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All Authors	Kazuma Nakazawa, Shinji Kinbara, Akihiro Mishina, Myint Kyaw Soe, Khin Than Tint, Junya Yoshida
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Progress on the study of double- Λ hypernuclei

Kazuma Nakazawa, Shinji Kinbara, Akihiro Mishina, Myint Kyaw
Soe, Khin Than Tint, Junya Yoshida

Physics Department, Gifu University, Gifu 501-1193, Japan

E-mail: nakazawa@gifu-u.ac.jp

Abstract. With use of nuclear emulsion, double-hypernuclei have been studied for aiming to understand Λ - Λ interaction via at-rest-capture of Ξ^- hyperon originated by quasi-free (K^-, K^+) reactions, where the beam K^- momentum was 1.66 GeV/c. Under the process for studying them, elementary feature for not only quasi-free reaction but also production of nuclei with single and double unit(s) of strangeness have been roughly understood, even the statistics were not large. So far we have succeeded to analyze 5 events of double-hypernuclei which introduced binding energies of two Λ hyperons on several nuclei. However its knowledge is very limited. We have started a new experiment, J-PARC E07, to give us rich information in $S = -2$ world. An event which may give us a new information about Ξ -nucleus interaction shall be introduced.

1. Introduction

Transfer reaction of two units of strangeness is quite interesting, because the reaction provides us information of double-strangeness systems such as H-dibaryon, Ξ hypernucleus and double- Λ hypernucleus. Conversely say, that transfer reaction would be the uniquely available source of information on study of Λ - Λ and Ξ - N interaction.

The first observation of a double- Λ hypernucleus was performed among expected four events of Ξ^- hyperon capture at rest in nuclear emulsion[1]. The capture reaction of Ξ^- hyperon is more reliable to produce double- Λ hypernuclei than directly production via (K^-, K^+) reaction due to small Q-value of at most 28 MeV, *i.e.* $\Xi^- + p \rightarrow \Lambda + \Lambda + 28$ MeV. When we detected typical sequential decay topologies of light double- Λ hypernuclei, kinematical analysis has been made for measurement of the mass of the nuclei under the energy and momentum conservation. The energies and momentum of decay daughter particles can be obtained by using the relation between track range and energy in the emulsion. The relation was calibrated with ranges of particles, which would be unique kinetic energies of 8.784 MeV and 5.367 MeV for α particles from ^{212}Po and ^{228}Th , respectively, and 4.259 MeV for μ^+ meson from stopped π^+ meson.

In the E176 experiment at KEK-PS, since the emulsion was used not only as a detector of production and decay of double- Λ hypernucleus but also for the (K^-, K^+) reaction target, we have studied elementary processes for (K^-, K^+) reaction regardless of whether quasi-free reaction, even the statistics were not so much. If we select events with K^+ momentum higher than 1.0 GeV/c, those events would present quasi-free production of Ξ^- hyperons very well. Sticking probabilities of single and double strangeness are discussed for light (C, N, O) and heavy (Ag, Br, I) elements in nuclear emulsion. Those probabilities are strongly related to theoretical calculation of formation and transition of $S = -2$ nuclear systems [2]. In the E373 experiment, (K^-, K^+) reactions were taken place in a diamond block located upstream the emulsion stack to get more events with Ξ^- hyperon stopping. Unfortunately, we suspended to



study such sticking probability in the E373 experiment at KEK-PS, because we need to develop some technology to identify Ξ^- stopping events except for clear events with double strangeness. However we have succeeded to detect several double- Λ hypernuclei, especially NAGARA event presented unique information on Λ - Λ interaction[3, 4, 5, 6].

In the coming E07 experiment at J-PARC, to search for nuclear mass dependence of binding energy of two Λ hyperons in nuclei, $B_{\Lambda\Lambda}$, nearly one hundred double- Λ hypernuclei can be detected by using fully automated system for tracking of Ξ^- hyperons. By the development of “Overall-scanning” method[7] to pick up characteristic decay topologies with three vertices of double- Λ hypernuclei, more than one thousand of the nuclei are expected to be observed.

