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Production of Two Single-Λ Hypernuclei by Ξ^- Capture

S. AOKI,[1,*] S. Y. BAHK,[2] K. S. CHUNG,[3] S. H. CHUNG,[3] H. FUNAHASHI,[4]
C. H. HAHN,[5] T. HARA,[6] S. HIRATA,[4,*] K. HOSHINO,[1] M. IEIRI,[7] T. IIJIMA,[4]
K. IMAI,[4] Y. ITOW,[4] T. JIN-YA,[8] M. KAZUNO,[8] K. KIKUCHI,[9] C. O. KIM,[10]
D. C. KIM,[3] J. Y. KIM,[11] K. KODAMA,[12] Y. MAEDA,[13] A. MASAIKE,[4]
A. MASUOKA,[12] Y. MATSUDA,[6] C. NAGOSHI,[14] M. NAKAMURA,[1]
S. NAKANISHI,[1] T. NAKANO,[4] K. NAKAZAWA,[15] K. NIWA,[1] H. ODA,[12]
H. OKABE,[16] S. ONO,[8] R. OZAKI,[15] I. G. PARK,[3] M. S. PARK,[3] Y. SATO,[9]
H. SHIBUYA,[8] H. M. SHIMIZU,[4] J. S. SONG,[3] M. SUGIMOTO,[13] M. TAIRADATE,[8]
H. TAJIMA,[1] R. TAKASHIMA,[17] F. TAKEUTCHI,[18] K. H. TANAKA,[7]
M. TERANAKA,[19] I. TEZUKA,[9] H. TOGAWA,[4,**] N. USHIDA,[12] T. WATANABE,[19]
N. YASUDA,[9] J. YOKOTA[16] and C. S. YOON[3]

[1] *Department of Physics, Nagoya University, Nagoya 464-01*
[2] *Wonkang University, Iri 570-749*
[3] *Gyeongsang National University, Jinju 660-701*
[4] *Department of Physics, Kyoto University, Kyoto 606-01*
[5] *Changwon National University, Changwon 641-773*
[6] *College of Liberal Arts, Kobe University, Kobe 657*
[7] *KEK, National Laboratory for High Energy Physics, Tsukuba 305*
[8] *Department of Physics, Toho University, Funabashi 274*
[9] *Faculty of Education, Utsunomiya University, Utsunomiya 321*
[10] *Korea University, Seoul 136-701*
[11] *Chonnam National University, Kwangju 500-757*
[12] *Aichi University of Education, Kariya 448*
[13] *Faculty of Education, Yokohama National University, Yokohama 240*
[14] *Institute for Nuclear Study, University of Tokyo, Tanashi 188*
[15] *Physics Department, Gifu University, Gifu 501-11*
[16] *Science Education Institute of Osaka Prefecture, Osaka 558*
[17] *Kyoto University of Education, Kyoto 612*
[18] *Faculty of Science, Kyoto Sangyo University, Kyoto 603*
[19] *Department of Physics, Osaka City University, Osaka 558*

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The $S=-2$ hypernuclear states formed through (K^-, K^+) reactions have been studied by using the 1.66 GeV/c K^- beam provided by KEK Proton Synchrotron. Investigation has been done on the stars due to the capture of the Ξ^- hyperons at rest in nuclear emulsion, which hyperons were produced in (K^-, K^+) reactions. We observed a clear case of an absorption of Ξ^- hyperon at rest by a nucleus followed by a back-to-back emission of two single-Λ hypernuclei.

§ 1. Introduction

The (K^-, K^+) reaction enables us to study the spectroscopy of $S=-2$ hypernu-

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[*] Present address: College of Liberal Arts, Kobe University, Kobe 657.

[**] Present address: Research Center for Nuclear Physics, Osaka University, Osaka 567.

clear states. Theoretical studies on this subject have been performed by Dover et al.[1),2)] Baltz et al.[3)] and recently by Akaishi.[4)] Several Ξ^- hypernuclear species have been identified in nuclear emulsion.[5)] More than twenty years ago, four nuclear states formed in K^- beam (3—10 GeV/c) experiments were reported by Bechdolff et al.[6)] They have investigated events in which two single-Λ hypernuclei (not collinear) were emitted directly at the point where a K^- meson interacted with an emulsion nucleus. The production of a Ξ^- hyperon was assumed and the mass of a Ξ^- hypernucleus was estimated from these two hypernuclei. However in these cases, since the K^- meson had a considerable energy when it interacted with a nucleus, a compound Ξ^- nucleus might be produced and some neutrons could have been emitted in the decay star. For this reason, we cannot take them as a clear sample of Ξ^--hypernuclear states. We have therefore carried out an experiment in which a Ξ^- hyperon was captured by a nucleus at rest. The Q-value for the production of two single hyperfragments is as small as 10 MeV. Therefore, the two single-Λ hypernuclei event which we report in this paper is a clear case and must be well suited for the investigation of Ξ^--nuclear states.

