# The nuclear double-strangeness experiments – achievments and perspectives –

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**Abstract**

Since the first sample of the double-$\Lambda$ hypernucleus was found, a slightly strong $\Lambda\Lambda$ interaction was circulated. Our E373 experiment(KEK-PS) presented an uniquly identified ${}^{6}_{\Lambda\Lambda}$He nucleus, so-called "NAGARA event", recently. The $\Lambda\Lambda$ interaction energy was obtained to be $1.01 \pm 0.20\ ^{+0.18}_{-0.11}$ MeV, which shows the attractive but weaker interaction. We are preparing an experiment providing ten times higher statistics than E373 as E964(BNL-AGS).

# 1 Introduction

The quantum chromodynamics (QCD) describes the atrong interaction between quarks, well. The characteristics, *e.g.* spin, parity and so on, of baryons which consists of three quarks is explained by phenomenological quark model. However, it is still difficult to derive the nuclear force from QCD.

As for the strangeness nuclear physics, the unified understanding of baryon-baryon interaction based on SU(3)$_{flavor}$ symmetry is one of the main purpose by the extension of our knowledge about nucleon-nucleon interaction. Especially, SU(3)$_{flavor}$ singlet state of two baryon system is informed only by the system with double strangeness ($S$=−2). Such system is closely related to the exsistence of $H$-dibaryon which was theoretically predicted by R.L. Jaffe [1]. If the predicted $H$-dibaryon is stable against strong interaction such as $H \rightarrow \Lambda\Lambda$, and if a seaquential weak decay can be seen in the double-$\Lambda$ hypernucleus, the mass of the $H$, $M(H)$, should be in the following region;

$$2M(\Lambda) > M(H) > 2M(\Lambda) \text{ - } B_{\Lambda\Lambda},$$

where the $B_{\Lambda\Lambda}$ is the binding energy of two $\Lambda$ hyperons in a nucleus.

In experimentally, more than 40 years ago, it was reported that an event in nuclear emulsion showed a sequential weak decay topology [2]. The event was appeared in four events which were expected to be occured by $\Xi^-$ hyperon captured at rest. In 1983, they decided the $\Lambda\Lambda$ interaction energy, $\Delta B_{\Lambda\Lambda}$, was 4.3±0.4 MeV [3]. The $\Delta B_{\Lambda\Lambda}$ is calcualated as $2B_\Lambda$ - $B_{\Lambda\Lambda}$, where $B_\Lambda$ is the binding energy of $\Lambda$ hyperon in nucleus. Three years later from the first report, the second report claimed that an uniquly identified ${}^{6}_{\Lambda\Lambda}$He nucleus was found and the $\Delta B_{\Lambda\Lambda}$ was obtained to be 4.6±0.5 MeV [4]. However, the authenticity of the second one was quite poor [3], because nobody checked the event in the emulsion and only hand-writing schematic drowing of the event was presented without topological data. In 1991, we succeeded to find a double-$\Lambda$ hypernucleus in ∼80 $\Xi^-$ stopping events with hybrid-emulsion method in the E176 experiment at KEK. We confirmed the exsistence of

double-$\Lambda$ hypernucleus which showed sequential weak decay. However, its interpretation of nuclide was not unique, unfortunately. One is ${}^{13}_{\Lambda\Lambda}$B nucleus and another is ${}^{10}_{\Lambda\Lambda}$Be nucleus. The $\Delta B_{\Lambda\Lambda}$ is +4.9±0.7MeV and −4.8±0.7MeV for ${}^{13}_{\Lambda\Lambda}$B and ${}^{10}_{\Lambda\Lambda}$Be, respectively [5]. By the trend of $\Delta B_{\Lambda\Lambda}\sim$5MeV, C.B. Dover claimed that would be an interesting theoretical problem in comparison with the strength of NN and $\Lambda$N interaction [6].

