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EVIDENCE OF STRANGENESS -1 HYPERNUCLEUS FORMATION VIA Ξ^- HYPERON CAPTURE POINT IN NUCLEAR EMULSION

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Abstract

A strangeness -1 single-Λ hypernucleus event which is detected in nuclear emulsion of hybrid-emulsion experiment KEK-PS E373 is analyzed starting from its decay point. Kinematical analysis is used to perform analysis. The neutral particle emission at point B is checked by two methods and it is observed that the neutral particles are also emitted as the decay products. +7+9+` 7t; possible decay modes are selected by calculating the energy and momentum of decay products and kinematical analysis is done. Masses and binding energies of possible hypernuclei were calculated. According to the analysis result, the event is assigned to be ${}^{7,8}{}_{\Lambda}\mathrm{Li}$ or ${}^{10}{}_{\Lambda}\mathrm{Be}$ or ${}_{\Lambda}{}^{14}\mathrm{C}$. The most probable decay mode is identified as ${}^{8}{}_{\Lambda}\mathrm{Li} \rightarrow d + \mathrm{He}^3 + 3n$ with 7641.4±0.006 MeV/c^2 mass and 9.65±0.06 MeV binding energy. Our results are consistent with other theoretical and experimental results.

Keywords: nuclear emulsion, strangness-1, single-Λ hypernucleus, neutral particle, kinematical analysis, mass, binding energy

Introduction

In the present research, a single-Λ hypernucleus event which is detected in nuclear emulsion of KEK-PS E373 experiment is analyzed by applying relativistic kinematics. The aim of KEK-PS E373 experiment is searching and studying the strangeness hypernuclei with ten times higher statistics than previous experiment KEK-PS E176 [Nakazawa K,2010].

In this experiment $p(K^-,K^+)\Xi^-$ reaction is used. Beam exposure is done at Japanese High Energy Accelerator Research Organization (KEK) and emulsion scanning is performed by laboratories of collaboration universities. The analyzed event is observed in Nakazawa Laboratory, Gifu University, Japan during the semi-automatic scanning of emulsion plates. In semi-automatic scanning system, Ξ^- hyperon tracks are searched by automatic scanning by using the predicted positions and angles. When Ξ^- hyperon is captured by nuclear emulsion, the scanning result was checked individually by human eyes.

A hypernucleus is a nucleus which consists of protons, neutrons and one or more hyperon (Λ, Σ, Ξ , Ω). A single-Λ hypernucleus is a bound system of nucleons and one Λ hyperon. It is also called strangeness -1 (S = -1) hypernucleus. A single-Λ hypernucleus can be seen as an event with two vertex points in nuclear emulsion. A single-Λ hypernucleus is mostly produced via quasifree $p(K^-, K^+)\Xi^-$ reaction in the particle accelerator and $\Xi^- + p \rightarrow \Lambda + \Lambda$ reaction in nuclear emulsion. Nuclear emusion is the most suitable detector to study hypernuclei events because the hypernuclei events can be recorded and measured the ranges of charged particle tracks precisely. The famous hypernuclei searching experiment KEK-PS E176, E373and J-PARC E07 experiments are carried out using nuclear emulsion.

For strangeness zero (S=0) ordinary nuclear systems 7000 nuclides are naturally observed. Among them 3000 nuclides are unstable nuclei and nearly 300 stable nuclei were observed experimentally. Using the ordinary nuclei, nucleon-nucleon (NN) interaction which is very fundamental for nuclear force has been studied. But after observing the hypernucleus event via cosmic ray interaction with nuclear emulsion, the main door of baryon-baryon (BB) interaction is

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opened. So, to complete the knowledge of baryon-baryon interaction, nucleon-nucleon interaction can be studied by ordinary nuclei, lambda-nucleon (Λ-N) interaction can be studied by single-Λ hypernuclei and lambda-lambda (Λ-Λ) interaction can be studied by double-Λ hypernuclei.

