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System size effects on probing nuclear dissipation with neutrons*

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Abstract Using a dynamical Langevin equation coupled with a statistical decay model, we calculate the excess of the pre-scission neutron multiplicities over its standard statistical-model values as a function of the nuclear dissipation strength for the three nuclei ^{190}Os, ^{200}Hg, and ^{210}Po which have the same neutron-to-proton ratio N/Z. We find that by decreasing the size of the fissioning nuclei, the effects of nuclear dissipation on the excess of the pre-scission neutron multiplicity are substantially amplified, and that the sensitivity of this excess to the nuclear friction strength is considerably increased as well. We suggest that for those fissioning systems with the same N/Z that are populated in fusion reactions, to obtain a more accurate information of the nuclear dissipation strength by measuring the pre-scission neutron multiplicity, it is best to choose a system with a small size.

Key words system size effects, neutron multiplicity, nuclear dissipation

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1 Introduction

The nature and magnitude of nuclear dissipation has attracted considerable interest because of its importance in understanding experimental data on fusion-fission, fusion-evaporation and quasifission processes [1–8]. The results in a deviation of measured pre-scission neutron multiplicity and evaporation residue cross section from that predicted by standard statistical models. Theoretically, diffuse models have been utilized [9–13] to explain the experimental data associated with dissipative fission. It has been shown that by adopting a phenomenologically deformation-dependent friction the Langevin model can successfully reproduce the evaporation residue cross section and light particle multiplicity over a wide range of excitation energies and angular momenta for a great number of compound nucleus systems [9, 14]. It has been reported in many recent experimental and theoretical works that a good determination of the dissipation strength can be made by suggesting new experimental observables (e.g., the width of the fission-fragment charge distribution [7, 15] and the spin distribution of the evaporation residue cross section [16]) or by performing model simulations [17]. Because neutrons are a main decay channel of excited compound nuclei, therefore, surveying its emission can provide a sensitive method to determine the nuclear dissipation strength. Correspondingly, neutrons are widely used by experimentalists as a probe to obtain information on the nuclear dissipation strength (see e.g., [18–20]).

Our recent work showed that the sensitivity of fission observables (such as light particle multiplicity) to nuclear dissipation changes with the variation of the neutron-to-proton ratio (N/Z) of a system (e.g., [8, 17]). This is so because for different fissioning systems, besides their difference in N/Z, also their sizes can be very different. So, a new issue arises, namely how the system size affects the sensitivity when these fissioning systems have the same N/Z. In particular, an experimental survey on the possible role of the system size in the dependence of the fission probability on nuclear dissipation has recently been attempted

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by Tishchenko et al [21]. In this context, to better instruct the experimental exploration, it is necessary to disentangle the effects of the system size and its N/Z on the sensitivity. For this aim we use in the present work three systems ^{190}Os, ^{200}Hg and ^{210}Po, which have the same N/Z, to investigate the role of the fissioning nucleus size in using neutrons to probe nuclear dissipation.

2 The Langevin model

A combination of a dynamical Langevin equation and a statistical model (CDSM) is utilized to compute the light particle multiplicity. Here a brief overview to the model is given; for more details see Ref. [9]. The dynamical part of the CDSM model is described by the Langevin equation that is driven by the free energy F. In the Fermi gas model F is related to the level density parameter $a(q)$ by

$$F(q,T)=V(q)-a(q)T^2, \tag{1}$$

where T is the nuclear temperature. $V(q)$ is the potential energy and is expressed in the form [22]

$$V(A,Z,L,q)=a_2\left[1-k\left(\frac{N-Z}{A}\right)^2\right]A^{2/3}\times [B_s(q)-1]+c_3\frac{Z^2}{A^{1/3}}[B_c(q)-1]+ c_rL^2A^{-5/3}B_r(q), \tag{2}$$

where $B_s(q)$, $B_c(q)$ and $B_r(q)$ are the surface, Coulomb, and rotational energy terms, respectively, which depend on the deformation coordinate q. The parameters a_2, c_3, k and c_r are taken from Ref. [23].

The coordinate-dependent level density parameter $a(q)$ is given by [24]

$$a(q)=a_1A+a_2A^{2/3}B_s(q). \tag{3}$$

Here A is the mass number of the compound nucleus, $B_s(q)$ is the dimensionless functional of the surface energy [25] and it can be computed with the formula suggested in Ref. [26]. The values of the parameters, a_1=0.073 MeV^{-1} and a_2=0.095 MeV^{-1} in Eq. (3), have been taken from the work of Ignatyuk et al. [27] and are consistent with the data [9, 12]. The fission rates turn out to be sensitive to the coordinate dependence of the level density parameter [28]. The level density parameter is an important parameter in dynamical calculations. It strongly affects the fission rate and the emission of light particles.

