TESTS OF NUCLEAR FRICTION IN SADDLE-TO-SCISSION MOTION OF FISSIONING NUCLEI* **

J. BŁOCKI AND J. WILCZYŃSKI

Institute for Nuclear Studies
05-400 Świerk-Otwock, Poland

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A selected set of precise measurements of the mean kinetic energy of fission fragments has been used for testing nuclear dissipation. Calculations of the kinetic energy release on the descent from saddle to scission have been done with a dynamical model based on the classical Rayleigh–Lagrange equations of motion. Both alternative dissipation mechanisms, one-body dissipation and two-body viscosity have been tested. An increasing strength of the dissipation with increasing mass of a composite system has been observed. However this effect may partly result from a specific shape parametrization used in the dynamical model.

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1. Introduction

The one-body dissipation [1] is generally assumed to be the main mechanism responsible for the damping of kinetic energy in deep-inelastic reactions and nuclear fission at relatively low excitation energies at which the nucleon mean free path is still large as compared with dimensions of the composite system. The rate of energy damping via the one-body dissipation mechanism is given by the wall-and-window formula that practically has no free parameters and to the first order is temperature independent.

Systematic experimental tests of the theoretical predictions of nuclear dissipation have not been carried out so far, mostly because of the insufficient precision of the measurements and the dependence of the results of

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such tests on particular assumptions in the underlying theoretical models. Results of the early measurements of the mean total kinetic energy $\langle E_k \rangle$ of fission fragments were analysed in Ref. [1] and seemed to prove the validity of the wall-and-window formula. Nix and Sierk, on the other hand, suggested in their analysis [2] of the $\langle E_k \rangle$ data that the effective nuclear dissipation is from two to five times weaker than predicted by the one-body dissipation model. In turn, recent measurements of the prescission neutron multiplicities, analysed in terms of a model based on the Fokker–Planck equation, seem to indicate that already at nuclear temperatures of about 2 MeV the effective friction required to explain the measured multiplicities has to be several times stronger than the one-body dissipation limit [3, 4].

2. Calculations of the total kinetic-energy release in fission

In the present paper we report on our attempt to deduce information on the friction coefficient from calculations of the fission fragment kinetic energies assuming both the one-body- and/or two-body dissipation and comparing the results of the calculations with the most recent collection of systematic measurements of the mean $\langle E_k \rangle$ values reported in Refs. [5, 6]. As it will be shown below, in a realistic overdamped-motion regime, differences in the calculated $\langle E_k \rangle$ values are not large, even for quite different values of the friction coefficient. Therefore it is essential for a reliable determination of the friction coefficient to use the most precise $\langle E_k \rangle$ data. The data selected for our analysis have been taken in one series of experiments, with the same experimental method, common calibration procedures *etc.* The measurements [5,6] involved composite systems of excitation energies above 50 MeV, produced in reactions with rather light ions (from ^{3}He to ^{16}O). Consequently, symmetric mass distributions have been observed for all studied systems, while expected magnitudes of the rotational energy were low and thus easy to account for.

The idea behind the calculations is the following: We solve the classical Rayleigh–Lagrange equations of motion starting from the saddle point till the moment when the two fragments scission. For the shape parametrization we have assumed axially symmetric surfaces consisting of two spheres connected smoothly by a second degree polynomial [7]. Out of the three degrees of freedom (ρ, λ, Δ) fully describing the shape we have chosen the motion in two degrees (ρ, λ), maintaining the asymmetry parameter $\Delta = 0$, which corresponds to symmetric fission. For the potential energy we have taken the sum of the Coulomb interaction energy and the "Yukawa-plus-exponential" potential of Ref. [8]. For the kinetic energy the quadratic form in the velocities was taken with an inertia tensor estimated with the Werner–Wheeler method [9]. The dissipative part of the energy was adopted either according to the one-body dissipation model [1] or as a two-body viscosity [10].

An important question in the calculations of one-body dissipation is how to pass from the mononuclear to dinuclear regime, or in other words, at what point of a trajectory should we replace the one-center wall expression by that corresponding to the window plus two-center wall dissipation. We have decided to set the border line at shapes characterized by the window opening parameter [7] $\alpha = 1$. (This corresponds to a configuration of two spheres connected by the frustum of a cone.) In order to make a smooth transition between these two regimes we have decided to use the following formula for the rate of the dissipation in actual calculations:

$$\frac{dE}{dt} = c\left(\frac{dE}{dt}\right)_{\text{mono}} + (1-c)\left(\frac{dE}{dt}\right)_{\text{dinuclear}} \tag{1}$$

with $c = \sin^2(\frac{\pi\alpha}{2})$. Above the $\alpha = 1$ border line in the (λ, ρ) space we take c=1 that corresponds to the pure mononuclear regime. Between the $\alpha = 1$ line and the scission line ($\alpha = 0$) we have a mixture of mono- and dinuclear regimes.

