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ISRS ISOLDE Superconducting Recoil Separator

Probing residual nuclei production to optimize ISRS performance

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ABSTRACT

The production of residual nuclei is investigated using EMPIRE and PACE4 codes to enhance ISRS performance. This study employs a modified version of EMPIRE, incorporating the post-form distorted wave Born approximation of the Ichimura-Austern-Vincent approach for elastic and nonelastic breakup predictions, alongside the exciton and statistical Hauser-Feshbach models to account for pre-equilibrium and compound-nucleus processes. Using EMPIRE, yields of residual nuclei produced in the reaction with a CD_2 target induced by a neutron-rich ^{68}Ni beam at a center-of-mass energy of 19.4 MeV are calculated and compared with those obtained from PACE4. Results show that EMPIRE predicts a broader range of residual nuclei and larger total cross sections. The key difference arises from the fact that PACE4 focuses on projectile absorption, whereas EMPIRE incorporates different types of pre-compound/compound nuclei formations, offering a more comprehensive view of reaction mechanisms. Subsequently, we scale the EMPIRE cross sections based on the angular distribution patterns observed in the PACE4 results and provide precise Gaussian fits for each residual nucleus, which will be used in beam dynamic simulations to optimize the design of ISRS.

INTRODUCTION

The ISRS nuclear reaction calculations aim to study residual nucleus production and various reaction mechanisms to optimize ISRS performance. The nuclear reactions to be studied at the ISRS project involve using CD_2 or CT_2 targets, and radioactive beams of ^{9}Li, ^{30}Mg, ^{68}Ni, ^{132}Sn, ^{185}Hg, and ^{223}Ra at energies of 5 and 10 MeV/u, which are delivered by HIE-ISOLDE at the secondary target with intensities superior to 10^4 pps. They correspond to a selection of physics cases of approved experiments. Specifically, this work examines residual nucleus yields for the ^{68}Ni+d system at 10 MeV/u, with ongoing calculations using the modified EMPIRE, PACE4 [1-2], and other codes. Preliminary results for this system are briefly reviewed.

FORMALISM

To evaluate the production of the residual nuclei, it is of great importance to first select a precise computational framework. Toward this goal, we used the modified version of the EMPIRE code to thoroughly examine the reaction mechanisms. The modified EMPIRE includes the post-form distorted wave Born expression of the Ichimura-Austern-Vincent (DWBA-IAV) approach [3-6] for the elastic breakup and nonelastic breakup predictions, as well as the exciton and statistical Hauser-Feshbach models accounting for pre-equilibrium and compound-nucleus processes. Employing this code, we investigated the production of all residual nuclei in the selected reaction. The obtained results were compared to those calculated using PACE4. Below is a comparison of some features of these codes:

EMPIRE

- *Comprehensive nuclear reaction modeling across various projectiles and energy ranges.*
- *The code accounts for the major nuclear reaction models including DWBA-IAV and performs precise estimation of individual processes.*
- *The emission of neutrons, protons, α-particles, deuterons, tritons, and He-3 is taken into account.*
- *A comprehensive library of input parameters based on the RIPL-3 library is available.*

PACE4

- *Evaporation-focused Monte Carlo code for fusion cross sections and projectile absorption.*
- *Efficient for evaporation-dominated reactions; ideal for rapid calculations with simplified setups.*
- *Specializes in modeling the emission of neutrons, protons, alpha particles, and gamma.*
- *User-friendly with simple parameter input.*

RESIDUAL NUCLEI PRODUCTION

To evaluate residual nuclei production, we compared predictions from EMPIRE with those obtained from PACE4 in Fig. 1. In addition to general computational differences, the main discrepancy in the predictions arises from the fact that PACE4 focuses on projectile absorption, while EMPIRE incorporates all key processes and predicts the formation of different types of pre-compound/compound nuclei in the reaction, making it a more comprehensive tool for examining the reaction mechanisms and residual nuclei.

