

# Double- $\Lambda$ Hypernuclei via the $\Xi^-$ Hyperon Capture at Rest Reaction in a Hybrid Emulsion

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## Abstract

We have obtained nearly one thousand events of the  $\Xi^-$  hyperon captured at rest in nuclear emulsion. Among them, production and decay of double- $\Lambda$  hypernuclei was successfully found and analyzed for five events which correspond to five nuclear species with double strangeness. Preliminary results are discussed for the binding energy and interaction energy of two  $\Lambda$  hyperons. By comparison with older data, the excitation energy of the  ${}_{\Lambda\Lambda}^{10}\text{Be}$  nucleus is also discussed. A new experiment, which is expected to provide 10 times more double-strangeness events than before, is introduced.

*Key words:* Double- $\Lambda$  hypernucleus,  $\Lambda\Lambda$  binding energy,  $\Lambda\Lambda$  interaction energy,  $\Xi^-$  capture at rest, Nuclear emulsion.

## 1. Introduction

Double- $\Lambda$  hypernuclei give us information about the  $\Lambda\Lambda$  interaction which is valuable for obtaining a unified understanding of the Baryon-Baryon interaction in  $SU(3)_f$  symmetry. This knowledge also guides us to multi-strangeness systems such as "strange matter". This research allows us to draw a three-dimensional nuclear chart with one axis being strangeness.

A system with double strangeness ( $s = -2$ ) is closely related to the H dibaryon predicted by R. L. Jafee [1]. Existence of the particle-like H dibaryon is, however, unlikely [2]. In the ground state of an  $s = -2$  nucleus, it is ordinarily understood that the two  $\Lambda$  hyperons are in  $s$ -orbits. However, the mass difference between the  $\Lambda\Lambda$  and  $\Xi N$  is so small, it is probable that a mixed state of  $\Xi N$ ,  $\Lambda\Lambda$  and  $\Sigma\Sigma$  appears, and an H dibaryon resonance may be formed as a result of the mixing. From this point of view, it is interesting that a bump appears around the threshold in an invariant mass spectrum of the two  $\Lambda$  hyperons from the  $(K^-, K^+)$  reaction on a  ${}^{12}\text{C}$  target [3].

In experiments studying  $s = -2$  systems, key values are the binding energy of the two  $\Lambda$  hyperons in the nucleus,  $B_{\Lambda\Lambda}$ , and the  $\Lambda\Lambda$  interaction energy,  $\Delta B_{\Lambda\Lambda}$ , which are defined as follows;

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

For twenty years, doubly strange systems based on double- $\Lambda$  hypernuclei have been studied at KEK. In this report, we introduce the double- $\Lambda$  hypernuclei obtained in the KEK E176 and E373 experiments, and discuss the preliminary results for  $B_{\Lambda\Lambda}$  and  $\Delta B_{\Lambda\Lambda}$  values with the binding

energy of the  $\Xi^-$  hyperon,  $B_{\Xi^-}$ , in nuclei existing in a nuclear emulsion. Also discussed is a future experiment, E07 at J-PARC, which is expected to provide 10 times more events with  $s = -2$ .

## 2. Experiments : KEK E176 and E373

The capture of  $\Xi^-$  hyperons at rest was observed in emulsion in the KEK E176 and E373 experiments. We tagged  $K^+$  mesons from the quasi-free reaction of  ${}^{\prime\prime}p^{\prime\prime}(K^-, K^+) \Xi^-$  in the emulsion (E176) and in a diamond target located upstream of the emulsion (E373).

In the E176 experiment, tracks of the  $K^+$  mesons were reconstructed by SSDs located downstream of the emulsion, and followed up in low track-density changeable sheet and emulsion stacks. From the reaction vertices located in the emulsion, all of the tracks were followed down to their end points and searched for the typical three vertices of the decay of double- $\Lambda$  hypernuclei. In E373, a scintillating-fiber bundle tracker (Scifi-bundle) [4] sandwiched by the target diamond [5] and the emulsion has reconstructed tracks of the  $\Xi^-$  hyperon candidate. We followed their tracks down to their stopping points in the emulsion, and also searched for the decay of double- $\Lambda$  hypernuclei around there.

