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Wilczynski, J; SiwekWilczynska, K; Siemssen, RH; Wilschut, H. W.

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NEUTRON CLOCK AS A FRICTION-METER*

J. Wilczyński[a], K. Siwek-Wilczyńska[b], R.H. Siemssen[c]

AND

H.W. Wilschut[c]

[a]Soltan Institute for Nuclear Studies, 05-400 Świerk-Otwock, Poland
[b]Institute of Experimental Physics, Warsaw University
00-681 Warsaw, Poland
[c]Kernfysisch Versneller Instituut, 9747 AA Groningen, The Netherlands

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Fast-fission reactions in collisions of four heavy systems (well below the fusion extra-push energy threshold), for which Hinde and coworkers had measured the prescission neutron multiplicities, have been analysed 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 must be reduced to at least half of the one-body dissipation strength ($k_s^{\rm in} \leq 0.5$), and in the exit channel (from a mononucleus shape to scission) it must be increased to about 10 times that value ($k_s^{\rm out} \approx 10$).

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1. Introduction

Recent experiments on the prescission γ-rays from giant dipole resonances (see *e.g.*, Refs [1–3] and references therein) have been interpreted in terms of the diffusion model [4–6], based on the Fokker-Planck equation. Results of such an analysis of the GDR data led to a surprisingly large value of the nuclear friction coefficient for fissioning nuclei excited to several tens of

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MeV. The deduced value of the dimensionless friction coefficient $\gamma = 10 \pm 3$ [1] implies unexpectedly 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 $\gamma = 10$ greatly exceeds the strength of one-body dissipation — commonly viewed as the most effective dissipation mechanism at low excitation energies.

Since information on the very large value of the friction coefficient for hot nuclear matter is based entirely on the compound-nucleus fission data analyzed in terms of the diffusion model [4–6], in the present work we attempted to estimate the value of the friction coefficient in *non-fusion* reactions which 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 leads to quite similar results, indicating an onset of very strong nuclear friction in hot composite systems.

2. "Neutron clock" in classical trajectory calculations

In Refs [7, 8] we proposed a new dynamical method of calculating the fusion-fission time scales from measured prescission neutron multiplicities [9]. In this method we combine a simple version of the time-dependent statistical model with Feldmeier's dynamical code HICOL, based on the one-body dissipation model [10]. Our statistical-model 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 can modify 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.

We use a simple Monte Carlo code for calculating the statistical-decay cascade (for details see Ref. [8]). The event-averaged results are used for determination of the time dependence of the multiplicity of neutrons, protons and all other light particles included in the evaporation code. The moment in time when the calculated neutron multiplicity reaches the measured value of the prescission neutron multiplicity $\nu_{\rm pre}^{\rm exp}$, determines the fusion-fission time scale τ_f.

3. Non-fusion reactions

The likelihood of the surprisingly strong nuclear dissipation, suggested [1–3] on the grounds of analysis of the compound-nucleus fission, can be verified independently on a completely different way by determination of nuclear friction in *non-fusion* reactions governed by the deterministic dynamics of nucleus-nucleus collisions (contrary to the stochastic approach in the case of fusion-fission reactions). For this purpose, however, prescission neutron multiplicities have to be measured for colliding systems which *cannot* fuse at all.

Analyzing existing data on prescission multiplicities, we found four reactions studied by Hinde *et al.* [9] and listed in Table I which, most probably, do not undergo fusion even in central collisions. Classical trajectory calculations with the HICOL code lead to reseparation of all four systems, for all partial waves. (For these very heavy systems the saddle configuration cannot be overpassed at these relatively low bombarding energies. A considerable "extra push" energy is needed for fusion.) Consequently, if the nuclear dynamics are correctly described by the one-body dissipation model [10], the neutron multiplicity calculated with our code DYNSEQ [8] and accumulated along the whole trajectory (until scission) should reproduce approximately the experimental value. Fig. 1 shows that this is not the case. With the standard HICOL predictions, the longest interaction time corresponding to the central collision in the ^{64}Ni + ^{238}U reaction (taken as an example) lasts only about 1.1×10^{-20} s and within that time only about 0.5 neutrons can be emitted. In order to reach the measured value of the prescission multiplicity ($\nu_{\rm pre}^{\rm exp} = 4.0 \pm 0.8$) the interaction time has to be much longer than predicted by the one-body dissipation model. Since the calculated interaction time directly depends on the assumed strength of nuclear dissipation, the measured neutron multiplicity can be used for determination of the dissipation coefficient. In other words, the "neutron clock" can be used as a "friction-meter".

