Isospin effect on first-chance fission probability

W. Ye[1,*] and N. Wang[2]
[1]Department of Physics, Southeast University, Nanjing 210096, People's Republic of China
[2]School of Science, Jiangsu University of Science and Technology, Zhenjiang 212100, People's Republic of China

(Received 8 May 2022; revised 3 August 2022; accepted 31 August 2022; published 15 September 2022)

A delayed fission due to nuclear dissipation results in a drop of first-chance fission probability (P_{f0}) with respect to predictions by standard statistical models. Using the stochastic Langevin model, we calculate P_{f0} as a function of presaddle dissipation strength (β) for fissioning nuclei ^{220}U, ^{230}U, ^{240}U, and ^{240}Cm. We find that with decreasing the isospin of the U nucleus, the sensitivity of P_{f0} to β is substantially enhanced, and that low-isospin ^{240}Cm exhibits a significantly larger dependence on β than high-isospin ^{240}U. Furthermore, it is shown that P_{f0} becomes more sensitive to β at low energy. These findings suggest that to accurately probe presaddle dissipation properties with first-chance fission probability, on the experimental side, it is best to produce those heavy fissioning systems with small isospin and low excitation energy.

DOI: 10.1103/PhysRevC.106.034603

I. INTRODUCTION

Heavy nuclei generally decay via fission and first-chance fission is their dominant decay channel. But with increasing energy deposited into a compound system, other decay channels, i.e., light particle emissions are opened. This leads to a strong competition between fission and evaporation. As a result, apart from first-chance fission, second- and higher-chance fission appear when a hot heavy nucleus de-excites.

In the most recent two decades, an important experimental finding associated with fission studies is that prescission particle multiplicities [1–6] measured at high energy significantly deviate from those predicted by standard statistical models (SMs). This discrepancy is ascribed to dissipation effects that are not addressed in the SMs, as clearly demonstrated in numerous calculations based on stochastic approaches [7–10]. In this approach, the interaction between the fission degree of freedom and the large number of intrinsic degrees of freedom (which constitute heat bath) generates a dissipative drag on the dynamics of fission [11,12]. In addition, dissipation also plays a crucial role in fusion, deep-inelastic scattering, and the synthesis of superheavy elements [13–15]. Because of the importance of dissipation in understanding a variety of phenomenon in low- and intermediate-energy nucleus-nucleus collisions, investigation of dissipation properties is the focus of current many works [16–20].

Dissipation hinders fission, resulting in a rise of prescission emission and, correspondingly, a drop of fission probabilities, as has been observed in a number of the measured excitation function of prescission particle numbers as well as fission and evaporation residue cross sections for many compound systems [21–24]. Additionally, experimental signals such as excitation energy at saddle [25] and fission-fragment charge distributions [26] were recently proposed to constrain the presaddle dissipation strength (β). Despite intensive experimental and theoretical investigations using these probes, the strength of presaddle dissipation is still quite uncertain and controversial [27]. To make a further progress in stringently constraining presaddle friction, identifying new and sensitive observables becomes urgent and necessary.

Dissipation directly affects fission channels, fission probabilities are thus considered to be the most fundamental and key indicator of presaddle dissipation effects and, thereby, they are widely employed to get information of β [22,28]. But heavy nuclei produced in current fusion reactions always fission, implying that their fission probabilities are insensitive to β. This limits the use of fission probability data from heavy systems in exploring nuclear dissipation properties.

Due to multiple particle emission, fission probabilities are actually composed of first-, second-, and higher-chance fission probabilities. So, in essence, a change in fission probability of a compound nucleus caused by dissipation originates from the effects of dissipation on its first-chance fission probability as well as on its second- and higher-chance fission probabilities. This means that first-chance fission probability could be a very sensitive signature of presaddle dissipation effects.

During a decay process, the competition between neutron emission and fission can be expressed by the ratio of their decay widths, $\frac{\Gamma_n}{\Gamma_f}$, and the survival probability at each step i of the de-excitation chain is given by $(\frac{\Gamma_n}{\Gamma_{\rm tot}})_i$, where $\Gamma_{\rm tot} = \Gamma_n + \Gamma_f$. The survival probability of a heavy nucleus is a crucial quantity to characterize its destine and moreover, its magnitude is a key factor for producing heavy evaporation residue, especially for the synthesis of superheavy elements. It is thus important to obtain precise information about $\frac{\Gamma_n}{\Gamma_f}$ [or $(\frac{\Gamma_n}{\Gamma_{\rm tot}})_i$] of heavy compound systems.

Earlier works [29–31] focused on analyzing production cross sections σ_{xn} of heavy elements formed in (HI, xn) reactions, and the parametric formulas were thus proposed to

*Corresponding author: yewei@seu.edu.cn

describe the average behavior of $\frac{\Gamma_n}{\Gamma_f}$ in the entire de-excitation chain of some No isotopes and transuranium nuclei in a certain range of excitation energy. Predictions for the average values of $\frac{\Gamma_n}{\Gamma_f}$ (or $\frac{\Gamma_n}{\Gamma_{\rm tot}}$) of ^{258}No with these formulas are an order of magnitude smaller than the measurement of Ref. [32], where a value of (0.7–0.9) for $\frac{\Gamma_n}{\Gamma_{\rm tot}}$ was deduced, though the value was evaluated by averaging over the two first stages of the ^{258}No compound nucleus de-excitation cascades. Also, the extracted values of 0.058 and 0.065 for $(\frac{\Gamma_n}{\Gamma_{\rm tot}})_1$ and $(\frac{\Gamma_n}{\Gamma_{\rm tot}})_2$ from the evaporation residue data measured in the $^{24,25,26}\mathrm{Mg} + {}^{232}\mathrm{Th}$ reactions [33] were significantly lower than that given in Ref. [32]. These works used experimental σ_{xn} which are more (less) dependent on the later (early) values of $\frac{\Gamma_n}{\Gamma_f}$ of an evaporation cascade. It is clear that to more accurately obtain the value of first-chance survival probability $(\frac{\Gamma_n}{\Gamma_{\rm tot}})_1$, it is better to be able to make a direct measurement on first-chance fission, and not resort to a model analysis that was needed in using evaporation residue data to get the value of $\frac{\Gamma_n}{\Gamma_{\rm tot}}$ in its initial stage.

