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KINEMATICAL ANALYSIS OF SINGLE-Λ HYPERNUCLEI WITH NEUTRAL PARTICLE DECAY PRODUCTS IN NUCLEAR EMULSION

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Abstract

In this research work, five single-Λ hypernuclei which were detected in nuclear emulsion of KEK-PS E373 experiment are analyzed by applying relativistic kinematics. The analyzed single-Λ hypernuclei decayed into a charged particle and invisible neutral particles. The ranges and position angles of charged particle tracks are firstly measured in nuclear emulsion. To perform kinematical analysis, both mesonic and non-mesonic decay of single-Λ hypernuclei are taken into account. The kinetic energy and momentum of charged particle decay products are extracted by range-energy relation and that of neutral particles are calculated by momentum conservation. Moreover, possible masses of single-Λ hypernuclei are deduced by mass-energy relation equation. Due to contamination of neutral particles, the single-Λ hypernuclei cannot be identified uniquely and the calculated masses are slightly less than known masses within the acceptable limit. According to our analysis, it is found that the possible species of single-Λ hypernuclei are either ${}^{3}_{\Lambda}H$ (or) ${}^{4}_{\Lambda}H$ and their decay products of charged particles are possible to be proton (or) deuteron.

Keywords: Single-Λ hypernuclei, nuclear emulsion, relativistic kinematics, decay, range-energy relation, mass-energy relation

Introduction

Hypernuclei are bound systems of nucleons with one or more hyperons which contain strange quark. Hyperons are unstable particles with a mean lifetime of the order of 10^{-10}s. In the family of hyperons, Λ is the lightest particle and it can stay in contact with nucleons inside nuclei and form hypernuclei. If a nucleus contains one Λ hyperon, it is said to be a single-Λ hypernucleus and a nucleus which made up of two Λ hyperons in addition to nucleons is called a double-Λ hypernucleus. Hypernuclei are considered to be the core of strange matter such as neutron stars that may exist in distant parts of the universe, and could allow physicists to probe the inside of the nucleus. One of the most important purposes of hypernuclear physics is to complete the knowledge of baryon-baryon interactions in a unified way. To do so, it is essential to understand the N-N, Λ-N and Λ-Λ interactions which can be extracted from ordinary nuclei, strangeness -1 hypernuclei and strangeness -2 hypernuclei. At the same time, one of the most important things for the study of strangeness hypernuclei is to identify the nuclear species and measure their masses. Observation of hypernuclei in nuclear emulsion will give significant contribution to strangeness -1 and -2 sectors of nuclear chart. Therefore, the more hypernuclei are expected and hypernuclei searching experiments are well developed.

Nuclear emulsion is a three-dimensional photographic tracking device for charged particles. A hypernucleus having the energy of a few MeV can transverse several micrometers before stopping and decaying. Hypernuclei can be identified in the emulsion by their sequential decay topology. In the year 1998, an experiment, KEK-PS E373 has been performed at High Energy Accelerator Research Organization, Japan to study strangeness hypernuclei by emulsion-

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counter hybrid technique. It aim was to search for strangeness hypernuclei such as double-Λ hypernuclei, twin-Λ hypernuclei, single-Λ hypernuclei and H-dibaryon. During the semi-automatic emulsion scanning of KEK-PS E373 experiment, seven events of double-Λ hypernuclei, two events of twin-Λ hypernuclei and 46 events of single-Λ hypernuclei were detected among the 10^3 Ξ^- hyperon captures. Among them, observation of Nagara event is very famous and epoch-making finding because it is uniquely identified as ${}^{6}_{\Lambda\Lambda}\mathrm{He}$. The data analysing is very interesting and important to extend the strangeness nuclear chart and to complete the knowledge of baryon-baryon interaction. In this paper, five events of single-Λ hypernuclei which were detected in the nuclear emulsion of KEK-PS E373 experiment are analyzed kinematically. The analyzed events have one charged particle decay product and one or more neutral particle decay products according to the conservation laws. We will discuss about the differences between the identified mass and known experimental mass of single-Λ hypernuclei due to contamination of neutron.

