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KINETIC ENERGY DISSIPATION IN HEAVY-ION COLLISIONS

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Федотов С.И., Джолос Р.В., Картавенко В.Г. E4 - 12281

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Основной вклад в диссипацию энергии дают не пропорциональные скорости силы трения, а явно зависящий от времени потенциал взаимодействия тяжелых ионов, перенормированный с учетом возбуждения ядер.

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Kinetic energy dissipation mechanism is considered in deep inelastic heavy-ion collisions. It is shown that the significant part of the kinetic energy loss can be explained by the excitation of the nuclear matter multipole vibrations.

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1. Introduction

Damping of the energy of the relative motion - the degree of the inelasticity of the collision process - determines main characteristics of the deep inelastic collisions of heavy ions[1], angular and mass distributions of the reaction products[2]. So, the elucidation of the energy damping mechanism allows the understanding of the hole reaction course.

Dissipation of the kinetic energy characterizes the reaction time, since in the reactions the energy of the relative motion always partly converts into the inner excitation energy, and the process of establishment of equilibrium is not finished during the heavy-ion deep inelastic collision. This fact gives us a possibility of useing the value of the kinetic energy loss as a measure of the reaction time, that is to get information about the development of the collision process in time.

The scale of the kinetic energy loss (100-300) MeV[3] tells us that the excited nuclear states due to the large value of the excitation energy can in principle be of the complicated structure. But since the time of the energy loss is short ($\sim 10^{-22}$ sec)[4], some coherent mechanism of the energy damping may exist. It means that the doorway states in the reaction can be of the collective type. It follows from the large value of the energy loss that first of all it is necessary to take into account high frequency

modes. Among them the most important are the multipole vibrations of the nuclear matter density (giant resonances)[5,6].

In the present paper we shall try to explain the effect of the kinetic energy dissipation in the deep inelastic collisions of heavy ions based on the assumption about the preferential excitation of giant resonances.

2. Equations of motion

From the variety of dynamical variables describing the process of heavy-ion collisions, we single out the coordinates of the relative distance $\vec{R}$ and the amplitudes $\alpha_{n\ell m}$, characterizing nuclear density vibrations[7]. The Hamiltonian of such a system can be written as a sum of three terms:

$$H = T_{kin} + H_0(\dot{\alpha},\alpha) + V(\vec{R},\alpha), \qquad (1)$$

where T_{kin} is the kinetic energy, $H_0(\dot{\alpha},\alpha)$ is the sum of the inner Hamiltonians of the interacting nuclei. From many excited nuclear states, we conserved in H_0 only multipole vibrations of the nuclear matter density. The last term in (1) is the potential energy of the colliding nuclei. It depends through the amplitudes $\alpha_{n\ell m}$ on the inner nuclear states. This term contains average nucleus-nucleus interaction potential $U(R)$ independent of $\alpha_{n\ell m}$ and the coupling term of the relative motion with the density vibrations $H_{int}(\vec{R},\alpha)$:

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In order to get $V(\vec{R},\alpha)$ we can use the folding procedure together with the expression for the densities $\rho_1(\vec{r},\alpha)$ and $\rho_2(\vec{r},\alpha)$ of the colliding nuclei[8]. This procedure is quite satisfactory for the description of the peripheral reactions and gives us the following expression for $V(\vec{R},\alpha)$:

$$V(\vec{R},\alpha) = \int d^3r_1\, d^3r_2\, \rho_1(\vec{r}_1,\alpha)\, v_{12}(\vec{R}+\vec{r}_2-\vec{r}_1)\, \rho_2(\vec{r}_2,\alpha). \qquad (2)$$

For the nuclear density $\rho(\vec{r},\alpha)$ the following expansion can be used[7]:

$$\rho(\vec{r},\alpha) = \rho_0(\vec{r}) + \rho_0(0) \sum_{n\ell m} j_\ell(K_{n\ell} r)\, Y^*_{\ell m}(\vec{r}/r)\, \alpha_{n\ell m},$$

where $\rho_0(\vec{r})$ is the nuclear ground state density, and $K_{n\ell}$ are the wave numbers, characterizing eigenmodes of nuclear density vibrations.

The nuclear part of the term in (2) independent of α can be given[8] in the proximity form[9]. This potential will be used in the present paper. The analogous result for $U(R)$ is obtained in the energy density formalism[10].

