Double-Λ hypernuclei observed in a hybrid emulsion experiment

J. K. Ahn,[1,*] H. Akikawa,[1] S. Aoki,[2] K. Arai,[3] S. Y. Bahk,[4] K. M. Baik,[5] B. Bassalleck,[6] J. H. Chung,[7] M. S. Chung,[5] D. H. Davis,[8] T. Fukuda,[9,†] K. Hoshino,[10,‡] A. Ichikawa,[1] M. Ieiri,[9] K. Imai,[1,§] K. Itonaga,[7] Y. H. Iwata,[7] Y. S. Iwata,[7] H. Kanda,[1,∥] M. Kaneko,[7] T. Kawai,[10] M. Kawasaki,[7] C. O. Kim,[5] J. Y. Kim,[11] S. H. Kim,[7,12,¶] S. J. Kim,[11] Y. Kondo,[1,§] T. Kouketsu,[7] H. N. Kyaw,[7,**] Y. L. Lee,[13] J. W. C. McNabb,[14] A. A. Min,[7,**] M. Mitsuhara,[7] K. Miwa,[1,∥] K. Nakazawa,[7,††] Y. Nagase,[7] C. Nagoshi,[15] Y. Nakanishi,[7] H. Noumi,[9] S. Ogawa,[3] H. Okabe,[16] K. Oyama,[3] B. D. Park,[12] H. M. Park,[7] I. G. Park,[12] J. Parker,[14] Y. S. Ra,[7] J. T. Rhee,[13] A. Rusek,[17] A. Sawa,[7] H. Shibuya,[3] K. S. Sim,[5] P. K. Saha,[9] D. Seki,[1] M. Sekimoto,[9] J. S. Song,[12] H. Takahashi,[1,‡‡] T. Takahashi,[18,‡‡] F. Takeutchi,[19] H. Tanaka,[20] K. Tanida,[21,§§] K. T. Tint,[7,∥∥] J. Tojo,[1] H. Torii,[1] S. Torikai,[7] D. N. Tovee,[8] T. Tsunemi,[1] M. Ukai,[7,∥] N. Ushida,[20] T. Wint,[7,¶¶] K. Yamamoto,[1,***] N. Yasuda,[22] J. T. Yang,[5] C. J. Yoon,[1] C. S. Yoon,[12] M. Yosoi,[1] T. Yoshida,[23,†††] and L. Zhu[1,‡‡‡]

(E373 (KEK-PS) Collaboration)

[1]*Department of Physics, Kyoto University, Kyoto 606-8502, Japan*
[2]*Faculty of Human Development, Kobe University, Kobe 657-8501, Japan*
[3]*Department of Physics, Toho University, Funabashi 274-8510, Japan*
[4]*Wonkwang University, Iri 570-749, Korea*
[5]*Department of Physics, Korea University, Seoul 136-701, Korea*
[6]*Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico 87131, USA*
[7]*Physics Department, Gifu University, Gifu 501-1193, Japan*
[8]*Department of Physics and Astronomy, University College London, London WC1E 6BT, United Kingdom*
[9]*Institute of Particle and Nuclear Studies, KEK, Tsukuba 305-0801, Japan*
[10]*Department of Physics, Nagoya University, Nagoya 464-8601, Japan*
[11]*Chonnam National University, Kwangju 500-757, Korea*
[12]*Department of Physics, Gyeongsang National University, Jinju 660-701, Korea*
[13]*Institute for Advanced Physics, Konkuk University, Seoul 143-701, Korea*
[14]*Department of Physics, Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA*
[15]*Higashi Nippon International University, Iwaki 970-8023, Japan*
[16]*Osaka Prefectural Education Center, Osaka 558-0011, Japan*
[17]*Brookhaven National Laboratory, Upton, New York 11973, USA*
[18]*Department of Physics, Tohoku University, Sendai 980-8578, Japan*
[19]*Faculty of Science, Kyoto Sangyo University, Kyoto 603-8555, Japan*
[20]*Aichi University of Education, Kariya 448-8542, Japan*
[21]*Department of Physics, University of Tokyo, Tokyo 113-0033, Japan*
[22]*National Institute of Radiological Science, Chiba 263-8555, Japan*
[23]*Department of Physics, Osaka City University, Osaka 558-8585, Japan*

(Received 22 May 2013; published 17 July 2013)

A hybrid experiment with nuclear emulsion and scintillating-fiber detectors (KEK-E373) has been performed to search for double-strangeness systems. Among about 10^3 events of Ξ^- hyperons captured at rest by emulsion nuclei, we have observed four events which clearly show the topology of cascade weak decays of double-Λ hypernuclei including the "*Nagara*" event. Regarding the *Nagara* event, values of the two-Λ binding energy ($B_{\Lambda\Lambda}$) and the Λ-Λ interaction energy ($\Delta B_{\Lambda\Lambda}$) of ${}^{\ 6}_{\Lambda\Lambda}$He have been revised to 6.91 ± 0.16 and 0.67 ± 0.17 MeV, respectively, due to the recent change of the Ξ^- mass value (Particle Data Group). For another three events, we have determined possible species of double-Λ hypernuclei together with their binding energies.

DOI: 10.1103/PhysRevC.88.014003 PACS number(s): 21.80.+a, 21.10.Dr, 25.80.Pw, 27.20.+n

*Present address: Department of Physics, Pusan National University, Pusan 609-735, Korea.
†Present address: Laboratory of Physics, Osaka Electro-Communication University, Neyagawa 572-8530, Japan.
‡Present address: Gifu University, Japan.
§Present address: Japan Atomic Energy Research Institute, Tokai 319-1195, Japan.
∥Present address: Tohoku University, Japan.
¶Present address: Kyungpook National University, Daegu, Korea.
**Present address: Mandalay University, Myanmar.
††Contact-person: nakazawa@gifu-u.ac.jp
‡‡Present address: IPNS at KEK.
§§Present address: Department of Physics, Seoul National University, Seoul, Korea.
∥∥Present address: Yadanabon University, Myanmar.
¶¶Present address: Shwebo University, Myanmar.
***Present address: Osaka City University.
†††Present address: Department of Physics, Fukui University, Fukui 910-8507, Japan.
‡‡‡Present address: Department of Physics, China Institute of Atomic Energy, P. O. Box 275(80), Beijing 102413, China.

I. INTRODUCTION

The observation of a double-strangeness ($S = -2$) nucleus in an emulsion was first reported by Danysz *et al.*, more than fifty years ago [1]. They observed that ${}^{10}_{\Lambda\Lambda}$Be was produced following a Ξ^- hyperon capture at rest and subsequently decayed by pionic emission in the emulsion exposed to a K^- beam. The existence of double hypernuclei stable against strong decay was considered to be inconsistent with a possible existence of a deeply bound H dibaryon predicted by Jaffe [2]. The existence of stable double hypernuclei had to be confirmed, since the number of stopping Ξ^- in their emulsion was estimated to be only a few.

An emulsion-counter hybrid experiment to observe $S = -2$ nuclei and/or H dibaryon at KEK (PS-E176) was, then carried out, and confirmed the existence of stable double-strangeness nuclei by observing their sequential weak decays [3,4]. The existence of the deeply bound H dibaryon was, thus, rejected. In E176, however, only one event showed a clear track of a double hypernucleus among the events of about 100 stopping Ξ^- hyperons in the emulsion. Its nuclear species was not uniquely identified, however one interpretation for the double hypernucleus was most probable, namely, production and decay of a ${}^{13}_{\Lambda\Lambda}$B nucleus.

Experimental inputs on hyperon (Y) – nucleon (N) and Y-Y interactions are important to understand the baryon-baryon interaction in flavor SU(3) and play an essential role in the study of the structure of neutron stars. The N-N interaction recently attracted much attention since a lattice QCD calculation was tried and successfully reproduced the basic feature of the nucleon-nucleon potential [5]. Therefore it is important to provide experimental information on Y-N and Y-Y interactions as an extension of the N-N interaction.

The Y-N interactions can be studied both by the spectroscopy of hypernuclei and Y-N scattering experiments although they are difficult. Regarding the Λ-Λ interaction, however, binding energies of double-Λ hypernuclei are the only source of the experimental information. It is, therefore, quite important to observe uniquely identified double hypernuclei and determine their binding energies. Thus, we have carried out a second-generation hybrid-emulsion experiment (KEK PS-E373) to observe ten times more double hypernuclei than E176 and determine their binding energies. The mass of a double hypernucleus provides binding energies of two Λ hyperons, from which one can obtain the Λ-Λ interaction energy ($\Delta B_{\Lambda\Lambda}$). The $\Delta B_{\Lambda\Lambda}$ can be written as

$$\begin{aligned}\Delta B_{\Lambda\Lambda}\left({}^{A}_{\Lambda\Lambda}Z\right) &= B_{\Lambda\Lambda}\left({}^{A}_{\Lambda\Lambda}Z\right) - 2B_{\Lambda}\left({}^{A-1}_{\Lambda}Z\right)\\ &= 2M\left({}^{A-1}_{\Lambda}Z\right) - M\left({}^{A-2}Z\right) - M\left({}^{A}_{\Lambda\Lambda}Z\right),\end{aligned}$$

where the $B_{\Lambda\Lambda}$ and the B_{Λ} are binding energies of two or one Λ hyperon(s) for the double or single hypernucleus, respectively.

