Observation of a ${}^{\,6}_{\Lambda\Lambda}$He Double Hypernucleus

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A double-hyperfragment event has been found in a hybrid-emulsion experiment. It is identified uniquely as the sequential decay of ${}^{\,6}_{\Lambda\Lambda}$He emitted from a Ξ^- hyperon nuclear capture at rest. The mass of ${}^{\,6}_{\Lambda\Lambda}$He and the Λ-Λ interaction energy $\Delta B_{\Lambda\Lambda}$ have been measured for the first time devoid of the ambiguities due to the possibilities of excited states. The value of $\Delta B_{\Lambda\Lambda}$ is $1.01 \pm 0.20^{+0.18}_{-0.11}$ MeV. This demonstrates that the Λ-Λ interaction is weakly attractive.

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The observation of double-Λ hypernuclei gives important information about the Λ-Λ interaction. The binding energy of two Λ hyperons, $B_{\Lambda\Lambda}$, and the Λ-Λ interaction energy, $\Delta B_{\Lambda\Lambda}$, can be obtained from the measurement of the masses of double-Λ nuclei, where $\Delta B_{\Lambda\Lambda}$ is defined by

$$\Delta B_{\Lambda\Lambda}({}^{\,A}_{\Lambda\Lambda}Z) = B_{\Lambda\Lambda}({}^{\,A}_{\Lambda\Lambda}Z) - 2B_{\Lambda}({}^{A-1}_{\ \ \Lambda}Z). \qquad (1)$$

There are three reports on the observations of double-Λ hypernuclei in nuclear emulsion. About three decades ago, an example of the double-hypernucleus ${}^{\,6}_{\Lambda\Lambda}$He was presented [1]. However, only a schematic drawing of the event was given in the Letter, and measured angles were not presented. The authenticity of it was considered doubtful [2]. The other two double-hypernucleus events [2–5] have either more than one interpretation for the species or the possibility of production of excited states. The production of ${}^{\,4}_{\Lambda\Lambda}$H hypernuclei was recently reported in a counter-experiment [6], but the statistics were limited and a value of $\Delta B_{\Lambda\Lambda}$ was not presented.

Theoretical calculations of the binding energies of double hypernuclei have been made since the 1960s, aiming to obtain information on the Λ-Λ interaction [7–9]. Among possible double-Λ hypernuclei, ${}^{\,6}_{\Lambda\Lambda}$He has been considered to be important because it gives information not only on the Λ-Λ interaction but also on the cluster structure of hypernuclei. The ${}^{\,6}_{\Lambda\Lambda}$He hypernucleus constitutes the lightest closed shell structure containing p,

n, and Λ baryons [10]. Double-Λ hypernuclei are closely related to the existence of the H dibaryon [11]. If the mass of the H dibaryon, M_H, was less than twice the Λ hyperon mass in a nucleus, two Λ hyperons in the nucleus would be expected to form the H. With this assumption, the lower limit of the mass of the H dibaryon can be calculated from the following relation:

$$M_H > 2M_\Lambda - B_{\Lambda\Lambda}\,, \tag{2}$$

where M_Λ is the mass of a Λ hyperon in free space.

In order to study such systems, an emulsion/scintillating-fiber hybrid experiment (E373) has been carried out at the KEK proton synchrotron using the 1.66 GeV/c separated K^- meson beam [12,13]. The schematic view around the target is given in Fig. 1. Ξ^- hyperons were produced via the quasifree (K^-, K^+) reactions in a diamond target [14] and brought to rest in Fuji ET-7C emulsion. The (K^-, K^+) reactions were tagged by a spectrometer system. The positions and angles of entry of the Ξ^- hyperons at the emulsion were measured with a scintillating microfiber-bundle detector [15] placed between the diamond target and the emulsion stack. The tracks of the Ξ^- hyperons were scanned and traced in the emulsion by a newly developed automatic track scanning system [16]. An emulsion stack consisted of a thin emulsion plate located upstream followed by eleven thick emulsion plates [17]. The thin plate had 70-μm-thick emulsion gel on both sides of a 200-μm-thick acrylic base film, and each thick plate had 500-μm-thick emulsion gel on both sides of a 50-μm-thick acrylic film.

