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| Title  | The first evidence of a deeply bound state of $\Xi^{-14}\text{N}$ system   |
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| Publication Type   | International publication  |
| Publisher<br>(Journal name,<br>issue no., page no<br>etc.) | Progress of Theoretical and Experimental Physics   |
| Abstract   | We have observed a deeply bound state of the $\Xi^{-14}\text{N}$ system that decayed into twin single hypernuclei in nuclear emulsion exposed in the E373 experiment at KEK-PS. The process is uniquely identified as $\Xi^{-} + {}^{14}\text{N} \rightarrow {}^{10}_{\Lambda}\text{Be} + {}^5_{\Lambda}\text{He}$ . We have measured the binding energy of the $\Xi^{-14}\text{N}$ system, $B_{\Xi^{-}}$ , to be $4.38 \pm 0.25\text{MeV}$ , which is significantly larger than that of the ${}^{14}\text{N}$ $3D$ atomic state (0.17 MeV), if both single-hypernuclei are emitted in the ground state from at-rest capture of a $\Xi^{-}$ hyperon. If the ${}^{10}_{\Lambda}\text{Be}$ nucleus is produced in an excited state, the $B_{\Xi^{-}}$ value mentioned above decreases by the excitation energy. Model calculations based on known values for ${}^9\text{Be}$ excited states have predicted two excited states in the bound region. Even in the case of ${}^{10}_{\Lambda}\text{Be}$ production in the highest excited state, the $B_{\Xi^{-}}$ value is far from the $3D$ atomic level of the $\Xi^{-14}\text{N}$ system by more than 3.7 standard deviations. The event provides the first clear evidence of a deeply bound state of the $\Xi^{-14}\text{N}$ system by an attractive $\Xi\text{N}$ interaction. |
| Keywords   | deeply bound state, twin single hypernuclei, binding energy  |
| Citation   |  |
| Issue Date   | 2015   |



# 日本物理学会論文賞

*Outstanding Paper Award of the Physical Society of Japan*

## Title of Article

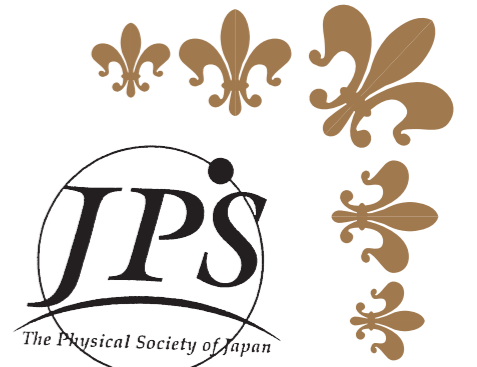
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## Journal

*Prog. Theor. Exp. Phys. 2015, 033D02 (2015)*

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**Journal of the Physical Society of Japan  
Progress of Theoretical and Experimental Physics  
Progress of Theoretical Physics  
JPS Conference Proceedings**

published by the Physical Society of Japan.

March 19, 2017

一般社団法人日本物理学会

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# The first evidence of a deeply bound state of $\Xi^- - {}^{14}\text{N}$ system

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Received October 27, 2014; Revised December 25, 2014; Accepted January 9, 2015; Published March 5, 2015

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 We have observed a deeply bound state of the  $\Xi^- - {}^{14}\text{N}$  system that decayed into twin single-hypernuclei in nuclear emulsion exposed in the E373 experiment at KEK-PS. The process is uniquely identified as  $\Xi^- + {}^{14}\text{N} \rightarrow {}^{10}_{\Lambda}\text{Be} + {}^5_{\Lambda}\text{He}$ . We have measured the binding energy of the  $\Xi^- - {}^{14}\text{N}$  system,  $B_{\Xi^-}$ , to be  $4.38 \pm 0.25$  MeV, which is significantly larger than that of the  $\Xi^- - {}^{14}\text{N}$   $3D$  atomic state (0.17 MeV), if both single-hypernuclei are emitted in the ground state from at-rest capture of a  $\Xi^-$  hyperon. If the  ${}^{10}_{\Lambda}\text{Be}$  nucleus is produced in an excited state, the  $B_{\Xi^-}$  value mentioned above decreases by the excitation energy. Model calculations based on known values for  ${}^9\text{Be}$  excited states have predicted two excited states in the bound region. Even in the case of  ${}^{10}_{\Lambda}\text{Be}$  production in the highest excited state, the  $B_{\Xi^-}$  value is far from the  $3D$  atomic level of the  $\Xi^- - {}^{14}\text{N}$  system by more than 3.7 standard deviations. The event provides the first clear evidence of a deeply bound state of the  $\Xi^- - {}^{14}\text{N}$  system by an attractive  $\Xi\text{N}$  interaction.  
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## 1. Introduction

The baryon–baryon interaction in the  $S = -2$  sector has attracted attention in relation to the possible existence of an  $H$ -dibaryon since its prediction by R. Jaffe [1]. The recent discovery of a neutron star with two solar masses has raised problems of hyperons in the core of neutron stars and  $YN$  (hyperon–nucleon) and  $YY$  interactions [2]. Recently, a lattice QCD calculation on the baryon–baryon interactions has started [3], and, again, the possible existence of the  $H$ -dibaryon near the  $\Lambda$ – $\Lambda$  threshold has been suggested [4]. In spite of its importance, however, experimental information on  $YN$  and  $YY$  interactions is still very limited.

Double- $\Lambda$  hypernuclei have been observed from at-rest captures of  $\Xi^-$  hyperons in nuclear emulsion [5–12]. The  $\Lambda$ – $\Lambda$  interaction can be studied by the spectroscopy of double hypernuclei. From the binding energy of  ${}^6_{\Lambda\Lambda}\text{He}$ , observed as the NAGARA event, the  $\Lambda$ – $\Lambda$  interaction has been found to be weakly attractive [11,12].