At present, two different experimental avenues were applied to directly extract the value of $(\frac{\Gamma_n}{\Gamma_{\rm tot}})_1$, i.e., measuring prescission neutron multiplicities [34] or measuring fission excitation functions [35] of two neighboring fission isotopes under matched conditions of excitation energy and angular momentum. A previous work [35] used the observed cumulative fission probabilities of two light neighboring isotopes ^{211}Po and ^{210}Po to extract first-chance fission probabilities of ^{211}Po. The cross bombardments method directly measures neutron emission in the compound-nucleus decay process, which is more sensitive to the first steps of a de-excitation chain than those of the evaporation residue. Loveland *et al.* [34] are the first to use the new technique to investigate first-chance fission. In their experiment on $^{25,26}\mathrm{Mg} + {}^{232}\mathrm{Th} \longrightarrow {}^{257,258}\mathrm{No}$ [34], they measured a value of 0.840 ± 0.050 for the first-chance $\frac{\Gamma_n}{\Gamma_{\rm tot}}$, which is currently the only value obtained for ^{258}No ($E^* = 61$ MeV) by a direct measurement. Furthermore, by applying the same experimental method to the case of superheavy nuclei, it was found that nuclear dissipation effects are invoked to satisfactorily explain the high value of 0.89 ± 0.13 for $(\frac{\Gamma_n}{\Gamma_{\rm tot}})_1$ of superheavy ^{274}Hs ($E^* = 63$ MeV) that was first measured via two matched reactions $^{25,26}\mathrm{Mg} + {}^{248}\mathrm{Cm}$ [36].

On the theoretical side, in the framework of standard statistical models, various systematics formulas (see, e.g., Refs. [29–31]) about $\frac{\Gamma_n}{\Gamma_f}$ were put forward, and they were frequently applied to estimate the cross section for the production of new isotopes of heavy and superheavy elements. It was suggested in Ref. [30] that the systematic formula needs to be extended to include the dependence of $\frac{\Gamma_n}{\Gamma_f}$ on nuclear viscosity in order to describe fission of heated nuclei. In Ref. [34], dissipation effects were first incorporated into the statistical model aiming at analyzing measured $(\frac{\Gamma_n}{\Gamma_{\rm tot}})_1$ of superheavy nuclei. Stochastic approaches developed in the last two decades have been demonstrated to be a suitable framework to address dissipation effects on the fission mechanism. Langevin calculations [37] showed that first-chance fission probability [a complementary quantity to the first-chance survival probability $(\frac{\Gamma_n}{\Gamma_{\rm tot}})_1$] of heavy nuclei is quite sensitive to presaddle friction, in contrast with their total fission probability, whose sensitivity to friction almost disappears. This contrast reveals the value of first-chance fission probabilities in strongly constraining the presaddle friction.

Measuring production cross sections σ_{xn} of heavy elements is a way to obtain $\frac{\Gamma_n}{\Gamma_{\rm tot}}$ in the first steps of a de-excitation chain [32]. But this way depends heavily on the statistical model used and the parametric formulas derived under some assumptions. In contrast, in the cross bombardments method [34], by fitting experimental neutron energy spectra in coincidence with two fission fragments, prescission neutron multiplicities associated with the compound nucleus source can be extracted. Then using prescission neutron multiplicities measured in two matched reactions, the experimental $(\frac{\Gamma_n}{\Gamma_{\rm tot}})_1$ was obtained in a model-independent way. Although the cross bombardments method has such a prominent advantage, the neutron multiplicities it requires are more difficult to measure than charged-particle multiplicities. Moreover, to measure first-chance survival probabilities of superheavy nuclei, the choice of the suitable projectiles and target nuclides is very limited. Thus, the observation of the first-chance fission in a highly excited parent nuclide is not so easy and there are no detailed data available even now. In particular, there exist difficulties in the experiment study on the first-chance fission, as mentioned above.

Apart from the importance of the precise information about $(\frac{\Gamma_n}{\Gamma_{\rm tot}})_1$ in the synthesis of superheavy elements [36], the new observable was found to be very sensitive to presaddle friction [37] and thereby, it could place tight constraints on presaddle dissipation properties. Actinides nuclei have a high fission probability and hence, the number of their first-chance fission events occupies a considerable part in the number of their total fission events, facilitating to investigate first-chance fission. However, experimental data available to date on the first-chance fission of actinide nuclei are quite scarce. Therefore, to further advance studies on first-chance fission, more detailed measurements on $(\frac{\Gamma_n}{\Gamma_{\rm tot}})_1$ of actinide nuclei are especially needed. In addition, to better guide experimental explorations on first-chance fission of heavy and superheavy nuclei, more theoretical works are called for.

In these contexts, the present work is devoted to studying under which experimental conditions, the sensitivity of the first-chance fission probability to presaddle friction can be significantly enhanced. To that goal, we will survey the isospin effect on first-chance fission probability as a probe of presaddle friction. For this, we will consider the stochastic approach. Many works [7–10,38–43] have shown a successful application of the Langevin model in reproducing a volume of experimental data on fission excitation functions and prescission particle multiplicities for many fissioning systems covering a broad range of excitation energy, angular momentum, and fissility.

In our previous works based on Langevin models, our calculated prescission neutron multiplicities from light ^{200}Pb up to heavy ^{251}Es compound systems were shown to agree well with experimental data [41]. In addition, backstreaming effects around the saddle point [44] were demonstrated to increase presaddle emission. A recent investigation [45] exhibited that the fission probability of heavy nuclei with a high neutron-to-proton ratio is a good observable of nuclear dissipation. Langevin calculations [37] predicted an obviously greater sensitivity of the first-chance fission probability of heavy systems to friction than their total fission probability. Using the same model as that in Refs. [37,41,44,45], we will calculate first-chance fission probabilities of heavy nuclei having different isospins as a function of friction, and the emphasise is placed on the isospin effects on first-chance fission.

II. THEORETICAL MODEL

To describe the driving force of a hot nuclear system, a thermodynamic potential rather than a bare potential should be used [8,10]. Free energy was considered and its derivative with respect to the deformation coordinate at fixed temperature gives the driving force [38,46]. Since temperature is not constant during the evolution of a fissioning system, we use entropy [47,48] to formulate Langevin equations in the present work.

Symmetric fission is a crucial decay mode of a hot compound nuclei. It has been further shown [34,36] that first-chance fission probability associated with symmetric fission can be extracted experimentally by measuring prescission neutron multiplicities evaporated in the symmetric fission process of two neighboring fissioning isotopes.

Because of these reasons mentioned above, we employ the following Langevin equation to perform the fully dynamical trajectory calculations for symmetric fission:

$$\frac{dp}{dt} = K - \beta p + g\Gamma(t), \quad \frac{dq}{dt} = \frac{p}{m}. \tag{1}$$

Here, q is the dimensionless fission coordinate and is defined as half the distance between the center of mass of the future fission fragments divided by the radius of the compound nucleus, and p is its conjugate momentum. The reduced dissipation coefficient (also called the dissipation strength) $\beta = \gamma/m$, as is usual in the literature (see, e.g., Refs. [1,5,8,16,17,22,24,26,27,48–50]), denotes the ratio of the friction coefficient γ to the inertia parameter m obtained in the Werner-Wheeler approximation for the irrotational flow of an incompressible liquid [51]. $\Gamma(t)$ is random force satisfying $\langle\Gamma(t)\rangle = 0$ and $\langle\Gamma(t)\Gamma(t')\rangle = 2\delta(t - t')$. The strength of the random force is related to the dissipation strength through the fluctuation-dissipation theorem and is $g = \sqrt{m\beta T}$ with T being the temperature.

