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RELAXATION TIMES OF COLLECTIVE MODES IN THE FISSION OF EXCITED NUCLEI

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1. INTRODUCTION

In refs.[1-3] we achieved a good description of all the experimentally observed characteristics of the fission-fragment mass-kinetic energy distribution. The calculations were performed in the framework of the diffusion model for highly excited nuclei. In particular, we reproduced the large values of variances of the fission-fragment mass distribution σ_M^2 and their significant increase with an increase in the compound-nucleus fissility parameter. So we have overcome the traditional difficulties of the statistical and dynamical fission models.

The value of σ_M^2 is defined to a large extent by the mass asymmetric coordinate variance, $\sigma_\alpha^2(t)$, at scission, i.e. $\sigma_M^2 \sim \sim \sigma_\alpha^2(t_{sc})$. The dynamical evolution of $\sigma_\alpha^2(t)$ in the framework of the diffusion model shows a systematic deviation from the instantaneous statistical limit value [1,3,4]. The deviation becomes large at the end (in time) of the descent of a fissioning nucleus from the saddle point to scission. The time dependence of $\sigma_\alpha^2(t)$ is one of the main reasons why the diffusion model calculations of σ_M^2 agree well with the experimental data. The charge coordinate variance, σ_Δ^2, behaves in time in another way [5]. Our calculations have shown that the mode is in statistical equilibrium during almost the whole descent. The variance $\sigma_\Delta^2(t)$ deviates from the instantaneous statistical limit only very near scission, much nearer than $\sigma_\alpha^2(t)$. Just before the scission point σ_Δ^2 "freezes" due to the inertia and the friction of the mode sharply increases.

Here we report on the results of the calculations of the relaxation times for the mass-asymmetric, charge and neck modes in the framework of the diffusion model. We aim at understanding the reasons for the above-mentioned $\sigma_\alpha^2(t)$ and $\sigma_\Delta^2(t)$ time dependences and at exploring the applicability of the statistical approach to research into the fission-fragment mass and charge distributions. A long time ago the characteristic times of collective modes were used [6,7] to assess the role the "memory" of the fissioning system plays during the descent. Karamyan, Oganessian and Pustyl'nik [6] used the oscillation periods of the mass-asymmetric mode (with the value $(1\text{-}3)\cdot 10^{-21}$s [8]) and of the charge mode (with the value 10^{-22}s) as the characteristic times. Comparing the values with the descent time $t_{sc} \approx (2\text{-}10)\cdot 10^{-21}$s the authors of [6] concluded that the statistical model [9] is not applicable to calculating the fission-fragment mass distribution and can be used in the case of the charge one.

The relaxation time is more suitable to play the role of the characteristic time provided there is dissipation in the system. Many experimental and theoretical papers are devoted to the investigation of the relaxation times of different collective modes observed in dissipative heavy-ion collisions (see refs in [10,11]). The experimental values of the relaxation times for the mass-asymmetric (τ_α) and charge (τ_Δ) modes in dissipative heavy-ion collisions are equal [12] to $6\cdot 10^{-21}$s and $1.3\cdot 10^{-22}$s, respectively. In the experimental investigation of the quasi-fission reactions [13,14] the value $(5.3 \pm 1.0)\cdot 10^{-21}$s was obtained for τ_α. It should be noted that in the compound nuclear fission the relaxation times cannot be observed experimentally as opposed to quasi-fission and dissipative heavy-ion reactions where the relaxation time is the subject of experimental studies.

2. THE MODEL

In a good approximation the mass-asymmetric and charge modes in excited nuclei fission are harmonical [1,5,7,10]. The stiffness coefficients of the modes depend on the fission coordinate (e.g. elongation) and on the neck parameter. The inertia (m) and friction (γ) parameters of the modes depend on the same coordinates, too. Moving along the descent trajectory one has to take into account only one coordinate, more conveniently, the fission one. Then the time dependence of the coordinate defines the time dependence of the inertia and friction parameters.

