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Examination of isospin effects in multi-dimensional Langevin fission dynamics

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ABSTRACT

One-dimensional and three-dimensional dynamical fission calculations based on Langevin equations are performed for the compound nuclei ^{194}Pb, ^{200}Pb, ^{206}Pb, ^{182}Hg, and ^{204}Hg to investigate the influence of the compound nucleus isospin on the prescission particle multiplicities and on the fission fragment mass–energy distribution. It is found that the prescission neutron, proton, and alpha particle multiplicities have approximately the same sensitivity to the dissipation strength for a given nucleus. This is at variance with conclusions of recent papers. The sensitivity of the calculated prescission particle multiplicities to the dissipation strength becomes higher with decreasing isospin of fissioning compound nucleus, and the increase of prescission particle multiplicities could reach 200%, when the reduction coefficient of one-body viscosity k_s increases from 0.1 to 1, for the most neutron deficient nuclei considered. The variances of fission fragment mass and kinetic energy distributions are less sensitive to the change of dissipation strength than the prescission light particle multiplicities. A comparison to experimental data concerning ^{200}Pb nucleus is also presented.

1. Introduction

During last decades many experimental and theoretical investigations of dissipation properties of nuclear matter have been performed [1–3]. The dissipation causes the delay of the fission process [4–6] with respect to the statistical picture of compound nucleus decay and has an impact on many experimental observables, such as prescission particle multiplicities, fission probability, and mass–energy distribution of fission fragments. The estimates of the dissipation magnitude and delay time in fission process obtained from different studies predict quite different results [7]. In this respect it is useful to search for the observables which will have higher sensitivity to the dissipation strength. Ye and co-authors have proposed many one-dimensional (1D) dynamical fission calculations to investigate the sensitivity of the prescission particle multiplicities, gamma-ray emission [8–12], and evaporation–residue cross section [13,14] on the isospin of compound nucleus and viscosity coefficient.

Almost all the problems of collective nuclear dynamics are essentially multi-dimensional. However, 1D calculations could be used for the theoretical investigations of prescission particle emission and time characteristics of the fission process. As an advantage, 1D calculations do not need large computational time. On the other hand, for the correct description of the experimentally observed mass–energy distribution of fission fragments at least three independent shape parameters are needed [15–17]: the elongation parameter, the parameter which describes the appearance of the neck in the shape of the nucleus, and the mass-asymmetry parameter. The dimensionality of the model also influences the prediction of the fission rate [18–20].

In the present article we present 1D and 3D calculations of the same systems used in Refs. [8,13] to explore the importance of the dimensionality of the model on some observables and to test the influence of isospin on the nuclear viscosity. In Refs. [8,9] it was concluded that the sensitivity of the light particle multiplicities with increasing strength of the dissipation depends upon the type of particle. In particular, neutrons are most sensitive to dissipation strength for high isospin, whereas protons and alpha particles are more sensitive in the case of lower isospin. In the study presented here, we do not reach this conclusion independently of the dimensionality of the dynamical model used.

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2. Model

In our dynamical calculations we use a $\{c, h, \alpha\}$ parametrization [21] of the compound nucleus shape. In cylindrical coordinates the surface of the nucleus is given by:

$$\rho_s^2(z) = \begin{cases} (c^2 - z^2)(A_s + Bz^2/c^2 + \frac{\alpha z}{c}), & B \geqslant 0; \\ (c^2 - z^2)(A_s + \frac{\alpha z}{c})\exp(Bcz^2), & B < 0, \end{cases} \quad (1)$$

where z is the coordinate along the symmetry axis and ρ_s is the radial coordinate of the nuclear surface. In Eq. (1) the quantities B and A_s are defined as:

$$B = 2h + \frac{c-1}{2};$$
$$A_s = \begin{cases} c^{-3} - \frac{B}{5}, & B \geqslant 0; \\ -\frac{4}{3}\frac{B}{\exp(Bc^3) + (1 + \frac{1}{2Bc^3})\sqrt{-\pi Bc^3}\operatorname{erf}(\sqrt{-Bc^3})}, & B < 0. \end{cases} \quad (2)$$

In Eqs. (1) and (2), c denotes the elongation parameter, parameter h describes the variation in the thickness of the neck for a given elongation of the nucleus, and the parameter of the mass asymmetry α determines the ratio of the volumes of the future fission fragments. In the symmetrical case ($\alpha = 0$) a family of symmetric shapes is obtained, ranging from the spherical shape ($c = 1$, $h = 0$) to the two-fragment shapes ($A_s < 0$).