The driving force K of the Langevin equation is calculated in terms of derivatives of the entropy S at a constant excitation energy:

$$K(q) = T\frac{dS}{dq}. \tag{2}$$

The entropy $S(q)$ is calculated as

$$S = 2\sqrt{a(q)[E^* - V(q) - E_{\text{coll}}]}, \tag{3}$$

where E^* denotes the total excitation energy of the fissioning system, and E_{coll} is the kinetic energy of the collective degree of freedom. Equation (3) is constructed from the Fermi-gas expression [47]. The deformation coordinate q is obtained by the relation $q(c, h) = (3c/8)\{1 + \frac{2}{15}[2h + (c - 1)/2]c^3\}$ [8,52], where c and h are the Funny-Hills shape parameters [53] and they correspond to the elongation and neck degrees of the freedom of the nucleus, respectively. At the spherical ground state, $c = 1$, $h = 0$, and their values change in the fission process. They are determined by considering that the system evolves to follow the bottom of the potential valley in terms of the coordinates c and h, which is similar to the method used by Fröbrich *et al.* [8].

The potential energy $V(q)$ includes q-dependent surface, Coulomb, and rotation energy terms, which are calculated with a finite-range liquid-drop model [54]. The shell-correction energy is obtained by applying Strutinsky's method [53,55] of shell correction to the nucleonic levels generated with the two-centered Woods-Saxon mean field [56], and the BCS (Bardeen-Cooper-Schripffer) pairing is used to take account of nuclear superfluidity [53,56]. The potential barriers calculated with this method are shown to be in good consistent with the existing results [57]. We use Ignatyuk's [58] description to calculate the level density parameter $a(q)$ which takes into account the dependence on deformation and shell corrections.

In our calculation, the particle emission is taken into account via a Monte Carlo simulation technique. The emission width of a particle of kind ν ($=n, p, \alpha$) is evaluated by Blann's parametrization [59] that was used in many studies [8,38,60]. After each emission act of a particle, the intrinsic excitation energy, the potential energy, the entropy, and the temperature in the Langevin equation are recalculated and the dynamics is continued.

When the dynamic trajectory reaches the scission point, it is counted as a fission event. The scission is considered here to occur when the neck radius of the fissioning nucleus is equal to $0.3R_0$ (R_0 is the radius of the initial spherical compound nucleus) [10,46]. Fission probabilities and particle multiplicities are calculated by counting the number of corresponding fission and evaporated particle events. The present calculation allows for multiple emissions of light particles and higher-chance fission. So, the first, second, etc., chance fission probability can be calculated [8] by counting the number of corresponding fission events in which not a single presaddle particle is emitted, only a presaddle particle is emitted.

The first-chance fission probability (P_{f0}) is given by the number of first-chance fission events (N_{f0}) divided by the total simulated trajectory numbers (N_{tot}), which reads

$$P_{f0} = \frac{N_{f0}}{N_{\text{tot}}}. \tag{4}$$

Like most Langevin calculations [7–9,44,61], in the present study the initial conditions for the dynamical Eq. (1) are assumed to correspond to a spherical compound nucleus with an excitation energy E^* and the thermal equilibrium momentum distribution. For starting a Langevin trajectory an orbit angular momentum value is sampled from the fusion spin distribution, whose form is

$$\frac{d\sigma(\ell)}{d\ell} = \frac{2\pi}{k^2}\frac{2\ell + 1}{1 + \exp[(\ell - \ell_c)/\delta\ell]}. \tag{5}$$

The parameters ℓ_c and $\delta\ell$ are the critical angular momenta for fusion and diffuseness, respectively. The final results are weighted over all relevant waves; namely, the spin distribution is used as the angular momentum weight function. To accumulate sufficient statistics, 10^7 Langevin trajectories are simulated.

III. RESULTS

Three heavy fissioning nuclei ^{220}U, ^{230}U, and ^{240}U, which have a marked difference in their isospin (defined as a ratio of the neutron number of a compound system to its proton number, N/Z), are chosen here as a representative for exploring presaddle dissipation properties with first-chance fission probability (P_{f0}).

Light particles can be emitted in the entire presaddle region, thus the dissipation strength deduced with experimental signatures [16,17,21,22,25–27,36,48–50] including fission and evaporation residue cross sections that are proposed so far to exploit the characteristics of presaddle dissipation represents the average strength of presaddle dissipation. In other words, these observables are determined by the mean presaddle dissipation strength, and not by the dissipation strength at a presaddle deformation point. Due to this reason, to better reveal presaddle dissipation effects, here a fully dynamical calculation of the fission process is carried out considering different values of β, which stands for the average strength for presaddle dissipation.

As an illustration, we plot in Fig. 1 the evolution of P_{f0} of three U systems with β calculated at excitation energy $E^* = 50\,\text{MeV}$ and critical angular momentum $\ell_c = 40\hbar$. Two typical features are observed. First, one can see that the magnitude of P_{f0} of ^{240}U is smaller than that of ^{230}U, and ^{220}U has the largest P_{f0}. The cause is that ^{240}U is a neutron-rich system, its small neutron separation energy increases neutron emission. In addition, fission barriers are a rising function of the mass number of the U nucleus, i.e., the heavier the U system, the higher the fission barrier. A high barrier suppresses fission, favoring presaddle emission. As a result of the two factors, ^{240}U evaporates more presaddle neutrons than ^{230}U independently of the friction strength, and presaddle neutrons are least for neutron-deficient ^{220}U, see the solid lines presented in Fig. 2.

Fission and evaporation competes with each other in the decay process. An appreciable neutron emission results in a small fission probability, including first-chance fission probability. Figure 1 thus indicates that dissipation effects on P_{f0} are amplified for a low-isospin U system, demonstrating the prominent role of isospin in probing presaddle dissipation characteristics with first-chance fission probability.

Another feature is that the slope of the curve P_{f0} versus β, which reflects the sensitivity of the first-chance fission probability to presaddle friction, differs much for the three U systems. It is evident that the small P_{f0} of ^{240}U varies slowly with a change in β. A small P_{f0} decreases its sensitivity to β. But for ^{220}U, its greater P_{f0} leads to a quicker drop with increasing β. A drop of P_{f0} at a large friction is because fission is retarded more severely at strong dissipation and, correspondingly, a longer delay in fission provides more time for neutron emission. A rise of neutron emission at a large friction strength thus causes a decrease of P_{f0} with an increase of β. The comparison for the three fissioning nuclei U clearly illustrates that the sensitivity of the first-chance fission probability to presaddle friction is significantly enhanced with decreasing the isospin of the U system. It suggests that to more accurately determine the strength of presaddle friction through the measurement of first-chance fission probability, on the experimental side, it is best to yield low-isospin fissioning systems.

