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Observation of Coulomb-Assisted Nuclear Bound State of Ξ^-–^{14}N System

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In an emulsion-counter hybrid experiment performed at J-PARC, a Ξ^- absorption event was observed which decayed into twin single-Λ hypernuclei. Kinematic calculations enabled a unique identification of the reaction process as $\Xi^- + {}^{14}\mathrm{N} \to {}^{10}_{\Lambda}\mathrm{Be} + {}^{5}_{\Lambda}\mathrm{He}$. For the binding energy of the Ξ^- hyperon in the Ξ^-–^{14}N system a value of 1.27 ± 0.21 MeV was deduced. The energy level of Ξ^- is likely a nuclear $1p$ state which indicates a weak ΞN–$\Lambda\Lambda$ coupling.

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Strange nuclear systems cover a broad spectrum of phenomena. They range from two-body baryon-baryon interactions, over complex nuclei containing strange baryons, strangeness in hot nuclear systems created in heavy ion reactions, up to perhaps the inner core of neutron stars. In contrast to a relatively large amount of information on $S = -1$ Λ-hypernuclei, experimental data regarding $S = -2$ systems are still scarce. Double-Λ hypernuclei have represented the preferred method to study the Λ-Λ interaction, and a pioneering binding energy determination of ${}^{6}_{\Lambda\Lambda}\mathrm{He}$ revealed the $\Lambda\Lambda$ interaction to be weakly attractive [1,2]. Only recently, the Ξ^{-}–p interaction was studied by ALICE [3,4]. From the two-body correlations, the presence of a strongly attractive interaction was inferred.

In line with single Λ hypernuclei, the study of Ξ hypernuclei can provides meaningful information on the ΞN interaction. First (K^{-}, K^{+}) missing-mass spectroscopy studies were performed by the KEK E224 and BNL E885 collaborations. In both experiments, insufficient energy resolution prevented the observation of a peak in the bound state region [5,6]. Assuming a Woods-Saxon type potential, the BNL E885 experiment estimated the potential depth of the Ξ to be about 14 MeV which suggests a binding energy around 4.5 MeV. While an initial J-PARC experiment [7] measured the missing mass spectrum of the ${}^{12}\mathrm{C}(K^{-}, K^{+})$ reaction, a new experiment with a much improved energy resolution of better than 2 MeV FWHM is now planned at J-PARC [8].

Several emulsion experiments reported the possibility of an attractive Ξ-nucleus interaction. A remarkable event named “KISO” was found by the KEK E373 experiment [9]. The decay mode of that event was uniquely identified to be $\Xi^{-} + {}^{14}\mathrm{N} \rightarrow {}^{10}_{\Lambda}\mathrm{Be} + {}^{5}_{\Lambda}\mathrm{He}$. For the binding energy of the Ξ^{-} hyperon, $B_{\Xi^{-}}$, a value of 3.87 ± 0.21 MeV or 1.03 ± 0.18 MeV was deduced, depending whether the ${}^{10}_{\Lambda}\mathrm{Be}$ daughter nucleus is produced in the ground state or the excited state, respectively [10]. In either scenario, the bound state of the Ξ^{-}–${}^{14}\mathrm{N}$ system is expected to be deeper than the atomic $3D$ orbit.

The ΞN interaction can also be extracted by measuring the energy shift and width of x rays from Ξ atoms. Two experiments involving Ξ-atomic x-ray measurements using Ge detectors have been proposed at J-PARC [11,12], E07 being the one described in this paper.