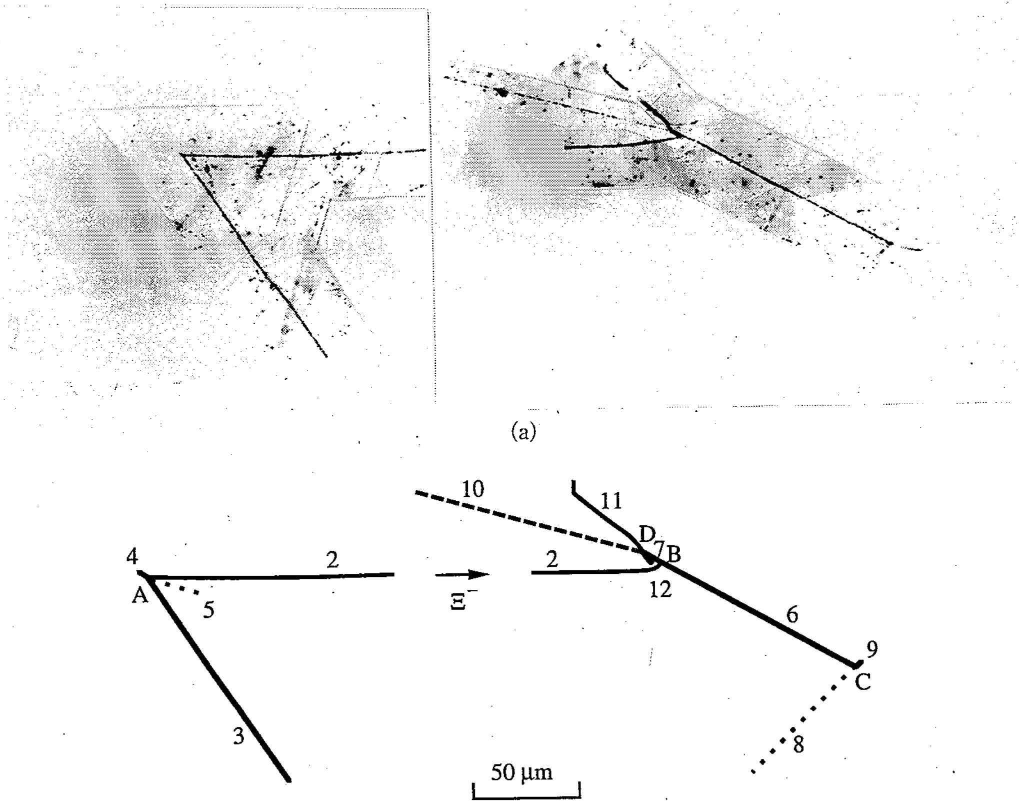
In our emulsion-counter hybrid experiment (E176) performed at KEK, a 1.66 GeV/c K^- beam was used. The object of this experiment is two-fold: a study of $S=-2$ hypernuclear states and a research of H dibaryon. The counter system was used to identify the (K^-, K^+) reaction which ensures that the strangeness of -2 is transferred to a nucleus in an emulsion target. The emulsion target comprising 43 double-coated sheets (547 μm thick Fuji ET-7B emulsion, coated on both sides of a 70 μm thick polystyrene support) of 23 cm×23 cm in size was held perpendicularly to the beam. Thirteen modules of the emulsion targets (30 liters in total volume) were exposed to a total number of 10^9 K^- beam mesons. This corresponds to a total number of 10^8 K^- interactions in the emulsion. Scattered K^+ mesons from the emulsion target were momentum- and velocity-analyzed by a K^+ spectrometer.