The ground state of a double strangeness nuclei is considered to be double-Λ hypernuclei. Although the deeply bound H dibaryon was rejected, the possible existence of a very weakly bound H or an H resonance is still allowed. A possible existence of the H resonance near the Λ-Λ threshold was even suggested, although it was not statistically significant [6,7]. In the case of $S = -2$ nuclei, the mass difference of Ξ^--N and Λ-Λ is small, compared to N-N with N-Δ and to Λ-N with Σ-N. Their coupling must be strong in $S = -2$ nuclei and it will affect the structure of double-Λ hypernuclei. If the H dibaryon exists near the Λ-Λ threshold (above or below), it will also have a strong effect on the structure of double hypernuclei. Therefore $S = -2$ nuclei can be quite different from ordinary nuclei and single-Λ hypernuclei. It is important to find various $S = -2$ nuclei and measure their binding energies and fundamental properties to expand the world of nuclei with strangeness.

In the early stages of the emulsion analysis of the E373 experiment, we found the "*Nagara*" event, which was uniquely identified as the production and decay of a ${}^{6}_{\Lambda\Lambda}$He nucleus. The $\Delta B_{\Lambda\Lambda}$ was determined as 1.01 ± 0.20 MeV, which means the Λ-Λ interaction is weakly attractive. The details of the event were already published [8].

From theoretical studies on various light double hypernuclei, the values of $\Delta B_{\Lambda\Lambda}$ vary depending on the change of the core structure of nuclei by Λ hyperons, even for the same Λ-Λ interaction [9,10]. The shrinkage of the core radius by as much as 20% was predicted for the ${}^{7}_{\Lambda}$Li nucleus [11] and observed in an experiment [12].

Therefore, to understand the Λ-Λ interaction without ambiguities due to the structure of $S = -2$ nuclei, it is important to find at least several nuclear species with $S = -2$ and determine their $\Delta B_{\Lambda\Lambda}$ values.

We have analyzed about 1000 events of stopping Ξ^- hyperons in the emulsion, which was more than ten times that of the previous one (KEK-E176). Among them, we have found four events which clearly show a topology of cascade weak decays of double-Λ hypernuclei. One of them is the *Nagara* event. Since the mass value of the Ξ^- hyperon was significantly changed in the recent Particle Data Group (PDG) results [13], we have revised the values of $B_{\Lambda\Lambda}$ and $\Delta B_{\Lambda\Lambda}$ of ${}^{6}_{\Lambda\Lambda}$He accordingly. In this paper, we describe details of the other three events ("*Mikage*", "*Demachiyanagi*", and "*Hida*" events) and present possible interpretations and species of double hypernuclei together with their binding energies, which were discussed in elsewhere [14].

II. KEK-E373 EXPERIMENT

The experiment E373 was performed using a 1.66 GeV/c K^- beam at the K2 beam line of the proton synchrotron facility at KEK. In this experiment, (K^-, K^+) reactions were identified by a beam-line spectrometer for incoming K^- particles and a KURAMA spectrometer for outgoing K^+. The Ξ^- hyperons produced in the quasifree 'p'(K^-, K^+)Ξ^- reaction were detected by a scintillating microfiber-bundle detector (SciFi-Bundle), and then entered a stack of emulsion plates. This experiment was designed to observe ten times more stopping Ξ^- hyperons in the emulsion than the previous experiment (E176). In order to optimize the yield of Ξ^- hyperons, the target should contain light nuclei because the cross section of the quasifree reaction is proportional to $A^{0.38}$ [15]. To optimize the stopping rate in the emulsion, density of the target material should be high to decelerate the Ξ^- hyperons in the target and the size of the target should be also optimized. We employed a diamond block

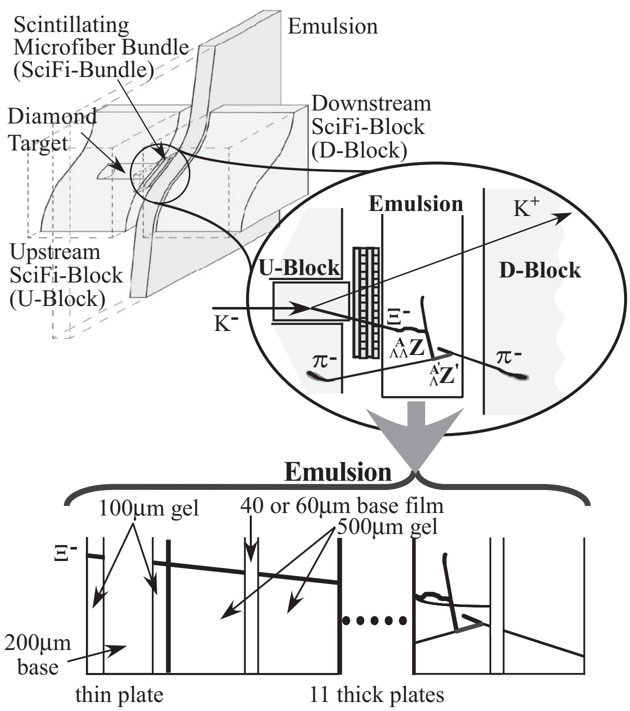

FIG. 1. Schematic view of the experimental setup around the (K^-, K^+) reaction target.

$(20\ [x] \times 20\ [y] \times 35\ [z\ \text{(beam direction)}]\ \text{mm}^3)$ as the target [16]. The experimental setup around the target is schematically shown in Fig. 1.

The SciFi-Bundle detector sandwiched between the diamond target and the emulsion stack measured the position and angle of each Ξ^- hyperon with a high precision. The positions and angles of the Ξ^- hyperons at the surface of the first emulsion plate (thin plate) were thus provided. Under a microscope, first we identified the tracks of Ξ^- hyperons detected with the SciFi-Bundle detector in the thin plate, and then followed the tracks to their end points in the emulsion plates. The production of a double-Λ hypernucleus and its decay were searched for around the end points. The hybrid system of the SciFi-Bundle detector and emulsion was described in detail by Ichikawa *et al*. [17]. We searched for the tracks of Ξ^- hyperons in the emulsion using a fully automated scanning system and followed each identified track using semiautomated scanning system (See details in Ref. [18]).

Scintillating fiber (SciFi) detectors, U-Block and D-Block, were placed both upstream and downstream of the emulsion stack. If a daughter track originating from the decay of a hypernucleus escaped from the emulsion stack, the track could be still observed in the U-Block and/or D-Block. Thus we could measure the range and identify the particle for the track to kinematically reconstruct the event. The detail of the performance of the SciFi detectors is described in Ref. [19].

In the experiment, we followed about 2×10^4 candidate tracks of Ξ^- hyperons, and found nearly 10^3 stopping vertices with charged daughter tracks in the emulsion. Among them, sequential decays with three vertices were found in seven events. Although we were not able to reconstruct three events because some tracks were difficult to be seen clearly, the Λ-Λ interaction can be discussed on four events with nuclear species in the following section.

The detail of the experiment can be seen in Refs. [8] and [18].

III. DOUBLE-Λ HYPERNUCLEAR EVENTS

A. *Nagara* event

In the recent PDG results [13], a huge amount of data from an experiment was taken into account for the mass of the Ξ^- hyperon, where other old data were not used for its compilation. The mass value was adopted to be $1321.71 \pm 0.07\ \text{MeV}/c^2$ which was $0.40\ \text{MeV}/c^2$ heavier than the old one of $1321.31 \pm 0.13\ \text{MeV}/c^2$. This mass change of the Ξ^- hyperon requires revision of the values of $B_{\Lambda\Lambda}$ and $\Delta B_{\Lambda\Lambda}$ obtained from the vertex of Ξ^- hyperon capture, i.e., the production point of the double-Λ hypernucleus in the *Nagara* event. In this chapter, although interpretation of the *Nagara* event has not been changed from the previous paper [8], numerical values are presented for revision.

A picture and schematic drawing of the event are shown in Fig. 2.

Three charged particles (tracks 1, 2, and 3) were emitted from Ξ^- hyperon stopping vertex A, and one of them (1) decayed into three charged particles (4, 5, and 6) at vertex B. At the end point of track 4 (vertex C), it was associated with two charged particles (7 and 8).

Since there were typographical errors in the data of lengths and angles of the tracks in the previous paper [8], they are listed with correction in Table I. Coplanarities calculated for the three tracks emitted from vertices A and B are again well presented to be -0.002 ± 0.030 and 0.003 ± 0.013, respectively.

Since the mass value of the Ξ^- hyperon was changed, we applied kinematic analysis to the production vertex A in the same manner as in the previous paper [8]. The results are presented in Table II. In the table, the modes with $\Delta B_{\Lambda\Lambda} - B_{\Xi^-} < 20$ MeV are listed.