A theoretical calculation of the binding energy of the Ξ^{-}–${}^{14}\mathrm{N}$ system was presented by Yamaguchi *et al.* using the ΞN one-boson-exchange potential called the Ehime potential [13]. In this model, the coupling constants were adjusted to reproduce the experimental result of the Ξ^{-}–${}^{12}\mathrm{C}$ bound states with $B_{\Xi^{-}} \sim 0.6$ MeV observed in the KEK E176 experiment [10,14]. The calculation also predicted for the Ξ^{-}–${}^{11}\mathrm{B}$ system a ground state binding energy, which is in agreement with the excitation energy spectrum in the BNL E885 experiment. More recently, T. T. Sun *et al.* performed a theoretical calculation with the relativistic-mean-field and Skyrme-Hartree-Fock models [15]. The preferred interpretation of the KISO event was an observation of an excited state of the ${}^{10}_{\Lambda}\mathrm{Be}$. When the ΞN interaction was adjusted to reproduce the binding energy for the KISO event assuming the $1p$ state for an excited ${}^{10}_{\Lambda}\mathrm{Be}$, the predicted Ξ^{-} removal energy of ${}^{15}_{\Xi}\mathrm{C}$ in the $1s$ state was 7.2–9.4 MeV. Very recent Lattice QCD calculations with almost physical quark masses ($m_{\pi} = 146$ MeV), provided the ΞN interaction potentials for various $S = -2$ channels [16]. These lattice results indicated that the coupling between $\Lambda\Lambda$ and ΞN states is weak.

J-PARC E07 is an emulsion-counter hybrid experiment aiming to identify the decay modes of about 10 events of $S = -2$ hypernuclei [12]. The experiment was carried out using a 1.81 GeV/c K^{-} beam at the K1.8 beam line of the Hadron Experimental Facility at J-PARC [17,18]. The Ξ^{-} hyperons produced in the quasifree “p”$(K^{-}, K^{+})\Xi^{-}$ reaction in a diamond target of 9.87 g/cm^2 thickness were injected into an emulsion module located downstream of the target. The emulsion module consisted of two 380-μm-thick sheets and eleven 1-mm-thick sheets with 34.5×35.0 cm^2 area. The incident Ξ^{-} hyperons were eventually slowed down and captured at rest in the atomic orbit of a nucleus in the emulsion material. Ξ hypernuclei or double-Λ hypernuclei are generated at the capture point with some probability [19], and the decay tracks of charged particles are recorded in the emulsion module. In total, 118 emulsion modules were exposed to 1.13×10^{11} K^{-} particles. About 100 events of $S = -2$ hypernuclei were expected to be produced as a result of the 10^4 Ξ^{-} hyperons stopped in the emulsion. More details on the experimental setup can be found in Ref. [20]. The Ξ-atomic x-rays were also measured by using germanium detectors. Details are presented in Ref. [21].

A remarkable event forming a twin-Λ hypernuclear topology was found in the tenth sheet of module #047. Figure 1 shows a superimposed image and a schematic drawing of the event. We named the event “IBUKI” [22].

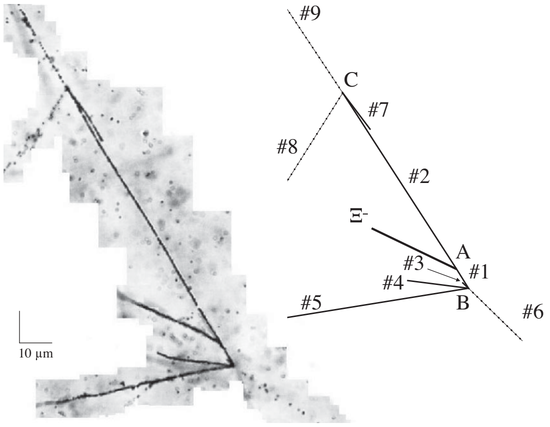

FIG. 1. Superimposed image and schematic drawing of the IBUKI event.

TABLE I. Table of the measured ranges and angles of the nine tracks.

Vertex	Track	Range [μm]	θ [deg]	ϕ [deg]	Comment
A	#1	8.2 ± 0.4	90.6 ± 1.9	301.9 ± 2.1	Λ hypernucleus
	#2	88.5 ± 0.3	93.5 ± 2.0	122.9 ± 1.5	Λ hypernucleus
B	#3	3.6 ± 1.1	124.6 ± 7.4	137.0 ± 6.4	
	#4	25.9 ± 0.3	109.8 ± 2.3	172.8 ± 1.5	
	#5	961.1 ± 4.6	49.6 ± 2.0	189.2 ± 2.0	
	#6	20509 ± 34	111.6 ± 2.7	325.5 ± 2.2	
C	#7	19.2 ± 0.1	86.8 ± 1.6	307.0 ± 1.2	
	#8	2159 ± 19	30.6 ± 1.5	237.8 ± 2.8	π^- with σ stop
	#9	2179.0 ± 3.6	106.7 ± 1.6	123.5 ± 1.2	