Using the above methods, we located  $77.6 \pm 5.1$  [6] and several hundreds of candidate events, emitting charged particles, caused by stopping  $\Xi^-$  hyperons, in the E176 and E373 experiments, respectively. Among them, we successfully detected one and four double- $\Lambda$  hypernuclei events in E176 and E373, along with some twin-hypernuclei events [7, 8, 9].

## 3. Double- $\Lambda$ hypernuclei

In the particle data report [10], the mass of the  $\Xi^-$  hyperon was changed by 0.4 MeV from the earlier compilation [11], *i.e.* from  $1321.31 \pm 0.13$  MeV to  $1321.71 \pm 0.07$  MeV. We used the new mass data in the following analyses. It was also adopted for the  $\Xi^-$  binding energies of 0.13, 0.17 and 0.23 MeV in  ${}^{12}\text{C}$ ,  ${}^{14}\text{N}$  and  ${}^{16}\text{O}$ , respectively, in the atomic 3D states.

### 3.1. Double- $\Lambda$ hypernucleus from the E176 experiment

In 1991, this event was reported in [12]. A photograph and schematic drawing are shown in Fig. 1.

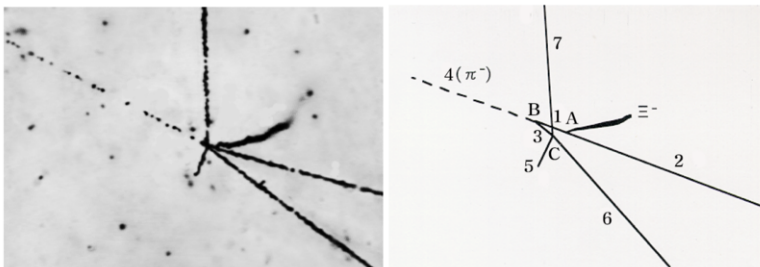
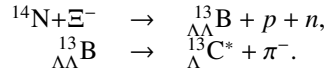


Figure 1: A picture and schematic drawing of a double- $\Lambda$  hypernucleus detected in the KEK E176 experiment.

Two charged particles were emitted from the  $\Xi^-$  hyperon capture point. One of them shows a decay topology associated with two charged particles, and particle #3 also decays into three

charged particles. By checking the consistency of  $B_{\Lambda\Lambda}$  and  $\Delta B_{\Lambda\Lambda}$  at the points of production and decay of the double- $\Lambda$  hypernucleus, respectively, the following reaction was found to be the most probable;



Taking into account a value of  $B_{\Xi^-} = 0.17$  MeV for an atomic  $3D$  state of the  ${}^{14}\text{N} + \Xi^-$  system, we obtained  $B_{\Lambda\Lambda}$  and  $\Delta B_{\Lambda\Lambda}$  to be  $23.3 \pm 0.7$  and  $0.6 \pm 0.8$  MeV, respectively, where we adopted 4.9 MeV as the excitation energy of  ${}^{13}\text{C}^*$ . More detailed discussion was given in [13].

### 3.2. The NAGARA event from the E373 experiment

The "NAGARA event" was reported in [14]. The values of  $B_{\Lambda\Lambda}$  and  $\Delta B_{\Lambda\Lambda}$  were also presented using the old mass of the  $\Xi^-$  hyperon. We therefore reanalyzed the event and succeeded in obtaining a unique interpretation of the event, again.

