The Hypernuclear station at KLF
(Technical Note)

M. Bashkanov*
Department of Physics, University of York, Heslington, York, Y010 5DD, UK

T.R. Saito†
High Energy Nuclear Physics Laboratory, RIKEN, Japan

(Dated: August 19, 2024)

---

[*] mikhail.bashkanov@york.ac.uk
[†] takehiko.saito@riken.jp

CONTENTS

Abstract. The purpose of this proposed experiment is systematic studies of single- and double- strange nuclei as well as determination of hyperon-nucleon scattering properties at very low energies. The experiment will utilise high-intensity neutral kaon beam in a parasitic mode and will be complimentary to a multiple J-PARC experiments performed with charged kaons. It will be the first such use of a neutral kaon beam and it will provide access to numerous observables never being measured before.

I. HYPERNUCLEAR PROGRAM

There are a lot of puzzles related to hyperons and their interactions, like neutron stars "hyperon puzzles", charge symmetry breaking in hypernuclei etc... To resolve them we need precise experimental information about hyperon-nucleon and hyperon-hyperon interactions at threshold to feed in our state of the art theoretical technique, χPT. Majority of events which our theory fellows are interested in have very small momenta and require μm scale measurements of a few mm long track which stops within target material. It is essentially impossible with conventional spectrometers like GlueX to address such kind of physics. For example a recent CLAS paper on a novel $\Lambda - N$ scattering cross section measurement technique has a threshold of $800 MeV/c$ - beyond χPT range of validity. To overcome this problem one needs to make target an active detector with high spacial resolution. We propose the use of nuclear emulsions as a way resolve this issues.

II. EXPERIMENTAL SETUP

A hypernuclear station will be installed in front of a beam dump, see Fig. reflocation. An additional few meters of a flight path combined with $\sim 30\%$ absorption of kaons in a cryogenic target will reduce kaon flux at a hypernuclear station position by about factor of 2-3 compare to a $10^4 K_L/s$ seen by a LH_2/LD_2. However a factor of ~ 100 higher density of an emulsion or even higher for germanium will overcompensate it in a luminosity factors enabling high statistics measurement to be performed. We expect more than an order of magnitude higher statistics compare to famous KEK-E373 experiment which discovered "Nagara" event in 100 days long KLF beamtime, which should lead to several thousands double-strange hypernuclear events to be detected, or about several double-strange hypernuclei events per day of measurement and a handful amount of single-strange hypernuclei.

A. Nuclear emulsions

In the proposed project, one of main experimental components for detecting production and decay of hypernuclei is a nuclear emulsion. It is a photographic film that can record the three-dimensional trajectories of charged particles with a submicrometer-scale spatial resolution. It is composed of silver halide (AgBr) crystals dispersed in gelatin. Nuclear emulsions were initially developed for particle and nuclear physics experiments to observe the tracks of charged particles. They were used to observe pions [4], hypernuclei [5, 6], charm particles [7] and double-strangeness hypernuclei [8]. The analysis speed of nuclear emulsions has increased remarkably with improvements in image-processing techniques [9, 10]. These improvements enabled the use of nuclear emulsions in modern experiments and led to the first direct detection of tau-neutrinos [11], the discovery of $\nu\mu \to \nu\tau$ oscillations in an appearance mode [12], the detection of hypernuclei [10, 13–16] and several other applications, including muon radiography [17, 18].

Identification of charged particles can be made by visual/automated inspections of their tracks recorded in the emulsions. Trajectories of high energy charged particles (for example, minimum ionising charged particles) are revealed as sparse lines. Figure 1 shows tracks of protons (upper panel) and π^- (lower panel) at different energies, recorded in the nuclear emulsions used in the J-PARC E07 experiment. As shown in the figures, for the both particles, they show sparse tracks at high energies ($>$ 200 MeV for protons and $>$ 100 MeV for π^- mesons). At lower energies, the sparseness of the tracks is getting less and they become more bold. Even at lower energies, they show staggered movement until they are stopped. When π^- mesons are stopped, they are absorbed by atomic nuclei in the nuclear emulsions, and particle trajectories produced from nuclear fragmentation reactions are appeared. Figure 2 shows trajectories of α-particles emitted in the ^{232}Th alpha-decay chain. The energies of these α-particles are ranged from 5.340 to 8.785 MeV. It is clearly shown that tracks are not sparse but thicker than protons and π^- mesons doe to its larger Z^2 value. For heavier ions, the boldness of their trajectories are more according to larger Z^2 value.