The Ξ^- traced in sequence from upstream was found to have stopped and decayed at vertex A, from which the two charged particles of tracks #1 and #2 were emitted. Track #1 decayed into four charged particles, tracks #3–6 at vertex B. Track #2 showed a decay into three charged particles, tracks #7–9 at vertex C. All nine tracks were manually followed and their stopping points were found inside of the emulsion module. No charged daughter particles were found at the ends of tracks #5, #6, and #9. Track #8 accompanied by particle emission at the stopping point indicates a negative particle. Additional support for this comes from the observed Auger emission. Table I summarizes the measured values of ranges and emission angles of the nine tracks. The angles are expressed by a zenith angle (θ) and an azimuthal angle (ϕ) with respect to the axis perpendicular to the emulsion sheet. The ranges in the base film were converted to those in the emulsion layer.

Since the energy calibration and the range correction were necessary for the kinematic analysis, the density of the emulsion was measured using 132 α tracks with a monochromatic energy of 8.785 MeV from the decay of ^{212}Po. The mean range and the emulsion density were measured to be 50.25 ± 0.11 μm and 3.544 ± 0.012 g/cm^3, respectively.

For each vertex point, all possible decay modes were kinematically examined considering both mesonic and nonmesonic decays. Among various nuclear species in the emulsion, C, N, and O were taken into account as nuclei to capture the Ξ^- hyperon. Emission of neutral particles was also considered. As for the mass of the Λ hypernuclei, the values obtained from the experimental data were utilized [23–30]. Mass values of some possible Λ hypernuclei were also taken into account via a calculation with linear interpolation and extrapolation of B_Λ, where a typical error in the fitting of the masses of 0.5 MeV/c^2 was uniformly assumed.

Figure 2 shows B_{Ξ^-}, and the magnitude of the total momentum, p_{total}, for all possible decay modes for vertex A. The black dots and open circles indicate the decay modes including known and possible Λ hypernuclei, respectively. The p_{total} value was required to be zero within 3σ tolerance. Since the stopped Ξ^- cascades down atomic orbitals before being absorbed by the nucleus, the binding energy will be positive, at least within the experimental error. The value of B_{Ξ^-} was required to be more than zero with 3σ tolerance, even if multiple neutral particles are emitted. Finally, only one decay mode of

$$\Xi^- + {}^{14}\mathrm{N} \to {}^{10}_{\Lambda}\mathrm{Be}(\#1) + {}^{5}_{\Lambda}\mathrm{He}(\#2)$$

was accepted around the position of $p_{\mathrm{total}} \sim 40$ MeV/c and $B_{\Xi^-} \sim 1$ MeV in Fig. 2.

At vertex B, the kinematic calculation was also performed using tracks #3–6; 358 possible decay modes remained within 3σ tolerance of the energy and the momentum conservation law independent of the result of vertex A. Among them, 13 decay modes for the case of track #1 being ${}^{10}_{\Lambda}$Be are listed in Table II.

Since the length of track #3 was very short, the topology without track #3 was also tested. The coplanarity of three tracks is defined as $(\hat{r}_1 \times \hat{r}_2)\hat{r}_3$, where $\hat{r}_i$ represents the unit vector of ith track direction. The coplanarity of tracks #4–6 was obtained to be -0.50 ± 0.03. This makes some

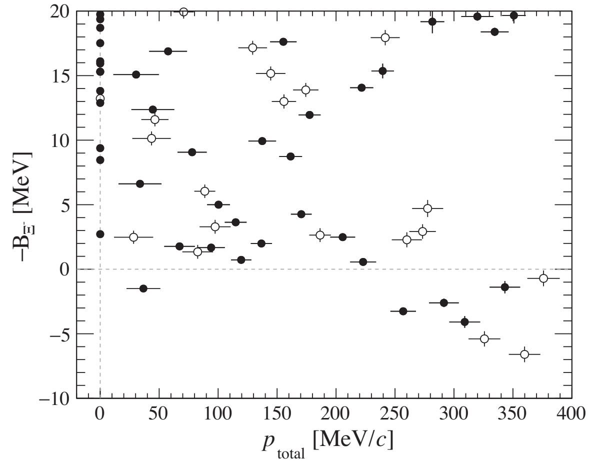

FIG. 2. Correlation plot of the binding energy and the magnitude of the total momentum at vertex A. Black dots and open circles indicate the decay modes including known and possible Λ hypernuclei, respectively.

