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MASS DRIFT IN STRONGLY DAMPED REACTIONS AS A TOOL FOR STUDYING NUCLEAR DISSIPATION* **

J. Błocki and J. Wilczyński

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

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Experimental results on correlation between the mean normalized mass drift towards symmetry and the reaction time in strongly damped collisions induced by ^{238}U nuclei, measured by Shen *et al.* at GSI Darmstadt, have been analysed in terms of a dynamical model based on classical Rayleigh–Lagrange equations of motion assuming alternatively either one-body or two-body dissipation.

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1. Introduction

We continue our program of testing nuclear friction by comparing a variety of experimental data on fusion–fission and strongly damped reactions with predictions of a dynamical model based on classical Rayleigh–Lagrange equations of motion.

In a recent study [1] we analysed the mean kinetic energies of fission fragments assuming both alternative dissipation mechanisms, one-body dissipation and two-body dissipation (viscosity). It was found that a collection of data embodied by the Viola systematics [2] is well reproduced by the "wall-and-window" formula representing the one-body dissipation mechanism. Alternatively, the same set of data can be reproduced with two-body dissipation assuming a value of the viscosity coefficient $\mu = 0.03$ TP. A more recent set of data reported by Itkis *et al.* [3] represents systematically lower mean kinetic energies of fission fragments than predicted by the Viola systematics, especially for heavy composite systems. Consequently, the

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dissipation constants deduced from our analysis of the data of Itkis *et al.* [3] turned out to be larger: up to two times the standard strength of one-body dissipation or, alternatively for two-body dissipation, $\mu = 0.2 - 0.5$ TP.

In the present study, we have analysed existing data on the equilibration of the mass asymmetry degree of freedom in strongly damped reactions studied at GSI Darmstadt by Shen *et al.* [4]. The mass drift in strongly damped reactions is one of the important observables which can be calculated in a dynamical model and compared with experimental observations. Independent information on nuclear dissipation can be obtained in such a way.

2. Calculations of the mass drift with a classical dynamical model

We have analysed experimental data on mass drift in strongly damped reactions in terms of a dynamical model based on the classical Rayleigh–Lagrange equations of motion. For this purpose we have modified the program FOTE [5]. Classical trajectories of nucleus–nucleus collisions are calculated in this program by solving the equations of motion for an axially symmetric system in a form of two spheres connected smoothly by a quadratic surface of revolution. The shape degrees of freedom, *i.e.* the separation or elongation variable ρ, the neck or fragment deformation variable λ, and the assymmetry variable Δ were chosen as proposed in Ref. [6]. For the potential energy we have taken the sum of the Coulomb interaction energy and the "Yukawa-plus-exponential" potential of Ref. [7]. For the kinetic energy the quadratic form in the velocities was taken with an inertia tensor estimated with the Werner-Wheeler method. The dissipative term in the Rayleigh–Lagrange equations of motion was taken either as one-body dissipation (in form of the "wall-and-window" formula [8,9]) or, alternatively, as two-body viscosity [10].

In a series of experiments carried out at GSI Darmstadt, Shen *et al.* [4] measured correlations between the mass division of a composite system, the loss of kinetic energy, and the emission angle of reaction products. The correlations were studied in reactions of a ^{238}U beam with different target nuclei. From the measured angles of rotation of the di-nuclear complex, Shen *et al.* could deduce the reaction time t, during which the di-nuclear complex remains in contact. It was found in Ref. [4] that there is almost a universal correlation between the mean normalized mass drift towards symmetry, $\Delta A/\Delta A_{\max}$ and the reaction time t. (Here, ΔA is the observed drift of mass, and $\Delta A_{\max}$ is the maximum possible drift corresponding to symmetric split.) The dependence of $\Delta A/\Delta A_{\max}$ on t can be directly calculated with our dynamical model and thus compared with experimental results.

From the data compiled in Ref. [4] we selected results for the most extensively studied system, ^{48}Ca + ^{238}U, and performed calculations of the mass drift in this reaction as a function of the angular momentum, at two bombarding energies, 5.4 and 7.5 MeV/nucleon. The calculations have been made assuming alternatively one-body and two-body dissipation.

Results of the calculations in the case of one-body dissipation are shown in Fig. 1. The "wall-and-window" formula which describes the rate of one-body dissipation does not contain free parameters. However for quantitative estimates we use a multiplication factor k_s that scales the rate of energy dissipation: $-dE/dt = k_s \times$(wall-and-window-formula). It is seen that for both energies the standard calculation ($k_s = 1$) gives too long time scales, especially for peripheral collisions corresponding to a smaller mass transfer ΔA. For an energy of 7.5 MeV/nucleon (full data points) the best overall fit corresponds to the standard one-body dissipation reduced by a factor $k_s = 0.6$. Comparison of the curves for 5.4 and 7.5 MeV/nucleon shows that the predicted dependence on energy is significant while the experimental results seem to be almost independent of the collision energy.