At present, about 4000 data of NN interaction are already obtained. For the hypernuclei observation, about 50 single Λ-hypernuclei and six double-Λ hypernuclei were found experimentally [Tamura H, 2012]. So, we have very few data of Λ-N and Λ-Λ interaction and observation of more and more hypernuclei is strongly desired to construct the baryon-baryon interaction model. To do so, hypernuclei identification is the most important work and the present research aims to perform kinematical analysis of single-Λ hypernucleus event which is produced by Ξ^- hyperon captured point in nuclear emulsion and to investigate the mass and binding energy of analyzed event. This research also aims to support the identification data to hypernuclear physics groups.

Event Description

The photograph and schematic diagram of analyzed single-Λ hypernucleus event are presented in figure 1.

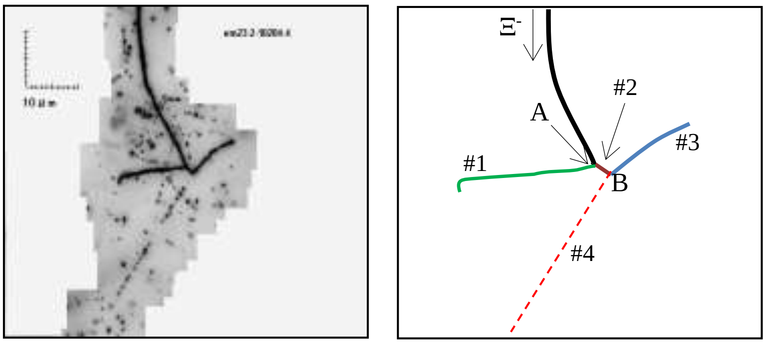

Figure 1 Photograph and schematic diagram of analyzed single-Λ hypernucleus in nuclear emulsion of KEK-PS E373 experiment

In the analyzed event, Ξ^- hyperon is captured by the emulsion nucleus at point A, from which two charged particles track #1 and track #2 are emitted. The particle of track #2 decays again into track #3 and track #4 at point B. So, point A is production vertex and point B is decay vertex of track #2. In the analyzed event, a single-Λ hypernucleus is produced with two charged particles decay products. In this event, there are two vertex points; one production vertex and one decay vertex. Therefore, we decided that a charged particle track #2 is a single-Λ hypernucleus. The experimental data of positions (x,y,z) are measured by Htaik Nandar Kyaw who is one of the collaborators of KEK-PS E373 experiment. The measured ranges and position angles of emitted charged particle tracks are presented in table 1.

Table 1 Measured ranges of hypernucleus track #1 and charged particle decay products

Vertex	**Track**	**Range (μm)**	**θ (degree)**	**ϕ (degree)**	**Remark**
A	#1	24.75±0.001	147.11±0.48	357.52±0.28	
	#2	4.27±0.001	159.52±0.21	121.03±0.44	Single-Λ hypernucleus
B	#3	11.99±0.001	101.17±0.34	233.11±0.64	
	#4	1486.80±0.14	73.18±1.79	57.15±2.784	

Identification of a Single-Λ Hypernucleus

In this section the analysis of single-Λ hypernucleus event which is observed via Ξ^- hyperon captured by nuclear emulsion is presented.

Checking the Neutral Particles Emission at Point B

In kinematical analysis, hypernuclei identification work is done by using the decay point of single-Λ hypernucleus event. Therefore, choosing the possible decay mode is the most important. In the analyzed event a single-Λ hypernucleus track #2 decays into two charged particles track #3 and #4.Therefore, it is necessary to check the neutral particle emission in the decay products other than two charged particles.

In our analysis, we checked the neutral particle(s) emission at point B using the unit vector plane checking method which is mentioned in equation 1. If coplanarity is zero, there is no neutral particle emission at the point B. If the coplanarity is not equal zero, there is neutral particle emission at point B. In this method, the unit vectors of charged particle tracks are used as follows.