TABLE II. Possible decay modes at vertex B for the case of track #1 being $^{10}_{\Lambda}\mathrm{Be}$.

#3	#4	#5	#6		Q [MeV]	B_{Λ} [MeV]
p	d	t	p	$3n$	120.06	<11.81
p	t	d	p	$3n$	120.06	<16.36
p	t	t	p	$2n$	126.32	<12.83
d	p	t	p	$3n$	120.06	<12.71
d	d	d	p	$3n$	116.03	<12.89
d	d	t	p	$2n$	122.28	<10.04
d	t	p	p	$3n$	120.06	<20.07
d	t	d	p	$2n$	122.28	<15.27
t	p	d	p	$3n$	120.06	<17.31
t	p	t	p	$2n$	126.32	<15.09
t	d	p	p	$3n$	120.06	<20.15
t	d	d	p	$2n$	122.29	<15.88
t	t	p	p	$2n$	126.32	<22.48

neutron(s) emission likely. The accepted decay modes for the case of track #1 being $^{10}_{\Lambda}\mathrm{Be}$ are listed in Table III. From 48 candidates, the listed three decay modes were consistent with the result at vertex A. Since no track from β decay of $^{6}\mathrm{He}$ to $^{6}\mathrm{Li} + e^{-} + \bar{\nu}$ is visible at the end of track #4, the case of track #4 being $^{6}\mathrm{He}$ was rejected.

For vertex C, consistency with the conservation laws was checked using tracks #7–9. In total, 263 candidates were accepted within 3σ tolerance of energy and momentum conservation. Almost all were nonmesonic decay modes with multiple neutral particles. Among the 263 candidates, the decay mode for the case of track #2 being $^{5}_{\Lambda}\mathrm{He}$ was the only reasonable one, obtained as the following decay mode,

$$^{5}_{\Lambda}\mathrm{He} \to {}^{4}\mathrm{He}(\#7) + \pi^{-}(\#8) + p(\#9).$$

This decay mode is consistent with a charged-particle emission at the end point of track #8. Since the value of the coplanarity of tracks#7–9 was 0.06 ± 0.03 at vertex C, no neutral particle was likely emitted at vertex C.

From the above discussions, the reaction process of the IBUKI event was obtained as follows,

$$\begin{aligned} \Xi^{-} + {}^{14}\mathrm{N} &\to {}^{10}_{\Lambda}\mathrm{Be}(\#1) + {}^{5}_{\Lambda}\mathrm{He}(\#2), \\ {}^{10}_{\Lambda}\mathrm{Be} &\to (3 \text{ or } 4 \text{ nuclei, } \#3\text{–}6) + 2 \text{ or } 3\ n), \\ {}^{5}_{\Lambda}\mathrm{He} &\to {}^{4}\mathrm{He}(\#7) + \pi^{-}(\#8) + p(\#9). \end{aligned}$$

TABLE III. Possible decay modes at vertex B without track #3 for the case of track #1 being $^{10}_{\Lambda}\mathrm{Be}$.

#4	#5	#6		Q [MeV]	B_{Λ} [MeV]	
$^{3}\mathrm{He}$	t	p	$3n$	125.55	<12.13	
$^{4}\mathrm{He}$	d	p	$3n$	139.87	<31.13	
$^{4}\mathrm{He}$	t	p	$2n$	146.13	<24.69	
$^{6}\mathrm{He}$	p	p	$2n$	138.63	<27.68	rejected

