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Abstract
KEK-PS E373, a hybrid emulsion experiment, was performed using a 1.66 GeV/c separated K^- meson beam at High Energy Accelerator Research Organization (KEK) proton synchrotron (PS). The purpose of this experiment is to study S = -2 nuclei produced via Ξ^- hyperon captured at rest in nuclear emulsion. We have completed the analysis of about 90% of total emulsion data, among which we have successfully observed seven events of double-Λ hypernucleus and two events of the production of twin Λ-hypernuclei. We succeeded to find the production and the decay of a \(_{\Lambda\Lambda}^6\)He nucleus. The value of \(\Lambda-\Lambda\) interaction energy, \(\Delta B_{\Lambda\Lambda}\), for double-Λ hypernucleus event#7 was \(-0.5 \pm 1.2\) MeV which is consistent with the result given by "NAGARA event" (event#2).

Key words: double-Λ hypernucleus, binding energy of two \(\Lambda\) hyperons, \(\Lambda-\Lambda\) interaction energy

Introduction
The experiment E373 was carried out at KEK-PS using a 1.66 GeV/c separated K^- meson beam with an upgraded hybrid-emulsion technique. The experimental purpose was to study nuclei with two units of strangeness (S = -2), i.e, double- Λ hypernucleus, twin Λ- hypernuclei, and the \(H\)-dibaryon, produced via Ξ^- hyperon capture at rest in the emulsion with ten time statistics (~10^3 Ξ^- hyperon stopping events) than those of the previous experiment (~80 Ξ^- hyperon stopping events in the E176 experiment). In this experiment, Ξ^- hyperons produced in a diamond target via quasi-free (K^-, K^+) reactions. A schematic view around the target region is shown in Fig. (1).
The $\Xi^-$ hyperons were brought to rest, captured by nucleus and could form compound nucleus with $S = -2$ in the emulsion. At the decay of the nucleus, a double-$\Lambda$ hypernucleus, twin-$\Lambda$–hypernuclei, single-$\Lambda$ hypernucleus or $H$-dibaryon (if exist) is emitted, in some case, as shown in Fig. (2).

The existence of double-$\Lambda$ hypernucleus is of very interest because it gives valuable information on $\Lambda$–$\Lambda$ interaction and is deeply related to nuclear system with double strangeness ($S = -2$ system) such as $\Xi^-$ hypernucleus and an $H$-particle. The binding energy of two $\Lambda$ hyperons, $B_{\Lambda\Lambda}$, and the $\Lambda$–$\Lambda$ interaction energy, $\Delta B_{\Lambda\Lambda}$, can be obtained from the measurement of the masses of double-$\Lambda$ hypernucleus. The $B_{\Lambda\Lambda}$ and the $\Delta B_{\Lambda\Lambda}$ can be written as

$$B_{\Lambda\Lambda}(^{\Lambda\Lambda}Z) = M(^{\Lambda\Lambda}Z) + 2M(\Lambda) - M(^{\Lambda\Lambda}Z),$$

$$\Delta B_{\Lambda\Lambda}(^{\Lambda\Lambda}Z) = B_{\Lambda\Lambda}(^{\Lambda\Lambda}Z) - 2B_{\lambda}(^{\Lambda\lambda}Z).$$

In the 20th century, double-$\Lambda$ hypernucleus events were reported by three experimental groups with nuclear emulsion. In 1963, Danysz et al. reported an event of the sequential weak decay of a double-$\Lambda$ hypernucleus (Danysz, 1963). It was interpreted as $^{10}_{\Lambda\Lambda}\text{Be}$ nucleus with $B_{\Lambda\Lambda} = 17.7 \pm 0.4$ and $\Delta B_{\Lambda\Lambda} = 4.3 \pm 0.4$ MeV in reanalysis.
Fig. (2). Production process of double-$\Lambda$ hypernucleus, twin-$\Lambda$ hypernuclei, single-$\Lambda$ hypernucleus and the $H$-dibaryon via $\Xi^-$ hyperon capture at rest.

In 1966, the event reported by Prowse claimed that a $\Lambda^6$He nucleus was uniquely identified in the emulsion. The $B_{\Lambda \Lambda}$ and $\Delta B_{\Lambda \Lambda}$ were presented to be $10.9 \pm 0.8$ and $4.6 \pm 0.5$ MeV, respectively (Prowse, 1966). However, for this event, only the schematic drawing was given and measured angles
were not presented in the literature. In 1980's, an emulsion counter hybrid experiment, the E176 experiment was carried out at the KEK 12GeV Proton Synchrotron (KEK-PS) to study double strange- ness nuclei. They confirmed the existence of a double-Λ hypernucleus in nearly 80 events of Ξ⁻ hyperon capture at rest. Unfortunately, identification of the nuclear species of the double-Λ hypernucleus was not unique. An interpretation is a $^{10}_{\Lambda\Lambda}$Be nucleus with $ΔB_{LL} = -4.9 ± 0.7$ MeV and another one is a $^{13}_{\Lambda\Lambda}$B nucleus with $ΔB_{LL} = 4.9 ± 0.7$ MeV (Aoki, 1991). The above three emulsion experiments led the $ΔB_{LL}$ value to be 4~5 MeV which should show strongly attractive Λ-Λ interaction, while $ΔB_{LL} = -4.9$ MeV expressed by E176 pointed out the repulsive Λ-Λ interaction.