Coplanarity of three tracks at point B can be calculated by

$$C_B = \hat{U}_A . (\hat{U}_B \times \hat{U}_C) \tag{1}$$

$$\vec{A} = A_x \hat{x} + A_y \hat{y} + A_z \hat{z} \tag{2}$$

$$\vec{B} = B_x \hat{x} + B_y \hat{y} + B_Z \hat{z} \tag{3}$$

$$\vec{C} = C_x \hat{x} + C_y \hat{y} + C_z \hat{z} \tag{4}$$

$$\hat{U}_A = \frac{\vec{A}}{|\vec{A}|}, \hat{U}_B = \frac{\vec{B}}{|\vec{B}|}, \quad \hat{U}_C = \frac{\vec{C}}{|\vec{C}|} \tag{5}$$

where, $\vec{A}$ is position vector of track #2, $\vec{B}$ is position vector of track #3 and $\vec{C}$ is position vector of track #4. In equation 5, $\hat{U}_A, \hat{U}_B$ and $\hat{U}_C$ are unit vectors of $\vec{A}, \vec{B}$ and $\vec{C}$. According to our calculation, the coplanarity of three tracks at point B is 0.269±0.164. Therefore, neutral particle emission at point B will be considered.

Checking the Neutral Particle Emission at Point B by using the Decay Modes without Neutron

To check the neutron emission at point B, we used another method which is comparing the total kinetic energy and Q-value of no neutron emission decay modes. To do so, the decay modes without neutron emission are firstly considered and (81) decay modes of ${}^{4}_{\Lambda}\mathrm{He}$ to ${}^{15}_{\Lambda}\mathrm{N}$ are obtained. The Q- values of above decay modes are calculated by the formula

$$Q(\mathrm{MeV}) = [\{M(\#2)-M(\#3)-M(\#4)\}\ \mathrm{MeV}/c^2]c^2 \tag{6}$$

Therefore, possible decay modes of single-Λ hypernucleus track #1 are chosen according to equation 2. Firstly, internal structures of possible single-Λ hypernuclei are considered. Track #1 decays into decay products of three charged particle tracks and neutral particles, the possible hypernucleus must be chosen ${}^{4}_{\Lambda}\mathrm{He}$ to ${}^{15}_{\Lambda}\mathrm{N}$.

The kinetic energy of decay products are calculated by R-E (Range-Energy) relation calculation package supported by Professor Nakazawa who is the spokesperson of KEK-PS E373 experiment [Nakazawa K, 2019]. Then, the total energies which are the sum of kinetic energies of two decay products track #3 and #4 for all decay modes are calculated. Moreover, the calculated Q-values and total energy are compared. If all charged particles are emitted as the decay products, the total energy should be equal to Q-values. According to our calculation, the Q-values are very much greater than total energy for all (81) decay modes. Therefore, the decay modes without neutron are rejected and we can concluded not only two charged particles but also neutral particles are emitted in the decay products for all possible decay modes.

Choosing the Possible Decay Modes at Point B

At point B, a single-Λ hypernucleus track#2 decayed into two charged particle tracks #3 and #4. Due to the coplanar checking we have found that there is neutron emission at point B in addition to two charged particles track #3 and track #4. Therefore the non-mesonic decay modes of single-Λ hypernucleus are considered as follows.

$$\#2 \rightarrow \#3 + \#4 + \text{Neutral particle(s)} \qquad (7)$$

According to non-mesonic decay process which is mentioned in equation (7), the possible (140) decay modes from ${}^{4}_{\Lambda}\mathrm{He} \rightarrow {}^{2}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} + 2\mathrm{n}$ to ${}^{15}_{\Lambda}\mathrm{N} \rightarrow {}^{3}_{2}\mathrm{He} + {}^{10}_{5}\mathrm{B} + 2\mathrm{n}$ are obtained. In order to choose the possible decay modes, one neutron emission, two neutrons emission and three neutrons emission cases are considered.