Even if the mass value of the Ξ^- hyperon were changed, the results of the kinematic analysis could not be changed for all possible decay modes at vertex B from the previous results. Very recently, the binding energy of a Λ hyperon in ${}^{7}_{\Lambda}\text{He}$ was

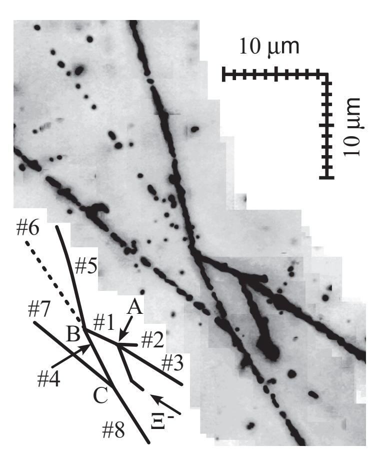

FIG. 2. Photograph and schematic drawing of the *Nagara* event.

TABLE I. Track lengths and emission angles from vertices A, B, and C of the *Nagara* event. Several values with underline are corrected ones for typos in the previous paper [8].

Point	Track	Length (μm)	θ (degree)	ϕ (degree)	Comment
A	1	8.1 ± 0.3	44.9 ± 2.0	337.5 ± 1.8	double-Λ hypernucleus
	2	3.2 ± 0.4	57.7 ± 5.2	174.9 ± 2.9	
	3	$88.\underline{6} \pm 0.5$	156.2 ± 0.5	143.0 ± 1.0	
B	4	9.1 ± 0.3	77.7 ± 1.6	115.9 ± 0.8	single-Λ hypernucleus
	5	82.1 ± 0.6	122.8 ± 1.0	284.2 ± 0.7	stopped in base
	6	13697	$81.\underline{0} \pm 0.\underline{5}$	$305.5 \pm 0.\underline{2}$	π^-
C	7	742.6 ± 0.6	138.5 ± 0.2	322.1 ± 0.3	stopped in D-Block
	8	5868 ± 20	52.2 ± 1.2	123.7 ± 0.7	scattered before stopping

given to be 5.68 MeV by Nakamura *et al.* [20]. Although we took 7.0 MeV as its upper limit in the previous paper, interpretation of the event is not influenced by the new value of the ${}^{7}_{\Lambda}$He binding energy.

We found again that the case of a ${}^{\;\;6}_{\Lambda\Lambda}$He is consistent in both processes of production and decay as follows:

$$
\begin{aligned}
{}^{12}\mathrm{C} + \Xi^- \rightarrow\ & {}^{\;\;6}_{\Lambda\Lambda}\mathrm{He} + {}^{4}\mathrm{He} + t \\
& \hookrightarrow {}^{5}_{\Lambda}\mathrm{He} + p + \pi^-.
\end{aligned}
$$

Kinematic fitting has been performed for the vertices A and B; the values of $B_{\Lambda\Lambda}$ and $\Delta B_{\Lambda\Lambda}$ were obtained as a function of the Ξ^- binding energy (B_{Ξ^-}):

$$
\begin{aligned}
B_{\Lambda\Lambda} &= 6.79 + 0.91\, B_{\Xi^-}\ (\pm 0.16)\ \mathrm{MeV}, \\
\Delta B_{\Lambda\Lambda} &= 0.55 + 0.91\, B_{\Xi^-}\ (\pm 0.17)\ \mathrm{MeV}.
\end{aligned}
$$

Taking into account a B_{Ξ^-} of 0.13 MeV [21] for the ^{12}C-Ξ^- system, the values of $B_{\Lambda\Lambda}$ and $\Delta B_{\Lambda\Lambda}$ are 6.91 ± 0.16 MeV and 0.67 ± 0.17 MeV, respectively.

TABLE II. Possible production modes of the double-Λ hypernucleus, the *Nagara* event. Although the vertex is also coplanar within error, the cases of neutron emission are presented. Only the cases of $\Delta B_{\Lambda\Lambda} - B_{\Xi^-} < 20$ MeV are listed. In case (1), values by kinematic fitting for the vertices A and B are presented in the text.

Target	1	2	3		$B_{\Lambda\Lambda} - B_{\Xi^-}$ [MeV]	$\Delta B_{\Lambda\Lambda} - B_{\Xi^-}$ [MeV]	
^{12}C	${}^{\;\;6}_{\Lambda\Lambda}$He	^{4}He	p	$2n$	>16.46	>10.22	
^{12}C	${}^{\;\;6}_{\Lambda\Lambda}$He	^{4}He	d	$1n$	14.08 ± 0.63	7.84 ± 0.63	
^{12}C	${}^{\;\;6}_{\Lambda\Lambda}$He	^{4}He	t		6.93 ± 0.19	0.69 ± 0.20	(1)
^{12}C	${}^{\;\;7}_{\Lambda\Lambda}$He	^{4}He	p	$1n$	21.24 ± 1.24	12.88 ± 1.26	
^{14}N	${}^{\;\;6}_{\Lambda\Lambda}$He	^{7}Li	p	$1n$	24.02 ± 1.98	17.78 ± 1.98	
^{14}N	${}^{\;\;6}_{\Lambda\Lambda}$He	^{6}Li	d	$1n$	25.42 ± 1.25	19.18 ± 1.25	
^{14}N	${}^{\;\;6}_{\Lambda\Lambda}$He	^{4}He	^{4}He	$1n$	17.55 ± 1.47	11.31 ± 1.47	
^{14}N	${}^{\;\;7}_{\Lambda\Lambda}$Li	^{4}He	t	$1n$	25.79 ± 0.87	16.79 ± 0.87	
^{14}N	${}^{\;\;8}_{\Lambda\Lambda}$Li	^{4}He	d	$1n$	31.16 ± 1.50	20.00 ± 1.50	
^{14}N	${}^{\;\;9}_{\Lambda\Lambda}$Li	p	^{4}He	$1n$	31.06 ± 1.33	17.46 ± 1.33	
^{16}O	${}^{\;\;8}_{\Lambda\Lambda}$Li	^{4}He	^{4}He	$1n$	30.66 ± 0.83	19.50 ± 0.83	

B. "*Mikage*" event

The event was tagged by a K^+ meson of which momentum and mass were measured to be 1.105 GeV/c and 0.493 GeV/c^2, respectively. Figure 3 shows a photograph and schematic drawing of production and decay of a double-hypernucleus for the *Mikage* event. A Ξ^- hyperon came to rest at point A, from which two charged particles (tracks 1, 2) were emitted. One of them (1) decayed into two charged particles (3, 4) at point B. The particle of track 3 decayed again to two charged particles (5, 6) at point C. The particle of track 6 was escaping from the emulsion stack to the upstream Scifi-Block detector (U-Block). The coplanarity calculated from angles of tracks 3, 5, and 6 was -0.35 ± 0.13, so the three tracks are coplanar within three standard deviations. The lengths and angles of these tracks are summarized in Table III.

The particle of track 4 stopped in the emulsion after nearly 20 mm flight from the decay point (B) of a double hypernucleus. There are no charged particles emitted from its stopping point. In order to identify the species of the track 4, we performed the energy-loss measurement (counting of developed grain per unit length of emulsion, "grain density") at four regions within 10 mm from point B. If we assume the particle of the track and its initial kinetic energy, the grain density can be calculated for each region along the track. Therefore, by minimizing the sum of the deviation between the measured grain density and calculated one at each region in the emulsion stack, we obtained the initial kinetic energy and the goodness of the fitting (χ^2) for each assumed species. Meanwhile, the kinetic energy was also derived from the range-energy relation, which is independent of the energy-loss measurement. These results are presented in Table IV, and thus the particle of track 4 was found to be a proton by comparison of both data.

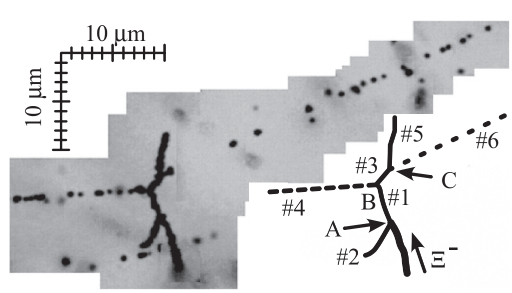

FIG. 3. Photograph and schematic drawing of the *Mikage* event.

TABLE III. Lengths and angles of the tracks of the *Mikage* event. The length of track 6 is the visible amount in the emulsion.