Let us consider the dynamics of the fluctuations of an oscillator with time-dependent parameters using the diffusion model [3,4,15] based on the Fokker-Plank equation (FPE) for collective variables. The Langevin equation which is equivalent to the FPE is

$$\ddot{y} + \tilde{\beta}\dot{y} + \omega^2 y = F_L(t)/m . \qquad (1)$$

Here y is a finite mode coordinate (α, Δ, etc); $\beta = \gamma/m$ and $\tilde{\beta} = \beta + \dot{m}/m$ are the damping constant and the generalized damping constant, respectively; $\omega = (C/m)^{1/2}$ is the y-oscillator frequency, $F_L(t)$ is the random Langevin force with the statistical properties

$\langle F_L(t)\rangle = 0$, $\langle F_L(t)F_L(t')\rangle = 2D\delta(t-t')$; D is the diffusion coefficient.

If we are interested in the mass-asymmetric mode, the coordinate α of the well-known [16] $\{c, h, \alpha\}$ - parametrization will be used instead of y in (1). In the case of the charge mode $\Delta = Z_L - Z_{LUCD}$ will replace y. Here Z_L is the light fragment charge, and Z_{LUCD} is the value of Z_L corresponding to the compound nucleus charge density. We will use the elongation parameter c, or the half-distance between the centers of mass of the future fragments, ρ, as x - the fission coordinate [16]. The collective coordinate h defines the neck radius when c and α are fixed.

Dealing with fission of compound excited nuclei we have $\langle y\rangle = 0$ (for α or Δ), in contrast to quasi-fission and dissipative heavy-ion reactions. So the variance $\sigma_y^2(t)$ will be the main subject of our investigation. The dynamics of oscillator fluctuations is described by the following system of equations for the second moments of the distribution function $f(y, p_y, t)$ which obeys the FPE

$$\begin{aligned} \frac{d\sigma_y^2}{dt} &= 2\sigma_{yp_y}/m(t) , \\ \frac{d\sigma_{p_y}^2}{dt} &= -2[C(t)\sigma_{yp_y} + \gamma(t)\sigma_{p_y}^2/m(t) - D(t)], \\ \frac{d\sigma_{yp_y}}{dt} &= C(t)\sigma_y^2 + \sigma_{p_y}^2/m(t) - \gamma(t)\sigma_{yp_y}/m(t) . \end{aligned} \qquad (2)$$

The time dependence of $\langle x\rangle$ and $\langle h\rangle$ defines c, m, γ and D as functions of t. Here the diffusion coefficient D is connected with nuclear temperature T and friction γ by the Einstein relation: $D = \gamma T^*$, where T^* is the effective temperature for the collective mode [1,5,15].

It should be noted that a similar system of equations for the second moments was obtained in [17] using the Schrödinger equation with friction [18,19]. The only difference lies in the last term of the second equation for $\sigma_{p_y}^2$.

System (2) may be reduced to two equations

$$\ddot{\sigma}_y + \tilde{\beta}\dot{\sigma}_y + \omega^2\sigma_y = U/(m^2\sigma_y^3) , \qquad (3)$$

$$\dot{U} = -2\beta U + 2D\sigma_y^2 , \qquad (4)$$

where $U = \sigma_y^2\sigma_{p_y}^2 - \sigma_{yp_y}^2$.

The exact solution of eq. (4) is

$$U = [2\int_0^t D\sigma_y^2 \exp(2\beta t')dt' + U_0]\exp(-2\beta t) . \qquad (5)$$

If we neglect diffusion and friction in (2), eq.(3) coincides with the equation for σ_y obtained earlier in /20/ where the dynamics of forming the charge distribution in dissipative heavy-ion collisions and in fission was investigated. In this case $\tilde{\beta} = \dot{m}/m$, i.e. the time dependence of the inertia leads to the occurrence of a kind of quasi-friction in the mode. In the process of the rapid descent the fissioning system remembers the value of σ_y^2 even if there is no friction along this coordinate at all. In that case $U = U_0 = \hbar^2/4$ /20/ along the descent trajectory.

An approximate solution of eq. (3) may be written as follows:

$$\sigma_y^2 = \sigma_{y0}^2 \, exp\left(-\frac{2t}{\tau}\right) + \sigma_{yst}^2 \left[1 - exp\left(-\frac{2t}{\tau}\right)\right]. \qquad (6)$$

It is similar to the ordinary law of the transition process which was exploited to analyze the experimental data in /13,14/, i.e.

$$< y > = y_0 \, exp\left(-\frac{t}{\tau}\right) + y_{st}\left[1 - exp\left(-\frac{t}{\tau}\right)\right]. \qquad (7)$$

The only difference is that σ_{y0}^2, σ_{yst}^2 and τ are time dependent in eq. (6), in contrast to the analysis of /13,14/.

