PRE- AND POST-SCISSION NEUTRON EVAPORATION FROM SUPERHEAVY COMPOSITE SYSTEMS*

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Correlations between pre-scission and post-scission multiplicities deduced with the backtracing method by the DéMoN Collaboration for a heavy composite system $Z = 110$ are analysed. The data are interpreted in terms of a hybrid model combining deterministic dynamics code of Feldmeier with a Monte Carlo statistical model of evaporation of light particles in competition with Kramers' dissipative fission.

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1. Introduction

Dynamic evolution of nuclear systems formed in nucleus–nucleus collisions at low energies gives a possibility to study properties of nuclear matter in well defined conditions of the liquid phase. One of the most important still open questions is the nature of nuclear dissipation and its influence on the time scale of nuclear dynamical processes.

Measurements of pre-scission neutron multiplicities may serve as a "neutron clock", an important tool for studying nuclear dynamics. The neutron clock can be used for determination of the time scale of fusion–fission and fast fission reactions. In this paper, a model for deducing information on the reaction mechanism from correlations between pre-scission and post-scission multiplicities is presented.

It was found already more than a decade ago that the fusion–fission processes proceed slower than expected on the grounds of the statistical transition-state theory formulated by Bohr and Wheeler [1]. An alternative approach to nuclear fission, proposed by Kramers [2] in terms of the transport theory, seems to explain this phenomenon. In Kramers' theory, the

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coupling between fluctuations and dissipation is assumed, leading to a dependence of the time scale of fission on nuclear dissipation. In such a way, measurements of the pre-scission neutron multiplicities can be used for determination of viscosity of nuclear matter.

Similarly, evaporation of light particles in strongly damped collisions and "fast-fission" reactions (when fusion does not occur) also may play a role of a clock measuring the time of nuclear interaction. Those non-fusion reactions can be described in terms of deterministic dynamical models [3] involving dissipative (frictional) forces.

Both theoretical tools, deterministic dissipative dynamics and the transport theory approach, have to be employed in analysis of pre-scission neutron multiplicities in fusion–fission reactions because the latter formalism applies only in the pre-saddle stage of fission. Beyond the saddle point, when fission is decided, deterministic dynamics become the most convenient framework for calculating post-saddle evaporation.

2. Model calculations

For heavy nuclear systems, the overcoming of the interaction barrier and formation of the composite system does not guarantee that the system will eventually fuse. Therefore, in our simulations we consider two scenarios: the fusion–fission scenario (in which the compound-nucleus fission is assumed), and the fast fission scenario, in which the time evolution of the combined system is entirely described with deterministic dynamics. For distinction between these two types of reactions we use predictions of the dynamical code HICOL [3], based on the concept of one-body dissipation [4] that was proved to reasonably describe essential features of nucleus–nucleus collisions.

Formation of the compound nucleus is predicted for all partial waves below a certain limiting value l_{fus}. For all higher partial waves, fast-fission-like processes are predicted. The boundary between the two types of processes strongly depends on details of the nucleus–nucleus interaction. Consistency between predicted cross sections of the fusion–fission and fast-fission components with observed mass distributions of the fission fragments is required.

For both, compound–nucleus fission and fast-fission scenarios, we calculate pre-scission and post-scission multiplicities, ν_{pre} and ν_{post}, respectively. In case of the compound-nucleus fission (left-side branch in Fig. 1), ν_{pre} consists of two differently calculated components: pre-saddle and saddle-to-scission multiplicities. The pre-saddle neutron multiplicity in the fusion-fission process is calculated [5] with a time-dependent Monte Carlo program, in which evaporation of light particles competes with dissipative fission described with a modified [6] Kramers formalism. The number of neutrons emitted during the pre-saddle stage depends on a value of the dissipation co-