Nuclear emulsions are especially powerful for searching double-strangeness hypernuclei, such as double-Λ and Ξ hypernuclei. Thoough those hypernuclei are produced very rarely (very small production cross section with kaon irradiations), they can identified very precisely by visual inspections by human eyes, and precise measurements of

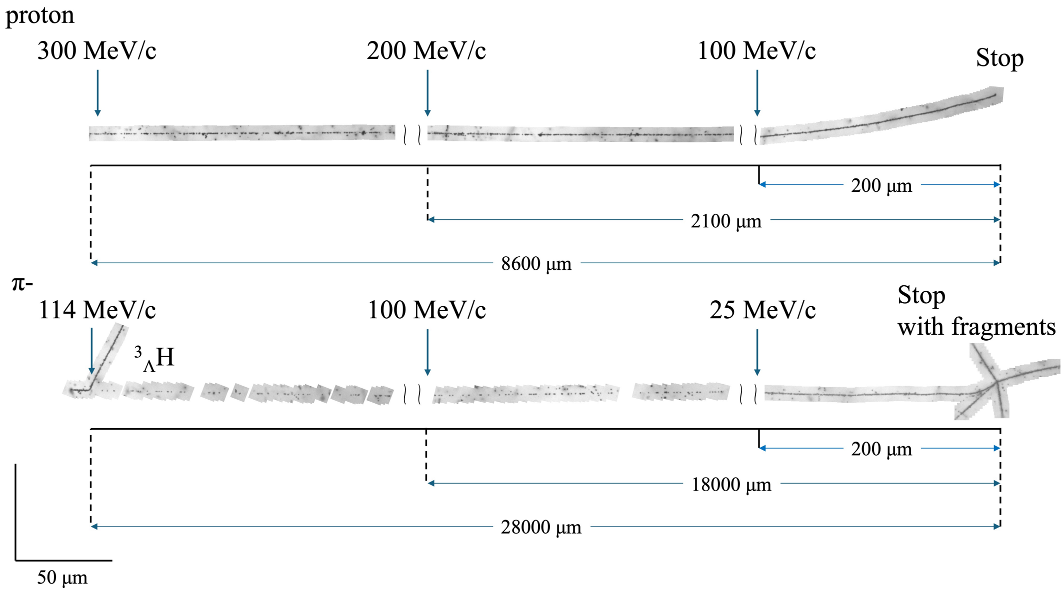

FIG. 1. Trajectories of protons (upper panel) and π^- (lower panel) at different energies, recorded in the nuclear emulsions used in the J-PARC E07 experiment

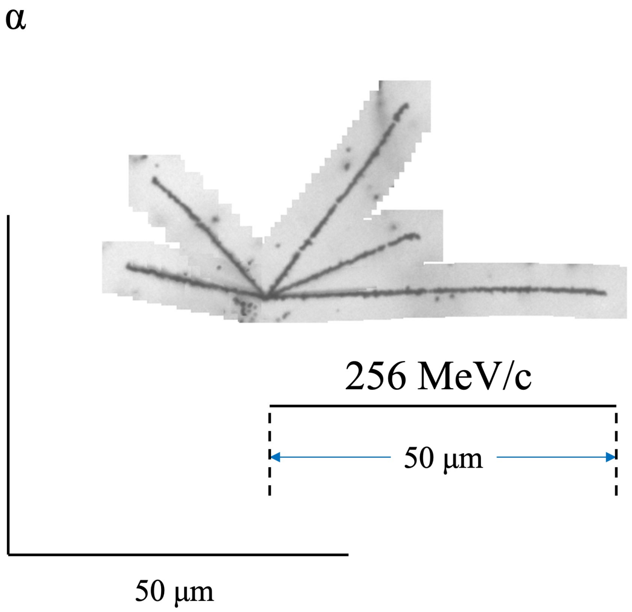

FIG. 2. Trajectories of α-particles emitted in the ^{232}Th alpha-decay chain. The energies of these α-particles are ranged from 5.340 to 8.785 MeV.

charged particle trajectories associated with production and decay of double-strangeness hypernuclei can offer a few hundred keV resolution for determining binding energies even with a single event. A pioneering experiment, the KEK PS-373 experiment, lead by Nakazawa (the member of this collaboration), discovered, the so-called Nagara event, to manifest very clearly the existence of double-Λ hypernucleus, ${}^{6}_{\Lambda\Lambda}$He, and its biding energy [19]. It is an benchmarking hypernuclei for theoretical calculations of double-strangeness hypernuclei. Later, Nakazawa and his collaborators performed another experiment, the E07 at J-PARC, and they irradiated approximately 1300 nuclear emulsion sheets with dimensions of 35×35 cm^2. With the novel method, the so-called the hybrid measurement [14, 15], and 33 events that should be associated with production of double-strangeness hypernuclei were observed. However, only a few could reach to identifications [14–16]. There should be approximately 1000 more double-strangeness hypernuclei events recorded in those emulsion sheets irradiated in the J-PARC E07 experiment, that can not be detected by the hybrid method. To mine those undiscovered hypernuclear events, the High Energy Nuclear Physics Laboratory (HENP-Lab) of RIKEN in Japan leads an international collaboration to develop machine learning models [10]. This group is contributing the nuclear emulsion part of this proposed project. They have already developed a novel technique to produce training data for machine learning development with Monte Carlo simulations and one of machine learning techniques, Generative Adversarial Network, GAN [20, 21]. For detecting hypernuclear events, they have developed models with one machine learning model, MASK R-CNN [22]. Initially, the project aims to precisely determine the hypertriton binding energy to resolve the hypertriton puzzle [10], and they are reaching to the best precision soon. The developed machine learning technology has been extended to mine double-strangeness hypernuclear events, and they have already discovered six double-strangeness hypernuclear candidates with analyses of only 0.2 % of the entire nuclear emulsion data of the E07 experiment [23]. The developed machine learning will be key technologies on the proposed project, and it will be further developed by the RIKEN HENP-Lab.