The oscillator (3) is underdamped provided $\omega > \tilde{\beta}/2$ and it is overdamped if $\omega < \tilde{\beta}/2$. In the case of underdamped motion eq. (6) is the result of time averaging of (10a) from /4/ over the oscillation period. The structure of the solution (6) corresponds to that of eq. (3): the left-hand part of eq. (3) describes the damped oscillator and the first term of (6) corresponds to it; the non-uniformity in the right-hand part of (3) generates the second term in (6).

In eqs. (6,7) the parameter τ is defined by the equations:

$$\tau = \begin{cases} 2\tilde{\beta}^{-1}, & \omega > \tilde{\beta}/2 \\ \left[\tilde{\beta}/2 - (\tilde{\beta}^2/4 - \omega^2)^{1/2}\right]^{-1}, & \omega < \tilde{\beta}/2 \\ \tilde{\beta}/\omega^2, & \omega \ll \tilde{\beta}/2 \end{cases} \qquad (8)$$

Eq. (7) shows that τ is the relaxation time of the collective coordinate mean value (this is the parameter which we shall exploit and discuss later on). It is obvious from eq. (6) that the variance σ_y^2 relaxes twice faster than $< y >$. Figure 1 shows the $\tilde{\beta}$ - dependence of the relaxation time. The dependence is not smooth and is of opposite nature for the underdamped and overdamped regimes of the oscillator.

3. THE RELAXATION TIMES FOR THE MASS-ASYMMETRIC MODE

The stiffness coefficients, inertia and friction parameters which define the relaxation time may be calculated using macroscopic approaches if we deal with fission of excited nuclei. Different versions of the LDM /21,22,23/ and droplet model /24/ were used to calculate the stiffness coefficients of the mass-asymmetric mode. The inertia parameters were computed in the framework of the Werner-Wheeler method /25/. We used two-body /25/ and "surface" one-body /26/ dissipation to calculate the mass-asymmetric friction parameters.

Figure 2 illustrates the dynamics of ω_α and $\tilde{\beta}_\alpha$ during the descent (note that the time dependence of the values is defined by their dependence on the coordinate ρ along the trajectory). It is interesting that the ρ -dependence of ω_α and β_α turns out to be universal for the different versions of the LDM and for a wide range of the Z^2/A of compound nuclei /3/. In Fig. 2 the difference between the frequencies of the mass-asymmetric mode is due to the type of viscosity (which changes the descent trajectory significantly), as well as to the used version of the potential energy calculations (LDM /22/ in case of two-body viscosity and the droplet model /24/ in the case of one-body dissipation). The value of ω_α gives us the possibility of evaluating the mass-asymmetric oscillation period: its value grows during the descent from $(2-3)10^{-21}$ s at the saddle point (according to the estimation of /6,8/) to $(5-6)10^{-21}$ s near the scission point.

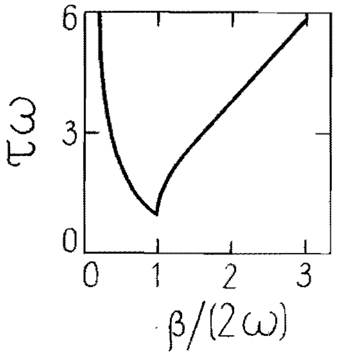


Fig. 1. Relaxation time (in units of inverse frequency) versus generalized damping coefficient (in units of twice frequency).

From Fig. 2 it is easy to see the strong difference between β_α and $\tilde{\beta}_\alpha$ in the case of two-body viscosity due to the contribution from term $\dot{m}_\alpha/m_\alpha$. In the case of one-body viscosity the contribution from $\dot{m}_\alpha/m_\alpha$ is negligibly small and the reason for an increase in $\tilde{\beta}_\alpha$ is the appearance of a "window" term in the "wall and window" formula for the friction parameter as the neck arises. Before that moment the value of $\tilde{\beta}_\alpha$ for one-body viscosity is even smaller than that for two-body one (in the latter case the fast descent results in a large value of $\dot{m}_\alpha/m_\alpha$).

