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# THE TRANSPORT COEFFICIENTS FOR SLOW COLLECTIVE MOTION

**F. A. Ivanyuk**

*Institute for Nuclear Research, National Academy of Sciences of Ukraine, Kyiv*

We study the collective motion of iso-scalar type at finite excitations and concentrate on slow motion, due to the presence of a strong friction force. In the present talk the extension of approach to the case of low excitation energies, where shell effects and pairing correlation are important, is reviewed. The case of rotating nuclei is also included. As an application of the theory, the numerical results are presented for the transport coefficients for few composite systems formed in the so called warm fusion reactions used for the synthesis of the super heavy systems.

## 1. Introduction

The synthesis of the super heavy elements is one of the most challenge problems of nuclear physics. Intensive experiments in this direction are carried out at GSI, Darmstadt, JINR, Dubna and RIKEN, Tokyo. The theoretical description of fusion-fission reaction is often based on the Langevin equation [1 - 3] for the collective variables $Q_\mu$ which parameterize the shape of the composite system,

$$\frac{dP_\mu}{dt} = -\frac{\partial V}{\partial Q_\mu} - \frac{1}{2}\frac{\partial}{\partial Q_\mu}(M^{-1})_{\rho\nu} P_\rho P_\nu -$$

$$-\gamma_{\mu\nu}(M^{-1})_{\rho\nu} P_\nu + g_{\mu\nu} R_\nu(t),$$

$$\frac{dQ_\mu}{dt} = (M^{-1})_{\mu\nu} P_\nu \qquad \rho, \mu, \nu = 1, 2, \dots N, \tag{1}$$

where $R_\nu(t)$ is the random force obeying conditions

$$< R_\nu(t) > = 0, \qquad < R_\nu(t) R_\nu(t') > = 2\delta(t - t')$$

$$\text{and} \qquad \sum_\rho g_{\mu\rho} g_{\nu\rho} = T\gamma_{\mu\nu}. \tag{2}$$

To solve the Langevin equation (1) for $Q_\mu(t)$ one would need first of all its coefficients - the potential energy $V(Q_\mu)$, friction $\gamma_{\mu\nu}$- and mass $M_{\mu\nu}$ -tensors.

The potential energy is commonly calculated within the microscopic-macroscopic shell correction method [4 - 6], which describes the collective energy in the quasi-static picture rather accurately. The tensors of friction $\gamma_{\mu\nu}$ and mass $M_{\mu\nu}$ are usually computed within the macroscopic approaches (the wall and window formula for friction [7] and the Werner - Wheeler (WW) method for the inertia [8]). These methods provide rather simple expressions for the collective friction and mass coefficients. However the deformation and temperature dependence of macroscopic transport coefficients $\gamma_{\mu\nu}$ and $M_{\mu\nu}$ is not very reliable, at least at small excitation energies. For example, the observed in [9] increase of the damping parameter $\eta = \gamma/2\sqrt{M\,|C|}$ with the excitation energy is impossible to explain neither with the wall formula value $\gamma^{wall}$ for friction (where the friction parameter practically does not depend on the temperature $T$ or excitation energy) nor within the hydrodynamic model (friction parameter decreases as $1/T^2$). Also the shell and pairing effects, which are very important at low excitation energies, are completely ignored in macroscopic models. Thus the necessity of having a microscopic theory for the collective transport coefficients becomes quite evident.

## 2. Linear response theory for the collective motion

It is supposed [10] that the nuclear many-body Hamiltonian can be approximated by

$$H(x_i, p_i, Q_\mu) = H_{mf}(x_i, p_i, Q_\mu) + V_{res}^{(2)}(x_i, p_i), \tag{3}$$

where the mean field Hamiltonian $H_{mf}$ depends explicitly on one or few collective variables $Q_\mu$ which specify the shape of nuclear surface and the residual two-body interaction $V_{res}^{(2)}$ is assumed to be *independent* of the collective coordinates $Q_\mu$. As the consequence the generators for the collective motion, namely,

$$F \equiv \left.\frac{\partial H(x_i, p_i, Q_\mu)}{\partial Q_\mu}\right|_{Q_\mu = Q_\mu^0} \equiv \left.\frac{\partial H_{mf}(x_i, p_i, Q_\mu)}{\partial Q_\mu}\right|_{Q_\mu = Q_\mu^0} \tag{4}$$

are the one-body operators, what allows applying the independent particle model. It is shown in [10] that the slow collective motion can be described locally in terms of so-called collective response function $\chi_{\rm coll}(t)$ whose Fourier transform has the form

$$\chi_{\rm coll}(\omega) = \kappa(\kappa + \chi(\omega))^{-1}\chi(\omega). \tag{5}$$