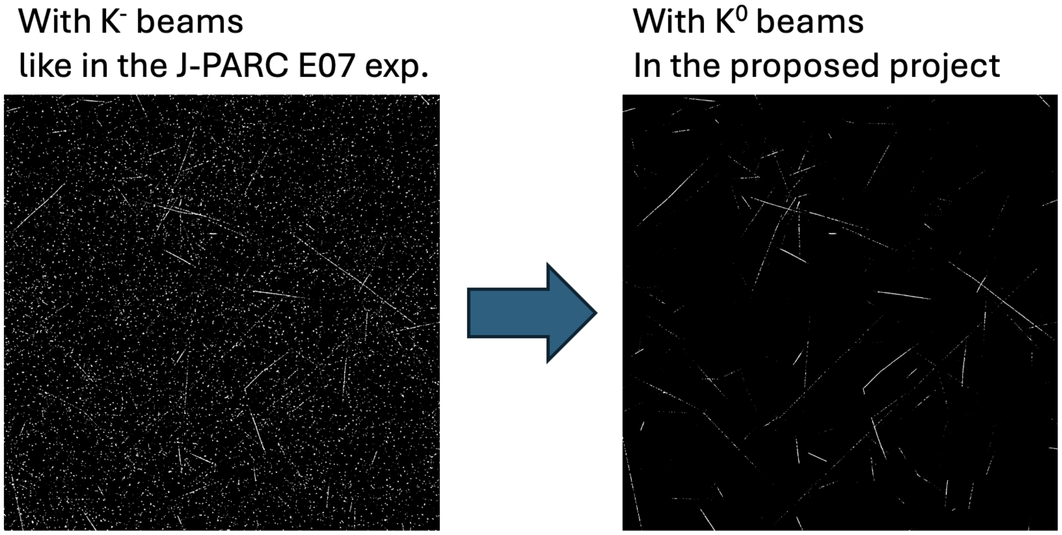

FIG. 3. The left panel shows a simulated and binarized image of a nuclear emulsion with irradiation with K^- beams. The right panel is corresponding image with neutral kaon beams foreseen in the proposed project.

In the analyses of the nuclear emulsions obtained in the J-PARC E07 experiments, one of difficulties are background produced by charged-K^- beams going through the emulsion sheets. Recorded beam track density is $10^4/\mathrm{mm}^2$. In the proposed project, nuclear emulsions are irradiated by neutral kaons, therefore, there is no charged beam-induced background as demonstrated in Figure. 3. The left panel shows an image of a simulated and binarized image of a nuclear emulsion with irradiation with K^- beams, like in the J-PARC E07 experiment. Dots shown in the figure are tracks of K^- beams penetrating perpendicularly to the emulsion sheet. The density of these dots is very large with beams irradiation, and emulsion images will be just black if beams tracks are accumulated largely. Therefore, in the J-PARC E07 experiment, a stack of 11 emulsion sheets, was moved automatically in order to decrease the density of beam tracks, and the stack was replaced by a stack of fresh nuclear emulsion sheets every six hours. With those efforts, the beam rack density was decreased, however, as described above, the beam track density is yet $10^4/\mathrm{mm}^2$, and it makes the imaging analyses for mining hypernuclear events difficult even with the machine learning techniques. In the proposed project, those beams tracks will not appear in the emulsion images since the beam particle are neutral (K_L, n, γ), and it is demonstrated in the right panel of Figure. 3. In the proposed project, there is no need to implement a sophisticated moving system of nuclear emulsion stacks. Expected background will be induced by reactions of high energy γ-rays and neutrons, however, the reaction cross section of those with nuclei in the emulsion will be reasonably small. The ratio between different reactions is expected to be similar to a main production experiment (1000:500:4, $K_L : n : \gamma$) In order to minimize tracks induced by high energy γ-rays and neutrons, we are considering to make a simple very slow descent system of a stack of 100 elongated emulsion sheets (20×80 cm^2)

by gravity. Irradiated nuclear emulsion will be transported from the KLF to Gifu University in Japan, where there is an infrastructure doe chemical development of nuclear emulsions. The RIKEN team will also be in charge of the chemical development, and then they will be transported to the RIKEN HENP-Lab for scanning nuclear emulsion by dedicated microscope systems. The data will be stored in the data server there, and analyses will be performed by the machine learning models that have been developed by the RIKEN HENP-lab.

Presently, we consider to mount a stack of 100 emulsion sheets in the last section of the hypernuclear setup (in front of the beam dump with radiation shielding materials). The emulsion sheets are a production target of hypernuclei as well as detectors of particles associated with their production and decay. In the following, we discuss the number of double-hypernuclear events recorded in nuclear emulsions, based on the already performed J-PARC E07 experiment with K^- beams at 1.8 GeV/c.