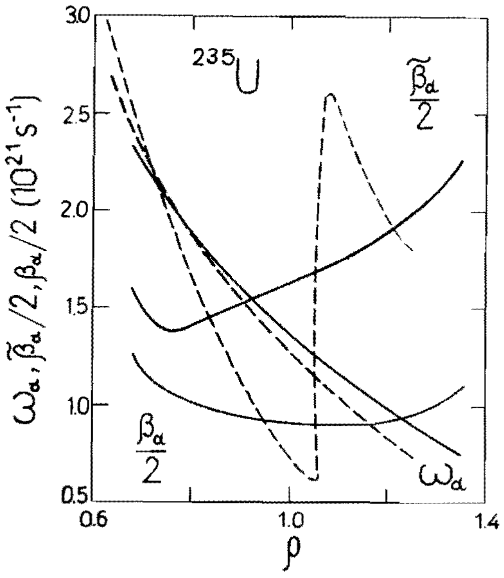
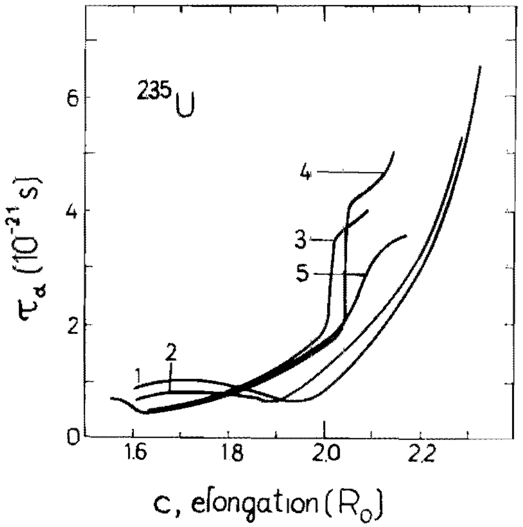


Fig. 2. The frequency, the damping and generalized damping coefficients of the mass-asymmetric mode versus the coordinate ρ along the trajectory of descent of ^{235}U. The solid curves represent the results of calculations using two-body viscosity ($\nu_0 = 1.5 \cdot 10^{-23} MeV \cdot s \cdot fm^{-3}$, the LDM /22/); The dashed curves represent the results of calculations using "surface" one-body viscosity and the droplet model /24/.

Fig. 3. The dependence of the relaxation time for the mass-asymmetric mode upon the elongation parameter c along the trajectory of descent of ^{235}U. Curves 1 and 2 represent the results of calculations using two-body viscosity. ($1 - \nu_0 = 10^{-23} MeV \cdot s \cdot fm^{-3}$ and the LDM /21/, $2 - \nu_0 = 1.5 \cdot 10^{-23} MeV \cdot s \cdot fm^{-3}$ and the LDM /22/). Curves 3-5 represent the results of calculations using "surface" one-body viscosity. (3 - the LDM /22/, 4 - the droplet model /24/, 5 - the LDM /23/).



Surprisingly, both one-body and two-body viscosities lead to a similar behaviour of the α-oscillator. It is explained by the similar ρ-dependence of $\tilde{\beta}_\alpha$ during descent (it should be noted that ρ-dependences of β_α are different in these cases). The mass-asymmetric oscillator is underdamped during the large part of descent, becoming overdamped until scission. The relaxation times plotted in Fig. 3 for two dissipation mechanisms are not very different. Figure 3 shows that the relaxation time increases sharply as the α-oscillator becomes overdamped. The increase arises in all the versions of calculations and agrees with Fig. 1. The values of τ_α are (4-6) x 10^{-21}s depending on the LDM version and on the type of viscosity used.

Our calculated values of τ_α agree with the experimental data on relaxation times for this mode in dissipative heavy-ion collisions /12/ and quasi-fission reactions /13,14/. The agreement allows one to conclude that the dynamics of the mass-asymmetric mode is defined by the same type of the collective motion in dissipative heavy-ion collisions, quasi-fission and fission of compound nuclei despite the different mechanisms of the reactions. Figure 4a shows the correlations between the elongation parameters of the nuclei at the saddle points and at the points where the regime of α-oscillator changes from underdamped to overdamped (below the switch points). (Here we see a remarkable independence of the version of LDM used in the calculations). The relaxation occurs very fast ($\tau_\alpha < 1 \cdot 10^{-21}$s, see Fig. 4b) before the switch point. Taking into account the fact that the descent is rather slow at the beginning it is easy to understand that the information about the part of descent between the two above-mentioned points is missing at all. This part of descent increases with growing Z^2/A. For rather light nuclei ($Z^2/A \le 34$) this part is small and, as a result, the α-oscillator "remembers" its saddle point σ_α^2-value well. Moreover, the part of descent between the switch point and scission is rather small for these nuclei.