In nuclear $S$=−2 physics, the experimental information has been quite limited. An experiment to solve the interesting problem was started on 1995 to provide ten times higher statistics than that of E176. We introduce the experimental result of the experiment, E373 at KEK, which clarified the $\Delta B_{\Lambda\Lambda}$ for ${}^{6}_{\Lambda\Lambda}$He by the "NAGARA event". After that, it is also introduced the BNL-E964 experiment can be expected to provide a *mini-chart* of double-$\Lambda$ hypernuclei.

# 2 KEK-PS E373 experiment

The basic principle of the analysis in E373 was the detection and mass measurement of double-$\Lambda$ hypernuclei in the nuclear emulsion. The nucleus was emitted from the $\Xi^-$ stopping point, where the Q-value is 28 MeV in the reaction $\Xi^- p \rightarrow \Lambda\Lambda$. The $\Xi^-$ hyperons were produced via. quasi-free '$p$'(K$^-$, K$^+$)$\Xi^-$ reactions. We used diamond (20×20×35mm$^3$)as a target for the production of $\Xi^-$ hyperons due to its higher effective proton numbers. The higher density of the diamond target was also a merit to decelerate $\Xi^-$ hyperons.

The setup near the target is shown in Fig.1. The position and angle of $\Xi^-$ tracks on the top of the emulsion plate are reconstructed by a Scintillating-microfiber-bundle tracking detector, which is sandwiched in between the target and the emulsion stack. Scintillating-fiber blocks are used for the measurement of the energies of escaping particles from the emulsion stack by their ranges. The emulsion stack was installed in a vacuum chamber during beam exposure to keep the position between plate by plate. To locate tracks of $\Xi^-$ hyperons using fully-automated scanning system, a thin-coated emulsion plate is set at the top of the emulsion stack. We follow the $\Xi^-$ candidate tracks found in the top emulsion plate down to the thick-coated emulsion plates by a computer aided scanning system.

# 3 ${}^{6}_{\Lambda\Lambda}$He nucleus : "NAGARA event"

At 35% scanning of all of the data, an event showing sequential weak decay topology was found. The photograph and schematic drawing is shown in Fig.2. The $\Xi^-$ hyperon was captured by a light nucleus ($^{12}$C, $^{14}$N or $^{16}$O) in the emulsion at point A. From pont A, three charged particles (#1, #3 and #4) were emitted and one of them decayed with three charged particles (#2, #5 and #6) at point B. The prticle of track#2 also decayed into two chrged particles (#7 and #8) at point C. All of charged particles except for #5 and #7 stopped in the emulsion. Track#7 escaped the bottom emulsion plate and stopped in the downstream fiber block (D-Block). Track#5 stopped in an acrylic base film. Ranges and angles of all tracks were listed in Table1.

The topology of the event is clearly sequential decay of a double-$\Lambda$ hypernucleus. Therefore, we carried out the kinematical fitting at the production point A and the decay point B. All possible production and decay modes were checked and finally we succeeded to identify the nuclei, uniquely, as follows;

$$\begin{aligned} {}^{12}\mathrm{C} + \Xi^- &\rightarrow {}^{6}_{\Lambda\Lambda}\mathrm{He} + {}^{4}\mathrm{He} + t \\ {}^{6}_{\Lambda\Lambda}\mathrm{He} &\rightarrow {}^{5}_{\Lambda}\mathrm{He} + p + \pi^- \end{aligned}$$

As for the $B_{\Lambda\Lambda}$ and $\Delta B_{\Lambda\Lambda}$,

$$\begin{aligned} B_{\Lambda\Lambda} &= 7.25 \pm 0.19\ ^{+0.18}_{-0.11}\ \mathrm{MeV}, \\ \Delta B_{\Lambda\Lambda} &= 1.01 \pm 0.20\ ^{+0.18}_{-0.11}\ \mathrm{MeV}, \end{aligned}$$

where we assumed that the $\Xi^-$ hyperon was captured at the atomic 3D orbit of $^{12}$C. The binding energy of $\Xi^-$ hyperon is 0.13 $^{+0.21}_{-0.13}$ MeV. The mass of the $H$, $M_H$, was limited as $M_H > 2223.7$ MeV/c$^2$ (90% confidence level). This double-$\Lambda$ hypernucleus was reported as "NAGARA event" in the ref[7].