Details of the experimental setup, analysis of the data of counters and procedure of emulsion scanning are described elsewhere.[7)] The (K^-, K^+) reactions with K^+ momentum greater than 1.0 GeV/c were selected for further analyses, where a quasi-free production $(K^- + p \longrightarrow K^+ + \Xi^-)$ is dominant.

The total number of (K^-, K^+) reactions analyzed in the emulsion is 866, and 594 Ξ^- candidates were observed. 99 Ξ^- candidates among them were captured at rest in the nuclear emulsion. In these events, we found a sequential weak decay of a light double-Λ hypernucleus and weak decays of heavy double-Λ hypernuclei. These were described in detail elsewhere.[8),9)] We searched for the H dibaryon directly produced by $K^- + (pp) \longrightarrow K^+ + H$ reaction, and obtained an upper limit for the production cross section of the H dibaryon.[7)] The method of finding and tracing the Ξ^- hyperon in this process was shown in detail in Refs. 7) and 8). In the process of scanning the emulsion, we found a clear case of Ξ^- absorption which involves a production of two single-Λ hypernuclei. The detail of this event is described in this paper. This indicates the existence of a Ξ^- atomic state or a Ξ hypernuclear state.

§ 2. Description of the event

A photograph and a brief sketch of the event are illustrated in Figs. 1(a) and (b), respectively. It was explained as the event in which the incident K^- meson interacted with a nucleus of the emulsion at point A and produced a Ξ^- hyperon (track 2) and a 1137 MeV/c K^+ meson (track 5). Also are seen an evaporation track (track 3) and a recoil track (track 4) at point A. The Ξ^- hyperon runs until it is captured by a nucleus at rest at point B where two nuclear fragments emitted back to back with each other (i.e., collinear). One of the fragments (track 6) shows the mesonic decay



(a)

(b)

Fig. 1. (a) and (b) A photograph and a schematic drawing of the production of two single-Λ hypernuclei and their decays. Incident K^- meson (track 1) can not be seen in this photograph, because K^- beam was irradiated vertically to the emulsion plates. The Ξ^- hyperon was produced at point A, and captured at rest at point B followed by the emission of two hyperfragments decaying at point C and point D.

point A: $K^- +$ emulsion nucleus$\longrightarrow \Xi^- + K^+ + p +$recoil

point B: $\Xi^- + {}^{12}\mathrm{C} \longrightarrow {}^{4}_{\Lambda}\mathrm{H} + {}^{9}_{\Lambda}\mathrm{Be}$

or $\Xi^- + {}^{14}\mathrm{N} \longrightarrow {}^{4}_{\Lambda}\mathrm{H} + {}^{11}_{\Lambda}\mathrm{B}$

or $\Xi^- + {}^{16}\mathrm{O} \longrightarrow {}^{4}_{\Lambda}\mathrm{H} + {}^{13}_{\Lambda}\mathrm{C}$

point C: ${}^{4}_{\Lambda}\mathrm{H} \longrightarrow \pi^- + {}^{4}\mathrm{He}$

point D: for example,

${}^{9}_{\Lambda}\mathrm{Be} \longrightarrow {}^{4}\mathrm{He} + {}^{2}\mathrm{H} + p + 2n$, etc.

Table I. Range and emission angle of each track.

Interaction point	Track number	Presumed identity	Range (μm)	Dip angle (degrees)	Azimuthal angle (degrees)
Point A	1	K^-		0.0	
	2	Ξ^-	3366.5±70.7	42.5±2.4	0.0
	3	p	163.7±4.0	41.0±2.2	305.0±1.5
	4	Recoil	2.2±0.9	90.0±28.6	155.0±5.5
	5	K^+		11.6±1.2	347.0±1.5
Point B	6	Hypernucleus	116.1±2.2	101.4±2.0	324.8±0.9
	7	Hypernucleus	4.7±0.6	76.9±10.0	147.9±5.0
Point C[a]	8	π^-	39992.0±1195.8	13.1±0.5	222.2±1.0
	9	^{4}He	9.5±0.6	170.7±0.9	46.7±1.9
Point D	10	Fast proton	21796.0±411.9	91.5±1.0	160.4±0.5
	11	^{2}H etc.	100.9±3.2	160.4±2.0	122.3±2.5
	12	^{4}He etc.	9.2±1.2	47.3±8.0	320.0±5.0

a) The emulsion was swollen by water with glycerin to the original thickness, and we could get a better resolution.

into a π^- meson (track 8) and a short recoil (track 9) at the end of the track (point C). The other fragment (track 7) leaves a very short track and emits a fast proton (track 10) with two short tracks (tracks 11 and 12) at point D. The latter is identified as a non-mesonic decay. The results of the measurements of ranges and emission angles of all the charged particles involved in the present event are summarized in Table I.

