# Determination of nuclear friction in strongly damped reactions from prescission neutron multiplicities

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Nonfusion, fissionlike reactions in collisions of four heavy systems (well below the fusion extra-push energy threshold), for which Hinde and co-workers had measured the prescission neutron multiplicities, have been analyzed in terms of the deterministic dynamic model of Feldmeier coupled to a time-dependent statistical cascade calculation. In order to reproduce the measured prescission multiplicities and the observed (nearly symmetric) mass divisions, the energy dissipation must be dramatically changed with regard to the standard one-body dissipation: In the entrance channel, in the process of forming a composite system, the energy dissipation has to be reduced to at least half of the one-body dissipation strength ($k_s^{\rm in} \leqslant 0.5$), and in the exit channel (from a mononucleus shape to scission) it must be increased by a factor ranging for the studied reactions from $k_s^{\rm out}=4$ to $k_s^{\rm out}=12$. These results are compared with the temperature dependence of the friction coefficient, recently deduced by Hofman, Back, and Paul from data on the prescission giant dipole resonance emission in fusion-fission reactions. The combined picture of the temperature dependence of the friction coefficient, for both fusion-fission and nonfusion reactions, may indicate the onset of strong two-body dissipation already at a nuclear temperature of about 2 MeV. [S0556-2813(96)05006-6]

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## I. INTRODUCTION

Following the early work by Kramers [1], the formalism of the Fokker-Planck equation was proposed for the description of fission by Grangé *et al.* [2–4] and also by Wu and Zhuo [5]. Within this concept, fission of a nucleus is described as a diffusion process of the fission degree of freedom over the fission barrier. The Brownian motion of the fissioning system towards the barrier is driven by the coupling (by viscosity) of the collective motion with the heat bath of the excited fissioning nucleus. Application of this model to early results on prescission neutron multiplicities led Grangé *et al.* [6] to the conclusion that the viscosity of the fissioning hot nuclei may reach quite a high level. On the other hand, at low excitation energies, the competition between fission and light-particle emission indicates that cold nuclei undergo fission in accordance with the standard Bohr-Wheeler statistical theory (which predicts the fission width to be nearly identical with that resulting from the Kramers formula in the extreme case of a very small but nonzero viscosity).

Recent experiments on prescission $\gamma$ rays from giant dipole resonances (see Ref. [7] and references therein) have also been interpreted in terms of the diffusion model [2–4]. Results of the analysis of the giant dipole resonance (GDR) data for fissioning nuclei excited to several tens of MeV led to a surprisingly large value of the nuclear friction coefficient. The deduced value of the dimensionless friction coefficient, $\gamma=10\pm3$ [8], implies strong overdamping of the collective mass flow. (In this dimensionless scale the critical damping corresponds to $\gamma=1$.) It should be noted that the value of $\gamma=10$ greatly exceeds the strength of one-body dissipation, commonly viewed as the most effective dissipation mechanism at low excitation energies.

In a recent work, Hofman, Back, and Paul [9] reanalyzed earlier results on the prescission GDR $\gamma$ emission for a range of relatively low excitation energies and found that the deduced value of the friction coefficient rapidly increases with increasing temperature, reaching the value $\gamma=10\pm3$ [8] at $T\approx1.7$ MeV. The sudden rise of nuclear viscosity can be associated with the observation reported by Thoennessen and Bertsch [10] who examined the validity of the Bohr-Wheeler theory and found a clear effect of the reduction of the fission width (relative to the Bohr-Wheeler predictions) at temperatures above 1.5 MeV.

Since the unexpectedly large values of the friction coefficient for hot nuclear matter [8,9] are based entirely on the analysis of compound-nucleus fission data in terms of the diffusion model [2–4], we performed an analysis of some selected experimental data that make it possible to estimate the value of the friction coefficient in *nonfusion* reactions. Contrary to fusion-fission reactions, nonfusion reactions (fast fission or deep inelastic reactions) can be interpreted in terms of a *deterministic* model of nucleus-nucleus dynamics based on classical equations of motion with friction (Lagrange-Rayleigh equations). We will demonstrate that this completely independent method applied to a different class of nuclear processes also leads to very large values of the friction coefficient. Results of our analysis seem to be consistent with the effect of the temperature dependence of the friction

 

TABLE I. Prescission neutron multiplicities for four selected nonfusion reactions studied by Hinde *et al.* [14] and deduced values of the friction strength factor $k_s^{\rm out}$. Values of the reduced friction coefficient $\beta$ (averaged over the outgoing part of the trajectory, $\overline{\beta}_{\rm out}$) and the corresponding average temperature, $\overline{T}_{\rm out}$ are also listed.