Although we have analyzed only 11% of the total emulsion, we have found an event of seminal importance, a mesonically decaying double hypernucleus emitted from a Ξ^- capture at rest [18]. A photograph and schematic drawing of the event are shown in Fig. 2. We named this event "NAGARA." A Ξ^- hyperon came to rest at point A, from which three charged particles (tracks No. 1, No. 3, and No. 4) were emitted. One of them decayed into a π^- meson (track No. 6) and two other charged particles (tracks No. 2 and No. 5) at point B. The particle of track No. 2 decayed again to two charged particles (tracks No. 7 and No. 8) at point C.

The measured lengths and emission angles of these tracks are summarized in Table I. The particle of track No. 7 left the emulsion stack and entered the downstream scintillating-fiber block detector (D-Block) [19]. Track No. 5 ended in a 50-μm-thick acrylic base film. The tracks of the three charged particles emitted from point A are coplanar within the error as are the three tracks from point B. The kinetic energy of each charged particle was calculated from its range, where the range-energy relation was calibrated using α decays of thorium series in the emulsion and μ^+ decays from π^+ meson decays at rest.

The single hypernucleus (track No. 2) was identified from event reconstruction of its decay at point C. Mesonic decay modes of single hypernuclei were rejected because their Q values are too small. The decay mode of the single hypernucleus is nonmesonic with neutron emission. If either track No. 7 or No. 8 has more than unit charge, the total kinetic energy of the two charged particles is much larger than the Q value of any possible decay mode because of the long ranges of tracks No. 7 and No. 8. Therefore, both tracks No. 7 and No. 8 are singly charged, and only ${}_\Lambda$He isotopes are acceptable.

The kinematics of all possible decay modes of the double hypernucleus (track No. 1) which decays into ${}_\Lambda$He (track No. 2) and π^- (track No. 6) were checked, and $B_{\Lambda\Lambda}$ and $\Delta B_{\Lambda\Lambda}$ were calculated. Since track No. 5 ended in the base film, only the lower limit of the kinetic energy

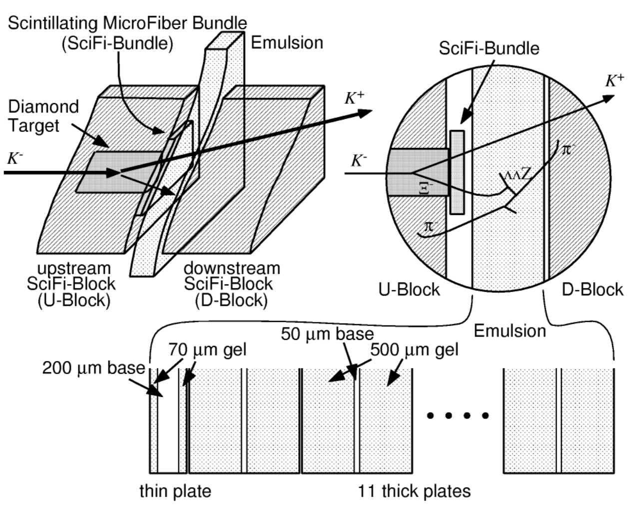

FIG. 1. Schematic view of the experimental setup.

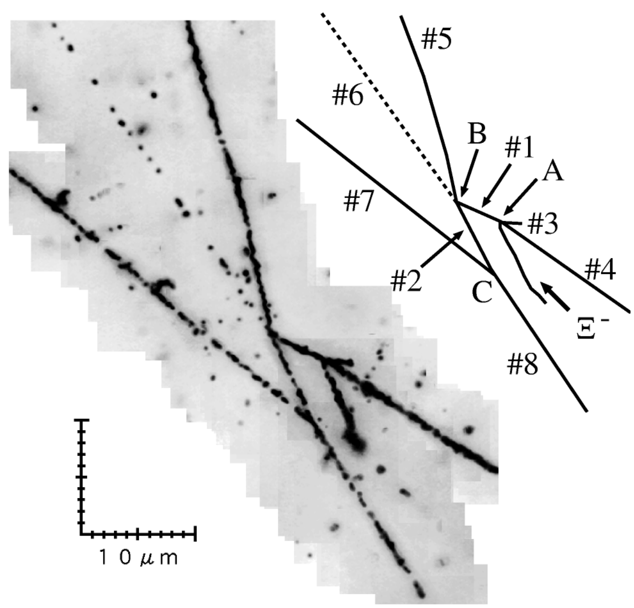

FIG. 2. Photograph and schematic drawing of NAGARA event. See text for detailed explanation.

