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Operation Steps for Data Analysis on Double Hypernuclei in E07 Experiment

Aung Nay Lin Nyaw[1], Hiroyuki Ekawa[2,4], Shuhei Hayakawa[3,4], Ayumi Kasagi[1], Kazuma Nakazawa[1], Junya Yoshida[4], and Masahiro Yoshimoto[1], on behalf of the E07 (J-PARC) collaboration

[1]*Physics Department, Gifu University, Gifu 501-1193, Japan*
[2]*Department of Physics, Kyoto University, Kyoto 606-8502, Japan*
[3]*Department of Physics, Osaka University, Toyonaka, Osaka 560-0043, Japan*
[4]*Advanced Science Research Center, Japan Atomic Energy Agency, Tokai, Ibaraki 319-1195, Japan*

E-mail: mgmgnyaw@gmail.com

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We have developed a new analysis scheme for event identification of double hypernuclei to deal with the largest amount of events which are obtained through the J-PARC E07 experiment. We developed dedicated computer programs which perform range and angle measurement, range-energy translation, measurement of density and shrinkage factor of an emulsion sheet, and kinematic analysis instead of the conventional manual method. The processing time for the production or decay process identification for an event is less than five minutes on a typical PC. Based on this method, we performed the entire analysis process within four days including alpha scanning and processing for range-energy calibration. This method has been applied in the analysis of newly found events including MINO event and IBUKI event by the J-PARC E07.

KEYWORDS: double hypernuclei, double strangeness, J-PARC E07, nuclear emulsion

1. Introduction

Research on double hypernuclei (DH) such as double Λ hypernucleus (DLH) and Ξ hypernucleus (XH) is one of the most important issues for nuclear physics. DH is expected to give us information on ΛΛ, Ξ*N* interactions and the information on ΛΛ-Ξ*N* mixing effects. So far, DLH and XH events including NAGARA and KISO have been reported via so-called emulsion experiments [1–3]. The nuclear emulsion is the best way to analyze rare, low energy and short life-time particles like DH with sub-μm resolution.

More statistical data on DH is necessary because the number of DH events is quite small to understand them. Therefore, the latest experiment J-PARC E07 was performed in order to obtain 100 DH events. The yield is 10 times more than the previous experiments. In addition, we will apply a new analysis method named Overall scanning method [4] to analyze the entire volume of the emulsion. Finally, we estimate that 1000 DH events will be detected in 5 years.

Speeding up physical analysis is essential to deal with the largest amount of events obtained through the E07 experiment. The previous experiments have only detected 10 DH in several years of analysis, and the analysis speed has not been discussed. However, it is necessary to speed up the method of events analysis in order to govern a large number of events. Therefore, we developed dedicated computer programs which extend and speed up the conventional analysis method depending on manual works.

2. Operation Steps for Data Analysis

The general flow of the analysis process is described in this paragraph. The goals of our analysis are the identification of a DH event and measurement of $B_{\Lambda\Lambda}$ and B_{Ξ^-} for DLH and XH respectively. At first, we measure geometrical features such as range and angle of tracks from micrographs. Secondly, we reconstruct the kinetic energy and momentum vector of each particle in emission from the range and angle of the track. The function of range-energy translation depends on the density and shrinkage factor of the emulsion layer. Then, we measure them with monochromatic alpha tracks in sequential decay events of Th series. For event identification, we evaluate the kinematic consistency for all possible combinations. Finally, $B_{\Lambda\Lambda}$ and B_{Ξ^-} are determined precisely by the kinematic fitting technique. The following sub-sections will describe the detail of each process.

2.1 Range and angle measurement

Precise measurement for a special event is performed by a dedicated image processing for a series of micrographs [4]. The micrographs are taken under 100x objective lens with a resolution of about 0.143μm/pixel. Usually, several hundred micrographs were taken for an observed event by changing the focal plane to capture enough volume around the event. A typical interval of micrographs is 0.2 μm in direction of the light-axis. Furthermore, we use several series of micrographs, typically 5 times, to estimate measurement reproducibility and error.

Our image processing is done by following procedures. At first, basic image processing is performed for the taken micrographs in order to distinguish track against the background: high-pass filtering, so-called "Difference of Gaussian", and brightness thresholding [5]. Secondary, we roughly define the range and angle of the tracks visually by mouse-click action by a dedicated GUI-tool. Then, further processing is automatically performed as the following steps. The tracks are divided into short segments every 10 μm for a line fitting because tracks are not straight due to multiple Coulomb scattering. For each segment, about ten points on it are defined as "the core of the track" by the brightness gradient. Finally, a linear fitting is performed for the segments to minimize chi-square value. These "core finding" and "linear fitting" are iterated until the parameters converge.