Identification of Single-Λ Hypernucleus Event

A single-Λ hypernucleus is decayed by weak interaction and identification of hypernucleus event is performed by its decay point. In section 3.3, 140 possible decay modes with neutral particles decay products are chosen. In order to check the possible decay modes that we have chosen are allowed or forbidden, Q-values at point B are calculated. If Q-value is positive, the reaction is exoergic and it will be energetically possible. If Q-value is negative, the reaction cannot energetically possible and the energy is needed to supply incident particle. In nuclear emulsion, the decay processes of hypernucleui should be exoergic because the lifetime of hypernucleus is $\sim 10^{-10}$s and it can decay energetically within 10^{-10}s. According to our calculation, Q-values at point B are positive for all possible decay modes and they all are acceptable to perform analysis.

Then Q-values and total energy of all decay products are compared. The kinetic energy of charged particles which is also defined as visible energy (E_{vis}) is calculated by range-energy relation calculation package [Nakazawa K, 2019]. The kinetic energy of neutral particles is calculated by momentum conservation. The total energy which is the sum of kinetic energy of charged particles and that of neutral particles is also calculated. In order to choose the most probable decay modes, Q-values and total energies are compared. If neutral particles are emitted as the decay products the total energy should be less than Q-value because neutral particles cannot be seen or measured in nuclear emulsion. So, we assumed that the neutral particle or particles emitted as back to back direction with charged particles. At that time we can get minimum kinetic energy and inserting the greater than sign for two or three neutron emission cases. In our research 133 decay modes have greater total energy than Q-value and these decay modes are rejected. Only 7 decay modes are acceptable because their total energies are less than Q-values and the results are presented in table 2 and figure 2.

Table 2 Comparison of Q-values and total energy for all acceptable decay modes at point B

No.	Decay Modes	Q(MeV)	E_{tot} (MeV)	Remark
1	${}^{5}_{\Lambda}He \to {}^{1}_{1}H + {}^{3}_{1}H + n$	152.14±0.05	127.74±0.003	Acceptable
2	${}^{6}_{\Lambda}He \to {}^{2}_{1}H + {}^{3}_{1}H + n$	154.21±0.12	138.82±0.003	Acceptable
3	${}^{7}_{\Lambda}Li \to {}^{1}_{1}H + {}^{3}_{2}He + 3n$	144.72±0.06	>131.74±0.006	Acceptable
4	${}^{8}_{\Lambda}Li \to {}^{2}_{1}H + {}^{3}_{2}He + 3n$	138.48±0.06	>137.16±0.006	Acceptable
5	${}^{9}_{\Lambda}Be \to {}^{7}_{3}Li + {}^{1}_{1}H + n$	150.11±0.06	136.80±0.007	Acceptable
6	${}^{10}_{\Lambda}Be \to {}^{6}_{3}Li + {}^{2}_{1}H + 2n$	141.02±0.23	>110.14±0.006	Acceptable
7	${}^{14}_{\Lambda}C \to {}^{10}_{5}B + {}^{1}_{1}H + 3n$	128.56±0.33	>103.93±0.012	Acceptable

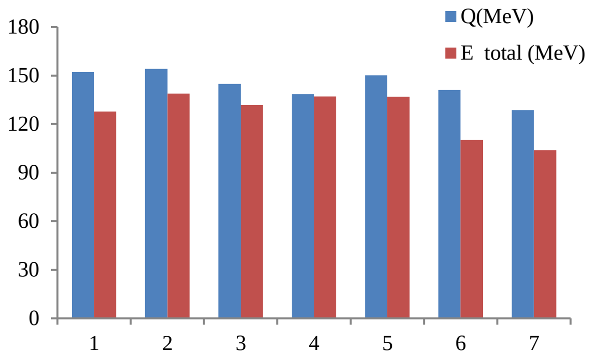

Figure 2 Comparison of Q and E_{tot} for Acceptable Decay Modes

After choosing the seven acceptable decay modes, three decay modes with one neutron emission, one decay mode with two neutrons emission and three decay modes with three neutrons emission are obtained. So, we tried to analyze a single-Λ hypernucleus event by calculating its mass and binding energy for seven acceptable decay modes. The possible masses of single-Λ hypernucleus are calculated by the formulae

$$M({}^{A}_{\Lambda}Z)\,c^2 = E_3 + E_4 + E_n \tag{8}$$

for one neutron emission case,

$$M({}^{A}_{\Lambda}Z)\,c^2 = E_3 + E_4 + E_{2n} \tag{9}$$

for two neutrons emission case and

$$M({}^{A}_{\Lambda}Z)\,c^2 = E_3 + E_4 + E_{3n} \tag{10}$$

for three neutrons emission case.