Point	Track	Length (μm)	θ (degree)	ϕ (degree)	Comment
A	1	2.9 ± 0.3	96.7 ± 1.7	109.0 ± 0.7	double-Λ hypernucleus
	2	3.5 ± 0.8	94.5 ± 2.1	247.6 ± 2.1	
B	3	1.8 ± 0.4	74.6 ± 11.3	44.7 ± 3.5	single-Λ hypernucleus
	4	19044.7 ± 10.6	78.2 ± 0.1	183.1 ± 0.1	proton
C	5	4.5 ± 0.6	54.2 ± 2.0	87.3 ± 2.1	
	6	>12975.6	49.6 ± 0.1	23.8 ± 0.1	π^- (49.1 ± 1.7 MeV)

The image of the scintillating-fiber detectors for the event is shown in Fig. 4. It is clearly recognized that one charged particle entered the U-Block, but out of the sensitive volume for three-dimensional measurement. We cannot distinguish whether the particle was scattered at point D in the figure, or stopped at point D from which an evaporated particle was emitted. However, by applying the grain-density fitting in the emulsion stack, the particle of track 6 was identified as a π^- meson with the kinetic energy of 49.1 ± 1.7 MeV at point C.

The large kinetic energy of the particle (track 6) gave us no solution to understand a mesonic decay after the stopping of a single-Λ hypernucleus (track 3), because total energy release ($E_{\rm tot}$) was greater than the Q value in all of the possible decay modes of a single-Λ hypernucleus. For example, among all possible decay modes of single-Λ hypernuclei, the following mode gives the minimum $E_{\rm tot}$ value as 68.6 MeV for the topology, but the Q value is 33.9 MeV:

$$ {}^{8}_{\Lambda}\mathrm{He} \to {}^{6}\mathrm{Li}(\text{track 5}) + \pi^-(\text{track 6}) + 2n + E_{\rm tot}(>68.6\ \mathrm{MeV}). $$

Taking into account the possibility of an in-flight decay of the single-Λ hypernucleus (track 3), it was found that three kinds of nuclide (${}^{3}_{\Lambda}$H, ${}^{7}_{\Lambda}$He, and ${}^{9}_{\Lambda}$Li) would fit within errors of three standard deviation as presented in Table V. Although the reconstruction has been made by assuming one neutron associated with the decay at point C, no such solution is obtained. Considering the coplanarity of the vertex point C, decay modes without any neutrons are acceptable for the decay of the single-Λ hypernucleus.

Kinematic analysis has been performed at the decay point (B) of a double hypernucleus (track 1). In Table VI, possible decay modes including ${}^{3}_{\Lambda}$H, ${}^{7}_{\Lambda}$He, or ${}^{9}_{\Lambda}$Li as a daughter nucleus are listed.

At the production point A, kinematical analysis has been made assuming a capture reaction of Ξ^- hyperon on a light nucleus (C, N, or O). Table VII presents the possible modes for the production of the double hypernuclei listed in Table VI.

In comparison with Tables VI and VII, the following processes denoted as (1), (2), and (3) in the tables were found to be acceptable for the *Mikage* event by checking consistency with the $\Delta B_{\Lambda\Lambda}$ value of *Nagara* event:

$$ {}^{12}\mathrm{C} + \Xi^- \to {}^{6}_{\Lambda\Lambda}\mathrm{He} + {}^{6}\mathrm{Li} + n \hookrightarrow {}^{3}_{\Lambda}\mathrm{H} + p + 2n \quad (1), $$

$$ {}^{12}\mathrm{C} + \Xi^- \to {}^{11}_{\Lambda\Lambda}\mathrm{Be} + p + n \hookrightarrow {}^{9}_{\Lambda}\mathrm{Li} + p + n \quad (2), $$

$$ {}^{14}\mathrm{N} + \Xi^- \to {}^{11}_{\Lambda\Lambda}\mathrm{Be} + {}^{3}\mathrm{He} + n \hookrightarrow {}^{9}_{\Lambda}\mathrm{Li} + p + n \quad (3). $$

Regarding the process of (1) for ${}^{6}_{\Lambda\Lambda}$He, the values of $B_{\Lambda\Lambda}$ and $\Delta B_{\Lambda\Lambda}$ were obtained as 10.01 ± 1.71 and 3.77 ± 1.71 MeV, respectively, from the production point with use of a B_{Ξ^-} value of 0.13 MeV [21] for the atomic 3D level of the ^{12}C-Ξ^- system. In processes of ${}^{11}_{\Lambda\Lambda}$Be for (2) and (3),

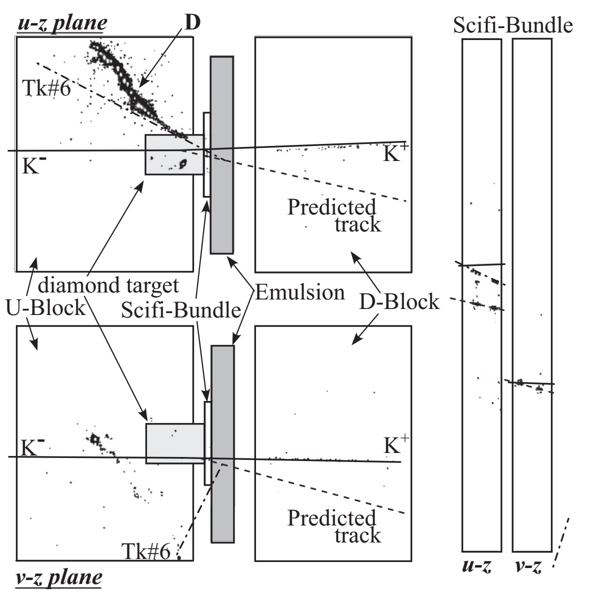

FIG. 4. Image of the scintillating-fiber detectors for the *Mikage* event. The solid lines are tracks of incoming K^- and outgoing K^+ mesons measured with the spectrometer system. The dashed line is a predicted track of Ξ^- hyperon reconstructed by Scifi-Bundle. The dashed-dotted line is an extrapolated one using the position and angle of track 6 (Tk#6 in the figure) in the emulsion.

TABLE IV. Kinetic energies (K.E.) based on the measurement of energy-loss and range of the particle (4) of the *Mikage* event. Degree of freedom was three for the fitting.

Particle	From energy loss		From range
assumption	K.E. (MeV)	χ^2	K.E. (MeV)
π^-	23.4 ± 0.1	767	34.1 ± 0.6
p	74.0 ± 1.6	6.4	74.7 ± 0.6
d	134.1 ± 3.4	3.6	100.5 ± 0.5
t	195.4 ± 5.2	6.9	119.6 ± 0.5

TABLE V. Possible decay modes of the single-Λ hypernucleus in the case for decay in-flight at vertex C without neutron emissions for the *Mikage* event. $E_{\rm visible}$ is a kinetic energy from both charged particles (tracks 5 and 6). The kinetic energy ($E_{\rm decay}$) of the single hypernucleus is calculated from momentum of daughters (5 and 6) at the decay point C. Again, the value of 5.68 MeV is taken for the Λ hyperon binding energy in ${}^{7}_{\Lambda}$He given by Nakamura *et al.* [20].

Single hyp.	Track 5	Track 6	Q value (MeV)	$E_{\rm visible}$ (MeV)	$E_{\rm visible} - E_{\rm decay}$ (MeV)
${}^{3}_{\Lambda}$H	^{3}He	π^-	43.20	50.53 ± 1.70	44.07 ± 1.73
${}^{7}_{\Lambda}$He	^{7}Li	π^-	42.14	51.20 ± 1.73	45.96 ± 1.78
${}^{9}_{\Lambda}$Li	^{9}Be	π^-	46.23	52.16 ± 1.77	46.08 ± 1.85

although the value of $\Delta B_{\Lambda\Lambda}$ at the decay point is much larger than that of the *Nagara* event, the errors are also large, to give consistency with *Nagara*. Thus we obtained the error-weighted mean values of $B_{\Lambda\Lambda}$ and $\Delta B_{\Lambda\Lambda}$ as 22.15 ± 2.94 MeV and 3.95 ± 3.00 MeV for the process (2) and 23.05 ± 2.59 MeV and 4.85 ± 2.63 MeV for the process (3), respectively. Since the mesonic decay rate of a daughter ${}^{9}_{\Lambda}$Li nucleus is not so large (about 20%) [22], the case of ${}^{\ 6}_{\Lambda\Lambda}$He would be more likely.

C. "*Demachiyanagi*" event

The event was tagged by the K^+ meson with 1.139 GeV/c and 0.487 GeV/c^2, which are the momentum and the reconstructed mass, respectively. No charged particle except for the K^+ meson was seen in the SciFi detector. This means all charged particles relating to the event were stopped in the emulsion.

A Ξ^- hyperon entered and stopped in the emulsion with a range of about 7 mm and formed a star. The photograph and schematic drawing of the event are shown in Fig. 5.

To get a better position resolution, we cut and swelled a small area of the emulsion plate and sliced it into a tiny piece of 0.5 mm width. That made it possible to observe the event from the vertical (ordinal) and the horizontal directions, and

TABLE VI. Possible decay modes of the double-Λ hypernucleus, the *Mikage* event, decaying to single-Λ hypernuclei listed in Table V. Only the cases of $\Delta B_{\Lambda\Lambda} > -20$ MeV are listed. Since the value of a Λ binding energy of a ${}^{11}_{\Lambda}$Be nucleus, $B_\Lambda({}^{11}_{\Lambda}{\rm Be})$, is not known, a parenthetic value of $\Delta B_{\Lambda\Lambda}$ is obtained assuming $B_\Lambda({}^{11}_{\Lambda}{\rm Be}) = B_\Lambda({}^{11}_{\Lambda}{\rm B})$.