In the stochastic approach [1,2] the evolution of the collective coordinates which describe the shape of the nucleus is considered as motion of Brownian particles which interact stochastically with a large number of internal degrees of freedom, constituting the surrounding "heat bath". The friction force is assumed to be derived from the random force averaged over a time larger than the collisional timescale between collective and internal degrees of freedom. The random part is modelled as a Gaussian white noise which causes fluctuations of the collective variables, and, as a result, fluctuations of the physical observables in the fission process will appear. The coupled Langevin equations have the form:

$$\frac{dq_i}{dt} = \mu_{ij} p_j,$$
$$\frac{dp_i}{dt} = -\frac{1}{2} p_j p_k \frac{\partial \mu_{jk}}{\partial q_i} - \frac{\partial F}{\partial q_i} - \gamma_{ij}\mu_{jk} p_k + \theta_{ij}\xi_j(t), \quad (3)$$

where $\mathbf{q}$ is the vector of collective coordinates, $\mathbf{p}$ is the vector of conjugate momenta, $F(\mathbf{q}) = V(\mathbf{q}) - a_\nu T^2$ is the Helmholtz free energy, $V(\mathbf{q})$ is the potential energy, $m_{ij}(\mathbf{q})$ ($\|\mu_{ij}\| = \|m_{ij}\|^{-1}$) is the tensor of inertia, $\gamma_{ij}(\mathbf{q})$ is the friction tensor. The normalized random variable $\xi_j(t)$ is assumed to be a white noise. The strength of the random force θ_{ij} is given by $\sum \theta_{ik}\theta_{kj} = T\gamma_{ij}$. The temperature T of the "heat bath" is determined by the Fermi-gas model formula $T = (E_{int}/a_\nu)^{1/2}$, where E_{int} is the internal excitation energy of the nucleus, and a_ν is the level-density parameter. The repeated indices in the equations above imply a sum over the collective coordinates.

The collective coordinates $\mathbf{q} = (q_1, q_2, q_3)$ are connected with the shape parameters c, h, and α by $q_1 = c$, $q_2 = (h + 3/2)/(\frac{5}{2c^3} + \frac{1-c}{4} + 3/2)$, and $q_3 = \alpha/(A_s + B)$, if $B \geqslant 0$, or $q_3 = \alpha/A_s$, if $B < 0$. The advantage of using the collective coordinates $\mathbf{q}$ instead of the (c, h, α) parameters is discussed in Refs. [16,22].

During a random walk along the Langevin trajectory in the collective coordinates space, the energy conservation law is used in the form $E^* = E_{int} + E_{coll} + V + E_{evap}(t)$. Here E^* is the total excitation energy of the nucleus, $E_{coll} = 1/2\sum \mu_{ij} p_i p_j$ is the kinetic energy of the collective motion. The value $E_{evap}(t)$ is the energy carried away by the evaporated particles by the time t. The inertia tensor is calculated by means of the Werner–Wheeler approximation for incompressible irrotational flow [23]. The potential energy of the nucleus is calculated within the framework of a macroscopic model with finite range of the nuclear forces [24]. A modified one-body mechanism of nuclear dissipation [25,26] is used for determination of the dissipative part of the driving forces with a reduction coefficient of the contribution from the "wall" formula k_s. The value $k_s = 1.0$ corresponds to "wall" and "wall-plus-window" formulas [27], whereas values $0.2 < k_s < 0.5$ allow the reproduction of different characteristics of the mass–energy distribution and particle multiplicities [15,17,16] and compatible with other predictions [26,28–31]. Evaporation of prescission light particles ($j = n, p, \alpha$) along Langevin trajectories is taken into account using a Monte Carlo simulation technique [2,32]. The partial decay widths of particle emission are calculated using the statistical model Lilita_N97 [33]. We chose the following main ingredients of statistical model. The level-density parameter $a_\nu = A/12$ assumed to be independent of deformation of the nucleus and $a_f/a_\nu = 1$, where a_f is the level density parameter for fission. The emission barriers for charged particle emission are calculated for spherical shape of the nucleus. The transmission coefficients are derived from fusion systematics [34]. The sharp rigid sphere prescription with radius parameter $r_0 = 1.2$ fm for yrast line is used.