TABLE I. Lengths and emission angles of the tracks. Angles are expressed by a zenith angle (θ) with respect to the direction perpendicular to the plate and an azimuthal angle (ϕ). The indicated errors are the measurement errors only. For tracks No. 4, No. 6, No. 7, and No. 8, the ranges in an acrylic base were converted to those in emulsion. The lengths of tracks No. 5 and No. 7 are the visible ones in the emulsion only. The length of track No. 7 inside the D-Block is 13.1 mm.

Point	Track No.	Length [μm]	θ [degree]	ϕ [degree]	
A	1	8.1 ± 0.3	44.9 ± 2.0	337.5 ± 1.8	Double hypernucleus
	3	3.2 ± 0.4	57.7 ± 5.2	174.9 ± 2.9	
	4	88.3 ± 0.5	156.2 ± 0.5	143.0 ± 1.0	
B	2	9.1 ± 0.3	77.7 ± 1.6	115.9 ± 0.8	Single hypernucleus
	5	82.1 ± 0.6	122.8 ± 1.0	284.2 ± 0.7	Stopped in base
	6	13 697	81.1 ± 0.8	305.5 ± 0.1	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

can be determined. For the decay modes without neutron emission, the range of the particle of track No. 5 was increased to minimize the missing momentum. If the sum of the momenta of the three charged particles (tracks No. 2, No. 5, and No. 6) deviated from zero by more than three standard deviations even after the range of track No. 5 was increased from the missing momentum, that decay mode was rejected. For the decay modes with neutron emission, the upper limits of $B_{\Lambda\Lambda}$ and $\Delta B_{\Lambda\Lambda}$ were obtained. Only the results for $\Delta B_{\Lambda\Lambda} > -20$ MeV are listed in Table II. The cases of double hypernuclei with more than two units of charge are not given because their values of $\Delta B_{\Lambda\Lambda}$ were less than -20 MeV.

Kinematical analysis of the production reaction was made by assuming that the Ξ^- hyperon was captured by a light nucleus in the emulsion (^{12}C, N^{14}, or ^{16}O). This assumption is reasonable, taking into account the existence of the short track No. 3 and the Coulomb barrier of the target nucleus. For each of the modes without neutron emission, if the sum of momenta deviated from zero by more than three standard deviations, the mode was rejected. For the modes with one neutron emission, the momentum of the neutron was assigned to the missing momentum of the three charged particles (tracks No. 1, No. 3, and No. 4). For the modes with more than one neutron emission, the lower limits of the total kinetic energy of the neutrons were calculated from the missing momentum. The results for $\Delta B_{\Lambda\Lambda} < 20$ MeV are presented in Table III. The values of $B_{\Lambda\Lambda}$ and $\Delta B_{\Lambda\Lambda}$ were calculated with the Ξ^- hyperon binding energy B_{Ξ^-} set to zero. Hence these values are lower limits of $B_{\Lambda\Lambda}$ and $\Delta B_{\Lambda\Lambda}$, and their true values are larger, depending on the actual value of B_{Ξ^-}.

A comparison of the values of $B_{\Lambda\Lambda}$ and $\Delta B_{\Lambda\Lambda}$ obtained from both points *A* and *B* was made. After rejecting the

TABLE II. Possible decay modes of the double hypernucleus which include $_{\Lambda}$He as a decay daughter. The errors on $B_{\Lambda\Lambda}$ and $\Delta B_{\Lambda\Lambda}$ do not include those of the binding energies of single hypernuclei. Only the cases of $\Delta B_{\Lambda\Lambda} > -20$ MeV are listed.