From Xi ( $\Xi$ )-hypernuclei and  $\Xi$ -atoms, the  $\Xi N$  interaction can be studied through a  $\Xi$ -nucleus potential. However, there have been no conclusive measurements on  $\Xi$ -hypernuclei or  $\Xi$ -atoms so far. The  $^{12}\text{C}(K^-, K^+)$  reactions were measured with  $K^+$  spectrometers at KEK-PS and BNL-AGS. Any peak structures corresponding to  $\Xi$ -nuclear states were not observed in the missing mass spectra due to insufficient resolution, although a  $^{12}_{\Xi}\text{Be}$  nucleus attractive potential of 14 MeV was suggested from the shape of the continuum spectrum [13,14]. High-resolution spectroscopy of  $\Xi$ -hypernuclei by the  $(K^-, K^+)$  reaction has been awaited and is now planned at J-PARC [15]. The shift and width of the low-lying states of  $\Xi$ -atoms due to a  $\Xi^-$ -nucleus strong interaction provide information on the  $\Xi^-$ -nucleus potential [16]. There has been no X-ray measurement of  $\Xi$ -atoms so far, although two experiments are planned at J-PARC [17,18].

In our previous emulsion experiments, production of twin hypernuclei from at-rest capture of a  $\Xi^-$  hyperon was found and three events were reported [10,19–21]. If the species of the two hyperfragments are identified and there is no neutron emission, the mass of the  $\Xi$ -atom from which hyperfragments are emitted can be obtained, and its binding energy,  $B_{\Xi^-}$ , is determined. For light atoms of the emulsion (C, N, O), the  $\Xi^-$  hyperon is expected to be absorbed most probably from the 3D state of the  $\Xi$ -atoms [16]. Several interpretations were possible for each event, unfortunately, and one of them was consistent with capture from the 3D state.

We have developed a new method, called *overall scanning* of the full emulsion volume, to primarily detect the  $\alpha$  decay vertices of U and Th series for calibration of the range–energy relation [22], and to hopefully detect double hypernuclei with no counter information. During test operations of this method, we have found an event with twin single-hypernuclei among  $7.9 \times 10^6$  pictures taken in a volume of  $1.46 \text{ cm}^3$  emulsion exposed in the E373 (KEK-PS) experiment. In this experiment, a diamond target of 3 cm thickness was placed just upstream of an emulsion stack consisting of 11 layers of 1 mm thick emulsion sheet. Some of the  $\Xi^-$  hyperons produced by  $(K^-, K^+)$  reactions in the target were expected to be brought to rest and to be captured by an atom in the emulsion. The details of the experiment can be found in Refs. [11,12,23,24]. A particular characteristic of the event is that it has a *hammer track* denoting  $2\alpha$  particles from  $^8\text{Be}^*(2^+)$  at the end point of a daughter track of a single-hypernucleus emitted from the  $\Xi^-$  hyperon capture vertex. The species of the two hyperfragments are uniquely identified. In this report, we describe the analysis of this event in detail.

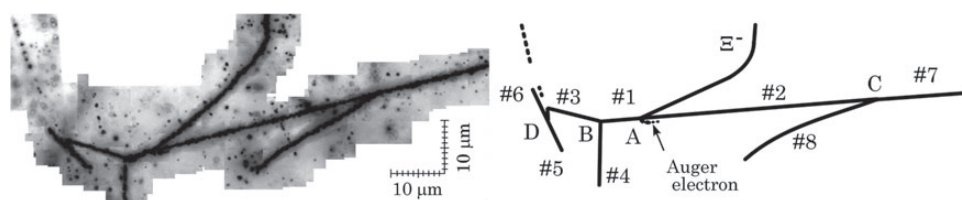
## 2. Analysis

### 2.1. The event topology

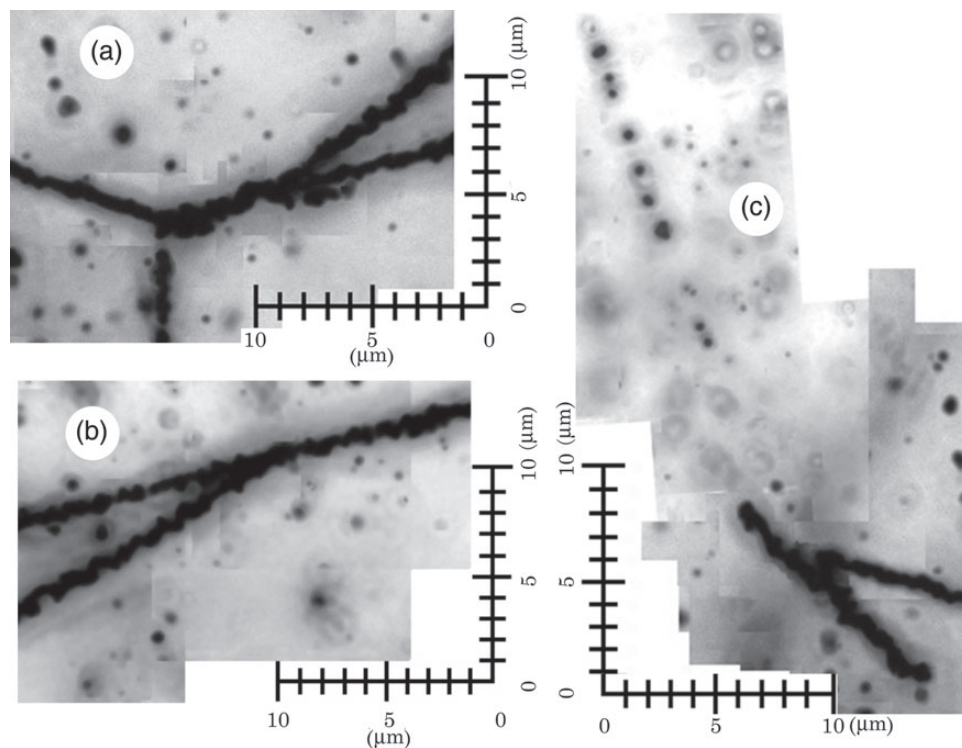
A superimposed image and a schematic drawing of the event are presented in Fig. 1. In Figs. 2(a), (b), and (c), magnified pictures are shown around the vertices A and B, vertex C, and vertex D, respectively. The range and angle of each track are listed in Table 1, where theta and phi denote zenith and azimuthal angles, respectively. We named this event “KISO”.

A curved track designated as  $\Xi^-$  in Fig. 1 can be followed for about 8 mm to the top of the emulsion stack. The particle must be produced in the upstream target, brought to rest, and captured at point A. The particle is interpreted as a  $\Xi^-$  hyperon because an Auger electron is found at point A, as shown in Fig. 2(a), and two weak decay vertices are associated in the event, as described below. This Auger electron makes the stopping point of the negatively charged particle clear. We assigned the  $\Xi^-$  capture point to the emission point of the Auger electron. Then we obtained the ranges and angles of tracks #1 and #2, as listed in Table 1.