In the heavier fissioning nuclei ($Z^2/A > 36$) the part of the descent from the saddle point to the switch point is approximately equal to that from the switch point to the scission one. The second part of the descent is even larger than the first one for the nuclei with $Z^2/A > 43$. However, this is not so for the durations of the two parts of the descent: as a result of the acceleration the duration of the first part of the descent is longer than that of the last part (see Fig. 4b). Obviously the part of the descent from the switch point to the scission point, which is passed rapidly and during which τ_α is rather large, is the part that defines the value of σ_M^2.

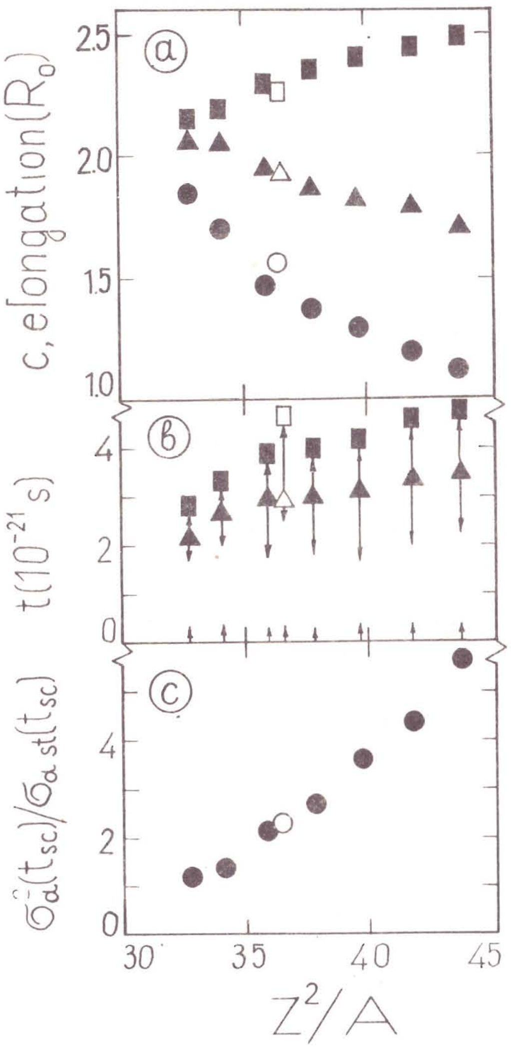


Fig. 4. a) The values of the elongation parameter of the saddle points (circles), the scission points (squares) and the points where the regime of α-oscillator changes from underdamped to overdamped (triangles) versus the parameter Z^2/A of compound nucleus.

b) The values of the relaxation times for the mass-asymmetric mode at the scission point (the lines with arrows on both sides) and at the saddle points (the lines with the arrows on one side) versus the parameter Z^2/A. All other marks have the same meaning as in Fig. 4a.

c) The ratio between the variance of the mass-asymmetric coordinate calculated in the diffusion model and its instantaneous statistical limit at the scission point versus the parameter Z^2/A.

The full marks in Fig.4 a,b,c represent the results of calculations using two-body viscosity ($\nu_0 = 10^{-23}$ $MeV\cdot s\cdot fm^{-3}$ and the LDM /21/, the open marks represent the results of calculations with $\nu_0 = 1.5\cdot 10^{-23} MeV\cdot s\cdot fm^{-3}$ and the LDM /22/).

In our view it is not correct to look for the point which defines the fission-fragment mass distribution. Rather the distribution is formed by the fluctuations of the α -coordinate during motion in the long part of the descent (see /3/ on the search for the boundaries of this part in numerical calculations). Taking into account that $\tau_\alpha(t_{sc})$ is much larger than the time of motion from the switch point to the scission (see Fig. 4b) it is easy to understand the abrupt deviation of $\sigma^2_\alpha(t)$ from its instantaneous statistical limit, which occurs at the end of the descent (see Fig. 4c).

