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Letter

Charge identification of low-energy particles for double-strangeness nuclei in nuclear emulsion

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A development has been achieved in the identification method of the charges 1 to 5 of nuclides from the decay of double hypernuclei to be uniquely recognized by their nuclear species. The method is basically the measurement of track volume by the widths, depths, and angles of tracks of exposed nuclei of ^{1}H, ^{4}He, ^{7}Li, ^{9}Be, and ^{11}B in nuclear emulsion at RIken Projectile-fragment Separator of RIKEN Radioactive Isotope Beam Factory. After their calibration by α particles, we obtained a quadric function to present a unified recognition of tracks with volume ratios of five nuclei to the α particles. The function in the emulsion has been applied to a candidate event of a Ξ hypernucleus for identification of the production and decay processes. We succeeded in recognizing a daughter nuclear fragment of a single-Λ hypernucleus as ^{6}He with a likelihood ratio of 0.9; the process was then uniquely identified as $\Xi^- + {}^{14}\text{N} \rightarrow {}_{\Lambda}{}^{9}\text{Be} + {}_{\Lambda}{}^{5}\text{He} + n$.

Subject Index H14

1. *Introduction* Double hypernuclei such as double-Λ and Ξ hypernuclei play an important role in the understanding of multi-strangeness systems. Neutron stars provably contain hyperons (Y) under denser conditions than nuclei. In such matter, interactions of Λ–Λ and Ξ–nucleon (N) perform crucial functions. Furthermore, the coupling effect of two systems by Λ–Λ and ΞN shall appear due to the small mass difference of at most 30 MeV between them.

Although we have performed hybrid experiments of E176 and E373 at KEK with nuclear emulsion for nearly 30 years, it has not been so easy to report unified information on the interaction of Λ–Λ and ΞN. The NAGARA [1,2] and KISO events [3] of limited nuclear species are unique samples of double-Λ and Ξ hypernuclei, respectively, even though they give us reliable information of Λ–Λ and ΞN interaction. In 12 samples of double hypernuclei, exclusive identifications were not made for each nuclide due to there remaining a few possibilities for the charge of the decay daughter fragments from the hypernuclei, even if we applied kinematical analysis to their production and decay sequences.

In the J-PARC E07 experiment, we expect to detect about 100 double hypernuclei [4]. Furthermore, by applying the overall scanning method [5], around 1000 events of double hypernuclei will be detected. However, the number of events with unique interpretations will decrease to nearly 10% of them just through kinematical analysis. To obtain several times more information than before, it is necessary to develop a charge identification method for the daughter fragments.

A study of the charge identification was performed for ^{3}He, ^{7}Li, ^{9}Be, ^{11}B, and ^{12}C with the emulsion chamber at Heavy Ion Medical Accelerator in Chiba (National Institute of Radiological Sciences). The experimental result was that the charges of each nuclide were well recognized by more than 2.3 standard deviations [6]. However, their energy was around 290 MeV/u, which is too large for the study of double hypernuclei because the Q values for the decay processes are at most 180 MeV and 40 MeV for non-mesonic and mesonic decays, respectively.

In an experiment at Tandem Laboratory of Kyoto University, three nuclides of ^{1}H (13 MeV), ^{4}He (19.5 MeV), and ^{7}Li (26 MeV) were exposed horizontally to the emulsion surface. Track volume, which will be reflected by energy loss in the emulsion, from the stopping point was measured for four tracks in each nuclide, and recognition was obtained over 3σ at a measured track length of 50 μm [7]. It was found that track volume measurement was one effective way to identify the charge.

To make this method fit for practical application, however, more careful and systematic study was required. Through optical microscopy to obtain image of tracks, it was found that the tracks have different volumes in the same charged tracks with varying angles in the emulsion due to halos from the non-focal plane. Furthermore, sheet-by-sheet calibration of the emulsion is necessary, depending on the photographic development conditions.

We have developed a method to measure the charge from 1 to 5 of nuclides with track lengths around 100 μm from their stopping points, independent of angle and photographic development conditions. The method consists of track width measurement with a graphics processing technique and its calibration with α particles. We have tested the effectiveness of the method on a candidate event of a Ξ hypernucleus detected in the E373 experiment.

2. *Emulsion exposure with several nuclei* An experiment was carried out at RIken Projectile-fragment Separator (RIPS) [8] of RIKEN Radioactive Isotope Beam Factory (RIBF) to develop the method. The nuclear emulsion sheet consisted of 0.5 mm thick emulsion coated on both sides of a polystyrene film of 0.04 mm thickness. Its size was 30×70 mm^2. Eight nuclear species with charges from 1 to 5 as ^{1}H (29 MeV/u), ^{2}H (20 MeV/u), ^{3}H (14 MeV/u), ^{3}He (34 MeV/u), ^{4}He (34 MeV/u), ^{7}Li (34 MeV/u), ^{9}Be (38 MeV/u), and ^{11}B (43 MeV/u) were exposed to each emulsion stack composed of six sheets. An emulsion stack was angled to the incident beam of the nuclei at $\theta \approx 25°$, 50°, and 75°, as shown in Fig. 1, to measure the angle dependence of the track width.

