DEPENDENCE OF THE FRICTION TENSOR ON REFLECTION ASYMMETRY*

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The friction tensor is evaluated within the linear response theory and the zero frequency limit approximation. The calculation are performed for ^{156}Dy at a deformation corresponding to the top of the fission barrier. The deformed Nilsson potential is used to describe the intrinsic degrees of freedom. It is found that the component of the friction tensor connected with the elongation mode grows significantly when the reflection symmetry of the nucleus is broken.

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1. Introduction

The nuclear dissipation plays an important role in heavy ion collisions, nuclear fission, the giant shape vibrations or damping of the giant resonance. The concept of dissipation, which was first introduced in nuclear theory by Kramers [1] in 1940, represents the transformation of collective motion into heat due to the damping mechanisms, *e.g.* friction. Since the mean free path of a nucleon in the nucleus is comparable with the nuclear radius the dissipation mechanism should be different from the ordinary two-body viscosity. It can be described within a macroscopic (classical) model which averages the global properties of a nucleus, or within a microscopic theory based on the many-body Hamiltonian.

The first macroscopic formula for the nuclear friction was derived under the assumption that nucleons form a gas of classical particles which collide with an infinitely high wall [2]. The wall originates from the mean-field potential and changes with nuclear deformation. This simple picture of

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one-body dissipation was then widely explored in nuclear physics. Next, it was shown in Ref. [3] that besides the one-body mechanism a two-body viscosity is necessary to describe nuclear friction.

The first microscopic explanation of nuclear dissipation was obtained within the linear response theory [4]. The mean-field potential $V(x_i; Q)$ introduces in a natural way the coupling between the single-particles (intrinsic) degrees of freedom x_i and the collectives coordinates Q, *e.g.* shape deformation parameters. A change of the collective coordinates causes an adequate response of the intrinsic system. Assuming that the intrinsic degrees of freedom are in a statistical equilibrium for all values of the collective variables, it is possible to derive the corresponding transport equation in the space of collective coordinates. The present formulation of the transport theory and the first results for the transport coefficients were published in Refs [5] and [6]. The main problem in the application of the above microscopic theory lies in the numerical difficulties when approximating peaks in the dissipative part of the response function by appropriate functions representing oscillators.

Another implementation of the transport theory [4], more convenient for the user, was proposed in Ref. [7]. The nuclear dissipation with the residual interactions was studied there by means of the Mori formalism. The correlation function technique was applied there to obtain the nuclear friction within the framework of a linear response theory. The deficiency of this approach with respect to that of Ref. [6] lies in the assumption of the zero-frequency limit when evaluating the friction parameter. Nevertheless the estimates of friction obtained in the both approaches are similar.

It was already found in Ref. [8] that the microscopic friction parameter depends significantly on temperature and angular momentum of the nucleus. In the present paper we are going to study the dependence of the quadrupole-quadrupole component of the friction tensor on the reflection asymmetry degrees of freedom (octupole and higher modes). Such an investigation can be important for the explanation of the latest measurements of the multiplicities of the particles emitted by the hot, fissioning nuclei [9] as well as the entrance-channel effects in the population of the superdeformed bands [10, 11].

2. Description of the model

A detailed description of the model we have used here was already presented in Ref. [7]. For the sake of completeness we shell present here only the formulae on which the numerical code for evaluating the microscopic friction was based. The aim of this section is to give an overview of the model and to fix the notation. A reader interested in the derivation of the formulae used here is referred to Refs [4, 5] and [7].