In E373 experiment, we have detected 7 double-Λ hypernu- cleus and 2 twin Λ-hypernuclei events. Among them, “NAGARA event” was uniquely identified as sequential weak decay of a $^{6}_{\Lambda\Lambda}$He nucleus. The process of the production and decay was

$$\Xi^- + ^{12}_{\Lambda\Lambda}C \rightarrow ^{6}_{\Lambda\Lambda}He + ^4_{\Lambda\Lambda}He + t, \ ^{6}_{\Lambda\Lambda}He \rightarrow ^5_{\Lambda\Lambda}He + p + \pi^-.$$  

The event provided the Λ-Λ interaction energy as $ΔB_{LL} = 1.01 ± 0.20^{+0.18}_{-0.11}$ MeV which would show the interaction to be weakly attractive (Takahashi, 2001). In this paper, the analysis of a newly found event with a double-Λhypernucleus is presented.

**Analysis**

**Event Description**

A photograph and schematic drawing of the 7th double-Λ hypernucleus event is shown in Fig. (3). The Ξ⁻ hyperon came to rest at point A with three charged particles (track #1, #3 and #4). The particle of track#1 decayed into two charged particles (track#2 and #5) at point B. Again, the particle of track#2 decayed into three charged particles (track#6, #7 and #8) at point C. This event was found in the pl#8 (down stream of the plate) of Mod#91. The particles of tracks #7 and #8 were stopped in the upstream of pl#9. Among them, an auger electron was emitted from the stop point of track#7 as shown in Fig. (4). The particle of track#7 can be
interpreted as a negative charged $\pi^-$ meson track due to the emission of the auger electron.

Fig. (3): A photograph and schematic drawing of Double-$\Lambda$ Hypernucleus Event

Fig. (4): A photograph of track#7 at its stop point

Range and angle measurement

We measured the range and angle of tracks in the double-$\Lambda$ hypernucleus event. The length of the track was measured by pointing the track’s edges on a computer display with a mouse device in microscope system which is shown in Fig. (5). We obtained the range, $R$, from $x$, $y$ and $z$ coordinates using the equation

$$ R = \sqrt{\Delta x^2 + \Delta y^2 + (\Delta z \cdot S)^2}, $$

where, the $S$ express as the shrinkage factor calculated from the thickness ratio of the plate at the time of the beam exposure and this measurement. $\Delta x$, $\Delta y$ and $\Delta z$ are the lengths of the tracks in the $x$, $y$ and $z$ direction, respectively.
Fig. (5). A photograph of the microscope system

To obtain the emission angle of tracks, we measured the x, y and z coordinates at each point as shown in Fig. (6). We deduced the zenith angle ($\theta$) with respect to the direction perpendicular to the plate and azimuthal angle ($\phi$). The ranges and emission angles of all tracks are shown in Table (1).

Fig. (6): A schematic drawing of double-$\Lambda$ hyper nucleus event with red colour cross where we clicked to obtain x, y, z coordinates of tracks to deduce emission angle of tracks.
Table (1) Range and emission angle of tracks in double-Λ hypernucleus event. All the lengths of tracks are visible ones in emulsion.

<table>
<thead>
<tr>
<th>Point</th>
<th>Track#</th>
<th>Range (μ m)</th>
<th>θ (degree)</th>
<th>φ (degree)</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>#1</td>
<td>5.9 ± 0.3</td>
<td>112.8 ± 7.1</td>
<td>84.7 ± 1.5</td>
<td>Double-Λ hypernucleus</td>
</tr>
<tr>
<td></td>
<td>#3</td>
<td>1.3 ± 0.1</td>
<td>91.5 ± 3.8</td>
<td>221.1 ± 6.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>#4</td>
<td>1.5 ± 0.2</td>
<td>88.7 ± 3.4</td>
<td>171.6 ± 6.7</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>#2</td>
<td>2.2 ± 0.5</td>
<td>128.2 ± 14.7</td>
<td>346.7 ± 4.4</td>
<td>Single-Λ hypernucleus</td>
</tr>
<tr>
<td></td>
<td>#5</td>
<td>55.2 ± 0.7</td>
<td>56.0 ± 1.2</td>
<td>101.6 ± 0.3</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>#6</td>
<td>28.9 ± 0.3</td>
<td>99.9 ± 3.3</td>
<td>80.3 ± 0.3</td>
<td>π⁻</td>
</tr>
<tr>
<td></td>
<td>#7</td>
<td>388.8 ± 1.4</td>
<td>137.9 ± 1.3</td>
<td>272.6 ± 0.3</td>
<td>π⁻</td>
</tr>
<tr>
<td></td>
<td>#8</td>
<td>676.1 ± 1.4</td>
<td>119.4 ± 1.5</td>
<td>252.5 ± 0.1</td>
<td></td>
</tr>
</tbody>
</table>