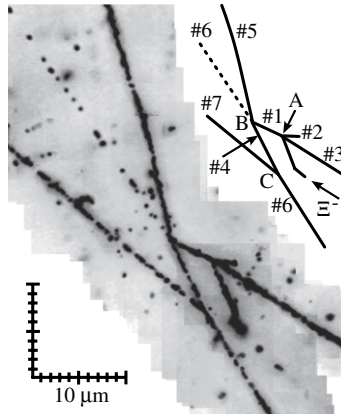
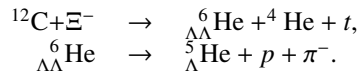


Figure 2: A picture and schematic drawing of a double- $\Lambda$  hypernucleus, the NAGARA event, detected in the KEK E373 experiment.

A photograph and schematic drawing are shown in Fig. 2. By kinematical analysis at production point A and decay point B, we checked all possible modes by  $\Delta B_{\Lambda\Lambda} - B_{\Xi^-} < 20$  MeV and  $\Delta B_{\Lambda\Lambda} < -20$  MeV at point A and B, respectively. Identification of nuclide and decay mode was the same as reported before:



The values of  $B_{\Lambda\Lambda}$  and  $\Delta B_{\Lambda\Lambda}$  have been shifted by 0.4 MeV due to the mass change of the  $\Xi^-$  hyperon. Weighted mean values of  $B_{\Lambda\Lambda}$  and  $\Delta B_{\Lambda\Lambda}$  at point A and B are obtained as

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

If we assume that the  $\Xi^-$  hyperon was captured in the atomic  $3D$  state, the values of  $B_{\Lambda\Lambda}$  and  $\Delta B_{\Lambda\Lambda}$  were  $6.91 \pm 0.16$  and  $0.67 \pm 0.17$  MeV, respectively.

### 3.3. The MIKAGE event from the E373 experiment

We reported this event as a non-uniquely identified one in [15]. A photograph and schematic drawing are shown in Fig. 3. After that, a measurement using a track image processing method was applied and we obtained precise data as listed in Table 1.

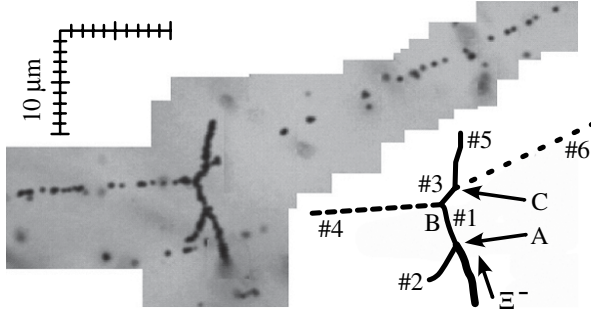
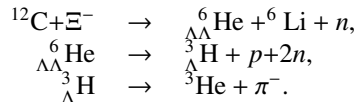


Figure 3: A picture and schematic drawing of a double- $\Lambda$  hypernucleus, the MIKAGE event, of the KEK E373 experiment.

Table 1: Track data of the MIKAGE event. The length of track #6 is the visible one in the emulsion.

point	track#	length [ $\mu\text{m}$ ]	$\theta$ [degree]	$\phi$ [degree]	
A	#1	$2.9 \pm 0.3$	$95.5 \pm 1.7$	$109.0 \pm 0.7$	double-hypernucleus
	#2	$3.5 \pm 0.8$	$97.0 \pm 2.1$	$247.6 \pm 2.1$	
B	#3	$1.8 \pm 0.4$	$72.0 \pm 11.2$	$44.7 \pm 3.5$	single-hypernucleus
	#4	$19044.7 \pm 10.6$	$80.5 \pm 0.1$	$183.1 \pm 0.1$	proton
C	#5	$4.5 \pm 0.6$	$57.9 \pm 5.3$	$87.3 \pm 2.1$	$\pi^-$ ( $49.1 \pm 1.7$ MeV)
	#6	$> 12975.6$	$49.6 \pm 0.3$	$23.7 \pm 0.1$	

