【Grant-in-Aid for Scientific Research (S)】

Study of Quantum Interactions Including Many-Body Forces through Precision Measurements of Hypernuclear Binding Energies

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Purpose and Background of the Research

●Outline of the Research

The goal of our research is to achieve a comprehensive understanding of the particle-particle interactions that govern the baryons, such as neutrons and protons (nucleons, N), which make up atomic nuclei. To do so, we study hypernuclei, which include hyperons (Y), and investigate the interactions between hyperons, protons, and neutrons. By precisely measuring the mass of hypernuclei and accurately determining the interactions strength between particles, including hyperons, within the hypernuclei, we aim to elucidate the full picture of the forces that act within atomic nuclei.

One approach to achieve this is to produce hypernuclei within a type of photographic film known as a “nuclear emulsion,” record the processes of their formation and decay, and perform precise analysis of the particle tracks contained in these events using a microscope. By applying kinematic principles, the mass of the hypernuclei can be determined. This method is the only one capable of precisely measuring the “double hypernucleus,” which contains two hyperons, a species that is difficult to produce, and determining the interactions between the hyperons. By studying various hypernuclei, we can elucidate the “nuclear medium dependence” of particle interactions involving hyperons, contributing to the understanding of the conditions inside neutron stars formed after supernova explosions.

In the J-PARC E07 experiment, about 1300 nuclear emulsion plates were used to observe 33 double hypernuclear events through an analysis method called the hybrid method. However, within these emulsion plates, over 2,000 double Λ-hypernucleus events containing two Λ-hyperons and more than one million single Λ-hypernucleus events have been recorded but not yet discovered. An international team, led by the principal investigator, has successfully developed an AI model to uncover hypernucleus events from the E07 nuclear emulsion data. In this research, we will further develop this model and also conduct new experiments at the U.S. accelerator facility (JLab) to investigate particle interactions involving hyperons, including many-body forces.

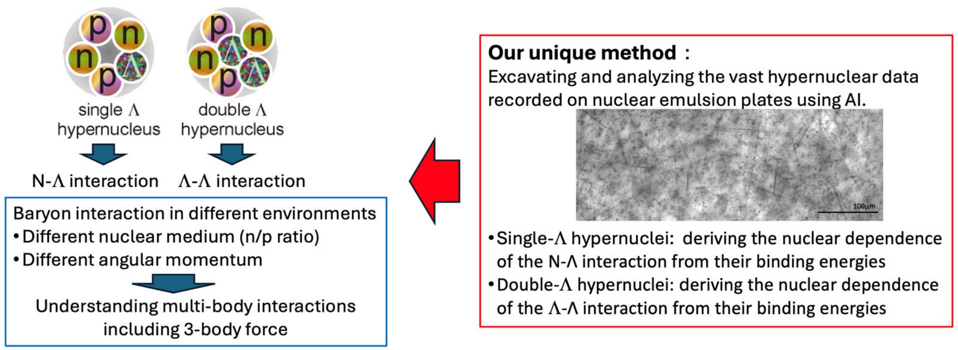

Figure 1. Overview of this project

●New experiment with nuclear emulsion and neutral K-meson beam

A hypernuclear station will be constructed downstream of the neutral K-meson beam facility (KLF) at the Thomas Jefferson Laboratory (JLab) in the US. Nuclear emulsion stacks will be installed there for irradiation experiments. A total of 400 days for irradiation is planned, which will prevent the recording of particle tracks caused by the beam, allowing for cleaner experimental data collection. It is expected this experiment will yield 2.3 times more hypernucleus data compared to the E07 experiment

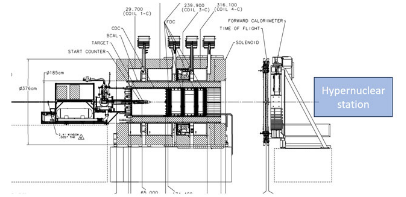

Figure 2. Hypernuclear station at the KLF

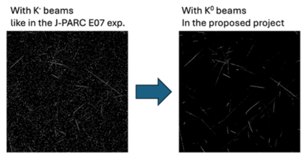

Figure 3. Comparison of binarized emulsion data between E07 (left) and new (right) experiments

Expected Research Achievements

● Precise Measurement of the Binding Energy of Single Hypernuclei to Determine Y-N Interactions

We will further develop the AI model to search for hypertriton events, increasing the statistics of hypertriton by a factor of ten. This will allow us to determine the binding energy of hypertritons with the best precision (a few tens keV). We aim to solve the hypertriton puzzle in hypernuclear research.

We will develop an AI model to detect three-body and many-body decay events of single hypernuclei. This will allow us to precisely determine the binding energy of the $^4{}_\Lambda$He hypernucleus. This measurement will address the issue of charge Symmetry breaking in the interaction between $^4{}_\Lambda$He and $^4{}_\Lambda$H.

We will develop an AI model to search for single Σ-hypernucleus events and systematically explore Σ-hypernuclei.

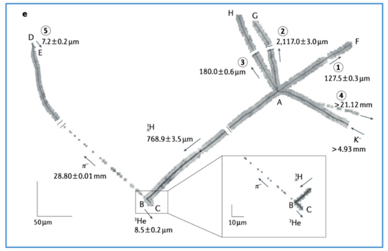

Figure 4. The first hypertriton event discovered and analyzed by AI (Nat. Rev. Phys. 3, 803-813 (2021)).

● Precise Measurement of the Binding Energy of Double-Λ Hypernuclei and Ξ-Hypernuclei to Determine the Λ–Λ and Ξ–Nucleon Interactions

We will further advance the AI model for the search of double-Λ hypernucleus events, systematically exploring double-Λ hypernuclei up to mass number 16. By determining their binding energies, we aim to reveal the nuclear medium dependence and angular momentum dependence of Λ–Λ interactions.

We will develop an AI model for the search of Ξ-hypernucleus events to elucidate the nature of the Ξ–nucleon interaction.

In this research, thousands of double hypernucleus events are expected to be observed, with hundreds of them likely to have their isotopes uniquely identified.

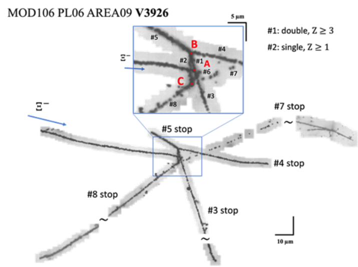

Figure 5. One of the double-Λ hypernucleus events discovered through the analysis of 0.2% of the entire E07 nuclear emulsion data. This event was uniquely identified as $^{13}{}_{\Lambda\Lambda}$B through detailed kinematic analysis, and its binding energy was determined. It is the second uniquely identified double-Λ hypernucleus in the history.

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