3. *Development of the method to recognize charge of nuclei in z = 1–5* To obtain clear recognition of the charges from 1 to 5, we have studied five nuclear species, ^{1}H, ^{4}He, ^{7}Li, ^{9}Be, and ^{11}B, among the eight exposed nuclei.

3.1. *Track width measurement with image processing technique*

The procedure of our image processing technique for measuring track width is shown in Fig. 2. Raw images were taken by a microscope with a 100× objective lens and 8 bit CCD camera, where the

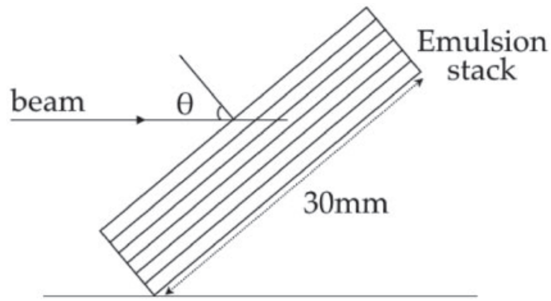

Fig. 1. The emulsion stack was tilted at various angles θ along the beam direction.

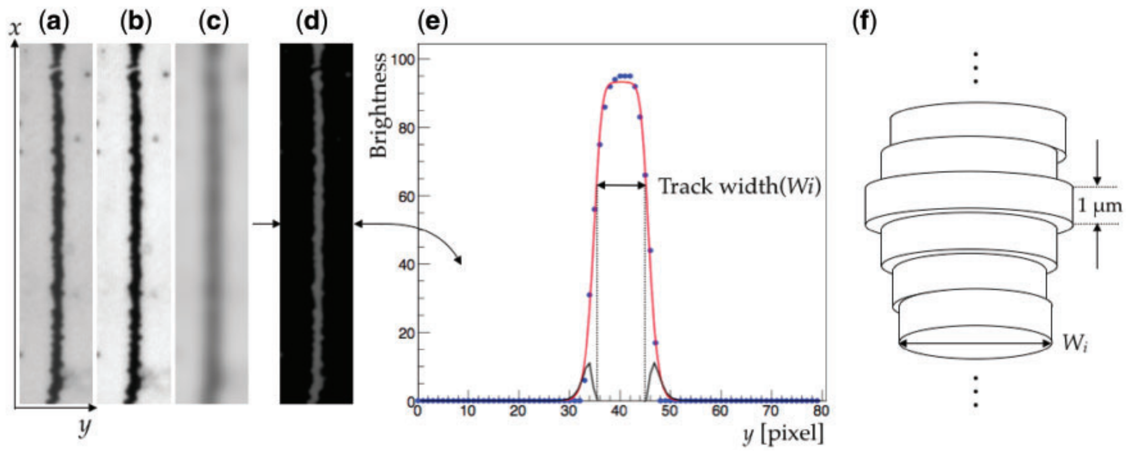

Fig. 2. The image processing procedure to get track volume with uniform background for the track image. (a) A focused image, (b) a contrast enhancement image, (c) a blurred image, (d) an image produced by subtraction of (b) from (c), (e) brightness of one pixel line of image (d) along the y axis. In (e), the red line is the fitting result with the function denoted in the text. The black line is given as a second derivative of the red line. (f) Schematic drawing of a track, which is assumed to be an aggregation of many cylinders with width of W_i and height of 1 μm.

pixel size of an image was $0.080(x) \times 0.080(y)\ \mu\text{m}^2$. During image taking, the light intensity of the microscope was set to a mean brightness of 200 in an image with $512(x) \times 440(y)$ pixels. A focused image as shown in Fig. 2(a) consists of the most focused layers of raw images. A contrast enhancement image, (b), was made according to the following equation: $B_{\text{out}} = 255 \times (B_{\text{in}} - B_{\text{min}})/(B_{\text{max}} - B_{\text{min}})$, where B_{in}, B_{max}, and B_{min} are the brightness of each pixel, the maximum and the minimum brightness in image (a), respectively. The value of 255 is the maximum brightness of 8 bits. The brightness in each pixel, B_{in}, was enhanced to B_{out}. Figure 2(c) shows a Gaussian blurred image [5,9] of (b). Then a uniform background image was obtained by subtraction of (b) from (c) as shown in Fig. 2(d). We measured brightness perpendicular to the track in image (d), and defined the track width as the distance between two inflection points, which were obtained by applying a fitting function, $f = a \times \tanh(\text{gauss}(x, \mu, \sigma))$, to the data in Fig. 2(e). A track is assumed to consist of many cylinders, as shown in Fig. 2(f). The volume of a cylinder can be given by a track width of W_i and its height of 1 μm. We got the track volume by summing up the cylinders.