# 4 BNL-AGS E964 experiment

To obtain higher statistics with ten times as large as E373, we proposed a new hybrid-emulsion method. In E964, we must be able to study $S = -2$ system, systematically.

The experimental setup and the detail of the target area are shown in Figs.3 and 4, respectively. The K$^-$ beam ($p_{K^-}$=1.7 GeV/c) with a better K$^-/\pi^-$ ratio ($\geq 9$) is usable at AGS D-line. $\Xi^-$ hyperons via (K$^-$, K$^+$) reactions in a diamond target are coming to rest in emulsion stack. Scattered K$^+$ mesons are detected by the spectrometer system with KURAMA magnet which promises a large acceptance ($\sim$0.2 str.). The nuclear emulsion stack is sandwiched between two units of Double-sided SSD (DSSD) system. The upstream DSSD precisely reconstructs the tracks of $\Xi^-$ hyperon which are followed to the stopping point by a fully automated scanning system in the emulsion. K$^+$ mesons originated by (K$^-$, K$^+$) reactions in the emulsion are also reconstructed by the downstream DSSD. Scintillating-fiber (SCIFI) blocks cover the emulsion-DSSD system to measure energies of decay daughters from $S$=$-2$ systems and to detect in-flight decays of neutral particles, such as $\Lambda$ hyperons. Hyperball (12 sets of Ge detector) [8] is used to measure X- and $\gamma$-rays with good energy resolution ($\leq$keV), where those rays are emitted from $\Xi^-$-atoms and $S$=$-2$ nuclei formed in the emulsion.

# 5 Summary

In the E964 experiment, we expect to obtain $10^4$ stopping $\Xi^-$ events in the emulsion. Among those events, about $10^2$ $S$=$-2$ nuclei will be identified. A *mini-chart* of nuclides with $S$=$-2$ will be made for the first time. The masses and binding energies will be obtained without any ambiguity for, at least, several nuclides.

The $A$ dependence of the $\Lambda\Lambda$ interaction energy is, thus, provided for the first time. The measurements of the $A$ dependence and the decay modes of $S$=$-2$ nuclei will answer

the question on existence of the $H$ dibaryon near threshold, which may possibly appear as a mixed state with $\Lambda\Lambda-\Xi N-\Sigma\Sigma$.

In emulsion analysis, stopping $\Xi^-$ events are located. We precisely measure, for the first time, the energies of X-rays from $\Xi^-$ atoms for located events using Hyperball. The data of energy shifts and yields of X-rays will be definite information on the $\Xi$-nucleus potential, *ie.* the $\Xi N$ interaction.

We can expect more high statistics by one order of magnitude for $S=-2$ system with use of J-PARC machine in near future.

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Table 1: Ranges and emission angles of tracks. Ranges in the emulsion are listed for track#5 and #7. The range of #7 in D-Block is 13.1mm.

| point | track# | Range ($\mu$m) | $\theta$ (degree) | $\phi$ (degree) | |
|---|---|---|---|---|---|
| A | #1 | $8.1 \pm 0.3$ | $44.9 \pm 2.0$ | $337.5 \pm 1.8$ | Double$\Lambda$ |
| | #3 | $3.2 \pm 0.4$ | $57.7 \pm 5.2$ | $174.9 \pm 2.9$ | |
| | #4 | $88.6 \pm 0.5$ | $156.2 \pm 0.5$ | $143.0 \pm 1.0$ | |
| B | #2 | $9.1 \pm 0.3$ | $77.7 \pm 1.6$ | $115.9 \pm 0.8$ | Single$\Lambda$ |
| | #5 | $82.1 \pm 0.6$ | $122.8 \pm 1.0$ | $284.2 \pm 0.7$ | Stop in the base |
| | #6 | 13697 | $81.0 \pm 0.5$ | $305.5 \pm 0.2$ | $\pi^-$ |
| C | #7 | $742.6 \pm 0.6$ | $138.5 \pm 0.2$ | $322.1 \pm 0.3$ | Stop in D-Block |
| | #8 | $5868 \pm 20$ | $52.2 \pm 1.2$ | $123.7 \pm 0.7$ | Scattered before stopping |

