Trapping probability of strangeness via Xi^{-} hyperon capture at rest in nuclear emulsion

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Abstract

Double hypernucleus, S = -2 nucleus, is a nucleus that contains two units of strangeness such as double-Λ and Ξhypernuclei. Double hypernucleus is very short-lived nucleus about ~10^{-10} s. In order to investigate such double hypernuclei, photographic plate or nuclear emulsion plate, was used as a detector with high position resolution of less than 1 μm. Our experimental setup was prepared to produce Ξ^- hyperons via the (K^-, K^+) reactions. The trapping probability of two Λ hyperons in nucleus is quite crucial to understand formation mechanism of double hypernuclei through $\Xi^- + p\ \Lambda + \Lambda \rightarrow$ via Ξ^- hyperon capture at rest.

The probability has been studied by the KEK-E176 experiment with the emulsion. In E176, the emulsion was production target of Ξ^- hyperons and detector of double hypernuclei. Therefore, really production of Ξ^- hyperon were able to be checked with study of kinematics at the (K^-, K^+) reaction vertex. In use of 52 σ-stop events emitting nuclear fragment(s) at Ξ^- hyperon captured point, it was reported that the probabilities were 4.8% and 1.7% (90% confidence level) for light (C, N, O) and heavy (Ag, Br) elements, respectively.

To get 10 times higher statistics of E176, the E373 experiment has been performed at KEK. We have obtained ~700 σ-stop events, however nobody didn't know the amount of background event, because it was impossible to check kinematics at the (K^-, K^+) reaction vertex with large error due to scattering in diamond target, not in the emulsion.

Therefore, a method to identify Ξ^- hyperon among the σ-stop events has been developed with multiple coulomb scattering method applying to almost straight

beam tracks. We found two peak shape for the scattering and obtained the number of $432.3 \pm 7.6\,^{+0.0}_{-14.0}$ tracks for real Ξ^- hyperon with 3.2% systematic error by contamination of Σ^- hyperons.

Remained tracks was well understood to be consistent with background by an independent detection of it. Well-known two events, Nagara and KISO, are understood via really captured of Ξ^- hyperon, and the candidate event of the formation of H dibaryon was found to be not candidate due to very low possibility caused by Ξ^- hyperon. Finally, we got trapping probability for two Λ hyperons and at least 1 Λ hyperon captured at rest in nuclear emulsion were found to be 5.0 ± 1.7 %, 69.4 ± 8.1% for light nuclei captured and for heavy nuclei captured were to be 4.2 ± 1.4 % and 51.1 ± 5.7% respectively.

CONTENTS

1. INTRODUCTION

Hypernuclei are composed of hyperons (Y), neutrons and protons. Ordinal nuclei which consist of nucleons (N) (proton and neutron) are well studied about the interaction between nucleons for more than several decades. Regarding nuclei with hyperons, they give information about the interaction between N and Y. This study has been steadily progressing for these two or three decades. In the history of investigation for normal nuclei and single-Lambda hypernuclei, there have been detected for ~3000 and 35 nuclides, respectively. Regarding double-Lambda hypernuclei and twin-single hypernuclei, so far only 9 and 5 events were found in the emulsion, respectively. Therefore, at present, one of the most important subjects in nuclear physics is the study of the nuclear systems with double units of strangeness. The nuclei including two hyperons (*ex*. ΛΛ) or a Ξ hyperon located at the bottom in the octet scheme of baryons as shown in Fig 1.1 give us information for not only Λ-Λ interaction but also Ξ- nucleon (N) interaction. Since the mass differences for M(ΞN) - M(ΛΛ) and M(ΣN) - M(ΛN) are so small as ~25 MeV and ~80 MeV, respectively, we will expect to study hyperon-hyperon mixing condition such as ΛΛ ⇔ ΞN ⇔ ΣN, so far as including H dibaryon.

When we get such information, the baryon baryon interaction in the Baryon Octet scheme would be firmly understood. On the other hand, it is understood, theoretically, that neutron stars formed after supernova explosion should include hyperons to keep their heavy and dense configuration, explain their cooling speed and so on. On the points of view, the Nagara event which was uniquely identified as the ^{4}He nucleus with two Λ hyperons informed us the interaction between two Λ hyperons to be attractive, thus Λ hyperons should exist and play important role of the subject in neutron stars. Regarding Σ hyperon, the interaction with nucleon was found to be repulsive nearly ten years before, it should not be a candidate particle in the neutron stars. There is no conclusive information about the role of Ξ hyperons, so far.

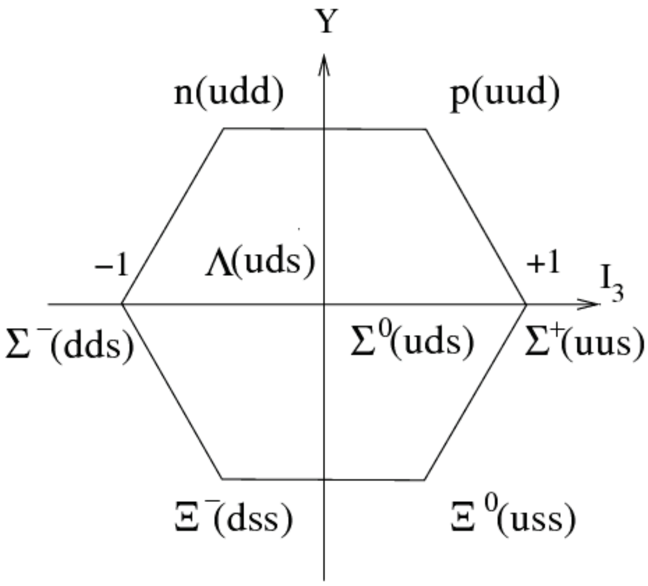


Fig 1.1 Octet scheme of Baryons

1.1 History of Hypernucleus

In order to detect hypernuclear events, the physicists M. Danysz and J.Pneiewski exposed cosmic rays to photographic emulsions around 26km above the ground. For the first time, they observed hypernuclear event in that photographic film. This observed event is shown in Fig. 2 and “A” is the star of the primary interaction of the high energy cosmic ray “p” colliding with a nucleus of the emulsion such as Ag and Br; “f” is the track of the produced hypernucleus; “B” is the vertex of the decay of the hypernucleus.

The other non-strange nuclear fragments stop in the matter. A high energy proton, colliding with a nucleus of the emulsion, breaks it in several fragments forming a star. All the nuclear fragments stop in the emulsion after a short path, but one decays, revealing the presence of an unstable particle, Λ hyperon, stuck among the nucleus. For this reason, this particular nuclear fragment, and the others obtained afterwards in similar conditions, were called hyperfragments or hypernuclei.

The Λ particle is the lightest particle among the hyperons. A hypernucleus is a normal nucleus, with atomic weight, A, and atomic number, Z, with the addition of one or more hyperons, such as Λ, Σ, Ξ, or Ω. For example, the hypernucleus ${}^{12}_{\Lambda}C$ has 12 baryons, with one of them being a Λ hyperon. Fig. 2 shows a transition which changes a neutron into Λ, leaving the hypernucleus ${}^{12}_{\Lambda}C$ in its ground state. It has atomic number 6, as noted by the label C, although for a hypernucleus the atomic number is a measure of the charge and not necessarily the number of protons. Neutrons, protons and hyperons are considered distinguishable particles

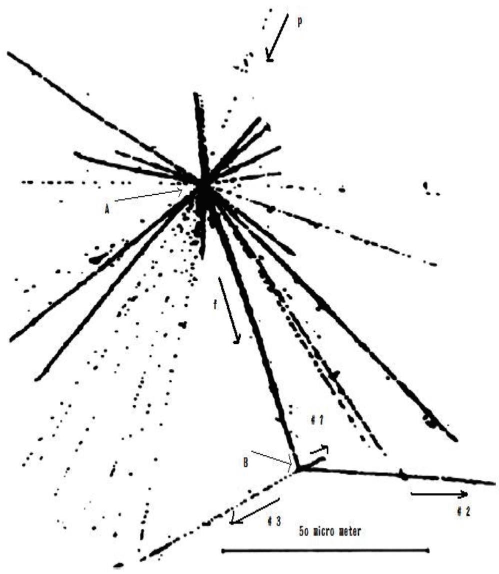


Fig 1.2 The first hypernuclear event observed in a nuclear emulsion

Each is placed in a potential well in which the Pauli Exclusion Principle is applied. The hyperon occupies the lowest shell (1s) when the hypernucleus is in its ground state. Since strangeness nuclear physics lies at the intersection of nuclear and elementary particle physics, it has a broad impact and also significant implications for astrophysics. A hyperon inside nuclei presents a unique probe and makes it possible to study and test nuclear models. The final hypernucleus is not necessarily the same as the one initially produced.

Therefore, hypernuclei can be studied either by:

(1) Production mechanisms where the reaction is identified by measuring the reaction products, or

(2) Decay mechanisms of the products to identify the hypernucleus.

It is very difficult to study the YN and YY interactions by two body scattering experiments experiments, because of the difficulties of the preparation of low energy hyperon beams and that no hyperon targets are available due to the short lifetimes of hyperons. Thus, one of the main goals to study the structure of these strangeness nuclei via nuclear emulsion is to understand the baryon-baryon interaction in a unified model through hyperon(Y)-hyperon(Y) interaction and hyperon(Y)-nucleon(N) interaction. Especially, ΛΛ interaction provided by the mass measurement of a double-Λ hypernucleus and ΞN interaction which can be obtained from Ξ^- hypernuclei and Ξ^- atoms are interesting as the gate way to complete the knowledges of baryon-baryon interaction. The sector of S=-2 nuclei, double Λ hypernuclei and Ξ^- nuclei is also just the entrance to the multistrangeness world. In order to understand it, studying the structure of double Λ hypernuclei and Ξ^- hypernuclei is quite essential [1, 2].

1.2 Production of Double Hypernuclei

In general, Ξ^- hyperons are produced from an elementary process $K^- + p \rightarrow \Xi^- + K^+$. This elementary process is called the combination of strangeness exchange and associated production of strangeness process. In order to produce a hypernucleus, the Ξ^- hyperon emitted from the reaction must remain the nucleus system. Such a nucleus contain Ξ^- hyperon is called Ξ^- hypernucleus. They decay into double-hypernuclei, twin single-hypernuclei or just single hypernuclei with the escape of one Λ particle. The binding energies of the possible Ξ^- hypernuclei were extracted by assuming that they decay into two hyperfragments [3].