| Reaction | $E_{\rm lab}$ (MeV) | $\nu_{\rm pre}^{\rm expt}$ | Mass number range | $k_s^{\rm out}$ | $\overline{\beta}_{\rm out}$ ($10^{21}$ s$^{-1}$) | $\gamma$ | $\overline{T}_{\rm out}$ (MeV) |
|---|---|---|---|---|---|---|---|
| $^{40}$Ar+$^{238}$U | 249 | 3.25±0.2 | 100–175 | $12\pm^{3}_{2}$ | $100\pm^{24}_{16}$ | $50\pm^{12}_{8}$ | 2.25 |
| $^{64}$Ni+$^{197}$Au | 418 | 3.15±0.6 | 120–140 | $4\pm^{2}_{1}$ | $34\pm^{16}_{8}$ | $17\pm^{8}_{4}$ | 2.55 |
| $^{64}$Ni+$^{208}$Pb | 418 | 3.25±0.6 | 105–165 | $4\pm^{2}_{1}$ | $33\pm^{16}_{8}$ | $17\pm^{8}_{4}$ | 2.50 |
| $^{64}$Ni+$^{238}$U | 418 | 4.00±0.8 | 135–165 | $10\pm^{6}_{3}$ | $80\pm^{48}_{24}$ | $40\pm^{24}_{12}$ | 2.40 |

coefficient reported in Ref. [9]. However, our analysis suggests that the fast rise of the friction coefficient with temperature is followed by a subsequent decrease at still higher temperatures, indicating the onset of two-body dissipation.

## II. EVAPORATION CASCADE IN DYNAMICAL CALCULATIONS

In Refs. [11,12] we proposed a dynamical method of calculating the fusion-fission time scales from measured neutron multiplicities. In this method we combine a simple Monte Carlo version of the time-dependent statistical model with Feldmeier's dynamical code HICOL, based on the concept of one-body dissipation [13]. The statistical decay code has been constructed in such a way that the excitation energy generated in the composite system, and known at a given time from the HICOL calculation, is coupled with the evaporation cascade calculation and thus adjusts the actual excitation energy at a given instant of time. This differential modification of the excitation energy is repeated step by step at each stage of the statistical decay sequence. More detailed information on the code DYNSEQ used in our calculations can be found in Ref. [12].

The code DYNSEQ (coupled to the nuclear dynamics code HICOL) predicts the accumulation in time of the multiplicity of neutrons and other evaporated light particles along a given classical trajectory. In the application of this method for the interpretation [12] of the prescission neutron multiplicities [14] in fusion-fission reactions the code was used for calculating the neutron emission along a part of the trajectory before fusion and then for the outgoing trajectory—from saddle to scission. In fusion-fission reactions these two components account only for a small part of the total prescission multiplicity and therefore a possible dependence of the time scale (and thus the respective multiplicity) of the ingoing and outgoing trajectories on nuclear dissipation could not be isolated and investigated. (The essential part of the measured effect of the prescission multiplicity in the fusion-fission reactions is associated with the compound-nucleus stage for which the HICOL code can only be used for the determination of a correct initial value of the excitation energy.) Summarizing these remarks, in the case of *fusion-fission* reactions, the analysis of the prescission neutron multiplicities in terms of the dynamical model of Ref. [12] leads to a determination of the time scale of the reaction, but obviously it cannot give direct information on the viscosity of the compound nucleus.

On the other hand, in the case of *nonfusion* reactions, the dynamical evolution of a colliding system can be traced along the whole trajectory. In that case information on the time dependence of the thermal excitation is available from the code HICOL all the way from the touching of the colliding nuclei until scission. Consequently, the neutron multiplicity predicted by the code DYNSEQ directly depends on the time scale of a given nonfusion trajectory and thus on the nuclear dissipation assumed in the dynamical code. Therefore, analysis of prescission neutron multiplicities in nonfusion reactions gives a possibility to deduce the effective strength of the nuclear dissipation.

## III. NONFUSION REACTIONS

The likelihood of the surprisingly strong nuclear dissipation (suggested in Refs. [8,9] as a result of an analysis of the compound-nucleus fission data in terms of the diffusion model) can be verified in an independent way by the determination of nuclear friction in *nonfusion* reactions governed by the deterministic dynamics. For this purpose, however, prescission neutron multiplicities have to be measured for colliding systems that for *all* partial waves do not fuse.

Analyzing existing data on prescission multiplicities, we found four reactions studied by Hinde *et al.* [14] and listed in Table I which, most probably, do not undergo fusion even in central collisions. Classical trajectory calculations with the HICOL code lead for all partial waves to reseparation of these systems. Figure 1 shows fusion excitation functions for these systems calculated with the code HICOL. It is seen that at the studied energies, indicated in Fig. 1 by arrows, the entire reaction cross section is comprised of nonfusion reactions. Predicted energy thresholds for fusion are located at much higher energies (in the case of the heaviest system, $^{64}$Ni + $^{238}$U, the fusion threshold is about 500 MeV above the beam energy). Clearly, a considerable ''extra-push'' energy [15] is needed for fusion of these colliding systems.

Figure 2 illustrates predictions [13] of the time dependence of the thermal energy $E_{\rm diss}$, dissipated along selected trajectories, for the $^{64}$Ni+$^{238}$U reaction taken as an example. In the considered collisions the kinetic energy is quickly dissipated within a time shorter than $10^{-21}$ s, and subsequently the combined system slowly moves on the potential energy surface towards scission, continuously converting the Coulomb energy into heat. (In Fig. 2, scission corresponds to the end point of each curve.) It is seen from Fig. 2 that the interaction time increases with decreasing angular momentum and the longest interaction time corresponds to a central collision, $t_{\rm int}=11\times10^{-21}$ s for $\ell=0$. As discussed in Sec. II, the dependence of $E_{\rm diss}$ on time, calculated with the code