Methods of Analysis

Kinematical Analysis

Analysis of strangeness hypernuclei events has a great physical interest. Since, hypernuclei consist of elementary particle hyperons, they are so small and very fast when they traverse the emulsion medium. Their velocity is nearly reaching the velocity of light, so we use relativistic kinematics to perform our analysis. Kinematical analysis is quite essential to identify the hypernucleus events which were observed in nuclear emulsion. Kinematical analysis is an analysis which is performed by using physical quantities due to particles’ motion such as range, velocity, momentum and kinetic energy, etc. After detecting the hypernucleus events in nuclear emulsion, we can measure the range and position angles of charged particle tracks only. Using the relativistic kinematics, kinetic energy, velocity, momentum, mass, binding energy and interaction energy can be derived. So many physical quantities will be obtained using the range data only. How beautiful is relativistic kinematics? We reconstructed the hypernucleus events which were observed in nuclear emulsion using the relativistic kinematics.

Characteristics of Analyzed Events

In this section, the characteristics of five single- Λ hypernuclei which observed in nuclear emulsion of KEK-PS E373 experiment are presented with the help of photograph and schematic diagram.

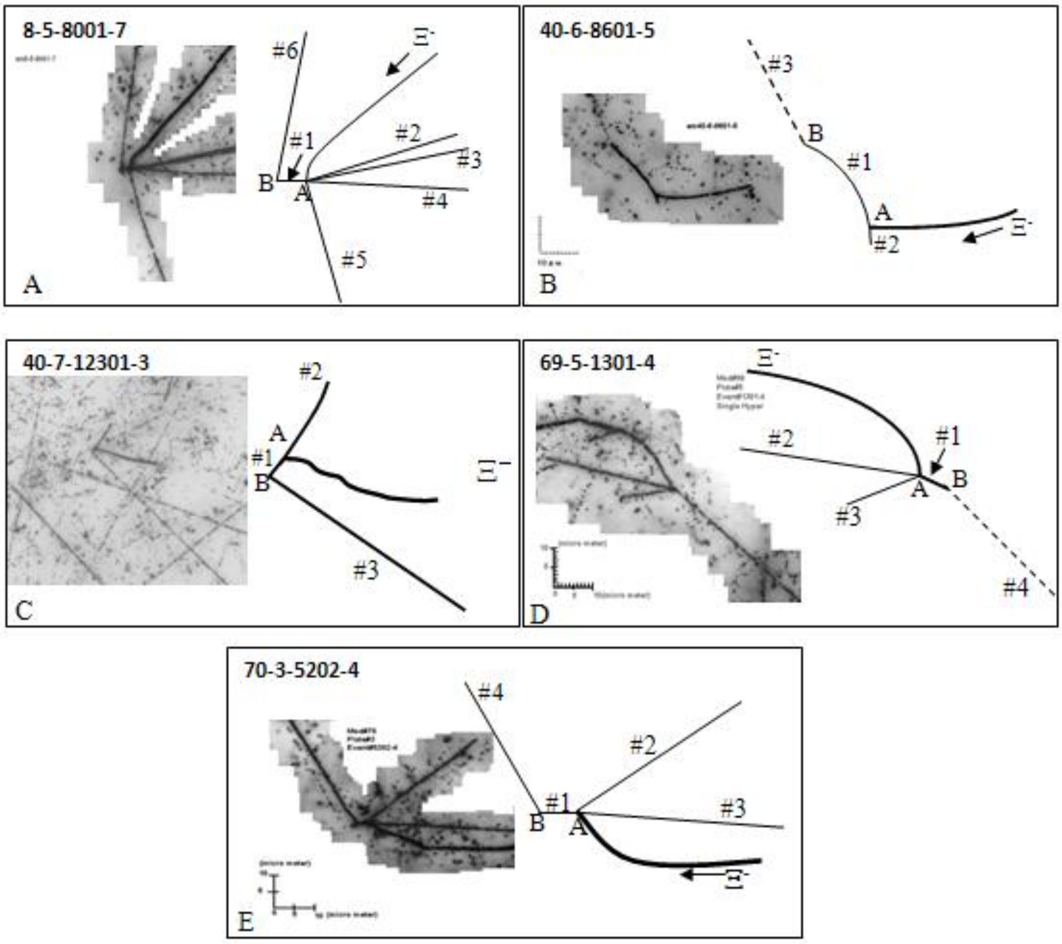

Figure 1 (A-E). Photographs and schematic diagrams of analyzed hypernuclei in nuclear emulsion of KEK-PS E373 experiment

In figure 1(A-E), a Ξ^- hyperon produced in the reaction (K^-,K^+) reaction is captured by an emulsion nucleus at point A, from which charged particles tracks are emitted. Among them, the particle of track #1 shows decay topology at point B, i.e., decays into a charged particle track. In the analyzed events, we found the formation point A and decay point B as the vertices. When the Ξ^- particles comes to rest in emulsion, double-strangeness system will be produced by reaction $\Xi^- p \rightarrow \Lambda\Lambda + 28\text{MeV}$. If one Λ is captured by the nucleus and another one Λ is escaped, the event can be interpreted as a single hypernucleus and this type of events has two decay vertex points in nuclear