUKI" was identified as a $^{15}_{\Xi}\mathrm{C}$ and decayed into $^{10}_{\Lambda}\mathrm{Be}$ and $^{5}_{\Lambda}\mathrm{He}$.

We will continue with event hunting to detect more identifiable DH events. In E07, approximately 10^{4} Ξ^{-} stop events and 10^{2} DH events will be obtained according to our estimation. We expect that new events and new nuclides are observed in the near future. The result will powerfully promote the studies of $\Lambda\Lambda$ and ΞN interactions.

Moreover, we aim to measure X-rays from Ξ^- hyperatoms, which are formed after the capture of Ξ^-s by Br or Ag atoms contained in the emulsion sheets. The X-ray spectrum will provide information on the interaction between Ξ^- and nuclei. A dedicated Germanium detector array, "Hyperball-X" measured the X-ray energy with about 0.2 keV accuracy. X-ray event selection is being performed using a combination of multiple detectors and finally by confirming whether the Ξ^-s are certainly stopped in the emulsion sheets or not.

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