3.2. *Calibrations and track volume measurement*

We did not take into account 10 μm from the stopping point, because of difficulties with the recognition of charge via narrowing of the width due to electron capture by nuclei. Therefore, the volume

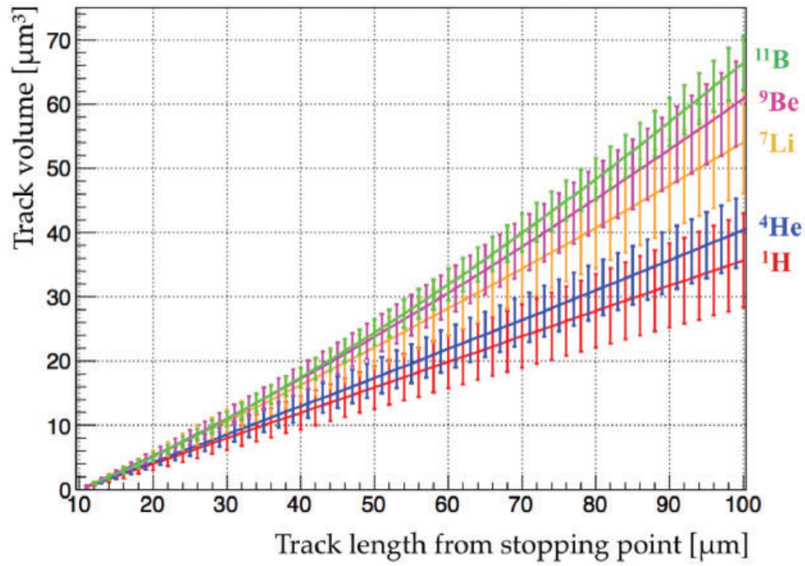

Fig. 3. Measurement track volumes for each nucleus at various depths in the emulsion. The error bar represents one standard deviation of the volume distribution.

was measured in the range of 10–100 μm from the stopping point. Figure 3 shows the average volumes for 100 tracks with $\theta \approx 75°$ for each nucleus measured at various depths in the emulsion. Although the gap seen between ^{4}He and ^{7}Li seems to appear due to the difference of M/z^2, where M is the mass in units of the proton mass and z is the charge number of the nucleus, charge recognition can be so difficult because the volumes for nuclei overlap with each other.

As a calibration source, α particles of decay daughters from a natural isotope of ^{212}Po with monochromatic 8.78 MeV were also measured from the stopping points with 1 μm steps along the track. Although it is desirable that the angle θ of track of the α particle is nearly 90°, where θ is presented with the same definition of the incident beam, their angles in the measured area were 90–70° close to the stopping points. The volumes of α particles with such angles are plotted in relation to the depth in Fig. 4. The line in Fig. 4 shows the calibration function with an assumption of a linear function of $v^\alpha(d) = \mathrm{A} + \mathrm{B}d$, where v^α is average track volume of α particles at the depth, d, from the emulsion surface.

To get the best calibration function, we searched for minimum values of σ_A and σ_B as one standard deviation errors for A and B, respectively, within an angle range of 90–70° of α particles. We took into account $v^\alpha(d)$ by gradually broadening the angle range by 0.5° from 90°. In Fig. 5, the values of σ_A and σ_B were plotted respecting the angle range. The plotted data were fitted with cubic functions and the minimum values of σ_A and σ_B were given in the angle range from 90° to 74°, where the calibration function was expressed as $v^\alpha(d) = (0.465 \pm 0.010) - (3.927 \pm 0.475) \times 10^{-4} d$ with 68 α particles.

Regarding nuclear tracks to be recognized for their charges, the widths were measured in every 1 μm cell along the tracks. Since the depth on the measured cells changes along the track, a volume ratio normalized by an α particle, V_r^α, for each nucleus can be obtained with the measured volume, V_i, in the ith cell as $V_r^\alpha = \sum_{i=1}^{90} V_i / \sum_{i=1}^{90} v^\alpha(d_i)$, where d_i is the depth of the ith cell.