**Event Reconstruction**

Event reconstruction in emulsion is based on the conservation laws of energy and momentum, and the masses of hypernuclei are calculated from the energies of their decay daughters. The kinetic energy of each charged particle was calculated from its range, where the range-energy relation was calibrated using a decays of thorium series in the emulsion. The single-Λ hypernucleus (track#2) was reconstructed at point C. For the decay mode with neutron(s) emission, the kinetic energies of the neutron(s) were calculated from the momentum valance. The sum of the kinetic energies of the charged and neutral particles is referred to as the total energy release, $E_{total}$. We calculated the possible decay modes of single-Λ hypernucleus by comparing with $E_{total}$ and Q-value. The possible decay modes of single-Λ hypernucleus (track#2) are expressed in Table (2).
Table (2) Possible decay mode of single hypernucleus

<table>
<thead>
<tr>
<th>Single- ( \Lambda ) Hypernucleus</th>
<th>#6</th>
<th>#7</th>
<th>#8</th>
<th>Neutron(s)</th>
<th>Q-value (MeV)</th>
<th>( E_{\text{total}} ) (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( ^4 \Lambda \text{H} )</td>
<td>p</td>
<td>( \pi^- )</td>
<td>p</td>
<td>2n</td>
<td>27.3</td>
<td>&gt;22.0</td>
</tr>
<tr>
<td>( ^6 \Lambda \text{He} )</td>
<td>( ^4 \text{He} )</td>
<td>( \pi^- )</td>
<td>p</td>
<td>1n</td>
<td>34.6</td>
<td>33.6±1.7</td>
</tr>
<tr>
<td>( ^7 \Lambda \text{He} )</td>
<td>( ^4 \text{He} )</td>
<td>( \pi^- )</td>
<td>p</td>
<td>2n</td>
<td>29.9</td>
<td>&gt;27.6</td>
</tr>
<tr>
<td>( ^8 \Lambda \text{He} )</td>
<td>( ^4 \text{He} )</td>
<td>( \pi^- )</td>
<td>p</td>
<td>3n</td>
<td>30.2</td>
<td>&gt;25.6</td>
</tr>
</tbody>
</table>

At point B, we checked the kinematics of all possible decay modes of the double-\( \Lambda \) hypernucleus (track\#1) which decayed into a single-\( \Lambda \) hypernucleus listed in Table (2). We calculated \( B_{\Lambda \Lambda} \) and \( \Delta B_{\Lambda \Lambda} \) of the double-\( \Lambda \) hypernucleus assuming its decay after stopping. We considered also for one of the mesonic decay modes, \( \Lambda \rightarrow n\pi^0 \) case. The possible decay modes of the double-\( \Lambda \) hypernucleus for \( \Delta B_{\Lambda \Lambda} > -20 \) MeV are listed in Table (3).

Table (3) Possible decay modes of the double-\( \Lambda \) hypernucleus. The errors on \( B_{\Lambda \Lambda} \) and \( \Delta B_{\Lambda \Lambda} \) are not included in those of the binding energies of single-\( \Lambda \) hypernuclei. Only the cases of \( \Delta B_{\Lambda \Lambda} > 20 \) MeV are listed.