The beam intensity of the E07 experiment was 280 k particles per spil (5.52 seconds), thus, roughly 50 k per second. The experiment took place for 25 days (about 600 hours), and the amount of irradiated K^- beams is a total of 120 billion particles. With this condition, it was expected to record 1000 double-hypernuclear events in the entire emulsion sheets. In the proposed project, an estimated intensity of neutral K_L beams is about 10 k per seconds, and the amount of K_L beams on emulsion target will be about 5k/s, with the rest either decay in flight or absorbed by the cryogenic target. About 1/10 of the E07 experiment, however the beamtime length at KLF is expected to be 10 times longer, so we expect similar quantity of recorded double-hypernuclei events as in E07. Furthermore, the data at KLF emulsion station are expected to be almost background-free leading to much higher detection efficiency of double-strangeness hypernuclear events. Based on our previous experience, we'll also optimise the composition of nuclear emulsions, making smaller sliver grain size, hence expecting to have a better resolution in track lengths reconstruction, leading to a better resolution of binding energies determination.

The team of the RIKEN HENP-Lab continues to analyze the emulsion data of the J-PARC E07 experiment, however, these data are the last ones, and there is no further plans to make experiments with nuclear emulsions at J-PARC. Additionally, as already discussed, the analyses of those data are not easy because of the beam-induced background. The proposed project will provide unique big data set for hypernuclei with hugely suppressed background, and it will provide the very unique large amount of information regarding double-hypernuclei.

As discussed earlier, majority of double-hypernuclei are formed in a multi-step process: a Ξ^- baryon produced in a $K_L n \to K^+ \Xi^-$ reaction is decelerated and stopped in emulsion forming first atomic and than nuclear system. However, double-hypenuclei can be produced in-flight as well. There was not much research done on such kind of events before due to associated difficulty in reconstruction of such events. In case of KLF such events might provide additional important information on charge symmetry breaking in strange systems, since one would populate mirror hypernuclei compare to K^--beam studies, e.g. $K^- p \to \Xi^- + K^+$ vs $K_L\ n \to \Xi^- + K^+$.

B. Germanium station

High purity germanium are the best detectors to measure nuclear gamma transitions, however their use in high-intensity experiments are challenging. There are few possibilities how one can implement HPG detectors in a hypernuclei experiments. Usually it is some station with rather low acceptance which measure gamma lines in coincidence with recoil particles precisely measured at magnetic spectrometer. Unlike in experiments with charged pion or kaon beams, neutral kaon beams have an advantage - in addition to conventional technique, one can use germanium detector as a target, producing germanium hypernuclei inside detector volume having 100% acceptance coverage. A segmentation of germanium detector will help to identify all the other hypernuclei decay products and couple of layers of simple plastic scintillator can help to trigger and tag recoils.

The UoY owns legacy GE6 germanium detector [2] and double sided silicon strip (DSSD) array which we plan to use for this experiment. Additionally we were awarded 20k GBP to build a supporting structure and a readout for this experiment.

The idea of experiment is the following a low energy neutral kaon produces $K^+\Xi^-$ event on neutron in a germanium array $K_L p \to K^+\Xi^-$. An outgoing positive kaon carries out all momentum and analysed by layers of Germanium and a plastic scintillator (the latter on is used for the trigger purposes). A slow Ξ^- looses its energy by ionisation very close to production vertex and form first a $\Xi^- - Ge$ atom with subsequent formation of $\Xi^- Ge$ nuclei. The photons from an atomic and nuclear transitions will be measured by the same Germanium detector and by surrounding Ge detectors as well. A delayed signal from hypernucler decay creates a unique pattern which is very hard to miss.

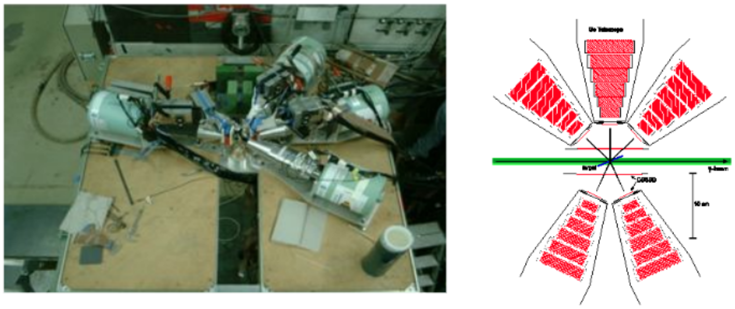

FIG. 4. The York HPG existing setup

III. HYPERNUCLEAR STATION LOCATION

The Hypernuclear station will be located behind the GlueX forward detector, before the beamdump, see Fig. 5. It is expected that hypernuclei station will be located on a dedicated platform to be able to move it in and out during beam development studies. The station will be build from a standard profiles and expected to be very light. For alignments reasons during data collection a hypernuclei station will be connected to a forward detector platform.