In (5) the $\chi(\omega)$ is the Fourier transform of the causal response function

$$\chi_{\mu\nu}(t-s) = \Theta(t-s)\frac{i}{\hbar}\,\mathrm{tr}\left(\rho_{\rm qs}(Q,T)[F^I_\mu(t), F^I_\nu(s)]\right). \quad (6)$$

Here $F^I_\mu(t)$ is the interaction representation of operator (4) and $\rho_{\rm qs}$ represents the thermal equilibrium $\rho_{\rm qs}(Q_\mu,T) \propto \exp(-H(Q_\mu)/T)$. The inverse of coupling tensor $\kappa_{\mu\nu}$ in (5) is defined by the quasi-static properties of the system,

$$\kappa_{\mu\nu} = -\chi_{\mu\nu}(0) - C_{\mu\nu}(0), \quad (7)$$

where $\chi_{\mu\nu}(0)$ is the static response and $C_{\mu\nu}(0)$ is the stiffness of quasi-static free energy, $C_{\mu\nu}(0) \equiv \partial^2 F/\partial Q_\mu \partial Q_\nu$.

It turns out that the transport coefficients for the average collective motion can be expressed in terms of $\chi_{\rm coll}(\omega)$. As shown in [11] one has to approximate the quantity $\kappa\chi_{\rm coll}{}^{-1}(\omega)\kappa$ by the second order polynomial in frequency

$$(\kappa\chi_{\rm coll}{}^{-1}(\omega)\kappa)_{\mu\nu} \;\Rightarrow\; -M_{\mu\nu}\omega^2 - i\gamma_{\mu\nu}\omega + C_{\mu\nu}. \quad (8)$$

Evidently, the coefficients $M_{\mu\nu}$, $\gamma_{\mu\nu}$ and $C_{\mu\nu}$ stand for the elements of the tensors for the mass, friction and stiffness. For slow collective motion the transport coefficients can be deduced by expanding the left hand part of (8) around $\omega = 0$. In this way one gets

$$\gamma \approx i\left.\frac{\partial(\kappa\chi_{\rm coll}{}^{-1}(\omega)\kappa)}{\partial\omega}\right|_{\omega=0} = \kappa\chi^{-1}(0)\gamma(0)\chi^{-1}(0)\kappa,$$

$$M \approx -\left.\frac{\partial^2(\kappa\chi_{\rm coll}{}^{-1}(\omega)\kappa)}{2\partial\omega^2}\right|_{\omega=0} =$$

$$= \kappa\chi^{-1}(0)[M(0) + \gamma(0)\chi^{-1}(0)\gamma(0)]\chi^{-1}(0)\kappa. \quad (9)$$

The friction $\gamma(0)$ and mass $M(0)$ tensors are expressed in terms of first and second derivatives of the intrinsic response function $\chi_{\mu\nu}(\omega)$ at $\omega = 0$,

$$\gamma_{\mu\nu}(0) = -i\left.\frac{\partial\chi_{\mu\nu}(\omega)}{\partial\omega}\right|_{\omega=0}, M_{\mu\nu}(0) = \frac{1}{2}\left.\frac{\partial^2\chi_{\mu\nu}(\omega)}{\partial\omega^2}\right|_{\omega=0}. \quad (10)$$

For obvious reasons, expressions (10) are referred to as the "zero frequency limit".

An example of numerical results for the ratio of the friction coefficient to the mass parameter is shown in Fig. 1. These results were obtained with the deformed Woods-Saxon shell model potential. The shape of nuclear surface was parameterized in terms of Cassini ovaloids [12]. As the compound nucleus the system $^{208}Pb + ^{16}O \Rightarrow ^{224}Th$ was chosen here for which the rapid increase of dissipation with the excitation energy was found [13].