emulsion. Therefore, we can predict track #1 as a single hypernucleus because of its decay topology. There is no V-topology around the decay vertex. So, another one lambda may decay into neutral particles ($\Lambda \rightarrow n\pi^0$). The measured ranges of single-Λ hypernucleus track #1 and charged particle decay products of analyzed events are shown in the following table1.

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

Event	8-5-8001-7 A	40-6-8601-5 B	40-7-12301-3 C	69-5-1301-4 D	70-3-5202-4 E
R(μm) of Tk#1	6.7±0.1	6.2 ± 0.1	5.1±0.1	5±0.1	3.1±1.0
R(μm) of decay products	4292.6±0.9	8140.6 ± 0.8	2023.7±0.7	5878±0.9	61.5±0.7

Possible Decay Modes and Q-value Calculation

The analysis was performed on the decay vertex B of all events. Because of visible structure and decay topology, track #1 can be identified as a single-Λ hypernucleus. If track #1 is a single-Λ hypernucleus, we have to consider the main characteristics of the decay processes such as mesonic decay and non-mesonic decay. For the mesonic decay mode (decay with the emission of π meson), a single-Λ hypernucleus decays via the pionic channels: $\Lambda \rightarrow p\pi^-$ and $\Lambda \rightarrow n\pi^0$. For the non-mesonic decay process (decay without the emission of π meson), the main decay modes are $\Lambda n \rightarrow nn$ and $\Lambda p \rightarrow np$. At the decay vertex B, we observed only a charged particle track #1. Therefore, track #1 should be a proton, deuteron, triton or helium, etc. For the analyzed events of single- Λ hypernuclei, the following decay mode is allowed at point B.

$$\text{rack \#1} \rightarrow \text{charged particle} + \text{neutral particles} \qquad (1)$$

In this analysis, we take into account the possible single-Λ hypernuclei from ${}^{3}_{\Lambda}\mathrm{H}$ to ${}^{9}_{\Lambda}\mathrm{Li}$ and twenty possible decay modes are obtained. In order to check the decay modes are allowed or forbidden, the Q-values at point B are calculated by the formula

$$Q(\mathrm{MeV}) = [M(\text{track \#1}) - M(\text{charged particle}) - M(\text{neutral particles})]c^2 \qquad (2)$$

According to our calculation, the calculated Q-values are all positive and all possible decay modes are taken into consideration to perform analysis.