The friction tensor has been obtained within the linear response theory [4]. We evaluate namely, the response of the system on the external perturbation of the mean-field potential

$$\delta V = V(x_i;Q) - V(x_i;Q_0)\,, \tag{1}$$

where Q represents the collective coordinates which are the fission (Q_1) and mass asymmetry (Q_2) modes in our case. The perturbation δV can be expanded around a fixed point Q_0

$$\delta V = \sum_{i=1,2}(Q_i - Q_i^0)\frac{\partial V}{\partial Q_i} \equiv \sum_{i=1,2}(Q_i - Q_i^0)\hat{F}(r;Q_0)\,. \tag{2}$$

All transport coefficients, like collective mass, friction and diffusion tensors, appearing in the final equation of motion for $Q(t)$ can be obtained from the response function [4]

$$\begin{aligned}\tilde{\chi}''_{ij}(t-s) &= \tfrac{1}{2}\langle[\hat{F}_i^I(t),\hat{F}_j^I(s)]\rangle \\ &= \tfrac{1}{2}\,\mathrm{Tr}\{\rho(r,T;Q_0)\;[\hat{F}_i^I(t),\hat{F}_j^I(s)]\}\,,\end{aligned} \tag{3}$$

where $\hat{F}_k^I(t)$ is the perturbative force from Eq. (1) in the interaction picture

$$\hat{F}_k^I = \mathrm{e}^{i\hat{H}_{\mathrm{sp}}(r;Q_0)t}F_k(r;Q_0)\mathrm{e}^{-i\hat{H}_{\mathrm{sp}}(r;Q_0)t}\,. \tag{4}$$

$\hat{H}_{\mathrm{sp}}$ is the single-particle Hamiltonian and

$$\hat{\rho}(r,T;Q_0) = \frac{1}{\mathcal{Z}}\exp\left(-\frac{\hat{H}_{\mathrm{sp}}(r;Q_0)}{T}\right)\,, \tag{5}$$

defines a statistical density operator.

The friction tensor γ_{ij} was evaluated in the zero frequency limit by the relation

$$\gamma_{ij} = \lim_{\Omega\to 0}\frac{\chi''_{ij}(\Omega)}{\Omega}\,. \tag{6}$$

The Fourier transform $\chi''_{ij}(\Omega)$ of the response function (3) has been obtained by the fluctuation dissipation theorem

$$\chi''_{ij}(\Omega) = \tanh(\frac{\Omega}{2T})S_{ij}(\Omega)\,, \tag{7}$$

where $S_{ij}(\Omega)$ is the one-sided Fourier transform of the correlation function $\psi_{ij}(t)$ and T is the temperature of nucleus. The function $S_{ij}(\Omega)$ was estimated in Ref. [7] and reads:

$$S_{ij}(\Omega) = 2\sum_{\nu\neq\mu}\langle\nu|\hat{F}_i|\mu\rangle\langle\mu|\hat{F}_j|\nu\rangle\frac{N_{\nu\mu}\Gamma_{\nu\mu}(\Omega)}{(\Omega - e_\nu - e_\mu)^2N_{\nu\mu}^2 + \Gamma_{\nu\mu}^2(\Omega)}\,, \tag{8}$$

where e_ν and $|\nu\rangle$ are eigenvalues and eigenfunctions of the mean-field Hamiltonian, respectively. The parameter $\Gamma_{\nu\mu}$ in Eq. (8) related to the width of the single-particle levels is equal to

$$\Gamma_{\nu\mu} = \frac{\Gamma_0}{2}\{N_{\nu+\Omega,\nu}[(\Omega+e_\nu)^2+(\pi T)^2]+N_{\mu-\Omega,\mu}[(\Omega-e_\mu)^2+(\pi T)^2]\} \quad (9)$$

and

$$N_{\nu\mu} = n_\nu(1-n_\nu)+n_\mu(1-n_\mu)\,. \quad (10)$$

Here, n_ν is the occupation probability of a state $|\nu\rangle$ and is equal to

$$n_\nu(T) = \left\{1+\exp\left(\frac{e_\nu-\lambda}{T}\right)\right\}\,, \quad (11)$$

where T is the temperature (in energy units) of nucleus. The chemical potential λ in (11) is evaluated from the equation for the number of particles

$$\mathcal{N} = \sum_\nu n_\nu(T)\,. \quad (12)$$

The other coefficients N in Eq. (9) are defined as follows

$$N_{\nu\pm\Omega,\nu} \equiv N_{\nu\tau}(e_\nu, e_\tau = e_\nu \pm \Omega)\,. \quad (13)$$

The parameter Γ_0 in Eq. (9) was estimated in Ref. [12] and is equal 0.03 MeV^{-1}.