From point A, two charged particles, tracks #1 and #2, were emitted in back-to-back directions. Both particles of tracks #1 and #2 decayed into two charged particles and neutron(s), which are



**Fig. 1.** A superimposed image from photographs and a schematic drawing of the KISO event.



**Fig. 2.** Close-up images around each vertex; see Fig. 1 for locations of points and tracks. (a) Points A and B. From point A, an Auger electron can be seen below track #2. (b) Point C. (c) point D.

**Table 1.** Range and angle data of related tracks. The ranges and angles for tracks #1 and #2 are discussed in the text. The total range was measured to be  $77.1 \pm 0.3 \mu\text{m}$  from point B to C.

| Track | Range ( $\mu\text{m}$ ) | theta (deg.)    | phi (deg.)      | Comments                               |
|-------|-------------------------|-----------------|-----------------|--|
| #1    | $8.0 \pm 0.3$           | $133.0 \pm 3.0$ | $13.2 \pm 3.2$  | Single-hypernucleus                    |
| #2    | $69.1 \pm 0.5$          | $40.4 \pm 0.9$  | $193.1 \pm 1.2$ | $77.1 \pm 0.3 \mu\text{m}$ from B to C |
| #3    | $13.3 \pm 0.4$          | $102.3 \pm 2.3$ | $340.4 \pm 1.6$ |  |
| #4    | $>4990.7$               | $145.0 \pm 0.9$ | $85.4 \pm 1.3$  | Out of the emulsion stack              |
| #5    | $6.7 \pm 0.3$           | $49.6 \pm 4.2$  | $132.6 \pm 4.3$ | $\alpha$ from $^8\text{Be}$            |
| #6    | $5.8 \pm 0.3$           | $131.0 \pm 4.5$ | $318.9 \pm 4.7$ | $\alpha$ from $^8\text{Be}$            |
| #7    | $2492.0 \pm 3.9$        | $43.1 \pm 1.3$  | $191.8 \pm 1.5$ |  |
| #8    | $37.3 \pm 0.7$          | $131.9 \pm 1.3$ | $29.2 \pm 1.3$  |  |

consistent with the decay of the hyperfragment at points B and C, respectively. This event topology is consistent with an event of at-rest capture of a  $\Xi^-$  hyperon by a  $^{12}\text{C}$ ,  $^{14}\text{N}$ , or  $^{16}\text{O}$  nucleus in the emulsion, followed by production of twin single-hypernuclei. In the case of  $\Xi^-$  hyperon capture by these nuclei, the total  $A$  and  $Z$  numbers of the hyperfragments do not exceed 17 and 7, respectively.

**Table 2.** Reconstructed masses are listed in (a) and (b) by using the measured ranges of each  $\alpha$  particle and the momentum balance for the two  $\alpha$  particles, respectively. The known mass value of  ${}^8\text{Be}^*(2^+)$  is listed but the state has a width of 1.50 MeV [25].

|     | Reconstructed mass<br>(MeV/c <sup>2</sup> ) | Known mass of ${}^8\text{Be}^*(2^+)$<br>(MeV/c <sup>2</sup> ) |
|-----|---|---|
| (a) | $7458.531 \pm 0.307$                        | 7457.890  |
| (b) | $7458.540 \pm 0.308$                        |   |

At point B, two charged particles were emitted, probably via a non-mesonic weak decay of the particle for track #1, as shown in Fig. 2(a). Track #4 went out of the bottom of the emulsion. The particle of track #3 emitted two charged particles (tracks #5 and #6) in back-to-back directions at point D, as shown in Fig. 2(c). This shows the typical shape of a so-called *hammer track*, where a  ${}^8\text{Be}^*(2^+)$  nucleus decayed to two  $\alpha$  particles at point D. Such a  ${}^8\text{Be}^*(2^+)$  nucleus can only be produced by  $\beta$  decay of a  ${}^8\text{He}$ ,  ${}^8\text{Li}$ , or  ${}^8\text{B}$  nucleus. This interpretation is supported by a track of low ionization density, which corresponds to a fast particle, such as an electron, emitted from point D, as shown in Fig. 2(c).

Regarding track #8, the closest approach distances of track #8 to tracks #2 and #7 were measured as  $0.25 \pm 0.33 \mu\text{m}$  and  $0.36 \pm 0.31 \mu\text{m}$ , respectively, and found to be consistent with zero. If we assume track #8 to be a single track of an  $\alpha$  particle from natural isotopes of thorium and uranium series, the only possible isotopes are  ${}^{232}\text{Th}$ ,  ${}^{238}\text{U}$ ,  ${}^{234}\text{U}$ , and  ${}^{230}\text{Th}$  due to their longer lifetime than the recording period ( $< 1$  year) in the emulsion, since other decays have several associated tracks. Kinetic energies of  $\alpha$  particles from the above nuclei are less than 5 MeV, which are inconsistent with the kinetic energy ( $7.39^{+0.28}_{-0.27}$  MeV) obtained by the range of track #8. Therefore, the chance coincident location of track #8 on the line of tracks #2 and #7 is very unlikely.

Before studying the kinematics for the event, we checked the density of the emulsion to calibrate the range–energy relation. For a standard emulsion (Ilford G5), the achieved accuracy was 0.02 MeV for protons within an energy range from 0.1 MeV to several tens of MeV. In the same emulsion sheet where this event was found, we observed tracks of  $\alpha$  particles from the decays of  ${}^{212}\text{Po}$  and  ${}^{228}\text{Th}$ , respectively, which exist naturally in emulsion. The ranges of  $\alpha$  particles were found to be  $48.46 \pm 0.35 \mu\text{m}$  and  $23.37 \pm 0.26 \mu\text{m}$  for each decay of  ${}^{212}\text{Po}$  and  ${}^{228}\text{Th}$  with unique known energies of 8.784 MeV and 5.367 MeV, respectively. We determined our emulsion density to be  $3.621 \pm 0.105 \text{ g/cm}^3$ , which is consistent with  $3.667 \pm 0.066 \text{ g/cm}^3$  obtained by a measurement of its size and weight at the time of the beam exposure. The density error of  $0.105 \text{ g/cm}^3$  gives rise to inaccuracies of range and energy of 1.1% ( $\Delta R/R$ ) and 0.7% ( $\Delta E/E$ ), respectively, for a proton to  ${}^{12}\text{C}$  with their energies less than several tens of MeV.