It is noted that the angle also changes in each cell; then the representative angle, θ, for each nucleus is obtained as the average value of the angles for 90 cells. Calibrated volume data of 200 tracks for each nucleus are shown in Fig. 6(a). We put together four areas, and fitted them respecting

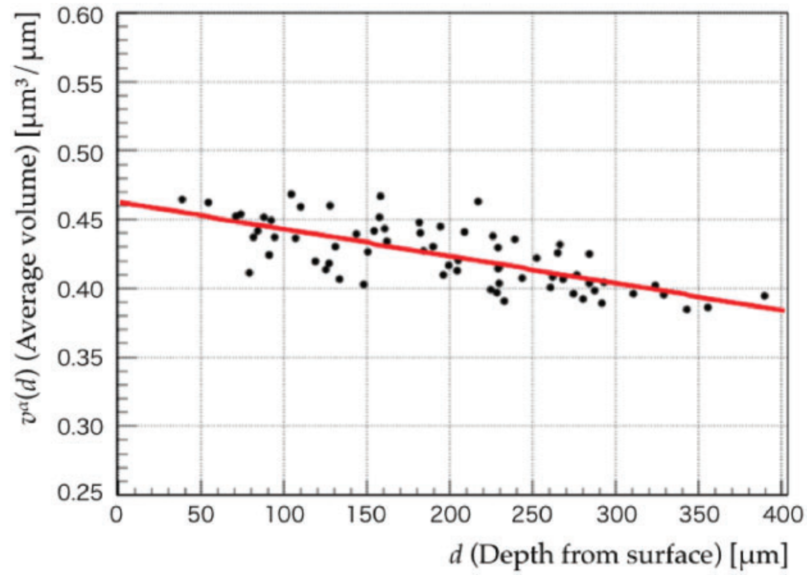

Fig. 4. The track volume of α particles along the depth from the emulsion surface.

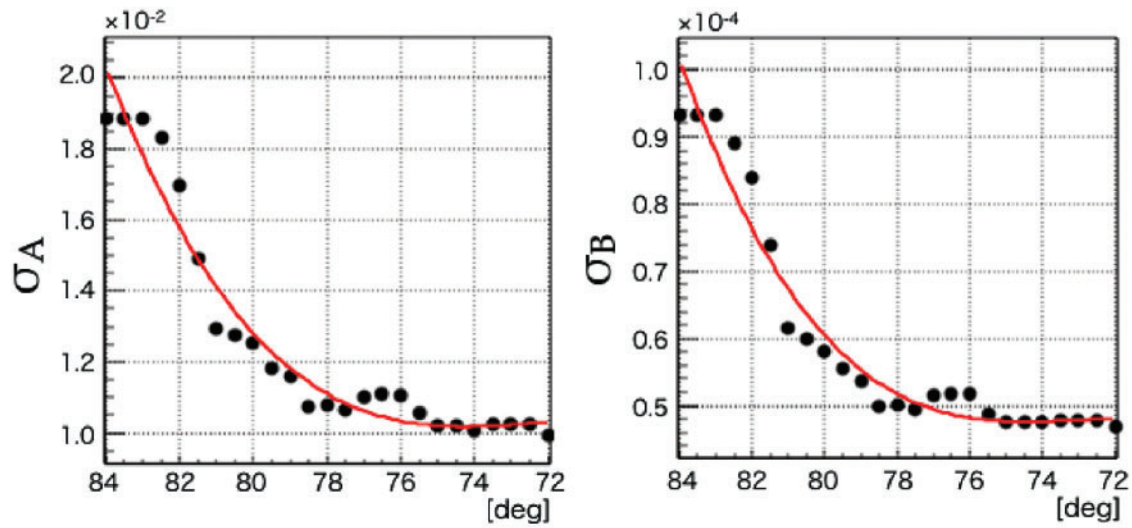

Fig. 5. Values of σ_{A} and σ_{B} in the angle range from 90° to 72°.

Table 1. Parameters of the linear function, $V_r^{\alpha}(\xi) = \mathrm{C} + \mathrm{D}\xi$, for each nucleus, where ξ is $\log(1/\sin\theta)$.

parameter	^{1}H	^{4}He	^{7}Li	^{9}Be	^{11}B
C(σ_{C})	0.90 (0.05)	1.02 (0.08)	1.35 (0.10)	1.48 (0.09)	1.75 (0.10)
D(σ_{D})	6.4 (0.8)	11.4 (1.4)	13.4 (1.9)	15.7 (1.3)	22.6 (2.1)

$\log(1/\sin\theta)$, where we set $\log(1/\sin\theta)$ at ξ, as the angle dependence of the volume ratio, $V_r^{\alpha}(\xi)$, to the volume of the α particle. By applying a linear function, $V_r^{\alpha}(\xi) = \mathrm{C} + \mathrm{D}\xi$, to the fitted data, we got the parameters of C and D, and their errors, σ_{C} and σ_{D}, as listed in Table 1.