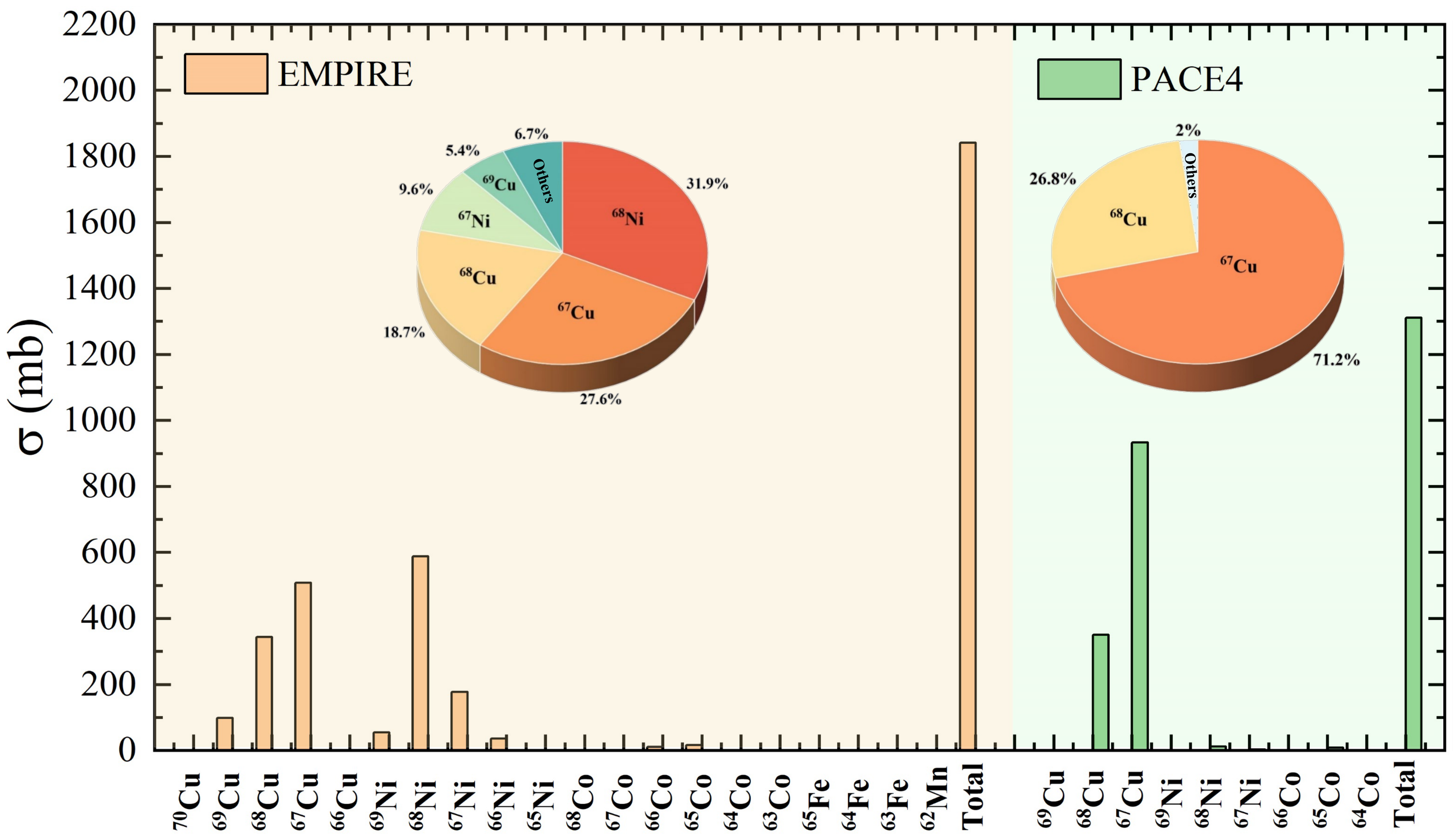

Fig. 1: Comparison of the yields of residual nuclei obtained from EMPIRE and PACE4 calculations. 3D color pie charts illustrate the percentages of residual nuclei in each calculation.

Further analysis of angular distributions for residual nuclei in the ^{68}Ni + d reaction was conducted using PACE4, which showed that nearly all residual nuclei yields are concentrated at forward angles of less than 2 degrees. Cross sections from EMPIRE were scaled to match these observed angular patterns. Precise Gaussian fits, shown in Fig. 2, were found for each residual nucleus, ensuring the consistency of the area corresponding to each angular range.