## 2.2. Vertex D

We reconstructed the mass of the parent nucleus from the two  $\alpha$  particles (tracks #5 and #6) with their measured ranges, and compared it with the known mass value of  ${}^8\text{Be}^*(2^+)$  as listed in (a) of Table 2. In (b) of Table 2, the reconstructed mass is obtained by using the momentum balance between the two  $\alpha$  particles, where the decay point of the parent nucleus is determined to be the midpoint on the line made by the two tracks (#5 and #6). Taking the mass width (1.50 MeV) of  ${}^8\text{Be}^*(2^+)$  into account, the reconstructed masses agree well with the known mass of  ${}^8\text{Be}^*(2^+)$ . Thus, we conclude that vertex D is the decay point of  ${}^8\text{Be}^*(2^+)$  to the two  $\alpha$  particles.

**Table 3.** Calculated  $Q$ -values for several processes in the assumption of the daughter particle of track #1 as  ${}^8\text{He}$  or  ${}^8\text{Li}$ .

| Reaction                              | #1   | #2                           | Decay process |                                  | $Q$ -value (MeV) |
|---------------------------------------|--|------------------------------|---------------|----------------------------------|------------------|
| $\Xi^- + {}^{12}\text{C} \rightarrow$ | ${}^9_{\Lambda}\text{Li} + {}^4_{\Lambda}\text{He}$    | ${}^9_{\Lambda}\text{Li}$    | $\rightarrow$ | ${}^8\text{He} + p + \pi^0$      | $23.06 \pm 0.12$ |
| $\Xi^- + {}^{14}\text{N} \rightarrow$ | ${}^9_{\Lambda}\text{Be} + {}^6_{\Lambda}\text{He}$    | ${}^9_{\Lambda}\text{Be}$    | $\rightarrow$ | ${}^8\text{Li} + p + \pi^0$      | $19.21 \pm 0.04$ |
|                                       | ${}^{10}_{\Lambda}\text{Be} + {}^5_{\Lambda}\text{He}$ | ${}^{10}_{\Lambda}\text{Be}$ | $\rightarrow$ | ${}^8\text{Li} + p + \pi^0 + n$  | $15.15 \pm 0.22$ |
|                                       | ${}^{11}_{\Lambda}\text{Be} + {}^4_{\Lambda}\text{He}$ | ${}^{11}_{\Lambda}\text{Be}$ | $\rightarrow$ | ${}^8\text{Li} + p + \pi^0 + 2n$ | $9.25 \pm 0.87$  |
| $\Xi^- + {}^{16}\text{O} \rightarrow$ | ${}^9_{\Lambda}\text{Be} + {}^8_{\Lambda}\text{Li}$    | ${}^9_{\Lambda}\text{Be}$    | $\rightarrow$ | ${}^8\text{Li} + p + \pi^0$      | $19.21 \pm 0.04$ |
|                                       | ${}^{10}_{\Lambda}\text{Be} + {}^7_{\Lambda}\text{Li}$ | ${}^{10}_{\Lambda}\text{Be}$ | $\rightarrow$ | ${}^8\text{Li} + p + \pi^0 + n$  | $15.15 \pm 0.22$ |

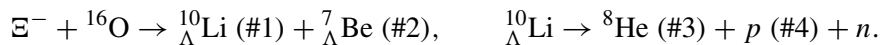
### 2.3. Vertex B

We first checked whether the decay at vertex B is mesonic or not. Track #4 has a range of more than about 5 mm. We have measured the energy loss (number of grains/100  $\mu\text{m}$ ) of the particle for track #4 near point B and have compared it with that of the identified  $\pi^-$  meson at 5 mm before stopping in the NAGARA event. The obtained ratio of the energy loss of track #4 to the NAGARA one was  $1.41 \pm 0.08$ . Track #4 is thus determined not to be a  $\pi^-$  meson.

The momentum imbalance of the two decay charged particles needs neutral particle(s) from point B. If track #4 is a proton or a deuteron, its observed range in Table 1 limits its kinetic energy to be more than 34.8 MeV and 46.8 MeV, respectively. In Table 3, we give  $Q$ -values calculated for several possible processes of  $\pi^0$  mesonic decay, assuming the daughter particle of track #1 to be  ${}^8\text{He}$  or  ${}^8\text{Li}$ . Since it is necessary for the large momentum for the neutral particle to balance momentum, the neutral particle cannot be a  $\pi^0$  meson, as seen in Table 3. Therefore, the decay at point B is concluded to be a non-mesonic weak decay of the hyperfragment of track #1.

As mentioned in the previous section, the total charge ( $Z$  number) of the two hyperfragments (tracks #1 and #2) is not more than 7. Because the hyperfragment (#2) decayed to two charged particles at point C in non-mesonic decay mode,  $Z$  of the hyperfragment (#2) is at least two. Therefore,  $Z$  of the hyperfragment (#1) is not over 5. Since  $Z$  of the track #4 particle is at least one,  $Z$  of the track #3 nucleus is not more than 4. The only possible assignment for the track #3 nucleus is, therefore, either a  ${}^8\text{He}$  or  ${}^8\text{Li}$  nucleus and not a  ${}^8\text{B}$  nucleus owing to the conservation of charge.

The assignment of  ${}^8\text{He}$  for track #3 can be rejected for the following reason. In this case, the hyperfragment (#1) must be a Li isotope, of which the minimum  $A$  number is 10, since at least a proton and a neutron are emitted from point B by non-mesonic decay. Considering that the hyperfragment (#2) has minimum  $Z = 2$  and minimum  $A = 4$  and both hyperfragments are bound states, only the following process is allowed:



However, momentum is not balanced between the  ${}^{10}_{\Lambda}\text{Li}$  (#1) and  ${}^7_{\Lambda}\text{Be}$  (#2) by  $373.1 \pm 13.4 \text{ MeV}/c$ , where we take a  $\Lambda$  binding energy,  $B_{\Lambda}$ , of 9.42 MeV for  ${}^{10}_{\Lambda}\text{Li}$  by linear extrapolation of  $B_{\Lambda}({}^6_{\Lambda}\text{Li}) = 4.50 \text{ MeV}$ ,  $B_{\Lambda}({}^7_{\Lambda}\text{Li}) = 5.58 \text{ MeV}$ ,  $B_{\Lambda}({}^8_{\Lambda}\text{Li}) = 6.80 \text{ MeV}$ , and  $B_{\Lambda}({}^9_{\Lambda}\text{Li}) = 8.50 \text{ MeV}$ . Therefore, the nucleus of track #3 was determined to be not  ${}^8\text{He}$  but  ${}^8\text{Li}$ . In addition, for  ${}^8\text{He}$ , cascade  $\beta$  decays are necessary to produce  ${}^8\text{Be}^*(2^+)$ , but only one  $\beta$ -ray was observed at vertex D. The observation is also consistent with this conclusion.