The one-dimensional overdamped Langevin equation reads

$$\frac{\mathrm{d}q}{\mathrm{d}t}=-\frac{1}{M\beta(q)}\frac{\partial F(q,T)_T}{\partial q}+\sqrt{D(q)}\Gamma(t), \tag{4}$$

where q is the dimensionless fission coordinate and is defined as half of the distance between the center of mass of the future fission fragments divided by the radius of the compound nucleus. $\beta(q)$ is the dissipation strength. The fluctuation strength coefficient $D(q)$ can be expressed according to the fluctuation-dissipation theorem as

$$D(q)=\frac{T}{M\beta(q)}, \tag{5}$$

where M is the inertia parameter that drops out of the overdamped equation. $\Gamma(t)$ is a time-dependent stochastic variable with a Gaussian distribution. Its average and correlation function are written as

$$\langle\Gamma(t)\rangle=0,\quad \langle\Gamma(t)\Gamma(t')\rangle=2\delta(t-t'). \tag{6}$$

After the fissioning system passes over the fission barrier and the probability flow attains its quasi-stationary value, the decay of the compound system is described by a statistical model, which is called the statistical part of the CDSM. In the CDSM the light-particle evaporation is coupled to the fission mode by a Monte Carlo procedure allowing for the discrete emission of light particles. The widths for light particle (n,p,α) decay are given by the parametrization of Blann [29].

3 Results and discussion

To explore how the size of the fissioning nucleus affects neutron multiplicity as an observable of nuclear dissipation, three fissioning systems with different sizes but with the same neutron-to-proton ratio (N/Z = 1.5), namely, ^{190}Os, ^{200}Hg, and ^{210}Po, are considered. In this work, to accumulate sufficient statistics, 10^7 Langevin trajectories are simulated. Moreover, to better survey the variation of pre-scission neutron emission with dissipation strength (β), β is set in the calculations throughout the whole fission process equal to (3, 5, 7, 10, 15 and 20)$\times10^{21}$ s^{-1}.

As mentioned before, nuclear dissipation causes the excess of the pre-scission neutrons, and this excess is extremely sensitive to the dissipation strength. To investigate the role of the system size in using neutrons to pin down the nuclear dissipation effects, we adopt a definition similar to that suggested by Lazarev, Gontchar and Mavlitov [30], and define the relative excess of pre-scission neutrons calculated by taking into account the dissipation and fluctuations of collective nuclear motion over its standard statistical-model (SSM) value,

$$n_{\rm pre}^{\rm excess}=\frac{\langle n_{\rm pre}^{\rm dyn}\rangle-\langle n^{\rm SSM}\rangle}{\langle n^{\rm SSM}\rangle},\tag{7}$$

where $n_{\rm pre}^{\rm dyn}$ and $n^{\rm SSM}$ denote Langevin (which accounts for the nuclear dissipation effect) and standard statistical-model predictions for pre-scission neutron multiplicity, respectively.

Figure 1 displays the excess of pre-scission neutrons ($n_{\rm pre}^{\rm excess}$) of the systems ^{190}Os, ^{200}Hg and ^{210}Po versus the dissipation strength (β) at excitation energy $E^*=150$ MeV and angular momentum $\ell=30\hbar$. Two typical features can be noticed from this figure. First, irrespective of the variation of β the symbol $\square$ is always above $\bigcirc$, and the latter is above $\triangle$. Note that in our calculations except for the difference in the system size, other initial conditions (excitation energy, angular momentum, friction strength, etc.) that can affect the decay of excited compound nuclei, are the same for these three systems. Thus the first feature demonstrates that a light fissioning system is favorable to increase the effects of the nuclear dissipation on the neutron evaporation. A physical understanding of the system size dependence is as follows.

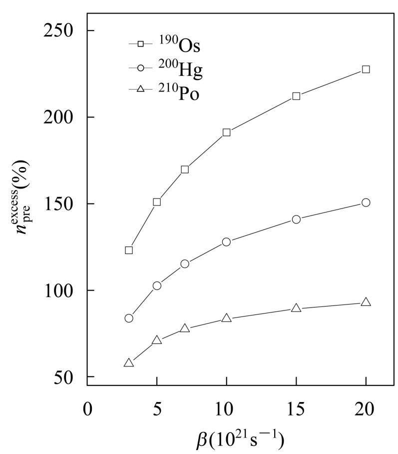

Fig. 1. The relative excess of the dynamical pre-scission neutron multiplicity of the systems ^{190}Os, ^{200}Hg and ^{210}Po relative to that of standard statistical models [Eq. (7)] as a function of the dissipation strength (β) at excitation energy E^*=150 MeV and angular momentum ℓ=30$\hbar$. The lines are guides to the eyes.