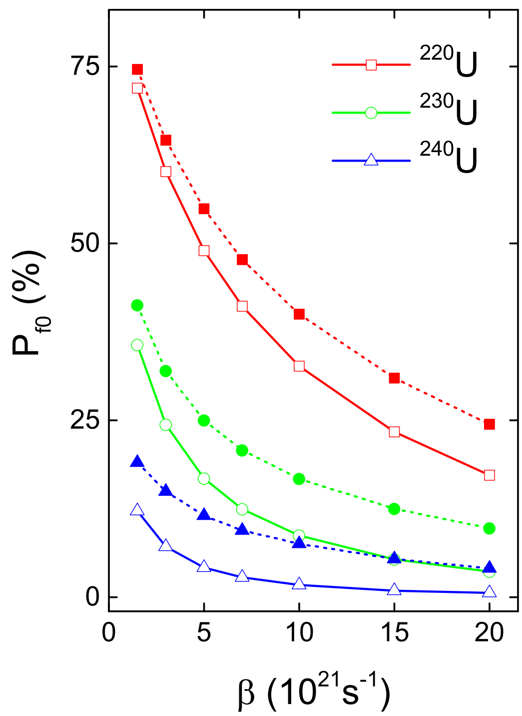

FIG. 1. First-chance fission probability (P_{f0}) of ^{220}U, ^{230}U, and ^{240}U as a function of the presaddle dissipation strength (β) calculated at excitation energy $E^* = 50\,\text{MeV}$, critical angular momentum for fusion $\ell_c = 40\hbar$ and diffuseness $\delta\ell = 5\hbar$. Solid lines are Langevin calculations starting at a spherical ground state, and dashed lines denote Langevin calculations to start at an initial deformation position which is chosen as the midpoint of the ground state and the saddle point.

To further reveal the isospin effect on first-chance fission probability, we compare in Fig. 3 the calculated P_{f0} as a function of β for ^{240}U and ^{240}Cm, which have the same mass number but have a different isospin. The most apparent feature that can be seen is that P_{f0} of ^{240}U shows a weak dependence on β, exhibiting that first-chance fission probability of the high-isospin ^{240}U is not a good observable of presaddle dissipation. In contrast, for low-isospin ^{240}Cm, its P_{f0} depends sensitively on β. Specifically, P_{f0} of ^{240}Cm changes 46% as β varies from 1.5×10^{21} s^{-1} to 20×10^{21} s^{-1}, which is much larger than that of ^{240}U, where the change is 12% only. The obvious difference in P_{f0} of the two nuclei with increasing friction stems from the difference in their presaddle neutron numbers. This demonstrates that producing low-isospin fissioning systems in experiments can substantially enhance

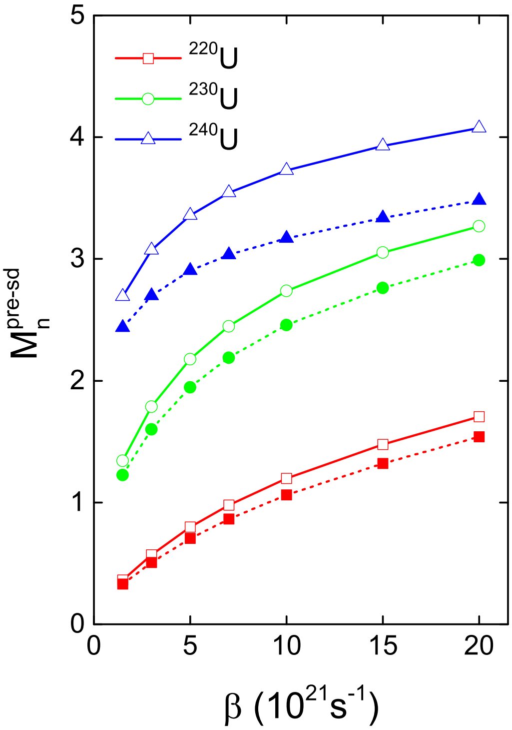

FIG. 2. Presaddle neutron multiplicities of ^{220}U, ^{230}U, and ^{240}U calculated at excitation energy $E^* = 50$ MeV and critical angular momentum $\ell_c = 40\hbar$ for different presaddle friction strengths (β). Solid lines and dashed lines represent Langevin calculations starting at a spherical ground state and starting at an initial deformation position which is chosen as the midpoint of the ground state and the saddle point, respectively.

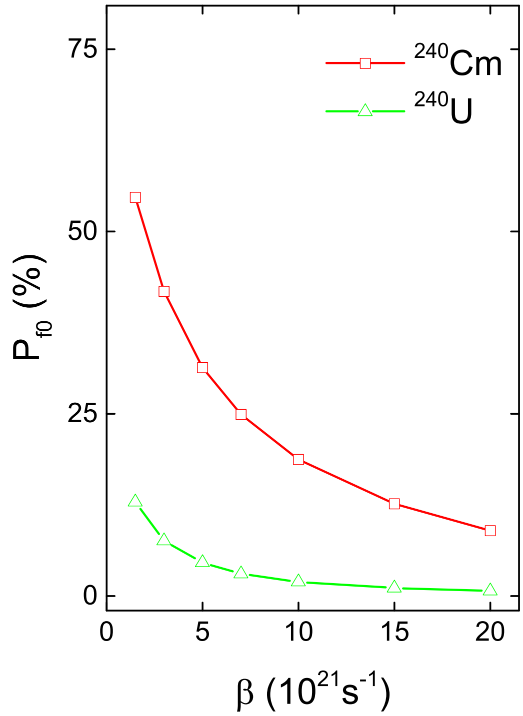

FIG. 3. First-chance fission probability (P_{f0}) of ^{240}Cm and ^{240}U as a function of the presaddle dissipation strength (β) calculated at excitation energy $E^* = 55$ MeV and critical angular momentum $\ell_c = 45\hbar$.

the sensitivity of first-chance fission probability to presaddle friction.

Presaddle emission is a function of excitation energy. The effect of the excitation energy on P_{f0} was calculated in Ref. [37], where it was seen that with decreasing excitation energy, the first-chance fission probability has a greater sensitivity to friction. We note that the calculations of Ref. [37] were performed for a fissioning nucleus only and they do not involve the role of isospin of the fissioning system in the effect of excitation energy. The new aspect is connected with the goal of the present study. For that goal, here we calculate the evolution of P_{f0} with β at two excitation energies $E^* = 40$ MeV and 80 MeV for ^{220}U and ^{240}U systems which have an obvious difference in their isospin.