By measurement of the ionization ( $dE/dx$ ) and the lengths of tracks #4 and #6 in the emulsion and SciFi-Block, particles were identified as proton and  $\pi^-$  for #4 and #6, respectively, and the kinetic energy of the  $\pi^-$  meson was established to be  $49.1 \pm 1.7$  MeV. Such a large energy release corresponds to in-flight decay of a single- $\Lambda$  hypernucleus. Due to point C consisting of a coplanar vertex, no neutron emission is assumed at the decay of the single- $\Lambda$  hypernucleus (#3). Then, possible decay modes of particle #3 were limited to the two cases  ${}^3_{\Lambda}\text{H} \rightarrow {}^3\text{He} + \pi^-$  or  ${}^9_{\Lambda}\text{Li} \rightarrow {}^9\text{Be} + \pi^-$ . Finally, a consistency check of  $\Delta B_{\Lambda\Lambda}$  and  $\Delta B_{\Lambda\Lambda} - B_{\Xi^-}$  at point A and B as done for the NAGARA event gave a most probable interpretation as follows:



Values of  $B_{\Lambda\Lambda} - B_{\Xi^-}$  and  $\Delta B_{\Lambda\Lambda} - B_{\Xi^-}$  were obtained as  $9.93 \pm 1.72$  and  $3.69 \pm 1.72$  MeV, respectively. At present, we are developing a measurement method to obtain more precise track angles for better energy resolution.

### 3.4. The DEMACHIYANAGI event from the E373 experiment

This event was discussed in [16]. Photographs and schematic drawings of the event are presented in Fig. 4, and lengths and angles of all tracks are listed in Table 2.

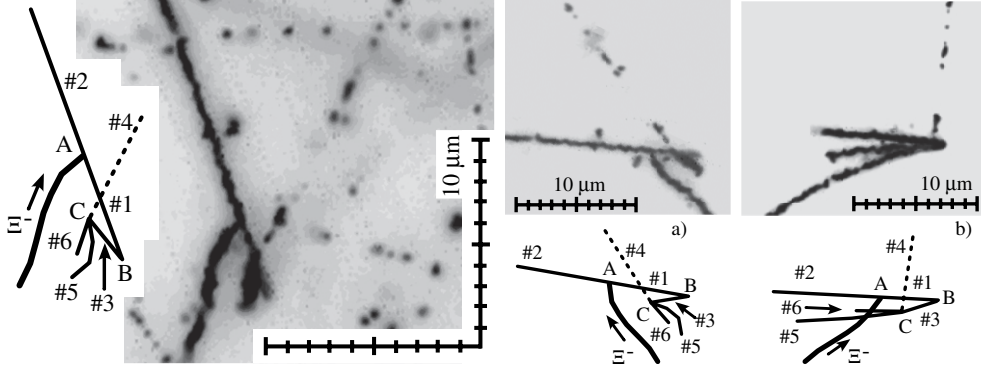
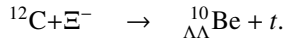


Figure 4: On left side, photograph and schematic drawing of the “DEMACHIYANAGI event” are presented. Right-hand photographs and schematic drawings viewed from the vertical (a) and the horizontal (b) direction after the emulsion was swelled and sliced. Each photo was obtained by summing up images taken at various focusing positions of the microscope.

Table 2: Lengths and angles of the tracks of the DEMACHIYANAGI event. The length of track #4 is the only visible one in the emulsion.

point	track#	length [ $\mu\text{m}$ ]	$\theta$ [degree]	$\phi$ [degree]	
A	#1	$4.2^{+0.25}_{-0.07}$	$124.5 \pm 5.1$	$343.2 \pm 3.5$	double-hypernucleus
	#2	$287.0 \pm 1.9$	$57.7 \pm 1.1$	$159.4 \pm 0.5$	
B	#3	$3.7^{+0.3}_{-0.1}$	$32.6 \pm 7.8$	$145 \pm 10$	single-hypernucleus
C	#4	23575	$94.2 \pm 0.4$	$209.8 \pm 0.3$	
	#5	$11.3 \pm 0.7$	$9.4 \pm 3.4$	$341 \pm 20$	
	#6	$8.4 \pm 0.7$	$7.2 \pm 2.5$	$21 \pm 19$	

Among possible production modes with  $\Delta B_{\Lambda\Lambda} - B_{\Xi^-} < 20$  MeV, the following case was the most probable taking into account a no-neutron emission from point A hypothesis, because the two tracks #1 and #2 were collinear within measurement error.