Kinetic Energy of Charged Particle Decay Product

In nuclear emulsion, event reconstruction of hypernuclei is based on the conservation laws of energy and momentum, and the mass of hypernuclei are calculated from the energies of their decay daughters. Since the kinetic energy of a charged particle is obtained by measuring its range. So, the range-energy relation is quite important for emulsion analysis. Range-Energy relation in nuclear emulsion is different from range-energy relation in one element medium. Because nuclear emulsion consists of mixture of eight elements and we have to consider the various factors which depend on these elements. To calculate range-energy relation in nuclear emulsion, we firstly use a traditionally used range-energy formula in nuclear emulsion such as

$$R = R_1 + R_2 = \frac{R_s/F}{Z^2(M_p.M_{mass})} + \frac{M}{R_{ext}} \qquad (3)$$

where, $R_1 = \frac{R_s/F}{Z^2(M_p.M_{mass})}$ is the measured range. In this equation, $\frac{R_s}{F}$ is range straggling of proton, $F = \frac{RR \times D - 1}{RR \times D_0 - 1} + \frac{RR(D_0 - D)}{RR.D_0 - 1}.\frac{R_s}{R_w}$ is range of a proton at velocity β, RR is ratio of the volume increment in cubic centimeters to the weight increment in grams, D is emulsion density, D_0 is density of standard emulsion, R_s is proton range in standard emulsion and R_w is proton range in water. In the second term, $R_2 = \frac{M}{R_{ext}}$ is the range of correction of track end. Here, $R_{ext} = Mz^{2/3}C_z$ is the range of electrons captured by the positive charged ions, C_z is a unique function of $\beta/_Z$, independent of the species of the incident particle and β is the velocity of the incident particle relative to the velocity of light.

Kinetic Energy of Neutral Particles

It is known that the neutral particles cannot be seen in nuclear emulsion because of non-electric property, we assumed that the neutral particle decay products go off together in the opposite direction of charged particle track as shown in figure 2.

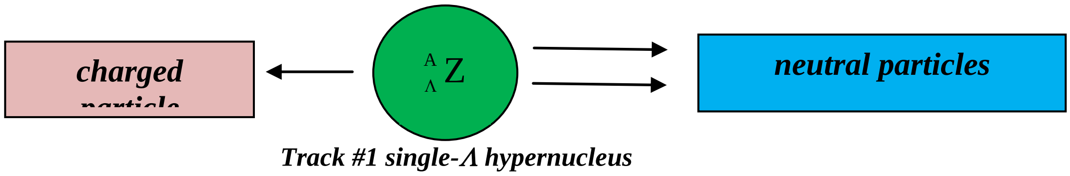

Figure 2 Schematic diagram of decay of analyzed single-Λ hypernuclei events

The kinetic energy of neutral particles are obtained from total energy conservation law such as,

$$E_n = M_n + T_n \tag{4}$$

where, E_n refers to total energy of neutral particles, M_n refers to rest mass energy of neutral particles and T_n refers to kinetic energy of neutral particles. Again, we considered the energy-momentum relation equation and the kinetic energy of neutral particles can be calculated by the formula

$$T_n = -M_n \pm \sqrt{\left(M_n^2 + p_n^2\right)} \tag{5}$$

According to the equations (3) and (5), the kinetic energy of charged particle decay product and neutral particle decay products can be calculated.

Mass of Single-Λ Hypernucleus

The reconstruction of all events was performed at point B by comparing the calculated masses and known masses of single-Λ hypernuclei for all possible decay modes. We assumed that a single-Λ hypernucleus (track #1) at rest decays into a charged particle and invisible particles and the mass of a single-Λ hypernucleus was calculated from kinetic energy value of its decay products by the relativistic total energy equation such as

$$E = T + M \tag{6}$$

$$Mc^2 = T + M \tag{7}$$

$$M\left({}^A_\Lambda Z\right)c^2 = \sum_i \left(M_i + T_i\right) \tag{8}$$

In equation 8, M_i and T_i denotes the mass and kinetic energy of i^{th} particles emitted from the decay of single-Λ hypernucleus and $M\left({}^A_\Lambda Z\right)$ is mass of identified single-Λ hypernucleus.