Double hypernucleus	No. 2	No. 5	No. 6		$B_{\Lambda\Lambda}$ [MeV]	$\Delta B_{\Lambda\Lambda}$ [MeV]
$^{5}_{\Lambda\Lambda}$He	$^{4}_{\Lambda}$He	p	π^-		7.1 ± 0.5	2.4 ± 0.5
$^{6}_{\Lambda\Lambda}$He	$^{5}_{\Lambda}$He	p	π^-		6.9 ± 0.6	0.6 ± 0.6
$^{7}_{\Lambda\Lambda}$He	$^{5}_{\Lambda}$He	p	π^-	1n	<8.6	<0.3
$^{7}_{\Lambda\Lambda}$He	$^{6}_{\Lambda}$He	p	π^-		6.3 ± 0.7	−2.0 ± 0.7
$^{8}_{\Lambda\Lambda}$He	$^{5}_{\Lambda}$He	p	π^-	2n	<6.8	< − 7.2
$^{8}_{\Lambda\Lambda}$He	$^{5}_{\Lambda}$He	d	π^-	1n	<7.4	< −6.6
$^{8}_{\Lambda\Lambda}$He	$^{6}_{\Lambda}$He	p	π^-	1n	<6.6	< −7.4
$^{8}_{\Lambda\Lambda}$He	$^{7}_{\Lambda}$He[a]	p	π^-		7.7 ± 0.8	−6.3 ± 0.8
$^{9}_{\Lambda\Lambda}$He	$^{5}_{\Lambda}$He	p	π^-	3n	<7.2	< −7.1
$^{9}_{\Lambda\Lambda}$He	$^{5}_{\Lambda}$He	d	π^-	2n	<8.2	< −6.1
$^{9}_{\Lambda\Lambda}$He	$^{5}_{\Lambda}$He	t	π^-	1n	<11.2	< −3.1
$^{9}_{\Lambda\Lambda}$He	$^{6}_{\Lambda}$He	p	π^-	2n	<7.2	< −7.1
$^{9}_{\Lambda\Lambda}$He	$^{6}_{\Lambda}$He	d	π^-	1n	<8.4	< −5.9
$^{9}_{\Lambda\Lambda}$He	$^{7}_{\Lambda}$He[a]	p	π^-	1n	<11.2	< −3.1
$^{9}_{\Lambda\Lambda}$He	$^{7}_{\Lambda}$He[a]	d	π^-		13.4 ± 0.5	−0.9 ± 0.5
$^{9}_{\Lambda\Lambda}$He	$^{8}_{\Lambda}$He	p	π^-		6.4 ± 0.8	−7.9 ± 0.8

[a]We took the value of 7.0 MeV for the upper limit of the Λ hyperon binding energy in $^{7}_{\Lambda}$He, because it has not yet been averaged [21].

TABLE III. Possible production modes of the double hypernucleus. The errors on the mass of Ξ^- hyperon and the binding energies of single hypernuclei are not included in the errors on $B_{\Lambda\Lambda}$ and $\Delta B_{\Lambda\Lambda}$. Only the cases of $\Delta B_{\Lambda\Lambda} < 20$ MeV are listed.

Target	No. 1	No. 3	No. 4		$B_{\Lambda\Lambda}$ [MeV]	$\Delta B_{\Lambda\Lambda}$ [MeV]
^{12}C	$^{6}_{\Lambda\Lambda}$He	^{4}He	p	2n	>16.9	>10.6
^{12}C	$^{6}_{\Lambda\Lambda}$He	^{4}He	d	1n	14.5 ± 0.7	8.2 ± 0.7
^{12}C	$^{6}_{\Lambda\Lambda}$He	^{4}He	t		7.3 ± 0.2	1.1 ± 0.2
^{12}C	$^{7}_{\Lambda\Lambda}$He	^{4}He	p	1n	21.6 ± 1.3	13.3 ± 1.3
^{14}N	$^{6}_{\Lambda\Lambda}$He	^{7}Li	p	1n	24.4 ± 2.1	18.2 ± 2.1
^{14}N	$^{6}_{\Lambda\Lambda}$He	^{6}Li	d	1n	25.8 ± 1.3	19.6 ± 1.3
^{14}N	$^{6}_{\Lambda\Lambda}$He	^{4}He	^{4}He	1n	17.9 ± 1.5	11.7 ± 1.5
^{14}N	$^{7}_{\Lambda\Lambda}$Li	^{4}He	t	1n	26.2 ± 0.9	17.2 ± 0.9
^{14}N	$^{9}_{\Lambda\Lambda}$Li	p	^{4}He	1n	31.5 ± 1.8	17.9 ± 1.8
^{16}O	$^{8}_{\Lambda\Lambda}$Li	^{4}He	^{4}He	1n	31.1 ± 0.9	19.9 ± 0.9

