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Study of double-strangeness nuclear systems with nuclear emulsion

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Abstract

Double strangeness nuclei such as double-Λ and Ξ hypernuclei have been studied with nuclear emulsion due to its fine position resolution. Recently, we have started an experiment to study Λ-Λ interaction more accurately than that information given by the NAGARA event with ~10^2 double-Λ hypernuclei which may provide us understanding free from nuclear medium effect. It is necessary to develop treatment method for huge amount, 2.1 tons of the emulsion gel, even if very pure K^- beams are available at J-PARC. We have developed the base film to support the emulsion, emulsion surface coating method with a special layer of 0.5 μm thick, method for making large-size plate (35.0 x 34.5 cm^2) and scanning method, called "*overall scanning*". The first evidence of a deeply bound state of Ξ^--^{14}N system, named KISO, was successfully detected in the test operation of the overall scanning.

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Keywords: Nuclear emulsion, plate making, double-Λ hypernucleus, Ξ hypernucleus;

1. Introduction

In nuclear physics, the interaction between ordinal nucleons, *N-N*, has been continuously studied for more than 60 years. Its research has provided us three thousand nuclei among seven thousand ones predicted by theory. Regarding

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the hyperon-nucleon (Y-*N*) interaction, where Y is a Σ or Λ hyperon, its research is steadily progressing. We had a stereoscopic nuclear chart by adding a hyperon inside nuclei. Such single hypernuclei of nearly forty samples are located on the 2nd floor in the chart, so far. To understand hadron-hadron interaction in baryon octet scheme, it is necessary to study double-strangeness systems, e.g. Λ-Λ interaction and Ξ-*N* interaction. Because of short lifetime ($\sim 10^{-10}$ s), we input two units of strangeness (S = -2) into nuclei, called double-Λ or Ξ hypernuclei, and measure masses via their decay sequence. An effective way to produce S = -2 nuclei is to stop Ξ^- hyperons captured by some nuclei. Since the Q-value of their production is at most 30 MeV through the reaction of Ξ^- + "*p*" => Λ + Λ, nuclear emulsion is the best detector to observe the production and decay of S = -2 nuclei. Since the emulsion scanning procedure took a long time, the NAGARA event was the only clearly identified (${}^{6}_{\Lambda\Lambda}\mathrm{He}$) event introduced by Takahashi et al. (2001), Nakazawa and Takahashi (2010) and Ahn et al. (2013). Although the NAGARA event suggested the Λ-Λ interaction to be weakly attractive, it is necessary to detect double-Λ hypernuclei in other nuclear species than NAGARA to get conclusive information free from nuclear medium effect. Recently, a new hybrid experiment to provide $\sim 10^2$ double-Λ hypernuclei has been approved as the E07 experiment at J-PARC. To get such a number of events, we expose a large volume of emulsion with highly pure K^- beams ($K^-/\pi^- \sim 6$). In this paper, a series of mass production of emulsion plates will be introduced. We also discuss the development of the scanning system, which is introduced by Yoshida et al. (2014) in detail.

2. Mass production of emulsion plate

In the E373 experiment at KEK-PS, we have detected 7 double-Λ hypernuclei among $\sim 10^3$ Ξ^- stopping events and just the NAGARA event was uniquely identified. To detect other nuclear species with S = -2, it is necessary to record $\sim 10^4$ Ξ^- stopping events in the emulsion. Therefore we should process 2.1 tons of emulsion gel, what is nearly 3 times more than the case of E373. To make nuclear emulsion plates with the gel, many kinds of R&D have been made. Three of them are introduced bellow.

2.1. Improvement on hydrophilia of emulsion support film (R&D No.1)

We must use the support film to avoid upswell and strain of the plate during development in the photographic solution and after drying, respectively. We prepared two types of emulsion plate. One is the plate with thin emulsion (100 μm) layers on both sides of polystyrene (PS) film (*t* = 180 μm) to detect Ξ^- hyperon tracks reconstructed by counter system at the top of the emulsion stack. Another one with thick (500 μm) layers on both sides of thin PS film (*t* = 40 μm) is intended for the detector of production and decay of S = -2 nuclei. Since original PS-film had no hydrophilia, dried emulsion was easily separated from the film in the process of photographic development. Therefore we applied Corona discharge on both sides of the film.