Double-hyp.	Track 3	Track 4		$B_{\Lambda\Lambda}$ (MeV)	$\Delta B_{\Lambda\Lambda}$ (MeV)	
${}^{\ 6}_{\Lambda\Lambda}$He	${}^{3}_{\Lambda}$H	p	$2n$	<46.07	<39.83	(1)
${}^{\ 7}_{\Lambda\Lambda}$He	${}^{3}_{\Lambda}$H	p	$3n$	<54.55	<46.19	
${}^{\ 8}_{\Lambda\Lambda}$He	${}^{3}_{\Lambda}$H	p	$4n$	<56.49	<45.13	
${}^{\ 9}_{\Lambda\Lambda}$He	${}^{3}_{\Lambda}$H	p	$5n$	<59.22	<44.90	
${}^{\ 9}_{\Lambda\Lambda}$Li	${}^{7}_{\Lambda}$He	p	$1n$	47.50 ± 8.35	33.90 ± 8.35	
${}^{10}_{\Lambda\Lambda}$Li	${}^{7}_{\Lambda}$He	p	$2n$	<67.07	<50.07	
${}^{11}_{\Lambda\Lambda}$Be	${}^{9}_{\Lambda}$Li	p	$1n$	37.59 ± 10.58	19.37 ± 10.59	(2),(3)
${}^{12}_{\Lambda\Lambda}$Be	${}^{9}_{\Lambda}$Li	p	$2n$	<54.53	(<34.05)	

TABLE VII. Possible production modes of the double-Λ hypernucleus, the *Mikage* event. Only the cases of $\Delta B_{\Lambda\Lambda} - B_{\Xi^-} < 20$ MeV are listed.

Target	Track 1	Track 2		$B_{\Lambda\Lambda} - B_{\Xi^-}$ (MeV)	$\Delta B_{\Lambda\Lambda} - B_{\Xi^-}$ (MeV)	
^{12}C	${}^{\ 6}_{\Lambda\Lambda}$He	^{6}Li	$1n$	9.88 ± 1.71	3.64 ± 1.71	(1)
^{12}C	${}^{\ 9}_{\Lambda\Lambda}$Li	^{3}He	$1n$	22.98 ± 1.44	9.38 ± 1.44	
^{12}C	${}^{11}_{\Lambda\Lambda}$Be	p	$1n$	20.73 ± 3.06	2.51 ± 3.09	(2)
^{14}N	${}^{\ 6}_{\Lambda\Lambda}$He	^{7}Be	$2n$	>17.41	>11.17	
^{14}N	${}^{\ 7}_{\Lambda\Lambda}$He	^{7}Be	$1n$	22.27 ± 3.23	13.91 ± 3.24	
^{14}N	${}^{11}_{\Lambda\Lambda}$Be	^{3}He	$1n$	21.95 ± 2.67	3.73 ± 2.71	(3)
^{16}O	${}^{\ 9}_{\Lambda\Lambda}$Li	^{7}Be	$1n$	33.10 ± 2.82	19.50 ± 2.82	

these photographs and schematic drawings are shown in Fig. 6. Comparing the two photos, one can recognize three vertices in the event.

From the Ξ^- hyperon capture point A, two charged particles (tracks 1 and 2) were emitted in collinear topology within measurement error. Track 1 shows a decay topology into a charged particle (track 3) and neutral one(s) at point B. Two or three charged particles [tracks 4, 5 (6)] were emitted from the end point C of track 3. Because the first half of track 5 is rather thick, another track may exist parallel to track 5. This possible track was assigned as track 6. Ranges and angles of tracks are listed in Table VIII, where they were measured before swelling the emulsion. The range of track 1 is quite important in determining its mass. Then we determined the most probable value and an upper and lower limit of its range. The reason why the range error of track 1 is different values for the sign, (+) and (−), is that the Ξ^- hyperon seems to have turned to the (+) direction before stopping. Regarding track 3, the range error is also determined by the stopping point of the track. The particle of track 4 was identified as a proton from the measurements of the grain density and the range. The effect on the measurement of the angles by any distortion due to swelling was checked and found to be negligibly small within quoted errors.

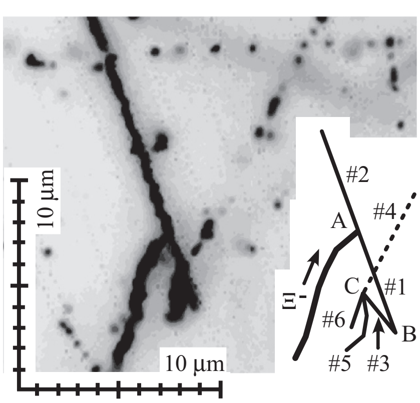

FIG. 5. Photograph and schematic drawing of the *Demachiyanagi* event. A photograph was obtained by summing up images taken at various focusing position of the microscope.

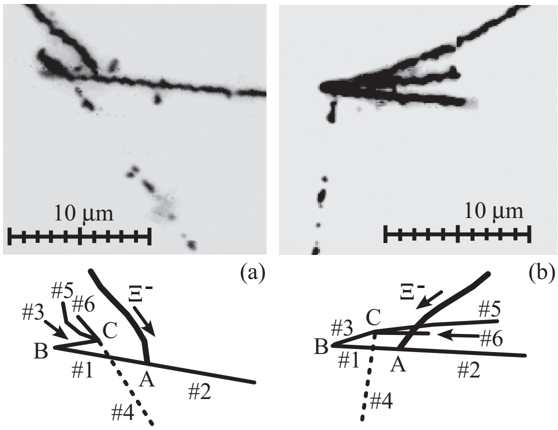

FIG. 6. Photographs and schematic drawings of the event viewed from the vertical (a) and the horizontal (b) direction of the *Demachiyanagi* event. Each photo was made after swelling and slicing a tiny piece of the emulsion, as described in the text.

Kinematic analysis has been made at the production point A and its result is listed in Table IX.

Many possible modes remained under the cut of $\Delta B_{\Lambda\Lambda} - B_{\Xi^-} < 20$ MeV. However, the following processes give values of $B_{\Lambda\Lambda}$ and $\Delta B_{\Lambda\Lambda}$ consistent with previous data:

$$^{12}\mathrm{C} + \Xi^- \to {}^{10}_{\Lambda\Lambda}\mathrm{Be} + t \qquad (1),$$
$$^{12}\mathrm{C} + \Xi^- \to {}^{11}_{\Lambda\Lambda}\mathrm{Be} + p + n \qquad (2),$$
$$^{14}\mathrm{N} + \Xi^- \to {}^{13}_{\Lambda\Lambda}\mathrm{B} + p + n \qquad (3).$$

By the kinematical fitting for process (1), $B_{\Lambda\Lambda} - B_{\Xi^-}$ and $\Delta B_{\Lambda\Lambda} - B_{\Xi^-}$ values were obtained as 11.77 ± 0.13 and -1.65 ± 0.15 MeV, respectively. With the assumption for Ξ^- hyperon capture in the atomic 3D level, the values of $B_{\Lambda\Lambda}$ and $\Delta B_{\Lambda\Lambda}$ are obtained as 11.90 ± 0.13 and -1.52 ± 0.15 MeV, respectively.

Note that if the double-Λ hypernucleus had been produced in an excited state, the binding energy of the ground state of the double-Λ hypernucleus would be increased by the excitation energy. If we assume the excitation energy of ${}^{10}_{\Lambda\Lambda}\mathrm{Be}^*$ is almost the same as those of $^8\mathrm{Be}^*$ and ${}^{9}_{\Lambda}\mathrm{Be}^*$ (about 3 MeV [23]), process (1) is not in contradiction with the *Nagara* result. This shows a probable production of a ${}^{10}_{\Lambda\Lambda}\mathrm{Be}^*$ nucleus in this event.

Dalitz *et al.* [24] they reported 17.7 ± 0.4 and 4.3 ± 0.4 MeV for $B_{\Lambda\Lambda}$ and $\Delta B_{\Lambda\Lambda}$ values, respectively, for the event given by Danysz *et al.* [1]. They assigned the event as a ${}^{10}_{\Lambda\Lambda}\mathrm{Be}$ nucleus, which decayed into a ${}^{9}_{\Lambda}\mathrm{Be}$, a proton and a π^- meson. The $\Delta B_{\Lambda\Lambda}$ value is inconsistent with the *Nagara* event, if the ${}^{9}_{\Lambda}\mathrm{Be}$ nucleus was not emitted in an excited state at the decay of a ${}^{10}_{\Lambda\Lambda}\mathrm{Be}$ nucleus [25]. In the case of decay with an excited ${}^{9}_{\Lambda}\mathrm{Be}$ nucleus, the values for $B_{\Lambda\Lambda}$ and $\Delta B_{\Lambda\Lambda}$ should decrease by 3.05 MeV [23] and would become 14.7 ± 0.4 and 1.3 ± 0.4 MeV, respectively.