To avoid charged particle contaminations we plan to install a permanent sweeping magnet in front of the station. The main contaminants are expected to be low energy proton events originated from np-elastic scattering in cryogenic target. These protons can be easily bent away from the hypernuclear station.

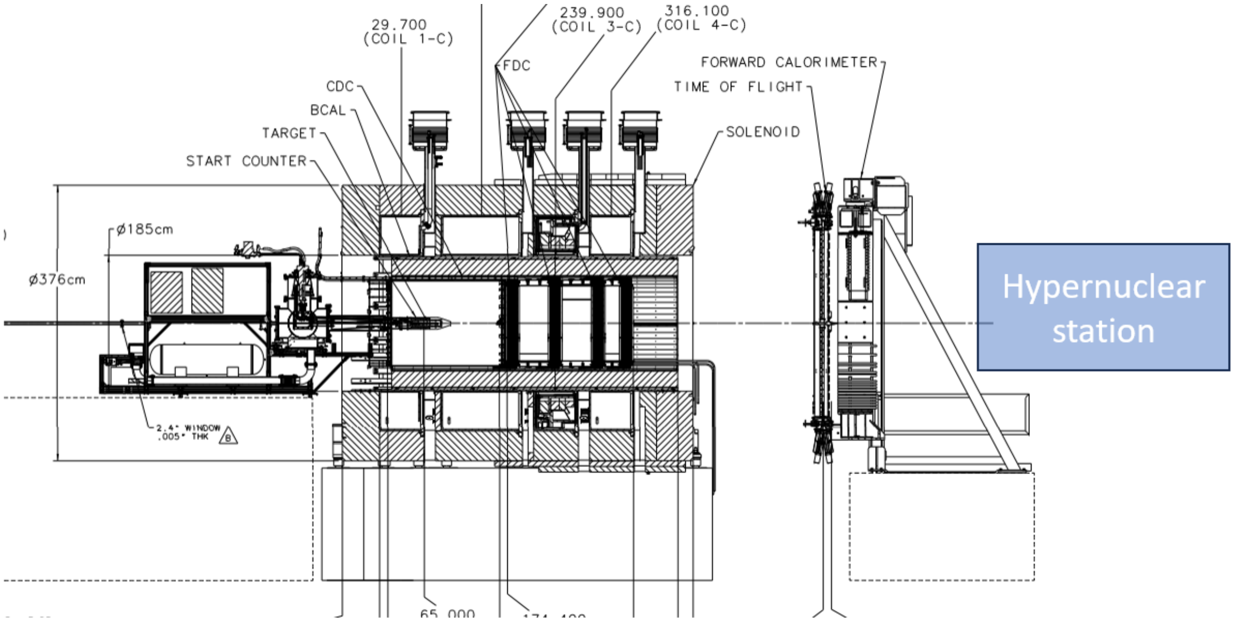

FIG. 5. The hypernucler station location in Hall D.

IV. EXISTING EQUIPMENT AND RELOCATION TIMELINE

It is expected that York HGe detecors will be shiped to Japan for tests in the beginning of 2025 and will be ready for installation in Fall 2025 fitting the installation schedule. The emulsion station will be ready for the installation in about the same time. A hypernucler station will be installed in a very different part of the hall-D compare to CPS, Kaon Production Target or Flux Monitor, so it can be installed in parallel without a need to prioritise and queue the work. A station will be installed using UoY and RIKEN manpower and would not require any additional help from the lab.

V. DECOMMISSIONING

Since the both kaon and neutron fluxes are rather low at that position we do not expect building up of any contaminants. The station can be removed immediately after the end of experiment. Denistallation time is expected to be about 1 month.

VI. COSTS

All equipment related costs will be covered by involved institution. The University of York has in-kind contribution of HPG's, we also were awarded with a 20k GBP grant to build support station and readout system for this experiment. It also has funding of one core PDRA at 40% FTE level for a full duration of KLF experiment to maintain UoY equipment.

The High Energy Nuclear Physics Laboratory (HENP-Lab) of RIKEN in Japan will contribute to the construction of the nuclear emulsion station, namely 100 emulsion sheets per year from 2025-2029, including developments, production, transportation to/from JLab from/to Japan and chemical development development of irradiated nuclear emulsions. It will corresponds to 60-70 million JPY (12-14 million JPY per year) which is about 300-350 k GBP if the funding application in Japan is successful. Three research staffs, one postdocs and one Ph.D. student of the RIKEN HENP-Lab will contribute to this project. RIKEN will also provide some administrative contributions.

VII. JLAB CONTRIBUTION

We expect Hall to provide mounting points and a platform place in front of the beam dump position. We would need some regular power supply in the order of ∼1-2kW. In case of running with HPG station one would need to have a regular refill with liquid nitrogen.