Identification of Single-Λ Hypernucleus

After calculating the possible masses by extracting the rest mass energy and kinetic energy of decay products, the possible masses of single-Λ hypernuclei track #1 for analyzed events are obtained. In order to identify the hypernuclei species using relativistic kinematics, we have to compare our calculated masses with known experimental masses of single-Λ hypernuclei which are assigned by experimental particle physics group and 15 acceptable modes are obtained. For the decay modes of event E (70-3-5202-4), the calculated masses are very much smaller than the known masses and we rejected those decay modes. The results are summarized in following table 2.

Table 2 Comparison of calculated masses and known masses of analyzed single-Λ hypernuclei

Event	Decay modes			Calculated mass of single-Λ hypernucleus (MeV/c^2)	Known mass of single-Λ hypernucleus (MeV/c^2)	ΔM (MeV/c^2)	ΔM (%)
	Track #1	Charged particle	Neutral				
8-5-8001-7 A	$^{3}_{\Lambda}H$	$^{1}_{1}H$	nn	2864.90±0.07	2991.12±0.07	126.22±0.14	4.2
	$^{3}_{\Lambda}H$	$^{2}_{1}H$	n	2939.79±0.07	2991.12±0.07	51.33±0.14	1.7
	$^{4}_{\Lambda}H$	$^{1}_{1}H$	nnn	3799.18±0.06	3922.53±0.06	123.35±0.12	3.1
	$^{4}_{\Lambda}H$	$^{2}_{1}H$	nn	3839.60±0.06	3922.53±0.06	82.93±0.12	2.1
40-6-8601-5 B	$^{3}_{\Lambda}H$	$^{1}_{1}H$	nn	2886.01±0.07	2991.12±0.07	105.11±0.14	3.5
	$^{4}_{\Lambda}H$	$^{1}_{1}H$	nnn	3817.84±0.06	3922.53±0.06	104.69±0.12	2.7
	$^{4}_{\Lambda}H$	$^{2}_{1}H$	nn	3878.05±0.06	3922.53±0.06	44.48±0.12	1.1
40-7-12301-3 C	$^{3}_{\Lambda}H$	$^{1}_{1}H$	nn	2848.29±0.07	2991.12±0.07	142.83±0.14	4.8
	$^{3}_{\Lambda}H$	$^{2}_{1}H$	n	2986.54± 0.07	2991.12±0.07	4.58±0.14	0.2
	$^{4}_{\Lambda}H$	$^{1}_{1}H$	nnn	3784.43±0.06	3922.53±0.06	138.10±0.12	3.5
	$^{4}_{\Lambda}H$	$^{2}_{1}H$	nn	3809.77±0.06	3922.53±0.06	112.76±0.12	2.8
69-5-1301-4 D	$^{3}_{\Lambda}H$	$^{1}_{1}H$	nn	2878.35±0.07	2991.12±0.07	112.77±0.14	3.8
	$^{3}_{\Lambda}H$	$^{2}_{1}H$	n	2968.87±0.07	2991.12±0.07	22.25±0.14	0.7
	$^{4}_{\Lambda}H$	$^{1}_{1}H$	nnn	3807.51±0.06	3922.53±0.06	115.02±0.14	2.9
	$^{4}_{\Lambda}H$	$^{2}_{1}H$	nn	3857.01±0.06	3922.53±0.06	65.52±0.12	1.7
70-3-5202-4 E	Could not identify the hypernuclear mass because the calculated masses are very much smaller than known masses of hypernucleus						