The study of double strangeness S=−2 hypernuclei is quite crucial not only for understanding baryon-baryon interactions but also for investigating ever multistrangeness system. The (K^-, K^+) reaction leads to the direct formation of Ξ^- hypernuclei. As for Ξ^- hypernuclei, there have been a few events attributed to the formation of Ξ^- hypernuclei in the interaction of mesons with emulsion nuclei.

The events in the unbound region are mainly due to free Ξ^- production. The events in the bound region are the signal of either double Λ-hypernuclei, Ξ^- hypernuclei or H dibaryon production. An emulsion-counter hybrid experiment was carried out at the KEK Proton Synchrotron by using a 1.66GeV/c separated K^- beam in order to study S=–2 systems [4, 5]. The Ξ^- emission probability from the target nucleus strongly depends on the mean free path of the Ξ^- in the nucleus.

2. Experiments for searching double-Λ hypernuclei

2.1 Nuclear Emulsion

Nuclear emulsion films are the best three-dimensional charged particle detectors and it is one of the most important instruments for detecting short-lived particles in nuclear physics. Consequently, it has been mainly used as a detector to search for short-life particles which have the submicron resolution (of the order of 1um). The emulsion is very sensitive for all charged particles. Therefore, we can see the tracks of charged particles at production and decay of double-Λ hypernuclei in emulsion through an optical microscope.

Both sides of the polystyrene films are sandwiched with emulsion gel and the base is not sensitive for all charged particles and it is a dead space. The main components of the nuclear emulsion gel are basically the same as ordinary photographic films, gelatin and silver halide micro-crystals (usually bromides AgBr) are suspended in gelatin with uniform in size. When a charged particle passing through nuclear emulsion, silver ions (Ag+) contained in AgBr crystals became silver atoms (Ag) by the reduction reaction of silver and formed a small cluster of metallic silver atoms called a latent image which is an invisible image. Table 2.1 shows summary of the constitutions of the emulsion gel.

Table 2.1: The composition of the ET-7C/D emulsion

Material	Weight ratio (%)	Mol ratio(%)
I	0.3	0.06
Ag	45.4	11.2
Br	33.4	11.1
S	0.2	0.2
O	6.8	11.3
N	3.1	5.9
C	9.3	20.6
H	1.5	40.0

2.2 Nuclear Emulsion Experiments

2.2.1 E176 Experiment at KEK-PS

Investigation of double strangeness system is influential to give more information about Λ-Λ interaction and Ξ-N interactions that are very important to study baryon-baryon interaction. For the detecting strategy of double-Λ hypernuclei and Ξ hypernuclei, nuclear emulsion has been using as a detector and it makes the visible path of charged particles through emulsion layers. Moreover, extra-sensitive photographic emulsion can detect very short tracks in the production and decay processes of those hypernuclei with high spatial resolution better than 1 μm. The produced Ξ^- hyperons via p (K^-, K^+) Ξ^- reactions lead to the direct formation of Ξ hypernuclei. The captured events give a probability for making hypernuclei with S=-2 and S=-1 via Ξ^- hyperon capture at rest. The KEK E176, emulsion counter hybrid experiment, was carried out to study 1.66 GeV/c K^- beam induced (K^-, K^+) reactions in the nuclear emulsion target. In the setup of this experiment, nuclear emulsion was used as the target and detector for the production and decay process of Ξ^- hyperons via (K^-, K^+) reactions [6]. On the other hand, the short-lived H dibaryon was searched around the Ξ^- hyperons capture points in this experiment. Ξ^- hyperons can be identified by this kind of criteria for the STOP events and one evidence of double hyperfragment was found in the identified 796 (K^-, K^+) reactions [7, 8].

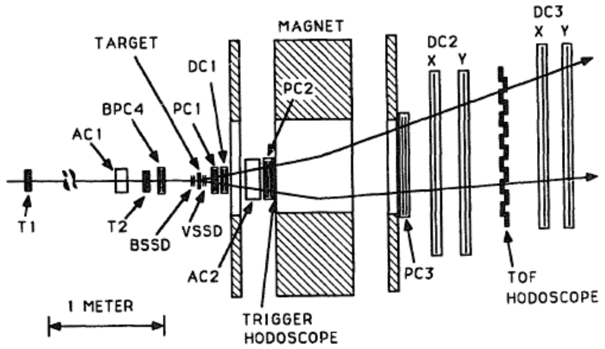


Fig 2.1 Experimental Setup of KEK-E176 experiment

2.2.2 E373 at KEK-PS

The second experiment, KEK E373 experiment,Fig 2.2, was performed with the aim to get higher statistics of double-Λ hypernuclei, twin hypernuclei and H dibaryon than the past E176 experiment at KEK, by using the upgraded hybrid-emulsion technique. The setup was prepared to create Ξ hyperons via the (K^-, K^+) reaction with diamond target and brought to be resting in nuclear emulsion. A scintillating-fiber-block detector measured the position and angle of the produced Ξ hyperons. The decay process of the hyper fragments was observed in nuclear emulsion and as the expected objective of the experiment, higher statistics of the previous experiment were detected in this experiment. As we could not find the production reaction of Ξ hyperons in nuclear emulsion, particle identification technique is necessary to pick up the Ξ hyperons captured events. To recognize primary particles of the captured events, multiple coulomb scattering has been measured for the Ξ hyperon candidate particles of the KEK-E373 experiment. The well-known event, Nagara event, could be detected as the first observation of weak decays of the double-Λ hypernucleus with respects to the Λ-Λ interaction and the existence of H-nucleus, one candidate event was detected.

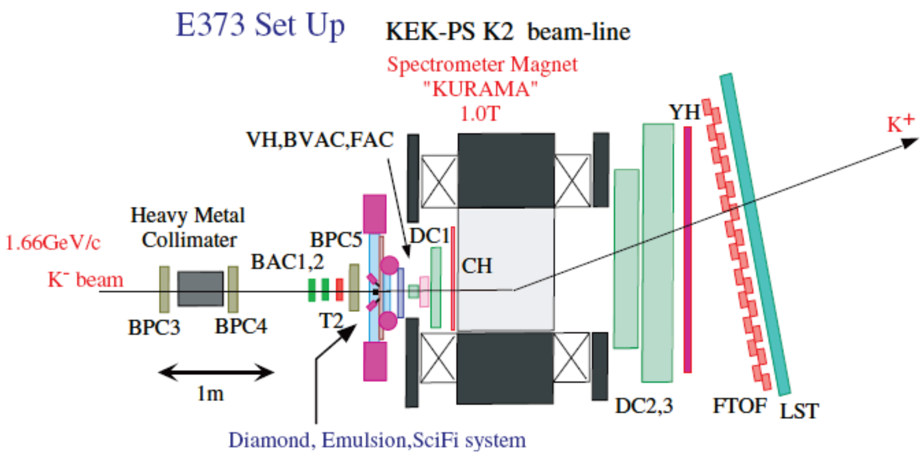


Fig 2.2 Experimental Setup of KEK-E373 experiment

2.2.3 E07 at J-PARC

We had been carrying out the E07 experiment to find nuclear mass dependences of Λ-Λ and Ξ-N interaction with ten time's higher statistics than that of KEK-PS E373. In the experiment, the number of Ξ- hyperon stopping at rest is about ten thousands (~ 10^4) which is ten times larger than that of E373. Such number of tracks for Ξ^- hyperon candidate should be followed in nuclear emulsion plate up to their stopping point. The experimental setup is shown in Fig 2.3. We expect we will get 10 times higher statistics of the E373 experiment. We had planned the set up to get higher statistics than E373 experiment as shown in the following table 2.2.

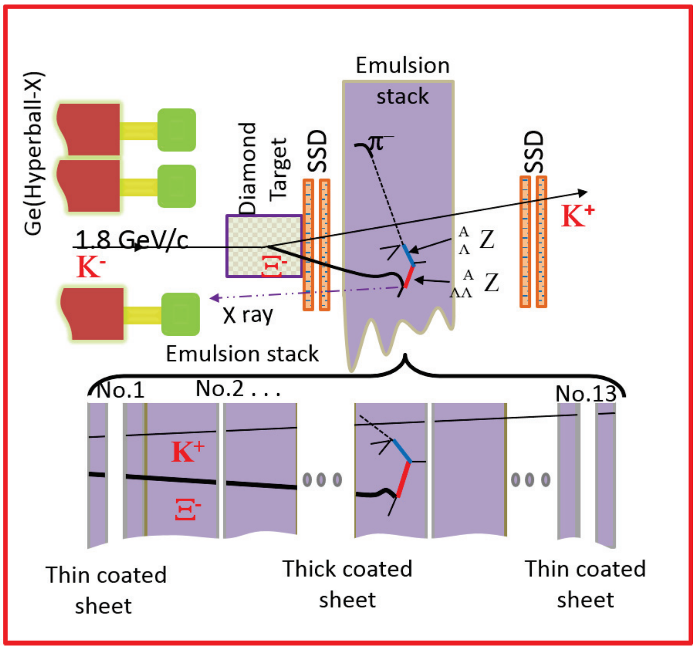


Fig 2.3 Experimental Setup of KEK-E373 experiment

Table 2.2 : Specification of the KEK-PS E373 & J-PARC E07

Experiment	KEK-PS E373(1999-2000)	J-PARC E07(2016-2017)
K^- : π- ratio	K^-: $\pi-\approx$ 1:4 (25% K- purity)	K^-: $\pi-\approx$ 6:1(60% K-purity)
	KEK K2 beam line	J-PARC K1.8 beam line
Emulsion size	245 x 250 mm^2	345 x 350 mm^2
Emulsion gel	0.8 ton (Fuji ET-7C & ET-7D)	2.1 ton (GIF-003T)
Stack structure	1thin + 11 thick	1thin + 11thick+ 1thin
Number of stack	100	~120
Detector	Sci-Fi detector	Hyperball-X
Ξ- stop events	$\sim 10^2$	$\sim 10^4$
Detected $\Lambda\Lambda$ Nucleus	7	$\sim 10^2$
Identified $\Lambda\Lambda$ Nucleus	1(Nagara event as ${}_{\Lambda\Lambda}{}^{6}$He)	~10

2.3 Scanning Systems for Hypernuclear Events

The emulsion scanning system is necessary to detect hypernuclear events and trace a huge number of Ξ^- hyperon tracks in nuclear emulsion. In the emulsion scanning system, two kinds of method are applied for the system; the first one is Hybrid emulsion method and the second is “Overall scanning” method.

The Hybrid emulsion method has been applied to search for double-Lambda and twin hypernuclei, effectively. The Ξ^- hyperons are produced in a diamond target via the ‘p’ (K^-, K^+) Ξ^- reaction, which is triggered with a spectrometer system. Those Ξ^- hyperons are brought to be rest and captured in the emulsion and then they will produce the hyperfragments as double-Lambda, twin hypernuclei and single-lambda hypernuclei.