VIII. SUMMARY

There is a lot of interest in hypernucler physics and low-energy hyperon-nucleon interactions form many directions - chiral perturbation theory, nuclear structure studies, astrophysics... The only available way to access this domain is an experiment with nuclear emulsions and kaon beams. Neutral kaon beams offered unique opportunity to perform the cleanest possible experiment for a first time and access many observables never measured before. In case of KL-Facility such experiment can be performed in a parasitic mode enhancing knowledge output of already approved experiment. The experiment requires little to no contribution from a JLab and can be performed with external manpower and external funding.

---

[1] M. G. Albrow, D. Aston, D. P. Barber, L. Bird, R. J. Ellison, C. Halliwell, A. E. Harckham, F. K. Löbinger, P. G. Murphy, J. Walters *et al.* “Photoproduction of k0 mesons from protons and from complex nuclei,” Nucl. Phys. B **23**, 509 (1970).

[2] Branford, Foehl, Harrington, Jude, Watts, Roche, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment Volume 602, Issue 2, 21 April 2009, Pages 511-519

[3] J. K. Ahn *et al.* Phys. Rev. C**88**, 014003, 2013

[4] C. M. G. Lattes, G. P. S. Occhialinidr, and C. F. Powelldr, “Observations on the tracks of slow mesons in photographic emulsions,” Nature 160, 453–456 (1947)

[5] M. Danysz and J. Pniewski, “Delayed disintegration of a heavy nuclear fragment: I,” Lond. Edinb. Dublin Philos. Mag. J. Sci. 44, 348–350 (1953).

[6] D. Davis, “50 years of hypernuclear physics: I. The early experiments,” Nucl. Phys. A 754, 3–13 (2005).

[7] K. Niu, E. Mikumo, and Y. Maeda, “A possible decay in flight of a new type particle,” Prog. Theor. Phys. 46, 1644–1646 (1971).

[8] M. Danysz, K. Garbowska, J. Pniewski, T. Pniewski, J. Zakrzewski, E. Fletcher, J. Lemonne, P. Renard, J. Sacton, W. Toner, D. O’Sullivan, T. Shah, A. Thompson, P. Allen, S. Heeran, A. Montwill, J. Allen, M. Beniston, D. Davis, D. Garbutt, V. Bull, R. Kumar, and P. March, “The identification of a double hyperfragment,” Nucl. Phys. 49, 121–132 (1963).

[9] M. Yoshimoto, T. Nakano, R. Komatani, and H. Kawahara, “Hyper-track selector nuclear emulsion readout system aimed at scanning an area of one thousand square meters,” Prog. Theor. Exp. Phys. 2017, 103H01.

[10] T. R. Saito, W. Dou, V. Drozd, H. Ekawa, S. Escrig, Y. He, C. M. G. Lattes, G. P. S. Occhialinidr, and C. F. Powelldr, “Observations on the tracks of slow mesons in photographic emulsions,” Nature 160, 453–456 D. Davis, “50 years of hypernuclear physics: I. The early experiments,” Nucl. Phys. A 754, 3–13 (2005). N. Kalantar-Nayestanaki, A. Kasagi, M. Kavatsyuk, E. Liu, Y. Ma, S. Minami, A. Muneem, M. Nakagawa, K. Nakazawa, C. Rappold, N. Saito, C. Scheidenberger, M. Taki, Y. K. Tanaka, J. Yoshida, M. Yoshimoto, H. Wang, and X. Zhou, “New directions in hypernuclear physics,” Nat. Rev. Phys. 3, 803–813 (2021).

[11] K. Kodama, N. Ushida, C. Andreopoulos, N. Saoulidou, G. Tzanakos, P. Yager, B. Baller, D. Boehnlein, W. Freeman, B. Lundberg, J. Morfin, R. Rameika, S. Chung, J. Song, C. Yoon, P. Berghaus, M. Kubantsev, N. Reay, R. Sidwell, N. Stanton, S. Yoshida, S. Aoki, T. Hara, J. Rhee, D. Ciampa, C. Erickson, M. Graham, E. Maher, K. Heller, R. Rusack, R. Schwienhorst, J. Sielaff, J. Trammell, J. Wilcox, T. Furukawa, K. Hoshino, H. Jiko, M. Komatsu, M. Nakamura, T. Nakano, K. Niwa, N. Nonaka, K. Okada, B. Park, O. Sato, S. Takahashi, V. Paolone, C. Rosenfeld, A. Kulik, T. Kafka, W. Oliver, T. Patzak, and J. Schneps, “Observation of tau neutrino interactions,” Phys. Lett. B 504, 218–224 (2001).