The discrepancy of $B_{\Lambda\Lambda}$ values between the one of the *Demachiyanagi* event and 14.7 MeV can be interpreted as the excitation energy of a ${}^{10}_{\Lambda\Lambda}\mathrm{Be}^*$ nucleus, which is obtained to be 2.8 ± 0.4 MeV.

Regarding processes (2) and (3), it is impossible to apply the kinematical fitting because of neutron emission. Assuming Ξ^- hyperon capture in the atomic 3D level, the values of $B_{\Lambda\Lambda}$ and $\Delta B_{\Lambda\Lambda}$ are $22.44^{+1.70}_{-1.09}$ and $4.22^{+1.75}_{-1.18}$ for ${}^{11}_{\Lambda\Lambda}\mathrm{Be}$ in (2) and $27.94^{+3.16}_{-2.02}$ and $5.20^{+3.17}_{-2.03}$ for ${}^{13}_{\Lambda\Lambda}\mathrm{B}$ in (3), respectively. The values of process (3) agree with the previous event ($B_{\Lambda\Lambda} = 23.3 \pm 0.7$ MeV and $\Delta B_{\Lambda\Lambda} = 0.6 \pm 0.8$ MeV for ${}^{13}_{\Lambda\Lambda}\mathrm{B}$ [4]) within three standard deviation errors.

Among the above three processes, only process (1) is accompanied with no neutron emission, while the other processes include a neutron in the fragments as shown in Table IX. The back-to-back topology at production point A

TABLE IX. Possible production modes of the double-Λ hypernucleus, the *Demachiyanagi* event. Only the modes of $\Delta B_{\Lambda\Lambda} - B_{\Xi^-} < 20$ MeV are listed. Kinematic fitting has been applied for the process (1) and its result can be seen in the text.

Target	Track 1	Track 2		$B_{\Lambda\Lambda} - B_{\Xi^-}$ (MeV)	$\Delta B_{\Lambda\Lambda} - B_{\Xi^-}$ (MeV)	
^{12}C	${}^{9}_{\Lambda\Lambda}$Be	t	1n	$30.83^{+0.65}_{-0.53}$	$17.15^{+0.66}_{-0.54}$	
^{12}C	${}^{10}_{\Lambda\Lambda}$Be	p	2n	>19.85	>6.43	
^{12}C	${}^{10}_{\Lambda\Lambda}$Be	d	1n	$17.39^{+0.59}_{-0.34}$	$3.97^{+0.60}_{-0.35}$	
^{12}C	${}^{10}_{\Lambda\Lambda}$Be	t		$11.46^{+0.24}_{-0.13}$	$-1.96^{+0.25}_{-0.15}$	(1)
^{12}C	${}^{11}_{\Lambda\Lambda}$Be	p	1n	$22.31^{+1.70}_{-1.09}$	$4.09^{+1.75}_{-1.18}$	(2)
^{14}N	${}^{11}_{\Lambda\Lambda}$B	p	3n	>35.12	>17.34	
^{14}N	${}^{11}_{\Lambda\Lambda}$B	d	2n	>32.61	>14.83	
^{14}N	${}^{11}_{\Lambda\Lambda}$B	t	1n	$26.20^{+0.65}_{-0.39}$	$8.42^{+0.69}_{-0.46}$	
^{14}N	${}^{12}_{\Lambda\Lambda}$B	p	2n	>29.84	>9.36	
^{14}N	${}^{12}_{\Lambda\Lambda}$B	d	1n	$27.59^{+1.68}_{-1.04}$	$7.11^{+1.69}_{-1.04}$	
^{14}N	${}^{13}_{\Lambda\Lambda}$B	p	1n	$27.81^{+3.16}_{-2.02}$	$5.07^{+3.17}_{-2.03}$	(3)
^{16}O	${}^{13}_{\Lambda\Lambda}$C	t	1n	$37.28^{+1.77}_{-1.04}$	$15.68^{+1.81}_{-1.10}$	
^{16}O	${}^{14}_{\Lambda\Lambda}$C	p	2n	>32.63	>9.25	
^{16}O	${}^{14}_{\Lambda\Lambda}$C	d	1n	$32.41^{+3.18}_{-1.98}$	$9.03^{+3.19}_{-1.99}$	
^{16}O	${}^{15}_{\Lambda\Lambda}$C	p	1n	$43.83^{+4.86}_{-3.14}$	$19.49^{+4.90}_{-3.21}$	

TABLE VIII. Lengths and angles of the tracks for the *Demachiyanagi* event. The length of track 4 is the visible amount in the emulsion only.

Point	Track	Length (μm)	θ (degree)	ϕ (degree)	Comment
A	1	$4.2^{+0.25}_{-0.07}$	124.5 ± 5.1	343.2 ± 3.5	double-Λ hypernucleus
	2	287.0 ± 1.9	57.7 ± 1.1	159.4 ± 0.5	
B	3	$3.7^{+0.3}_{-0.1}$	32.6 ± 7.8	145 ± 10	single-Λ hypernucleus
C	4	23575	94.2 ± 0.4	209.8 ± 0.3	proton
	5	11.3 ± 0.7	9.4 ± 3.4	341 ± 20	
	6	8.4 ± 0.7	7.2 ± 2.5	21 ± 19	

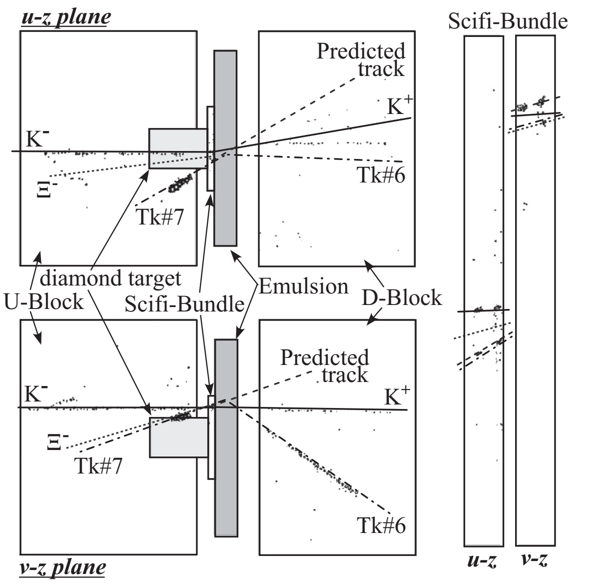

FIG. 7. Image around the target region for the *Hida* event. The solid lines are tracks of incoming K^- and outgoing K^+ mesons measured with the spectrometer system. The dashed line is a predicted track to be the reconstructed Ξ^- hyperon scanned with the SciFi-Bundle. The dotted and dashed-dotted lines are extrapolated ones for the track of the Ξ^- hyperon (associated with point A in Fig. 8) and tracks 6 and 7 using the position and angle of those tracks in the emulsion, respectively.

says that process (1) is the most probable, though processes (2) and (3) cannot be rejected.

Regarding the excitation of the double-Λ hypernuclei, theoretical study has been made for the nuclei with $A = 7$–10 based on four-body cluster structure [9]. In the paper given by Hiyama *et al.*, they discussed the 2^+ excited state and obtained 2.86 MeV of the excitation energy for the ${}^{10}_{\Lambda\Lambda}\mathrm{Be}^*$ nucleus, which is in very good agreement with our result in process (1).

D. "*Hida*" event

The momentum and mass of the tagged K^+ meson were 1.119 GeV/c and 0.495 GeV/c^2, respectively. An image of the target region for the event is shown in Fig. 7. A track shown as "predicted track" in the figure has been followed and arrived at a star presented in Fig. 8, which is a photograph and schematic drawing of the *Hida* event.

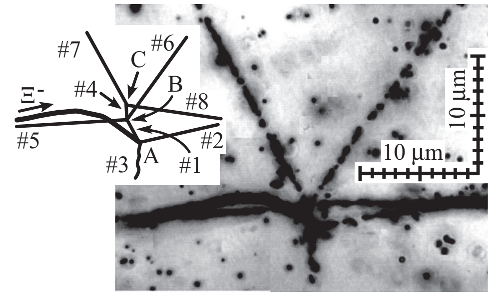

FIG. 8. Photograph and schematic drawing of the *Hida* event.

The reconstructed Ξ^- hyperon candidate in the Scifi-Bundle was a particle of track 7, and this track was followed downstream of the emulsion to its end point. A heavily scattered track associated at point A becomes straight upstream of the emulsion stack, thus this particle must be a Ξ^- hyperon from the (K^-, K^+) reaction vertex. Its track was escaping from upstream of the emulsion and was not recorded in the Scifi-Bundle. From Fig. 7, the (K^-, K^+) reaction seems to have occurred at the most downstream position of the Scifi-Bundle.

Three charged particles (tracks 1, 2, and 3) were emitted from the at-rest capture point A of the Ξ^- hyperon candidate. One of them (1) decayed into three charged particles (4, 5, and 6) at point B. The particle of track 4 decayed again into two charged particles (7 and 8) at point C. The particle of track 6 escaped from downstream of the emulsion stack and its trajectory was recorded in the v-z plane of D-Block.