Thus, the formation process of twin Λ hypernuclei was uniquely identified as $^{10}_{\Lambda}\mathrm{Be}$ and $^{5}_{\Lambda}\mathrm{He}$. Since the final state was a two-body system at vertex A, the momenta of the twin Λ hypernuclei should balance if the initial state is at rest. The range from vertexes B to C was measured to be $97.1 \pm 0.4\ \mu\mathrm{m}$. To minimize the measurement errors, a kinematic fitting was applied at vertex A [31]. The fitting result is summarized in Table IV. From the constraint of the total length between vertex B and C, the ranges of track #1 and #2 were calculated to be $9.4 \pm 0.2\ \mu\mathrm{m}$ and $87.7 \mp 0.2\ \mu\mathrm{m}$, respectively, so that their momenta correspond to each other. Straggling was taken into account in this fitting. The angles represent twin Λ hypernuclei being emitted back to back. The χ^{2} value was obtained to be 2.4 with 3 degrees of freedom. Considering the effects of straggling and the error in the emulsion density, the error of $B_{\Xi^{-}}$ was estimated to be 0.08 MeV. The mass errors of Ξ^{-} hyperon ($1321.71 \pm 0.07\ \mathrm{MeV}/c^{2}$ [32]), $^{10}_{\Lambda}\mathrm{Be}$ ($9499.88 \pm 0.13\ \mathrm{MeV}/c^{2}$ [33]), and $^{5}_{\Lambda}\mathrm{He}$ ($4839.94 \pm 0.02\ \mathrm{MeV}/c^{2}$ [24]) were also taken into account. The mass of $^{10}_{\Lambda}\mathrm{Be}$ was evaluated as the average of the 1^{-} and 2^{-} states in the ground-state doublet. The energy spacing between these two states is expected to be less than 0.1 MeV. Therefore, the binding energy of the Ξ^{-} hyperon in the Ξ^{-}–$^{14}\mathrm{N}$ system, $B_{\Xi^{-}}$ was obtained to be 1.27 ± 0.21 MeV, where the error includes the spin-doublet uncertainty of $^{10}_{\Lambda}\mathrm{Be}$. Kinematic fitting was also applied at vertex C. The result is listed in Table V. The χ^{2} value was obtained to be 6.6 with 4 degrees of freedom. The binding energy of the Λ hyperon in $^{5}_{\Lambda}\mathrm{He}$, B_{Λ}, was obtained to be 2.77 ± 0.23 MeV, which agrees well with the world average [24].

The $B_{\Xi^{-}}$ value of 1.27 ± 0.21 MeV represents a bound Ξ^{-}–$^{14}\mathrm{N}$ system. However, the case of $^{10}_{\Lambda}\mathrm{Be}$ being produced in an excited state must be considered. In a missing mass experiment at JLab the energy spectrum of $^{10}_{\Lambda}\mathrm{Be}$ was measured [33]. A low-lying excited state at 2.78 ± 0.11 MeV was observed. In case of the KISO event, the production of the $^{10}_{\Lambda}\mathrm{Be}$ in that excited state could not be excluded so that the Ξ^{-} binding energy was not uniquely determined (see Table VI). In case of the IBUKI event, the small Ξ^{-} binding energy of 1.27 MeV excludes a production of $^{10}_{\Lambda}\mathrm{Be}$ in the 2.78 MeV state. Instead, the $^{10}_{\Lambda}\mathrm{Be}$ is produced in one of the levels of the ground-state doublet. Thus, the reaction process of the IBUKI event was determined to be a bound state of Ξ^{-}–$^{14}\mathrm{N}$ decaying into ground states of both $^{10}_{\Lambda}\mathrm{Be}$ and $^{5}_{\Lambda}\mathrm{He}$, having a $B_{\Xi^{-}}$ value of

TABLE IV. Ranges and emission angles for vertex A with the kinematic fitting. The value of χ^{2}/ndf is 2.4/3.

Vertex	Track	Range [μm]	θ [deg]	ϕ [deg]
A	#1	9.4 ± 0.1	88.7 ± 1.4	302.5 ± 1.2
	#2	87.7 ± 0.7	91.4 ± 1.4	122.5 ± 1.2

TABLE V. Ranges and emission angles for vertex C with the kinematic fitting. The value of χ^2/ndf is 6.6/4.

Vertex	Track	Range [μm]	θ [deg]	ϕ [deg]
C	#7	19.1 ± 0.2	87.0 ± 1.0	308.9 ± 0.9
	#8	2146 ± 71	29.5 ± 1.5	236.3 ± 2.2
	#9	2194 ± 28	105.7 ± 1.0	121.6 ± 0.8

1.27 ± 0.21 MeV. This is the first observation of a twin-Λ hypernuclei event in which the binding energy was precisely determined.