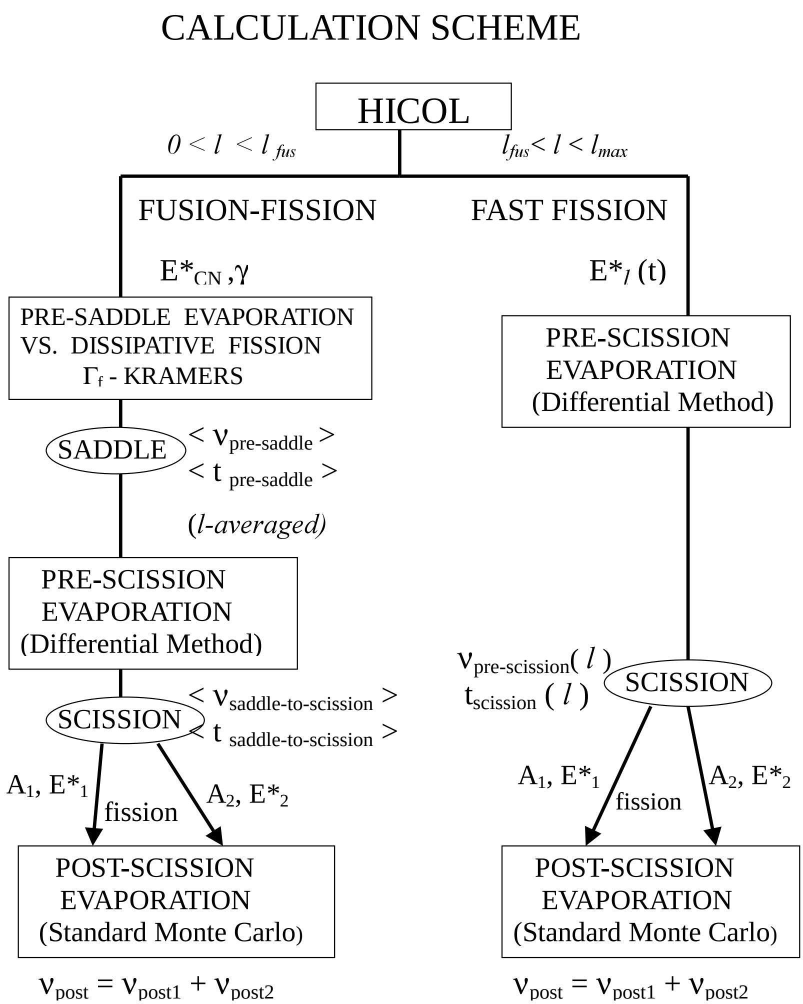

Fig. 1. Calculation scheme of pre- and post-scission neutron multiplicities in fusion–fission and fast fission reactions.

efficient in the Kramers hindrance factor that in the stationary limit reduces the fission width $\Gamma^{\rm K}$ relative to the nonviscous Bohr–Wheeler width $\Gamma^{\rm BW}$:

$$\Gamma^{\rm K} = \Gamma^{\rm BW}\left(\sqrt{1+\gamma^2}-\gamma\right), \tag{1}$$

where γ is the dimensionless dissipation coefficient. Following the Grangé–Weidenmüller model [6], a time dependence of $\Gamma^{\rm K}$ is introduced to Eq. (1) accounting for the transient time needed to build up the quasistationary probability flow over the fission barrier.

When the saddle point is reached (see left-side branch in Fig. 1), fission is decided, and the system descends down to scission point. Evaporation of neutrons (and other light particles) during the saddle-to-scission stage is simulated with a time-dependent "differential" Monte Carlo code, in which light-particle emission or non-emission probability is being drawn in small consecutive time intervals. (Since fission is decided, during the post-saddle cascade, its width is switched off from competition, $\Gamma_{\mathrm{f}} = 0$.) The "differential" approach is essential in description of statistical cascades from rapidly evolving systems, in which excitation energy is generated in a time scale comparable with the decay rate, or faster. Time dependence of the excitation energy generated in the fissioning system along the fission trajectory is calculated using the code HICOL.

The same method, as for calculating the saddle-to-scission component of ν_{pre} in fusion-fission reactions outlined above, is used to calculate the pre-scission neutron multiplicity in the fast-fission scenario, see the right-hand side branch in Fig. 1. The rate of excitation energy generated along the whole fast fission trajectory is calculated for a given angular momentum using the code HICOL. This information is then supplied to the evaporation cascade calculations. The upper limit of angular momenta for fast fission processes, $l_{\max}$, is determined requiring that for $l = l_{\max}$ HICOL reproduces a maximum value of the mass asymmetry of the fragments used in the experiment to trigger pre-scission neutrons.

Both scenarios, fusion–fission and fast fission, end at scission of the composite system. At this point each individual Monte Carlo cascade is finished and information on the final value of the thermal- and deformation excitation energies, mass and charge of the fragments is stored and can be used for calculating deexcitation cascades in post-scission fragments.