The range measurement is essential to calculate the kinetic energy of particles. The track range before shrinkage is calculated by summing the segmented ranges as following.

$$R(S) = \sum_{i=1}^{n} \sqrt{\Delta x_i^2 + \Delta y_i^2 + (S \times \Delta z_i)^2}, \tag{1}$$

where Δx_i, Δy_i, and Δz_i represent the observed length of the i-th segment of a track in x-y-z coordinates. S is the shrinkage factor, the ratio of layer thickness before the photographic development to that in observation.

Track ranges are described as "emulsion layer equivalent" range. If a track passes through a polystyrene base, a correction factor, about 0.4-0.6, is multiplied to ΔR in the base. The factor is depending on the distance from the stop point and obtained by "SRIM 2013".

The emission angle of a particle, θ as zenith and ϕ as azimuthal angle, are also obtained by the linear fitting in order to calculate the momentum vector. Typically, 5 μm length from the vertex point is used for the fitting for angle definition.

2.2 Range-energy relation

The kinetic energy of a charged particle stopped in an emulsion layer is obtained by the following range-energy formula given by Barkas *et. al.*, [7, 8].

$$R = \frac{M}{Z^2} \cdot \lambda(\beta) + R_{ext}, \tag{2}$$

where, R, Z, and M are respectively the range of the track, charge, and mass of the particle in the unit of the proton mass. $\lambda(\beta)$ represents a range of a proton at the velocity of β in the standard emulsion, Ilford G5 emulsion with the density of 3.815 $\mathrm{g/cm^3}$. R_{ext} means a range extension caused by electron capture for particles with multiple positive charges. This function is described as follows.

$$R_{ext} = MZ^{2/3}C_z(\beta/Z), \tag{3}$$

where, C_Z, a function of β/Z, is a empirical one given by some experiments.

The range of a particle depends on the density, in other words, the moisture content, of an emulsion layer. When the density of our emulsion is different from that of the standard emulsion, the following formula is used to correct the range in a moisturized emulsion layer as a mixture of the standard emulsion and water by calculating the weighted harmonic average of their ranges.

$$\frac{\lambda_s}{\lambda} = \frac{rd-1}{rd_s-1} + \frac{r(d_s-d)}{rd_s-1} \cdot \frac{\lambda_s}{\lambda_w}, \tag{4}$$

where, λ_s and λ_w are ranges of proton track in the standard emulsion and water, respectively. d and d_s are the density of our emulsion and that of the standard emulsion, respectively. r $(=\Delta V/\Delta W)$ is the ratio of the volume increment, which has the unit of $\mathrm{cm^3/g}$, by the addition of moisture to an emulsion layer. It was measured as 0.884 for our emulsion layer.

The "range straggling effect" should be taken into account as an uncertainty of range-energy translation. Even if the energies of charged particles are monochromatic, their ranges vary stochastically. The main contribution to range straggling is that caused by electron collision. This effect is given by Barkas as a numerical table.

These functions such as C_z, λ_s, $\frac{\lambda_s}{\lambda_w}$, and "range straggling caused by electron collision" are expressed as polynomial functions in our software library.

2.3 Measurement of density and shrinkage factor of an emulsion sheet

In order to measure the density and shrinkage factor of an emulsion sheet, decay alpha particles in the emulsion layer are used. Although these values are able to obtain by mechanical measurements, the way with alpha particles is the best solution to minimize the systematic uncertainties.

We usually use the alpha tracks with monochromatic energy of 8.784 MeV from decays of ^{212}Po. They are originated from natural isotopes of Thorium distributing in an emulsion layer randomly. They can be identified easily because they have a characteristic topology: the longest track in "alpha-star" having 5 alpha tracks. A modern scanning technique, "Overall scanning method" is used for the alpha decay search [4]. We collect about 100 tracks and measure their range with the image processing. The mean range, R, and S can be obtained to minimize the chi-square expressed as following.

$$\chi^2 = \sum_{k=1}^{N} \left(\frac{R - R_k(S)}{\sigma_{R_k}} \right)^2, \tag{5}$$

where, R_k represents the range of the k-th alpha tracks with S. And σ_{R_K}, resolution of track measurement, is given depending on the zenith angle of the track.

For instance, for the 7th sheet in module #069, R and S are measured to be 50.77 ± 0.12 μm and 1.98 ± 0.02, respectively. From this result and the range-energy formula, the density of the emulsion layer was determined to be 3.486 ± 0.013 $\mathrm{g/cm^3}$. The scanning time for alpha search, eye-check for alpha decay selection, image taking of the selected alpha, and fitting are 20 hours, 8 hours, 3 hours, and 3 hours, respectively. There is no method that can process faster than our current analysis scheme untill now.

2.4 Event reconstruction

We perform event reconstruction to identify the nuclide of a double strangeness system. At first, we assign all the possible particle to each track. Then, for each track, the kinematic energy is defined by range-energy translation. The momentum vector is also did by energy-momentum translation. Secondly, we check the kinematic consistency for the all possible combinations. If a single reasonable interpretation is survived, the nuclide is identified successfully.