By applying the kinematic fitting, we obtained values of  $B_{\Lambda\Lambda} - B_{\Xi^-}$  and  $\Delta B_{\Lambda\Lambda} - B_{\Xi^-}$  as  $11.77 \pm 0.13$  MeV and  $-1.65 \pm 0.15$  MeV, respectively. If the double- $\Lambda$  hypernucleus was produced in an excited state, *ie.*  $^{12}\text{C} + \Xi^- \rightarrow \begin{smallmatrix} 10 \\ \Lambda\Lambda \end{smallmatrix} \text{Be}^* + t$ , the value of the  $\Delta B_{\Lambda\Lambda}$  of  $\begin{smallmatrix} 10 \\ \Lambda\Lambda \end{smallmatrix} \text{Be}$  ground state increases by the excitation energy. If we assume its energy should be nearly 3 MeV, the same as for  $^9_{\Lambda}\text{Be}$  and  $^8_{\Lambda}\text{Be}$ , then the  $\Delta B_{\Lambda\Lambda} - B_{\Xi^-}$  value is consistent with the NAGARA result.

### 3.5. The HIDA event from the E373 experiment

Figure 5 shows a photograph and schematic drawing of the event; track #7 was followed down to its end point C. The  $\Xi^-$  hyperon was followed upstream and recorded in SciFi-Bundle.

Track data of lengths and angles are listed in Table 3. By measurement of the  $dE/dx$  in the emulsion and SciFi-Blocks, we identified both track #6 and #7 as a proton.

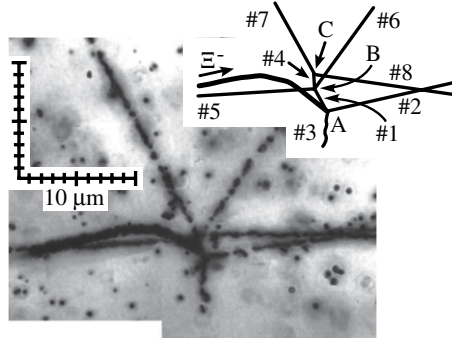
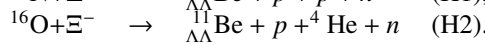
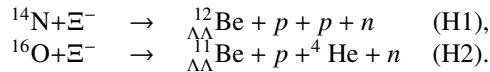


Figure 5: Photograph and schematic drawing of the "HIDA event".

Table 3: Lengths and angles of the tracks for HIDA event.

point	track#	length [ $\mu\text{m}$ ]	$\theta$ [degree]	$\phi$ [degree]	
A	#1	$2.3 \pm 0.1$	$52.5 \pm 3.8$	$116.1 \pm 5.9$	double-hypernucleus
	#2	$53.5 \pm 0.2$	$102.1 \pm 0.2$	$7.0 \pm 0.1$	
	#3	$4.7 \pm 0.6$	$93.8 \pm 3.2$	$256.7 \pm 1.0$	
B	#4	$7.8 \pm 0.1$	$4.1 \pm 0.5$	$95.3 \pm 6.2$	single-hypernucleus
	#5	$74.9 \pm 0.4$	$76.4 \pm 0.1$	$180.5 \pm 0.1$	
	#6	$5847.9 \pm 11.3$	$148.2 \pm 0.1$	$51.2 \pm 0.1$	
C	#7	$6728.8 \pm 8.2$	$31.5 \pm 0.1$	$115.3 \pm 0.1$	proton
	#8	$96.0 \pm 0.4$	$109.0 \pm 0.1$	$356.6 \pm 0.1$	