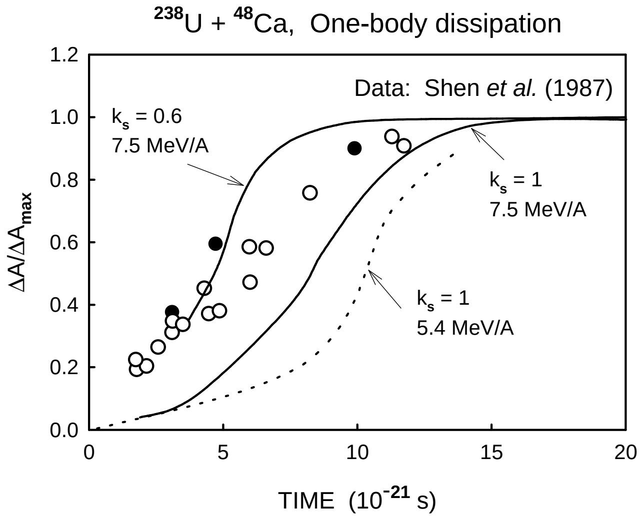

Fig. 1. Correlation between the mean normalized mass drift towards symmetry, $\Delta A/\Delta A_{\rm max}$, and the reaction time t determined [4] from the angles of rotation of the di-nuclear complex in collisions ^{238}U + ^{48}Ca. Data taken at the highest energy studied, 7.5 MeV/nucleon, which according to the authors of Ref. [4] are most accurate and reliable, are shown as full circles. Results for lower energies, in the range 4.6-6.7 MeV/nucleon, are shown as open circles. Experimetal data are compared with predictions of a dynamical model assuming one-body dissipation (see text).

The same set of data was analysed assuming two-body dissipation. In this mechanism the energy dissipation is determined by a magnitude of nuclear viscosity μ which, contrary to one-body dissipation, is expected to depend on nuclear temperature. It is seen from Fig. 2 that calculations with a fixed value of the viscosity coefficient cannot accurately reproduce the whole range of the drift-time correlation. A reasonable agreement with experimental data is obtained for μ of about 0.1 TP (1 TP $= 10^{12}$ dyne s cm^{-2} $= 6.24 \times 10^{22}$ MeV s fm^{-3}). However, the discrepancies observed for small values of the mass transfer ΔA are even more severe than in the case of one-body dissipation.

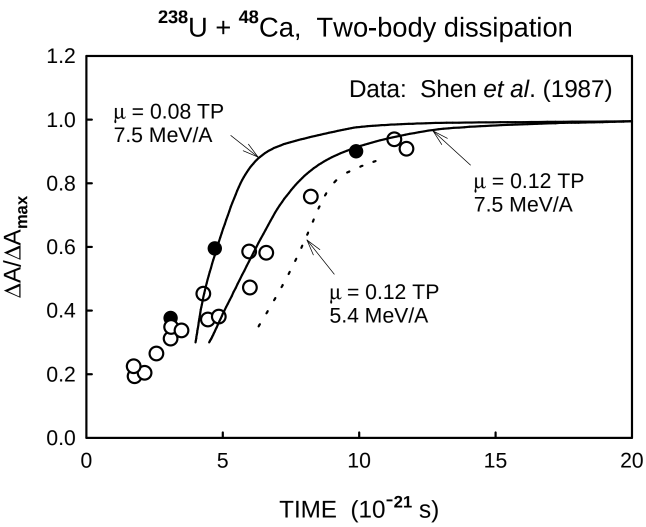

Fig. 2. Comparison of the same data as shown in Fig. 1 with predictions of a dynamical model assuming two-body dissipation.

Summarizing, we have analysed experimental data on mass equilibration in the strongly damped reactions [4] in terms of a dynamical model assuming either one-body or two-body dissipation. In the case of one-body dissipation the model calculations reasonably reproduce the measured correlation between the mean mass drift towards symmetry and the reaction time. The best fit is obtained when the standard rate of energy dissipation, given by the "wall-and-window" formula, is reduced by 10-25% for central collisions and by 30–40% for peripheral collisions. Assuming two-body dissipation, the best fit is obtained for a value of nuclear viscosity $\mu = 0.10$–0.13 TP for central collisions and $\mu = 0.06$–0.10 TP for peripheral collisions. These values of μ are much larger than those deduced from our analysis [1] of the mean kinetic energies of the fission fragments. This inconsistency of results for two-body dissipation can be used as an argument supporting the idea that at such low energies (below 10 MeV/nucleon) one-body dissipation still plays a dominating role.

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