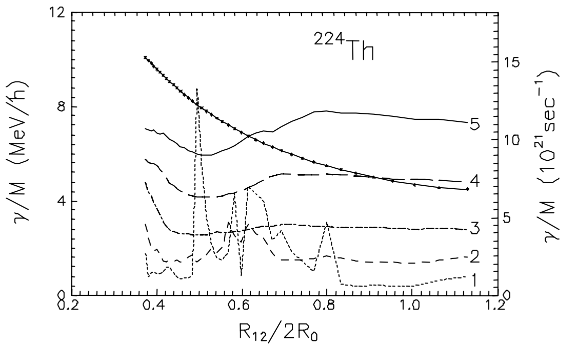


Fig. 1. The reduced friction coefficient $\gamma/M$ as function of deformation and temperature $T = (1-5)\,\mathrm{MeV}$ (indicated in the Figure). The curve with dots marks $\gamma^{wall}/M_{irr}$

It is seen from Fig. 1 that $\gamma/M$ is essentially constant over the whole deformation region, for all computations but $T = 1\,\mathrm{MeV}$, a case for which the fluctuations are seen. However, there is a marked dependence on excitation: $\gamma/M$ increases strongly with $T$. This is in clear distinction to the result one gets from applying the wall formula $\gamma_{wall}$ for friction and that of irrotational flow $M_{irr}$ for the inertia. Note also that the numerical values of $\gamma/M$ are in agreement with those deduced from the analysis of experimental data [14].

### 3. The effect of pairing

The pair correlations are vital for understanding of many elementary features of nuclear physics at small thermal excitations. It is of great interest to account for pair correlations also in the description of typical transport problems of dissipative systems. On general grounds one could expect that pairing will greatly diminish nuclear dissipation.

To account for the pairing interaction we add to the mean field Hamiltonian the pairing part

$$H_{mf} \Rightarrow H_{mf} - GP^\dagger P, \qquad P^\dagger = \sum_k a_k^\dagger a_{\bar{k}}^\dagger, \quad (11)$$

where the coupling constant $G$ is assumed to be state independent and $a_k^\dagger$ and $a_k$ being the creation and annihilation operators. The Hamiltonian (11) is solved then within the independent quasiparticle approximation.

The explicit expression for the response function $\chi_{\mu\nu}(\omega)$ is found directly from (6) after straightforward though somewhat lengthy derivation

$$\chi_{\mu\nu}(\omega) = \sum_{kj}{}' \frac{(n_k^T - n_j^T)\xi_{kj}^2 \, 2(E_k - E_j)^2}{(\hbar\omega + i\Gamma_{kj})^2 - (E_k - E_j)^2} F_\mu^{kj} F_\nu^{jk},$$

$$+\sum_{kj} \frac{(n_k^T + n_j^T - 1)\eta_{kj}^2 \, 2(E_k + E_j)^2}{(\hbar\omega + i\Gamma_{kj})^2 - (E_k + E_j)^2} F_\mu^{kj} F_\nu^{jk}, \quad (12)$$

where $n_k^T = 1/(1+\exp(E_k/T))$, $\eta_{kj} \equiv u_k v_j + v_k u_j$, $\xi_{kj} \equiv u_k u_j - v_k v_j$ and $u_k$, $v_k$ are coefficients of Bogolyubov - Valatin transformation.

In (12) the width $\Gamma_{kj}$ is the average width of the two-quasiparticle state, $\Gamma_{kj} = (\Gamma(E_k, \Delta, T) + \Gamma(E_j, \Delta, T))/2$. The calculation of $\Gamma$ with pairing included is discussed in detail in [11]. We would mention only that in the presence of pairing no analytical expression is available for the width $\Gamma(E_k, \Delta, T)$ and this quantity is computed numerically, $\Gamma(E_k) = \Gamma_d(E_k)/(1 + \Gamma_d(E_k)\Gamma_0/c^2)$, with

$$\Gamma_d(E) = \frac{2}{\Gamma_0}\int d\varepsilon_2 d\varepsilon_3 d\varepsilon_4 \delta(E + E_2 + E_3 + E_4) \times$$

$$\times\ (n_2^T n_3^T n_4^T + (1 - n_2^T)(1 - n_3^T)(1 - n_4^T)). \quad (13)$$

For the $\Gamma_0$ and $c$ the values $\Gamma_0 = 33$ MeV, $c = 20$ MeV are taken, (see [10]).

The dependence of collisional width $\Gamma(E = \Delta, \Delta, T)$ on the temperature for few fixed values of pairing gap $\Delta$ is shown in Fig. 2.