[12] N. Agafonova, A. Aleksandrov, A. Anokhina, S. Aoki, A. Ariga, T. Ariga, D. Bender, A. Bertolin, I. Bodnarchuk, C. Bozza, R. Brugnera, A. Buonaura, S. Buontempo, B. Büttner, M. Chernyavsky, A. Chukanov, L. Consiglio, N. D’Ambrosio, G. De Lellis, M. De Serio, P. Del Amo Sanchez, A. Di Crescenzo, D. Di Ferdinando, N. Di Marco, S. Dmitrievski, M. Dracos, D. Duchesneau, S. Dusini, T. Dzhatdoev, J. Ebert, A. Ereditato, R. A. Fini, F. Fornari, T. Fukuda, G. Galati, A. Garfagnini, J. Goldberg, Y. Gornushkin, G. Grella, A. M. Guler, C. Gustavino, C. Hagner, T. Hara, H. Hayakawa, A. Hollnagel, B. Hosseini, K. Ishiguro, K. Jakovcic, C. Jollet, C. Kamiscioglu, M. Kamiscioglu, J. H. Kim, S. H. Kim, N. Kitagawa, B. Klicek, K. Kodama, M. Komatsu, U. Kose, I. Kreslo, F. Laudisio, A. Lauria, A. Ljubicic, A. Longhin, P. F. Loverre, A. Malgin, M. Malenica, G. Mandrioli, T. Matsuo, T. Matsushita, V. Matveev, N. Mauri, E. Medinaceli, A. Meregaglia, S. Mikado, M. Miyanishi, F. Mizutani, P. Monacelli, M. C. Montesi, K. Morishima, M. T. Muciaccia, N. Naganawa, T. Naka, M. Nakamura, T. Nakano, Y. Nakatsuka, K. Niwa, S. Ogawa, A. Olchevsky, T. Omura, K. Ozaki, A. Paoloni, L. Paparella, B. D. Park, I. G. Park, L. Pasqualini, A. Pastore, L. Patrizii, H. Pessard, C. Pistillo, D. Podgrudkov, N. Polukhina, M. Pozzato, F. Pupilli, M. Roda, T. Roganova, H. Rokujo, G. Rosa, O. Ryazhskaya, O. Sato, A. Schembri, W. Schmidt-Parzefall, I. Shakirianova, T. Shchedrina, A. Sheshukov, H. Shibuya, T. Shiraishi, G. Shoziyoev, S. Simone, M. Sioli, C. Sirignano, G. Sirri, A. Sotnikov, M. Spinetti, L. Stanco, N. Starkov, S. M. Stellacci, M. Stipcevic, P. Strolin, S. Takahashi, M. Tenti, F. Terranova, V. Tioukov, S. Tufanli, P. Vilain, M. Vladymyrov, L. Votano, J. L. Vuilleumier, G. Wilquet, B. Wonsak, C. S. Yoon, and S. Zemskova (OPERA Collaboration), “Discovery of τ neutrino appearance in the CNGS neutrino beam with the opera experiment,” Phys. Rev. Lett. 115, 121802 (2015).

[13] E. Hiyama and K. Nakazawa, “Structure of S=-2 hypernuclei and hyperon-hyperon interactions,” Annu. Rev. Nucl. Part. Sci. 68, 131–159 (2018).

[14] H. Ekawa, K. Agari, J. K. Ahn, T. Akaishi, Y. Akazawa, S. Ashikaga, B. Bassalleck, S. Bleser, Y. Endo, Y. Fujikawa, N. Fujioka, M. Fujita, R. Goto, Y. Han, S. Hasegawa, T. Hashimoto, S. H. Hayakawa, T. Hayakawa, E. Hayata, K. Hicks, E. Hirose, M. Hirose, R. Honda, K. Hoshino, S. Hoshino, K. Hosomi, S. H. Hwang, Y. Ichikawa, M. Ichikawa, M. Ieiri, K. Imai, K. Inaba, Y. Ishikawa, A. Iskendir, H. Ito, K. Ito, W. S. Jung, S. Kanatsuki, H. Kanauchi, A. Kasagi, T. Kawai, M. H. Kim, S. H. Kim, S. Kinbara, R. Kiuchi, H. Kobayashi, K. Kobayashi, T. Koike, A. Koshikawa, J. Y. Lee, J. W. Lee, T. L. Ma, S. Y. Matsumoto, M. Minakawa, K. Miwa, A. T. Moe, T. J. Moon, M. Moritsu, Y. Nagase, Y. Nakada, M. Nakagawa, D. Nakashima, K. Nakazawa, T. Nanamura, M. Naruki, A. N. L. Nyaw, Y. Ogura, M. Ohashi, K. Oue, S. Ozawa, J. Pochodzalla, S. Y. Ryu, H. Sako, Y. Sasaki, S. Sato, Y. Sato, F. Schupp, K. Shirotori, M. M. Soe, M. K. Soe, J. Y. Sohn, H. Sugimura, K. N. Suzuki, H. Takahashi, T. Takahashi, Y. Takahashi, T. Takeda, H. Tamura, K. Tanida, A. M. M. Theint, K. T. Tint, Y. Toyama, M. Ukai, E. Umezaki, T. Watabe, K. Watanabe, T. O. Yamamoto, S. B. Yang, C. S. Yoon, J. Yoshida, M. Yoshimoto, D. H. Zhang, and Z. Zhang, “Observation of a Be double-Lambda hypernucleus in the J-PARC E07 experiment,” Prog. Theor. Exp. Phys. 2019, 021D02.