The considered case is summarized in Table I. As the initial state, Ξ^- capture at rest, three cases are listed: Ξ^- + ^{12}C, ^{14}N, or ^{16}O, which are the medium-heavy nucleus in an emulsion layer. For each reaction, neutral particles emission are also considered. 41 kinds of single Λ hypernuclei (SH) and 40 DLH are listed. The mass of some SH are an estimated by linear-extrapolation using by that of several isotopes of SH. The mass of DLH is estimated by SH with the condition of $\Delta B_{\Lambda\Lambda}$=0.

Table I. Particles considered in the event identification

Type	# of case	Example
Initial state	3	Ξ^- + ^{12}C, ^{14}N, or ^{16}O
Daughters without strangeness	65	π^-, p, d, t, ^{3}He, ^{4}H, ^{4}He, ... ^{19}B, ^{19}C, ^{19}N, or ^{19}O
Neutral particles	10	n, 2n, 3n, π^0, π^0+n, π^0+2n, Λ, Λ+n, Λ+2n, or none
Single Λ hypernuclei	41	$^3_\Lambda$H, $^4_\Lambda$H, $^4_\Lambda$He, $^5_\Lambda$He, ... , $^{17}_\Lambda$N, or $^{18}_\Lambda$N
Double Λ hypernuclei	40	$^4_{\Lambda\Lambda}$H, $^5_{\Lambda\Lambda}$H, $^5_{\Lambda\Lambda}$He, ... , $^{17}_{\Lambda\Lambda}$N, or $^{18}_{\Lambda\Lambda}$N

These calculations are implemented in Python-language. The program evaluates kinematic consistency for all possible cases with round-robin combinations. This method is quite effective compared to the conventional manual calculation in term of search completeness and speed. The processing time to evaluate a 3-prong decay is less than 5 minutes on a typical PC.

Particle ID with track feature is important to refine the event reconstruction. The grain density and boldness of tracks have information on dE/dx of the particle in the emulsion layer. For a track having about 100 μm range, charge ID method developed by Kinbara [5] is applied. Furthermore, the feature of the track endpoint has plenty of information. If an electron-like track is seen from there, it shows the nucleus occurred a β-decay. In the case of a "hammer track", it is one of the A=8 nuclei. A π^- track has characteristic features: thin and straight around the emitting point, however dense and dizzy near the stop point, and a few nuclear fragments are often seen at the stop point.

For an identified event, mass calculation of double strangeness system is performed. The mass of a DH is reconstructed by energy conservation in the production and decay process, i.e., $M(Z') + M(\Xi^-) - B_{\Xi^-} = M(_{\Lambda\Lambda}Z) + K.E.(_{\Lambda\Lambda}Z) + \sum M_{other} + \sum K.E._{other}$, and $M(_{\Lambda\Lambda}Z) = \sum M_{daughter} + \sum K.E._{daughter}$, respectively. Usually, the value of B_{Ξ^-} is used that of 3D state of Ξ^- in Z' = C, N, or O. Finally, $B_{\Lambda\Lambda}$ of a DH is defined as the difference between $M(^A_{\Lambda\Lambda}Z)$ and $M(^{A-2}Z) + 2M(\Lambda)$. Also, B_{Ξ^-} of XH event are reconstructed by $M(Z') + M(\Xi^-) - B_{\Xi^-} = E_{final\_state}$, where, two single Λ hypernuclei must be seen in the final state, i.e., the event must be twin hypernuclear event.

2.5 Kinematic fitting

The "kinematic fitting" is applied to refine $B_{\Lambda\Lambda}$ or B_{Ξ^-}. They can be restricted more precisely if we take into account the momentum conservation law. Therefore, we use the method of Lagrange multipliers to reduce the kinematic uncertainties under constraints on energy and momentum conservation. Since the equations are non-linear, a linear approximation is applied to solve simultaneous linear equations. A mathematical formulation is introduced by Avery [9]. In our calculation, the mass of double hypernucleus is treated as an unknown parameter. Furthermore, if a range of a decay daughter is not determined, the momentum of the particle is also treated in the same manner. The typical uncertainty $B_{\Lambda\Lambda}$ and B_{Ξ^-} is about 0.2 MeV after the kinematic fitting. The chi-square value of the kinematic fitting can be used to evaluate which interpretation is the most probable among multiple ones. Validation of the program is performed with MC data and found events such as NAGARA and KISO event.

Finally, we consider whether the daughter nuclei were in the ground state or excited state. The value of $B_{\Lambda\Lambda}$ and B_{Ξ^-} shall need revising by the excited energy because the kinematic calculation was performed under the condition that any nuclei were in the ground state.

3. Conclusion

We have developed a new analysis scheme for event analysis of double hypernuclei in the nuclear emulsion. We developed dedicated computer programs which perform each step of analysis instead of the conventional manual method. This method has been validated and applied the analysis of newly found events named MINO [10] and IBUKI [6] event. Further improvement is ongoing to save the processing time, to apply more generic cases.

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