§ 3. Analysis

The fragment of track 6 is considered a single-Λ hypernucleus because it decayed into a π^- meson (track 8) and a stable recoil nucleus (track 9) at point C. The kinetic energies of a π^- meson in the two-body decays of all known light hypernuclei are listed in Table II which were obtained in the foregoing experiments.[10] The kinetic energy of the π^- meson (track 8) is estimated to be $51.99^{+0.95}_{-0.96}$ MeV from the range measurement. Referring to Table II, this decay is clearly identified as ${}^4_\Lambda\mathrm{H} \longrightarrow \pi^- + {}^4\mathrm{He} + 55.56$ MeV. Table III shows the total kinetic energy E_{sum} of this decay process analyzed by two methods, namely, by the use of range-energy relation and that of momentum balance.

On the other hand, the fragment of track 7 is also considered a hypernucleus for the following reasons. We reject the assumption that track 7 is a fast proton from a non-mesonic weak decay at point B which comes to interact with an emulsion nucleus at point D, because the energy loss of track 7 due to ionization is more than 5 times greater than that of track 10 which was identified as a fast proton. There remains another possibility that a Ξ^- hyperon was captured at point D after being scattered at point B, and overlapped with the emitted ${}^4_\Lambda$H (track 6) in the section between point D and point B. The probability of such an overlap to occur is, however, topologically less than 1 %. Therefore, it is most plausible to consider that the fragment decayed through a weak interaction associating with a fast proton with the kinetic energy of 79.4 MeV derived from the range-energy relation.

Table II. Decay modes for track 6 as a light Λ-hypernucleus decaying into a π^- and a stable nucleus.

Decay mode	Q_{known} (MeV)	Kinetic energy of π^-	Remarks
${}^{3}_{\Lambda}\mathrm{H} \to \pi^- + {}^{3}\mathrm{He}$	43.16 ± 0.07	40.83 ± 0.07	Rejected
${}^{4}_{\Lambda}\mathrm{H} \to \pi^- + {}^{4}\mathrm{He}$	55.56 ± 0.06	53.19 ± 0.06	Acceptable
${}^{6}_{\Lambda}\mathrm{He} \to \pi^- + {}^{6}\mathrm{Li}$	38.20 ± 0.12	37.15 ± 0.12	Rejected
${}^{7}_{\Lambda}\mathrm{Li} \to \pi^- + {}^{7}\mathrm{Be}$	37.81 ± 0.06	36.92 ± 0.06	Rejected
${}^{9}_{\Lambda}\mathrm{Li} \to \pi^- + {}^{9}\mathrm{Be}$	46.19 ± 0.13	45.32 ± 0.13	Rejected
${}^{10}_{\Lambda}\mathrm{Be} \to \pi^- + {}^{10}\mathrm{B}$	35.26 ± 0.23	34.68 ± 0.22	Rejected
${}^{12}_{\Lambda}\mathrm{B} \to \pi^- + {}^{12}\mathrm{C}$	42.36 ± 0.08	41.76 ± 0.08	Rejected
${}^{14}_{\Lambda}\mathrm{C} \to \pi^- + {}^{14}\mathrm{N}$	33.16 ± 0.33	32.77 ± 0.33	Rejected

Table III. Total kinetic energy E_{sum} calculated with the use of range-energy relation[a)] and momentum balance in the ${}^{4}_{\Lambda}\mathrm{H} \to {}^{4}\mathrm{He} + \pi^-$ reaction.

	Momentum (MeV/*c*) (Kinetic energy (MeV))		E_{sum}(MeV)
	π^-	${}^{4}\mathrm{He}$	
Range-energy	$131.21\,^{+1.38}_{-1.41}$ $(51.99\,^{+0.95}_{-0.96})$	$139.64\,^{+3.30}_{-3.45}$ (2.62 ± 0.13)	$54.60\,^{+0.96}_{-0.97}$
Momentum balance	$131.21\,^{+1.38}_{-1.41}$ $(51.99\,^{+0.95}_{-0.96})$	$131.21\,^{+1.38}_{-1.41}$ (2.31 ± 0.05)	$54.30\,^{+1.00}_{-1.01}$

a) The range-energy relation had been calibrated by measuring the ranges of α-particles (emitted from ThC′) and muons (decay products of stopped π^+).