In the rquations 8, 9 and 10,

$M({}^{A}_{\Lambda}Z)$ = mass of single-Λ hypernucleus

E_3 = total energy of charged particle track #3

E_4 = total energy of charged particle track #4

E_n, E_{2n}, E_{3n} = total energy of neutron or neutrons

The binding energy of single-Λhypernucleus is calculated by the formula,

$$B_\Lambda = M(^{A-1}Z) + M_\Lambda - M(^{A}_{\Lambda}Z) \qquad (11)$$

where,

B_Λ= binding energy of single-Λ hypernucleus,

M_Λ= mass of Λ hyperon

$M(^{A-1}Z)$ = mass of core nucleus

The detailed calculated results of mass and binding energy are also presented in table 3.

According to the mass calculation, our results are slightly smaller but consistent with known experimental results as shown in the following graph of figure 3.

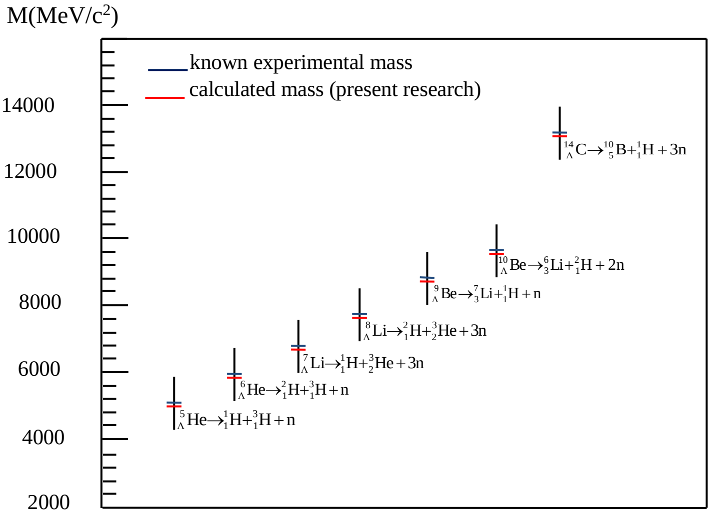

Figure 3 Comparison of known experimental mass and calculated Mass

In figure 3, the blue line represents the known experimental mass of observed single-Λ hypernuclei and the red line represents the calculated mass of present research for all acceptable decay modes. According to the figure 4, it is found that the calculated masses are slightly smaller than known experimental masses for all acceptable decay modes because of neutron contamination in the decay products. In the seven acceptable decay modes of present research, the mass differences between calculate masses and known masses are ≤ 30 MeV/c^2. We compared our calculated results with the previous calculations of two charged particles and one or two or three neutral particles decay products [Htaik Nandar Kyaw, 2020, Takahashi, 2010, Bando, 1990 & Samanta, 2019]. It is found that the results are consistent with the results of previous calculations.