Since both double- $\Lambda$  (#1) and single- $\Lambda$  (#4) hypernuclei show non-mesonic decay, production of Be or B double- $\Lambda$  nucleus is possible via the capture reaction on  $^{12}\text{C}$ ,  $^{14}\text{N}$  or  $^{16}\text{O}$ . By rejecting production modes with  $\Delta B_{\Lambda\Lambda}$  far from the previous data of the NAGARA event, there remained only two possible modes:



In the case of (H1), the value of  $B_{\Lambda\Lambda} - B_{\Xi^-}$  for  $^{12}\text{Be}$  was found to be  $22.6 \pm 1.15$  MeV. However, the value related to  $\Delta B_{\Lambda\Lambda}$  could not be calculated due to no average value for  $B_{\Lambda}({}^{11}\text{Be})$ . As for the case of (H2), the values of  $B_{\Lambda\Lambda} - B_{\Xi^-}$  and  $\Delta B_{\Lambda\Lambda} - B_{\Xi^-}$  for  $^{11}\text{Be}$  were  $20.26 \pm 1.15$  MeV and  $2.04 \pm 1.23$  MeV, respectively.

A new measurement method, developed for the MIKAGE event, should be applied to this event for better energy resolution and nuclide identification.

#### 4. Concluding remarks

We detected nearly  $10^3$  events for a  $\Xi^-$  hyperon captured at rest in nuclear emulsion in the KEK E176 and E373 experiments. We succeeded in analyzing five events which show sequential

decay topology of double- $\Lambda$  hypernuclei. Under the assumption of  $3D$  atomic state level for the  $\Xi^-$  hyperon captured at rest for all presented events, the resulting values of  $B_{\Lambda\Lambda}$  and  $\Delta B_{\Lambda\Lambda}$  were summarized in Table 4.

Table 4:  $B_{\Lambda\Lambda}$  and  $\Delta B_{\Lambda\Lambda}$  for all double- $\Lambda$  hypernuclei under the assumption that each case resulted from the capture reaction of a  $\Xi^-$  hyperon in a  $3D$  atomic level for each target nucleus.

event	${}^A_{\Lambda\Lambda}Z$	Target	$B_{\Lambda\Lambda}$ [MeV]	$\Delta B_{\Lambda\Lambda}$ [MeV]
NAGARA	${}^6_{\Lambda\Lambda}\text{He}$	${}^{12}\text{C}$	$6.91 \pm 0.16$	$0.67 \pm 0.17$
MIKAGE	${}^6_{\Lambda\Lambda}\text{He}$	${}^{12}\text{C}$	$10.06 \pm 1.72$	$3.82 \pm 1.72$
DEMACHIYANAGI	${}^{10}_{\Lambda\Lambda}\text{Be}$	${}^{12}\text{C}$	$11.90 \pm 0.13$	$-1.52 \pm 0.15$
HIDA	${}^{11}_{\Lambda\Lambda}\text{Be}$	${}^{16}\text{O}$	$20.49 \pm 1.15$	$2.27 \pm 1.23$
	${}^{12}_{\Lambda\Lambda}\text{Be}$	${}^{14}\text{N}$	$22.23 \pm 1.15$	–
E176	${}^{13}_{\Lambda\Lambda}\text{B}$	${}^{14}\text{N}$	$23.3 \pm 0.7$	$0.6 \pm 0.8$
Danysz <i>et al</i> [17]	${}^{10}_{\Lambda\Lambda}\text{Be}({}^9_{\Lambda}\text{Be}^*)$	${}^{14}\text{N}$	$14.7 \pm 0.4$	$1.3 \pm 0.4$

Under the assumption that the  $\Xi^-$  hyperon is captured in an atomic  $3D$  state for the NAGARA and the MIKAGE events, the average values weighted by their errors for  $B_{\Lambda\Lambda}$  and  $\Delta B_{\Lambda\Lambda}$  of  ${}^6_{\Lambda\Lambda}\text{He}$  are:

$$\begin{aligned} B_{\Lambda\Lambda} &= 6.93 \pm 0.16 \text{ MeV,} \\ \Delta B_{\Lambda\Lambda} &= 0.70 \pm 0.17 \text{ MeV.} \end{aligned}$$

For consistency between the NAGARA and MIKAGE events, the  $\Xi^-$  hyperon is likely captured in a shallow level (*i.e.* smaller  $B_{\Xi^-}$ ) for the case of MIKAGE event.