We obtained two variances of σ_{C}^2 and σ_{D}^2, and a covariance of σ_{CD}, then a standard deviation, $\sigma_{V_r^{\alpha}}$, is given by $\sigma_{V_r^{\alpha}} = \sqrt{\sigma_{\mathrm{C}}^2 + 2\xi\sigma_{\mathrm{CD}} + \xi^2\sigma_{\mathrm{D}}^2}$. Taking into account the fitting function as a quadric

Table 2. Parameters of the quadric fitting function, $V_r^{\alpha}(\xi) = \mathrm{C} + \mathrm{D}\xi + \mathrm{E}\xi^2$, for each nucleus.

parameter	^{1}H	^{4}He	^{7}Li	^{9}Be	^{11}B
C	0.90 ± 0.04	1.02 ± 0.06	1.35 ± 0.08	1.48 ± 0.08	1.75 ± 0.08
D	6.4 ± 0.4	11.4 ± 0.3	13.4 ± 0.2	15.7 ± 0.2	22.6 ± 0.6
E	0.0 ± 1.2	0.0 ± 3.2	0.0 ± 5.5	0.0 ± 4.4	0.0 ± 4.6

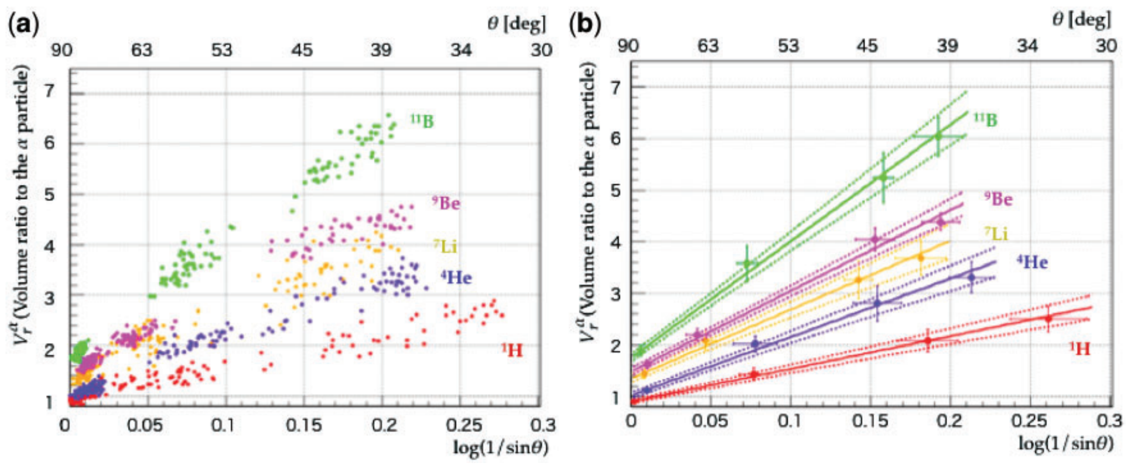

Fig. 6. (a) The track volume ratio of each nucleus to the calibration α particle. (b) Solid lines show mean value as a function of $\log(1/\sin\theta)$. Dotted lines cover one standard deviation.

function, $V_r^{\alpha}(\xi) = \mathrm{C} + \mathrm{D}\xi + \mathrm{E}\xi^2$, the fitting functions for five nuclei are presented with errors as summarized in Table 2. In Fig. 6(b), the functions are shown with the yields of one standard deviation for each nucleus by dotted lines.

3.3. *Charge recognition for five nuclei with lengths less than 100 μm*

We have checked the angle dependence of recognition for each nucleus at 100 μm length by using Ashman's D [10]. This is defined as $\sqrt{2}|\mu_1 - \mu_2|/\sqrt{\sigma_1^2 + \sigma_2^2}$, where μ and σ denote the mean value and one standard deviation of the two checked nuclei, respectively. For clear recognition of the two Gaussian distributions of (μ_1, σ_1) and (μ_2, σ_2), it is required to be $D > 2$. We checked the values of D for two nuclei with adjacent charges, and they are plotted in Fig. 7(a). Good recognition of all the nuclei is achieved for $\log(1/\sin\theta)$ less than 0.2 ($\theta \geqq 39°$).

We have also tested D for nuclear tracks with lengths less than 100 μm from the stopping point. The track length dependence of D at $\log(1/\sin\theta) = 0$ is shown in Fig. 7(b). All the nuclei with $z = 1$–5 can be recognized with lengths more than 90 μm from the stopping point. Even if the lengths are 50 μm, the two nuclei of (^{4}He, ^{7}Li) and (^{9}Be, ^{11}B) are well distinguished.