It can be noted from Table 1 that the neutron multiplicity $n_{\rm dyn}^{\rm pre}$ has a dependence on the system size. This possibly has an effect on the sensitivity of neutron emission to nuclear dissipation for the fissioning systems with different sizes. Furthermore, one can see from Eq. (7) that the relative enhanced magnitude of neutron emission with respect to the SSM predictions stemming from dissipation effects, $n_{\rm pre}^{\rm excess}$, depends upon not only the value of $n_{\rm dyn}^{\rm pre}$, but also the value of $n^{\rm SSM}$. It means that the magnitude of the $n^{\rm SSM}$ also has a direct influence on $n_{\rm pre}^{\rm excess}$ as a function of β. Obviously, a large $n^{\rm SSM}$ will mask the dissipation effects on the neutron emission more strongly than a small one. The SSM predicts that, under the conditions assumed in Fig. 1, ^{190}Os emits the least number of neutrons and ^{210}Po the most. A similar variation of $n^{\rm SSM}$ with the system size was also suggested in other work (e.g., [9]). Consequently, the effect of the slowing down of the fission process caused by dissipation clearly manifests itself as a significant increase of the excess of the pre-scission neutrons for ^{190}Os. This means that dissipation effects on neutrons are amplified for a lighter fissioning system. The feature indicates that, when using neutrons as a tool to reveal nuclear dissipation effects, it is desirable to experimentally populate a compound system with a small size.

Table 1. Comparison of the computed pre-scission neutron multiplicity ($n_{\rm pre}^{\rm dyn}$) for three systems with different sizes, ^{190}Os, ^{200}Hg and ^{210}Po, at an excitation energy of 150 MeV and an angular momentum of 30$\hbar$ for different friction strengths (β).

β ($10^{21}{\rm s}^{-1}$)	^{190}Os	^{200}Hg	^{210}Po
3	5.698	6.928	8.833
5	6.413	7.642	9.574
7	6.894	8.111	9.958
10	7.439	8.595	10.292
15	7.976	9.090	10.614
20	8.371	9.447	10.811

Another feature that can be observed from Fig. 1 is the difference of the steepness of $n_{\rm pre}^{\rm excess}$ with increasing β, which reflects the sensitivity of the excess neutron emission to the variation of the friction strength. We note that the steepness is very different for the three systems. For instance, for ^{190}Os the difference of $n_{\rm pre}^{\rm excess}$ at $\beta=20\times10^{21}$ s^{-1} with that at $\beta=3\times10^{21}$ s^{-1} is 105%. It is larger than that of ^{200}Hg for which the corresponding difference is 67%, and the difference further drops down to 35% for ^{210}Po. The physical mechanism for this phenomenon is the following. From Table 1 one notices that as β changes from 3×10^{21} s^{-1} to 20×10^{21} s^{-1}, $n_{\rm pre}^{\rm dyn}$ rises by 2.673, 2.519 and 1.978 for ^{190}Os, ^{200}Hg and ^{210}Po, respectively, showing that the rise of $n_{\rm pre}^{\rm dyn}$ with β slightly decreases with an increase in system size. In contrast to this are the $n^{\rm SSM}$ values of 2.55, 3.77 and

5.61 for ^{190}Os, ^{200}Hg and ^{210}Po, respectively. Despite this fact one can easily see the influence arising from the change of β on the rise of $n_{\rm pre}^{\rm excess}$ [Eq. (7)] of these three fissioning systems. It is the strongest for ^{190}Os and the weakest for ^{210}Po. In other words, with a decreasing system size, a change in β will result in a more prominent dissipation effect on the enhancement of neutron evaporation relative to the SSM values. Therefore, the second feature appearing in Fig. 1 also implies that a small-size condition can provide a more precise determination of the nuclear friction strength.

Shown in Fig. 2 are the results evaluated at an excitation energy of 200 MeV. It is evident that increasing excitation energy does not alter the conclusions drawn from Fig. 1. It should be mentioned that we also carried out the same calculations at other angular momenta and found similar results which are not repeated here.