Linear in α terms in (2) describe the coupling of the relative motion with the density vibrations. Assuming that the density fluctuations are relatively small, we neglect in the present work the quadratic in α terms.
As a result we get for $H_{int}(\vec{R},\alpha)$: [1]

$$H_{int} = \sum_{n\ell m} \tilde{\gamma}_{n\ell m}(\vec{R})\, \alpha_{n\ell m}$$

If the nucleon-nucleon potential is given by the expression [11]:

$$v_{12}(\vec{r}_1-\vec{r}_2) = f_{in} \left(\frac{d\rho_0(0)}{d\epsilon_F}\right)^{-1} \delta(\vec{r}_1-\vec{r}_2),$$

where f_{in} is the constant of the effective interaction of nucleons in nucleus and $d\rho_0(0)/d\epsilon_F$ is the derivative of the density with respect to the Fermi energy, then $\tilde{\gamma}_{n\ell m}$ takes the form

$$\tilde{\gamma}^{(1)}_{n\ell m}(\vec{R}) = \rho_0(0) \left(\frac{d\rho_0(0)}{d\epsilon_F}\right)^{-1} f_{in}\, A_{(1)}\, F_{n\ell}(R)\, Y_{\ell m}(\vec{R}/R).$$

In the last expression the form factor $F_{n\ell}$ includes the parameters characterizing the size of the interacting nuclei, and $A_{(1)}$ is the number of nucleons in the target nucleus.

[1] In $\alpha_{n\ell m}$ we omit the indices referring them to one of the colliding nucleus and suppose H_{int} contains the terms pertaining to both interacting nuclei.

The expression for H_{int} can be obtained also in the another more phenomenological way. To this end let us use the fact that the parameters of the potential $U(R)$ such as nuclear radii $R_{1,2}$ are in principle the dynamical variables depending on α :

$$R_{1,2}(\vartheta,\varphi) = R_{1,2}\left(1 + \sum_{n\ell m} (K_{n\ell} R_{1,2})^{-1} j_\ell'(K_{n\ell} R_{1,2})\, \alpha_{n\ell m}\, Y^*_{\ell m}(\vartheta,\varphi)\right). \quad (3)$$

Substituting (3) in the expression for $U(R)$, expanding it in powers of $\alpha_{n\ell m}$ and taking into account only the first order terms in α , we get:

$$H_{int} = \sum_{n\ell m} \tilde{\gamma}_{n\ell m}(\vec{R})\, \alpha_{n\ell m},$$

$$\tilde{\gamma}_{n\ell m}(\vec{R}) = R_{1,2} \frac{\partial U}{\partial R_{1,2}} \sum_{n\ell m} j_\ell'(K_{n\ell} R_{1,2}) \cdot (K_{n\ell} R_{1,2})^{-1} Y^*_{\ell m}(\vec{R}/R).$$

Let us get the equations of motion for $\vec{R}$ and $\alpha_{n\ell m}$:

$$i\hbar\,\dot{\vec{R}} = [H, \vec{R}] = -\frac{\hbar^2}{M}\vec{\nabla}_R,$$

$$-\hbar^2 \ddot{\vec{R}} = [H,[H,\vec{R}]] = \frac{\hbar^2}{M}\left(\vec{\nabla} U(R) + \sum_{n\ell m} \vec{\nabla}\tilde{\gamma}_{n\ell m}(\vec{R}) \cdot \alpha_{n\ell m}\right). \quad (4)$$

And for $\alpha_{n\ell m}$

$$-\ddot{\alpha}_{n\ell m} = \omega^2_{n\ell}\alpha_{n\ell m} + \Gamma_{n\ell}\dot{\alpha}_{n\ell m} + \frac{\hbar^2\omega^2_{n\ell}}{2 f_{in}\rho_0^2(0)\mathcal{N}_{n\ell}} \frac{d\rho_0(0)}{d\epsilon_F}\tilde{\gamma}_{n\ell m}(\vec{R}), \quad (5)$$

where $\mathcal{N}_{n\ell} = \int_0^{R_1} z^2\, dz\, j_\ell^2(K_{n\ell} z)$.

In deducing equation (5), the harmonic approximation for the density vibrations has been used. Moreover, the damping $\Gamma_{n\ell}\dot{\alpha}_{n\ell m}$ has been included into this equation to describe effectively the coupling of the density vibrations with the other nuclear degrees of freedom not included in the Hamiltonian. The equation analogous to (5) but for the variable describing longitudinal nuclear deformation in fission has been analyzed in /12/.

Solving (5) with respect to $\alpha_{n\ell m}$ and substituting the result into (4), we get:

$$M\ddot{\vec{R}} + \vec{\nabla} U(\vec{R}) = \frac{2}{\hbar}\sum_{n\ell m} \vec{\nabla}\tilde{\gamma}^*_{n\ell m}(\vec{R}) \frac{\hbar\omega_{n\ell}\; d\rho_0(0)/d\epsilon_F}{4 f_{in}\rho_0^2(0)\mathcal{N}_{n\ell}} \cdot \frac{\omega_{n\ell}}{\Omega_{n\ell}} \times$$

$$\times \int_0^t \exp\left(-\tfrac{1}{2}\Gamma_{n\ell}(t-t')\right) \sin\Omega_{n\ell}(t-t') \cdot \tilde{\gamma}^*_{n\ell m}(\vec{R}(t'))\; dt', \quad (6)$$

where $t = 0$ is the moment when nuclear forces begin to act, and $\Omega^2_{n\ell} = \omega^2_{n\ell} - \frac{1}{4}\Gamma^2_{n\ell}$.