4. *Application of the method to a candidate event of a Ξ hypernucleus* To confirm the utility of this method, it was applied for one track of a Ξ hypernucleus candidate event detected in the KEK-PS E373 experiment. A microscope image and schematic drawing of this event are shown in Fig. 8. A Ξ^- hyperon was absorbed by a nucleus such as ^{12}C, ^{14}N, or ^{16}O in the emulsion at point A. Two single-Λ hypernuclei (tracks #1 and #2) were emitted from point A. One single-Λ hypernucleus (#1) decayed into three charged particles (tracks #3, #4, and #5) at point B and another

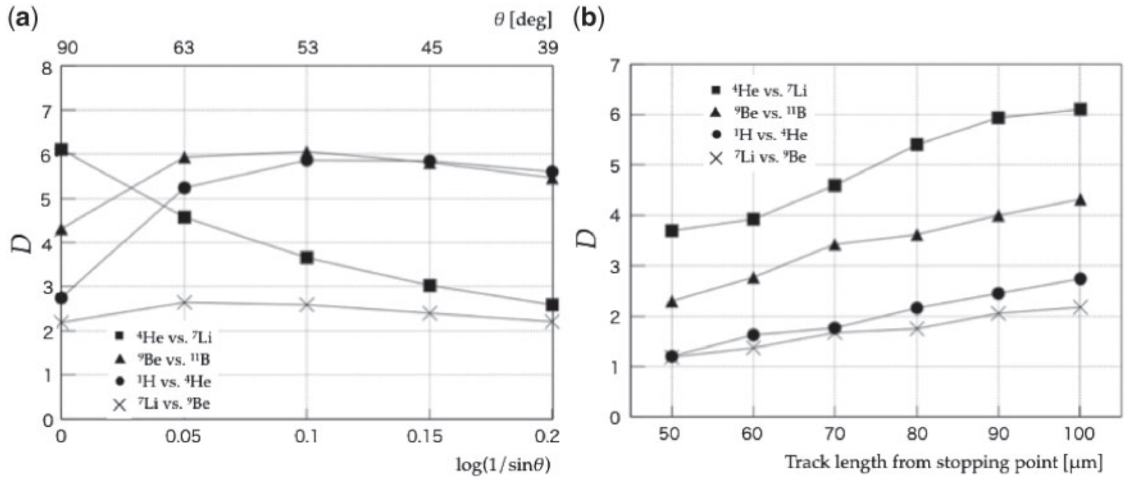

Fig. 7. (a) The angle dependence of D at 100 μm. (b) The track length dependence of D between 50 μm and 100 μm at $\log(1/\sin\theta) = 0$.

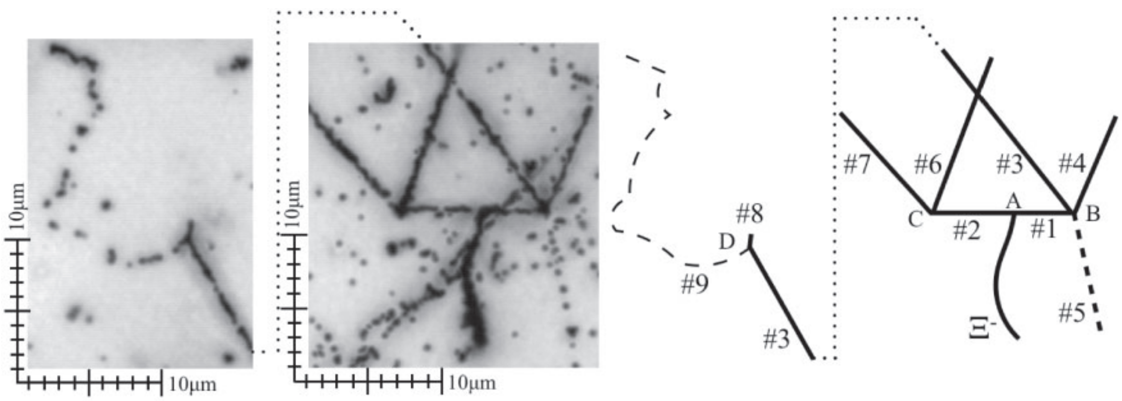

Fig. 8. A superimposed image and schematic drawing of a Ξ hypernucleus candidate.

one (#2) decayed into two charged particles (tracks #6 and #7) at point C. At the end point D of track #3, a recoiled particle and an electron (tracks #8 and #9) were emitted via β decay.