Results and Discussions

We have identified the five single-Λ hypernuclei which were observed in nuclear emulsion of KEK-PS E373 experiment during semi-automatic scanning. A type of analysis based on relativity theory, namely "kinematical analysis" is performed in this research. In the analyzed events, a single-Λ hypernucleus (track #1) decayed into a charged particle and invisible neutral particles at point B. Therefore, our analysis is started from decay point B of all single-Λ hypernuclei. Both mesonic and non-mesonic decay modes of track #1 were taken into considerations for our analysis. The hypernuclei tracks are visible and it is concluded that the Ξ^- hyperon is captured by the light emulsion nucleus. As the first step of analysis, the range and position angles of hypernuclei and their decay products particle are measured. In this analysis, we take into account ${}^{3}_{\Lambda}\mathrm{H}$ to ${}^{9}_{\Lambda}\mathrm{Li}$ single-Λ hypernuclei and twenty possible decay modes are obtained according to the charge and baryon conservation. We considered the decay modes which have one to three neutrons to perform analysis. Then, the Q-values for all possible decay modes are calculated and it is found that all calculated results have positive values. Therefore, the possible decay modes are energetically possible and taken into considerations to perform analysis. In our analysis, it is also assumed that the charged particle track is emitted back-to-back with neutral particle decay products. Accordingly the masses of single-Λ hypernuclei are deduced from the kinematics of the decay products. Kinetic energy of charged particles is calculated by range-energy relation and that of neutral particles are derived by momentum conservation. The possible masses of hypernuclei are calculated by mass-energy relation equation and the results are compared with known experimental masses of hypernuclei as presented in table 2.

According to the table 2, event A (8-5-8001-7) has four acceptable decay modes, event B (40-6-8601-5) has three acceptable decay modes, event C (40-7-12301-3) has four acceptable decay modes, and event D (69-5-1301-4) has also four acceptable decay modes. Unfortunately, event E (70-3-5202-4) has three possible decay modes and they are rejected because the calculated masses are very much smaller than the known mass of single hypernucleus.

If all charged particles are emitted as decay products, the calculated masses of single-Λ hypernucleus should be equal to known mass. If neutral particles exist in decay products, the calculated masses of single-Λ hypernucleus should be less than known mass. In our results, the calculated masses are slightly smaller than known mass because of contamination of neutrons in decay products. According to that assumptions, it is found that the possible species of single-Λ hypernuclei is either ${}^{3}_{\Lambda}\mathrm{H}$ or ${}^{4}_{\Lambda}\mathrm{H}$ and the charged particle decay product is possible to be proton or deuteron.

We observed that the smallest mass difference is 4.58 MeV/c^2 and the largest mass difference is 51.33 MeV/c^2 for the mode ${}^{3}_{\Lambda}\mathrm{H}$ hypernucleus decays into one deuteron and one neutron. In this case the calculated masses are 0.15% to 2% smaller than known masses. In the decay of ${}^{3}_{\Lambda}\mathrm{H}$ with one proton and two neutrons, the smallest mass difference is 105.11 MeV/c^2 and the largest mass difference is 142.83 MeV/c^2. In this decay, the calculated masses are 3.5% to 4.8% smaller than known masses. Moreover, in the decay of ${}^{4}_{\Lambda}\mathrm{H}$ with one deuteron and two neutrons, the smallest mass difference is 44.48 MeV/c^2 and the largest mass difference is 112.76 MeV/c^2 so that the calculated masses are 1.1% to 2.8% smaller than known masses.

Furthermore, in the decay of ${}^{4}_{\Lambda}\mathrm{H}$ with one proton and three neutrons, it is found that the calculated masses are 2.6% to 3.7% smaller than known masses. In this decay mode, the smallest mass difference is 104.69 MeV/c^2 and the largest mass difference is 138.10 MeV/c^2. The summarized results are presented in table 3. According to table 3, it is concluded that the mass difference of hypernucleus is quite small for one neutron emission case. If two or three neutrons are emitted as the decay products, the mass differences are slightly larger than one neutron emission case.