4. THE RELAXATION TIMES OF THE CHARGE MODE

For the charge mode, the coefficients entering into the Langevin equation (1) were calculated in the framework of the hydrodynamical model /27/ in which the dipole isovector oscillations are suggested to be the main cause of the redistribution of charge between the future fragments. The methods used to calculate the stiffness coefficients and inertia parameters of the charge mode are described in refs /28, 29/, respectively. On the other hand, there is no well elaborated approach to computing the dissipation of the charge mode. So the charge mode friction parameter γ_Δ is often assumed to be a coordinate-independent free variable coefficient /5,30/. The model of the stationary flow of viscous liquid through a cylindrical tube /31/ was used in /17/ to estimate the dissipation of the charge mode. The neck of the nucleus is supposed to play the role of the tube.

This simplified model allows us to obtain only the collective coordinate dependence of the damping coefficient β_Δ rather than the friction parameter γ_Δ . Solving the Navier-Stokes equation with the boundary condition $\vec{v}$ (surface) = 0 we obtain /31/, in the framework of the model, the following equation

$$\beta_\Delta = 6\nu_0/(\rho_\Delta r_n^2) \equiv 6\nu/r_n^2 , \qquad (9)$$

where $\rho_\Delta = \rho_p \cdot \rho_n/\rho_0$, $\rho_0 = \rho_p + \rho_n$, ρ_p , ρ_n and ρ_0 are proton, neutron and total densities, respectively; r_n is the neck radius; ν_0 and ν are dynamical and kinematical viscosities, respectively. The value of ν in /17/ was obtained by fitting /32/ the giant dipole resonances widths.

Obviously one can use the model for the mass-asymmetric mode and get the following result

$$\beta_\alpha = 6\nu_0/(\rho_0 r_n^2) = \frac{Z\cdot N}{A^2}\rho_\Delta . \qquad (10)$$

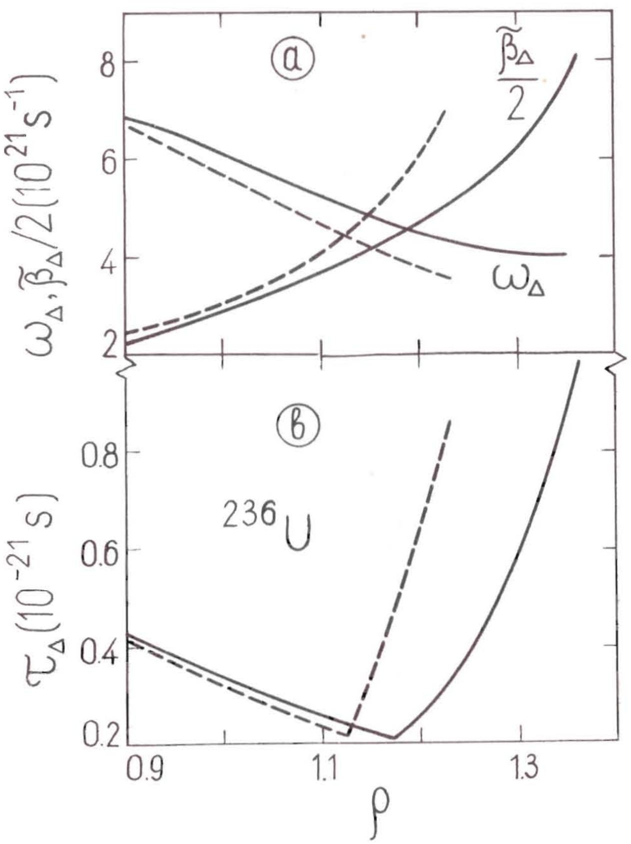


Fig. 5. The frequency, the generalized damping coefficient (above) and the relaxation time (below) of the charge mode versus the coordinate ρ along the trajectory of descent of ^{236}U. The solid curves represent the results of calculations using two-body viscosity ($\nu_0 = 1.5 \cdot 10^{-23}$ MeV·s·fm^{-3}, the LDM /22/). The dashed curves represent the results of calculations using "surface" one-body viscosity (the LDM /22/).