The lengths and angles of these tracks are summarized in Table X. Regarging the particle of track 6, it was identified as a proton using range data in the emulsion and D-Block, and by ionization measurement in the emulsion. The particle of track 7 was also found to be a proton by ionization measurement in the emulsion and brightness of the track in U-Block.

Since both of the double-Λ and the single-Λ hypernucleus decayed nonmesonically, it was found that the double-Λ hypernucleus must be a $_{\Lambda\Lambda}$Be or $_{\Lambda\Lambda}$B nucleus, only from the number of the emitted charged particles and the assumption of a Ξ^- capture by a light nucleus (^{12}C, ^{14}N, or ^{16}O). Kinematic analysis has been made at production point A and possible modes are listed in Table XI. The event reconstruction at points B and C gave us no constraints to the nuclide identification.

TABLE X. Lengths and angles of the tracks for the *Hida* event. The length of track 7 is only the visible amount in the emulsion. Points A and B are noncoplanar vertices, where coplanarities are -0.434 ± 0.073 and -0.449 ± 0.006 for points A and B, respectively.

Point	Track	Length (μm)	θ (degree)	ϕ (degree)	Comment
A	1	2.3 ± 0.2	53.3 ± 4.0	116.0 ± 5.8	double-Λ hypernucleus
	2	53.5 ± 0.2	100.7 ± 0.2	7.0 ± 0.1	
	3	4.7 ± 0.6	91.7 ± 3.2	256.7 ± 1.0	
B	4	7.7 ± 0.1	4.1 ± 0.5	95.1 ± 6.2	single-Λ hypernucleus
	5	74.9 ± 0.4	74.6 ± 0.1	180.5 ± 0.1	
	6	$>5847.9 \pm 11.3$	147.6 ± 0.1	51.2 ± 0.1	proton
C	7	$>6728.8 \pm 8.2$	31.0 ± 0.1	115.3 ± 0.1	proton
	8	96.0 ± 0.4	107.2 ± 0.1	356.6 ± 0.1	

TABLE XI. Possible production modes of the double-Λ hypernucleus, the *Hida* event. The modes of $\Delta B_{\Lambda\Lambda} - B_{\Xi^-} < 20$ MeV are listed. Parenthetic values for $\Delta B_{\Lambda\Lambda} - B_{\Xi^-}$ are obtained with the assumptions of $B_{\Lambda}({}^{11}_{\Lambda}\mathrm{Be}) = B_{\Lambda}({}^{11}_{\Lambda}\mathrm{B})$ and $B_{\Lambda}({}^{13}_{\Lambda}\mathrm{B}) = B_{\Lambda}({}^{13}_{\Lambda}\mathrm{C})$ for ${}^{12}_{\Lambda\Lambda}$Be and ${}^{14}_{\Lambda\Lambda}$B, respectively.

Target	Track 1	Track 2	Track 3		$B_{\Lambda\Lambda} - B_{\Xi^-}$ (MeV)	$\Delta B_{\Lambda\Lambda} - B_{\Xi^-}$ (MeV)	
^{14}N	${}^{10}_{\Lambda\Lambda}$Be	p	p	$3n$	>25.86	>12.44	
^{14}N	${}^{10}_{\Lambda\Lambda}$Be	d	p	$2n$	>25.98	>12.56	
^{14}N	${}^{10}_{\Lambda\Lambda}$Be	p	d	$2n$	>24.21	>10.79	
^{14}N	${}^{10}_{\Lambda\Lambda}$Be	t	p	$1n$	26.26 ± 1.05	12.84 ± 1.06	
^{14}N	${}^{10}_{\Lambda\Lambda}$Be	p	t	$1n$	19.99 ± 1.09	6.57 ± 1.10	
^{14}N	${}^{10}_{\Lambda\Lambda}$Be	d	d	$1n$	26.25 ± 0.95	12.83 ± 0.95	
^{14}N	${}^{11}_{\Lambda\Lambda}$Be	p	p	$2n$	>25.42	>7.20	
^{14}N	${}^{11}_{\Lambda\Lambda}$Be	d	p	$1n$	28.40 ± 0.98	10.18 ± 1.07	
^{14}N	${}^{11}_{\Lambda\Lambda}$Be	p	d	$1n$	25.50 ± 1.16	7.28 ± 1.24	
^{14}N	${}^{12}_{\Lambda\Lambda}$Be	p	p	$1n$	22.31 ± 1.21	(1.83 ± 1.21)	(1)
^{16}O	${}^{10}_{\Lambda\Lambda}$Be	p	^{4}He	$2n$	>20.73	>7.31	
^{16}O	${}^{10}_{\Lambda\Lambda}$Be	d	^{4}He	$1n$	20.57 ± 1.21	7.15 ± 1.21	
^{16}O	${}^{11}_{\Lambda\Lambda}$Be	p	^{4}He	$1n$	20.60 ± 1.27	2.38 ± 1.34	(2)
^{16}O	${}^{12}_{\Lambda\Lambda}$Be	p	^{3}He	$1n$	34.73 ± 1.25	(14.25 ± 1.25)	
^{16}O	${}^{12}_{\Lambda\Lambda}$B	p	t	$1n$	40.35 ± 2.00	19.87 ± 2.00	
^{16}O	${}^{13}_{\Lambda\Lambda}$B	p	p	$2n$	>33.90	>11.16	
^{16}O	${}^{13}_{\Lambda\Lambda}$B	d	p	$1n$	39.21 ± 1.72	16.47 ± 1.72	
^{16}O	${}^{13}_{\Lambda\Lambda}$B	p	d	$1n$	36.57 ± 2.10	13.83 ± 2.11	
^{16}O	${}^{14}_{\Lambda\Lambda}$B	p	p	$1n$	37.59 ± 2.34	(14.21 ± 2.34)	

For all the modes of a Boron double-Λ hypernucleus, the values of $B_{\Lambda\Lambda}$ and $\Delta B_{\Lambda\Lambda}$ are quite far from previous data of a ${}^{13}_{\Lambda\Lambda}$B nucleus (KEK-E176) [4]. Therefore, the following two processes remain as possible ones which gave consistent $\Delta B_{\Lambda\Lambda}$ values with the *Nagara* event within three standard deviation errors:

$$ {}^{14}\mathrm{N} + \Xi^- \rightarrow {}^{12}_{\Lambda\Lambda}\mathrm{Be} + p + p + n \qquad (1), $$

$$ {}^{16}\mathrm{O} + \Xi^- \rightarrow {}^{11}_{\Lambda\Lambda}\mathrm{Be} + p + {}^{4}\mathrm{He} + n \qquad (2). $$

Regarding process (1), the value of $B_{\Lambda\Lambda}$ is obtained to be 22.48 ± 1.21 with 0.17 MeV [21] for B_{Ξ^-} in the atomic 3D level. The $\Delta B_{\Lambda\Lambda}$ cannot be obtained because the Λ binding energy of the ${}^{11}_{\Lambda}$Be nucleus is not known experimentally. Therefore, we took an experimental value, 10.24 MeV, of $B_{\Lambda}({}^{11}_{\Lambda}\mathrm{B})$ for $B_{\Lambda}({}^{11}_{\Lambda}\mathrm{Be})$ into account, and obtained the value of $\Delta B_{\Lambda\Lambda}({}^{12}_{\Lambda\Lambda}\mathrm{Be})$ to be 2.00 ± 1.21 MeV, which is in agreement with the one of the *Nagara* event. Process (2) presents a value of $\Delta B_{\Lambda\Lambda} - B_{\Xi^-}$ consistent with the *Nagara* event. Taking 0.23 MeV [21] for the 3D atomic level in the ^{16}O-Ξ^- system, values of $B_{\Lambda\Lambda}$ and $\Delta B_{\Lambda\Lambda}$ were measured to be 20.83 ± 1.27 and 2.61 ± 1.34 MeV for a ${}^{11}_{\Lambda\Lambda}$Be nucleus, respectively.

Very recently, a five-body cluster ($\alpha\alpha n\Lambda\Lambda$) calculation has been carried out for a ${}^{11}_{\Lambda\Lambda}$Be nucleus by Hiyama *et al.* [10]. In the paper, the authors obtained a $B_{\Lambda\Lambda}({}^{11}_{\Lambda\Lambda}\mathrm{Be})$ value of 18.23 MeV, which would be in agreement with our value within two standard deviations. For the possible ${}^{12}_{\Lambda\Lambda}$Be case, it is expected to be obtained by performing a six-body cluster model calculation ($\alpha + \alpha + 2n + \Lambda + \Lambda$).

IV. CONCLUDING REMARKS

A hybrid emulsion experiment (KEK-E373) with scintillating-fiber detectors has been carried out and successfully stopped $\sim 10^3$ Ξ^- hyperons captured by emulsion nuclei. Among them, seven events with sequential weak decay topologies of a double-Λ hypernucleus have been observed. Four events among seven were discussed on their nuclear species and also $B_{\Lambda\Lambda}$ and $\Delta B_{\Lambda\Lambda}$ values, although another three events were unanalyzable due to difficulties of recognition of some tracks.

