Spallation reaction and the probe of nuclear dissipation with excitation energy at scission (Postprint)

Authors: YE Wei, WANG Ning

Date: 2023-06-18T00:00:00+00:00

Abstract

We study in the framework of the Langevin model the influence of initial excitation energy (E*) of Hg compound nuclei (CNs) on the sensitivity of the excitation energy at scission (Esc*) to the nuclear friction strength (β). It is shown that the sensitivity is enhanced substantially with increasing E*. Moreover, we find that the significant sensitivity of Esc* to β at high E* is little affected by a marked difference in the neutron-to-proton ratio of a CN and in its size and fissility. Our findings suggest that, on the experimental side, a measurement of Esc* in energetic proton-induced spallation reactions can provide not only a sensitive but also a robust probe of nuclear dissipation in fission of highly excited nuclei. Further development of a suitable approach to spallation reaction is discussed.

Full Text

Preamble

Nuclear Science and Techniques 24 (2013) 050521

Spallation Reaction and the Probe of Nuclear Dissipation with Excitation Energy at Scission

YE Wei*, WANG Ning

Department of Physics, Southeast University, Nanjing 210096, China

Abstract

We investigate, within the framework of the Langevin model, the influence of the initial excitation energy (E*) of Hg compound nuclei (CNs) on the sensitivity of the excitation energy at scission (scE*) to the nuclear friction strength (β). Our results demonstrate that this sensitivity is substantially enhanced with increasing

E. Moreover, we find that the significant sensitivity of scE to β at high E* remains largely unaffected by marked differences in the neutron-to-proton ratio of a CN, as well as in its size and fissility. These findings suggest that measuring scE in energetic proton-induced spallation reactions can provide not only a sensitive but also a robust probe of nuclear dissipation in fission of highly excited nuclei. Further development of a suitable approach to spallation reactions is discussed.

Key words: Spallation reaction, Nuclear dissipation, Excitation energy at scission

Introduction

Over the past two decades, fusion-fission reactions have been widely employed as a standard approach for probing nuclear dissipation properties in fission [1-6]. Despite intensive efforts in both experimental analyses and theoretical calculations, the precise magnitude of nuclear friction in fission remains controversial and hotly debated [7-11]. This uncertainty may arise from numerous factors that affect the sensitivity of observables (such as particle multiplicity and evaporation residue cross-section) to nuclear dissipation, consequently leading to large uncertainties in the extracted friction strength β. To constrain the friction strength more stringently, it is urgent to develop new experimental methods and identify suitable observables.

Heavy-ion fusion reactions differ fundamentally from spallation reactions in their production of compound nuclei. In heavy-ion fusion, the formed CNs possess low excitation energy (<200 MeV) but high angular momentum (up to 70). In contrast, CNs produced in spallation reactions induced by energetic protons [12,13] have high excitation energy (up to 1 GeV) and low angular momentum. As an excited CN evolves toward scission, light particles are evaporated, resulting in a lower excitation energy at scission (scE). The presence of nuclear friction strongly suppresses particle emission, leading to a significantly larger scE. This quantity thus carries essential information about nuclear dissipation. In this work, we utilize scE to probe nuclear dissipation.

Theoretically, we adopt the Langevin model to perform calculations of scE at various energies. This stochastic approach has been widely used to describe fission data at high energy [14] and has achieved impressive success in reproducing various types of fission data [15-17].

2 Brief Description of Theoretical Model

The model employed here combines the Langevin equation with a statistical decay model (CDSM). We refer the reader to Ref. [15] for more details. The dynamic part of CDSM is described by entropy. The one-dimensional overdamped Langevin equation is employed to perform trajectory calculations:

$$dtM\beta dq$$

Here, q is the dimensionless fission coordinate defined as half the distance between the center of mass of the future fission fragments divided by the radius of the compound nucleus, M is the inertia parameter, and β is the dissipation strength. The temperature in Eq.(1) is denoted by T, and Γ(t) is a fluctuating force whose average and correlation function are Γ(t) and Γ(t)Γ(t') , respectively. The driving force of the Langevin equation is calculated from the entropy:

$$\Gamma()\Gamma(')SqEaqE()]$$

where E* is the total internal energy of the system, and a(q) is the deformation-dependent level density parameter, taken from the description by Ignatyuk et al. [18] and calculated using the formula given in Refs. [18,19].

Eq.(2) is constructed from the Fermi-gas expression with a finite-range liquid-drop potential V(q) in the {c, h, α} parametrization [20,21]. The q-dependent surface, Coulomb, and rotation energy terms are included in the potential V(q).

In the CDSM, light-particle evaporation is coupled to the fission mode through a Monte Carlo procedure. The particle emission width is given by Blann' s formula [22].