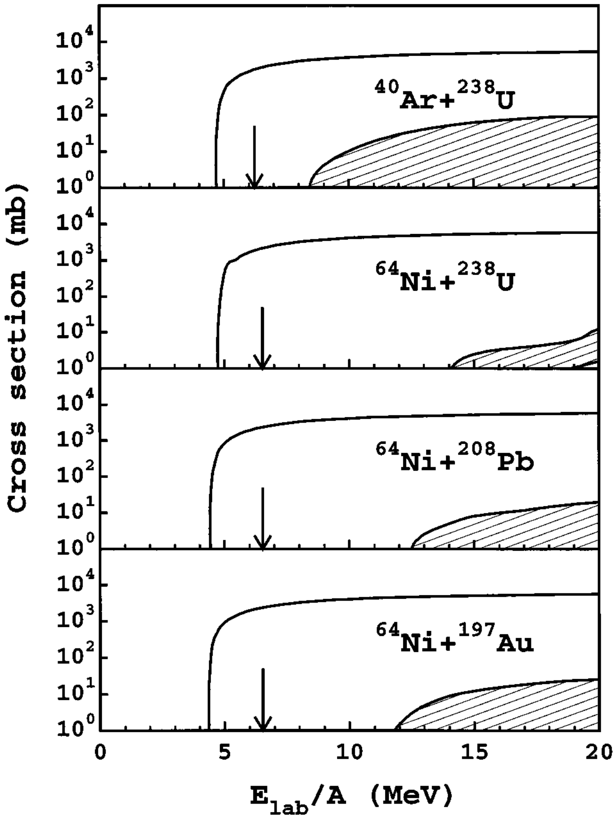


FIG. 1. Energy dependence of the fusion (hatched) and the reaction cross section predicted by HICOL calculations for four systems for which prescission neutron multiplicities had been measured [14] at energies indicated by the arrows.

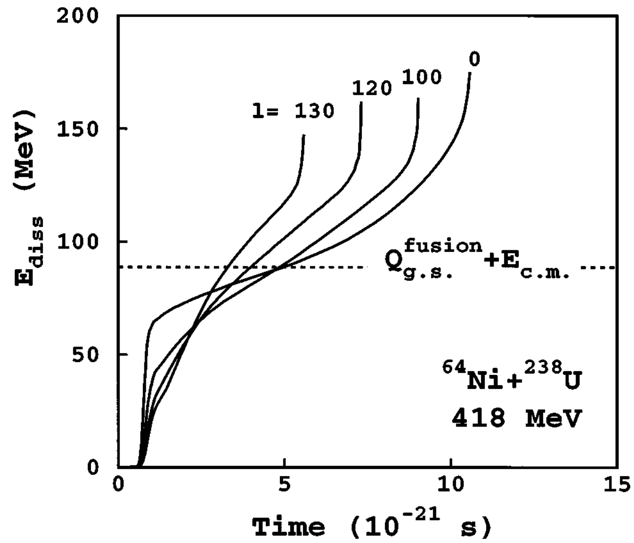


FIG. 2. Thermal excitation energy $E_{\mathrm{diss}}$ of the $^{64}$Ni+ $^{238}$U composite system as a function of time for selected $\ell$ values (predicted with the code HICOL). The excitation energy of the compound nucleus, $Q_{\mathrm{g.s.}}^{\mathrm{fusion}}+E_{\mathrm{c.m.}}$, is indicated by the dashed line.

HICOL, is fed to our statistical decay code DYNSEQ in order to calculate the average number of neutrons emitted along a given trajectory.

It is clear that if the interaction time dictated by the one-body dissipation model is correct, the neutron multiplicity calculated along the slowest trajectory (for $\ell=0$) should approximately reproduce the measured value. (As a matter of fact, the calculated multiplicity should even exceed the measured value because in experiments the multiplicity is averaged over a range of partial vaves corresponding to the interaction times shorter than that for the central collision.) Figure 3 demonstrates that this is not the case. In two parts of this figure is presented the time dependence of the accumulated multiplicity (bottom) in correlation with the time dependence of the thermal excitation energy along the trajectory (top). Predictions based on standard one-body dissipation dynamics are indicated by dashed lines. It is seen that the longest interaction time $t_{\mathrm{int}}=11\times10^{-21}$ s, corresponding to $\ell=0$, evidently is too short because within that time (until scission) only about 0.5 neutrons can be emitted, while the measured value of the multiplicity is $\nu_{\mathrm{pre}}^{\mathrm{expt}}=4.0\pm0.8$. In order to slow down the relative motion to such an extent that the calculated multiplicity will rise to the experimental value, it is necessary to considerably increase the nuclear dissipation, well above the fixed level of one-body dissipation that is assumed in Feldmeier's code HICOL. The solid lines in Fig. 3 represent results of a calculation with a considerably incresed friction. It is seen that then the