In this report, past obtained knowledge about double strangeness reaction and systems will be summarized, briefly, and it will be introduced for a new event of uniquely identified twin hypernuclei which was detected in test operation of *Overall-scanning* method.

2. Present knowledge with (K^-, K^+) reaction

2.1. strangeness transfer via (K^-, K^+) reaction

The setup around target emulsion was seen for the E176 experiment at KEK-PS in Figure 1. In the experiment, the emulsion was used for the target of (K^-, K^+) reaction and for the detector of double-hypernuclei. The K^-/π^- ratio in beam particles of 1.66 GeV/c momentum was typically 1/3 with the intensity of 3×10^3 K^- /spill. Tracks of K^+ mesons reconstructed by silicon microstrip detectors (VSSD) were scanned at Changeable emulsion sheet, and if they were detected, we followed up them to the (K^-, K^+) reaction vertices. If some track(s) were emitted from the vertex, we followed them to their end points and checked the production and decay of hypernucleus.

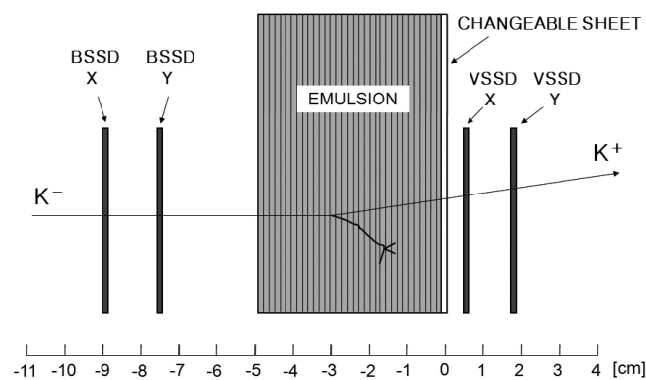


Figure 1. (K^-, K^+) reactions were recorded in the emulsion stack. The K^+ mesons were identified by the spectrometer system with USHIWAKA magnet. Detected K^+ mesons were located at the changeable emulsion sheet which recorded 10 % track density of the emulsion stack. The detected K^+ mesons were followed up to the reaction vertex.

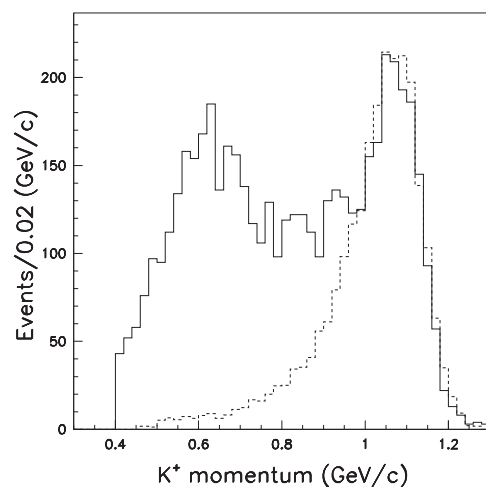


Figure 2. K^+ momentum spectra obtained by the experiment (solid line) and by simulation with fermi-motion (dotted line).

In Figure 2, K^+ momentum spectra are presented with the result of a simulation based on quasi-free $p(K^-, K^+)\Xi^-$ reaction. In the higher momentum region ($p_{K^+} \geq 1.0$ GeV/c), the (K^-, K^+) reaction is considered to be in quasi-free process.

We have located 796 (K^-, K^+) events in the region of $p_{K^+} \geq 1.0$ GeV/c. After rejection of events without the production of Ξ^- hyperon such as Ξ^{*-} production, $\Xi^0\pi^-$ production, two step process, and so on, 761 events were studied for interaction cross section Ξ^- hyperon and nucleon, $\sigma_{\Xi N}$. Since Ξ^- emission rate from target nuclei in the emulsion was $73.9^{+4.5}_{-4.6}$ % (± 5

% from non quasi-free process), we obtained mean-free-path of Ξ^- hyperon in nucleus and $\sigma_{\Xi N}$ to be $4.7_{-1.0}^{+1.5}$ fm and $12.7_{-3.1}^{+3.5}$ mb, respectively. In 18 events, hyperfragment was emitted from (K^-, K^+) reaction vertex [8].