Kinematical reconstruction of the non-mesonic decay at point B was performed assuming  ${}^8\text{Li}$  to be the track #3 nucleus. Minimum reconstructed masses,  $M_r$ , of the hyperfragment (#1) are listed in

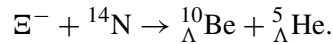
**Table 4.** Mass difference between the sum of the mass ( $M_c$ ) of a core nucleus and a  $\Lambda$  hyperon, and the mass ( $M_r$ ) reconstructed by tracks (#3 and #4) and neutron(s) for the particle of track #1. The difference,  $M_c - M_r$ , denotes the maximum value of  $\Lambda$  binding energy,  $B_\Lambda$ , with the same error of  $M_r$ , because the error of  $M_c$  can be neglected. Therefore, the cases for  $B_\Lambda$  with plus values within three standard deviations are accepted to be a single-hypernucleus for track #1.

| Track #3        | Track #4        | Track #1                  | $M_c$<br>(MeV/c <sup>2</sup> ) | $M_r$<br>(MeV/c <sup>2</sup> ) | $M_c - M_r$<br>(MeV/c <sup>2</sup> ) | Comment  |                   |
|-----------------|-----------------|---------------------------|--------------------------------|--------------------------------|--------------------------------------|----------|-------------------|
| <sup>8</sup> Li | <i>p</i>        | <i>n</i>                  | ${}^{10}_\Lambda\text{Be}$     | 9508.43                        | $9478.60 \pm 4.07$                   | 29.83    | <b>acceptable</b> |
|                 | <i>p</i>        | <i>2n</i>                 | ${}^{11}_\Lambda\text{Be}$     | 10441.19                       | $10375.74 \pm 3.40$                  | 65.45    | <b>acceptable</b> |
|                 | <i>d</i>        | <i>n</i>                  |                                |                                | $10482.27 \pm 5.76$                  | -41.08   | rejected          |
|                 | <i>p</i>        | <i>3n</i>                 | ${}^{12}_\Lambda\text{Be}$     | 11380.25                       | $11300.37 \pm 3.07$                  | 79.88    | <b>acceptable</b> |
|                 | <i>d</i>        | <i>2n</i>                 |                                |                                | $11354.65 \pm 4.92$                  | 25.60    | <b>acceptable</b> |
|                 | <i>t</i>        | <i>n</i>                  |                                |                                | $11487.43 \pm 7.16$                  | -107.18  | rejected          |
|                 | <sup>3</sup> He | <i>n</i>                  | ${}^{12}_\Lambda\text{B}$      | 11368.23                       | $11714.51 \pm 10.06$                 | -346.28  | rejected          |
| <sup>3</sup> He | <i>2n</i>       | ${}^{13}_\Lambda\text{B}$ | 12304.42                       | $12495.38 \pm 9.42$            | -190.96                              | rejected |                   |
| <sup>4</sup> He | <i>n</i>        |                           |                                | $12777.93 \pm 11.89$           | -473.51                              | rejected |                   |

Table 4 for all the possible combinations of the particle species of track #4 and number of emitted neutrons. Because the particle of track #4 went out from the emulsion stack, its kinetic energy estimated from its range listed in Table 1 is a lower bound. Therefore, the values of  $M_r$  are the minimum mass of the single-hypernucleus (#1). In Table 4,  $M_c$  is the sum of the masses of a core nucleus and a  $\Lambda$  hyperon for each species of the hypernucleus. The mass difference, i.e.,  $M_c - M_r$ , represents the maximum value of  $B_\Lambda$ . Since  $B_\Lambda$  should have a positive value for bound hypernuclei, the hypernucleus of track #1 should be the nucleus of one of  ${}^{10}_\Lambda\text{Be}$ ,  ${}^{11}_\Lambda\text{Be}$ , or  ${}^{12}_\Lambda\text{Be}$ , as listed in Table 4.

#### 2.4. Vertices A, B, and C

We have reconstructed the event at point A using the measured ranges of tracks #1 and #2 for all possible combinations. Possible nuclides for track #1 are  ${}^{10}_\Lambda\text{Be}$ ,  ${}^{11}_\Lambda\text{Be}$ , and  ${}^{12}_\Lambda\text{Be}$ , as listed in Table 4. In the case of  ${}^{12}_\Lambda\text{Be}$ , however, no bound hyperfragment is possible for track #2 with or without neutron emission. The results are listed for the cases without neutron emission and with a neutron emission at point A in Tables 5 and 6, respectively. The estimated binding energies of the  $\Xi^-$  hyperon,  $B_{\Xi^-}$ , are presented in Table 5. Only one case is accepted because the values of  $B_{\Xi^-}$  should be positive. It should be noted that the case with neutron emission is also rejected, as shown in Table 6. Among the listed hypernuclei, the  $B_\Lambda$  value for  ${}^{11}_\Lambda\text{Be}$  is not known and is estimated by extrapolating the  $B_\Lambda$  values of past-observed Be hypernuclei. In conclusion, the KISO event is uniquely identified as the following reaction:



We have noticed the topology at point B is coplanar with  $-0.017 \pm 0.042$ , which is defined as  $\vec{r}(\#1) \cdot \{\vec{r}(\#3) \times \vec{r}(\#4)\}$  with  $\vec{r}$  of a unit position vector obtained by measured angle of each track. By assuming the in-flight decay of  ${}^{10}_\Lambda\text{Be}$  to  ${}^8\text{Li}(\#3)$  and a deuteron ( $\#4$ ) without neutron emission due to coplanarity, the momentum of the track #4 particle was estimated by the transverse momentum of the track #3 nucleus, and then we obtained the momentum of the track #1 nucleus at the decay point. The difference between the reconstructed mass value of  ${}^{10}_\Lambda\text{Be}$  and the known value is more than 130 MeV.