Table 3 Comparison of our Calculated Results of Masses and Binding Energies of Acceptable Single-Λ Hypernuclei and Previous Experimental and Theoretical Values

Decay Modes	Calculated Mass MeV/c²	Known Mass MeV/c²	B.E. (MeV)	Known B.E. (MeV)	Remark
${}^{5}_{\Lambda}\mathrm{He}\rightarrow{}^{1}_{1}\mathrm{H}+{}^{3}_{1}\mathrm{H}+\mathrm{n}$	4815.52 ± 0.003	4839.92 ± 0.05	28.56 ± 0.06	3.12±0.02	Reject
${}^{6}_{\Lambda}\mathrm{He}\rightarrow{}^{2}_{1}\mathrm{H}+{}^{3}_{1}\mathrm{H}+\mathrm{n}$	5763.94 ± 0.003	5779.33 ± 0.12	20.44 ± 0.15	4.18 ± 0.10	Reject
${}^{7}_{\Lambda}\mathrm{Li}\rightarrow{}^{1}_{1}\mathrm{H}+{}^{3}_{2}\mathrm{He}+3\mathrm{n}$	**>6698.64 ± 0.01**	**6711.61 ± 0.06**	**<20.10± 0.06**	**5.58 ± 0.03**	**Acceptable**
${}^{8}_{\Lambda}\mathrm{Li}\rightarrow{}^{2}_{1}\mathrm{H}+{}^{3}_{2}\mathrm{He}+3\mathrm{n}$	**>7641.40 ± 0.01**	**7642.71 ± 0.06**	**<9.65 ± 0.06**	**6.80 ± 0.03**	**Acceptable**
${}^{9}_{\Lambda}\mathrm{Be}\rightarrow{}^{7}_{3}\mathrm{Li}+{}^{1}_{1}\mathrm{H}+\mathrm{n}$	8550.52 ± 0.01	8563.83 ± 0.06	22.06 ± 0.07	6.71 ± 0.04	Reject
${}^{10}_{\Lambda}\mathrm{Be}\rightarrow{}^{6}_{3}\mathrm{Li}+{}^{2}_{1}\mathrm{H}+2\mathrm{n}$	**>9468.45± 0.01**	**9499.33 ± 0.06**	**<42.03± 0.23**	**9.11 ± 0.22**	**Acceptable**
${}^{14}_{\Lambda}\mathrm{C}\rightarrow{}^{10}_{5}\mathrm{B}+{}^{1}_{1}\mathrm{H}+3\mathrm{n}$	**>13188.41± 0.01**	**13213.03± 0.08**	**<39.83± 0.34**	**12.17 ± 0.33**	**Acceptable**

For the binding energy calculation, we used equation 11 and our calculated results are presented in table 3. It is also observed that our calculated results are consistent with the binding energy values of previous theoretical and experimental results [Bando H, 1990 & Samanta C, 2019].

Results and Discussions

A single-Λ hypernucleus event of KEK-PS E373 experiment is kinematically analyzed. Our calculated results are compared with previous calculations and the following four decay modes are most acceptable.

$${}^{7}_{\Lambda}\mathrm{Li}\ (\#2) \rightarrow {}^{1}\mathrm{H}\ (\#3) + {}^{3}\mathrm{He}\ (\#4) + 3\mathrm{n} \tag{12}$$

$${}^{8}_{\Lambda}\mathrm{Li}\ (\#2) \rightarrow {}^{2}\mathrm{H}\ (\#3) + {}^{3}\mathrm{He}\ (\#4) + 3\mathrm{n} \tag{13}$$

$${}^{10}_{\Lambda}\mathrm{Be}\ (\#2) \rightarrow {}^{6}\mathrm{Li}\ (\#3) + {}^{2}\mathrm{H}\ (\#4) + 2\mathrm{n} \tag{14}$$

$${}^{14}_{\Lambda}\mathrm{C}\ (\#2) \rightarrow {}^{10}\mathrm{B}\ (\#3) + {}^{1}\mathrm{H}\ (\#4) + 3\mathrm{n} \tag{15}$$

In the ${}^{7}_{\Lambda}\mathrm{Li}\ (\#2) \rightarrow {}^{1}\mathrm{H}\ (\#3) + {}^{3}\mathrm{He}\ (\#4) + 3\mathrm{n}$ decay mode, the calculated mass is >6698.64±0.01MeV/c^2 and the known experimental mass of ${}^{7}_{\Lambda}\mathrm{Li}$ is 6711.61±0.06 MeV/c^2. So, the mass difference value is 12.97±0.07 MeV/c^2. The calculated binding energy is <20.10±0.06 MeV and known binding energy is 5.58±0.03 MeV. Therefore, this decay mode is acceptable.