In the present work we investigated what information on the strength of nuclear dissipation results from the data listed in Table I. On the grounds of the one-body dissipation mechanism, the friction force is given by the "wall-and-window" formula [11] that has no free parameters. However in our calculations, using the code HICOL, we made it possible to scale the strength of nuclear dissipation by a factor k_s treated as a free parameter: $-dE/dt = k_s \times$(one-body dissipation). Here we keep the notation used by Nix and Sierk [12] who scaled the wall formula by a factor k_s in their "surface-plus-window" expression.

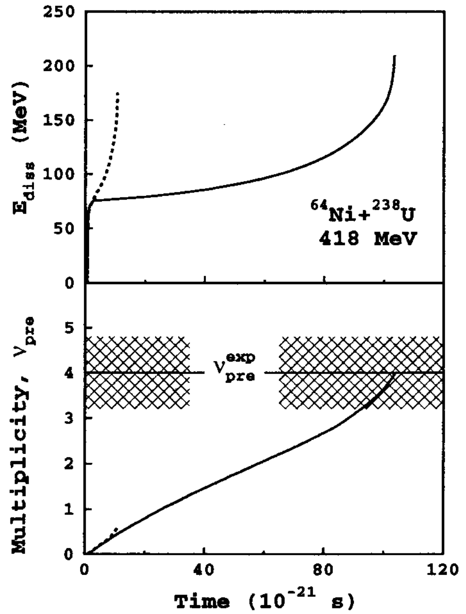

Fig. 1. Dissipation of energy (top) and neutron multiplicity (bottom) as a function of time, calculated for the ^{64}Ni + ^{238}U reaction for standard one-body dissipation, $k_s^{\rm out} = 1$ (dashed lines) and the increased friction factor, $k_s^{\rm out} = 10$ that fits the measured value of the multiplicity, $\nu_{\rm pre}^{\rm exp}$ (solid lines).

TABLE I

Prescission neutron multiplicities [9] and deduced friction coefficients for selected (presumably) non-fusion reactions.

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

Our first-guess attempt to fit the experimental values $\nu_{\rm pre}^{\rm exp}$ by increasing the friction strength factor k_s did not work. It turned out that the very strong friction, necessary to sufficiently extend the interaction time, prevents the colliding nuclei from penetrating deep enough in the early stage of the collision. Consequently, the mass asymmetry degree of freedom would be almost completely frozen preventing symmetric mass divisions. This would contradict the experimental observation of symmetric and nearly symmetric fission-like processes, which were selected in the experiment to gate the measured neutron multiplicities [9].

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, $k_s \leq 0.5$. Such weak friction in the early stage of the reaction (*i.e.*, for relatively *cold* nuclear matter) is consistent with results of the analysis of isoscalar giant quadupole and octupole widths by Nix and Sierk [12] who found that the friction strength factor that fits this set of low-energy data is $k_s = 0.27$. For other experimental results and theoretical arguments supporting the supposition of weak friction at low temperatures see recent paper by Hoffman *et al.* [3] and references therein.

For all four studied reactions we assumed identical weak friction of $k_s^{\mathrm{in}} = 0.5$ 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^{out} necessary to fit the neutron multiplicity $\nu_{\mathrm{pre}}^{\mathrm{exp}}$. Since the entrance-channel part of the trajectory is very fast, independently of the value of k_s^{in}, the prescission neutrons are emitted mostly during the outgoing part of the trajectory. Therefore the determination of k_s^{out} practically does not depend on the assumed entrance-channel friction.