According to eq. (10), β_α must increase during descent because τ_n is decreasing. This contradicts the results of our calculations using the Werner-Wheeler method (see Fig. 2, where β_α decreases weakly as the fissioning nucleus approaches the scission point. The discrepancy may indicate that the model of the stationary flow through a

cylindrical tube is oversimplified and incapable of describing the real motion of the charge (and mass) modes. On the other hand, the estimation (10) of β_α is in qualitative agreement with the β_α value calculated in the framework of the "surface" one-body viscosity model (see Fig. 2).

Figure 5a illustrates the dynamics of ω_Δ and $\tilde{\beta}_\Delta$ during the descent. As the fissioning nucleus approaches scission, $\tilde{\beta}_\Delta$ sharply increases according to eq. (9). It should be noted that the $\dot{m}_\Delta/m_\Delta$ contribution to $\tilde{\beta}_\Delta$ is small (not exceeding 5%) even for two-body viscosity), in contrast to the mass-asymmetric mode. In Fig. 5 the different curves for the two types of viscosity are due to differences in the trajectories of the descent from the saddle point to scission.

In agreement with Fig. 1, the increase in $\tilde{\beta}_\Delta$ leads to a decrease in τ_Δ when Δ -oscillator is underdamped, and, on the contrary, to an increase in τ_Δ when the Δ -oscillator is overdamped (see Fig. 5b). It is seen that at scission τ_Δ is equal to (0.8 - 0.9)$\cdot 10^{-21}$ s. These values are much larger than the experimental ones deduced from the dissipative heavy-ion collisions data /12/. On the other hand, our estimate of β_Δ is close to the value obtained in ref. /17/.

It is easy to understand the reason of the charge mode equilibration during the whole descent if we compare τ_Δ with the typical times of descent ((4-5)$\cdot 10^{-21}$ s for two-body viscosity and (20-30) x 10^{-21} s for one-body viscosity). In the case of two-body viscosity the variance of the charge distribution "freezes" just before scission due to a sharp increase in β_Δ .

5. THE RELAXATION TIMES OF THE NECK MODE

The relaxation of the mass-asymmetric and charge mode are studied in dissipative heavy-ion collisions and quasi-fission rather in detail, at the same time much less is known about the relaxation processes of the deformation and neck formation coordinates in dissipative heavy-ion collisions.

The analysis of the h-mode relaxation time (remember that the h-coordinate determines the neck radius) is a very complicated problem in fission, too. First, the C and h coordinates are not normal and cannot be investigated as independent ones /1,3,16/. In particular, the nondiagonal component of the inertia tensor m_{ch} is, on the average, equal to the square root of the product of the diagonal components m_{cc} and m_{hh} /1,3,16/ during the descent. In the "ideal" parametrization using the normal coordinates the nondiagonal component of the inertia tensor must be small. The $\{\rho, h\}$ -parametrization satisfies this condition /3,16/. The calculations show that the inertia and friction tensors are more diagonal in the $\{\rho, h\}$-parametrization than in $\{c, h\}$ -one. So, the coordinates ρ and h can be used as approximately independent ones.

The potential deformation energy depending upon the coordinates can be written as follows /33,34/

$$V(x, h) = V_1(x) + \frac{C_h(x)}{2}(h - h_o(x)), \tag{11}$$

where $h_o(x)$ describes the location of the fission valley bottom, $x = 2(\rho - \rho_{sd})$, ρ_{sd} is the saddle point ρ -value. Eq. (11) shows that the neck mode is a harmonical one. As a result, the above - described model can be used to estimate the σ_h^2 -relaxation time.

But there is a second difficulty. Namely, when the fissioning nucleus approaches scission, the stiffness coefficient C_h begins to decrease rapidly. Thus the h-mode becomes an infinite one at the scission point defined as the point at which the ridge between the fission valley and the valley of the separated fragments vanishes. However, h-mode remains finite at scission with $C_h \approx$ 200 MeV if the scission point is determined by the condition $F_c(\rho, h) = F_n(\rho, h)$, where F_c is the Coulomb repulsive force between the future fragments and F_n is the force of nuclear attraction /2,3/.