We have assumed that the fissioning (or fusioning) system is described by the elongation (plus neck) parameter (Q_1) and the reflection asymmetry mode (Q_2). Q_1 and Q_2 are expressed as a linear combinations of the Nilsson deformation parameters (ε_i).

The single-particle energies and states are obtained by solving the eigenvalue problem:

$$H_{\rm sp}(\varepsilon_\lambda)|\nu\rangle = e_\nu(\varepsilon_\lambda)|\nu\rangle\,. \quad (14)$$

of the mean-field Hamiltonian consisting of the kinetic energy part and the potential V in the form of the modified harmonic oscillator originally proposed by Nilsson:

$$V(\boldsymbol{r},\varepsilon_\lambda) = \tfrac{1}{2}\hbar\omega_0\rho^2\left\{1-\tfrac{2}{3}\varepsilon P_2+2\varepsilon_1P_1+2\varepsilon_3P_3+2\varepsilon_4P_4+2\varepsilon_5P_5\right\} \\ -\kappa\hbar\omega_0^0\{2\boldsymbol{l}\cdot\boldsymbol{s}+\mu[\boldsymbol{l}^2-N(N+3)]_N\}\,, \quad (15)$$

where ε_λ denotes here the deformation of multipolartity λ. The potential is written here in the stretched coordinates and the standard Nilsson notation has been used.

3. Results and discussion

We would like to study the dependence of the friction on the mass asymmetry mode in connection with the experiment described in Ref. [10], where the entrance-channel effects have been observed in the population of the ^{152}Dy superdeformed yrast band. It was found there that for the same compound nucleus ^{156}Dy formed at similar excitation energies and angular momenta, the relative intensity of the band depends on the entrance-channel mass asymmetry. The different population intensities possibly reflect differences in the formation and decay time of the compound nucleus for mass-symmetric versus -asymmetric systems. This formation time is for sure strongly affected by the dependence of the friction forces on the mass asymmetry mode.

The calculation was performed for ^{156}Dy at the point corresponding to the top of the fission barrier the position of which was estimated using a rotating, hot liquid drop model. Following Ref. [10] we have assumed the angular momentum $I = 75\hbar$ and the excitation energy $E^* = 75$ MeV. The parameters of the liquid drop were taken from Ref. [13] and their temperature dependence from Ref. [14]. The position of the top of the barrier was found at $\varepsilon = 1.155$ and $\varepsilon_4 = 0.154$ and its height was equal to $E_B = 6.9$ MeV. This saddle point corresponds to the distance between fragments of $R_{12} = 13.4$ fm. A much higher barrier ($E_B = 33.1$ MeV) has been obtained for the nonrotating case $I = 0$ and $E^* = 75$ MeV but situated ($\varepsilon = 1.180$, $\varepsilon_4 = 0.164$, $R_{12} = 13.9$) not far from the previous saddle point.

The direction of the fission mode in the plane $(\varepsilon, \varepsilon_4)$ was established by looking for the minimal stiffness of the liquid drop potential when the nucleus elongates

$$\vec{\varepsilon}_{24} = (1.0, 0.175)\,.$$

The direction of the mass asymmetry mode in the $(\varepsilon_3, \varepsilon_5)$ plane is given by the vector

$$\vec{\varepsilon}_{35} = (1.0, -0.356)\,.$$

The friction parameter connected with the fission mode ($\gamma_{\epsilon\epsilon}$) was evaluated using the formulae (6)–(8). For the numerical reasons we have neglected here the effect of the nuclear rotation in the present microscopic calculation. It was already shown in Ref. [8] that this effect increases the value of $\gamma_{\epsilon\epsilon}$. The result obtained for ^{156}Dy of the $I = 75\hbar$ saddle point, are plotted in Fig. 1 as a function of the mass asymmetry parameter ε_{35}. The data are presented for three temperatures $T = 2$ MeV (solid line), 1.5 MeV (long dashes) and 1 MeV (short dashes). The temperature $T = 2$ MeV corresponds approximately to the excitation energy $E* = 75$ MeV. In the upper scale of the plot the corresponding mass of the target (or projectile) is marked. It is assumed here that the position of the neck in the saddle configuration determines the magnitude of the mass asymmetry of the fragments (or target and projectile). This is of course only a rough approximation. A similar increase of the friction with the increasing mass asymmetry is presented in Fig. 2, where $\gamma_{\varepsilon\varepsilon}$ evaluated of the $I = 0$ saddle (long dashes) is compared with that for $I = 75\hbar$ (solid line) where in the both cases $T = 2$ MeV.