In the calculation of Yamaguchi *et al.* using the Ehime potential [13], the B_{Ξ^-} values for the Ξ^-–^{14}N system are 5.93 and 1.14 MeV in the nuclear $1s$ (atomic $1S$) and nuclear $1p$ (atomic $2P$) states, respectively. The bound states of both the IBUKI and the KISO events are consistent with the calculation for the $1p$ state. In the nuclear $1p$ state both Coulomb and nuclear forces are at work, resulting in a binding energy of 0.39 and 0.75 MeV, respectively, according to this calculation. Thus the result is a Coulomb-assisted nuclear bound state. The calculated B_{Ξ^-} of ${}^{15}_{\Xi}\mathrm{C}$ and ${}^{12}_{\Xi}\mathrm{Be}$ by T. T. Sun *et al.* [15] are also consistent with the experimental data.

From the above considerations, in order to satisfy the experimental results of KEK E176, BNL E885, the KISO event, and the IBUKI event, the interpretation of the KISO event likely results in $B_{\Xi^-} = 1.03 \pm 0.18$ MeV. In that case, the energy level of Ξ^- in both KISO and IBUKI events is considered to be the $1p$ state, although several spins are possible. Here, the isospin dependence of the ΞN interaction (Lane potential) is proportional to $1/A$ and has a weak effect. Assuming that the initial state is the same in both KISO and IBUKI events, the weighted average of the binding energy of Ξ^- in the $1p$ state is obtained to be 1.13 ± 0.14 MeV for the Ξ^-–^{14}N system. This now gives the depth of the Ξ^- potential for the first time. On the other hand, in the case of the binding energy of Ξ^- in the $1p$ state being 3.87 ± 0.21 MeV in the KISO event, the indicated width is too wide, despite the large contribution of the Coulomb potential. Thus, the present result is the first observation of the Coulomb-assisted bound state for the Ξ^-–^{14}N system. The probabilities of Ξ^- hyperon capture from the s, p, and d orbits for ^{14}N atom were estimated to be 0.00–0.07%, 0.2–5.7%, and 47.9–75.7%, respectively [34,35]. Therefore, the observation of a Ξ^- capture event in the p orbit experimentally indicates the ΞN–$\Lambda\Lambda$ coupling is weak, which agrees with the recent study of the lattice QCD calculations [16].

TABLE VI. Summary of the binding energy of the Ξ^- hyperon measured in the past and present experiments.

Event	Target	Decay mode		B_{Ξ^-} [MeV]
KISO [9,10]	^{14}N	${}^{10}_{\Lambda}\mathrm{Be}$	${}^{5}_{\Lambda}\mathrm{He}$	3.87 ± 0.21
	^{14}N	${}^{10}_{\Lambda}\mathrm{Be}^*$	${}^{5}_{\Lambda}\mathrm{He}$	1.03 ± 0.18
IBUKI (present data)	^{14}N	${}^{10}_{\Lambda}\mathrm{Be}$	${}^{5}_{\Lambda}\mathrm{He}$	1.27 ± 0.21

In summary, the J-PARC E07 experiment observed a twin-Λ hypernuclei event, named IBUKI. The reaction process was clearly identified as $\Xi^- + {}^{14}\mathrm{N} \to {}^{10}_{\Lambda}\mathrm{Be} + {}^{5}_{\Lambda}\mathrm{He}$. The binding energy of the $\Xi^- + {}^{14}\mathrm{N}$ system was determined to be 1.27 ± 0.21 MeV by applying kinematic fitting. By considering an excited state, the energy level for ${}^{10}_{\Lambda}\mathrm{Be}$ was interpreted to be the ground state (1^-) or the (2^-) spin doublet partner. This is the first observation of twin-Λ hypernuclei in which the binding energy is precisely determined. By considering the experimental data and the theoretical calculations, the energy level of Ξ^- is likely the Coulomb-assisted nuclear $1p$ state for both the KISO and IBUKI events. Assuming the same initial state for both events, a binding energy of 1.13 ± 0.14 MeV was obtained as the weighted average. Furthermore, the observation of a Ξ^- capture event in the p orbit indicates that the ΞN–$\Lambda\Lambda$ coupling is weak.

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