The angular momentum L for each Langevin trajectory is simulated by the Monte Carlo method from the triangular spin distribution function [2] with the maximum critical angular momentum L_c for fusion.

The 1D Langevin calculations have been carried out using the elongation parameter c as a collective coordinate, while the parameters h and α have been set to zero. Such calculations will follow the bottom of the fission valley [21], which corresponds to the most probable path from spherical shape of compound nucleus to the two-fragment shape. The 3D Langevin calculations have been performed using the collective coordinates q_1, q_2, and q_3.

3. Results and discussions

In the present study the fission of compound nuclei ^{194}Pb, ^{200}Pb, and ^{206}Pb at 100 MeV of excitation energy is investigated by using our 1D and 3D models. The prescission neutron (n_{pre}), proton (p_{pre}), alpha-particle (α_{pre}) multiplicities, fission probability (P_f) as well as the variances of fission fragment mass (σ_M^2) and kinetic energy ($\sigma_{E_K}^2$) distributions have been calculated in the 3D dynamical model. The same observables except the variances of fission fragment mass (σ_M^2) and kinetic energy ($\sigma_{E_K}^2$) distributions have also been computed within our 1D model ($h = 0$ and $\alpha = 0$). Due to the limited dimensionality, no mass–energy distribution of fission fragments is computable in this case. Consequently σ_M^2 and $\sigma_{E_K}^2$ are not available in the 1D case. The use of the 1D model has two aims: 1) to enlighten the effect of the dimensionality of the model on the observables for changing viscosity and isospin, 2) to favour the comparison of the calculations of our 1D model with the theoretical results from Ref. [8].

There are some experimental data on the prescission particle multiplicities, fission and evaporation–residue cross sections for the reaction ^{19}F + ^{181}Ta → ^{200}Pb at the excitation energies close to 100 MeV [35–37]. The fusion cross section (σ_{fus}) for this reaction has been estimated to be 1200 mb [35] (the fusion–fission cross section $\sigma_{FF} \approx 900$ mb and evaporation–residue cross section $\sigma_{ER} \approx 300$ mb), which corresponds to $L_c \approx 60\hbar$. Thus, we use $L_c = 60\hbar$ in the present analysis. The value of fission probability $P_f = \sigma_{FF}/\sigma_{fus} = 0.75$ is found from the experimental data. The experimental prescission particle multiplicities for this reaction are $n_{pre}^{exp} = 3.72 \pm 0.36$ [36], $p_{pre}^{exp} = 0.040(4)$, and $\alpha_{pre}^{exp} = 0.050(7)$ [37].