Therefore, an electronic detector, Silicon Strip Detector (SSD) will be used to detect incident point of Ξ^- hyperon into the emulsion. Angle of the Ξ^- hyperon reconstructed by SSD are checked in the top plate of the emulsion stack under microscopic view. If the angle of a track in the emulsion is comparable to the angle of the reconstructed track, the track in the emulsion can be traced up to the stop points.

In the E07 experiment scanning, after one year for the emulsion scanning with Hybrid emulsion method, we have a plan to apply the “Overall-Scanning” method. It is a new method that is intended to search for more events of the double-Lambda and twin hypernucleus in the emulsion.

In this method, a computer-controlled optical microscope scans full volume of emulsion layers with high-speed and the high-resolution camera for taking their microscopic images. A dedicated image process picks up hypernuclear events with multi vertices. At the moment, although development for this method is on-going, new double-Lambda and twin hypernucleus can be obtained by increasing scanning area. The icroscope system is shown in the following figure.

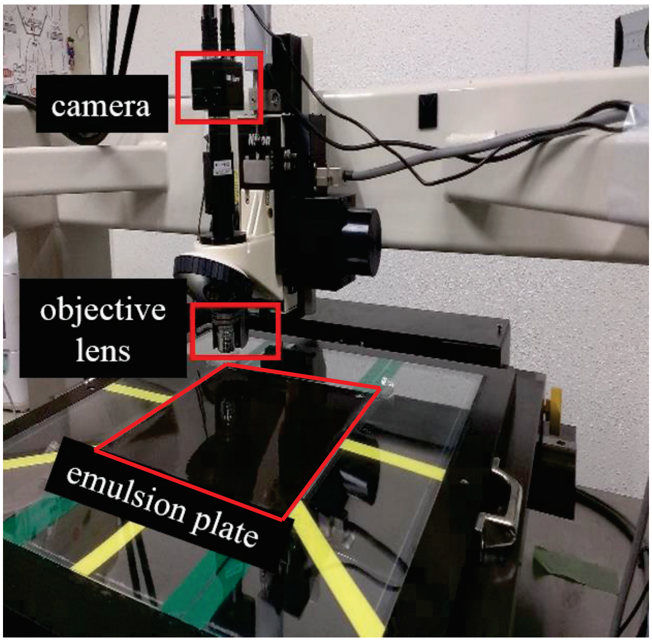


Fig. 2.4 An optical microscope system

2.4 Topologies of at rest events of Ξ^- hyperons

After scanning all the candidates events of Ξ^- hyperons, several kinds of hypernuclear events were classified according to their visible visible structure topologies at the stopping points. The first kind of stop event was named as σ stop and the second was also as ρ stop in the nuclear emulsion. After carefully scanning at rest of the stopping points,

ρ stop: No charged particle tracks except for auger electron at the stopping point.

σ stop: The event with one or more charged particles track is called "σ stop" and the original particle is well understood as negatively charged particles. Among those events, σ stop events can be classified into four types. They are-

(i) No Hypernuclear event: There is only one vertex exist in the captured point of Ξ hyperons.

(ii) Single Hyper event: There are two vertices, production and decay of strangeness nuclei at the captured points.

(iii) Double Hyper event: Three vertices, production point of double strangeness, decay vertex of double strangeness and non-strangeness nucleus decay series from strangeness particles.

(iv) Twin Hyper event : There are also three vertices topologies as the same with double hypernuclear case at the stop points, event with emission of two single hyper nuclei in the opposite direaction from the rest point of Ξ^- hyperon.

Decay: Events with thin tracks (π^-) at the end point of the straight tracks of Ξ^- hyperon are assigned as decay events.

Secondary interaction (SI): No beam track at the reaction point of the straight track is categorized as "secondary interaction", in-flight interaction with emulsion nuclei. If a thick and deflected track accompanies at the vertex, it could be σ-stops of a Ξ^- Hyperon produced via the (K^-, K^+) reaction in the emulsion stack. In real, the traced track is one of the fragments emitted from the Ξ^- hyperon capture point or decay of hypernuclei in the secondary interaction case.

Beam interaction (BI): A primiary beam, K^- particle with high momentum, interacts with emulsion nuclei. A beam track can be categorized as a black track almost perpendicular to the emulsion plate.

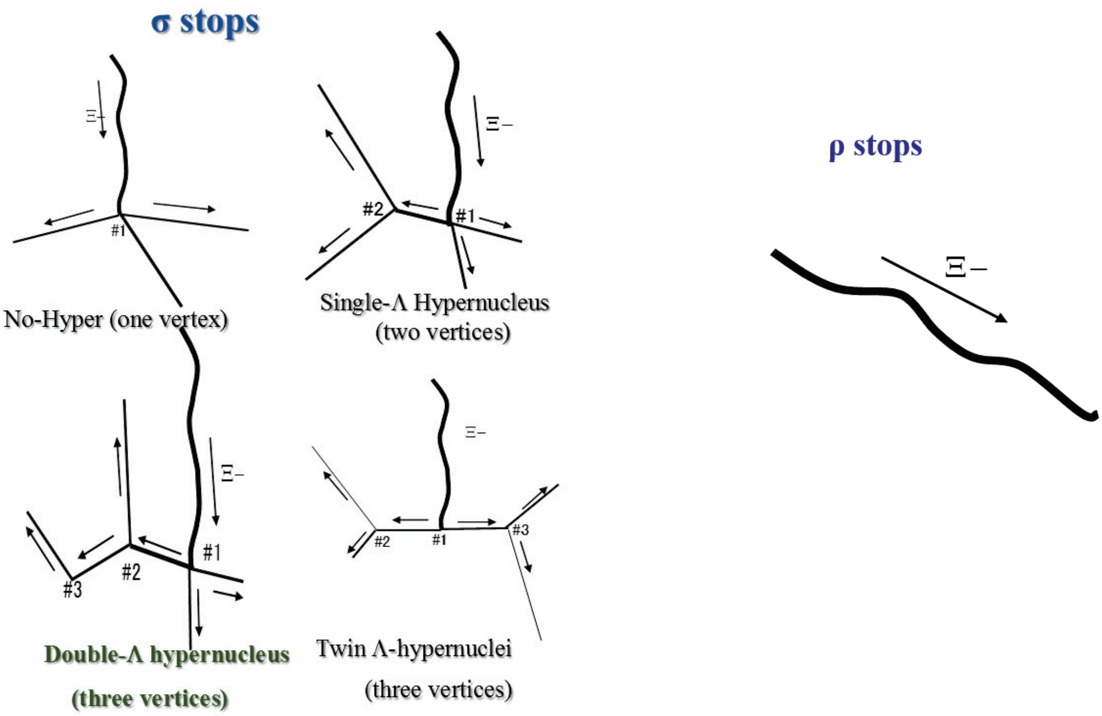


Figure 2.5: Topologies of stop events observed in nuclear emulsion

2.5 Hypernuclear Events in Nuclear Emulsion via Ξ captured processes

In particular, ΛΛ interaction is interesting as the doorway to study YY interaction. A typical event of double-Λ hypernucleus is presented in Fig.2.6. In this event, a Ξ^- hyperon was captured at point A. From point A, three charged particles (tracks #1, #2 and #3) were emitted and track #1 is the double-Λ hypernucleus. Among them, track #1 (double-Λ hypernucleus) decayed into π^- meson (track #6) and two other charged particles (tracks #4 and #5) at point B. The particle of track#4 represents single-Λ hypernucleus and it decayed again into two charged particles (tracks #7 and #8) at point C. By this nagara event, ΛΛ interaction is uniquely identified as 0.67 ± 0.17 MeV.

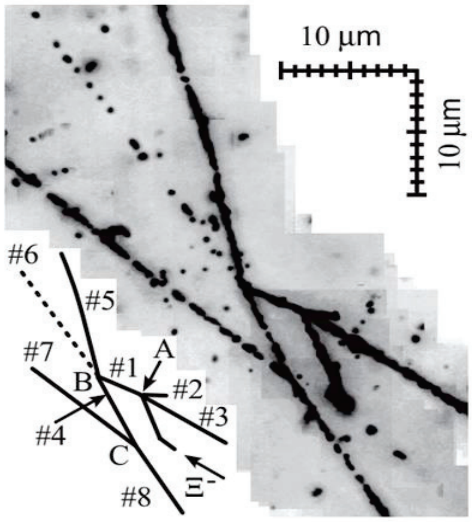


Fig. 2.6. Well-known double-Lambda hypernuclear event named NAGARA

We have observed a deeply bound state of the Ξ^--^{14}N system that decay into twin single hypernuclei in nuclear emulsion exposed in the E373 experiment at KEK-PS. The process is uniquely identified as $\Xi^- + {}^{14}\mathrm{N} \rightarrow {}^{10}_{\Lambda}\mathrm{Be} + {}^{5}_{\Lambda}\mathrm{He}$. We had measured the binding energy of the Ξ^--^{14}N system, B_{Ξ}, to be 4.38±0.25 MeV, which is significantly larger than that of the Ξ^--^{14}N 3*D* atomic state (0.17 MeV), if both single-hypernuclei are emitted in the ground state from at rest capture of a Ξ^- hyperon. If the ${}^{10}_{\Lambda}\mathrm{Be}$ nucleus is produced in an excited state, the B_{Ξ^-} value mentioned above decreases by the excitation energy. Although there is no experimental data for its excited states, model calculations based on known values for ^{9}Be excited states have predicted two excited states in the bound region with consistent excitation energy. Even in the case of ${}^{10}_{\Lambda}\mathrm{Be}$ production in the highest excited state, the B_{Ξ^-} value is far from the 3*D* atomic level of the Ξ^--^{14}N system by more than 3.7 standard deviations. The event provides the first clear evidence of a deeply bound state of Ξ^{-}-^{14}N system by an attractive ΞN interaction.