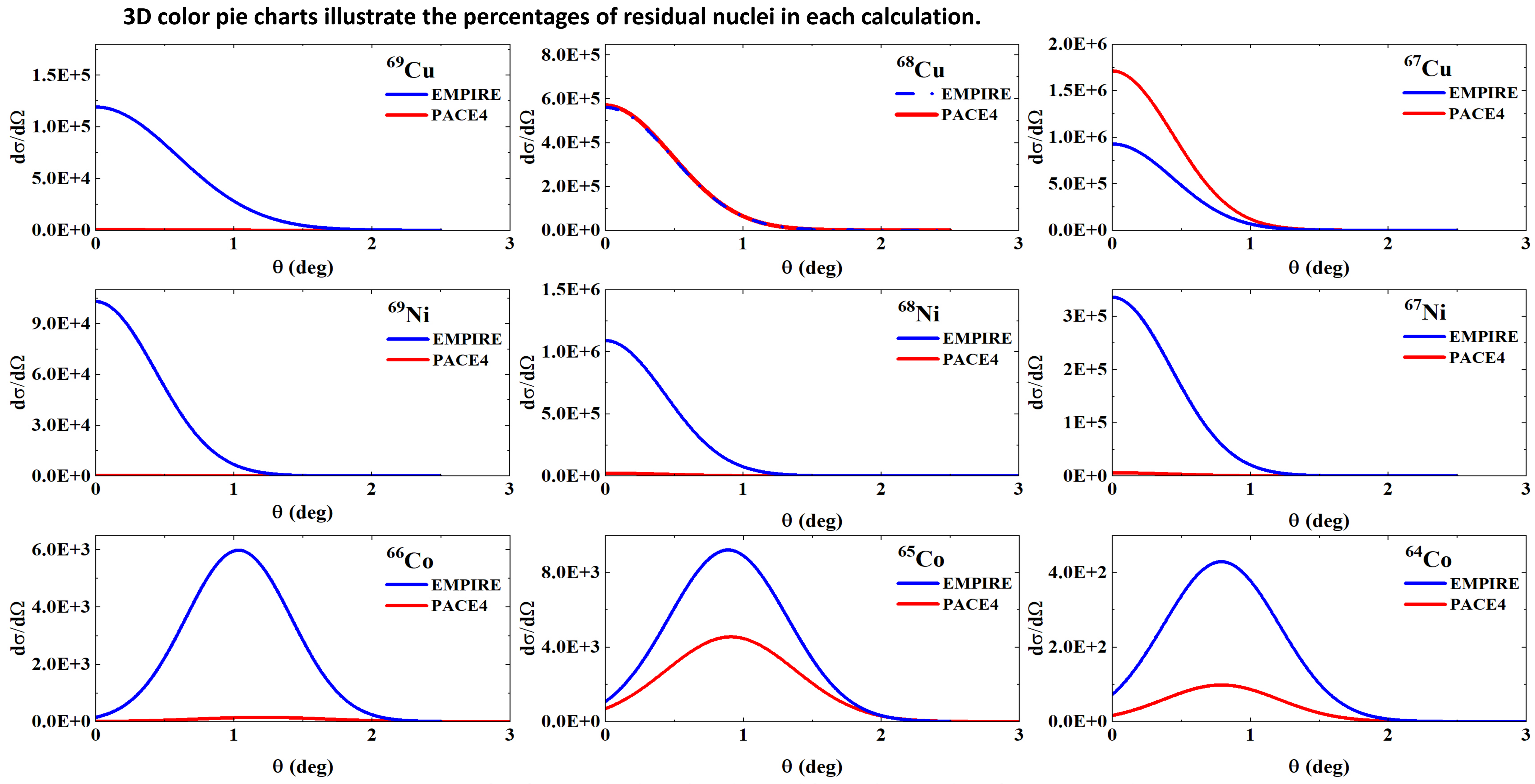

Fig. 2: Gaussian fits for residual nuclei, derived from the results of EMPIRE and PACE4.

FUTURE DIRECTIONS

- Using FRESCO [7], we estimated the (d,p) transfer cross section for the ^{68}Ni + d system, emphasizing the role of the first two excited states of ^{68}Ni, with a resulting cross section of approximately 2.3 mb. This analysis will be extended to other reactions to further explore nuclear structure.
- To enhance the performance of ISRS, our analysis of residual nuclei production will be expanded to include a broader range of systems. Furthermore, we plan to compile a comprehensive library of available experimental data on residual nuclei production.
- Our studies in the ISRS project will also focus on possibly investigating individual mechanisms, such as incomplete fusion processes in weakly bound systems. Analyzing such data could significantly contribute to improving the theoretical framework of reaction dynamics.

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