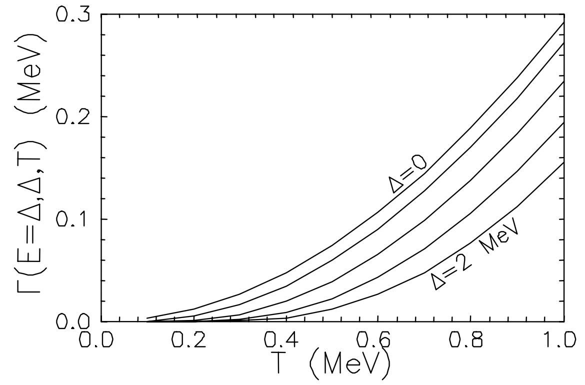


Fig. 2. The collisional width (13) taken at the Fermi energy ($E = \Delta$) as function of the temperature. Different curves correspond to different values of pairing gap $\Delta$ indicated in the Figure.

One can see that with increasing $\Delta$ the value of $\Gamma$ gets smaller. Eventually, this leads to the suppression of the collective friction by pairing.

This effect is clearly demonstrated in Fig. 3 where the friction coefficient, reduced friction coefficient and the damping factor for $QQ$-mode are shown as function of the temperature. As it is seen from Fig. 3 the friction coefficients demonstrate kind of super fluidity. It is negligibly small until the pairing gap would disappear at critical temperature $T_c \approx (0{,}5 - 0{,}6)$ MeV. These results are in qualitative agreement with the "onset of dissipation" found experimentally in [13].

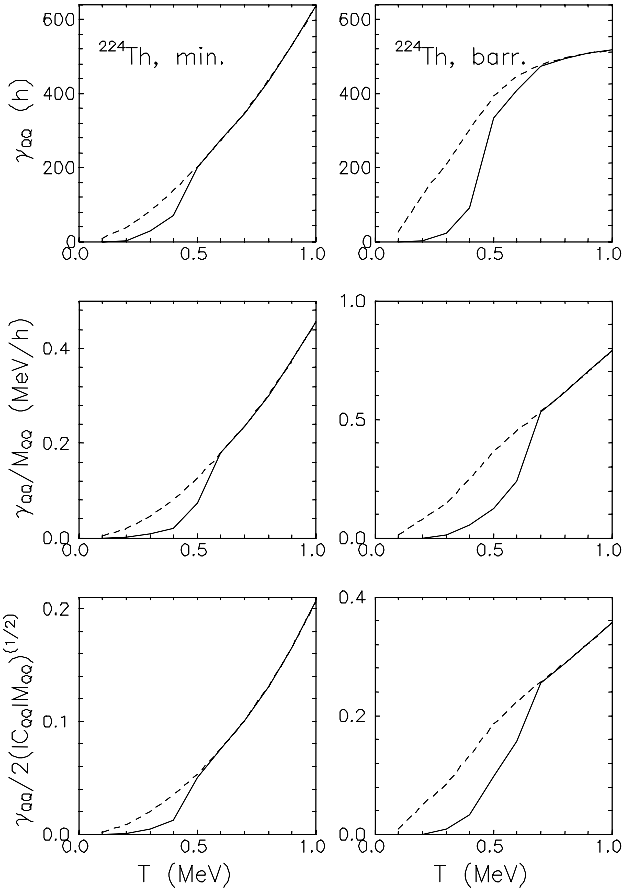


Fig. 3. The $QQ$-friction coefficient $\gamma_{QQ}$, reduced friction coefficient $\beta_{QQ} \equiv \gamma_{QQ}/M_{QQ}$ and the damping factor $\eta_{QQ} = \gamma_{QQ}/2\sqrt{C_{QQ}M_{QQ}}$ at the ground state (top) and fission barrier (bottom) of $^{224}Th$ as function of temperature. The dash curves show the results obtained neglecting pairing.