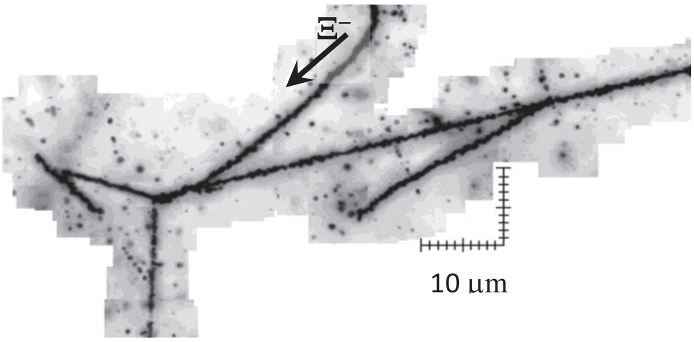


Fig. 2.7 Twin-single hypernuclear event named KISO event

2.6 Trapping Probability obtained by E176 experiment

In the KEK-PS E176 experiment, the nuclear emulsion was used as a detector for production and decay of the double-Λ hypernuclei and as well as for (K^{-}, K^{+}) reactions target. Therefore, we can detect almost stopping are originated from Ξ^{-} hyperons of (K^{-}, K^{+}) except Σ^{-} contamination as a systematic error. In this experiment, the number of Ξ^{-} hyperons capture at rest events was finally determined to be $77.6 \pm 5.1^{+0.0}_{-12.2}$ ($52.0 \pm 0.0^{+0.0}_{-5.0}$ for σ- stop and $25.6 \pm 5.1^{+0.0}_{-7.2}$ for ρ- stop). Among them, in order to calculate trapping probability via light nuclei captured, events with S=-1 and S=-2 are described below:

Double-Λ hypernucleus	1 event
twin single-Λ hypernucleus	2 events
single-Λ hypernucleus	7 events
σ-stop events with E-visible ≥ 28 MeV	8 events.

Consequently, via those events, the lower limits for trapping probabilities of 2 Λ and at least 1 Λ hyperon in Ξ^- hyperon captured at light emulsion nuclei were found to be 4.8% and 48.4% (90% confidence level) respectively.

Similarly, the number of heavy double-hypenuclei and σ- stop with E_{vis} beyond 28 MeV are as follows.

Double-Λ hypernucleus	3 event
σ-stop events with E-visible ≥ 28 MeV	19 events

By these observed events, the lower limits for trapping probabilities of 2 Λ and at least 1 Λ hyperon by the heavy nuclei were found to be 1.7% and 35.7% (90% confidence level) respectively.

3. Particles Identification Method and Trapping Probability

3. 1 Analysis of stopping Ξ^- events in the emulsion of E373 experiment

In order to get 10 times higher statistics of the E176, we had performed the E373 experiment at KEK-PS. Consequently, we obtained ~700 stopping events from the KEK_PS E373 experiment. Even though it was not known about the amount of the background with certainly the capture of Ξ hyperons because we couldn't construct the kinematic analysis to confirm the Ξ^- hyperons captured processes. The main reason was that 'p' (K^-, K^+) Ξ^- reaction vertices were in diamond target, but not in the emulsion, then it was not available to check kinematic analysis sufficiently, due to scattering in the target.

Therefore, as the first step, in order to purify the real Ξ^- hyperons, we had developed the particles identification technique. To get trapping probability, we applied this PID method to identify Ξ^- hyperons in the stopping events by measuring the multiple coulomb scattering with respect to almost straight beam tracks. We applied this method for all σ-stop events with checking by known double hypernuclei and obtained trapping probabilities if two Λ hyperons for both light and heavy elements in the emulsion. In the following section, the evaluation of this method will be introduced and trapping probabilities will be discussed in the next section.

3.2 Ξ^- hyperons identification with Multiple Coulomb scattering measurement

Ξ^- hyperons in the emulsion were mainly classified to be σ-stop, ρ-stop and decay with a π^- thin track as discussed in the previous section. The classified results of

E176 and E373 in table 3.1 with simulated ratio. In the decay events, it was found that there is no background for Ξ^- hyperons. By taking the scanned results of the E176 and the ratio into account, we are able to estimate the number of the stop and σ-stop events to be about 180 and 120 respectively, for E373 experiment. Although it may turn out that ~640 events are mixed in σ-stop events as background, it will be not reliable, because this methods in both experiments are quite different for selection of Ξ^- hyperons. In the ρ-stop events, the amount of Ξ^- candidates had been found as stopped events, where almost all of them would be positive charged particles as protons. Therefore, we have performed measurement of multiple coulomb scattering for 695 σ-stop events, which would have enough track length 2.0 mm from stopping point in the emulsion. The following table shows the scanned results for Ξ^- hyperons in the emulsion. In the E176, the number of true Ξ^- hyperons are listed after kinematics analysis. The first and second errors are by statistics and contamination of Σ^- hyperons, respectively. Raw data, Ξ^- hyperon candidates, is presented for E373. The ratios of the number of decay events to stop events are shown by Monte-Carlo simulation as 'M.C ratio' for both experiments.

Table 3.1 Scanned results of the E176 and E373 experiment.

	E176		E373	
	Ξ^- hyperon	M.C ratio	Ξ^- candiates	M.C ratio [4]
σ-stop	$52 \pm 0.0\ _{-5.0}^{+0.0}$		766	
ρ-stop	$25.6 \pm 5.1\ _{-7.2}^{+0.0}$	1	12843	1
Decay	284	6	807	7.5

3.3 Multiple Coulomb scattering in Nuclear Emulsion

When charged particles are passing through a finite thickness of matter, they suffer repeated elastic Coulomb Scattering. The cumulative effect of these small angle scatterings is a net deflection from the original particle direction. Therefore we are able to recognize scattering of charged particles when they pass through the emulsion. Trajectory of a charged particle in the emulsion will be seen as shown in the Fig 3.1.

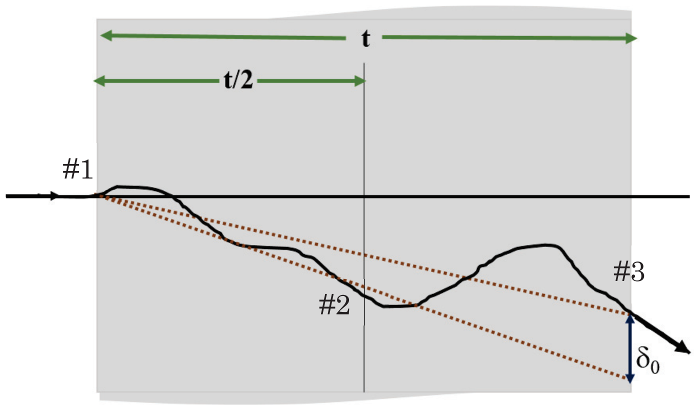


Fig. 3.1. Multiple coulomb scattering in Emulsion

$$\theta_0 = \frac{13.6[MeV/c]}{\beta p} z \sqrt{t/X_0}\left[1 + 0.038\ln(t/X_0)\right] \qquad \text{Eq. 1}$$

$$\delta_0 = \frac{1}{2\sqrt{3}} t\theta_0 \qquad \text{Eq. 2}$$

In the above equations, p, β and z express momentum, velocity and charge number of the incident particle, respectively. *t /X0* is the thickness of the scattering medium in radiation length scale. We calculated the second difference as a function of range, the distance from stopping point of the particles in nuclear emulsion for the range 100μm to 4000μm with corresponding cell length, t. Energy and momentum of particles for their corresponding ranges are calculated using range-energy relation based on Barkas literature.

In our calculation method, in the cell with length of t, the second difference δ_0 in Fig 3.1 is defined to be shift between two sagittas given from position #1, #2 and # 3. If they have enough high velocity, eg. $\beta \sim 1$, fixed value of t may give almost constant δ_0 [10]. This method will be discussed in the next section.

3.4 Constant Sagitta Method

As discussed in the previous section, if they have enough high velocity, eg. $\beta \sim 1$, fixed value of t may give almost constant δ_0. However, the velocities of stopping points Ξ candidates are very low, δ_0 may frequently be changed with single large angle scattering. Therefore we tried to apply the Constant Sagitta Method, in which t is changed to give constant δ_0 [11, 12]. To obtain such δ_0, the cell length will be defined as following,

$$t_i = \left[\sigma_0 \left(\frac{1}{0.00348 \times K_s}\right) R_i^{0.58} \times Z^{0.16} \times M^{0.42}\right]^{\frac{2}{3}} \qquad \text{Eq. 3}$$

This is an empiric formula with σ_0 which is set to correspond to an expected δ0 values. In this equation, range (R), Z and M are range from stopping point, charge and mass of the particle, respectively. Scattering constant, Ks will be assigned to well present measured second difference of particle to be σ_0. If we take M to be the mass of Ξ hyperons for the trajectories of π meson, obtained second difference will be different with that of real Ξ hyperons. And, in our calculation, we followed the procedures; second difference δ_0 is maintained to be constant and the cell length *t*, is chosen for various ranges getting from the coordinates of tracks in nuclear emulsion.

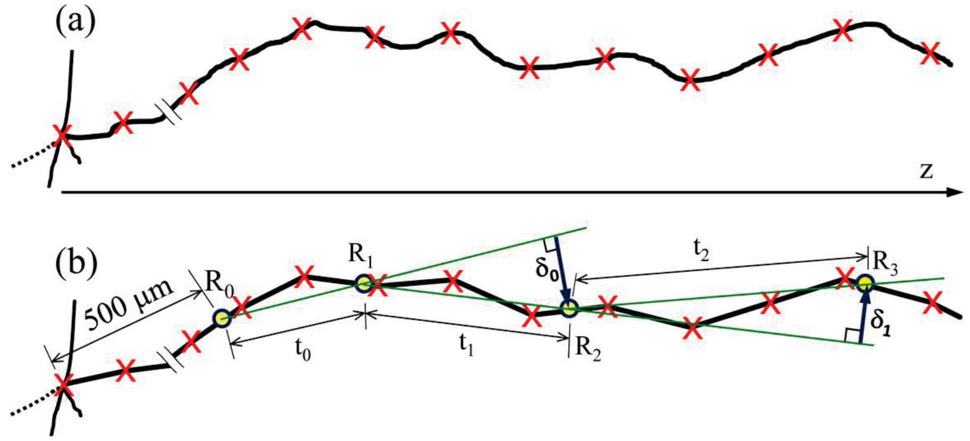


Fig. 3.2. A schematic drawing of σ-stop counting by a negative particle form the right

In this scheme, 'x' marks show measured positions in 20 μm step along the beam. The arrow of the z-direction points from the down to upstream of the emulsion stack. The cell-length t_i is calculated by Eq. 3. The 'o' marks assigned for R_i shows the position from the stopping point with the length of R_i.

3.5 Measurement of Multiple Coulomb Scattering of parent particle tracks of KEK-E373 Experiment

When a charged particle is passing through the nuclear emulsion, its deflection generates into many small scattering due to Coulomb interaction. In our research, we have measured such scattering of Ξ^- hyperon candidate tracks with 20μm step in the light axis of microscope. As the first step of measurement, we had measured the primary particles of the stop events from their stopping points to their origin with 20 um step of z-axis as illustrated in Fig. 3. At the same time, secondly, beam tracks measurement for distortion correction is carried out with the similar procedure of track measurement.