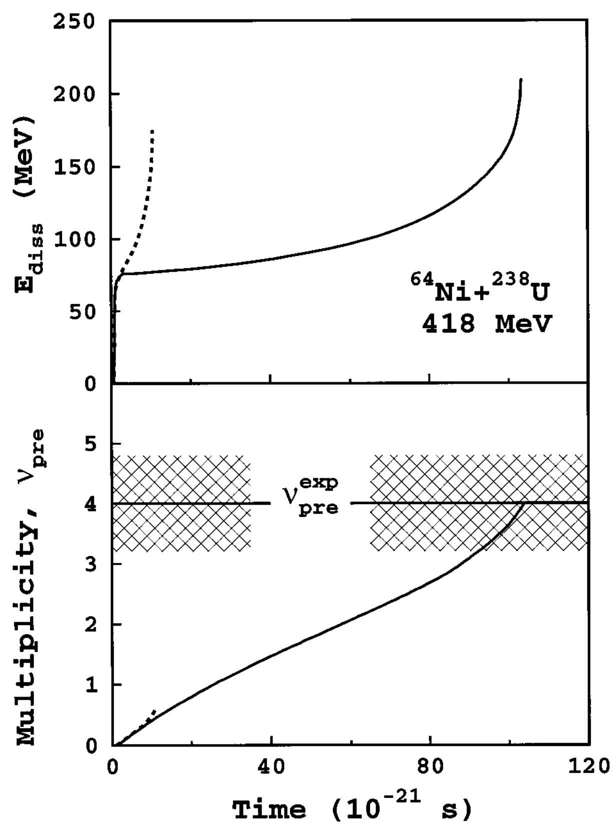


FIG. 3. Accumulated neutron multiplicity in time (bottom) calculated assuming generation of the excitation energy $E_{\mathrm{diss}}$ as predicted by the HICOL code (top) for the $^{64}$Ni+ $^{238}$U reaction ($E_{\mathrm{lab}}=418$ MeV, $\ell=0$). Predictions corresponding to the standard one-body dissipation ($k_s=1$) are shown by dashed lines. In order to reach the experimental value of the multiplicity $\nu_{\mathrm{pre}}^{\mathrm{expt}}$, the friction strength must be increased (solid lines for $k_s=10$).

''creeping'' motion towards scission becomes much slower. Since the calculated interaction time directly depends on the assumed strength of the nuclear dissipation, the measured neutron multiplicity can be used for the determination of the dissipation coefficient. In other words, the ''neutron clock'' can be used as a ''friction meter'' [16].

## IV. RESULTS OF CALCULATIONS AND DISCUSSION

In the present work we investigate what information on the strength of the friction force can be deduced from the data listed in Table I. As demonstrated in Fig. 3, the one-body dissipation mechanism assumed in Feldmeier's code HICOL is insufficient to explain the measured prescission neutron multiplicities. In the code HICOL the friction force is determined by the rate of one-body dissipation given by the ''wall-and-window'' formula [17,18,13]:

$$-\left(\frac{dE}{dt}\right)_{\text{wall}}=\rho\overline{v}\oint(\dot{n}-D)^2 d\sigma, \tag{1}$$

where $\rho$ is the nuclear mass density, $\overline{v}$ is the average speed of nucleons (equal to $\frac{3}{4}v_F$), $\dot{n}$ is the normal velocity of the surface element $d\sigma$, and $D$ is the normal component of the average drift velocity of nucleons about to impinge on the surface element $d\sigma$. For two nuclei interacting through a window of area $\Delta\sigma$, the rate of energy dissipation is given by two ''wall'' terms, Eq. (1), one for each fragment, plus a ''window'' contribution

$$-\left(\frac{dE}{dt}\right)_{\text{window}}=\frac{1}{4}\rho\overline{v}\Delta\sigma(u_t^2+2u_r^2)+\frac{16}{9}\frac{\rho\overline{v}}{\Delta\sigma}\dot{V}_1^2. \tag{2}$$

In this equation, $u_t$ and $u_r$ are the tangential and radial components of the relative velocity of the two fragments and $\dot{V}_1$ is the rate of change of the volume of one of the fragments. [The second term in Eq. (3) represents the dissipation associated with the mass asymmetry degree of freedom.]

In spite of the fact that the wall-and-window formula has no adjustable parameters, in our calculations we scaled the rate of one-body dissipation by a factor $k_s$ treated as a free parameter:

$$-\frac{dE}{dt}=k_s\times(\text{wall-and-window formula}). \tag{3}$$

Here we keep the notation used by Nix and Sierk [19] who scaled the wall formula by a factor $k_s$ in their ''surface-plus-window'' expression. On the grounds of the concept of one-body dissipation one can interpret $k_s$ as the average probability of an energy-changing (i.e., unblocked) collision between a single nucleon and the moving one-body potential. This justifies a possible reduction of the standard strength of one-body dissipation by a factor $k_s\leqslant 1$ [19]. However, in the present study we treat $k_s$ as a completely free parameter, also allowing values of $k_s>1$. Certainly, in the case of $k_s>1$ the concept of one-body dissipation is no longer applicable, and such a result should be interpreted as evidence of a strong two-body dissipation mechanism.

Returning now to Fig. 3 and the question of fitting experimental values of the prescission neutron multiplicities in the model calculations, we would like to note that a straight application of the scaling of the wall-and-window formula with the strength parameter $k_s$ leads to a certain inconsistency within the data: The very strong friction, necessary to sufficiently extend the fusion-scission time interval, prevents the colliding nuclei from penetrating deep enough in the early stage of the collision. Consequently, the mass asymmetry degree of freedom is almost completely frozen, preventing symmetric mass divisions. This contradicts the experimental observation [14] of symmetric and nearly symmetric fissionlike processes. (A range of mass numbers corresponding to the measured multiplicity for each reaction is given in Table I.)