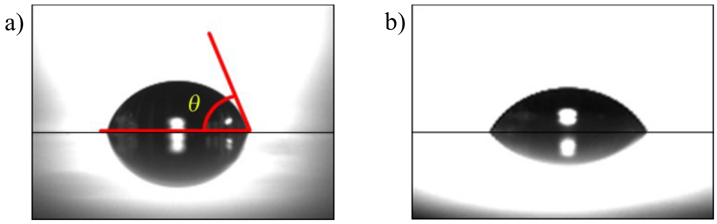

Fig. 1. Contact angle, θ, in a) is larger than that of b) after Corona discharge application on the PS-film.

Corona discharge machine[1] was applied for PS film inside with voltage of 3 kV and feed speed of 20 m/min. However the discharge effect was found to be not uniform over the 1 m wide and 200 m long film being water-soaked. To evaluate the effect of the Corona discharge, therefore, we have measured contact angle, θ, of a water drop (10.0 ± 0.1 mg) with the film as displayed in Fig. 1 a). In Fig. 1 a) before Corona application, the θ was (68.5 ± 0.5)° by elliptical fitting. Then the discharge machine was applied again with 4 kV and 10 m/min., and

[1] ONOKOGYO Co., ltd. ; http://www.onokogyo.com

hydorophilically-augmented characteristic was obtained for the film, uniformly. The shape of a water drop after its application is shown in Fig. 1 b), and the contact angle became $(54.0 \pm 0.8)^{o}$. It was found that the contact angle smaller than 60^{o} was enough for support of the emulsion to the plate.

2.2. Surface coat on emulsion plate (R&D No. 2)

2.3. After the photographic development of the emulsion plate, silver is separated out on the plate surface as shown in Fig. 2 a). Under the microscope, nobody can observe any events inside the emulsion without removing this silver. Wiping with abrasive powder takes long time, e.g. 30 min for 600 cm^2 at the KEK-E373 experiment. In the coming E07 experiment, the size of plate is 1.2×10^3 cm^2 and number of plates is 1.6×10^3, thus we need to spend 3.2×10^3 hours for removing surface silver. Therefore we have developed surface coating with gelatin as used for normal photographic film. We found the best condition to achieve the uniform thin skin thickness of 0.54 ± 0.14 μm. After photographic development, the surface with no separated silver was obtained as shown in Fig. 2 b). In the right-hand picture of Fig. 2 b), a visible track is an α particle, 5.7 MeV from ^{241}Am, which was exposed to check skin thickness.

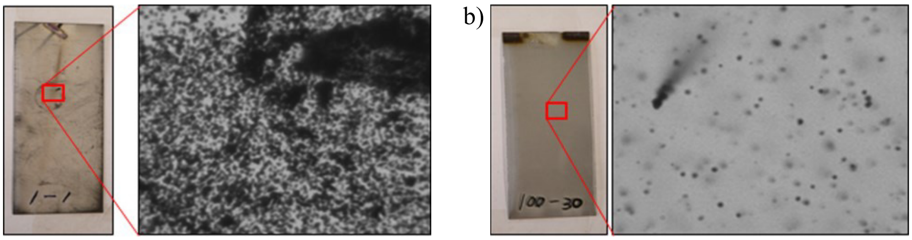

Fig. 2. a) Separated silver on the surface of developed emulsion plate w/o gelatin coat; b) the surface of developed emulsion with gelatin coat.

2.4. Emulsion facility in Gifu University

For gel pouring on the support film, drying and photographic development, the emulsion facility with an area of 100 m^2 was built in the campus of Gifu University in 2012. In the facility, there are three separated rooms as shown in Fig. 3.

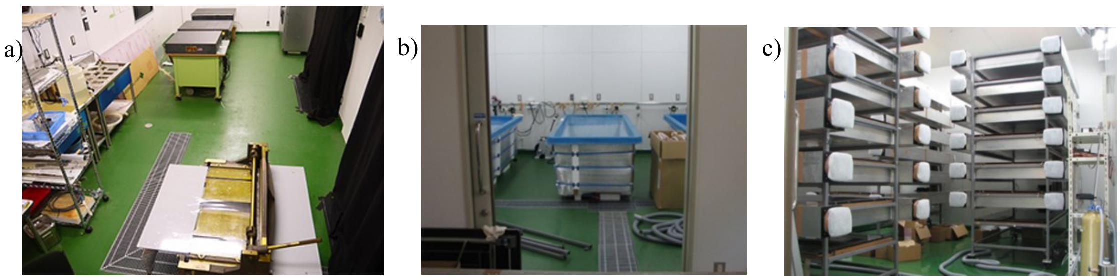

Fig. 3. a) A room for pouring emulsion gel on the flat film; b) A room for drying of poured gel; c) Photographic development room.