The results of detailed numerical calculation of the friction tensor for the system $^{48}Ca + ^{244}Pu \Rightarrow ^{292}114$ given by three deformation parameters $\alpha, \alpha_3$ and $\alpha_4$ are shown in Fig. 4. Because of the lack of space only most important diagonal components of friction tensor are shown. For convenience the friction coefficients were divided by the wall formula value. Otherwise the details of the structure of $\gamma_{\alpha\alpha}$, $\gamma_{\alpha_3\alpha_3}$ and $\gamma_{\alpha_4\alpha_4}$ would not be seen on the scale of Figure. The most important conclusion from Fig. 4 is that the values of $\gamma_{\alpha\alpha}$, $\gamma_{\alpha_3\alpha_3}$ and $\gamma_{\alpha_4\alpha_4}$ differ substantially from their wall formula counterparts. Unlike $\gamma^{wall}$, $\gamma_{\alpha\alpha}$, $\gamma_{\alpha_3\alpha_3}$ and $\gamma_{\alpha_4\alpha_4}$ demonstrate not regular dependence on the deformation. The period of fluctuations is approximately the same as in case of the deformation energy, thus one can attribute these fluctuations to the effect of the shell structure. The value and deformation dependence of the corresponding components of mass tensor also differ very much [15] from their macroscopic counterparts (obtained within Werner - Wheeler method [8]).