modes which have inconsistent values, only one interpretation remained,

$$^{12}\mathrm{C} + \Xi^- \rightarrow {}^{6}_{\Lambda\Lambda}\mathrm{He} + {}^{4}\mathrm{He} + t$$

$${}^{6}_{\Lambda\Lambda}\mathrm{He} \rightarrow {}^{5}_{\Lambda}\mathrm{He} + p + \pi^- .$$

The fact that the tracks of the reaction products were coplanar at both points A and B also suggests that no neutrons were emitted from either vertex. The decay mode of $^{5}_{\Lambda}$He is nonmesonic but undetermined.

The possibilities that the double hypernucleus or the single hypernucleus was produced in an excited state can be rejected for the following reasons. If the double-hypernucleus or the other fragments emitted from the Ξ^- stopping point had been produced in an excited state, the value of $\Delta B_{\Lambda\Lambda}$ calculated at the production point A would be increased by the excitation energy. On the other hand, if the single hypernucleus or the residual particles emitted from the decay of the double hypernucleus had been created in an excited state, the value of $\Delta B_{\Lambda\Lambda}$ calculated at the decay point B would be decreased by the excitation energy. In both cases, the difference between $\Delta B_{\Lambda\Lambda}$ calculated at point A and at point B would be enlarged and the consistency of the values of $\Delta B_{\Lambda\Lambda}$ would not be satisfied. Hence, our event, NAGARA, has been interpreted uniquely as the sequential weak decay of $^{6}_{\Lambda\Lambda}$He. Moreover, in the production and decay of $^{6}_{\Lambda\Lambda}$He, no particle-stable excited states are known or expected for any of the reaction products. Therefore, there are no ambiguities arising from excited states.

The value of $\Delta B_{\Lambda\Lambda}$ was obtained as 0.62 ± 0.61 MeV from the decay vertex B of the double hypernucleus, while its lower limit was determined as 1.08 ± 0.22 MeV from the production point A. These errors also include the uncertainties in the values of the mass of the Ξ^- hyperon (0.13 MeV) [20] and the binding energy of $^{5}_{\Lambda}$He (0.02 MeV) [21]. A kinematic fit was applied at each vertex independently using the kinematic constraints of conservation of momentum and energy. In the fit at vertex B the momentum of the proton (track No. 5) was constrained to have a value consistent with the particle entering the acrylic base film but not emerging from it, whereas the mass of the double hypernucleus was a free parameter in both the fit at vertex A and the fit at vertex B. By minimizing the χ^2, we obtained $\Delta B_{\Lambda\Lambda} = 0.69 \pm 0.54$ MeV from the decay vertex B, and $\Delta B_{\Lambda\Lambda} - B_{\Xi^-} = 0.92 \pm 0.21$ MeV from the production point A. The value of B_{Ξ^-} was obtained experimentally from these values as -0.24 ± 0.58 MeV. The fitted momentum of the proton (track No. 5) was 87.9 ± 3.0 MeV$/c$ and the corresponding range was 127 ± 15 μm, which agrees with the fact that the proton entered but did not emerge from the base film.