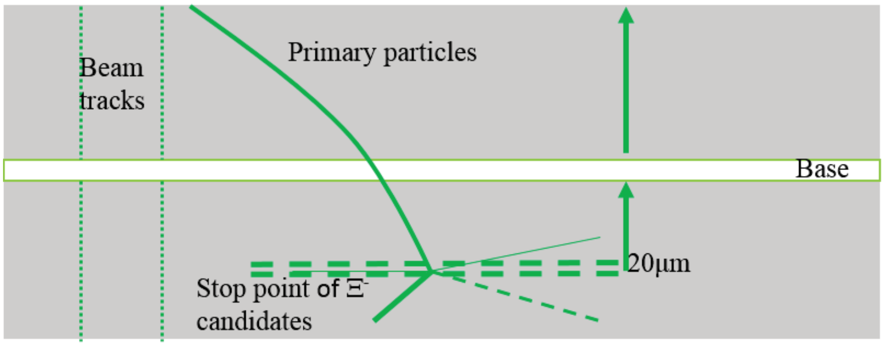


Fig. 3.3 Sketch of measurement of multiple coulomb scattering

To identify Ξ^- hyperons, we studied second differences starting at 100 μm from the rest point of the track in nuclear emulsion. Additionally, we measured beam tracks to get the correction parameter by the distortion of the emulsion within the one view of the candidate track. In the second difference calculation of constant Sagitta method, several cell lengths were applied as second difference to be constant.

3.6 Distortion correction by high momentum beam tracks

In our research, we had been using photographic nuclear emulsion to study double strangeness system that can mainly support the baryon-baryon interaction in hypernucelar physics. As the merit of the usage of emulsion, there is distortion effects while development process. Especially, the thick plates have large distortion effects and this effect has strong correlation with the scattering of particles tracks in nuclear emulsion. Consequently, we need to correct distortion with the aid of high momentum beam track measurements by the following procedures;

(1) By using two beam tracks, take a track (#1) and drawing the base track using two coordinates at base

(2) obtained the coordinates difference of base track and beam track (#1)

(3) By using above coordinates difference, track #2 is corrected.

(4) By this way, x and y coordinates of charged particle track are corrected.

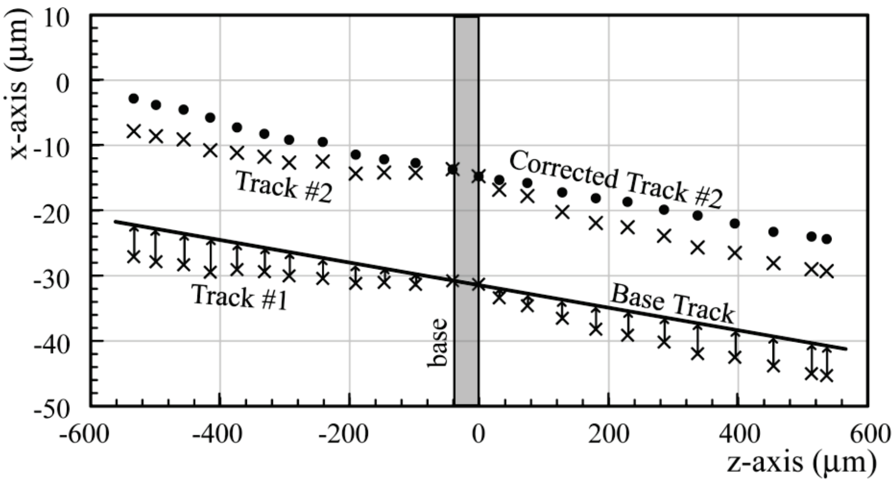


Fig. 3.4 Distortion Correction by using beam tracks

3.6.1 Estimation of measurement error by using high momenta beam tracks

In the strategy of the measurement errors estimation, we used high momenta beam tracks (1.66 GeV/c) because they passed through nuclear emulsions straightly and perpendicularly. We had estimated the measurement error in the following procedures;

(i) At first, measured two beam tracks in one view of the optical microscope,

(ii) As the second step, one track was chosen as the reference track and draw base track by using the microscope coordinates of the upper and lower surface of the base,

(iii) Thirdly, calculated the coordinates differences of the base track and beam tracks for X and Y components at the same Z coordinates.

Secondly, the second beam track (track #2) is corrected by using the coordinate differences of track#1. Then, the corrected coordinates of track #2 are fitted with a straight line. Finally, residuals were accumulated from coordinate differences between corrected beam (track #2) and linear fitting line. As the same manner, residual Y components were also obtained. Then the measurement error was estimated for X and Y components from Gaussian fitting of residual. The results are 0.246 ± 0.020 μm and 0.251 ± 0.025 μm respectively as expressed in Fig 3.5 (a, b).

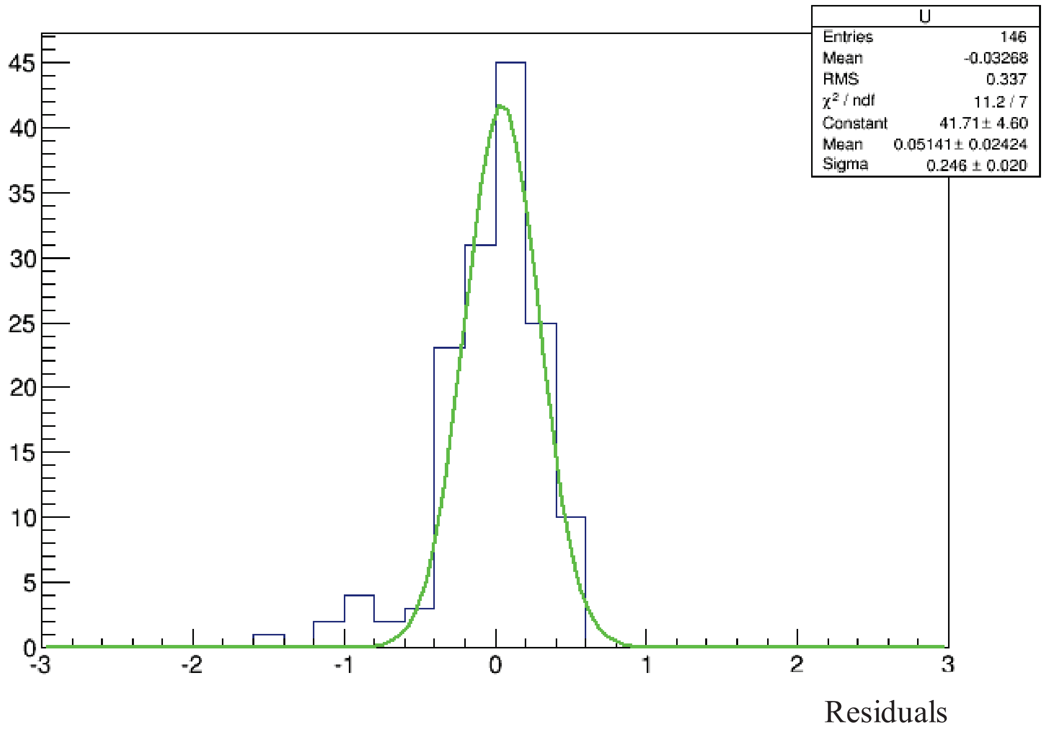


Fig 3.5 (a). Obtaining measurement error of X components from Gaussian fitting of residuals Distortion Correction by using beam tracks

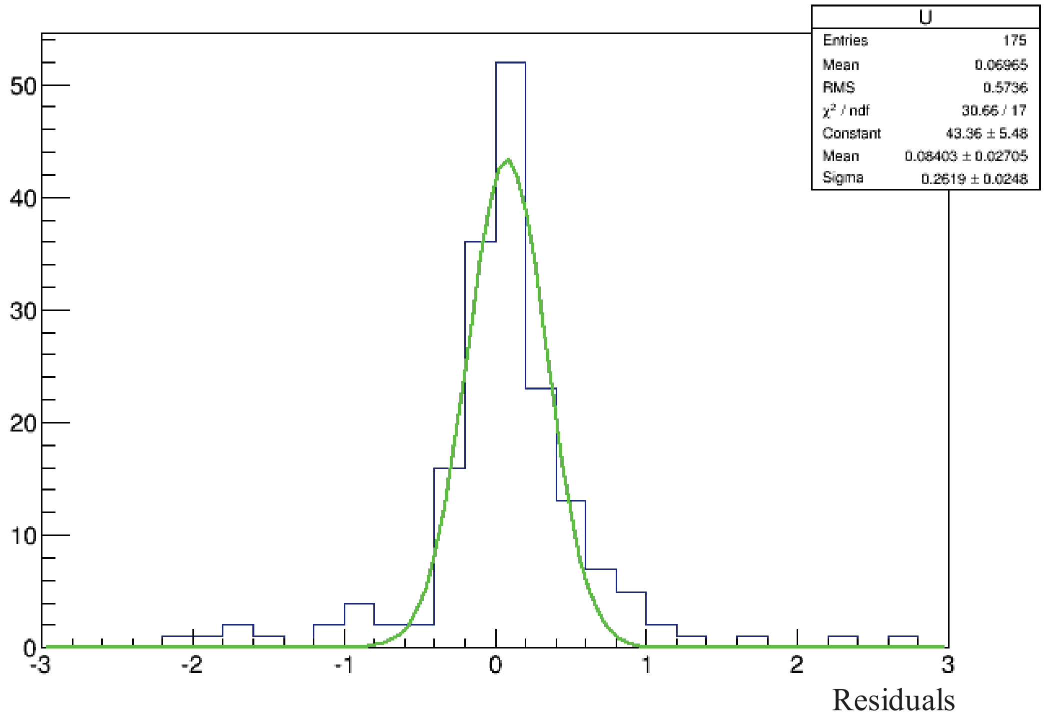


Fig. 3.5 (b). Obtaining measurement error of Y components from Gaussian fitting of residuals Distortion Correction by using beam tracks

We input measurement error= 0.25 μm at X, Y, Z coordinates at every 40μm steps in Z axis. Because we measured the Ξ^- hyperon tracks and pion tracks with 20μm step. Therefore, we input measurement error at every 40μm step of Z axis. Moreover, we modified produced MC simulation data associate with those measurement errors. After input measurement error, we produced the most suitable Ks by setting σ_0 to be 1 μm.

3.6.2 Checking the root mean square second difference for σ_0 = 1.0μm and corresponding K_s value for PID

For σ_0 = 1.0 μm and measurement error = 0.25μm, we estimated RMS values of second difference for revised 20000 samples in the range 500 to 4000 μm produced by MC simulation by changing the Ks value appropriate with δ_0. And, the Ks value is obtained that is associated with the mean of the RMS value, δ_{rms} that is very closing to the setting σ_0 = 1.0 μm.