**Table 5.**  $\Xi^-$  binding energies are listed for the cases without any neutron emission at point A. The values of  $B_{\Xi^-}$  were calculated using the observed range for each track.

| Absorption                | Track #1                     | Track #2                  | $B_{\Xi^-}$ (MeV) | Comment           |
|---------------------------|------------------------------|---------------------------|-------------------|-------------------|
| $\Xi^- + {}^{14}\text{N}$ | ${}^{10}_{\Lambda}\text{Be}$ | ${}^5_{\Lambda}\text{He}$ | $4.43 \pm 0.34$   | <b>acceptable</b> |
|                           | ${}^{11}_{\Lambda}\text{Be}$ | ${}^4_{\Lambda}\text{He}$ | $-10.08 \pm 0.90$ | rejected          |
| $\Xi^- + {}^{16}\text{O}$ | ${}^{10}_{\Lambda}\text{Be}$ | ${}^7_{\Lambda}\text{Li}$ | $-22.65 \pm 0.34$ | rejected          |

**Table 6.**  $\Xi^-$  binding energy is listed for the case with a neutron emission at point A. The value of  $B_{\Xi^-}$  was obtained so as to balance momenta for tracks #1, #2 and a neutron using the observed ranges for #1 and #2.

| Absorption                | Track #1                     | Track #2                  |     | $B_{\Xi^-}$ (MeV) | Comment  |
|---------------------------|------------------------------|---------------------------|-----|-------------------|----------|
| $\Xi^- + {}^{14}\text{N}$ | ${}^{10}_{\Lambda}\text{Be}$ | ${}^4_{\Lambda}\text{He}$ | $n$ | $-17.73 \pm 0.89$ | rejected |

**Table 7.** Momenta, kinetic energies and ranges for  ${}^{10}_{\Lambda}\text{Be}$  and  ${}^5_{\Lambda}\text{He}$  in the cases of  $B_{\Xi^-} = 4.43$  and  $0.00$  MeV. Ranges for the case of  $B_{\Xi^-} = 0.00$  MeV were estimated by kinetic energies using the range–energy relation. Errors were obtained by ranges, their straggling and the density error of the emulsion and mass errors.

| $B_{\Xi^-}$<br>(MeV) | ${}^{10}_{\Lambda}\text{Be}$ (Track #1) |                         |                      | ${}^5_{\Lambda}\text{He}$ (Track #2) |                         |                      |
|----------------------|---|-------------------------|----------------------|--------------------------------------|-------------------------|----------------------|
|                      | range<br>( $\mu\text{m}$ )              | kinetic energy<br>(MeV) | momentum<br>(MeV/c)  | range<br>( $\mu\text{m}$ )           | kinetic energy<br>(MeV) | momentum<br>(MeV/c)  |
| 4.43                 | 8.0<br>$\pm 0.3$                        | 6.09<br>$\pm 0.23$      | 340.76<br>$\pm 6.40$ | 69.1<br>$\pm 0.5$                    | 12.11<br>$\pm 0.10$     | 342.56<br>$\pm 1.41$ |
| 0.00                 | 10.1                                    | 7.65                    | 381.31               | 96.7                                 | 15.00                   | 381.31               |

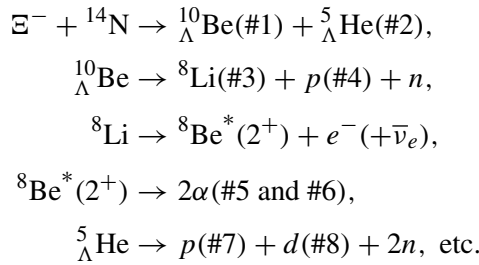
To further check the possibilities for in-flight decay(s) of  ${}^{10}_{\Lambda}\text{Be}$  and/or  ${}^5_{\Lambda}\text{He}$  nucleus, we compared values of momenta, kinetic energies and ranges of them in the cases of  $B_{\Xi^-} = 4.43$  and  $0.00$  MeV and the results are listed in Table 7. For the case of  $B_{\Xi^-} = 0.00$  MeV, using the momentum balance, the range and kinetic energy were calculated for each nucleus. Both ranges are larger than the measured ranges, which means both nuclei decay in flight. The rates of in-flight decay were estimated to be at most 0.6% and 2.9% for  ${}^{10}_{\Lambda}\text{Be}$  and  ${}^5_{\Lambda}\text{He}$ , respectively, therefore the probability of in-flight decays of both hypernuclei becomes 0.2% or less, which is very improbable. As shown in the case of  $B_{\Xi^-} = 4.43$  MeV in Table 7, the momenta obtained from the measured ranges are very well balanced. Therefore, for both nuclei of  ${}^{10}_{\Lambda}\text{Be}$  and  ${}^5_{\Lambda}\text{He}$ , a quite reasonable interpretation turned out to be decays after stopping.

Although the particle #4 went out the bottom of the emulsion, it should be a proton due to the assignments of  ${}^{10}_{\Lambda}\text{Be}$  (#1) and  ${}^8\text{Li}$  (#3). Assuming the particle #4 to be a proton that stopped in the emulsion, we obtained its range to be  $7933 \mu\text{m}$  from point B, where a neutron is emitted to give the known mass of  ${}^{10}_{\Lambda}\text{Be}$  nucleus. Since two fast protons, with their energies larger than 30 MeV, are emitted from the decay of a heavy double hypernucleus, we measured the energy loss around 8 mm from the stopping point of one of the two fast protons. The energy-loss ratio of the particle #4 to the fast proton was  $1.01 \pm 0.06$ , therefore the particle #4 is consistent with a proton. The ratios obtained

by the range–energy relation for a deuteron and a triton are 1.35 and 1.61, respectively, which are inconsistent for the particle #4.

Regarding the decay of  ${}^5_{\Lambda}\text{He}$  at point C, the mass reconstruction has been made using the data for tracks #7 and #8. In the case of  $\pi^0$  mesonic decay, there are no possibilities for decays with or without neutron(s), since obtained masses exceeded the known mass by at least 60 MeV. In the case of one neutron emission in non-mesonic decay, the reconstructed mass is smaller than the known mass (4839.94 MeV) of  ${}^5_{\Lambda}\text{He}$  hypernucleus by  $32.06 \pm 1.77$  MeV, where the decay process is considered as  ${}^5_{\Lambda}\text{He} \rightarrow t(\#7) + p(\#8) + n$ . In the case of two neutron emission at point C, e.g.,  ${}^5_{\Lambda}\text{He} \rightarrow p(\#7) + d(\#8) + 2n$ , we find it can be possible to reconstruct the known mass of  ${}^5_{\Lambda}\text{He}$ .