Regarding non quasi-free reaction ($p_{K^+} < 1.0$ GeV/c), 901 events have been located in the emulsion. Single- Λ and double- Λ hypernuclei were produced in 42 and 3 events, respectively, at (K^-, K^+) reaction point. Production rate, 4.6 ± 0.7 %, of single- Λ hypernuclei was in good agreement with old data [9]. It was found that the 0.3 ± 0.2 % would be the production rate for double- Λ hypernuclei in (K^-, K^+) reaction with non quasi-free process.

2.2. strangeness transfer via Ξ^- capture at rest

We have located 77.6 ± 5.1 events with at rest capture of Ξ^- hyperon in E176. Among them, 42 % of the events were occurred in capture by light elements, ^{12}C , ^{14}N and ^{16}O , in the emulsion nuclei. On the other hand, capture reaction by heavy elements, Ag and Br, was 58%. One event of double- Λ hypernucleus and three events of twin single- Λ hypernuclei provided us lower limits of sticking probabilities for two and at least one Λ hyperon(s) to be 4.8% and 48.4%, respectively, at 90% confidence level for light elements. Regarding heavy elements, 1.7% and 35.7% were for sticking probabilities of two and at least one Λ hyperon(s) at 90% confidence level, respectively[5].

Table 1. Double- Λ hypernuclei in the world.

Event	${}_{\Lambda\Lambda}^AZ$	Ξ^- captured	$B_{\Lambda\Lambda} - B_{\Xi^-}$ (MeV)	$\Delta B_{\Lambda\Lambda} - B_{\Xi^-}$ (MeV)	Level	$B_{\Lambda\Lambda}$ (MeV)	$\Delta B_{\Lambda\Lambda}$ (MeV)
NAGARA	${}_{\Lambda\Lambda}^6\text{He}$	^{12}C	$B_{\Lambda\Lambda} = 6.79 + 0.91B_{\Xi^-} (\pm 0.16)$ $\Delta B_{\Lambda\Lambda} = 0.55 + 0.91B_{\Xi^-} (\pm 0.17)$		3D	6.91	0.67
MIKAGE	${}_{\Lambda\Lambda}^6\text{He}$	^{12}C	9.88 ± 1.71	3.64 ± 1.71	3D	10.01	3.77
	${}_{\Lambda\Lambda}^{11}\text{Be}$	^{14}N	21.95 ± 2.67	3.73 ± 2.71	3D	22.12	3.94
DEMACHI-YANAGI	${}_{\Lambda\Lambda}^{10}\text{Be}^*$	^{12}C	11.77 ± 0.13	-1.65 ± 0.15	3D	11.90	-1.52
HIDA	${}_{\Lambda\Lambda}^{11}\text{Be}$	^{16}O	20.60 ± 1.27	2.38 ± 1.34	3D	20.83	2.61
	${}_{\Lambda\Lambda}^{12}\text{Be}$	^{14}N	22.31 ± 1.21	–	3D	22.48	–
E176	${}_{\Lambda\Lambda}^{13}\text{B}$	^{14}N	–	–	3D	23.3	0.6
						± 0.7	± 0.8
Danysz	${}_{\Lambda\Lambda}^{10}\text{Be}$	–	Reconstructed by decay daughters			14.7	1.3
						± 0.4	± 0.4