Results of simulations described above are compared in Fig. 2 with the correlation between the pre-scission and post-scission multiplicities deduced with the backtracing method for the ^{58}Ni + ^{208}Pb reaction by the DéMoN Collaboration [7]. Black stripe in Fig. 2 represents predicted correlation between average ν_{pre} and average ν_{post} multiplicities for fast fission processes in the range of angular momenta $31 \leq l \leq 120$, with the upper limit consistent with the range of fragment masses used as triggers in the experiment. For fusion–fission reactions, expected to occur for $l \leq 30$, the predicted correlation between average ν_{pre} and average ν_{post} multiplicities was calculated for two values of the dissipation coefficient, $\gamma = 5$, corresponding effectively to one-body dissipation (black circle at $\nu_{\mathrm{pre}} \approx 6$ in Fig. 2), and for about twice that value, $\gamma = 11$ (another black circle at $\nu_{\mathrm{pre}} \approx 8$).

Very similar experimental results obtained by the DéMoN Collaboration on the ^{40}Ca + ^{232}Th reaction [8] are shown in Fig. 3. Results of model calculations, carried out according to the same scheme as for the ^{58}Ni + ^{208}Pb

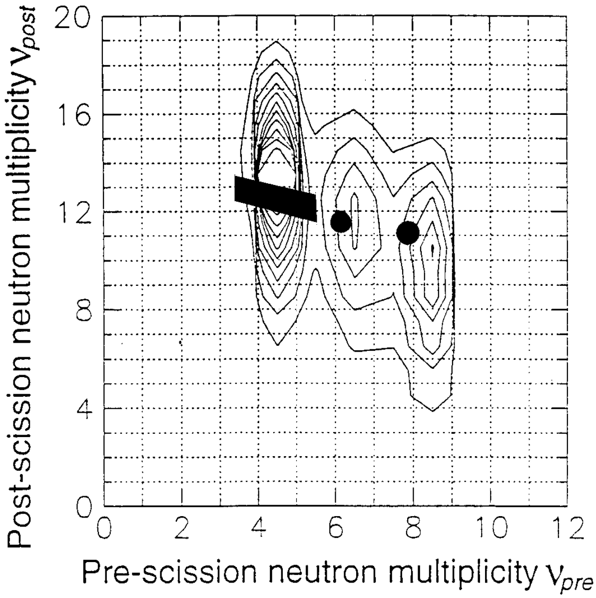

Fig. 2. Correlation between pre-scission and post-scission neutron multiplicities in the ^{58}Ni + ^{208}Pb reaction — see text.

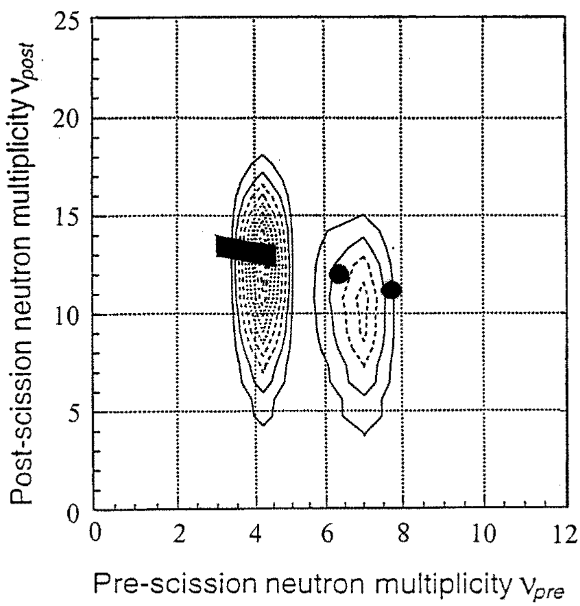

Fig. 3. Correlation between pre-scission and post-scission neutron multiplicities in the ^{40}Ca + ^{232}Th reaction — see text.

reaction, are also shown. For both systems, the model calculations reproduce essential features (average values) of the observed correlation $\nu_{\rm pre}$ vs. $\nu_{\rm post}$. Results of the calculations are consistent with an interpretation that the studied fission-like fragments originate mostly (main maxima in Figs. 2, 3) from fast fission reactions, consistently described with the HICOL model (implying one-body dissipation). For both studied systems, the $\nu_{\rm pre}$ *vs.* $\nu_{\rm post}$ correlations reveal presence of an additional, well separated, but weaker component that can be interpreted as resulting from fusion–fission-like processes at nearly central collisions. Our analysis implies that the fusion–fission process is slowed down by intense dissipative forces comparable in strength with one-body dissipation, or even stronger.

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