In the pouring room as shown in Fig. 3 a), we have used three stone level blocks 75 x 100 cm^2 each to get uniformly thick emulsion plates, where polystyrene (PS) supporting film (t = 40 or 180 μm) was chucked in vacuum on 10mm thick acrylic plate to the block. Poured area of the gel for one emulsion sheet was 70.0 x 71.0 cm^2. 36 acrylic plates were installed into drying shelves in the drying room as shown in Fig. 3 b), which is the adjacent room of the pouring room. In the drying room, the temperature and humidity were kept at 28°C and 75%, respectively, until the poured emulsion was dried. After the application of the final drying at 28°C and R.H. 60%, we divided the sheet into 4 plates with the size of 34.5 x 35.0 cm^2 each. The process took a half year while we made 1380 plates with 0.5mm thick emulsion layers on both sides of the thin (40μm) PS film. We also made additional 240 plates with 0.1 mm thick emulsion on both sides of 180 μm thick PS-film. In total, the ~1600 plates are stocked in lead box with 10 cm thickness at the KAMIOKA mine to avoid cosmic and γ-ray irradiation before beam exposure. After beam exposure in future, we will develop the plates in the development room as shown in Fig. 3 c).

3. Fruit by the "overall scanning"

Regarding a hybrid method with nuclear emulsion and counters, the outcome strongly depends on trigger-counter efficiencies and/or acceptance of spectrometer, etc. However, wanted events would be recorded in the emulsion. Therefore un-triggered important events shall be detected, if we are able to scan full volume of the emulsion within reasonable period of time.

During test operation of overall scanning in the E373 emulsion, we searched for events with three vertices which would be a typical topology of double-Λ and Ξ hypernuclei. Among ~8 x 10^6 pictures, we have detected the event, named KISO, with emission of two (twin) single-Λ hypernucleus as shown in Fig. 4. By the analysis, the event process was uniquely identified to be;

$$\Xi^- + {}^{14}N \Rightarrow {}^{10}_{\Lambda}Be\ (\#1) + {}^{5}_{\Lambda}He\ (\#2), \Rightarrow {}^{8}Li\ (\#3) + p\ (\#4) + n,\ {}^{8}Li \Rightarrow 2\alpha + e^-\ (+\ \bar{\nu}_e).$$

Regarding $\Xi^{-14}N$ atom, the 3*D* level is a state formed by almost Coulomb interaction with the energy of 0.17 MeV, which corresponds to a Ξ^- binding energy, B_{Ξ^-}. However, in this KISO event, the B_{Ξ^-} value was obtained to be 4.38 $\pm$ 0.25 MeV if a daughter ${}^{10}_{\Lambda}Be$ was produced in ground state. By the theoretical prediction for excited state of ${}^{10}_{\Lambda}Be$ due to no experimental data, the lowest B_{Ξ^-} value would be 1.11 $\pm$ 0.25 MeV, what indicates the first clear evidence of the formation of a deeply bound $\Xi^{-14}N$ system. The details are introduced by Nakazawa et al. (2015).

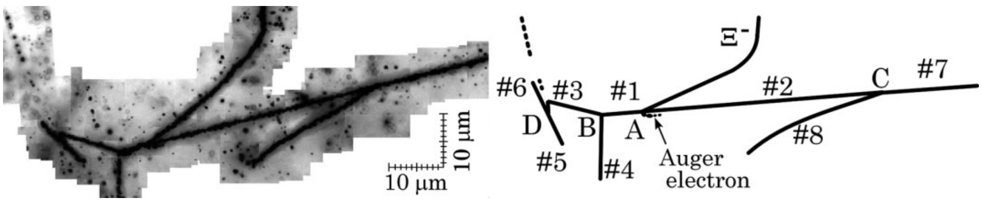

Fig. 4. Twin single-Λ hypernucleus, the KISO event, with schematic drawing.

4. Summary

A huge amount of emulsion gel, 2.1 tons, were processed for the ~1600 plates for study of S = -2 nuclei. The support film of the emulsion has got hydrophilia characteristic by the application of Corona discharge. The plate surface was coated with thin skin of 0.54 $\pm$ 0.14 μm thickness by gelatin not to produce separated silver after photographic development. Under the development of overall scanning method, we successfully detected the first clear evidence of a deeply bound state of $\Xi^{-14}N$ system which suggests an attractive Ξ- N interaction.

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