In the ${}^{8}_{\Lambda}\mathrm{Li}$ (#2) $\rightarrow$ ^{2}H (#3) + ^{3}He (#4) + 3n decay mode, the calculated mass is >7641.40±0.01MeV/c^2 and the known experimental mass of ${}^{8}_{\Lambda}\mathrm{Li}$ is 7642.71±0.06 MeV/c^2. So, the mass difference value is 1.31±0.07 MeV/c^2. The calculated binding energy is <9.65±0.06 MeV and known binding energy is 6.80±0.03 MeV. Therefore, this decay mode is acceptable.

In the ${}^{10}_{\Lambda}\mathrm{Be}$ (#2) $\rightarrow$ ^{6}Li (#3) + ^{2}H (#4) + 2n decay mode, the calculated mass is >9468.45±0.01 MeV/c^2 and the known experimental mass of ${}^{10}_{\Lambda}\mathrm{Be}$ is 9499.33±0.06 MeV/c^2. So, the mass difference value is 30.88±0.07 MeV/c^2. The calculated binding energy is <42.03±0.23 MeV and known binding energy is 9.11±0.22 MeV. Therefore, this decay mode is acceptable.

In the ${}^{14}_{\Lambda}\mathrm{C}$ (#2) $\rightarrow$ ^{10}B (#3) + ^{1}H (#4) + 3 decay mode, the calculated mass is >13188.41±0.01 MeV/c^2 and the known experimental mass of ${}^{14}_{\Lambda}\mathrm{C}$ is 13213.33±0.03 MeV/c^2. So, the mass difference value is 24.62±0.07 MeV/c^2. The calculated binding energy is <39.83±0.34 MeV and known binding energy is 12.17±0.33 MeV. Therefore, this decay mode is acceptable.

According to our analysis, a single-Λ hypernucleus track #2 can be assigned as ${}^{7}_{\Lambda}\mathrm{Li}$ (or), ${}^{8}_{\Lambda}\mathrm{Li}$ (or), ${}^{10}_{\Lambda}\mathrm{Be}$ (or) ${}^{14}_{\Lambda}\mathrm{C}$ and the decay particles are p,d, ^{3}He, ^{6}Li, ^{10}B and neutrons. Among the most acceptable four decay modes, ${}^{8}_{\Lambda}\mathrm{Li}$ (#2) $\rightarrow$ ^{2}H (#3) + ^{3}He (#4) + 3n decay is most probable because its mass difference between calculated mass and known mass is very small value; 1.31±0.07 MeV/c^2. The binding energy difference is also close to the known value in this decay mode.

Conclusions

The major objectives of nuclear physics are exploring the unknown nuclei to understand the evolution of matter in the universe and studying the origin of nuclear force to understand the formation of atomic nuclei. To fulfill those purposes, the theoretical and experimental investigations have been performed on the nuclear structure, nuclear force and various nuclear properties. Due to those efforts, observation of hypernuclei opens the main door of baryon-baryon interaction to investigate the nuclear forces between hyperon- nucleon (Y-N) and hyperon-hyperon (Y-Y).

At present, hypernuclei are searched via (K^-, K^+) reaction in nuclear emulsion at KEK and J-PARC. In the present research, a single-Λ hypernucleus event which is observed in nuclear emulsion of KEK-PS E373 experiment is analyzed to identify its species and to investigate its mass and binding energy. Kinematical analysis which is based on relativity theory is used to perform present research and it is found that lithium hypernucleus decay is most probale by the emission of deuteron, helion and three neutrons as the decay products.

From our analysis, it can be obtained useful information for Λ-N interaction. Hypernuclear physics is now developing and it is necessary to get more and more information and data on hypernuclear production, decay, life time, mass and binding energy, etc. The present research can support those data to hypernuclear physics group.

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