<table>
<thead>
<tr>
<th>Double- ( \Lambda ) Hypernucleus</th>
<th>#2</th>
<th>#5</th>
<th>Neutron(s)</th>
<th>( \pi^0 )</th>
<th>( B_{\Lambda \Lambda} ) (MeV)</th>
<th>( \Delta B_{\Lambda \Lambda} ) (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( ^6 \Lambda \text{He} )</td>
<td>( ^4 \text{He} )</td>
<td>p</td>
<td>1n</td>
<td>( \pi^0 )</td>
<td>&lt;19.34</td>
<td>&lt;13.1</td>
</tr>
<tr>
<td>( ^6 \Lambda \text{He} )</td>
<td>( ^4 \text{He} )</td>
<td>d</td>
<td></td>
<td>( \pi^0 )</td>
<td>-5.56±2.2</td>
<td>-11.8±2.2</td>
</tr>
<tr>
<td>( ^7 \Lambda \text{He} )</td>
<td>( ^4 \text{He} )</td>
<td>p</td>
<td>2n</td>
<td>( \pi^0 )</td>
<td>&lt;155.76</td>
<td>&lt;147.4</td>
</tr>
<tr>
<td>( ^7 \Lambda \text{He} )</td>
<td>( ^4 \text{He} )</td>
<td>p</td>
<td>2n</td>
<td>( \pi^0 )</td>
<td>&lt;20.86</td>
<td>&lt;12.5</td>
</tr>
<tr>
<td>( ^7 \Lambda \text{He} )</td>
<td>( ^4 \text{He} )</td>
<td>d</td>
<td>1n</td>
<td>( \pi^0 )</td>
<td>&lt;19.26</td>
<td>&lt;10.9</td>
</tr>
<tr>
<td>( ^8 \Lambda \text{Li} )</td>
<td>( ^8 \text{He} )</td>
<td>p</td>
<td></td>
<td>( \pi^0 )</td>
<td>&lt;19.8</td>
<td>6.2±3.9</td>
</tr>
</tbody>
</table>
The $\Xi^-$ hyperon was assumed to be absorbed by a light emulsion nuclei ($^{12}\text{C}$, $^{14}\text{N}$ or $^{16}\text{O}$) at point A. The values of $B_{\Lambda\Lambda}$ and $\Delta B_{\Lambda\Lambda}$ were calculated from the mass of the double-$\Lambda$ hypernucleus assuming that it was produced in the ground state and binding energy of $\Xi^-$ hyperon ($B_{\Xi^-}$) was zero. The possible production mode of double-$\Lambda$ hypernucleus are listed in Table (4). 

Table (4) Possible production modes of the double-$\Lambda$ hypernucleus. Only the cases of $\Delta B_{\Lambda\Lambda}<20$ MeV are listed.

<table>
<thead>
<tr>
<th>Target</th>
<th>Track#1</th>
<th>Track#3</th>
<th>Track#4</th>
<th>Neutron(s)</th>
<th>$B_{\Lambda\Lambda}$(MeV)</th>
<th>$\Delta B_{\Lambda\Lambda}$(MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{12}\text{C}$</td>
<td>$^6\text{He}$</td>
<td>$^4\text{He}$</td>
<td>p</td>
<td>2n</td>
<td>$&gt;14.24$</td>
<td>$&gt;8.0$</td>
</tr>
<tr>
<td>$^{12}\text{C}$</td>
<td>$^6\text{He}$</td>
<td>p</td>
<td>$^4\text{He}$</td>
<td>2n</td>
<td>$&gt;16.14$</td>
<td>$&gt;9.9$</td>
</tr>
<tr>
<td>$^{12}\text{C}$</td>
<td>$^6\text{He}$</td>
<td>$^4\text{He}$</td>
<td>d</td>
<td>1n</td>
<td>$16.84 \pm 0.8$</td>
<td>$10.6 \pm 0.8$</td>
</tr>
<tr>
<td>$^{12}\text{C}$</td>
<td>$^6\text{He}$</td>
<td>d</td>
<td>$^4\text{He}$</td>
<td>1n</td>
<td>$19.94 \pm 1.2$</td>
<td>$13.7 \pm 1.2$</td>
</tr>
<tr>
<td>$^{14}\text{N}$</td>
<td>$^6\text{He}$</td>
<td>$^4\text{He}$</td>
<td>1n</td>
<td></td>
<td>$5.74 \pm 1.2$</td>
<td>$-0.5 \pm 1.2$</td>
</tr>
<tr>
<td>$^{12}\text{C}$</td>
<td>$^7\text{He}$</td>
<td>$^4\text{He}$</td>
<td>p</td>
<td>1n</td>
<td>$20.76 \pm 0.9$</td>
<td>$12.4 \pm 0.9$</td>
</tr>
</tbody>
</table>

According to the comparison of the values of $B_{\Lambda\Lambda}$ and $\Delta B_{\Lambda\Lambda}$ obtained from point A and B, the most probable interpretation of the event is

$$\Xi^- + ^{14}\text{N} \rightarrow ^{6}\Lambda\Lambda\text{He} + ^4\text{He} + ^4\text{He} + 1\text{n},$$

$$^{6}\Lambda\Lambda\text{He} \rightarrow ^4\Lambda\text{He} + p + 1\text{n} + \pi^0.$$ 

The double-$\Lambda$ hypernucleus event #7 can be interpreted as the production and sequential weak decay of a $^6\Lambda\Lambda\text{He}$ nucleus. The value of $\Lambda-\Lambda$ interaction energy for double-$\Lambda$ hypernucleus event #7 obtained from production point A was $-0.5 \pm 1.2$ MeV which is consistent with the result given by “NAGARA event” within the errors. It is important to find more double-$\Lambda$ hypernucleus events to determine the value of $\Delta B_{\Lambda\Lambda}$ uniquely.
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