Regarding the *Nagara* event, a recalculation has been made due to change of the mass of the Ξ^- hyperon. Again, we obtained unique information for $B_{\Lambda\Lambda}$ and $\Delta B_{\Lambda\Lambda}$ of a ${}^{6}_{\Lambda\Lambda}$He nucleus to be 6.91 ± 0.16 and 0.67 ± 0.17 MeV, respectively, with the assumption of the Ξ^- hyperon capture at the atomic 3D level in a ^{12}C nucleus. This result suggests a weak attractive Λ-Λ interaction.

Taking the Ξ^- hyperon capture in the atomic 3D level into account, we obtained $\Delta B_{\Lambda\Lambda}$ values in three other events consistent with that of the *Nagara* event.

For the *Mikage* event, two possibilities for a nuclide of a double-Λ hypernucleus are obtained by the kinematic analysis at the production and decay points. One is the process of a ${}^{6}_{\Lambda\Lambda}$He nucleus with ${}^{3}_{\Lambda}$H as one of daughters. $B_{\Lambda\Lambda}$ and $\Delta B_{\Lambda\Lambda}$ values were 10.01 ± 1.71 and 3.77 ± 1.71 MeV, respectively. Another possibility is the production and decay of a ${}^{11}_{\Lambda\Lambda}$Be nucleus. The values of $B_{\Lambda\Lambda}$ and $\Delta B_{\Lambda\Lambda}$ were 22.15 ± 2.94 and 3.95 ± 3.00 MeV, respectively, in the process of the Ξ^- hyperon capture in the ^{12}C nucleus. In the case of ^{14}N capture, the values of 23.05 ± 2.59 and 4.85 ± 2.63 MeV were obtained for $B_{\Lambda\Lambda}$ and $\Delta B_{\Lambda\Lambda}$, respectively. For two capture cases, a ${}^{9}_{\Lambda}$Li nucleus was associated with the decay of ${}^{11}_{\Lambda\Lambda}$Be. Since a π^- meson was associated with the decay of the daughter single-Λ hypernucleus, the event is likely the production and decay of a ${}^{6}_{\Lambda\Lambda}$He nucleus.

Topological characteristics give us the most probable interpretation without any neutron emission for the *Demachiyanagi* event. A ${}^{10}_{\Lambda\Lambda}$Be nucleus was probably produced in an excited state, because the obtained $\Delta B_{\Lambda\Lambda}$ value of -1.52 ± 0.15 MeV is in good agreement with the *Nagara* result by assuming an excitation energy of ~3 MeV, like the ones of ^{8}Be* and ${}^{9}_{\Lambda}$Be. The $B_{\Lambda\Lambda}$ value of this event was 11.90 ± 0.13 MeV which would be different from 14.7 ± 0.4 MeV presented in the case of the excitation of the daughter nucleus of ${}^{9}_{\Lambda}$Be for the event by Danysz *et al*. The value of 2.8 ± 0.4 MeV was obtained as the excitation energy of ${}^{10}_{\Lambda\Lambda}$Be nucleus, for the first time, by the discrepancy of $B_{\Lambda\Lambda}$ values between the one of the *Demachiyanagi* event and 14.7 MeV.

In the *Hida* event, two possibilities remained as a ${}^{11}_{\Lambda\Lambda}$Be or ${}^{12}_{\Lambda\Lambda}$Be nucleus. The values of $B_{\Lambda\Lambda}$ and $\Delta B_{\Lambda\Lambda}$ are 20.83 ± 1.27 and 2.61 ± 1.34 MeV for ${}^{11}_{\Lambda\Lambda}$Be, respectively. For the ${}^{12}_{\Lambda\Lambda}$Be case, the $B_{\Lambda\Lambda}$ value was obtained to be 22.48 ± 1.21 MeV. In the above two cases, since one or two neutrons are attached inside the ${}^{10}_{\Lambda\Lambda}$Be nucleus, it would be very interesting from the point of view of a theoretical cluster model, i.e., two α clusters, two Λ hyperons, and neutron(s). Shell model calculation has been made to obtain $B_{\Lambda\Lambda}$ values for p-shell double-Λ hypernuclei using the $(2J+1)$-averaged B_Λ in single-Λ hypernucleus [26].

The E373 experiment has opened the door of the $S=-2$ world with multiple nuclides of a double-Λ hypernucleus for the first time. However, to get knowledge of Λ-Λ interaction without ambiguity due to the differences of core nuclei, it will be very important to observe uniquely identified events which are independent of the *Nagara* event. In the E07 experiment [27] at J-PARC, it is expected that the extensive study of the $S=-2$ system will be carried out with more than several tens of double-Λ hypernuclei.

ACKNOWLEDGMENTS

The authors thank the KEK staff for support of the experiment and Professor E. Hiyama for theoretical comments. This work was supported by the Saito Seijiro Science Foundation in 2007, by JSPS Grants No. 14340069 and No. 23224006, by KRF Grant No. 2008-313-C00201, and by MEXT Grants No. 08239103 and No. 15001001.

[1] M. Danysz *et al.*, Nucl. Phys. **49**, 121 (1963).
[2] R. L. Jaffe, Phys. Rev. Lett. **38**, 195 (1977).
[3] S. Aoki *et al.*, Prog. Theor. Phys. **85**, 1287 (1991).
[4] S. Aoki *et al.*, Nucl. Phys. A **828**, 191 (2009).
[5] N. Ishii, S. Aoki, and T. Hatsuda, Phys. Rev. Lett. **99**, 022001 (2007).
[6] J. K. Ahn *et al.*, Phys. Lett. B **444**, 267 (1998).
[7] C. J. Yoon *et al.*, Phys. Rev. C **75**, 022201(R) (2007).
[8] H. Takahashi *et al.*, Phys. Rev. Lett. **87**, 212502 (2001).
[9] E. Hiyama, M. Kamimura, T. Motoba, T. Yamada, and Y. Yamamoto, Phys. Rev. C **66**, 024007 (2002).
[10] E. Hiyama, M. Kamimura, Y. Yamamoto, and T. Motoba, Phys. Rev. Lett. **104**, 212502 (2010).
[11] T. Motoba, H. Bando, and K. Ikeda, Prog. Theor. Phys. **70**, 189 (1983); T. Motoba, H. Bando, K. Ikeda, and T. Yamada, Prog. Theor. Phys. Suppl. **81**, 42 (1985); E. Hiyama, M. Kamimura, K. Miyazaki, and T. Motoba, Phys. Rev. C **59**, 2351 (1999).
[12] K. Tanida *et al.*, Phys. Rev. Lett. **86**, 1982 (2001).
[13] C. Amsler *et al.* (Particle Data Group), Phys. Lett. B **667**, 1 (2008).
[14] H. Takahashi *et al.*, Nucl. Phys. A **721**, 951c (2003); K. Nakazawa and H. Takahashi, Prog. Theor. Phys. Suppl. **185**, 335 (2010); K. Nakazawa, Nucl. Phys. A **835**, 207 (2010).
[15] T. Iijima *et al.*, Nucl. Phys. A **546**, 588 (1992).
[16] D. E. Alburger and M. May, Nucl. Instrum. Methods A **443**, 27 (2000).
[17] A. Ichikawa *et al.*, Phys. Lett. B **500**, 37 (2000).
[18] A. Ichikawa, Ph.D. thesis, Kyoto Univeriesty, 2001 (unpublished); H. Takahashi, Ph.D. thesis, Kyoto Univeriesty, 2003 (unpublished).
[19] H. Takahashi *et al.*, Nucl. Instrum. Methods A **483**, 689 (2002).
[20] S. N. Nakamura *et al.*, Phys. Rev. Lett. **110**, 012502 (2013).
[21] C. J. Batty, E. Friedman, and A. Gal, Phys. Rev. C **59**, 295 (1999).
[22] K. Itonaga (private communication).
[23] O. Hashimoto and H. Tamura, Prog. Part. Nucl. Phys. **57**, 564 (2006). In the paper, excitation energies of the ${}^{9}_{\Lambda}\mathrm{Be}^*$ nucleus have been presented to be 3.024 and 3.067 MeV for the doublet states of $5/2+$ and $3/2+$, respectively, by γ-ray measurement. We took a mean value, 3.05 MeV, of doublet states to obtain the excitation energy of the ${}^{10}_{\Lambda\Lambda}\mathrm{Be}^*$ nucleus.
[24] R. H. Dalitz *et al.*, Proc. R. Soc. London A **426**, 1 (1989).
[25] D. H. Davis, Nucl. Phys. A **754**, 3c (2005).
[26] A. Gal and D. J. Millener, Phys. Lett. B **701**, 342 (2011).
[27] K. Imai, K. Nakazawa, and H. Tamura, J-PARC E07 proposal, 2006, http://j-parc.jp/researcher/Hadron/en/Proposal_e.html