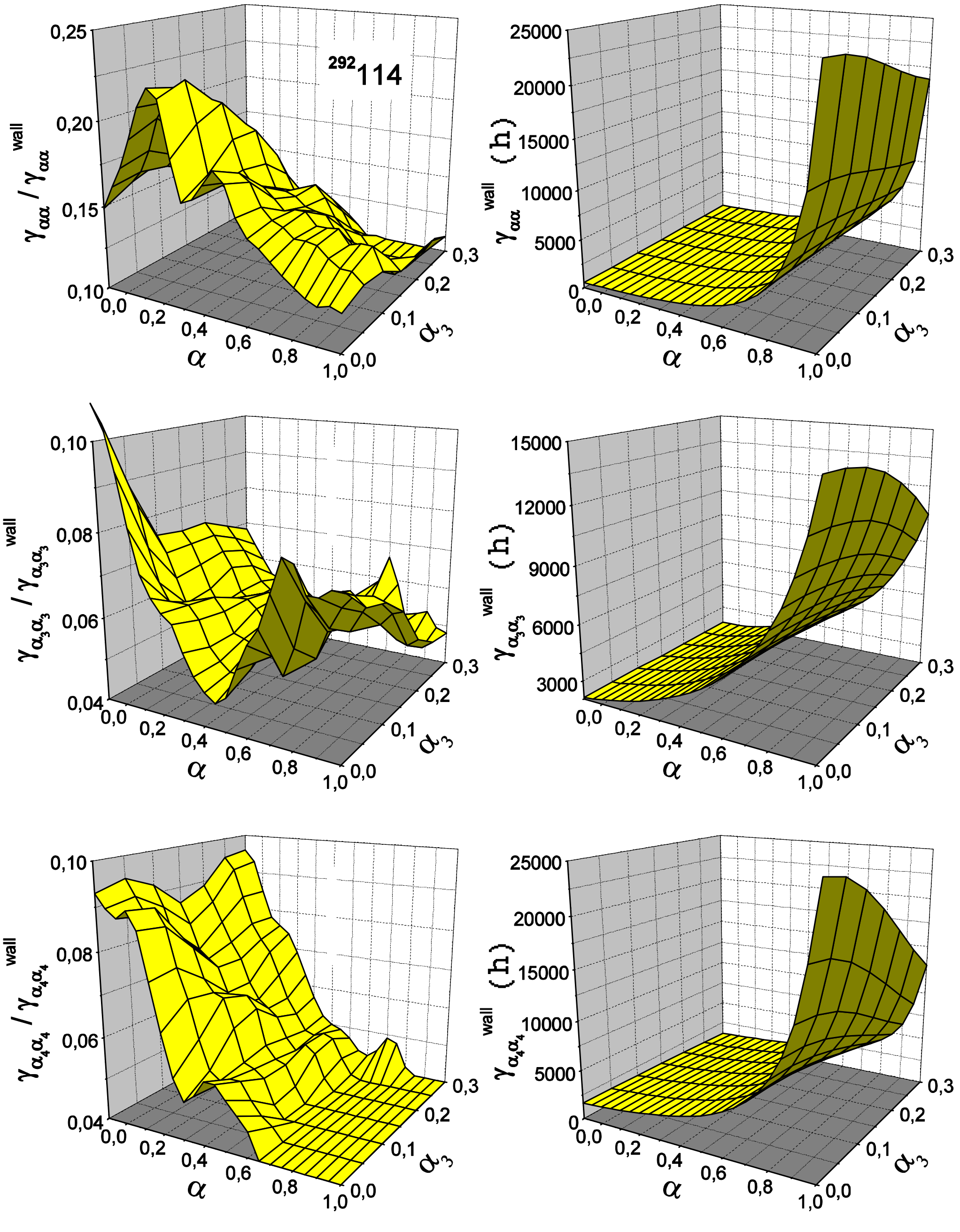


Fig. 4. The diagonal components $\gamma_{\alpha\alpha}$, $\gamma_{\alpha_3\alpha_3}$ and $\gamma_{\alpha_4\alpha_4}$ of friction tensor as function of deformation parameters $\alpha$ (left) and $\alpha_3$ in units of the wall formula value (right). The calculations are done for the compound system $^{292}114$ at the temperature $T = 0{,}5\,\mathrm{MeV}$.

Thus the results of dynamical computations using macroscopic friction and mass parameters [7, 8] are not reliable at least at low excitation energies.

The microscopic transport coefficients were used recently in [16] where the two stage approach to the description of fusion-fission reactions is suggested. On each stage (fusion or fission) the three-dimensional Langevin equation for the variables describing the shape of nuclear system was solved. The results obtained on the first stage are used as the input data for description of fission dynamics. In this way it turned out possible to describe both fusion and fission cross sections for the reaction $^{18}O+^{208}Pb$, the energy and mass distribution of fission fragments, the probability of the evaporation residue formation, the dependence of pre-fission neutron multiplicities on the fragment mass number.

The computations of the transport coefficients shown above are rather time consuming. For practical use in codes based on the Langevin equation the simple analytical approximation is highly desirable. The one of the most important quantities in such calculations is the reduced friction coefficient $\gamma/M$. In Fig. 5 we show it on the left hand panel as function of $T$ together with the following approximation, see [17],

$$\frac{\hbar\gamma}{M} \approx 2\Gamma_{sp}(\mu,T) = \frac{2}{\Gamma_0}\frac{\pi^2T^2}{1+\pi^2T^2/c^2} \approx \frac{0,6T^2\text{MeV}}{1+T^2/40} \quad (14)$$

$(T \text{ in MeV})$. The approximation (14) represents the microscopic result quite well.

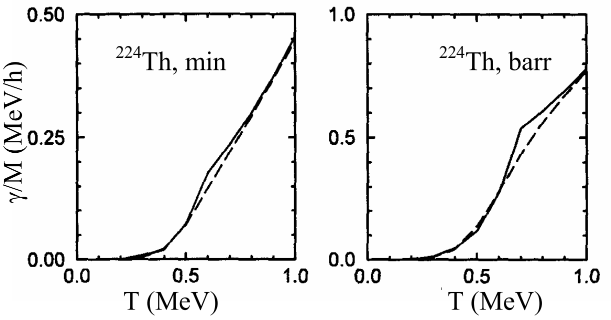


Fig. 5. The reduced friction coefficient $\gamma/M$ as function of temperature: the microscopic results (solid curves) are compared to the approximation (14) (dotted curves).

The analytical approximations of [17] were used recently by [18] to describe the formation probability of super heavy system. By examining the long time behavior of the Fokker - Planck equation for the distribution function it was shown that the formation probability increase by few orders of magnitude if microscopic transport coefficients are used rather than those of the common picture.

## 4. The transport coefficients for rotating nuclei

The nuclear compound systems formed in the result of fusion of heavy ions are commonly formed with nonzero angular momentum. The effect of rotation on the fusion or fission probability is included at most in the calculation of the macroscopic part of the deformation energy. The possible dependence on rotation of the shell correction as well as friction and inertia is completely ignored. However one might expect some dependence of the transport coefficients on rotation since the rotation changes considerably the single-particle spectrum. To clarify this problem we have carried out the calculation of transport coefficients for rotating nuclei [19]. The computations are preformed with two-center shell model which allows for rather flexible parameterization of the shape around the touching point and which was used earlier in dynamical computations [20]. Due to technical reasons we had to limit ourselves to the excitations above $T = 1\,\text{MeV}$ where the pairing can be neglected.

By describing the rotating nuclei one usually transforms the Hamiltonian from the laboratory co-ordinate system to the body fixed (or intrinsic) co-ordinate system. As the result, instead of the Hamiltonian $H(Q_\mu)$ one has to consider the Routhian operator

$$R(Q_\mu, \omega_{\text{rot}}) = H(Q_\mu) - \omega_{\text{rot}} J_x, \quad (15)$$

with $\omega_{\text{rot}}$ being the rotational frequency and $J_x$ - the projection of angular momentum on the rotation axes ($x$-axes).