By kinematical analysis, four possible modes were accepted at point A as follows: (I) $\Xi^- + {}^{12}\mathrm{C} \rightarrow {}_{\Lambda}{}^{7}\mathrm{Li}(\#1) + {}_{\Lambda}{}^{6}\mathrm{He}(\#2)$, (II) $\Xi^- + {}^{12}\mathrm{C} \rightarrow {}_{\Lambda}{}^{7}\mathrm{Li}(\#1) + {}_{\Lambda}{}^{5}\mathrm{He}(\#2) + n$, (III) $\Xi^- + {}^{12}\mathrm{C} \rightarrow {}_{\Lambda}{}^{8}\mathrm{Li}(\#1) + {}_{\Lambda}{}^{5}\mathrm{He}(\#2)$, (IV) $\Xi^- + {}^{14}\mathrm{N} \rightarrow {}_{\Lambda}{}^{9}\mathrm{Be}(\#1) + {}_{\Lambda}{}^{5}\mathrm{He}(\#2) + n$. Regarding mesonic decay, there was no possibility for both decays of single-Λ hypernuclei. In the case of ${}_{\Lambda}\mathrm{Li}$ decay at point B for (I)–(III), therefore, three daughters (#3, #4, and #5) have a single charge. For the case of (IV), a decay mode of ${}_{\Lambda}{}^{9}\mathrm{Be} \rightarrow \mathrm{He}(\#3) + \mathrm{H}(\#4) + \mathrm{H}(\#5) + n$ was approved under kinematical analysis. Taking into account the β decay at point D, the method is applied to recognition of ${}^{3}\mathrm{H}$ or ${}^{6}\mathrm{He}$ for track #3.

With RIKEN data, we prepared $V_r^\alpha(\xi)$ for a track length of 75 μm, which was one of track #3, and the parameters of the quadric function of $V_r^\alpha(\xi)$ were obtained as listed in Table 3. The functions for each nucleus are shown in Fig. 9(a).

By measurement of track width and the depths of 138 α particles from ${}^{212}\mathrm{Po}$, the depth dependence of $v^\alpha(d)$ was obtained to be $(0.215 \pm 0.004) - (1.003 \pm 0.129) \times 10^{-4} d$. The average angle θ of track #3 was 84.2°($\log(1/\sin\theta) = 2.23 \times 10^{-3}$), and the volume ratio of the calibrated volume of track #3 by $v^\alpha(d)$ to volume of the α particle is shown with the function of $V_r^\alpha(\xi)$ in Fig. 9(b).

Table 3. Parameters of $V_r^\alpha(\xi) = \mathrm{C} + \mathrm{D}\xi + \mathrm{E}\xi^2$ for a length of 75 μm.

parameter	^{1}H	^{4}He	^{7}Li	^{9}Be	^{11}B
C	0.91 ± 0.04	1.01 ± 0.07	1.29 ± 0.08	1.40 ± 0.07	1.62 ± 0.08
D	6.3 ± 0.4	11.4 ± 0.2	14.4 ± 0.3	15.7 ± 0.1	21.2 ± 0.7
E	0.0 ± 1.2	0.0 ± 3.6	0.0 ± 5.6	0.0 ± 4.8	0.0 ± 4.8

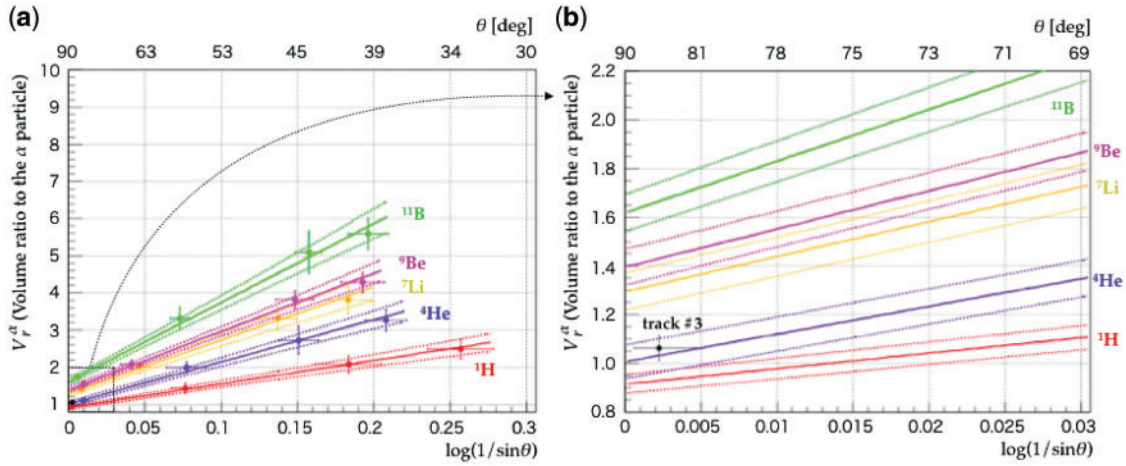

Fig. 9. (a) Track volume ratio of each nucleus to the α particle as a function of $\log(1/\sin\theta)$. (b) A close-up of the angle range from 0 to 0.03 in (a).