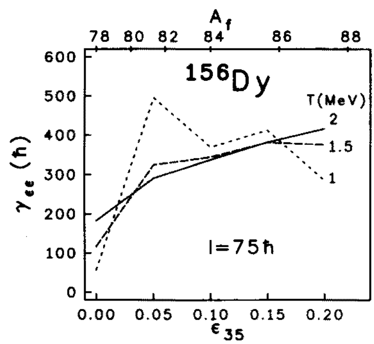

Fig. 1. The $\gamma_{\varepsilon\varepsilon}$ component of the friction tensor evaluated within the linear response theory for ^{156}Dy as a function of the reflection asymmetry deformation ε_{35}. The data are presented for three temperatures: $T = 2$ MeV (solid line), 1.5 MeV (long dashes) and 1 MeV (short dashes). In the upper scale of the plot the corresponding mass of the heavier fragment is marked.

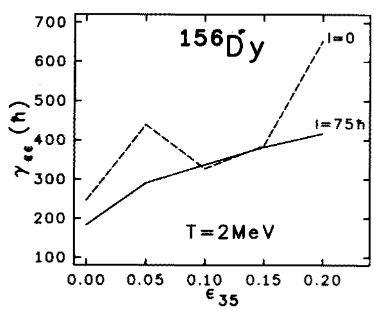

Fig. 2. The same as in Fig. 1 but at two different saddle points corresponding to the rotating case ($I = 75\hbar$, solid line) and the nonrotating case ($I = 0$, dashed line).

It is seen in the figures that the symmetric combination of the masses of the target and projectile

$$A_t = A_p = {}^{A}\!/_{2} = 78\,,$$

leads to the value of the friction three times smaller on average than that obtained for the asymmetric masses in the entrance channel.

This result, surprising at first sight, may be explained by simple symmetry arguments. Namely, the appearance of the left-right asymmetry destroys the symmetry of the system and the parity is no longer a good quantum number. The "gas" of particles of odd parity begins to interact with the "gas" of particles with even parity. Such an effect is not present *e.g.* in the wall plus window formula and the friction estimated within that macroscopic model is almost independent on the mass asymmetry.

A similar dependence of the friction parameter connected with the fission mode was found for different elongations of the fissioning nucleus as well as for other hot compound nuclei. We think that the effect we have found has rather universal character and it should also occur in the region of the fusion barrier. The smaller value of the friction for mass-symmetric heavy ions collisions may lead to a different feeding mechanism of the yrast states than for a asymmetric projectile-target combination. This effect could explain the entrance-channel phenomenon in producing the yrast superdeformed band in ^{152}Dy which was obtained from the hot ^{156}Dy nucleus after evaporation of 4 neutrons. In Ref. [10] it was found that the superdeformed band in this nucleus is less populated when the mass asymmetry between target and projectile is larger. It was even explicitly suggested in Ref. [11] that the enhanced feeding of the superdeformed yrast band in ^{152}Dy found for a mass-symmetric combination of target and projectile should be connected with the magnitude of dissipative effects.

We think also that the strong dependence of the friction parameter on the asymmetry mode can help to explain the experimentally measured dependence of the multiplicities of prescission neutrons on the mass of the fission fragment [9]. For this purpose we are going to perform a dynamical calculation similar to that in Ref. [15], where the Fokker–Planck equation for the fission mode coupled with the Master equation for the evaporations of light particles was solved, but now including the mass asymmetry mode.

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