Within the model of nucleus-nucleus dynamics used in our calculations, the only possibility to reproduce a fast-fission process with an approximately symmetric mass division is to *decrease* nuclear dissipation in the *entrance* channel at least to about half of the one-body dissipation value, $k_s\leqslant 0.5$. We recall, however, that this conclusion is based on predictions of a strictly deterministic model that excludes fluctuations. Therefore arguments relying on the difference between the observed and calculated (most probable) mass split are only indicative of the decreased friction in the entrance channel (i.e., for relatively *cold* nuclear matter). This conclusion is, however, supported by results of the analysis of isoscalar giant quadrupole and octupole widths by Nix and Sierk [19] who found that the friction strength factor for this set of low-energy data is $k_s=0.27$. Our indirect conclusion that at the ''warm-up'' stage of a collision the nuclear dissipation is weak, i.e., well below the full one-body dissipation limit, agrees also with results of the analysis of Hofman, Back, and Paul [9], suggesting that for cold compound nuclei of $T<1.2$ MeV the effect of nuclear dissipation is negligible.

Taking into account the above arguments, for all four studied reactions we assumed identical weak friction of $k_s^{\text{in}}=0.5$ throughout the entrance part of the trajectory (until reaching a compact mononucleus configuration), and for the rest of the trajectory the friction strength was allowed to rise (in one step, for simplicity) to a value $k_s^{\text{out}}$ necessary to fit the neutron multiplicity $\nu_{\text{pre}}^{\text{expt}}$. Since the entrance-channel part of the trajectory is very fast, independently of the value of $k_s^{\text{in}}$, the prescission neutrons are emitted mostly during the outgoing part of the trajectory. Therefore the determination of $k_s^{\text{out}}$ practically does not depend on the assumed entrance-channel friction.

The dependence of the calculated prescission neutron multiplicity $\nu_{\text{pre}}^{\text{expt}}$ on the assumed friction strength factor $k_s^{\text{out}}$, for all four studied reactions, is shown in Fig. 4. It is seen that in order to explain the measured prescission multiplicities, the process of descending from the mononucleus configuration to scission must be slowed down by a very strong friction, ranging from 4 to 12 times the strength of one-body dissipation. All the calculations presented in Fig. 4 correspond to central collisions characterized by the longest interaction time. Therefore the deduced values of the strength factor $k_s^{\text{out}}$ (see Table I) represent the *lower limit* of the required dissipation. Note, however, that for larger $\ell$ values the mass division becomes asymmetric and, consequently, those noncentral collisions have been effectively excluded in the experiment [14] by the applied gates on the fragment mass (see Table I).

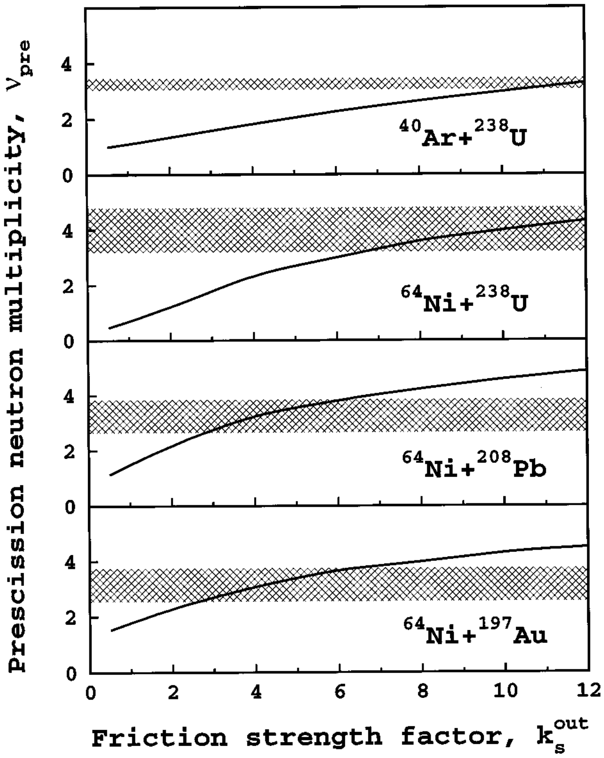


FIG. 4. Prescission neutron multiplicity as a function of an assumed value of the friction strength factor $k_s^{\rm out}$ for the four studied reactions. Experimental values $\nu_{\rm pre}^{\rm expt}$ determine the factor $k_s^{\rm out}$ for each reaction individually.

The analysis presented in Fig. 4 gives evidence of a strong nuclear dissipation in fast-fission-type reactions. We associate this result with a large value of the friction coefficient deduced by Butsch *et al.* [8] from the analysis of the GDR data in fusion-fission reactions. In order to quantitatively compare our estimates of the friction strength for hot nuclear matter with the results for the compound-nucleus fission, we have to translate the energy dissipation in the functional form of the wall-and-window formula into the form of the reduced friction coefficient $\beta$ used in the diffusion model [2–4]. Figure 5 shows the dependence of

$$\beta = \frac{1}{E_{\rm kin}} \left( \frac{dE}{dt} \right)_{\rm diss} \tag{4}$$

on the relative distance parameter $s^{\rm out}$ (on the way to scission) calculated with the code HICOL for the $^{64}$Ni+ $^{238}$U reaction, for two values of the friction strength parameter, $k_s^{\rm out}=1$ and $k_s^{\rm out}=10$. In Eq. (4), $\beta$ is expressed by the rate of the dissipated energy, $(dE/dt)_{\rm diss}$, relative to the actual value of the kinetic energy of the dinuclear system, $E_{\rm kin}$.

