Correlation Analysis of Nuclear Properties and Prediction of Halo Structure Using Machine Learning

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Introduction

Nuclei near the drip lines can exhibit exotic properties, such as the halo structure observed in nuclei like ^{6}Li, ^{11}Be, ^{19}C, ^{34}Na, etc. These halo nuclei are characterized by an extended nucleon distribution, where one or two nucleons are very loosely bound, resulting in a long tail in the density distribution. Understanding the structures and reactions of these nuclei is crucial as they play a significant role in the r-process nucleosynthesis, which is responsible for the production of more than half of the heavy elements [1].

Breakup reaction is a widely used tool to study the halo nuclei. In breakup reactions, a projectile (beam of the nuclei of interest) impinges on a target and breaks up into fragment in the field of the target. The reaction observable, parallel momentum distribution (PMD) can directly be used to investigate the halo structure of nuclei [2]. A small FWHM (full width at half maximum) of the PMD indicates a larger spatial extension. PMD is least affected by reaction mechanism, allowing a direct correlation with a long tail in the matter distribution, as suggested by Heisenberg's uncertainty principle. Theoretical studies indicate that the momentum distribution parallel to the incoming beam ($P_{||}$) is less perturbed by the interaction in breakup process, making them suitable for probing halo structure, compared to the perpendicular momentum distribution ($P_{\perp}$). The observed narrow widths in the fragment momentum distribution of halo nuclei are about one-fifth of those seen in the fragmentation of non-halo, tightly bound nuclei. However, estimating FWHM requires resource-intensive experiments or computational resources.

Recent advancements in machine learning (ML) offer promising applications to nuclear reactions and nuclear astrophysics. In this study, we aim to use machine learning techniques to investigate the importance of the nuclear properties that can affect the FWHM of the PMD in the breakup of a nucleus. Subsequently, we aim to develop a predictive model to determine the probable 'halo structure' of a nucleus using these properties.

Methodology

As a test case, we compile a dataset of ten nuclei, each characterized by nine associated properties. The properties include nuclear characteristics such as the atomic number, mass number, and binding energies of both the projectile and the target nuclei. Additionally, we incorporated radius and diffuseness parameters from a phenomenological Woods-Saxon potential for the projectile nucleus, and the beam energy of the projectile (E_{aL}) that may influence the FWHM of the PMD. To investigate the relationships between these properties, we construct a correlation matrix that allows us to quantify the linear dependencies among the various nuclear properties, indicating which factors are most strongly correlated with FWHM. Following this analysis, the relative importance of each property in determining the FWHM can be estimated. Subsequently, a random forest classifier can be employed to predict the halo structure of each nucleus.

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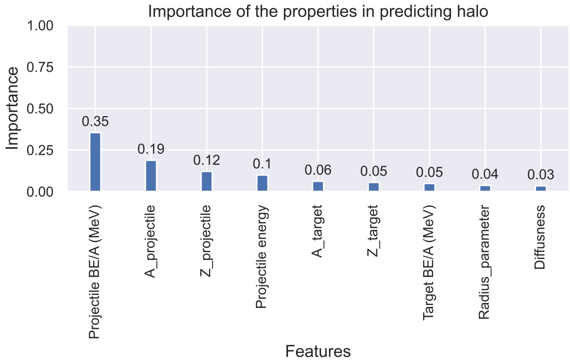

FIG. 1: Feature importance plot to quantify the importance of each property on the FWHM of the PMD.

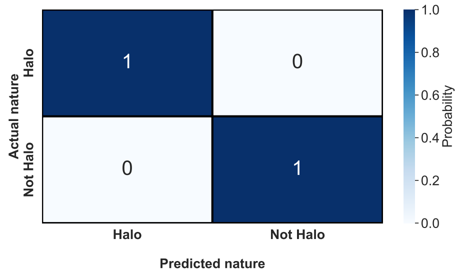

FIG. 2: Confusion matrix

Results and Discussions

In this study, we used machine learning to predict the halo nature of nuclei using various nuclear properties as input features. At first, we calculate a correlation matrix, estimating the linear relationship between the associated properties of each nucleus in the dataset. A correlation coefficient quantifies the strength and direction of the linear relationship between two variables. A positive correlation indicates that as one variable increases, the other variable also tends to increase and a negative correlation means that as a variable increases, the other variable tends to decrease. The coefficient ranges from -1 to 1. A coefficient 0 indicates that no linear relationship is present between the variables. Moreover, by dividing the data set into a train and a test dataset, a decision tree based random forest classifier is employed to train our model and evaluate its performance on the test dataset. The classifier provided a quantitative measure of the contribution from each property. The bar plot in Fig. 1 indicates that the binding energy of the nucleus (projectile) is the most influential property to FWHM. Interestingly the atomic number and mass numbers also showed a significant role.

Furthermore, to assess the predictive accuracy of the model, we computed a confusion matrix on the test dataset. By identifying and analyzing key nuclear properties, the decision tree model successfully predicted halo characteristics. The high probabilities along the diagonal of the confusion matrix (Fig. 2) demonstrate the model's ability to predict correctly. This approach complements experimental advancements and provides a scalable framework for future research. Nevertheless, considering the limited size of the input data, this may be an overestimation. We intend to include additional nuclear properties with a larger data set and employ optimized Machine learning techniques to enhance the predictive accuracy. We will also present the importance of the nuclear properties by considering various combinations such as $N_{(\text{projectile})}/A_{(\text{projectile})}$, and $Z_{(\text{projectile})}/A_{(\text{projectile})}$.

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