By the above discussion, the reaction process of the KISO event was identified as follows:



We determine the position of vertex A by using the momentum balance of  ${}^{10}_{\Lambda}\text{Be}$  and  ${}^5_{\Lambda}\text{He}$  under the constraint of the sum of the two track ranges to be  $77.1 \pm 0.3$   $\mu\text{m}$ . This method reduces the error of energy measurements. Then we found the ranges of tracks #1 and #2 to be  $8.10 \pm 0.02$   $\mu\text{m}$  and  $69.02 \pm 0.30$   $\mu\text{m}$ , respectively, which are consistent with the ranges via assignment by the Auger electron listed in Table 1. Considering the effects of straggling and the error of the emulsion density, the error of  $B_{\Xi^-}$  becomes 0.09 MeV. The error of  $B_{\Xi^-}$  from the mass errors of  ${}^{10}_{\Lambda}\text{Be}$  ( $9499.32 \pm 0.22$  MeV/ $c^2$ ),  ${}^5_{\Lambda}\text{He}$  ( $4839.94 \pm 0.02$  MeV/ $c^2$ ), and the  $\Xi^-$  hyperon ( $1321.71 \pm 0.07$  MeV/ $c^2$ ) is 0.23 MeV. Thus, we have determined  $B_{\Xi^-}$  to be  $4.38 \pm 0.25$  MeV with use of the momentum balance of the two hypernuclei.

### 3. Discussion

The  $B_{\Xi^-}$  value of  $4.38 \pm 0.25$  MeV shows evidence of a deeply bound  $\Xi^- - {}^{14}\text{N}$  system, since the level energy of the bound state is no longer equal to that of an atomic state bound by only the Coulomb force. However, we have to study the case of  ${}^{10}_{\Lambda}\text{Be}$  being produced in some excited states. Unfortunately, there are no published experimental data for the excited states of  ${}^{10}_{\Lambda}\text{Be}$ , although a preliminary result from a JLab experiment has been reported [26]<sup>1</sup>. Low-lying states of  ${}^{10}_{\Lambda}\text{Be}$  consist of core excited states of  ${}^9\text{Be}$  and a  $\Lambda$  hyperon in the  $s$ -orbit. The energies of the excited states of  ${}^9\text{Be}$  are well known [25]. Energies of the low-lying excited states of  ${}^{10}_{\Lambda}\text{Be}$  will be approximately determined from the core excited states of  ${}^9\text{Be}$ . The excited states of non-zero spin  $J$  split into doublets due to the spin-dependent  $\Lambda N$  interactions, which have been well studied by high-precision  $\gamma$ -ray spectroscopy of many  $p$ -shell hypernuclei [27]. Therefore, we use theoretical results of the excited energies of  ${}^{10}_{\Lambda}\text{Be}$  to estimate the  $\Xi^-$  binding energy for the case of the emission of  ${}^{10}_{\Lambda}\text{Be}$  in the excited states.

<sup>1</sup> Recently, the JLab E05-115 experiment presented a preliminary result for the excitation energies of the  ${}^{10}_{\Lambda}\text{Be}$  hypernucleus. The measured level energies of both the 1st and 2nd doublets are consistent with the referred theoretical calculations within experimental error.

**Table 8.** Excitation energies of  $^{10}_{\Lambda}\text{Be}$  calculated by cluster (Hiyama & Yamamoto) and shell (Millener) models. The  $B_{\Xi^-}$  value for the ground state, g.s., is  $4.378 \pm 0.250$  MeV, determined by our experiment.

| State | Hiyama & Yamamoto<br>(cluster model) [28]<br>(MeV) | Expected $B_{\Xi^-}$<br>(MeV) | Millener<br>(shell model) [29]<br>(MeV) | Expected $B_{\Xi^-}$<br>(MeV) |
|-------|--|-------------------------------|---|-------------------------------|
| g.s.  | 0 ( $1^-$ )  | 4.38                          | 0 ( $1^-$ )                             | 4.378                         |
|       | 0.08 ( $2^-$ )                                     | 4.30                          | 0.110 ( $2^-$ )                         | 4.268                         |
| 1st   | 2.36 ( $2^-$ )                                     | 2.02                          | 2.482 ( $2^-$ )                         | 1.896                         |
|       | 2.41 ( $3^-$ )                                     | 1.97                          | 2.585 ( $3^-$ )                         | 1.793                         |
| 2nd   | 3.07 ( $0^+$ )                                     | 1.31                          | 3.202 ( $0^-$ )                         | 1.176                         |
|       | 3.27 ( $1^+$ )                                     | 1.11                          | 3.228 ( $1^-$ )                         | 1.150                         |
| 3rd   | —  | —                             | 6.433 ( $3^-$ )                         | $\Xi^-$ unbound               |
|       |  |                               | 6.509 ( $4^-$ )                         |                               |

**Table 9.** Theoretical prediction of  $B_{\Xi^-}$  values for the  $\Xi^-$ - $^{12}\text{C}$  and  $\Xi^-$ - $^{14}\text{N}$  systems using the Coulomb and Ehime potentials [30].

| State | $B_{\Xi^-}$ - [ $\Xi^-$ - $^{12}\text{C}$ ] (MeV) | $B_{\Xi^-}$ - [ $\Xi^-$ - $^{14}\text{N}$ ] (MeV) |
|-------|---|---|
| 1s    | 4.77  | 5.93  |
| 2p    | 0.58  | 1.14  |
| 3D    | 0.126   | 0.174   |
| 2s    | 0.40  | 0.54  |
| 3p    | 0.19  | 0.28  |

Theoretical calculations of the excited states of  $^{10}_{\Lambda}\text{Be}$  were performed with a cluster model by Hiyama and Yamamoto [28] and with a shell model by Millener [29]. The calculated energies for the low-lying states are shown in Table 8. The energy values of both calculations are similar and the difference is less than 200 keV. It should also be noted that the spin doublet splitting of these states are rather small (less than 200 keV) in both calculations. We, therefore, calculate  $B_{\Xi^-}$  when  $^{10}_{\Lambda}\text{Be}$  is emitted in its excited states, as listed in Table 8 for both theoretical values. In the case of  $^{10}_{\Lambda}\text{Be}$  production in its highest excited state, the  $B_{\Xi^-}$  value was measured to be  $1.11 \pm 0.25$  MeV.