Figure 4 shows that for the two U systems, their different isospins do not alter the conclusion; that is, low energy increases the sensitivity of P_{f0} to β, as reached in Ref. [37]. However, by comparing Fig. 4(b) and Fig. 4(a), one can observe the significant role of isospin in the effect of the excitation energy. Specifically speaking, at high energy $E^* = 80$ MeV, the P_{f0} of high-isospin ^{240}U is almost independent of β, which is clearly different from the case of low-isospin ^{220}U whose P_{f0} has an apparent drop with increasing β. This comparison exhibits the role that isospin plays in the effect of excitation energy on the evolution of P_{f0} with β. While decreasing E^* can increase P_{f0} and enhance its sensitivity to β, the increased amplitude in P_{f0} and the enhanced amplitude in its sensitivity differ much for the two U systems. Figure 4(b) shows that for high-isospin ^{240}U, its P_{f0} varies rather slowly with β even at low $E^* = 40$ MeV. But Fig. 4(a) reveals that for low-isospin ^{220}U, not only its P_{f0} rise rapidly with decreasing E^* compared to the case of ^{240}U, but also P_{f0} shows a quicker drop with increasing β than that of ^{240}U. Thus the effect of excitation energy noticed in Ref. [37] has a strong dependence on the isospin of the fissioning nucleus. We explain the observation in the following way: With a decrease in E^*, neutron evaporation becomes weak, especially for the low-isospin system, which increases the magnitude of first-chance fission probability. A larger P_{f0} can raise its sensitivity to β, as pointed out previously. The results in Fig. 4 thus indicate that experiments on the presaddle dissipation properties can be substantially optimized by choosing low-isospin systems at small excitation energies.

IV. DISCUSSION

We note that the conclusions drawn on the isospin effect on first-chance fission probability in symmetric fission apply to the case of asymmetric fission as well. The physical causes are as follows. Due to the competition among different decay channels, an enhanced neutron evaporation suppresses not only symmetric fission but also asymmetric fission. As a result, the first-chance fission of a high-isospin system is rather weak not only for the symmetric fission process but also for the asymmetric fission process. It is seen from Fig. 1 that

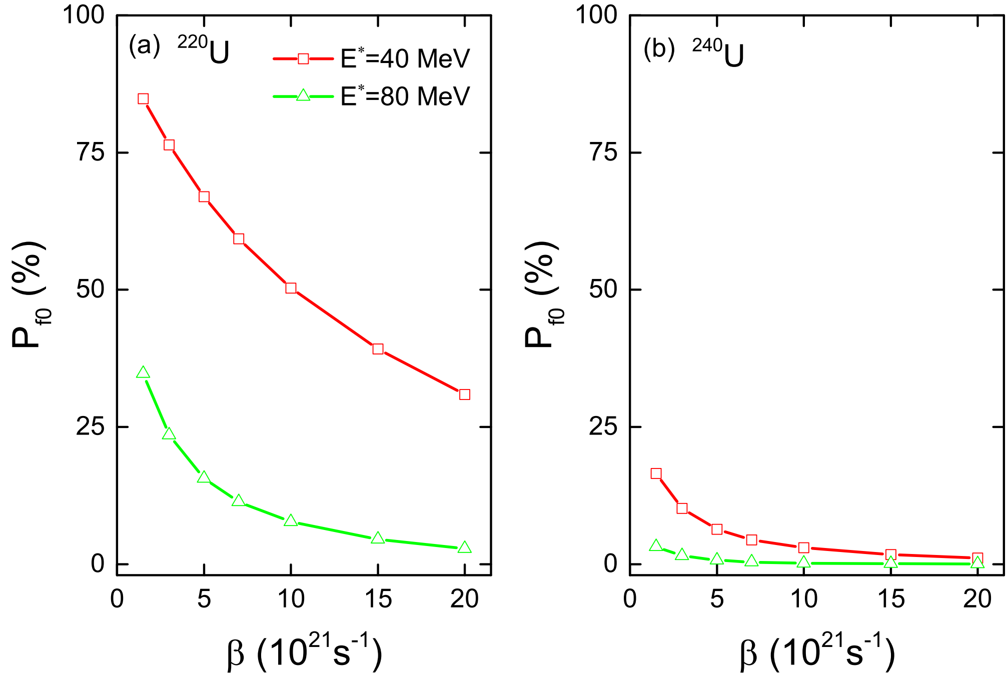

FIG. 4. Evolution of P_{f0} with β for (a) ^{220}U and (b) ^{240}U calculated at two excitation energies $E^* = 40$ MeV and 80 MeV and at critical angular momentum $\ell_c = 35\hbar$.

the very small first-chance fission probability of a high-isospin U system is responsible for a weak sensitivity to friction. Thus for a low-isospin fissioning system, a larger first-chance fission probability for asymmetric fission can be predicted to exhibit a stronger sensitivity to friction, similar to that observed for the case of symmetric fission (Fig. 1).

As mentioned previously, besides stochastic approaches to fission, statistical-type models that are modified to contain dissipation effects by correcting the fission width with Kramers factor have been widely used to analyze the competition between evaporation and fission channels. Due to the stochastic feature of the fission motion, there exists a backstreaming around the saddle point. By backstreaming is meant that because of thermal fluctuation, the decaying system has a probability to return back inside saddle even if it has crossed over the saddle point. In Ref. [45], it was shown that the backstreaming affects postsaddle particle multiplicities and increases presaddle emission.

Here we examine the backstreaming effect on the first-chance fission probability. The calculated results are depicted in Fig. 5. It is seen that the solid lines are below the dashed ones, indicating that P_{f0} becomes smaller for the case considering the backstreaming effect. A physical understanding for this is as follows. The backstreaming effect enables the fissioning system to stay a longer time inside the barrier, which increases the presaddle neutron emission, as was pointed out in Ref. [45]. As a result, the backstreaming effect decreases the first-chance fission probability. While the backstreaming effect does not alter the evolution trend of P_{f0} with β for these U systems having different isospins, it reduces the rate at which the first-chance fission probability changes with friction, meaning that the backstreaming effect further decreases the sensitivity of P_{f0} of the high-isospin ^{240}U to β. These results show that on the theoretical side, to more precisely describe first-chance fission, it is rather necessary to fully take the backstreaming effect into account in the model

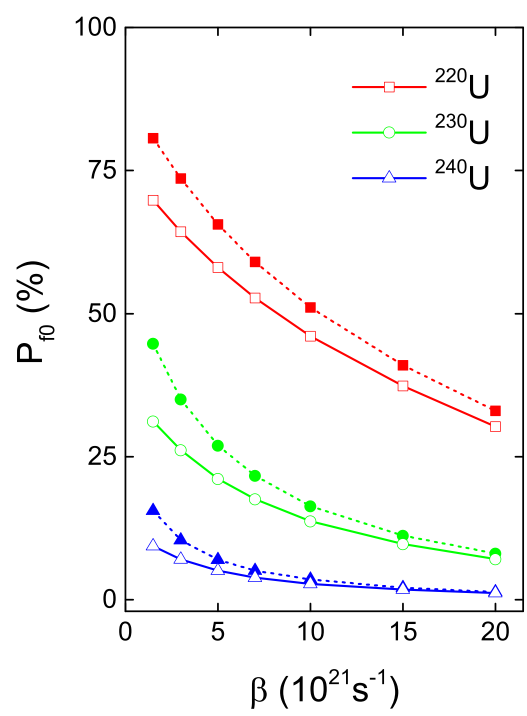

FIG. 5. First-chance fission probabilities P_{f0} as a function of the presaddle friction strength β calculated at $E^* = 45$ MeV and $\ell_c = 35\ \hbar$ for ^{220}U, ^{230}U, and ^{240}U systems. The dashed lines and solid lines correspond to Langevin calculations without and with account of backstreaming around the saddle point, respectively.