A limited set of the mean values of the fission fragments' kinetic energy, $\langle E_k \rangle$, selected from Refs. [5,6] and used for our tests, is shown in Fig. 1. The measured $\langle E_k \rangle$ values are denoted by open squares (for composite systems produced in reactions with light ions ^{3}He or ^{4}He) and full circles (for systems produced with ^{16}O ions). The kinetic energies are plotted as a function of $Z^2/A^{\frac{1}{3}}$. Experimental errors for the selected data points are in the range of 1–2 MeV, practically within the size of the symbols used in Fig. 1 to depict the data. The experimental values of the mean kinetic energy are compared with results of our numerical calculations in two opposite extremes, one-body dissipation (solid line) and two-body viscosity (dashed line). As mentioned above, the one-body dissipation model has no adjustable parameters. The two-body dissipation mechanism requires the specification of a value of nuclear viscosity μ. For the calculations presented in Fig. 1 we have taken $\mu = 0.03$ TP. It can be seen that for this value of the viscosity coefficient predictions of the two-body dissipation model are very similar to those of the one-body dissipation.

Fig. 1 shows that the predictions for both dissipation mechanisms have the same systematic tendency of slightly underestimating the kinetic energies for small values of the $Z^2/A^{\frac{1}{3}}$ parameter and overestimating them for heavy composite systems. Taking advantage of the high precision of the experimental $\langle E_k \rangle$ values, in the case of the two-body dissipation model, we have determined the viscosity coefficient μ for each individual value of $\langle E_k \rangle$ (see Fig. 2b). Similarly, in the case of one-body dissipation we have determined a value of the multiplication factor by which one should multiply

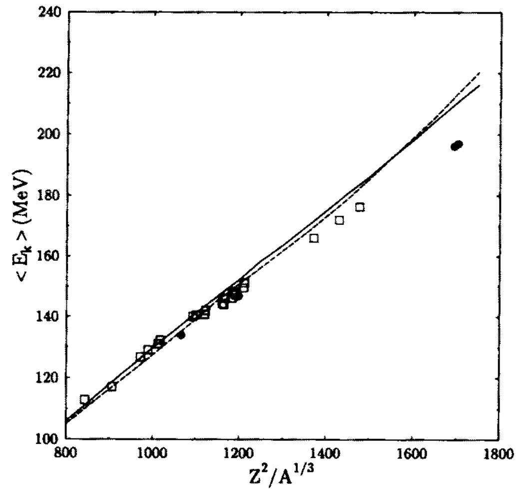

Fig. 1. Mean kinetic energies of fission fragments, $\langle E_k \rangle$, for selected reactions [5,6], plotted as a function of $Z^2/A^{\frac{1}{3}}$ of a composite system. The measured values are compared with theoretical predictions for one-body dissipation (solid line), and two-body dissipation for $\mu = 0.03$ TP (dashed line).

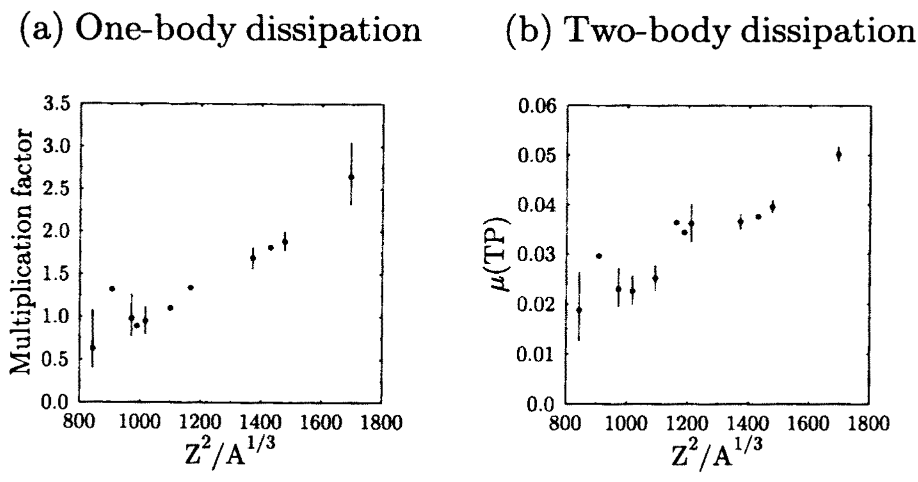

Fig. 2. Deduced strength of the one-body dissipation relative to predictions of the wall-plus-window formula (a), and the viscosity coefficient μ deduced from calculations with the two-body dissipation (b), plotted as a function of $Z^2/A^{\frac{1}{3}}$ of the composite system.

the rate of the energy dissipation given by the wall-plus-window formula in order to fit each energy $\langle E_k \rangle$ individually (see Fig. 2a). The error bars shown in Figs. 2a and 2b correspond to experimental uncertainties of the $\langle E_k \rangle$ values quoted in Refs. [5,6].

It is too early to draw firm conclusions concerning the strength and mechanism of nuclear dissipation on the basis of the results presented in Figs. 2a and 2b. Our reservations are connected with a possibility that, to a large extent, the effect of the very strong friction necessary to explain the $\langle E_k \rangle$ values for heavy composite systems may be a consequence of a limited freedom of the system caused by the shape parametrization used in our calculations. It should be noted that Sierk and Nix [10] in their calculations used a different shape parametrization in which apart from the neck degree of freedom, the fragments were allowed to evolve into elongated spheroids. In their calculations with the two-body dissipation the kinetic energies of the fision fragments have been reasonably reproduced with a value of the viscosity coefficient $\mu = 0.02$ TP in a wide range of the $Z^2/A^{\frac{1}{3}}$ parameter, including the heaviest systems. Therefore further tests of nuclear viscosity based on the kinetic energy release in fission would require a careful investigation of the role of particular shape parametrizations underlying the dynamical models.

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