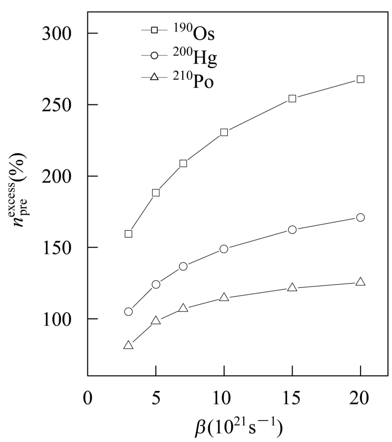

Fig. 2. Same as Fig. 1 but at excitation energy E^*=200 MeV.

As is well known, the pre-scission neutron multiplicity can be easily extracted by measuring neutron energy spectra in coincidence with the fission fragments and by means of a fit procedure of three source models, i.e. a compound nucleus source and two fission fragment sources [18]. The neutron multiplicity is a main source of getting information on the nuclear dissipation effect, hence the conclusions obtained in the present study indicate that on the experimental side, populating a lighter compound system can significantly enhance the sensitivity of the neutron emission to nuclear dissipation. Because these fissioning nuclei with different sizes can be produced by heavy-ion fusion reactions, current theoretical predictions concerning the system size effects can therefore be directly compared with the data available in future experiments.

4 Summary

In summary, for three fissioning systems with equal N/Z we exploit the role of the system size in using neutrons to probe nuclear dissipation in the framework of a Langevin model. The excess of the pre-scission neutron multiplicity over its standard statistical-model value originates from dissipation effects. It is shown that a lighter system substantially increases the effect of nuclear dissipation on the excess of the pre-scission neutron multiplicities and the sensitivity of the excess to nuclear friction. The results suggest that in experiments to accurately determine the dissipation strength by measuring the neutron evaporation multiplicities during a fission process, it is optimal to choose among the various compound systems with equal N/Z those with the smallest size.

References

1 Peterson D et al. Phys. Rev. C., 2009, **79**: 044607
2 Jacquet D, Morjean M. Prog. Part. Nucl. Phys., 2009, **63**: 155
3 Sadhukhan J et al. Phys. Rev. C, 2008, **78**: 011603(R)
4 YE W, YANG H W, WU F. Chin. Phys. C (HEP & NP), 2008, **32**: 816
5 Fröbrich P. Nucl. Phys. A, 2007, **787**: 170c
6 Andersen U J et al. Phys. Rev. Lett., 2007, **99**: 162502
7 Schmitt C et al. Phys. Rev. Lett., 2007, **99**: 042701
8 YE W. Phys. Lett. B, 2007, **647**: 118
9 Fröbrich P, Gontchar I I. Phys. Rep., 1998, **292**: 131
10 Abe Y et al. Phys. Rep., 1996, **275**: 49
11 YE W et al. Z. Phys. A, 1997, **359**: 385
12 Nadtochy P N et al. Phys. Rev. C, 2002, **65**: 064615
13 Ryabov E G et al. Phys. Rev. C, 2008, **78**: 044614
14 Fröbrich P. Prog. Theor. Phys. Suppl., 2004, **154**: 279
15 Jurado B et al. Phys. Rev. Lett., 2004, **93**: 082501
16 Shidling P D et al. Phys. Rev. C, 2006, **74**: 064603
17 YE W. Phys. Rev. C, 2008, **77**: 011302(R)
18 Hilscher D, Rossner H. Ann. Phys. (Paris), 1992, **17**: 471
19 Ramachandran K et al. Phys. Rev. C, 2006, **73**: 064609
20 Singh H et al. Phys. Rev. C, 2008, **78**: 024609; 2006, **76**: 044610
21 Tishchenko V et al. Phys. Rev. Lett., 2005, **95**: 162701
22 Myers W D, Swiatecki W J. Nucl. Phys., 1961, **81**: 1
23 Myers W D, Swiatecki W J. Ark. Fys., 1967, **36**: 343
24 Balian R, Bloch C. Ann. Phys., 1970, **60**: 401
25 Brack M et al. Rev. Mod. Phys., 1973, **44**: 320
26 Gontchar I I, Fröbrich P, Pischasov N I. Phys. Rev. C, 1993, **47**: 2228
27 Ignatyuk A V et al. Sov. J. Nucl. Phys., 1975, **21**: 612
28 Fröbrich P et al. Nucl. Phys. A, 1993, **556**: 281
29 Blann M. Phys. Rev. C, 1980, **21**: 1770
30 Lazarev Y A, Gontchar I I, Mavlitov N D. Phys. Rev. Lett., 1993, **70**: 1220