Like in the case without rotation we will use for calculation of the potential energy the Strutinsky shell correction method [4, 6]. Following [21, 22] one can express the intrinsic energy $E(Q_\mu, I)$ as

$$E(Q_\mu,\ I) = E_{LDM}(Q_\mu,\ I) + \delta R(Q_\mu,\ I), \quad (16)$$

where $E_{LDM}(Q_\mu, I)$ is the liquid drop energy of rotating nucleus and $\delta R(Q_\mu, I)$ is the shell correction. In the case of finite temperature instead of the shell correction to the intrinsic energy one has to consider the shell correction to the free energy $\delta R \Rightarrow \delta F = \delta R - T\delta S$, where $\delta S$ is the shell correction to the entropy.

The Fig. 6 shows the rotational dependence of the liquid drop part of deformation energy. As it is seen the rotational dependence of the deformation energy is rather strong. The fission barrier disappears completely at $I \approx 60\hbar$ for the nucleus $^{224}Th$ shown in the figure. The effect of rotation on the fission barriers is known for decades. The rotational dependence of the shell correction is less clear. It is assumed usually that this dependence is weak and the shell correction is computed at $\omega_{\text{rot}} = 0$ only. To clarify this point we have computed the shell correction for several values of $I$ as a function of deformation along the liquid drop fission valley of $^{224}Th$. Indeed, see Fig. 7, the fluctuation of $\delta F$ is less then $1\,\text{MeV}$ for variation of $I$ from zero to $I = 60\hbar$. Very likely such weak dependence of $\delta F$ on $I$ can be neglected.

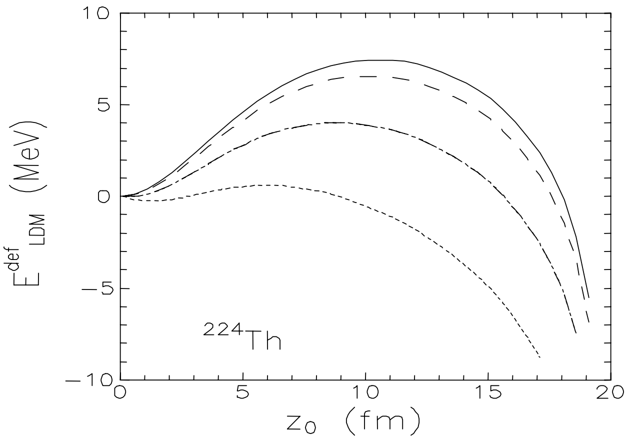


Fig. 6. The liquid drop deformation energy for temperature $T = 1\,\text{MeV}$ as function of the deformation parameter $z_0$. The solid, dash, dotted-dash and dotted lines correspond to the values of angular momentum equal to 0, 20, 40 and 60 $\hbar$.

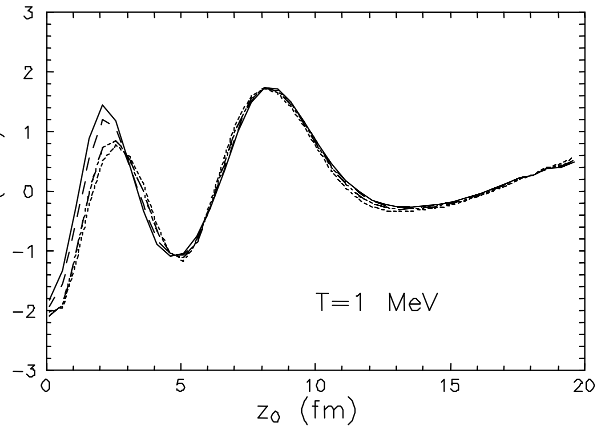


Fig. 7. The shell correction $\delta F = \delta R - T\delta\,\text{S}$ to the free energy for temperature $T = 1\,\text{MeV}$ as function of the deformation parameter $z_0$. The solid, dash, dotted-dash and dotted lines correspond to the values of the nuclear angular momentum equal to 0, 20, 40 and 60 $\hbar$.