TABLE I. Proposed experimental reactions. From left to right, the symbols denote incident energy ($E_{\rm lab}$), reaction system, compound nucleus (CN), and excitation energy (E^*).

$E_{\rm lab}$ (MeV)	Reaction	CN	E^* (MeV)
193.2	^{32}S + ^{206}Pb	^{238}Cf	60.0
181.1	^{32}S + ^{205}Pb	^{237}Cf	48.6
179.1	^{30}Si + ^{206}Pb	^{236}Cm	60.0
167.2	^{30}Si + ^{205}Pb	^{235}Cm	49.2
172.6	^{28}Si + ^{206}Pb	^{234}Cm	60.0
160.6	^{28}Si + ^{205}Pb	^{233}Cm	48.8
155.8	^{26}Mg + ^{206}Pb	^{232}Pu	60.0
143.9	^{26}Mg + ^{205}Pb	^{231}Pu	49.5
155.9	^{26}Mg + ^{204}Pb	^{230}Pu	60.0
139.9	^{25}Mg + ^{204}Pb	^{229}Pu	48.9
202.6	^{40}Ar + ^{184}W	^{224}U	60.0
186.7	^{40}Ar + ^{183}W	^{223}U	49.2

calculations and that, experimentally, to better probe the presaddle friction with P_{f0}, it is preferable to populate low-isospin heavy systems.

Excited heavy nuclei produced in fusion reactions are generally not spherical at their ground state, which could be caused by the entrance channel effect. It implies that the fission process of a hot nuclear system may not start from the spherical equilibrium ground state, but starts to decay at a position with an initial deformation. Due to a shorter distance between the deformed ground state and the saddle point, the transient time required for the decaying nucleus to cross the saddle point becomes short, increasing the total fission probability [45] and decreasing presaddle neutrons (see Fig. 2). Consequently, the initial deformation could increase the first-chance fission probability. This expectation is confirmed by our calculations, see the dashed lines presented in Fig. 1. We further note in Fig. 1 that the initial deformation effect does not alter the conclusion that under the condition of low isospin, P_{f0} shows a greater sensitivity to β.

Our calculated results suggest that low-isospin heavy systems favor to probe presaddle nuclear dissipation with first-chance fission probability. Heavy-ion-induced fusion reactions are an efficient experimental approach for the production of neutron-deficient nuclides. To guide further experimental researches on first-chance fission of heavy nuclei, based on presently available stable projectiles (e.g., ^{25,26}Mg, ^{28,30}Si, ^{32}S, ^{40}Ar) and target nuclides (e.g., ^{204,205,206,207,208}Pb and ^{180,182,183,184,186}W), suitable combinations between these projectiles and targets are proposed to produce low-isospin heavy nuclei (Table I).

In Table I, excitation energies E^* of compound nuclei (CNs) ^{237}Cf, ^{235}Cm, ^{233}Cm, ^{231}Pu, ^{229}Pu, and ^{223}U, respectively correspond to those of residual nuclei generated by emitting a neutron from their parent nuclei ^{238}Cf, ^{236}Cm, ^{234}Cm, ^{232}Pu, ^{230}Pu, and ^{224}U, whose E^* are uniformly set as 60 MeV. Incident energies $E_{\rm lab}$ of various projectiles are determined according to reaction systems and E^* of CNs they produce.

Figure 6 shows the calculated P_{f0} as a function of β for parent nuclei ^{238}Cf, ^{234}Cm, ^{230}Pu, and ^{224}U, which are

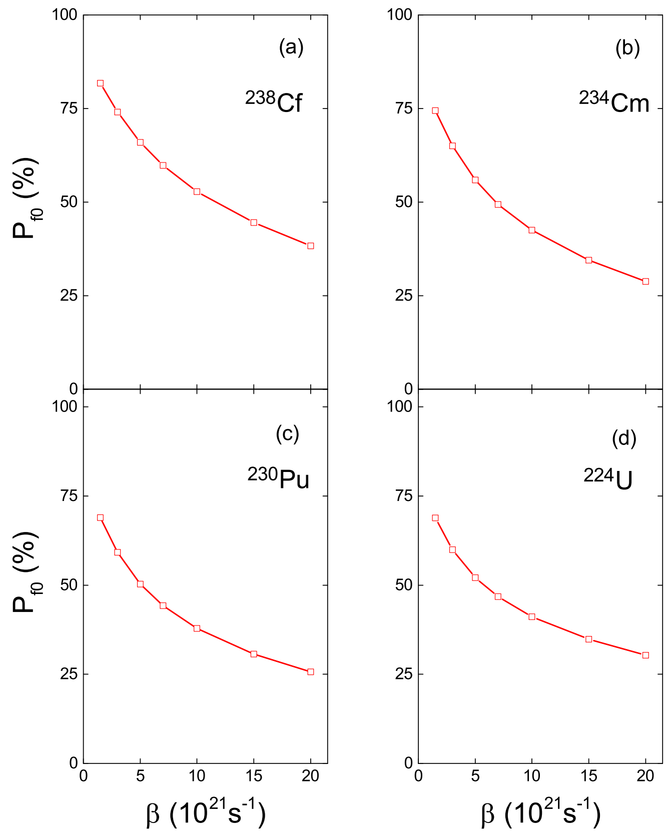

FIG. 6. First-chance fission probabilities (P_{f0}) as a function of the presaddle friction strength (β) calculated at excitation energy $E^* = 60$ MeV for nuclei (a) ^{238}Cf, (b) ^{234}Cm, (c) ^{230}Pu, and (d) ^{224}U, which are formed by reaction systems suggested in Table I.

formed by the corresponding reaction systems and incident energies given in Table I. The spin distributions of these parent nuclei generated via fusion are obtained with the methods of Refs. [8,62]. Projectiles ^{25,26}Mg were used in previous cross bombardments experiments [34,36] to yield ^{258}No and ^{274}Hs by fusion mechanisms aiming at directly observing first-chance fission of superheavy nuclei.

The most prominent feature seen in Fig. 6 is that P_{f0} drops quickly with increasing β. Overall, this figure reveals that first-chance fission probabilities of low-isospin actinides nuclei produced via stable nuclear beams are a good observable of exploring presaddle dissipation properties. Thus, measurements on P_{f0} of these heavy systems can put a strict constraint on β.

With the establishment of many radioactive beam facilities around the world and with the development of techniques in producing radioactive nuclear beams (RNBs), a number of RNBs may be used in the future experiments. In this context, apart from stable-projectile beams, RNBs could provide an alternative approach to generating low-isospin heavy nuclei. More details and discussions about the intensities and types of available RNBs can be found in Refs. [63,64].