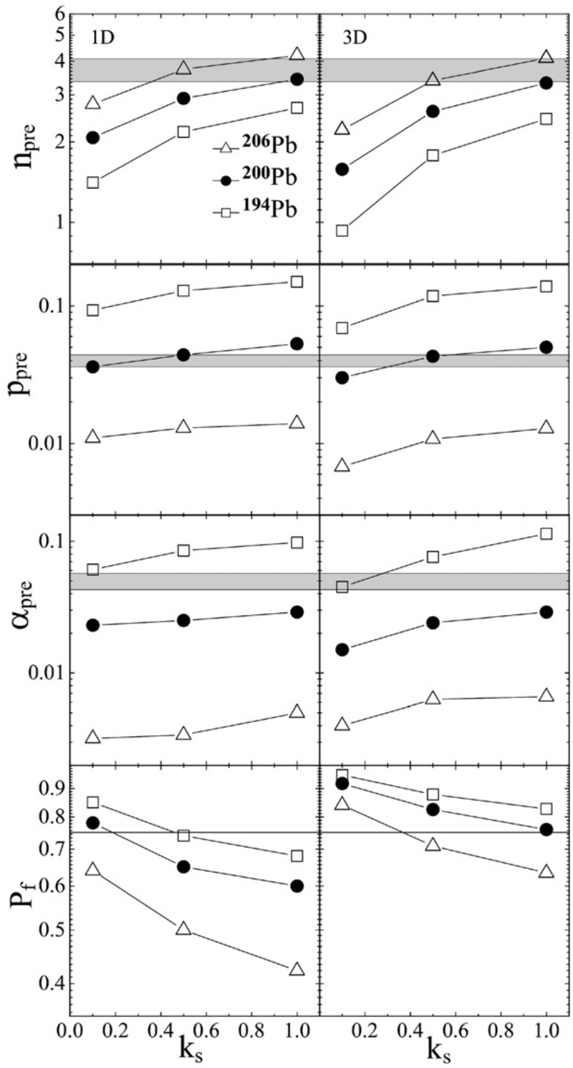

Fig. 1. Prescission particle multiplicities and fission probability obtained in 1D (left column) and 3D (right column) calculations for the ^{194}Pb (squares), ^{200}Pb (filled circles), and ^{206}Pb (triangles). The horizontal solid line and hatched areas are experimental data with error bars for the ^{200}Pb nucleus (see text for details).

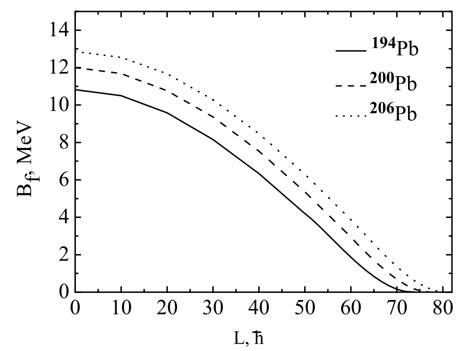

Fig. 2. The fission barriers B_f for the ^{194}Pb (solid curve), ^{200}Pb (dashed curve), and ^{206}Pb (dotted curve) nuclei as a function of angular momentum L.

Table 1
Prescission particle multiplicities, normalized to those for the same system and particle type with the value of $k_s = 0.1$. See text for details.

C.N.	k_s	1D calc.			3D calc.		
		n_{pre}	p_{pre}	α_{pre}	n_{pre}	p_{pre}	α_{pre}
^{194}Pb	0.5	1.55	1.39	1.39	1.91	1.71	1.69
	1.0	1.90	1.61	1.61	2.62	2.01	2.53
^{200}Pb	0.5	1.40	1.22	1.10	1.65	1.43	1.60
	1.0	1.65	1.47	1.26	2.10	1.67	1.93
^{206}Pb	0.5	1.35	1.18	1.07	1.53	1.59	1.58
	1.0	1.52	1.27	1.56	1.85	1.90	1.70

Table 2
The calculated prescission particle multiplicities for Pb isotops obtained with $k_s = 0.1$.

C.N.	1D calc.			3D calc.		
	n_{pre}	p_{pre}	α_{pre}	n_{pre}	p_{pre}	α_{pre}
^{194}Pb	1.41	0.093	0.061	0.93	0.069	0.045
^{200}Pb	2.07	0.036	0.023	1.58	0.03	0.015
^{206}Pb	2.77	0.011	0.0032	2.22	0.0068	0.004

In Fig. 1 the calculated values of prescission particle multiplicities and fission probability in 1D and 3D calculations are presented as a function of k_s. The available experimental data for ^{200}Pb are plotted in Fig. 1 as hatched area which represents the experimental error. The qualitative monotone trend of the theoretical curves with increasing value of k_s is the same in 1D and 3D calculations. The n_{pre}, p_{pre}, and α_{pre} values calculated in 3D are systematically lower than in 1D, whereas the predicted values of fission probability P_f in 3D calculations are higher than in 1D. This is consistent with the fact that the fission rate R_f in 3D calculations is larger than in 1D calculations [18]. A feature that remains unchanged with the dimensionality of the model is the dependence of the observables on the isospin: n_{pre} increases with the isospin of the compound nucleus, whereas all the other observables are decreasing functions.

