Modeling of Nuclear Fission X(p,pf)Y to Support the Development of an Experimental Nuclear Data (END) Facility in Indonesia Using a Wavefunction-Based Approach

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Abstract

The proposed research aims to support the development of the Nuclear Data Experimental (NDE) facility—specifically the DECY-13 system—at BRIN. As is typical for NDE facilities, the experimental results will be processed into nuclear data suitable for various applications in nuclear technology. This process consists of two stages: data evaluation through modeling, and data enrichment. The data evaluation and modeling phase serves as the focus of this research proposal, which is submitted under ITB's flagship research program. Given that physical modeling is often excessively complex, this proposal introduces a stochastic modeling approach for fission reactions. This represents the intended innovation, offering a potential breakthrough in the field of nuclear reaction modeling.

Keyword: EDN-BRIN, data evaluation, modeling, fission reactions

Introduction

Accurate calculation of fusion cross sections requires a precise determination of the underlying barrier potential, which is primarily governed by the effective nucleon-nucleon (NN) interaction. In this study, we systematically evaluate the suitability of various NN interaction models and Relativistic Mean Field (RMF) parameter sets for determining fusion barrier potentials in asymmetric systems. Specifically, we investigate the reactions ^{4}He+^{208}Pb and ^{9}Be+^{208}Pb . The total double-folding potentials are computed using a high-precision six-dimensional Monte Carlo integration method, explicitly incorporating the isovector component of the effective interaction. Our analysis compares the relativistic 3-Range Yukawa (R3Y) model with conventional non-relativistic M3Y interactions across three standard RMF parameter sets and recent parameterizations based on chiral effective field theory (CEFT). The results demonstrate that the R3Y model provides a superior and more physically consistent framework for describing the barrier characteristics compared to M3Y. Furthermore, the evaluated RMF parameter sets exhibit overall reliability, serving as robust benchmarks for broader nuclear reaction and astrophysical applications. Obtaining the desired fission product yield distribution remains challenging because experimental fission product data are incomplete. Two theoretical approaches are commonly considered to address this problem. The first is based on modeling the fission process, whereas the second uses curve-fitting techniques. Each approach has its own advantages and limitations. In this study, we propose a curve-fitting method that retains the physical aspects of nuclear fission in the calculation. The method offers two main advantages. First, only seven experimental data points are required to obtain a good fit to the fission yield distribution. Second, the method provides information on the classical nucleon dynamics during the fission process. In the proposed method, a fission event is initialized using three random numbers that determine the initial nucleon distribution on both sides of the nuclear surface. A fitting-function analysis is then applied to group the nucleons according to these random numbers. Each cluster is assigned to one of three established fission modes: superlong, standard-1, and standard-2. These clusters represent candidates for the resulting fission products. The fitted function determines the classical nucleon distribution through the continuity equation, and scission is assumed to occur when the density in the nuclear neck region no longer changes. The method was tested using ^{235}U, ^{240}Pu, and ^{241}Am at neutron energies of 0.00254 eV, 500 eV, and 14 MeV, respectively, using evaluated fission-yield data such as those from JENDL as references. From the calculated fission product yields, the classical nucleon distributions during fission were obtained. At a neutron energy of 0.002543 eV, the nucleons are concentrated near the central region with relatively small separations. At 14 MeV, the nucleons are distributed over a wider region with larger variations in their relative positions. At 500 eV, the nucleon distribution is slightly more dispersed than that at 0.002543 eV, while showing a distribution pattern that is relatively similar to that obtained at 14 MeV.

Research Method

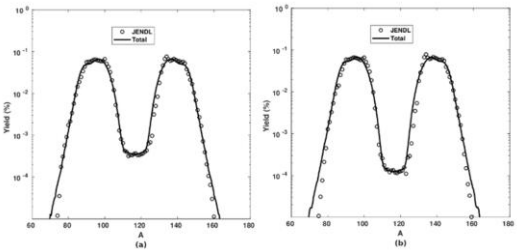
The research determines the nucleon-nucleon (NN) potential, validates it against nuclear fusion calculations, and then uses it to calculate fission products via a micro-macro method. A wave function model incorporating a Monte Carlo method addresses the stochastic nature of fission.

Discussion & Result

The following are the potential outcomes:

$$V^{00}(\rho,r) = 12113.4\frac{e^{-4r}}{4r} - 2467.2\frac{e^{-2.5r}}{2.5r} + \frac{3}{16}\left(830\rho + 1478\rho^{\frac{1}{3}}\right)\delta(r)$$

$$V^{01}(\rho,r) = 680.6\frac{e^{-4r}}{4r} + 219.2\frac{e^{-2.5r}}{2.5r} + \frac{1}{16}\left(830\rho - 4434\rho^{\frac{1}{3}}\right)\delta(r)$$



Picture 1. Fission-yield curves for ^{235}U at low neutron energies, obtained from 10^6 fission events on a logarithmic scale: (a) 500 eV and (b) 0.002543 eV

The results in Picture 1 indicate that the present calculation follows the expected statistical behavior: increasing the number of sampled fission events improves the representation of the full fission-yield distribution. Picture 1 also shows that symmetric fission products are associated mainly with the superlong mode. At low energy, the calculated contribution in the symmetric-product region is therefore relatively small. However, when the 0.02543 eV and 500 eV cases are compared with the 14 MeV result, the symmetric fission-product region becomes smoother. This behavior indicates that a larger number of symmetric fission events contributes at higher neutron energy.

Conclusion

This research proposes a calculation technique for nuclear fission data based on an LDM-derived nucleon distribution, particularly for FPY applications, while retaining relevant physical information such as nucleon dynamics during the fission process. In the present approach, the nucleon dynamics are treated classically, with particular emphasis on the stochastic nature of fission. This stochastic behavior arises from the random formation of fission products and the corresponding spatial distribution of nucleons within the nuclear surface. The method has two main advantages. First, it can reproduce the fission-yield distribution using only a limited number of experimental data points. Second, it provides information on the nucleon distribution within the fragments during the fission process. The method also reproduces the three principal fission modes considered in this work: superlong (SL), standard-1 (ST-1), and standard-2 (ST-2). At low neutron energies, the contribution of the superlong mode is substantially smaller than those of the other modes. As the neutron energy increases, however, the superlong contribution also increases. In contrast, the ST-1 fraction decreases with increasing neutron energy. This behavior is consistent with the increasing contribution of near-symmetric fission products at higher incident neutron energies. Consequently, the valley between the two main peaks of the mass-yield distribution becomes progressively shallower and may eventually become nearly flat. In other words, a reduction in the ST-1 contribution may lead the fission-yield distribution toward a single-peaked structure. Within the present interpretation, the superlong mode corresponds to a configuration in which nucleons tend to be located farther from the center of mass. ST-1 corresponds to a configuration in which nucleons are distributed more broadly throughout the system, whereas ST-2 represents a condition in which nucleons are concentrated both near the center and near the outermost region relative to the center of mass. When all fission modes are accumulated, the resulting probability distribution of nucleon positions in the fragments at the pre-scission stage is discrete. Thus, although the underlying random numbers are generated from a uniform distribution, the resulting spatial probability distribution of the nucleons is not continuous.