The values of $B_{\Lambda\Lambda}$ and $\Delta B_{\Lambda\Lambda}$ were determined uniquely from vertex B with large errors, whereas the values obtained from vertex A were more precise but depend on B_{Ξ^-}. In order to obtain their most probable values, we combined the two independent determinations for several fixed values of the Ξ^- hyperon binding energy B_{Ξ^-}. The results, expressed as a function of B_{Ξ^-} (MeV), were

$$B_{\Lambda\Lambda} = 7.13 + 0.87\, B_{\Xi^-}\ (\pm 0.19)\ \mathrm{MeV}, \qquad (3)$$

$$\Delta B_{\Lambda\Lambda} = 0.89 + 0.87\, B_{\Xi^-}\ (\pm 0.20)\ \mathrm{MeV}. \qquad (4)$$

According to theoretical calculations for the nuclear absorption rate of Ξ^- hyperons [22–24], Ξ^- hyperon capture from an atomic $3D$ state in ^{12}C is dominant, but capture from a $4F$ or $2P$ state is not negligible. The value of B_{Ξ^-} of the $2P$ state varies with the Ξ^- hyperon-nucleus potential well depth, whereas the energy level of the $3D$ state is better known because it depends overwhelmingly on the Coulomb interaction rather than the Ξ^- hyperon-nucleus strong interaction. The value of B_{Ξ^-} of the $3D$ state is 0.13 MeV, which is consistent with the present experimental result of -0.24 ± 0.58 MeV. Adopting the value $B_{\Xi^-} = 0.13$ MeV as the most probable value, the weighted mean values are $B_{\Lambda\Lambda} = 7.25 \pm 0.19^{+0.18}_{-0.11}$ MeV and $\Delta B_{\Lambda\Lambda} = 1.01 \pm 0.20^{+0.18}_{-0.11}$ MeV, where the systematic errors are determined from the fact that the value of B_{Ξ^-} is uncertain in the range from 0 to 0.34 MeV in our measurement.

Two of the past experiments [2–5] gave a value of $\Delta B_{\Lambda\Lambda}$ to be about 4.5 MeV. As mentioned above, there remains the possibility in both events that the single hypernuclei was produced in excited states. In such cases, $\Delta B_{\Lambda\Lambda}$ would be about 1 MeV and not in contradiction with our result.

From the relation (2), the E176 experiment presented a lower limit on the mass of the H dibaryon as 2203.7 ± 0.7 MeV$/c^2$ [4]. Several counterexperiments have put the upper limits on the production rate of the H dibaryon [25–27], which were below the theoretical calculation [28] in the mass region below 2200 MeV$/c^2$, and indicate the nonexistence of a deeply bound H dibaryon. Using the present result of $B_{\Lambda\Lambda}$ from the decay vertex, the lower limit of the H mass was found to be 2223.7 MeV$/c^2$ at a 90% confidence level, which is much closer to the two-Λ threshold.

In summary, a double-hypernucleus event, NAGARA, has been observed in an emulsion stack exposed to the 1.66 GeV$/c$ K^- meson beam. It is interpreted uniquely as the sequential decay of ${}^{6}_{\Lambda\Lambda}$He emitted from a Ξ^- hyperon nuclear capture at rest. The mass has been measured, and the binding energy of the two Λ hyperons, $B_{\Lambda\Lambda}$, and the Λ-Λ interaction energy, $\Delta B_{\Lambda\Lambda}$, have been determined for the first time without the ambiguities arising from the possibilities of excited states. The value of $\Delta B_{\Lambda\Lambda}$ obtained from the decay kinematics is 0.69 ± 0.54 MeV. By using both the production and decay kinematics, we obtained $\Delta B_{\Lambda\Lambda} = 1.01 \pm 0.20^{+0.18}_{-0.11}$ MeV, where the Ξ^- binding energy of an atomic $3D$ state in ^{12}C, 0.13 MeV, is used as the most probable value, and the systematic error is determined from the error of the B_{Ξ^-} obtained from this event. It established that the Λ-Λ interaction energy is attractive but considerably smaller than that previously estimated experimentally. The violent disagreement between our result for $\Delta B_{\Lambda\Lambda}$ and that reported in Ref. [1] confirms the doubts on the authenticity of the previous event. In addition, the lower limit of the mass of the H dibaryon has been obtained as 2223.7 MeV$/c^2$ at a 90% confidence level.

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