Danysz *et al.* reported  $B_{\Lambda\Lambda}$  and  $\Delta B_{\Lambda\Lambda}$  to be  $17.7 \pm 0.4$  and  $4.3 \pm 0.4$  MeV, respectively. If one takes into account the excitation of the decay daughter of  ${}^9_{\Lambda}\text{Be}$ , those values decrease by the excitation energy (3.0 MeV) as listed in Table 4 [17]. The differences of  $B_{\Lambda\Lambda}$  and  $\Delta B_{\Lambda\Lambda}$  between the DEMACHIYANAGI event and the Danysz event may indicate the excitation energy of  ${}^{10}_{\Lambda\Lambda}\text{Be}^*$  nucleus to be  $2.8 \pm 0.4$  MeV.

We have an experiment (E07 at J-PARC) ready to improve our knowledge of the  $s = -2$  systems with ten times more events than before. The experimental setup is shown in Fig. 6.

In the experiment, nearly ten thousand events of  $\Xi^-$  stopping are located in three-times the volume of the E373 emulsion. The  $K^-$  beams (1.7 GeV/c) with  $K^-/\pi^- \geq 6$  are expected to be supplied at  $3 \times 10^5$   $K^-/\text{spill}(2 \text{ sec.})$  in 4.8 sec. cycle.

The ( $K^-, K^+$ ) reaction on a diamond target is tagged by the KURAMA spectrometer as in E373 and  $\Xi^-$  hyperons and scattered  $K^+$  mesons are reconstructed by DSSDs (Double-sided Silicon Strip Detectors). The upstream DSSDs should help uniquely locate the  $\Xi^-$  candidate track in the top emulsion plate.  $K^+$  tracks reconstructed by downstream DSSDs are followed up in the emulsion stack to locate ( $K^-, K^+$ ) reactions and the  $\Xi^-$  stopping point by following tracks down in the emulsion. SCIFI-Blocks are used to detect daughter tracks of hypernuclei and identify those particles by flight length (kinetic energy) and darkness (ionization). A typical detector like the Hyperball located upstream of the emulsion stack can be efficiently used to detect X-rays from strong capture reaction of  $\Xi^-$  hyperons during the sequential transition in atomic orbit. The  $\gamma$ -rays from the excitation of double- $\Lambda$  hypernuclei can be measured. We are able to treat just events which are identified as coming from a  $\Xi^-$  stopping in the emulsion; these photon measurements can be done with very low background. The experiment shall be carried out in the near future.

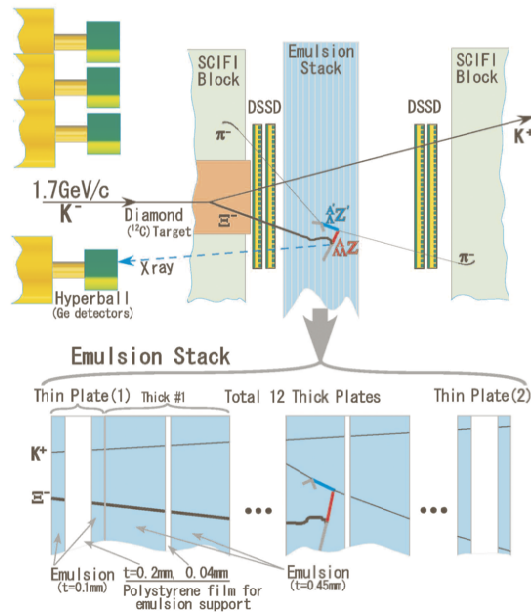


Figure 6: Setup of the E07 experiment at J-PARC.

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