Table 3 Percentage of mass difference for each decay mode

Event	Decay modes			ΔM (MeV/c^2)	ΔM (%)
	Track #1	Charged particle	Neutral		
40-7-12301-3	${}^{3}_{\Lambda}\mathrm{H}$	${}^{2}_{1}\mathrm{H}$	n	4.58±0.14	0.2
69-5-1301-4	${}^{3}_{\Lambda}\mathrm{H}$	${}^{2}_{1}\mathrm{H}$	n	22.25±0.14	0.7
8-5-8001-7	${}^{3}_{\Lambda}\mathrm{H}$	${}^{2}_{1}\mathrm{H}$	n	51.33±0.14	1.7
40-6-8601-5	${}^{3}_{\Lambda}\mathrm{H}$	${}^{1}_{1}\mathrm{H}$	nn	105.11±0.14	3.5
69-5-1301-4	${}^{3}_{\Lambda}\mathrm{H}$	${}^{1}_{1}\mathrm{H}$	nn	112.77±0.14	3.7
8-5-8001-7	${}^{3}_{\Lambda}\mathrm{H}$	${}^{1}_{1}\mathrm{H}$	nn	126.22±0.14	4.2
40-7-12301-3	${}^{3}_{\Lambda}\mathrm{H}$	${}^{1}_{1}\mathrm{H}$	nn	142.83±0.14	4.8
40-6-8601-5	${}^{4}_{\Lambda}\mathrm{H}$	${}^{2}_{1}\mathrm{H}$	nn	44.48±0.12	1.1
69-5-1301-4	${}^{4}_{\Lambda}\mathrm{H}$	${}^{2}_{1}\mathrm{H}$	nn	65.52±0.12	1.7
8-5-8001-7	${}^{4}_{\Lambda}\mathrm{H}$	${}^{2}_{1}\mathrm{H}$	nn	82.93±0.12	2.1
40-7-12301-3	${}^{4}_{\Lambda}\mathrm{H}$	${}^{2}_{1}\mathrm{H}$	nn	112.76±0.14	2.8
40-6-8601-5	${}^{4}_{\Lambda}\mathrm{H}$	${}^{1}_{1}\mathrm{H}$	nnn	104.69±0.14	2.7
69-5-1301-4	${}^{4}_{\Lambda}\mathrm{H}$	${}^{1}_{1}\mathrm{H}$	nnn	115.02±0.14	2.9
8-5-8001-7	${}^{4}_{\Lambda}\mathrm{H}$	${}^{1}_{1}\mathrm{H}$	nnn	123.35±0.14	3.1
40-7-12301-3	${}^{4}_{\Lambda}\mathrm{H}$	${}^{1}_{1}\mathrm{H}$	nnn	138.10±0.14	3.5

Conclusion

In this work, five single-Λ hypernuclei which were detected in nuclear emulsion of KEK-PS E373experiment are analyzed kinematically. The analyzed events have one charged particle decay product and one or more neutral particle decay products. Because of contamination of neutrons in decay products we could not identify uniquely. According to our calculation, it is found that the possible species of single-Λ hypernuclei is either ${}^{3}_{\Lambda}\mathrm{H}$ or ${}^{4}_{\Lambda}\mathrm{H}$ and the charged particle decay product is possible to be proton or deuteron. Moreover, we established the differences between calculated mass and known mass of single-Λ hypernuclei in non-mesonic decay as the first time. It is observed that the calculated masses are 0.15% to 2% smaller than known masses for ${}^{3}_{\Lambda}\mathrm{H}\rightarrow{}^{1}_{1}\mathrm{H}+\mathrm{n}$ decay mode. In the decay of ${}^{3}_{\Lambda}\mathrm{H}\rightarrow{}^{1}_{1}\mathrm{H}+2\mathrm{n}$, the calculated masses are 3.5% to 4.8% smaller than known masses. Moreover, in the decay of ${}^{4}_{\Lambda}\mathrm{H}$ with one deuteron and two neutrons, the calculated masses are 1.1% to 2.8% smaller than known masses.

Furthermore, in the decay of ${}^{4}_{\Lambda}\mathrm{H} \rightarrow {}^{1}_{1}\mathrm{H} + 3\mathrm{n}$, it is found that the calculated masses are 2.6% to 3.7% smaller than known masses.

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