As shown in Fig. 5, for the standard value of one-body dissipation ($k_s^{\rm out}=1$), the friction coefficient $\beta$ takes values in the range from $5\times10^{21}$ s$^{-1}$ to $15\times10^{21}$ s$^{-1}$. A curve for $k_s^{\rm out}=10$ shows that $\beta$ scales almost linearly with the factor $k_s^{\rm out}$. It should be noted, however, that to some extent $\beta$ is trajectory dependent. The radial dependence of $\beta$ is connected with the functional form of the wall-and-window formula which, however, is not applicable in the diffusion

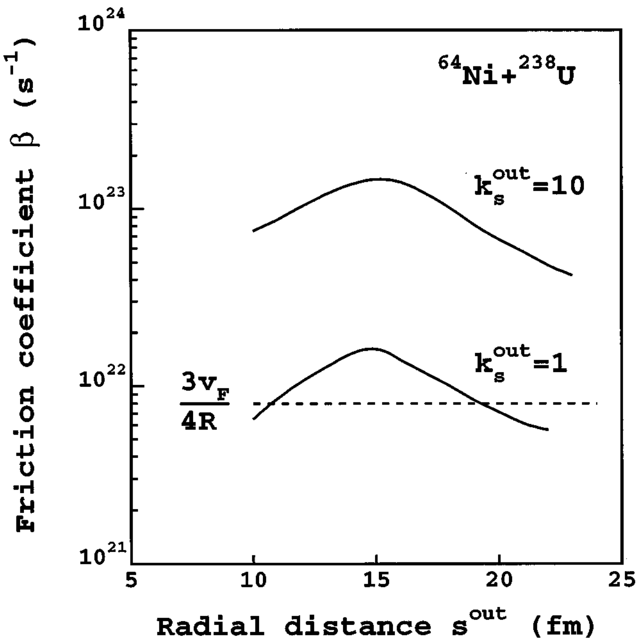


FIG. 5. Friction coefficient $\beta$ calculated with the code HICOL for the $^{64}$Ni+ $^{238}$U reaction at $E_{\rm lab}=418$ MeV as a function of the radial distance parameter $s^{\rm out}$ on the way from a mononucleus shape to scission for $k_s^{\rm out}=1$ and $k_s^{\rm out}=10$.

model based on the concept of two-body dissipation. Therefore, for comparisons with the results of Refs. [8] and [9] we use an effective value of $\beta$ averaged over the outgoing part of the trajectory, $\overline{\beta}_{\rm out}$. Using the example of the $^{64}$Ni+ $^{238}$U system, we show in Fig. 5 that a rough estimate of $\beta \approx \overline{v}/R$, based on the functional form of the wall-and-window formula [17], is a fairly accurate approximation for the average value $\overline{\beta}_{\rm out}$. (In Fig. 5 a value of $\overline{v}/R=8\times10^{21}$ s$^{-1}$, calculated for the $^{64}$Ni+ $^{238}$U composite system, is indicated by a dashed horizontal line. We recall here that $\overline{v}$ is the internal average speed of nucleons, and $R$ is the radius of the combined system.) In Table I we list the estimated values of the reduced friction coefficient

$$\overline{\beta}_{\rm out} \approx k_s^{\rm out} \frac{\overline{v}}{R} = k_s^{\rm out} \frac{54\times10^{21}}{A^{1/3}} \ {\rm s}^{-1}, \tag{5}$$

which is evaluated for the Fermi momentum $p_F=1.36$ $\hbar$/fm and $R=1.15A^{1/3}$ fm. The reduced friction coefficient $\beta$ is directly related to the dimensionless friction coefficient $\gamma$ used in Refs. [8] and [9] in the analysis of the compound-nucleus fission data:

$$\gamma = \frac{\beta}{2\omega} \approx \frac{k_s^{\rm out}\overline{v}}{2\omega R}, \tag{6}$$

where $\omega$ is the frequency parameter determined by the curvature of the potential energy surface at the saddle point. In Refs. [8] and [9] the frequency $\gamma$ was assumed to be $\omega = 10^{21}$ s$^{-1}$.

As is seen from Table I, the dimensionless friction coefficient $\gamma$, deduced in our analysis, takes strikingly large values in the range from $\gamma=17$ to $\gamma=50$. These values consid-

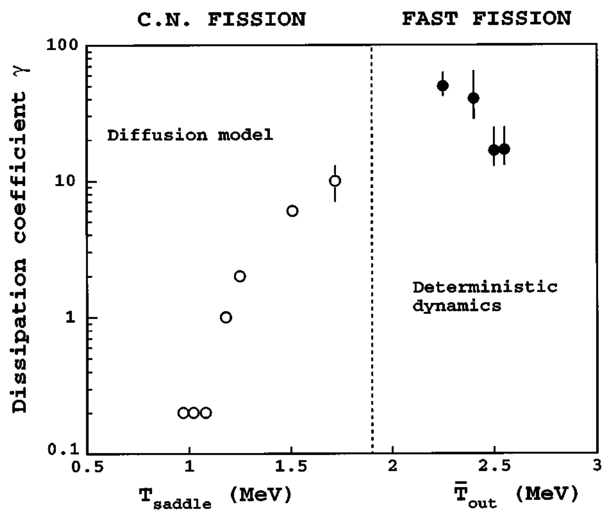


FIG. 6. Dimensionless dissipation coefficient $\gamma$ derived in Ref. [9] from the prescission $\gamma$-ray multiplicities plotted as a function of the temperature at the saddle point (left), and the same quantity $\gamma$ deduced in the present analysis of the prescission neutron multiplicities in nonfusion reactions, plotted as a function of the mean temperature $\overline{T}_{out}$ during the descent from a mononucleus shape to scission (right).