Table IV. Momenta and kinetic energies in the $\Xi^- + (\mathrm{C, N, O}) \to {}^{4}_{\Lambda}\mathrm{H} + {}_{\Lambda}X$ reaction.

	Momentum (MeV/*c*) (Kinetic energy (MeV))			
	${}^{4}_{\Lambda}\mathrm{H}$	${}_{\Lambda}X$		
		${}^{9}_{\Lambda}\mathrm{Be}$	${}^{11}_{\Lambda}\mathrm{B}$	${}^{13}_{\Lambda}\mathrm{C}$
Range-energy	$224.60\,^{+1.47}_{-1.48}$ $(6.43\,^{+0.08}_{-0.09})$	$238.63\,^{+16.68}_{-15.61}$ (3.33 ± 0.48)	$301.86\,^{+21.62}_{-23.04}$ $(4.37\,^{+0.65}_{-0.64})$	$363.89\,^{+28.78}_{-28.56}$ $(5.39\,^{+0.89}_{-0.81})$
Momentum balance	$224.60\,^{+1.47}_{-1.48}$ $(6.43\,^{+0.08}_{-0.09})$	$224.60\,^{+1.47}_{-1.48}$ (2.95 ± 0.04)	(2.42 ± 0.03)	$(2.05\,^{+0.03}_{-0.02})$

As there is a track with a short range of 9.2 μm (track 12) at point D, the hyperfragment of track 7 must be a light hypernucleus. It should be noted that the energy of this particle is insufficient to surmount the Coulomb barrier of heavy emulsion nuclei (Ag, Br).[11)]

Since two light hypernuclei were emitted back to back with each other and no Auger electron was found[12)] at point B, it is obvious that the Ξ^- hyperon was captured at rest by a light emulsion nucleus (${}^{12}\mathrm{C}$, ${}^{14}\mathrm{N}$ or ${}^{16}\mathrm{O}$). Consequently, it will be enough to discuss the following candidates for the reaction process at point B:

Table V. Expected range of a hypernucleus (track 7) which is deduced using the momentum balance to ${}^{4}_{\Lambda}$H.

Hypernucleus	Expected Range (μm)[a)]	Remarks
in case of ${}^{9}_{\Lambda}$Be	4.2	Most probable
in case of ${}^{11}_{\Lambda}$B	2.9	Not rejected
in case of ${}^{13}_{\Lambda}$C	2.1	Not rejected

a) See text about the error of expected ranges.

Table VI. Observed total kinetic energy E_{sum} and the energy difference $\varDelta Q$ subtracting the known Q-value from E_{sum}.

	${}^{4}_{\Lambda}\mathrm{H}+{}^{9}_{\Lambda}\mathrm{Be}$	${}^{4}_{\Lambda}\mathrm{H}+{}^{11}_{\Lambda}\mathrm{B}$	${}^{4}_{\Lambda}\mathrm{H}+{}^{13}_{\Lambda}\mathrm{C}$
E_{sum}(MeV)	9.37 ± 0.12	8.84 ± 0.12	$8.48^{+0.12}_{-0.11}$
$\varDelta Q$(MeV)	-0.54 ± 0.20	-0.35 ± 0.20	$-6.62^{+0.23}_{-0.22}$

$$\Xi^- + {}^{12}\mathrm{C} \longrightarrow {}^{4}_{\Lambda}\mathrm{H} + {}^{9}_{\Lambda}\mathrm{Be} + (9.91\pm0.16)\ \mathrm{MeV}\,,$$

$$\Xi^- + {}^{14}\mathrm{N} \longrightarrow {}^{4}_{\Lambda}\mathrm{H} + {}^{11}_{\Lambda}\mathrm{B} + (9.19\pm0.16)\ \mathrm{MeV}\,,$$

$$\Xi^- + {}^{16}\mathrm{O} \longrightarrow {}^{4}_{\Lambda}\mathrm{H} + {}^{13}_{\Lambda}\mathrm{C} + (15.09\pm0.19)\ \mathrm{MeV}\,.$$