In the E373 experiment at KEK-PS, we have expected to observe nearly 10 double- Λ hypernuclei. We have changed the (K^-, K^+) reaction target and SSDs to a diamond block ($2 \times 2 \times 3$ cm³) upstream of the emulsion and fiber bundle detectors, respectively, for getting much events for Ξ^- hyperon capture at rest. We followed Ξ^- hyperon candidate tracks reconstructed by fiber bundle detector. The expected number of Ξ^- stopping events was nearly 10^3 . Although we did not get the correct number of Ξ^- stopping events due to impossibility of checking (K^-, K^+) reaction vertices in the diamond target, 4 events from 7 samples of double- Λ hypernucleus were succeeded to be analyzed. Among them, the NAGARA event was the event uniquely identified as the production and decay of a ${}_{\Lambda\Lambda}^6\text{He}$ nucleus. Assuming Ξ^- hyperon capture at atomic 3D state in the NAGARA event, two Λ binding energy, $B_{\Lambda\Lambda}$, and Λ - Λ interaction energy, $\Delta B_{\Lambda\Lambda}$, obtained by $2B_{\Lambda}({}^5_{\Lambda}\text{He}) - B_{\Lambda\Lambda}({}_{\Lambda\Lambda}^6\text{He})$ to be 6.91 ± 0.16 MeV and 0.67 ± 0.17 MeV, respectively, where B_{Λ} is a Λ binding energy of single-hypernucleus. Under the consistency of $\Delta B_{\Lambda\Lambda}$ of the NAGARA event, other three and two events by E176[3, 5] and Danysz *et al.* [1] were summarized as listed in Table 1. Since the error of the atomic 3D state

is quite small, the errors of $B_{\Lambda\Lambda}$ and $\Delta B_{\Lambda\Lambda}$ are same as ones of $B_{\Lambda\Lambda} - B_{\Xi^-}$ and $\Delta B_{\Lambda\Lambda} - B_{\Xi^-}$, respectively. The difference, 2.8 MeV, of $B_{\Lambda\Lambda}$ between the events of DEMACHIYANAGI and Danysz *et al.* is considered as the excitation energy of ${}^{10}_{\Lambda\Lambda}\text{Be}$ nucleus.

3. The E07 experiment at J-PARC

In the E07 experiment, we will study nuclear mass dependence of $B_{\Lambda\Lambda}$, precisely, by detecting many double- Λ hypernuclei. Its statistics is expected to be ten times more than the previous E373 experiment by following Ξ^- hyperons detected by SSDs. We also measure the energies of X-ray emitted from atomic levels to know the energy shift by the strong interaction of Ξ^- hyperon capture on nucleus by using Ge detector array, for the first time. Since the Ξ^- stopping events are clearly detected in the emulsion, the measurement of X-rays will be performed in almost background free for several thousands' events of Ξ^- stopping.

The tracking efficiency of Ξ^- hyperons is about 10% of ' $p'(K^-, K^+)\Xi^-$ ' events, therefore nearly 10^3 double- Λ hypernuclei stay in the emulsion. To perform scanning for the full volume of the emulsion and detect typical topologies of three vertices of double- Λ hypernuclei, we have been developing “*Overall-scanning*” method in two steps[7] which is listed in Table 2.

In the 1st step, we drive the microscope stage without stopping by taking images in a half side of the emulsion plate by CCD camera. It is necessary for 1.5 seconds to take images and 1.5 seconds to store image data. After that, we apply graphic processing method to image data. Graphics process consists of routines by contrast maximization, background homogenization with Gaussian filter, track sharpness with matrix filter, binarization, track edge detection, thinning, Hough transformation and vertex detection.

Table 2. Specifications for two steps of *Overall-scanning* method.

	the 1 st step	the 2 nd step
Objective lens	$\times 50$ (NA. 0.9)	$\times 20$ (NA. 0.35)
Camera	XC_HR300	HXC20
Frame rate (Hz)	100	800
Device	CCD	CMOS
pixel	512×440	2048×358
Area (μm^2)	130×110	$1,140 \times 200$
Stage	non-stop	non-stop
driving	Motor	Piezo
Capture rate (Hz)	0.3	5

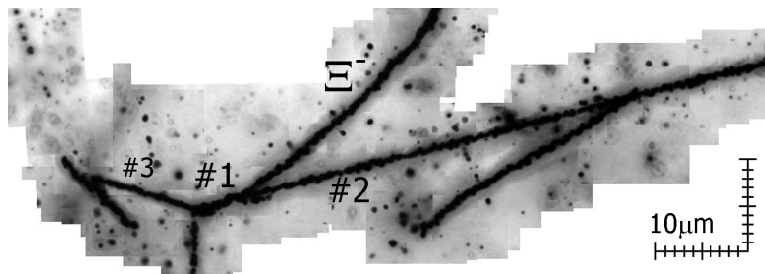


Figure 3. A newly found event of twin hypernuclei.