erably exceed even the well-known result of Butsch *et al.* [8] ($\gamma = 10 \pm 3$) obtained in an analysis of GDR data. In spite of a conceptual difference between our analysis of the nonfusion reactions (in terms of a deterministic model) and the study of the fusion-fission reactions of Refs. [8,9] (in terms of the diffusion model), it seems that both analyses consistently lead to the same conclusion, that a very strong nuclear dissipation sets in when a composite system is sufficiently hot. In a recent paper, Hofman, Back, and Paul [9] presented the temperature dependence of the friction coefficient $\gamma$ deduced from reanalyzed GDR data. (The data have been analyzed with the Stony Brook modification of the CASCADE code which according to van 't Hof [20] may overestimate the friction coefficient.) In Fig. 6 we show a plot combining our results with those of Ref. [9], both as a function of the temperature.

In the analysis of the fusion-fission data, Hofman *et al.* [9] examined the dependence of the deduced friction coefficient on the temperature of the compound nucleus, corresponding to the excitation energy at the saddle point, $T_{saddle}$. In the case of *nonfusion* reactions, the excitation energy of the composite system is gradually generated throughout the entire trajectory (see Fig. 2). Therefore, in order to compare our results with the fusion-fission data we need to define an effective temperature characterizing the composite system on its way to scission, which would be equivalent to the temperature of the compound nucleus in the case of a fusion-fission reaction. For simplicity, as an equivalent of $T_{saddle}$ we took the mean value of the temperature in the outgoing part of the trajectory, $\overline{T}_{out}$, calculated with the code HICOL. The values of $\overline{T}_{out}$ for all four studied reactions are included in Table I. In Fig. 6 we have included the results of Hofman *et al.* [9] (open circles) together with the $\gamma$ values deduced in our analysis, jointly plotted as a function of $T_{saddle}$ and $\overline{T}_{out}$, respectively. It is seen that the effective temperatures $\overline{T}_{out}$ in the studied nonfusion reactions considerably exceed the compound-nucleus temperatures in reactions reported in Ref. [9]. Both parts of Fig. 6 seem to complement each other.

The combined data shown in Fig. 6 represent a consistent trend of a steep rise of the dissipation coefficient at nuclear temperatures in the range from 1 to 2 MeV, followed apparently by a maximum value ($\gamma \approx 50$) at a temperature between 2 and 2.5 MeV, and subsequent fall at higher temperatures. Our estimates of the upper limit of the friction coefficient in the first stage of the reaction ($k_s^{in} \leqslant 0.5$ for $T_{in} < 1.7$ MeV) are not shown in Fig. 6, but they also qualitatively agree with this dependence. We recall here that a value of $\gamma$ corresponding to full one-body dissipation is about $\gamma = 4$ (for $\omega = 10^{21}$ $s^{-1}$). From Fig. 6 it is seen that this value is reached at a temperature of about 1.5 MeV. Therefore the further rise of the friction coefficient with temperature has to be related to the onset of two-body dissipation. A strong two-body dissipation has been predicted in a series of theoretical studies [21–23]. As a rule, a decreasing dependence of the friction coefficient on the temperature, $\beta \propto 1/T^2$, is expected in these models. Our results do allow for such a dependence. However, an open question is at what temperature is the onset of the two-body dissipation and the turnover from the increasing to the decreasing dependence of $\gamma$ on $T$ expected theoretically. As is seen from Fig. 6, the evidence of the turnover of the $\gamma$ vs temperature dependence is mostly based on the result for the $^{40}Ar + ^{238}U$ reaction. However, it cannot be excluded that the friction coefficient for this reaction is overestimated to some extent because the potential-energy surface for this system has a distinct compound-nucleus minimum (contrary to the other three systems), and thus fusion, although not allowed in the deterministic calculation, may occur with a small probability due to fluctuations. Without the data point for the $^{40}Ar + ^{238}U$ reaction, Fig. 6 would suggest a rather monotonically increasing friction throughout the whole studied range of temperatures. The theoretically expected decline of the friction coefficient would then have to begin at still higher temperatures, i.e., above 2.5 MeV. Therefore additional studies that could verify the temperature dependence of the friction coefficient would be of great interest. If the results presented in Fig. 6 indeed represent the effect of a strong two-body dissipation, they could be used for empirical determination of the temperature dependence of the mean free path of nucleons in nuclear matter and thus for establishing some solid grounds for dynamical models of hot nuclear matter.