Let us estimate the h-mode relaxation time taking the latter fact into account. The h-cuts of the potential energy surface and plots of the stiffness coefficients C_h versus ρ -coordinate are presented in Figs 1 and 2 of ref. /33/ and in Fig.2b of ref./34/. Figure 6a illustrates the dynamics of ω_h and $\tilde{\beta}_h$ during the descent. It is seen that the h-oscillator is underdamped during the large part of the descent and becomes overdamped near scission. The switch of the regime is due to the decrease in C_h and, mainly, to the significant growth of friction parameter γ_h . As was the case for the α - and Δ -modes, the switch of regime is accompanied by an increase in τ_h from value $0.3 \cdot 10^{-21}$ s during almost the whole descent to the value $1.8 \cdot 10^{-21}$ s at scission.

In ref. /7/ the characteristic time of the mode corresponding to the formation of the fission-fragment kinetic energy distribution was deduced from the temperature dependence of the energy variance. The time value obtained is approximately one order of magnitude smaller than the characteristic time of mass-asymmetric mode. In the framework of our model /3,33,34/ the formation of the fission-fragment kinetic energy distribution is determined at least partly by the neck

mode. Figures 6 and 3 show that $\tau_h \approx \tau_\alpha/2$ during large part of the descent and $\tau_h \approx (\tau_\alpha/4 - \tau_\alpha/3)$ just before scission. The ratio ω_α / ω_h is not larger than 2 during the whole descent.

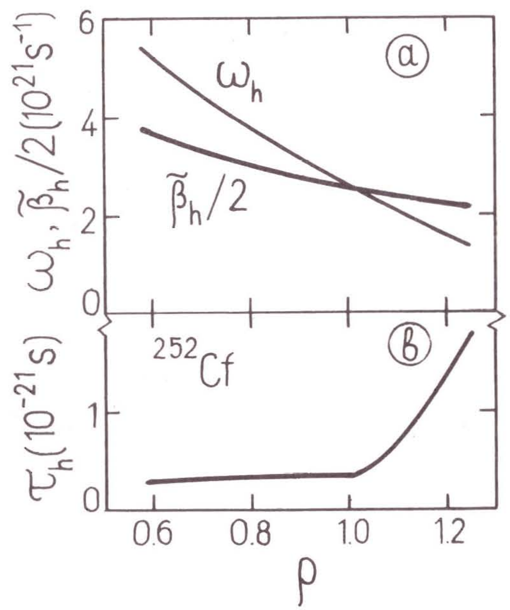


Fig. 6. The frequency, the generalized coefficient (above) and the relaxation time (below) of the neck mode versus the coordinate ρ along the trajectory of descent of ^{252}Cf. The droplet model /24/ and "surface" one-body viscosity have been used in the calculations.

6. CONCLUSION

The main results of the work can be summarized as follows.

The oscillators of all modes exhibit a similar behaviour: during the first stage of the descent all of them are underdamped and become overdamped nearer to scission due to a sharp increase in inertia and friction parameters.

The calculated values of the relaxation times for the mass-asymmetric mode in compound nucleus fission agree with the relaxation times observed in dissipative heavy-ion collisions and quasi-fission reactions. Consequently, despite the different types of the reactions used the evolution of the mass-asymmetric mode is determined by the same type of collective motion. The value of the mass-asymmetric mode relaxation time depends weakly upon the type of viscosity (one-body or two-body) used in the calculations although the descent times differ by a factor of 5-8 . In refs /13,14/, after analysing the τ_α excitation energy dependence it is concluded that nuclear viscosity in quasi-fission reactions is of one-body nature. Our calculations (neglecting the dependence of viscosity upon temperature) do not allow one to say anything about the type of nuclear viscosity. The time dependence of τ_α during the descent help to understand the time evolution of the mass-asymmetric coordinate variance σ_α^2 in exact numerical calculations /1,3/.

The relaxation times for the charge mode do not agree with the experimental values from dissipative heavy-ion collisions, in particular, the calculated values are several times larger than the experimental ones. The discrepancy can result from the use of a very crude model to estimate the damping coefficient of the mode discussed. Therefore, the exact numerical calculations of the charge-mode friction parameter must be carried out.

The relaxation times for the neck mode are about one quarter of τ_α at scission; these values of τ_h are in qualitative agreement with the experimental values deduced from the temperature dependence of the variances of the kinetic energy distribution.

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