Values of k_s^{out} that fit the measured prescission neutron multiplicities are given in Table I. To explain the measured multiplicities it is necessary to slow down the process of descending from the mononucleus configuration to scission by very strong friction, ranging from 5 to 12 times the strength of one-body dissipation. It appears that the result obtained for the ^{64}Ni + ^{238}U reaction ($k_s \approx 10$) is most reliable because due to the highest extra-push energy a contribution of the complete fusion processes in this reaction is most likely negligible. On the other hand, a relatively narrow mass range around symmetric mass division in the measurement of the neutron multiplicity for this reaction eliminates shorter interaction times expected for non-central collisions.

4. Conclusions

In summary, the analysis of neutron multiplicities for the studied non-fusion reactions indicate that at the early stage of a nucleus-nucleus collision the nuclear friction is rather weak ($k_s^{\mathrm{in}} \leq 0.5$), but in the later stage, on the way from the mononucleus configuration to scission, it becomes much stronger ($k_s^{\mathrm{out}} \approx 10$). Consequently, a quite sudden rise of the friction strength (by a factor of at least 20) must occur at about the time when a compact-shape mononucleus is formed. It is natural to relate this rise of friction to the rapid heating up of the composite system during its formation at the early stage of the collision (up to the temperature of about 1.7-2.0 MeV in the studied reactions).

In the last column of Table I we give the values of the reduced friction coefficient β, averaged over the outgoing part of the trajectory. The β values can be directly compared with other experimental results and theoretical estimates. (In Table I the approximate values, $\langle\beta\rangle_{\mathrm{out}} \approx k_s^{\mathrm{out}} \times \bar{v}/R$ are given. Here $\bar{v}$ is the average speed of nucleons equal to 3/4 of the Fermi velocity and R is the radius od the composite system.) Clearly, the deduced friction (for the heated up nuclear matter) is unexpectedly strong. It even considerably exceeds the value deduced by Butsch *et al.* [1]. ($\gamma = 10$ corresponds to $\beta \approx 20 \times 10^{21}$ s^{-1}.) However, this result seems to be consistent with a recent analysis of the temperature dependence of the prescission γ-ray emission reported in Ref [3]. Hofman and coworkers demonstrated that in compound-nucleus fission reactions the deduced value of the friction coefficient steeply increases with the temperature of the compound nucleus. Since nuclear temperatures achieved in the studied non-fusion reactions are still higher than in case of the hottest compound system considered in Ref. [3] ($T_{\mathrm{saddle}} = 1.7$ MeV for which $\gamma = 10$), the larger value of the friction coefficient deduced in the present study essentially agrees with conclusions of Hofman *et al.* [3].

Obviously, the energy dissipation larger than that corresponding to $k_s = 1$ cannot originate from the one-body-dissipation mechanism. Therefore the results of the analysis of the compound-nucleus fission reported in Ref. [3], as well as our analysis of non-fusion reactions, consistently indicate that a very strong *two-body*-dissipation mechanism sets in when nuclear matter is heated up above $T = 1.5 - 2.0$ MeV. It is interesting to note that this conclusion generally coincides with the idea of the "threshold for dissipative fission" suggested by Thoennessen and Bertsch [13], who examined the validity of the Bohr–Wheeler theory of nuclear fission and observed the onset of significant deviations from predictions of this theory at threshold temperatures of about 1.5 MeV.

It is an open question to what extent the deduced magnitude of the strong friction (β in the range from 30 to 100×10^{21} s^{-1}) can be justified theoretically. If the fast rise of β with temperature is indeed due to the onset of two-body friction then at still higher temperatures one should expect the reversed trend — the decreasing friction coefficient with increasing temperature, $\beta \propto 1/T^2$, as predicted *e.g.*, by Danielewicz [14]. Therefore experimental studies at higher excitation energies could clarify this intriguing problem of the nature of nuclear dissipation.

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