## V. CONCLUSIONS

Summarizing, we have analyzed a set of four *nonfusion* reactions of known prescission neutron multiplicities (measured by Hinde and co-workers [14]) in terms of the deterministic dynamic model of Feldmeier coupled to a time-dependent statistical cascade calculation. Since the studied composite systems cannot fuse at all, the measured prescission neutron multiplicities must be accumulated during the *fast-fission* process that can be described throughout with a deterministic model based on the Lagrange-Rayleigh equations of motion. By using Feldmeier's model, we demonstrated that in order to reproduce the measured prescission multiplicities and the observed (nearly symmetric) mass divisions, the energy dissipation must be dramatically changed with regard to standard one-body dissipation: In the entrance channel, on the way to form a composite system, the energy dissipation has to be reduced to at least half of the one-body dissipation strength ($k_s^{\rm in} \leqslant 0.5$), and in the exit channel (from a mononucleus shape to scission) it must be increased by a factor ranging for the studied reactions from $k_s^{\rm out} = 4$ to $k_s^{\rm out} = 12$. Since the excitation energy of the colliding system gradually increases along the trajectory, our result indicates that nuclear friction is relatively weak at low excitation energies and becomes very strong when the composite system gets hot. This conclusion is consistent with earlier results of Butsch *et al.* [8] and the reanalysis of GDR data by Hofman, Back, and Paul [9], demonstrating a fast rise of the friction coefficient in compound nuclei at temperatures in the range 1.2–1.7 MeV. It should be emphasized that consistent results have been obtained for completely different types of nuclear processes interpreted with different theoretical tools: for compound-nucleus fission interpreted in terms of a stochastic model and (in the present work) for nonfusion reactions analyzed in terms of the deterministic model of nucleus-nucleus dynamics.

The results of our analysis give information on the magnitude of the friction coefficient at higher temperatures than those accessible in Ref. [9]. They are consistent with a decreasing dependence of the friction coefficient with temperature (for $T > 2.2$ MeV) that can be associated with the $1/T^2$ dependence expected for two-body dissipation. Therefore, the temperature dependence of the friction coefficient that emerges from the combined results of Ref. [9] and the present work can be interpreted as evidence of the onset of a strong two-body dissipation at rather unexpectedly low temperatures, already below $T = 2$ MeV.

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[1] H.A. Kramers, Physica (Utrecht) **7**, 284 (1940).
[2] P. Grangé, H.C. Pauli, and H.A. Weidenmüller, Phys. Lett. **88B**, 9 (1979).
[3] P. Grangé and H.A. Weidenmüller, Phys. Lett. **96B**, 26 (1980).
[4] P. Grangé, Li Jun-Quing, and H.A. Weidenmüller, Phys. Rev. C **27**, 2063 (1983).
[5] Wu Xi-Zhen and Zhuo Yi-Zhong, Chin. Phys. **1**, 671 (1981); **1**, 693 (1981).
[6] P. Grangé, S. Hassani, H.A. Weidenmüller, A. Gavron, J.R. Nix, and A.J. Sierk, Phys. Rev. C **34**, 209 (1986).
[7] P. Paul and M. Thoennessen, Annu. Rev. Nucl. Part. Sci. **44**, 65 (1994).
[8] R. Butsch, D.J. Hofman, C.P. Montoya, P. Paul, and M. Thoennessen, Phys. Rev. C **44**, 1515 (1991).
[9] D.J. Hofman, B.B. Back, and P. Paul, Phys. Rev. C **51**, 2597 (1995).
[10] M. Thoennessen and G.F. Bertsch, Phys. Rev. Lett. **71**, 4303 (1993).
[11] K. Siwek-Wilczyńska, J. Wilczyński, R.H. Siemssen, and H.W. Wilschut, in Proceedings of the Fifth International Conference on Nucleus-Nucleus Collisions, Taormina, Italy, 1994, edited by M. Di Toro, E. Mignelo, and P. Piattelli [Nucl. Phys. **A583**, 141c (1995)].
[12] K. Siwek-Wilczyńska, J. Wilczyński, R.H. Siemssen, and H.W. Wilschut, Phys. Rev. C **51**, 2054 (1995).
[13] H. Feldmeier, Rep. Prog. Phys. **50**, 915 (1987).
[14] D.J. Hinde, D. Hilscher, H. Rosner, B. Gebauer, M. Lehmann, and M. Wilpert, Phys. Rev. C **45**, 1229 (1992).
[15] W.J. Swiatecki, Nucl. Phys. **A376**, 275 (1982).
[16] J. Wilczyński, K. Siwek-Wilczyńska, R.H. Siemssen, and H.W. Wilschut, in Proceedings of XXIV Mazurian Lakes School of Physics, Piaski, 1995, Acta Phys. Pol. **27**, 517 (1996).
[17] J. Blocki, Y. Boneh, J.R. Nix, J. Randrup, M. Robel, A.J. Sierk, and W.J. Swiatecki, Ann. Phys. (N.Y.) **113**, 330 (1978).
[18] J. Randrup and W.J. Swiatecki, Nucl. Phys. **A429**, 105 (1984).
[19] R.J. Nix and A.J. Sierk, in Proceedings of the International School-Seminar on Heavy-Ion Physics, Dubna, 1986, Report No. JINR-D7-87-68, 1987, p. 453.
[20] G. van 't Hof, Ph.D. thesis, Vrije Universiteit, Amsterdam, The Netherlands, 1995.
[21] P. Danielewicz, Phys. Lett. **146B**, 168 (1984).
[22] B.W. Bush, G.F. Bertsch, and B.A. Brown, Phys. Rev. C **45**, 1709 (1992).
[23] D. Boilley, E. Suraud, Y. Abe, and S. Ayik, Nucl. Phys. **A556**, 67 (1993).