During test operations of the 1st step applying E373 emulsion plate, we have detected a typical event showing twin hypernuclei from 7.9×10^6 images as shown in Figure 3. A Ξ^- hyperon was brought to rest after ~ 8 mm flying from the top of the emulsion and produced two single- Λ hypernuclei (tracks #1 and #2). Two charged particles were emitted from the end

point of track #1. Among them, track #3 is typical shape of ‘hammer track’ of the decay of ${}^8\text{Be}^*(2^+)$ nucleus to two α particles. We will measure the binding energy of Ξ^- hyperon and the analysis is on-going.

We obtained quite high speed with $\times 300$ than the system of the 1st step by Piezo driving of the microscope head. This speed assures the detection of $\sim 10^3$ double- Λ hypernuclei in the E07 emulsion plates within a few years.

4. Concluding remarks

We have performed two experiments, E176 and E373 at KEK-PS, to study doubly strangeness systems for these twenty years.

In the E176 experiment, we have studied not only quasi-free (K^-, K^+) reaction but also (K^-, K^+) reaction itself in the range of ($0.4 \text{ GeV}/c < p_{K^+} < 1.2 \text{ GeV}/c$) with separated K^- beams ($p_{K^-} = 1.66 \text{ GeV}/c$) at KEK-PS. From the quasi-free reaction ($1.0 \text{ GeV}/c \leq p_{K^+}$), mean-free-path of Ξ^- hyperon in nucleus was obtained to be $4.7^{+1.5}_{-1.0} \text{ fm}$. By this result, we presented the interaction cross section $\sigma_{\Xi N} = 12.7^{+3.5}_{-3.1} \text{ mb}$. Hyperfragments were produced at 18 reaction vertices among 796 reactions. Regarding non quasi-free reaction ($p_{K^+} < 1.0 \text{ GeV}/c$), 901 reaction vertices were located in the emulsion. Production rates of double- Λ and single- Λ hypernuclei for non quasi-free reaction were obtained to be $0.3 \pm 0.2 \%$ and $4.6 \pm 0.7 \%$, respectively. At rest captures of Ξ^- hyperon were seen in 77.6 ± 5.1 events which were caused in 58% and 42% by heavy (Ag, Br) and light (C, N, O) elements, respectively, in the emulsion. Sticking probabilities of two Λ hyperons or at least one Λ hyperon(s) in light nuclei would be 4.8% or 48.4% at 90% confidence level. In heavy nuclei, such probabilities of two or at least one Λ hyperon(s) was 1.7% or 35.7% (90% CL).

Double- Λ hypernuclei in several nuclear species were detected. The NAGARA event was uniquely assigned to be the production and decay of ${}^6_{\Lambda\Lambda}\text{He}$ double- Λ hypernucleus and presented $B_{\Lambda\Lambda}$ and $\Delta B_{\Lambda\Lambda}$ for $6.79 + 0.91B_{\Xi^-} (\pm 0.16) \text{ MeV}$ and $0.55 + 0.91B_{\Xi^-} (\pm 0.17) \text{ MeV}$, respectively, as a function of B_{Ξ^-} . If we took the atomic 3D capture of Ξ^- hyperon into account, $B_{\Lambda\Lambda}$ and $\Delta B_{\Lambda\Lambda}$ were obtained to be $6.91 \pm 0.16 \text{ MeV}$ and $0.67 \pm 0.17 \text{ MeV}$, respectively. By applying result to other nuclei, the excitation energy was obtained of ${}^{10}_{\Lambda\Lambda}\text{Be}$ as 2.8 MeV.

To study nuclear mass dependence of $B_{\Lambda\Lambda}$ with several tens’ double- Λ hypernuclei, the E07 experiment at J-PARC was started. *Overall-scanning* method is now developing to search for double- Λ hypernuclei with very high speed in full volume of the emulsion. In the test operations of the method, a twin hypernuclear event was detected which will be useful for study Ξ -Nucleus interaction.

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