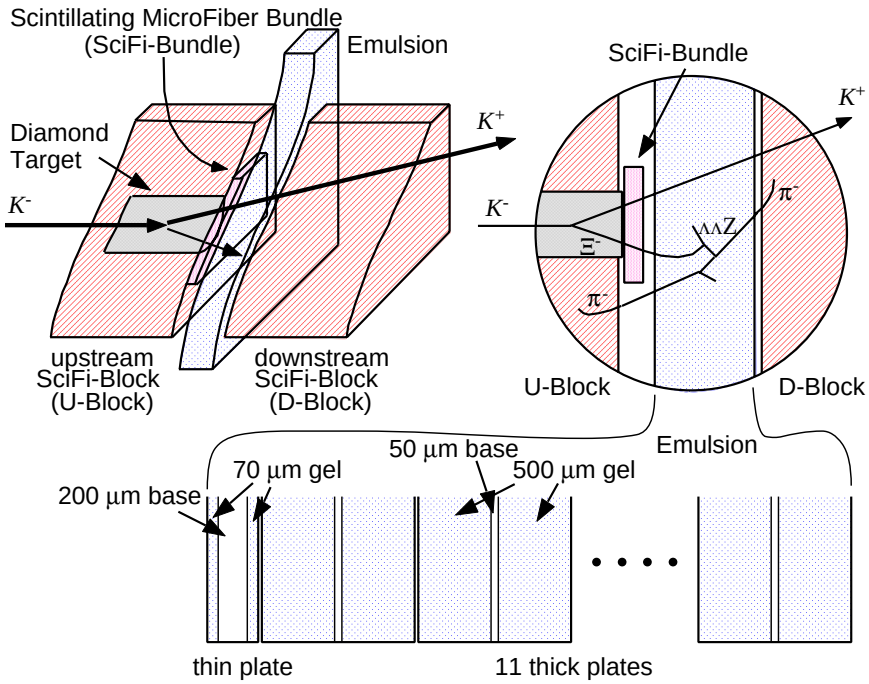


Figure 1: Setup around the target of the E373 experiment

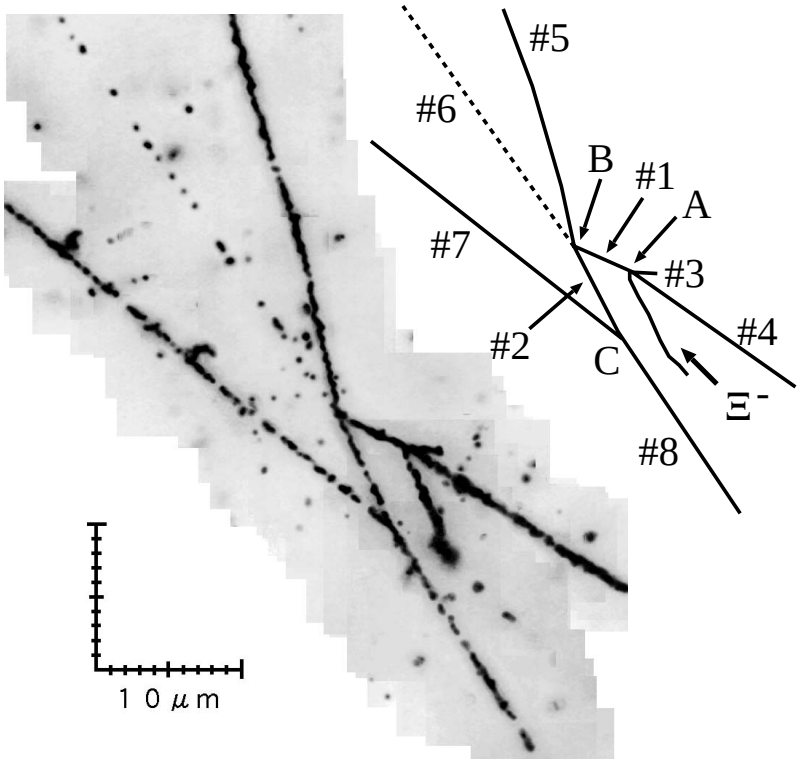


Figure 2: Photograph and schematic drawing of "NAGARA event".