We estimated the momenta and kinetic energies of track 7 for three cases (${}^{9}_{\Lambda}$Be, ${}^{11}_{\Lambda}$B and ${}^{13}_{\Lambda}$C) using the two methods mentioned above. The results are summarized in Table IV. It should be noted that the reliability of range-energy relation decreases as the range becomes shorter. For this reason, the observed range (4.7 ± 0.6 μm[*)]) of track 7 was compared with the expected ranges in the three cases satisfying the momentum balance with track 6(${}^{4}_{\Lambda}$H). The expected ranges are shown in Table V where the error of each number is 0.2 μm. This error was derived from the momentum error of ${}^{4}_{\Lambda}$H and an extrapolation of the range-straggling found in the Ilford nuclear emulsion data.[12)] There are no data of range-straggling in the very low energy region (i.e., less than a few MeV). Thus none of the three cases were rejected, but ${}^{9}_{\Lambda}$Be was found to be most probable for track 7. Table VI lists the total observed kinetic energies carried by two single-Λ hypernuclei and their energy differences $\varDelta Q$ with respect to the known Q-values for the three cases.

§ 4. Discussion and conclusion

In current stage, it should be noted that the energy differences $\varDelta Q$ are obtained by subtracting the known Q value from the total observed kinetic energy for the three cases, although it is not easy to determine the reaction process uniquely. The $\varDelta Q$ values are -0.54 ± 0.20 MeV, -0.35 ± 0.20 MeV and $-6.62^{+0.23}_{-0.22}$ MeV for $\Xi^-+{}^{12}\mathrm{C}$, $\Xi^-+{}^{14}\mathrm{N}$ and $\Xi^-+{}^{16}\mathrm{O}$, respectively. These energy differences $\varDelta Q$ seem too large to be explained as an experimental error. We suggest two possibilities for the interpretation of this discrepancy.

[*)] We moreover need to consider the error of the range of track 7 caused by the ambiguity of the Ξ^- stop position. That value should be about 0.7 μm which is the typical grain size of emulsion.

The first possibility is that the Ξ^- hyperon was captured by a light emulsion atom (^{12}C, ^{14}N or ^{16}O) at rest, and a Ξ^- atom was created. The Ξ^- hyperon changed its orbit to lower level with the emission of γ-ray, and an energy corresponding to ΔQ was carried away at this stage. Then the Ξ^- hyperon in the atomic orbit interacted with one of protons in the nucleus and two single-Λ hypernuclei were finally produced. The second possibility is the formation of a Ξ nucleus. Concerning both the atomic states and the nuclear states, the theoretical calculation has been performed by Akaishi.[4),13)] For the case of Ξ^- capture in a ^{12}C, he suggests the existence of an atomic state and the mixing between an atomic and a nuclear state.

In this experiment, we have found the evidence of the production of two single-Λ hypernuclei through the process of Ξ^- capture at rest by a light nucleus (^{12}C, ^{14}N or ^{16}O) in the nuclear emulsion. The statistical treatment and determination of cross section for the production of two single-Λ hypernuclei will be discussed elsewhere.[14)]

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13) The level energies and widths of both the ^{12}C$+\Xi^-$ and ^{12}B$+\Xi^0$ systems are calculated by Akaishi[4)] with the use of a nucleus-Ξ potential of Woods-Saxon type as follows:

$$U_{\text{nucl-}\Xi}(r) = -\frac{V_0 + iW_0}{1+\exp\{(r-R)/a\}},$$

where $V_0=24$ MeV, $W_0=3$ MeV, $R=1.1\times A^{1/3}$ and $a=0.65$ fm. The atomic level of the '1*s*' state in the ^{12}C$+\Xi^-$ system is shifted by a strong interaction between a Ξ^- hyperon and ^{12}C nuclei. This '1*s*' atomic state is $-0.55(\Gamma=0.1)$ MeV. The 0*s* nuclear state in the ^{12}B$+\Xi^0$ system is very close to the '1*s*' atomic state and lies under the threshold of the ^{12}C$+\Xi^-$ system by $-0.47(\Gamma=3.7)$ MeV. Therefore, there is a possibility of the mixing of the '1*s*' atomic state in the ^{12}C$+\Xi^-$ system and the 0*s* nuclear state in the ^{12}B$+\Xi^0$ system.

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