As an illustration, radioactive-projectile beams ^{29,30}S and ^{25,26}Si may be employed to produce low-isospin heavy systems ^{233,234}Cf and ^{229,230}Cm by hitting the ^{204}Pb target. We

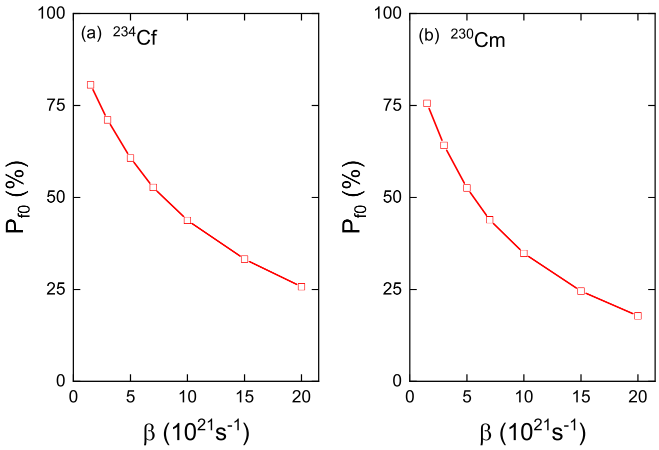

FIG. 7. First-chance fission probabilities (P_{f0}) as a function of the presaddle friction strength (β) for heavy nuclei (a) ^{234}Cf and (b) ^{230}Cm, which are populated to have an excitation energy of 55 MeV by reaction systems ^{30}S ($E_{\rm lab} = 174.2$ MeV) + ^{204}Pb and ^{26}Si ($E_{\rm lab} = 151$ MeV) + ^{204}Pb, respectively.

calculate the evolution of first-chance fission probabilities with friction for excited parent nuclei ^{234}Cf and ^{230}Cm formed by radioactive beams channels ^{30}S ($E_{\rm lab} = 174.2$ MeV) + ^{204}Pb and ^{26}Si ($E_{\rm lab} = 151$ MeV) + ^{204}Pb. The results are displayed in Fig. 7.

It is seen that P_{f0} of the two heavy fissioning nuclei are a quite sensitive function of β, indicating that RNBs induced reactions could provide an experimental way to investigate presaddle friction.

Currently, there exist some choices of stable projectiles that can be applied to produce two low-isospin neighboring isotopes of a heavy element required in the cross bombardments experiment. While the intensity of RNBs is weaker than that of stable nuclear beams, RNBs can expand the type of projectiles and the range of their isotopes that may be used in reaction experiments. Thus, RNBs may offer new and intriguing opportunities to study nuclear dissipation with first-chance fission probabilities by producing more low-isospin neighboring isotopes of heavy elements.

We note that different experimental suggestions are given for using first-chance fission probabilities and using the total fission probability to probe presaddle friction. Fission probabilities of heavy nuclei are generally close to 100%, resulting in their insensitivity to a change in friction. It was shown in Ref. [45] that populating neutron-rich heavy fissioning systems can affect the competition between evaporation channels and fission channels and hence, obviously enhance the friction effects on the total fission probability. In contrast, the present work shows that decreasing the competition of neutron emission with fission can significantly raise the sensitive dependence of the first-chance fission probability on friction (Fig. 1). So the experimental suggestion given for first-chance fission probability is different from that for the total fission probability; that is, to strongly constrain friction with the first-chance fission probability, either conventionally stable nuclear beams or RNBs that are combined with Pb and W target nuclides could be used to yield low-isospin heavy fissioning systems.

V. CONCLUSION

In the framework of the dynamical Langevin equation coupled to a statistical model of particle emission, we have explored the influence of isospin on probing presaddle dissipation properties with first-chance fission probability (P_{f0}) of heavy systems. It has been found that a low isospin increases P_{f0} and substantially enhances its sensitivity to presaddle friction (β). Moreover, it has been demonstrated that low energy can raise the sensitive dependence of P_{f0} on β. These results suggest that to tightly constrain the strength for presaddle dissipation by measuring first-chance fission probability, experimentally, it is optimal to generate those heavy fissioning systems with a small isospin and a low excitation energy.

ACKNOWLEDGMENTS

The authors thank the anonymous referee for comments and suggestions, which significantly improved this paper. This work is supported by the National Natural Science Foundation of China under Grant No. 11975074. N.W. acknowledges the support by the Natural Science Foundation of Jiangsu Province under Grant No. BK20220643.

[1] D. J. Hinde, D. Hilscher, H. Rossner, B. Gebauer, M. Lehmann, and M. Wilpert, Phys. Rev. C **45**, 1229 (1992).
[2] D. Hilscher and H. Rossner, Ann. Phys. (Paris) **17**, 471 (1992).
[3] N. P. Shaw *et al.*, Phys. Rev. C **61**, 044612 (2000).
[4] M. Thakur *et al.*, Phys. Rev. C **98**, 014606 (2018).
[5] N. Kumar *et al.*, Phys. Lett. B **814**, 136062 (2021).
[6] N. K. Rai *et al.*, J. Phys. G: Nucl. Part. Phys. **49**, 035103 (2022).
[7] K. Pomorski, J. Bartel, J. Richert, and K. Dietrich, Nucl. Phys. A **605**, 87 (1996).
[8] P. Fröbrich and I. I. Gontchar, Phys. Rep. **292**, 131 (1998).
[9] G. D. Adeev *et al.*, Phys. At. Nucl. **36**, 378 (2005).
[10] H. J. Krappe and K. Pomorski, *Theory of Nuclear Fission*, Lecture Notes in Physics Vol. 838 (Springer, Berlin, 2012).
[11] D. Boilley *et al.*, Nucl. Phys. A **556**, 67 (1993); T. Wada, Y. Abe, and N. Carjan, Phys. Rev. Lett. **70**, 3538 (1993).
[12] Y. Abe, S. Ayik, P. G. Reinhard, and E. Suraud, Phys. Rep. **275**, 49 (1996).
[13] W. U. Schröder and J. R. Huizenga, in *Treatise on Heavy-ion Science*, edited by D. A. Bromley (Plenum, New York, 1984).
[14] H. Feldmeier, Rep. Prog. Phys. **50**, 915 (1987).
[15] C. Simenel, K. Godbey, and A. S. Umar, Phys. Rev. Lett. **124**, 212504 (2020).
[16] D. Jacquet and M. Morjean, Prog. Part. Nucl. Phys. **63**, 155 (2009).
[17] A. N. Andreyev, K. Nishio, and K. H. Schmidt, Rep. Prog. Phys. **81**, 016301 (2018).