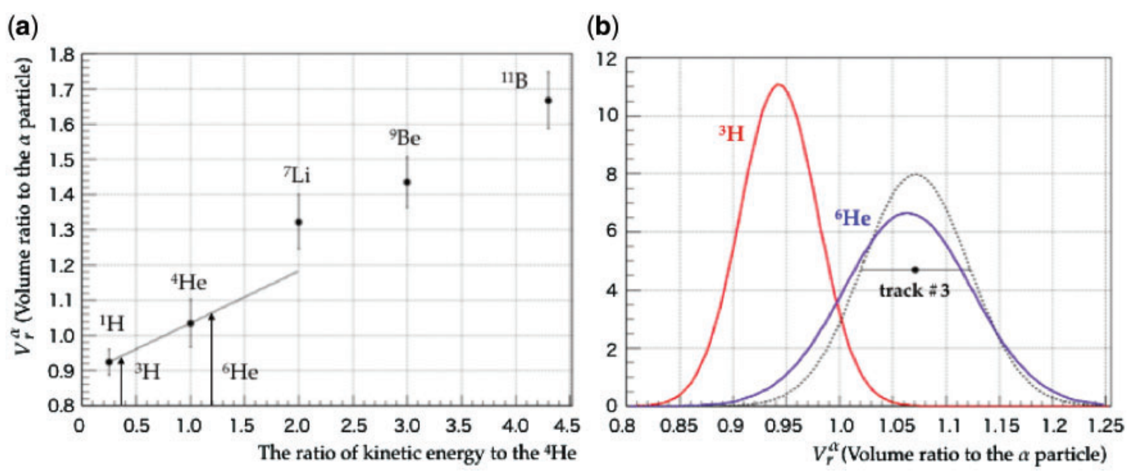

Fig. 10. (a) V_r^α of five nuclei as a function of the ratio of kinetic energy to ^{4}He. (b) The normalized distributions of volume ratio to the α particle of ^{3}H and ^{6}He at $\log(1/\sin\theta) = 2.23 \times 10^{-3}$ and track #3.

The relation of the kinetic energies to ^{4}He and V_r^α is obtained at $\log(1/\sin\theta) = 2.23 \times 10^{-3}$, as shown in Fig. 10(a). The values of V_r^α for ^{3}H and ^{6}He can be obtained on the line extrapolated by data points of ^{1}H and ^{4}He, because the data of ^{7}Li, ^{9}Be, and ^{11}B are not on the same line; we remind ourselves of the discussion about M/z^2 for Fig. 3 here. In Fig. 10(b), we focus on the volume ratio of track #3 in comparison with the normalized Gaussian distributions of the ratios for ^{3}H and ^{6}He with one σ of V_r^α for ^{1}H and ^{4}He, respectively. We conclude that the ^{6}He nucleus is plausible for track #3 with a likelihood ratio of 0.9.

5. *Conclusion* We have developed a method to identify charges of 1–5 for nuclei of low-energy daughters from the decay of double-strangeness nuclei for the study of Λ–Λ and ΞN interaction. The method was based on the measurement of track volumes of nuclei in the emulsion. However, the width of the track depended a great deal on the depths and the angles of the track in the thick emulsion, even for the same charged nuclei. We have exposed eight nuclear species with charges of 1–5 to the emulsion at RIPS of RIKEN, and we have studied five nuclear tracks of ^{1}H, ^{4}He, ^{7}Li, ^{9}Be, and ^{11}B. After understanding the width dependence on the depths and angles, we have succeeded in obtaining uniform understanding with a quadric function of $V_r^{\alpha}(\xi)$ for the relation between the track volume ratio to α particle and angles, $\log(1/\sin\theta)$. The α particles used are decay daughters of ^{212}Po, which are contaminated natural isotopes in the emulsion. Taking into account Ashman's D, nuclear charge from 1 to 5 can be well recognized for θ and a track length of 90° (or $\geqq$ 39°) and 90 μm (or 100 μm), respectively.

To clarify the feasibility for identification of the nuclear charge, we applied the method to a candidate event of a Ξ hypernucleus in the E373 emulsion. By kinematical analysis, it was not identified as ^{3}H or ^{6}He, which was one of the tracks of daughter fragments from the decay of the single-Λ hypernucleus. We also used the α particles from ^{212}Po as a calibration source in the E373 emulsion; then we calibrated the volume of the track of the daughters with the dependence on the depth, $v^{\alpha}(d)$, in the E373 emulsion. We have concluded that the daughter fragment is a ^{6}He nucleus with a likelihood ratio of 0.9. The utility of this method was confirmed for identification of charges of low-energy nuclear fragments from the decay of double-strangeness nuclei. We expect that many double hypernuclei will be identified by this method and rich information will be thus obtained.

Acknowledgements

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