[15] S. H. Hayakawa, K. Agari, J. K. Ahn, T. Akaishi, Y. Akazawa, S. Ashikaga, B. Bassalleck, S. Bleser, H. Ekawa, Y. Endo, Y. Fujikawa, N. Fujioka, M. Fujita, R. Goto, Y. Han, S. Hasegawa, T. Hashimoto, T. Hayakawa, E. Hayata, K. Hicks, E. Hirose, M. Hirose, R. Honda, K. Hoshino, S. Hoshino, K. Hosomi, S. H. Hwang, Y. Ichikawa, M. Ichikawa, K. Imai, K. Inaba, Y. Ishikawa, H. Ito, K. Ito, W. S. Jung, S. Kanatsuki, H. Kanauchi, A. Kasagi, T. Kawai, M. H. Kim, S. H. Kim, S. Kinbara, R. Kiuchi, H. Kobayashi, K. Kobayashi, T. Koike, A. Koshikawa, J. Y. Lee, T. L. Ma, S. Y. Matsumoto, M. Minakawa, K. Miwa, A. T. Moe, T. J. Moon, M. Moritsu, Y. Nagase, Y. Nakada, M. Nakagawa, D. Nakashima, K. Nakazawa, T. Nanamura, M. Naruki, A. N. L. Nyaw, Y. Ogura, M. Ohashi, K. Oue, S. Ozawa, J. Pochodzalla, S. Y. Ryu, H. Sako, S. Sato, Y. Sato, F. Schupp, K. Shirotori, M. M. Soe, M. K. Soe, J. Y. Sohn, H. Sugimura, K. N. Suzuki, H. Takahashi, T. Takahashi, T. Takeda, H. Tamura, K. Tanida, A. M. M. Theint, K. T. Tint, Y. Toyama, M. Ukai, E. Umezaki, T. Watabe, K. Watanabe, T. O. Yamamoto, S. B. Yang, C. S. Yoon, J. Yoshida, M. Yoshimoto, D. H. Zhang, and Z. Zhang (J-PARC E07 Collaboration), "Observation of Coulomb-assisted nuclear bound state of Ξ^--^{14}N system," Phys. Rev. Lett. 126, 062501 (2021).

[16] M. Yoshimoto, J. K. Ahn, B. Bassalleck, H. Ekawa, Y. Endo, M. Fujita, Y. Han, T. Hashimoto, S. H. Hayakawa, K. Hicks, K. Hoshino, S. Hoshino, S. H. Hwang, Y. Ichikawa, M. Ichikawa, K. Imai, Y. Ishikawa, H. Kanauchi, A. Kasagi, S. H. Kim, S. Kinbara, P. M. Lin, T. L. Ma, K. Miwa, A. T. Moe, Y. Nagase, K. Nakazawa, T. Nanamura, M. Naruki, A. N. L. Nyaw, J. Pochodzalla, H. Sako, S. Sato, M. M. Soe, M. K. Soe, J. Y. Sohn, H. Takahashi, T. Takahashi, H. Tamura, K. Tanida, A. M. M. Theint, K. T. Tint, M. Ukai, T. O. Yamamoto, S. B. Yang, C. S. Yoon, J. Yoshida, D. H. Zhang, and Z. Zhang, "First observationof a nuclear s-state of a Ξ hypernucleus, $^{15}_{\Xi}$C," Prog. Theor. Exp. Phys. 2021, 073D02.

[17] H. K. Tanaka, T. Nakano, S. Takahashi, J. Yoshida, M. Takeo, J. Oikawa, T. Ohminato, Y. Aoki, E. Koyama, H. Tsuji, and K. Niwa, "High resolution imaging in the inhomogeneous crust with cosmic-ray muon radiography: The density structure below the volcanic crater floor of Mt. Asama, Japan," Earth and Planetary Science Letters 263, 104–113 (2007).

[18] K. Morishima, M. Kuno, A. Nishio, N. Kitagawa, Y. Manabe, M. Moto, F. Takasaki, H. Fujii, K. Satoh, H. Kodama, K. Hayashi, S. Odaka, S. Procureur, D. Attié, S. Bouteille, D. Calvet, C. Filosa, P. Magnier, I. Mandjavidze, M. Riallot, B. Marini, P. Gable, Y. Date, M. Sugiura, Y. Elshayeb, T. Elnady, M. Ezzy, E. Guerriero, V. Steiger, N. Serikoff, J.-B. Mouret, B. Charlès, H. Helal, and M. Tayoubi, "Discovery of a big void in Khufu's Pyramid by observation of cosmic-ray muons," Nature 552, 386–390 (2017).

[19] Takahashi, H. et al., Phys. Rev. Lett. 87, 212502, (2001).

[20] Goodfellow, I. J. et al. Generative Adversarial Networks. arXiv preprint (2014).

[21] Wang, T. et al. High-resolution image synthesis and semantic manipulation with conditional gans. arXiv preprint (2017).

[22] He, K., Gkioxari, G., Dollar, P. and Girshick, R. B. Mask R-CNN. arXiv preprint (2017).

[23] Ya He, Ph.D. thesis, Lanzhou University, to be completed in 2025.