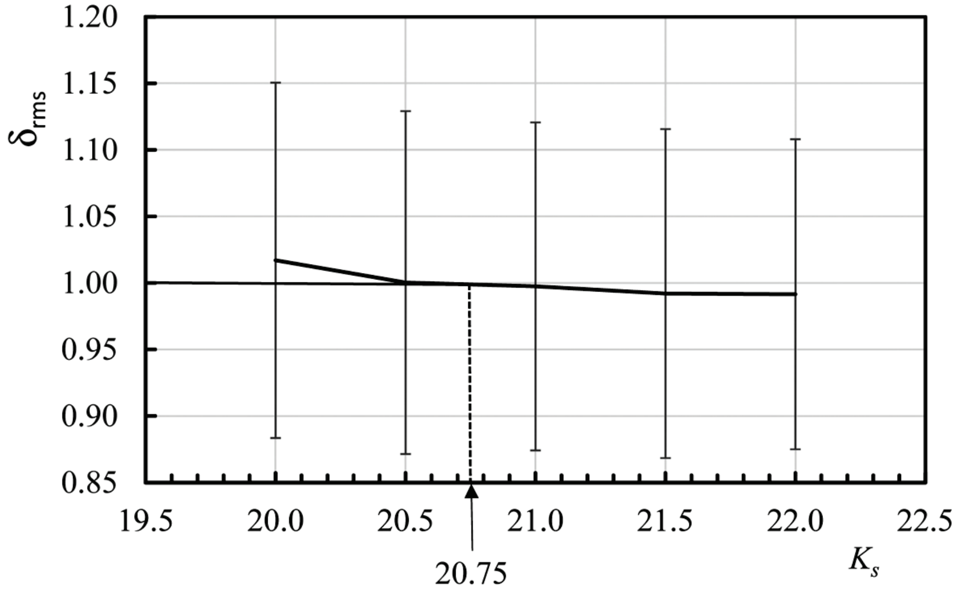


Fig. 3.6 Checking the second differences values with corresponding scattering constant Ks for 4 sigma of the measurement error (ME = 0.25 um) of the MC simulation [σ_0= 1.0 μm, Measurement Error=0.25]

Finally, the most suitable Ks value is to be 20.75 at the point of δ_{rms} = 1. We applied Ks = 20.75 and σ_0= 1.0 μm for RMS value of second difference of the revised data sample of Ξ^- and π^-. The distribution of the results will be in Fig. 3.7 and two particles peaks can be seen as well separated peaks.

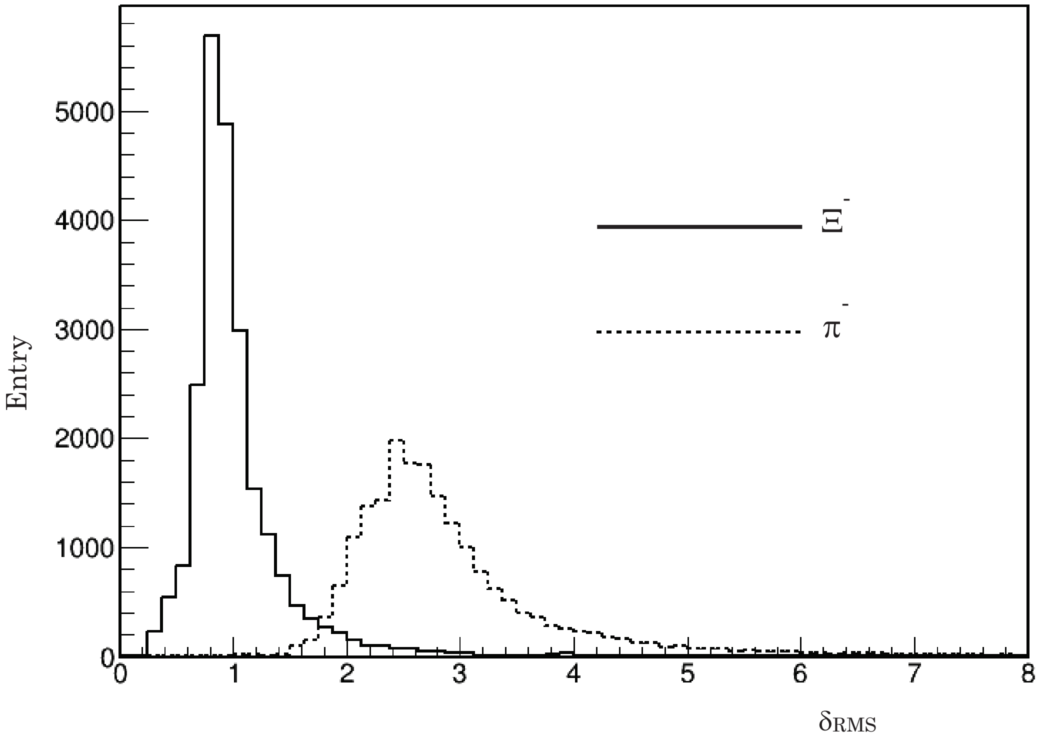


Fig 3.7 RMS of the second difference of revised data samples with measurement errors for Ξ^- and π^- produced by Geant4 package.

4. Results and Discussion

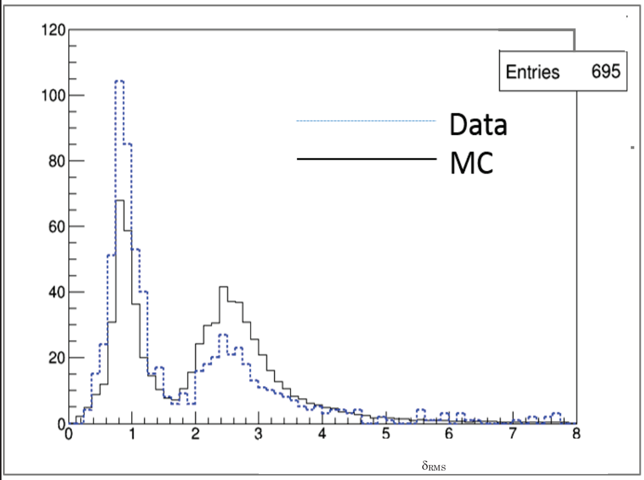
4.1 Analysis for Ξ hyperons candidates of the KEK-E373 experiment

In order to get 10 times statistics of E176, the E373 experiment had been performed at KEK. The SciFi Bundle measured the positions and angles of Ξ^- candidates produced via (K^-, K^+) reaction and we started following of these Ξ^- candidates.

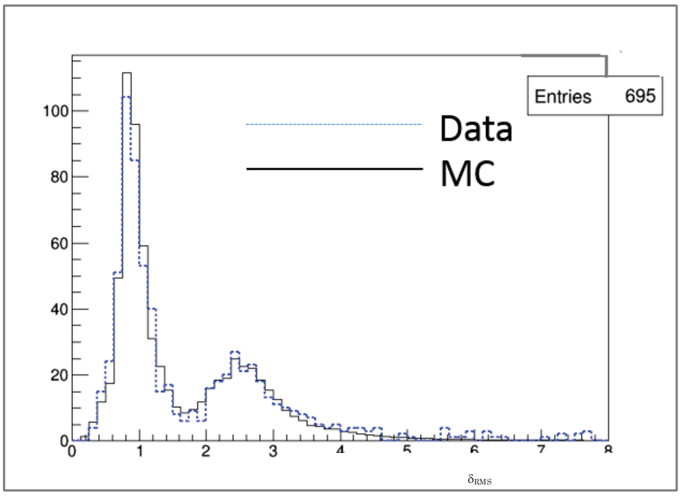
By this E373 experiment, we obtained ~700 σ-stop events after tracking the produced Ξ^- hyperons candidates and it means ~700 negative charged particles are captured in emulsion nuclei. However we did not know the amount of background events, because it was impossible to check kinematics at the (K^-, K^+) reaction vertex with large error due to scattering in diamond target, not in the emulsion. In order to estimate the trapping probability of strangeness by capture events, it is very important to determine the number of Ξ^- capture events among the candidates (STOP events). Among them, there is no proton background in the σ-stop events and in the ρ-stop events, background number is huge.

Therefore, a method to identify Ξ^- hyperons in σ-stop events has been developed with the multiple coulomb scattering method for almost straight beam tracks. Through this PID implementation, we can identify primary particles of Ξ^-stop events related trapping probability of strangeness. The second difference distribution for the σ-stop events is shown in Fig 4.1. This particles identification method is quite crucial in order to confirm primary particles of the double hypernucleus because if we know the primary particle is Ξ^- hyperons and it has three vertices, we can know very significantly they are real double hypernuclei. Moreover, we calculated the primary particles of well-known events, Nagara, Mikage, Demachi-Yanigi and Hida and they are well understood via real capture of Ξ^- hyperons with RMS values of Second Difference 1.04, 1.18, 0.97 and 1.34 that were located in the region of Ξ^- hyperons peak shown in Fig 4.4.

In order to produce the numbers of real Ξ^- for the σ-stop events, we generated 20000 tracks of Ξ^- and π^- particles by Geant4 Monte-Carlo simulation and applied PID method to all these data. Moreover, in order to be similar characteristics with the real data, we consider the range distribution of real tracks to the MC simulation data. Fig 4.1 represents the second difference distribution of the data and MC simulation data corresponding to the ratio of MC simulation Ξ^- to π^-.



(a) Rate (Ξ : π)=(0.48:0.52)



(b) Rate (Ξ : π)=(0.62:0.38)

Fig. 4.1 Second difference distribution of real data and (a) MC simulation (Ξ^- to π^- = 0.48:0.52), (b) MC simulation (Ξ^- to π^- = 0.62:0.38)

4.1.1 Chi2 minimum production by real data and MC simulation Ξ^- and π^-

In order to produce the minimum chi square of the Monte-Carlo and data, we check the most convenient ratio of Ξ^- and π^- generated by Monte-Carlo simulation that can give the minimum chi square. When we consider the ratio of Ξ^- and π^- of the simulation by adjusting, comparing with the data we produced the minimum chi square for MC and data.

In the MC simulation data, they suggest that these low energy scattering data should be reproduced by an optical potential only minimally different from that used for pionic atom analysis. And our experimental data has bigger tail than that of MC simulation data while second difference is large. In order to avoid those conditions, we changed the cut region of large RMS of second difference and also the mixing rate of Ξ^- and π^-. The results will be discussed in the next section.