The behaviour of the prescission particle multiplicities and fission probability with changing isospin can be explained from considerations on binding energies and fission barrier heights (B_f) for Pb isotopes. The neutron (proton) binding energies are 7.58 (0.75), 7.11 (2.49), and 6.74 (3.56) MeV for the ^{194}Pb, ^{200}Pb and ^{206}Pb, respectively. Therefore, charged particle emission is expected to increase with decreasing isospin. The dependence of B_f upon the angular momentum L for Pb isotopes is presented in Fig. 2. The lowest B_f values are for ^{194}Pb, and, as a result, this nucleus has the largest P_f values independently of the viscosity and dimensionality of the model. ^{194}Pb is also the most neutron deficient nucleus considered in the present study. Hence, it has higher p_{pre} and α_{pre} values. On the contrary, the nucleus ^{206}Pb has lowest P_f values and lower values of p_{pre} and α_{pre}. The results for ^{200}Pb lie in between the predictions for ^{194}Pb and ^{206}Pb.

In order to investigate the sensitivity of the observables on the dissipation strength, we present in Table 1 the increase of prescission particle multiplicities normalized to the values obtained with the $k_s = 0.1$ for the same system and particle type. As reference we give in Table 2 the prescission particle multiplicities obtained with the $k_s = 0.1$. One can see from Table 1 that the sensitivity of prescission particle multiplicities in 3D calculations are systematically higher than in 1D. For example, the n_{pre} value for ^{194}Pb increases by 2.62 times in 3D and by 1.9 times in 1D calculations when k_s increases from 0.1 to 1. This is an important consequence of the dimensionality of the model.

Considering the overall data for prescission particle multiplicity, one can also conclude that the sensitivity of n_{pre}, p_{pre} and α_{pre} to the viscosity is higher for the neutron deficient nucleus (lower isospin), in comparison with neutron rich, independently of the dimensionality of the model. The nucleus ^{194}Pb provides the largest sensitivity for all prescission particles. However, one should note

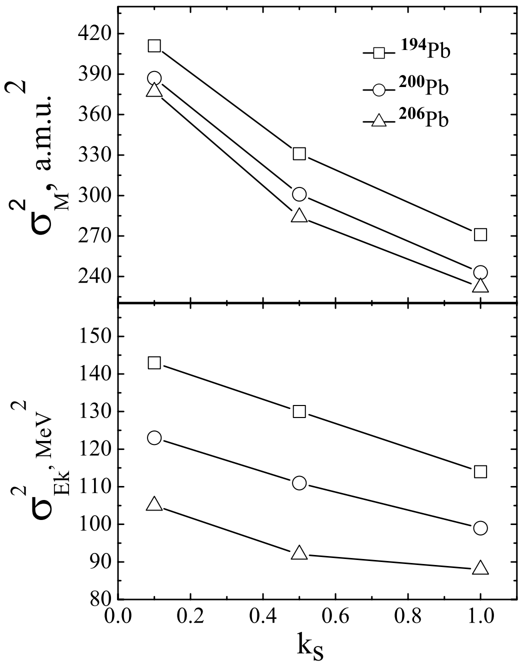

Fig. 3. The σ_M^2 and $\sigma_{E_K}^2$ as a function of viscosity coefficient k_s for the ^{194}Pb (squares), ^{200}Pb (circles), and ^{206}Pb (triangles) nuclei.