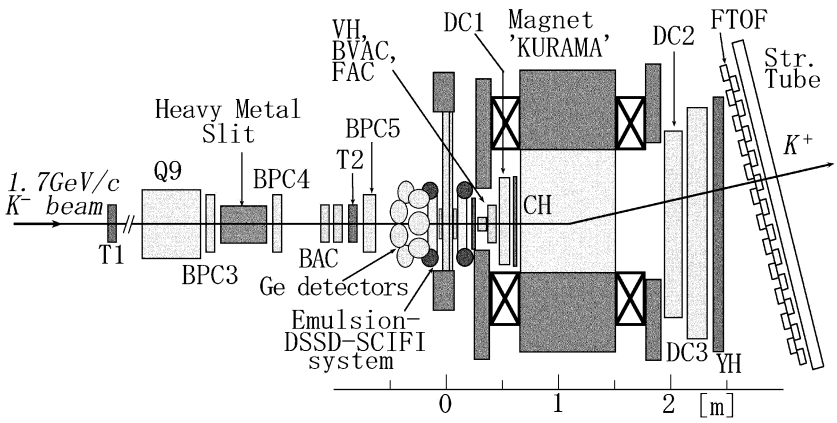


Figure 3: Experimental setup of AGS-E964 (BNL).

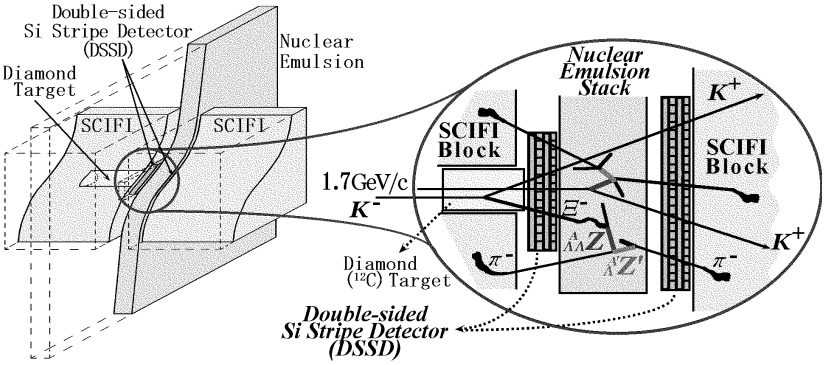


Figure 4: Photograph and schematic drawing of "NAGARA event".

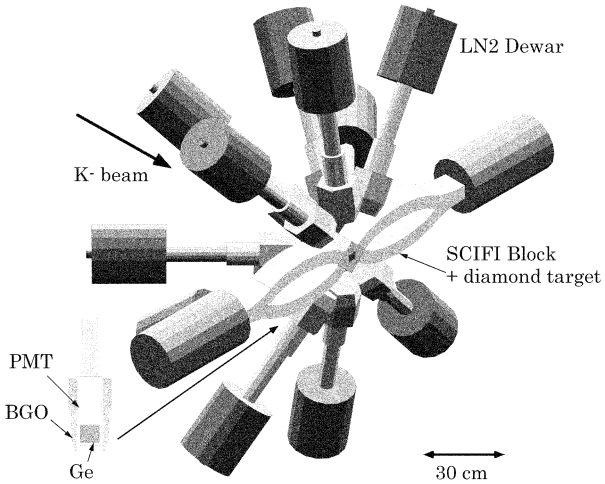


Figure 5: Photograph and schematic drawing of "NAGARA event".