[18] M. Bender *et al.*, J. Phys. G: Nucl. Part. Phys. **47**, 113002 (2020).
[19] A. Bulgac, S. Jin, and I. Stetcu, Front. Phys. **8**, 63 (2020).
[20] M. Pancic, Y. Qiang, J. C. Pei, and P. Stevenson, Front. Phys. **8**, 351 (2020).
[21] R. Mahajan *et al.*, Phys. Rev. C **98**, 034601 (2018); J. P. Lestone, Phys. Rev. Lett. **70**, 2245 (1993).
[22] V. Singh *et al.*, J. Phys. G: Nucl. Part. Phys. **48**, 075104 (2021).
[23] R. N. Sagaidak, M. L. Chelnokov, V. I. Chepigin, V. A. Gorshkov, O. N. Malyshev, A. G. Popeko, A. I. Svirikhin, and A. V. Yeremin, Phys. Rev. C **105**, 024604 (2022); M. M. Hosamani *et al.*, *ibid.* **101**, 014616 (2020).
[24] B. B. Back, D. J. Blumenthal, C. N. Davids, D. J. Henderson, R. Hermann, D. J. Hofman, C. L. Jiang, H. T. Penttila, and A. H. Wuosmaa, Phys. Rev. C **60**, 044602 (1999).
[25] B. Jurado, C. Schmitt, K. H. Schmidt, J. Benlliure, T. Enqvist, A. R. Junghans, A. Kelic, and F. Rejmund, Phys. Rev. Lett. **93**, 072501 (2004).
[26] C. Schmitt, K. H. Schmidt, A. Kelic, A. Heinz, B. Jurado, and P. N. Nadtochy, Phys. Rev. C **81**, 064602 (2010).
[27] K. H. Schmidt *et al.*, Rep. Prog. Phys. **81**, 106301 (2018).
[28] D. Fabris, G. Viesti, E. Fioretto, M. Cinausero, N. Gelli, K. Hagel, F. Lucarelli, J. B. Natowitz, G. Nebbia, G. Prete, and R. Wada, Phys. Rev. Lett. **73**, 2676 (1994).
[29] T. Sikkeland, A. Ghiorso, and M. J. Nurmia, Phys. Rev. **172**, 1232 (1968).
[30] E. A. Cherepanov, A. S. Iljinov, and M. V. Mebel, J. Phys. G: Nucl. Phys. **9**, 931 (1983); **9**, 1397 (1983).
[31] M. H. Simbel, Z. Phys. A **313**, 311 (1983).
[32] A. N. Andreyev, D. D. Bogdanov, V. I. Chepigin, A. P. Kabachenko, O. N. Malyshev, R. N. Sagaidak, L. I. Salamatin, G. M. Ter-Akopian, and A. V. Yeremin, Z. Phys. A **345**, 389 (1993).
[33] W. Loveland, Nuclear Chemistry Progress Report, Oregon State University, August 2000 (unpublished).
[34] D. Peterson, W. Loveland, O. Batenkov, M. Majorov, A. Veshikov, K. Aleklett, and C. Rouki, Phys. Rev. C **79**, 044607 (2009).
[35] L. G. Moretto, K. X. Jing, R. Gatti, Th. Rubehn, G. J. Wozniak, and R. P. Schmitt, Phys. Rev. Lett. **79**, 4295 (1997); B. B. Back, D. J. Hofman, and V. Nanal, *ibid.* **79**, 4294 (1997).
[36] R. Yanez, W. Loveland, L. Yao, J. S. Barrett, S. Zhu, B. B. Back, T. L. Khoo, M. Alcorta, and M. Albers, Phys. Rev. Lett. **112**, 152702 (2014).
[37] N. Wang and W. Ye, Phys. Rev. C **97**, 014603 (2018).
[38] P. N. Nadtochy, G. D. Adeev, and A. V. Karpov, Phys. Rev. C **65**, 064615 (2002).
[39] G. Chaudhuri and S. Pal, Phys. Rev. C **65**, 054612 (2002).
[40] V. M. Kolomietz and S. V. Radionov, Phys. Rev. C **80**, 024308 (2009).
[41] N. Wang and W. Ye, Phys. Rev. C **87**, 051601(R) (2013).
[42] H. Eslamizadeh and E. Ahadi, Phys. Rev. C **96**, 034621 (2017).
[43] N. Kumar, S. Mohsina, J. Sadhukhan, and S. Verma, Phys. Rev. C **96**, 034614 (2017).
[44] N. Wang and W. Ye, Phys. Lett. B **801**, 135138 (2020).
[45] N. Wang and W. Ye, Phys. Rev. C **103**, 024611 (2021).
[46] K. Mazurek, A. Szczurek, C. Schmitt, and P. N. Nadtochy, Phys. Rev. C **97**, 024604 (2018).
[47] P. Fröbrich, Nucl. Phys. A **787**, 170 (2007).
[48] S. G. McCalla and J. P. Lestone, Phys. Rev. Lett. **101**, 032702 (2008).
[49] Y. Ayyad *et al.*, Phys. Rev. C **91**, 034601 (2015).
[50] D. Mancusi, R. J. Charity, and J. Cugnon, Phys. Rev. C **82**, 044610 (2010).
[51] K. T. R. Davies, A. J. Sierk, and J. R. Nix, Phys. Rev. C **13**, 2385 (1976).
[52] R. W. Hass and W. D. Myers, *Geometrical Relationships of Macroscopic Nuclear Physics* (Springer, New York, 1988).
[53] M. Brack, J. Damgaard, A. S. Jensen, H. C. Pauli, V. M. Strutinsky, and C. Y. Wong, Rev. Mod. Phys. **44**, 320 (1972).
[54] H. J. Krappe, J. R. Nix, and A. J. Sierk, Phys. Rev. C **20**, 992 (1979); A. J. Sierk, *ibid.* **33**, 2039 (1986).
[55] V. M. Strutinsky, Nucl. Phys. A **122**, 1 (1968).
[56] F. Garcia, O. Rodriguez, J. Mesa, J. D. T. Arruda-Neto, V. P. Likhachev, E. Garrote, R. Capote, and F. Guzmán, Comput. Phys. Commun. **120**, 57 (1999).
[57] J. Dudek, W. Nazarewicz, and A. Faessler, Nucl. Phys. A **412**, 61 (1984).
[58] A. V. Ignatyuk, M. G. Itkis, V. N. Okolovich, G. N. Smirenkin, and A. S. Tishin, Sov. J. Nucl. Phys. **21**, 612 (1975).
[59] M. Blann, Phys. Rev. C **21**, 1770 (1980).
[60] G. Chaudhuri and S. Pal, Eur. Phys. J. A **18**, 9 (2003).
[61] E. Vardaci *et al.*, Phys. Rev. C **92**, 034610 (2015); M. V. Borunov *et al.*, Nucl. Phys. A **799**, 56 (2008); A. V. Karpov, P. N. Nadtochy, D. V. Vanin, and G. D. Adeev, Phys. Rev. C **63**, 054610 (2001).
[62] R. Bass, *Lecture Notes in Physics*, Vol. 117 (Springer, Berlin, 1980); Phys. Rev. Lett. **39**, 265 (1977).
[63] W. Loveland, Phys. Rev. C **76**, 014612 (2007); J. Phys.: Conf. Ser. **420**, 012004 (2013).
[64] W. Loveland, Front. Phys. **7**, 23 (2019).