A  $\Xi^-$  hyperon captured by a light atom such as C, N, O is expected to be absorbed by its nucleus largely from the atomic 3D state [16]. Since this atomic state is almost a Coulomb bound state, the level energy was calculated to be 0.17 MeV for a  $\Xi^-$ - $^{14}\text{N}$ -atom with good precision. The obtained energy levels are far from the binding energy of the 3D state [16]. Even for the case of  $^{10}_{\Lambda}\text{Be}$  production in the highest excited state, the 3D capture is rejected by more than 3.7 standard deviations.

Yamaguchi et al. [30] calculated the binding energies of the  $\Xi^-$ -nucleus Coulomb-assisted bound states for  $^{12}\text{C}$ ,  $^{14}\text{N}$  (and  $^{16}\text{O}$ ) with use of the Ehime potential, as listed in Table 9. The binding energy of the 2p nuclear bound state for the  $\Xi^-$ - $^{14}\text{N}$  system was estimated to be 1.14 MeV. This is consistent with the case for the 2nd excited states of the  $^{10}_{\Lambda}\text{Be}$  nucleus in the present event.

Two events of twin hypernuclei production were reported in Ref. [10], in which the revised  $\Xi^-$  mass value and kinematical fitting were applied to the previous analyses [19,20], and they were interpreted to be reactions of  $\Xi^-$  captured by  $^{12}\text{C}$  with the most probable modes as listed in Table 10. On the basis of results (b) and (f) in Table 10, we could not rule out capture from the 3D state because the

**Table 10.** Interpretations and  $B_{\Xi^-}$  of twin hypernuclear events reported in Ref. [10].

| Event No.       | Reaction                  | Products   | $B_{\Xi^-}$ (MeV) |     |
|-----------------|---------------------------|--|-------------------|-----|
| Event #10-09-06 | $\Xi^- + {}^{12}\text{C}$ | $\rightarrow {}^9_{\Lambda}\text{Be} + {}^4_{\Lambda}\text{H}$     | $0.82 \pm 0.17$   | (a) |
|                 |                           | $\rightarrow {}^9_{\Lambda}\text{Be} + {}^4_{\Lambda}\text{H}^*$   | $-0.23 \pm 0.17$  | (b) |
| Event #13-11-14 | $\Xi^- + {}^{12}\text{C}$ | $\rightarrow {}^9_{\Lambda}\text{Be} + {}^4_{\Lambda}\text{H}$     | $3.89 \pm 0.14$   | (c) |
|                 |                           | $\rightarrow {}^9_{\Lambda}\text{Be}^* + {}^4_{\Lambda}\text{H}$   | $0.82 \pm 0.14$   | (d) |
|                 |                           | $\rightarrow {}^9_{\Lambda}\text{Be} + {}^4_{\Lambda}\text{H}^*$   | $2.84 \pm 0.15$   | (e) |
|                 |                           | $\rightarrow {}^9_{\Lambda}\text{Be}^* + {}^4_{\Lambda}\text{H}^*$ | $-0.19 \pm 0.15$  | (f) |

values are within three standard deviations, as written in Ref. [10]. However, it is interesting to find that the claimed binding energies obtained for cases (a), (d) in Table 10 and the present data are in very good agreement with the calculations of the  $2p$  state in Table 9.

The possibility of  $\Xi^-$  hyperon capture from the  $2p$  state for C, N, O atoms was estimated to be at most a few % [16]. In E373, more than 300 events of the  $\Xi^-$  hyperon at-rest capture by light nuclear elements C, N, O were located in the emulsion. It is interesting to note that the total number of observed double hypernuclei and twin hypernuclei in E373 is a few % of  $\Xi^-$  captures by light atoms.

#### 4. Concluding remarks

For further studies of nuclei with double strangeness, we have been developing a new method, called the *overall-scanning* method, to speedily scan the full volume of nuclear emulsion. During its test operation on the emulsion exposed in the KEK-E373 experiment, we have found an event showing the topology of production of twin single-hypernuclei emitted from a  $\Xi^-$  hyperon capture at rest. The daughter nucleus from one of the twin single-hypernuclei shows a *hammer track*, which is well identified as the decay of  ${}^8\text{Be}^*(2^+)$  to two  $\alpha$  particles. Owing to this, the capture reaction is uniquely identified as  $\Xi^- + {}^{14}\text{N} \rightarrow {}^{10}_{\Lambda}\text{Be} + {}^5_{\Lambda}\text{He}$ , and the  $B_{\Xi^-}$  value of the  $\Xi^- - {}^{14}\text{N}$  system is determined to be  $4.38 \pm 0.25$  MeV. A  ${}^{10}_{\Lambda}\text{Be}$  nucleus can be produced in the excited states that have been calculated by two models. There are two possible doublet excited states and both calculations give similar energy values within 200 keV. The values of  $B_{\Xi^-}$  are then estimated for the production of  ${}^{10}_{\Lambda}\text{Be}$  excited states.

Even for the case of  ${}^{10}_{\Lambda}\text{Be}$  production in the highest excited state, the obtained  $B_{\Xi^-}$  value ( $1.11 \pm 0.25$  MeV) is inconsistent with that of the  $3D$  atomic state of the  $\Xi^- - {}^{14}\text{N}$  system (0.17 MeV) by more than 3.7 standard deviations. The present result of the KISO event shows the first clear evidence of  $\Xi^-$  nuclear capture from a deeper bound state than the atomic  $3D$  state and the existence of the Coulomb-assisted nuclear  $\Xi^-$  bound state. If the  ${}^{10}_{\Lambda}\text{Be}$  nucleus is emitted in an excited state, the parent  $\Xi^- - {}^{14}\text{N}$  bound state is consistent with a Coulomb-assisted nuclear  $2p$  bound state predicted by the Coulomb and Ehime potentials with an attractive  $\Xi N$  interaction.

#### Acknowledgements

The authors thank the KEK staff for support during the experiment, Professors D. H. Davis and D. Tovee for discussion on the analysis, and Professors E. Hiyama, Y. Yamamoto, T. Yamada, and T. Koike for theoretical comments. This work was supported by the Endo Seijiro Science Foundation in 2007, by JSPS KAKENHI Grant Numbers 14340069, and 23224006, MEXT KAKENHI Grant Numbers 08239103 (Priority Area), and 24105002 (Innovative Area 2404), and by a Korea Grant (NRF-2013R1A1A2061654).

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