The excitation energy at scission is determined using the energy conservation law:

$$scE$$

where Ecoll is the kinetic energy of the collective degrees of freedom, and Eevap(tsc) is the energy carried away by all evaporated particles by the scission time tsc. Eq.(3) has been demonstrated [23] to describe scE excellently for a great number of fissioning systems covering a wide range of fissilities and CN mass regions.

The CDSM describes the fission process as follows. At early times, the decay of the system is modeled by means of the Langevin equation. After the fission probability flow over the fission barrier attains its quasistationary value, the decay of the compound system is described by a statistical branch. Prescission particle multiplicities are calculated by counting the number of corresponding evaporated particle events registered in the dynamic and statistical branches of the CDSM. To accumulate sufficient statistics, 10^7 Langevin trajectories are simulated.

3 Results and Discussion

Figure 1 shows scE as a function of β at several E* and at critical angular momentum . One can see a weak dependence of scE on β at E* = 100 MeV. Raising E* to 350 MeV yields greater sensitivity of scE to β, and this sensitivity is further enhanced when E* reaches 500 MeV. This finding clearly reveals a substantial increase in the sensitivity of scE to β at high energy.

[Figure 1: see original paper]

The significant difference in prescission light particles at low and high energies causes the difference in scE at different E*. With increasing excitation energy, the particle evaporation time becomes shorter. In addition, decay channels like light charged particles (LCPs) are opened at high energy, since more energy can be provided to help them overcome Coulomb emission barriers. The emission of LCPs carries away more energy from the decaying system, leaving a colder nucleus at scission.

Aside from the initial excitation energy, the emitted particle number is another important factor that controls the magnitude of scE. It has been known from earlier work [24] that the neutron-to-proton ratio (N/Z) of a CN has an appreciable influence on neutrons and LCPs. Therefore, it is necessary to examine the robustness of the significant sensitivity of scE found at high energy, as shown in Fig.1, against a variation in N/Z. The calculation results for 194Hg, 200Hg, and 206Hg are presented in Fig.2.

[Figure 2: see original paper]

As seen from the figure, a similar sensitivity of scE is observed for the three Hg isotopes. A physical understanding for this is that while a larger N/Z increases neutron emission, it decreases LCP multiplicity. As a consequence, the excitation energy taken away by both neutrons and LCPs is almost comparable for these Hg systems with different N/Z.

A heavy nucleus favors particle emission due to a long descent of the decaying system from saddle to scission. Also, the fission lifetime is a function of the fissility, meaning that a change in the fissility parameter can affect the particle multiplicity emitted throughout the fission time scale. Here we survey the influences of these two factors on the sensitivity. Our calculation results are displayed in Fig.3 and Fig.4.

[Figure 3: see original paper]

[Figure 4: see original paper]

We notice from Fig.3 and Fig.4 that under high-energy conditions, while varying the size of a fissioning system and its fissility value can influence the number of different kinds of particles, overall, the significant sensitivity found at high energy remains unchanged.

The insensitivity of scE to β revealed in Figs.2-4 underlines the essential roles of excitation energy and friction strength in determining the emitted particle number. This feature is favorable for achieving a more reliable and tighter constraint on β. In other words, proton-nucleus collisions could provide an avenue to probe dissipation in fission of a highly excited CN.

In energetic proton-nucleus reactions, the populated residual nucleus has a distribution in its E*, J, A, and Z. As an illustration, we use the intranuclear cascade model (INCL) to simulate (1 GeV) p+Hg collisions, the results of which are plotted in Fig.5.

[Figure 5: see original paper]

This distribution information should be used as input for subsequent Langevin calculations of the formed hot nuclear systems. Thus, for more accurate results, it is necessary to combine the INCL, which treats the collision stage between protons and nuclei in spallation reactions, with the Langevin description of fission of excited nuclei. This new approach may offer a more suitable framework to explore scE deduced in spallation reactions. Work along this direction is in progress.

4 Conclusion

The Langevin model of fission is applied to survey the role of the initial excitation energy E* of Hg CNs in the sensitivity of scE as a tool for probing β. We find that the sensitivity of scE to β is increased significantly under high-energy conditions. Furthermore, we examine the robustness of this sensitivity to evident changes in the size of a fissioning system, its N/Z ratio, and fissility. These changes have been shown to have minor effects on the sensitivity. Our findings suggest that, experimentally, energetic proton-induced reactions can be used to populate highly excited nuclear systems when one uses scE to obtain information about nuclear friction. Additionally, scE measured at high energy and provided via this new experimental approach could place a more reliable and tighter constraint on the friction strength in nuclear fission.

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Note: Figure translations are in progress. See original paper for figures.