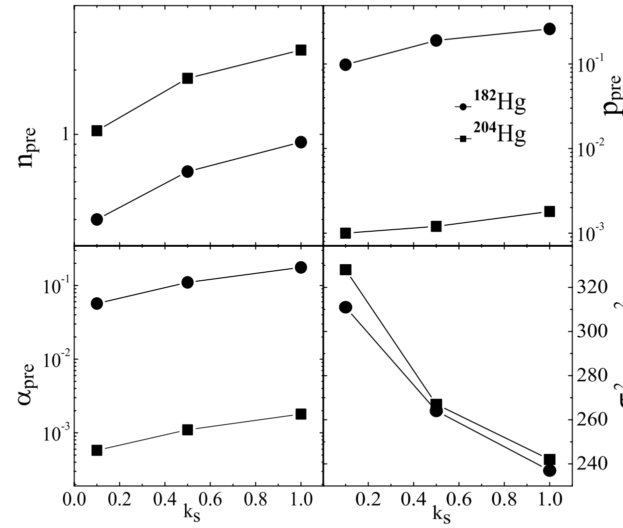

Fig. 4. The prescission particle multiplicities and variance of the fission fragment mass distribution for the ^{182}Hg (circles), ^{200}Hg (squares). The results are obtained in 3D calculations.

that even for the most neutron rich ^{206}Pb in 3D calculations the increase of prescission particle multiplicities is about 80%. From the data presented in Table 1 it can also be observed that the sensitivity of the data to the viscosity depends weakly on the type of particle. In other words, all the prescission particle multiplicities provide approximately the same sensitivity for a given nucleus. This result is at variance with that proposed in Ref. [8], where authors conclude that for neutron rich nuclei (higher isospin) the p_{pre} and α_{pre} are almost independent of dissipation and only n_{pre} demonstrate strong sensitivity to the viscosity. This conclusion seems to be based only on a graphical analysis of the calculated data. We suspect that if a quantitative analysis would be done by the authors of Ref. [8] their conclusions will coincide with ours.

The absolute values of our 1D calculations and the ones in Ref. [8] cannot be compared directly because of the different representation of the mass and dissipation parameters. In Ref. [8] mass and friction parameters, independent of deformation, were chosen and the reduced viscosity coefficient $\beta = \gamma/m$ was used as a free variable. Whereas we use both deformation dependent mass and friction coefficients, obtained from predictions of macroscopic models. We vary the reduction factor k_s of the contribution from the wall formula in the range $k_s = 0.1$–1.0, which approximately corresponds to the range of $\beta \simeq (2\text{–}20) \times 10^{21}\ \text{s}^{-1}$.

On the basis of our model it is possible to withdraw a general criterion to help in the choice of the most suitable system to study nuclear dissipation. The p_{pre} and α_{pre} values are about 10 and 30 times larger for neutron deficient ^{194}Pb than for ^{206}Pb. Moreover, the nucleus ^{194}Pb has the largest sensitivity of prescission particle multiplicities to the viscosity. Therefore, the neutron deficient ^{194}Pb nucleus, among the three isotopes, is the preferred fissioning system to investigate dissipation strength.

In Fig. 3 the variances of fission fragment mass σ_M^2 and kinetic energy $\sigma_{E_K}^2$ distributions obtained in 3D calculations are presented. The σ_M^2 and $\sigma_{E_K}^2$ values have a weak dependence on the viscosity and, in comparison with the prescission particle multiplicities, do not depend on the isospin of the compound nucleus. The σ_M^2 ($\sigma_{E_K}^2$) value decreases about 40% (20%) for all Pb isotopes, when k_s increases from 0.1 to 1. The dependence of σ_M^2 on the viscosity is determined by the dynamical effects [15,17,16] during the descend from saddle to scission point as well as by the temperature of the fissioning nucleus. The $\sigma_{E_K}^2$ is strongly affected by the scission criterion used in the numerical Langevin calculations [38] as well. Therefore, the determination of the dissipation strength from the σ_M^2 and $\sigma_{E_K}^2$ data alone gives rise to more uncertainty than from the prescission particle multiplicities.

The comparison of the calculations with the experimental data of ^{200}Pb (see Fig. 1) shows an interesting feature in favour of the 3D model. Besides the fact that α_{pre} is underestimated by both models, we observe that in the 1D model the group of observables n_{pre}, p_{pre}, and P_f can be reproduced but with different ranges of k_s values. For instance, n_{pre} requires a higher value of k_s (around 1) whereas p_{pre} and P_f are reproduced by a lower value of k_s. This result confirms that it is mandatory to measure simultaneously many observables to test a physical model. In the 3D calculation instead we see that a higher value of k_s (around 1) is more suitable for the same group of observables above. This is more coherent and gives strength to the argument that a 3D model implements a more realistic picture of the fission process. The calculated values of α_{pre} are nevertheless about 40% lower than the experimental datum. We do not vary the parameters of the model to reproduce the α_{pre}^{exp} values, as the exact reproduction of experimental data was not the aim of the present work. However, we should mention the possible improvements of the model which will lead to an increase of calculated α_{pre} values to fit the experimental data. One can take into account the deformation dependence of emission barriers for charged particles. This will lead to the lowering of emission barriers and increase of α_{pre} and p_{pre} values. The mechanism of alpha particle emission from strongly necked-in shapes [39,40] at the late stage of fission process could be taken into account also, and would help to reproduce the experimental data.