4.1.2 Number of Ξ hyperons captured events with topology of σ-stop with minimum value of $\chi 2/\mathrm{ndf}$

In order to identify the primary particles, we apply constant Sagitta method to the total events with ranges 0.5 mm to 4mm. When we estimate the numbers of the Ξ^- particles of the E373 experiment, we searched the appropriate distribution with the data by adjusting the ratio of the Ξ^- and π^- generated by Geant 4 simulation that can give the minimum chi square, Chi2 = 22.14, Ndf = 35 (90% confidence level).

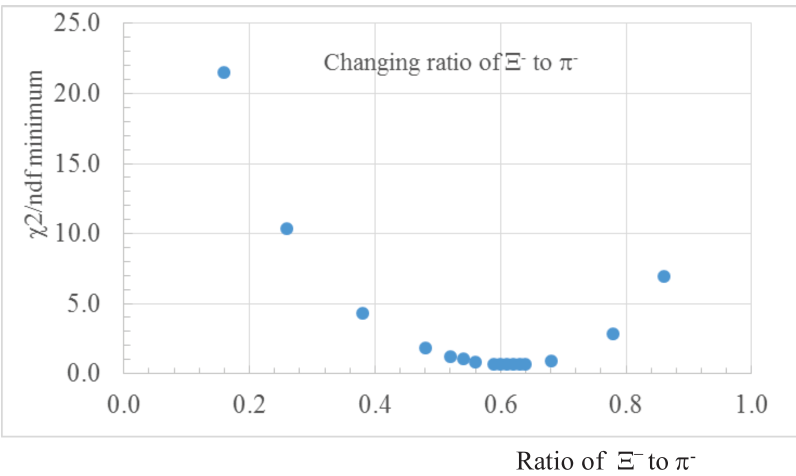


Fig. 4.2 Estimation of minimum $\chi 2/\mathrm{ndf}$ associated with ratio of Ξ^- and π^-

As mentioned in the previous section, for various cut regions, the result of $\chi 2/\mathrm{ndf}$ minimum versus with the ratio of Ξ^- and π^- is expressed in Fig 4.3.

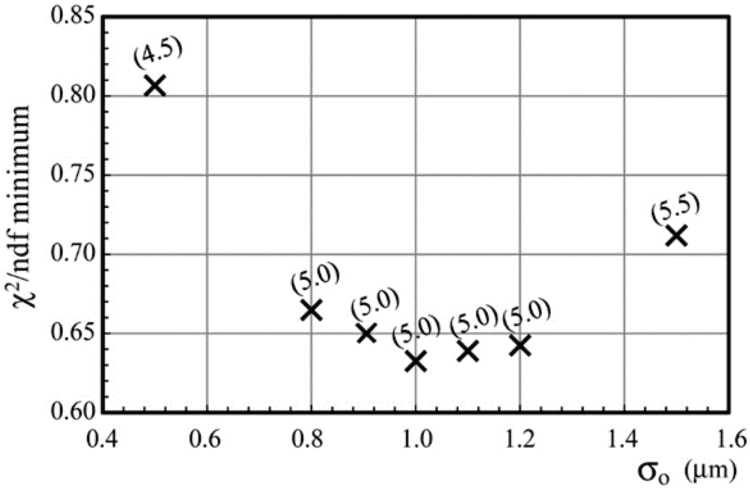


Fig. 4.3 Minimum $\chi 2/\mathrm{ndf}$ for various cut region in large RMS of second difference

Finally, as a result, the ratio (Ξ^-:π^- = 0.62: 0.38) with minimum chi square gives 430.90 ± 13.90 for Ξ^- hyperons as expressed in Fig 4.4. In Fig 4.2, the dotted line represents the second difference distribution of the revised MC simulation and the black line shows the second difference distribution of the σ-stop events of the E373 experiment.

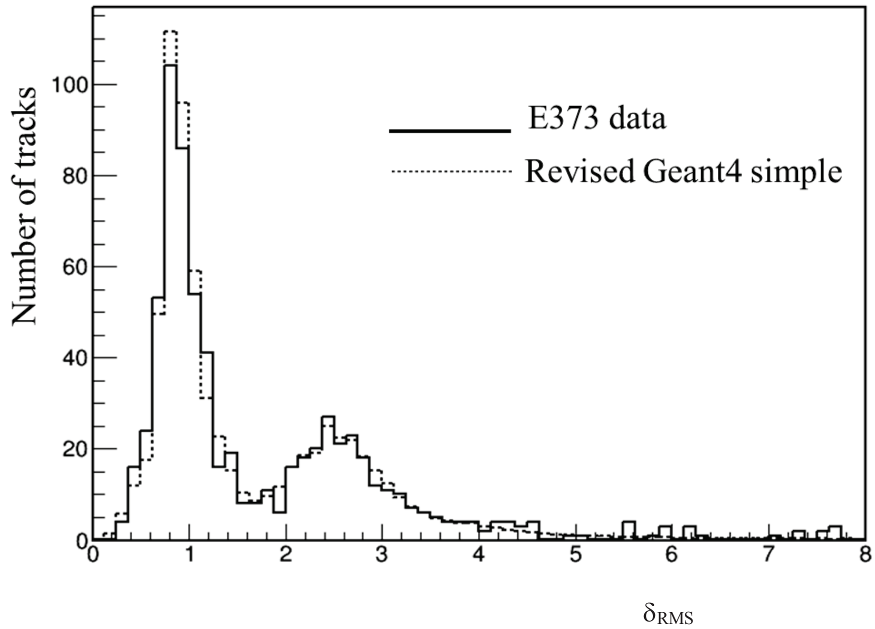


Fig. 4.4 RMS Second difference distribution of Ξ^- candidates of the E373 experiment and Monte_Carlo simulation Data

In this estimation, since one step of 0.01 in the ratio changes nearly 7 events, we employed a more fine step of three decimal (0.001) to reproduce the minimum value of $\chi 2$/ndf. The minimum value of $\chi 2$/ndf was given to be 0.629 at the ratio of 0.622 as shown in Fig. 4.5. The most appropriate ratio and number of Ξ^- in sigma-stop events is 0.6220 ± 0.0005 and 432.3 ± 7.6, respectively. Remained tracks are well understood to be consistent with background by an independent detection of it.

While considering a systematic error case, in the E176 experiment, the contamination of Σ^- hyperons was a huge amount in the Stop events of Ξ^- hyperons. Therefore, firstly, we estimated the ratio of Σ^- stop to Ξ^- stopping events with the aid of Geant4 simulation. The result was to be 8.0 +/- 0.3%. But, in the result of E176, the ratio was to be 15.7 +/- 4.8%. The number of Σ^- stops is 12.2 among 77.6 Ξ^- stopping that is nearly 2.0 times larger than the result of the simulation. Supposing that difference was caused by poor knowledge for Σ^- and Ξ^- hyperons cascade reaction in the emulsion, for those difference, we can produce in the E373 experiment via Geant4 simulation again. Then, the result was to be 1.6 +/- 0.2% and 3.2% of Σ^- hyperons, nearly 14.0 events, were contaminated in the 432.3 Ξ^- stopping events. Consequently, the number of σ-stop events via at rest of Ξ^--hyperons is to be $432.3 \pm 7.6\,^{+0.0}_{-14.0}$.

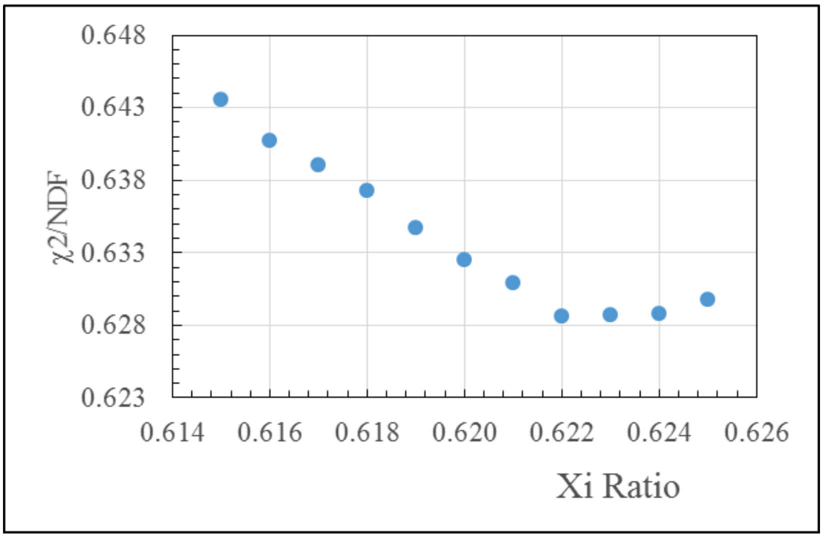


Fig. 4.5 Estimation of minimum $\chi 2/\mathrm{ndf}$ associated with ratio Ξ^- and π^-

4.2 Application of the method to Ξ^- hyperon 2 Λ trapping

There are two types of captured events;

(a) Ξ^- hyperons captured at light emulsion nuclei (C, N, O) and

(b) Ξ^- hyperons captured at heavy emulsion nuclei (Ag, Br).

We considered double-Λ hypernuclei, twin single-Λ hypernulcei and single-Λ hypernuclei as nuclei with multi-strangeness in calculating the trapping probabilities. Moreover, we counted the events with E-visible ≥ 28MeV as produced at least one strangeness via Ξ^- hyperons captured points in estimation of the trapping probabilities. The two bodies reaction of Ξ^- with a nucleon is as Ξ^- +

p = Λ + Λ + Q (28 MeV). Double-Λ hypernuclei with two strangeness and twin single-Λ hypernuclei are used to estimate trapping probabilities of 2Λ. In Light nuclei captured case, we used the following lists to calculate trapping probabilities.

We defined heavy double-Λ hypernuclei as the events with E-vissible ≥ 170 MeV because two bodies decay of the Ξ^- into non-mesonic decay is 166MeV. Therefore, we counted the events with E-visible ≥ 170 MeV as heavy double-Λ hypernuclei in the case of the heavy nuclei captured case.

Double-Λ hypernuclei were produced via Ξ^- hyperons captured at light emulsion nuclei (C, N, O) and heavy Double-Λ hypernucleus are those events with strangeness absorbed at heavy emulsion nuclei (Ag, Br). Moreover, we will count the events with E-visible 28MeV as at least one strangeness production.

Here, E-visible defined the total visible energy-release and the binding energy (assumed as 8 MeV per particle) and all visible tracks emitted from the captured points are considered to be protons. Two-body reaction of a Ξ^- with a nucleon in a nucleus is as Ξ^- + p = Λ + Λ + Q (28 MeV). Therefore, we assumed that events with at least 28 MeV defined as events with strangeness emission. The events with greater than 28 MeV are defined as production of strangeness at the captured points of the xi hyperons to the emulsion nuclei.

