

学位論文全文に代わる要約
Extended Summary in Lieu of the Full Text of a Doctoral Thesis

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学位論文題目 : Machine learning techniques for measurements of Λ binding energy
Thesis Title. on ${}^3_\Lambda\text{H}$ and ${}^4_\Lambda\text{H}$

学位論文要約 :
Summary of Thesis

The study of baryon-baryon interactions from a general framework is one clue to understanding how matter is structured in a quark-based hierarchy. Hyperons, which contain s -quarks distinguishable from the u - and d -quarks that make up ordinary nuclei, are particularly useful probes of the contribution of quarks to baryon-baryon interactions. Hypernuclei, in which hyperons are bound to nuclei, have been studied to systematically understand the interactions between hyperons and nucleons and among hyperons from the binding energies between hyperons and nuclei for various core nuclei.

Hypertriton, ${}^3_\Lambda\text{H}$, the lightest and simplest of the hypernuclei, is a benchmark in hypernuclear physics. The binding energy between Λ hyperon and deuteron-core was reported to be 130 ± 50 keV in experiments up to the 1970s, suggesting a loosely bound state. Therefore, the lifetime of ${}^3_\Lambda\text{H}$ has been considered equivalent to free Λ hyperons, 263 ± 2 ps. However, recent experimental measurements reported significantly shorter lifetimes than free Λ particles. This contradicts the known understanding of the binding energy, attracted attention as a hypertriton puzzle, and triggered the performance of many experiments. Precise experimental data on the binding energy and lifetime of ${}^3_\Lambda\text{H}$ is essential to solve the Hypertriton puzzle, drawing clear conclusions on hypernuclear physics fundamentals, and improving understanding of baryon-baryon interactions.

As an approach to measure the binding energy, we implemented a method to measure the invariant mass by analyzing the track information of hypernuclear decay recorded in the nuclear emulsion. In the nuclear emulsion experiment J-PARC E07, which was conducted to detect double-strangeness hypernuclei, approximately 1300 emulsion sheets were irradiated with K^- meson beams. A large number of single- Λ hypernuclei, including ${}^3_\Lambda\text{H}$, that were not triggered could have been recorded. The overall scanning method, in which the entire volume of the nuclear emulsion is comprehensively scanned and imaged with a microscope to search for hypernuclear events, has the potential to detect ${}^3_\Lambda\text{H}$ events. However, the conventional analytical filter based on line detection with image processing is not practical because the emulsion image data is vast, totaling 200 PB, and considering its signal-to-noise ratio, it was estimated to take approximately 560 years for ten human operators to perform manual visual inspection.

Therefore, an event search method was employed based on machine learning techniques, which have produced great results in image analysis. Using Mask R-CNN, a convolutional network-based object detection method, a model was developed to detect target events from microscopic images. Although a large amount of training data containing position and shape information of the detection target is required to tune the parameters of the model, no actual ${}^3_\Lambda\text{H}$ events had ever been identified from the nuclear emulsion used in the E07 experiment. Accordingly, Monte Carlo simulations with Geant4 were used to represent the particle track information in the nuclear emulsion, and surrogate images of the microscope image were generated by an image-style transformation using a machine learning technique with a generative adversarial network. The ability to produce surrogate images comparable to actual microscope images has enabled us to obtain a large

amount of training data for an object detection model that searches for rare events.

The performance of the object detection model trained with surrogated images was evaluated using α -decay events recorded in the nuclear emulsion. The model succeeded in improving the detection efficiency of α -decay events by a factor of 2 and reducing the amount of visual inspection to approximately 1/10, compared to the method using the conventional analytical filter. The model for ${}^3_{\Lambda}\text{H}$ detection developed by the same procedure has improved the signal-to-noise ratio in hypernuclear search from 10^{-8} to 4×10^{-4} , 10^4 times better and has decreased a load of human visual inspection significantly.

Implementing the machine learning technique has detected ${}^3_{\Lambda}\text{H}$ and ${}^4_{\Lambda}\text{H}$ events, which had never been identified in the data of E07, and the detection of hypernuclei by the overall scanning method was realized. Since the ${}^3_{\Lambda}\text{H}$ and ${}^4_{\Lambda}\text{H}$ mesonic two-body decay events are both associated with π - and helium isotopes and they cannot be distinguished by observations only near the decay point. Taking note that the π -particle tracks have a range of approximately 28 mm for ${}^3_{\Lambda}\text{H}$ and approximately 42 mm for ${}^4_{\Lambda}\text{H}$, the 36 cases of ${}^3_{\Lambda}\text{H}$ and 141 cases of ${}^4_{\Lambda}\text{H}$ events were uniquely identified by measurements of π -track lengths. The data analysis was performed for only 0.4% of the data used in the E07 experiment, indicating that detecting a large number of hypernuclei is feasible.

Detected events were analyzed to determine their Λ binding energy from invariant masses by calibrating the range-energy relation with measurements of mono-energetic α -particle tracks associated with α -decay events recorded near the detected position. Until the 1970s, the range-energy relation for the binding energy analysis of hypernuclei was calibrated for the entire volume of experimental data, approximately $6.5 \times 10^3 \text{ cm}^3$. In our analysis, the range-energy relation is calibrated for each 5 cm^3 volume to consider differences in characteristics of the emulsion sheet with the help of the α -decay detection model to speed up the analysis. The accuracy of the range-energy equation itself was also evaluated, and the systematic error in the nuclear emulsion analysis was estimated to be approximately 20 keV.

The method established detecting a rare event, hypernuclei, and analyzing binding energy using nuclear emulsion and machine learning. It demonstrates that data analysis shortly will detect a variety of hypernuclear events, including previously undetected events, and that a precise analysis of binding energies with large numbers of events will be feasible. It will contribute significantly to a systematic understanding of baryon-baryon interactions.