The effects found for the Pb isotopes can be even more pronounced when the compound nuclei are very far from the stability line. We performed the same calculations for the systems $^{118}\text{Sn} + {}^{64}\text{Zn} \to {}^{182}\text{Hg}$ and $^{134}\text{Sn} + {}^{70}\text{Zn} \to {}^{204}\text{Hg}$ at $E^* = 100$ MeV. ^{134}Sn is expected to be produced with relatively high intensity by the second generation facilities for radioactive beams, and in particular by SPES facility under construction at the Laboratori Nazionali di Legnaro (Italy) [41]. The results of 3D Langevin calculations for these reactions are presented in Fig. 4. In Table 3 the

Table 3
Prescission particle multiplicities, obtained in 3D calculations and normalized to those for the same system and particle type with the value of $k_s = 0.1$.

C.N.	k_s	n_{pre}	p_{pre}	α_{pre}
^{182}Hg	0.5	1.68	1.94	1.93
	1.0	2.30	2.65	3.09
^{204}Hg	0.5	1.76	1.20	1.89
	1.0	2.38	1.80	3.10

Table 4
The calculated prescission particle multiplicities for Hg isotops obtained with $k_s = 0.1$ in 3D calculations.

C.N.	n_{pre}	p_{pre}	α_{pre}
^{182}Hg	0.4	0.098	0.057
^{204}Hg	1.04	0.001	0.00058

normalized increase of prescission particle multiplicities are presented in comparison with values at $k_s = 0.1$ (given in Table 4). The same conclusions as for the Pb isotopes are confirmed also for the Hg isotopes. Moreover, the sensitivity of the prescission particle multiplicities to the viscosity is larger for ^{182}Hg than for ^{194}Pb.

4. Summary and conclusions

To summarize the findings of our calculations, one can conclude that the prescission particle multiplicities are the most sensitive probes for nuclear dissipation among the observables taken into consideration and are strongly dependent on the isospin of the fissioning nucleus. In particular, the increment of n_{pre}, p_{pre} and α_{pre} with the viscosity can reach up to 200% and depends weakly on the type of particle. This result contradicts that from Refs. [8,13] where the authors found that for neutron rich nuclei the p_{pre} and α_{pre} are almost independent of dissipation and only n_{pre} shows strong sensitivity to the viscosity.

The implications of such difference could be crucial in planning future experiments. In Refs. [8,9] it is suggested that in the investigations of the fission of neutron rich nuclei one can neglect the analysis of charged particles emission. Our results show instead that one should analyse n_{pre}, p_{pre} and α_{pre} together, as they have comparable sensitivity to the viscosity and could provide more constraints for determination of its nature and strength. For instance, in case of ^{200}Pb (see Fig. 1) the 3D model is able to reproduce n_{pre}, p_{pre} and P_f with k_s around 1, but does not reproduce α_{pre}.

The sensitivity of prescission particle multiplicities to the dissipation strength increases with decreasing isospin of compound nucleus. The investigation of neutron deficient compound nuclei could also provide a more precise determination of viscosity in comparison with neutron rich nuclei, due to larger values of p_{pre} and α_{pre}. The observables σ^2_M, $\sigma^2_{E_K}$, and P_f demonstrate the sensitivity to the dissipation strength lower than light particle multiplicities. Regarding the comparison of 1D and 3D calculations, one can conclude that 3D calculations predict overall lower values of prescission particle multiplicities and that these latters are more sensitive to the viscosity than in the case of 1D calculations.

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