4.3 Trapping Probabilities

In the case of estimation of the trapping probability of strangeness, we will count the events with E-visible 28MeV. For the light nuclei process, we will consider the hyperfragments emission and the cryptofragments in which E-visible 28MeV. I assumed σ-stop events with at least short length tracks (3 and 31 μm) as the Ξ^- captured at light nuclei. In order to produce trapping probabilities, we picked up

417 events in the region less than 1.5 μm of RMS of Second Differences that contaminated almost 1.2 π^- captured events. The following table 4.1 shows the properties of the σ-stop events observed in the stopping Ξ^- hyperons. After carefully checking at the stopping points, we observed totally 128 auger electrons emission from the captured point of the σ-stop events of the E373 experiment. Therefore, the probability of auger electron emission in σ-stop events is in the E373 nuclear emulsion experiment. We had checked the emission of auger electron at the stopping points of the sigma stop events.

Table 4.1 Stopping events with various characteristics

Presence of short prong	Presence of Auger electron	σ-stop events	
		E373	E176
Yes	Yes	25	4
Yes	No	155	18
No	Yes	103	17
No	No	134	13
Total		417	52

Therefore, auger electron emission probability for the σ-stop events is $30.7 \pm 3.1\%$ that is consistent with the result of the E 176 experiment (40 ± 2.1%). The ratio of Ξ^- hyperons captured at light to heavy nuclei was precisely 0.78 ± 0.08 which is good agreement with 0.73 ± 0.21 by R.D.Hill [13].

4.3.1 Trapping Probabilities of strangeness at light and heavy captured

In order to calculate trapping probability of 2 Λ and 1 Λ at the light nuclei captured, we use the following statistics;

Table 4.2 Events with multi-strangeness in the light nuclei captured case

double-Λ hypernucleus	7
twin single-Λ hypernucleus	2
single-Λ hypernucleus	28
σ-stop events with E-visible 28 MeV	88

7 double-Λ hypernucleus and 2 twin single-Λ hypernucleus are counted for calculating of 2 Λ hyperons trapping probability and 28 single-Λ hypernucleus and 88 σ-stop events with E-visible 28 MeV are used to calculate at least one Λ trapping probability.

In the heavy nuclei captured case, we will calculate the trapping probability of strangeness via 9 heavy double-Λ nuclei and 114 captured events with E-visible 28 MeV.

Table 4.3 Events with multi-strangeness in the heavy nuclei captured case

heavy double-Λ hypernucleus	10
(σ-stop events with E-visible > 160 MeV)	
σ-stop events with E-visible 28 MeV	111

Consequently, we got trapping probability for two Λ hyperons and at least 1 Λ hyperon captured at rest in nuclear emulsion were found to be 5.0 ± 1.7 %, 69.4 ± 8.1% for light nuclei captured and for heavy nuclei captured were to be 4.2 ± 1.4 % and 51.1 ± 5.7% respectively.

4.4 Background Ratification with following real background tracks

Consequently, we need to ratify the background of the calculated results, we scanned the emulsion module stacks. In this ratification, firstly, the automatic scan of the plate1 using the angle and position of the predicted Ξ^- SciFi Bundle detector was changed to another prediction. Its independent detection means background searching π^- and K^- hyperons inside the emulsion. By scanning, we found the captured events inside nuclear emulsion with the changed place of the predicted area that means independent detection, we can clearly know that these captured events are originated from π^- meson and a little contamination of K^- hyperons. In our research, we followed candidates' tracks with the aid of the predicted data via (K^-, K^+) reaction. Finally, we obtained the pure background particles (π^- , K^-) of the E373 experiment.

Table 4.5 Calculated and following background scan results

	Following Tracks	**Background**	**Rate**
Calculated Result	37935	~260	0.69 ± 0.05%
Scan Result	569	4	0.70 ± 0.35%

According to the above table, we can consider that this method was successful for primary particles identification via one kind of checking background by an independent detection.

5. Conclusion

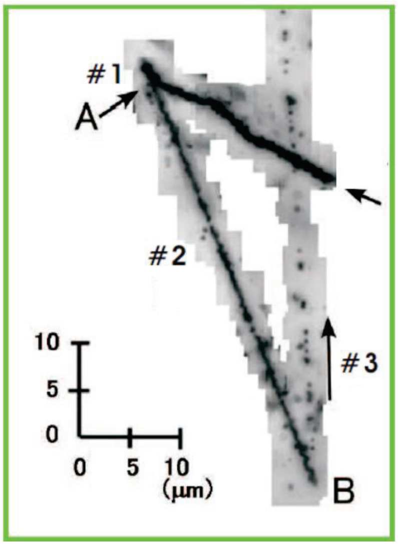
There are two types of STOP events that can give the probability of strangeness and categorized by their topologies; σstop, ρstop and decay with a π^- meson. The probability has been studied by the KEK-E176 experiment with the emulsion generated from the captured events. In E176, the emulsion was production target of Ξ^- hyperons and detector of double hypernuclei. Therefore, real production of Ξ^- hyperon were able to be checked with study of kinematics at the (K^-, K^+) reaction vertex. In use of 52 σ-stop events emitting nuclear fragment(s) at Ξ^- hyperon captured point, it was reported that the probabilities were 4.8% and 1.7% (90% confidence level) for light (C, N, O) and heavy (Ag, Br) elements. To get 10 times statistics of E176, the E373 experiment has been performed at KEK.

We have obtained ~700 σ-stop events, however we cannot know the amount of background event, because it was impossible to check kinematics at the (K^-, K^+) reaction vertex with large error due to scattering in diamond target, not in the emulsion. Therefore, a method to identify Ξ^- hyperon in σ-stop events has been developed with the multiple coulomb scattering method for almost straight beam tracks. We found two peak shapes for the scattering and obtained the number of $432.3 \pm 7.6\ ^{+0.0}_{-14.0}$ for real Ξ^- hyperon. For the remained tracks case, they were well understood to be consistent with background by an independent detection of it. With taking the ratio of (1/2) for ρ-stop toσ -stop, the total number of real Ξ^- hyperon captured at rest in nuclear emulsion is ~ 650 that is 10 times higher statistics of E176 experiment. Moreover, the well-known events, Nagara, Mikage, Demachi-Yanigi and Hida, are well understood via real capture of Ξ^- hyperons with RMS values of Second Difference 1.04, 1.18, 0.97 and 1.34. The trapping probabilities of two Λ hyperons and at least one Λ hyperon captured by the light nuclei are 5.0 ± 1.7 % and 69.4 ± 8.1% by using only σ-stop events, respectively. Similarly, we got the trapping probabilities of 4.2 ± 1.4 % and 51.1 ± 5.7% in the captured processes of the heavy nuclei. Now, in the current condition, the new experiment, the J-PARC E07 experiment is still in progress of the analysis. Via this experiment, we conjecture almost 100 double-Λ hypernuclear events will be detected and due to similar setup of the E373 experiment, the identifications of primary particles are also required. The Constant Sagitta method, particles identification technique can be applied for the identification of the primary particles and also for the recognization of decay daughters of the double-Λ hypernuclei.

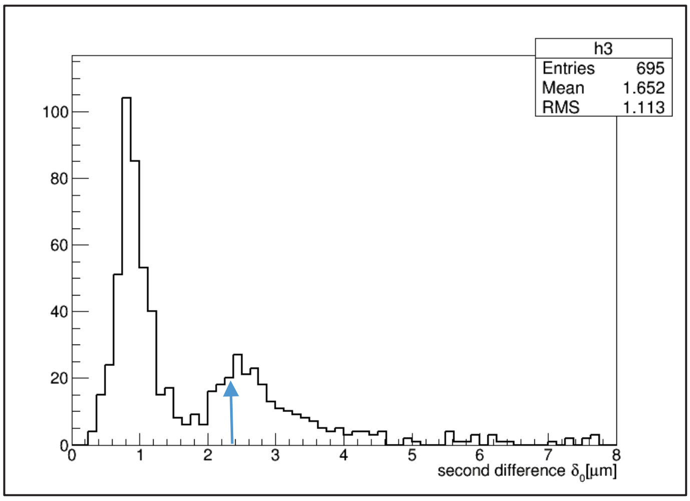
Appendix A

Identification of primary particle of H-dibaryon candidate event

A candidate event emitting a Σ^- hyperon from a Ξ^- hyperon nuclear capture at rest was observed in the E373 hybrid emulsion experiment. Identification of primary particle that produce the H-dibaryon is quite important for analysis process. Therefore, we apply PID to this primary particle and the violet arrow in Fig. b) represents second difference value of the candidate event. Then this particle could identify beyond the favor of the Ξ^- hyperons and become to be background as K^- or π^- by measuring coulomb scattering. But the thin track emitted from vertex B was proved as the pion by calculating energy deposit of this thin track and could confirm with the comparison of the pion of the well-known Nagara event. Consequently, we could identify the primary particle of this event as K^- captured. In the case of E07 experiment, we can apply this PID for the primary particles identification of 10 time's higher statistics of double hypernucleus and H-dibaryon.



a)



b)

Fig. a) Superimposed image of Sigma stop candidate and b) Second difference of Ξ^- candidate event illustration in the distribution of STOP events of the E373 experiment.

References

[1] D. Griffiths, “Introduction to Elementary Particles”, John Wiley & Sons, Inc., New York (1987).

[2] https://en.wikipedia.org/wiki/Strangeness

[3] K. Nakazawa and H. Takahashi, Prog. Theor. Phys. Suppl. 185, 335-343 (2010).

[4] K. Nakazawa, et al., Prog. Theor. Exp. Phys., 033D02-1~11, 2015.

[5] H. Takahashi, et al., Nucl. Instr. Meth. A**483**, 689 (2002).

[6] J. K. Ahn et al., Phys. Rev. C 88, 014003, (2013).

[7] S. Aoki, et al., Nucl. Phys. A 828, 191 (2009).

[8] S. Aoki, et al., Prog. Theor. Phys. 85 1287, (1991).

[9] H. Takahashi, Ph.D. Thesis, Kyoto University (2003).

[10] R. Baier, A. H. Nueller, D. Schi, and D. T. Son, Phys. Lett. B 502, 51(2001).

[11] H. Bichsel, D. E. Groom and AS. R. Klein, PDG. (2013).

[12] C. Dilworth, S. J. Goldsack and L. Hirschbere, Nuovo Cimento.113, 6 (1954).

[13] P. Khaustov,et al., . Phys. Rev. C 054003, 61 (2000).

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