Like in the case without rotation the transport coefficient of collective motion, can be derived within the linear response theory [10] replacing the mean field Hamiltonian by the Routhian (15). It turns out however [19] that the friction $\gamma$ and mass $M$ parameters for rotating nuclei are rather sensitive to such fine effects as the violation of rotational symmetry by Coriolis term $-\omega_{\text{rot}} J_x$. For the ground state deformation the spurious contributions to collective friction and mass are (at least) as large as those of physical importance. In order to remove the spurious contributions we had to modify the model of "stationary rotation" and to introduce the time-dependent rotational frequency. In this way we have obtained the friction and the mass parameters, which demonstrate rather weak dependence on the rotational frequency $\omega_{\text{rot}}$.

Fig. 8 shows the reduced friction coefficient $\beta_{qq} = \gamma_{qq}/M_{qq}$ at the saddle of $^{224}Th$ as the function of temperature. The $\beta_{qq}$ shown in Fig. 8 increase with the temperature. This behavior is in a qualitative agreement with that found in [13].

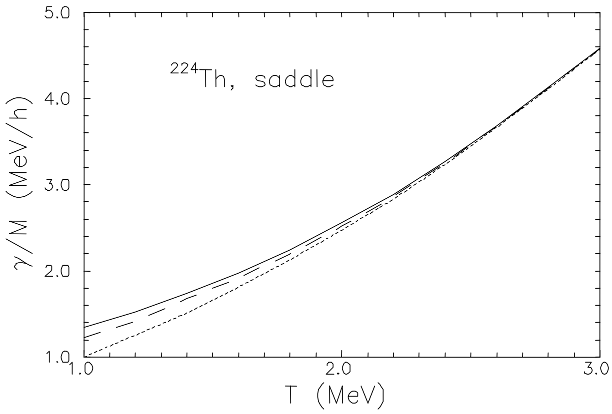


Fig. 8. The reduced friction coefficient $\beta_{qq} = \gamma_{qq}/M_{qq}$ (left) versus temperature. The dotted, dash and solid curves correspond to the values of the nuclear angular momentum equal to 0, 40 and 60 $\hbar$.

## 5. Summary

The microscopic approach for the transport coefficients (tensors of friction and inertia) for slow collective motion is reviewed which accounts in a natural way for the pairing interaction, shell effects and collective rotation.

As an application of the theory, the numerical results for the transport coefficients are presented for few composite systems formed in the so-called warm fusion reactions. It is demonstrated that both friction and inertia show a sensible dependence on the configurations of the mean field caused by the shell effects as well as by avoided crossings of single-particle levels. The dissipation decreases with decreasing temperature and growing pairing gap and falls well below the values of common "macroscopic models".

The semi analytical expressions are suggested for the temperature dependence of those combinations of the transport coefficients, which govern the fission process.

At the excitations corresponding to the temperatures $T \geq 1\,\text{MeV}$ the shell correction to the energy practically does not depend on nuclear rotation. The friction and mass parameters obtained within the linear response theory for the same excitations are rather stable with respect to rotations *provided* that the contributions from the spurious states arising due to the violation of rotational symmetry are removed.

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## ТРАНСПОРТНІ КОЕФІЦІЄНТИ ПОВІЛЬНОГО КОЛЕКТИВНОГО РУХУ

**Ф. О. Іванюк**

Було вивчено колективний рух ізоскалярного типу при скінченних енергіях збудження та зосереджено увагу на повільному через наявність великих сил тертя русі. Подано огляд розповсюдження теорії на випадок низьких енергій збудження, при яких важливі оболонкові ефекти та парні кореляції. Також розглядаються ядра, що обертаються. Як застосування теорії розраховано транспортні коефіцієнти для кількох об’єднаних систем, що утворюються в так званих реакціях теплого злиття, які застосовуються для синтезу надважких елементів.

## ТРАНСПОРТНЫЕ КОЭФФИЦИЕНТЫ МЕДЛЕННОГО КОЛЛЕКТИВНОГО ДВИЖЕНИЯ

**Ф. А. Иванюк**

Было изучено коллективное движение изоскалярного типа при конечных энергиях возбуждения и сконцентрировано внимание на медленном из-за наличия больших сил трения движении. Дан обзор обобщения теории на случай малых энергий возбуждения, при которых существенны оболочечные эффекты и парные корреляции. Рассматриваются также вращающиеся ядра. В качестве применения теории рассчитаны транспортные коэффициенты для некоторых составных систем, которые образуются в так называемых реакциях теплого слияния, используемых для синтеза сверхтяжелых элементов.

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