The presence of the integral term in (6) means that the character of the relative motion at the moment t is determined by the whole preceding motion along the trajectory.

In principle equation (6) can exactly be solved numerically, but for the comparison with the phenomenological models it is usefull to expand the quantity $\tilde{\gamma}_{n\ell m}(\vec{R}(t'))$ under the integral in (6) in powers of $(t-t')$:

$$\tilde{\gamma}_{n\ell m}(\vec{R}(t')) = \tilde{\gamma}_{n\ell m}(\vec{R}(t)) - \dot{\vec{R}}\vec{\nabla}\tilde{\gamma}_{n\ell m}(\vec{R}(t)) \cdot (t-t') + \ldots$$

In fact it will be the expansion in powers of the velocity $\dot{\vec{R}}(t)$ and of higher derivatives of $\vec{R}(t)$. Such an expansion has sense if the velocity of the relative motion is small in comparison with the characteristic velocities of inner motion or the widths $\Gamma_{n\ell}$ are large so that $\tilde{\gamma}_{n\ell m}$ is changed (slightly) during the time $\sim \frac{\hbar}{\Gamma_{n\ell}}$.

As a result the integro-differential equation (6) becomes differential equation. The first term in the right-hand side of (6) independent of time derivatives of $\vec{R}(t)$ $-\delta U(R,t)$ is the renormalization of the potential U . It is necessary to stress that this term is generated by the excitation of nuclei and depends on time. The second term is proportional to $\dot{\vec{R}}(t)$ and can be interpreted as a frictional force. The subsequent term proportional to $\ddot{\vec{R}}(t)$ is the renormalization of the reduced mass and so on. In the present work we consider only the first two terms. In such an

approximation equation (6) can be rewritten in the following way:

$$M\ddot{\vec{R}} + \vec{\nabla} U(R) = \sum_{n\ell m} \frac{\vec{\nabla} |\tilde{\gamma}_{n\ell m}(\vec{R})|^2}{\hbar \omega_{n\ell}} \cdot \frac{\hbar \omega_{n\ell}}{4 f_{in} \rho_0^2(0) \mathcal{N}_{n\ell}} \frac{d\rho_0(0)}{d\epsilon_F} \times$$

$$\times \left(1 - \exp\left(-\tfrac{1}{2}\Gamma_{n\ell} t\right) \left(\cos \Omega_{n\ell} t + \frac{\Gamma_{n\ell}}{2\Omega_{n\ell}} \sin \Omega_{n\ell} t\right)\right) -$$

$$- \sum_{n\ell m} \frac{?}{\hbar \omega_{n\ell}^3} \vec{\nabla} \tilde{\gamma}^{*}_{n\ell m}(\vec{R}) \cdot (\vec{R}\cdot\vec{\nabla}) \tilde{\gamma}_{n\ell m}(\vec{R}) \frac{\hbar \omega_{n\ell}}{4 f_{in} \rho_0^2(0) \mathcal{N}_{n\ell}} \frac{d\rho_0(0)}{d\epsilon_F} \times$$

$$\times \left(\Gamma_{n\ell} - \exp\left(-\tfrac{1}{2}\Gamma_{n\ell} t\right)\left(\left(\Gamma_{n\ell} + \omega_{n\ell}^2 t\right) \cos \Omega_{n\ell} t - \right.\right.$$

$$\left.\left. - \left(1 - \tfrac{1}{2}\Gamma_{n\ell} t\right) \frac{\omega_{n\ell}^2}{\Omega_{n\ell}} \sin \Omega_{n\ell} t - \frac{\Gamma_{n\ell}^2}{2\Omega_{n\ell}} \sin \Omega_{n\ell} t\right)\right).$$

The dependence of the additional potential δU and the form-factor of the frictional force on time is a consequence of the memory of the system about the history of the collision process. Disregard of this effect is equivalent to changing of the low limit of integration in (6) from $t = 0$ to $t \to -\infty$, as in linear response theory /13/. In this case the additional potential δU and the form factor of friction force are independent of time and take asymptotic values.

The results of calculations of the potential $\delta U(R,t)$:

$$\delta U(R,t) = \sum_{n\ell m} \frac{|\tilde{\gamma}_{n\ell m}(R)|^2}{4 f_{in} \rho_0^2(0) \mathcal{N}_{n\ell}} \frac{d\rho_0(0)}{d\epsilon_F} \left(1 - \exp\left(-\tfrac{1}{2}\Gamma_{n\ell} t\right) \times \right. \qquad (7)$$

$$\left. \times \left(\cos \Omega_{n\ell} t + \Gamma_{n\ell}/2\Omega_{n\ell} \times \sin \Omega_{n\ell} t\right)\right)$$

are shown in fig. 1 for the reaction $A_2 + Th$ /14/. It is seen that δU takes an asymptotic value at $t \sim 10^{-22}$ sec.

According to the estimates made in the phenomenological analysis of the deep inelastic collisions of heavy ions, this time is of the same order as the kinetic energy loss time. Consequently,

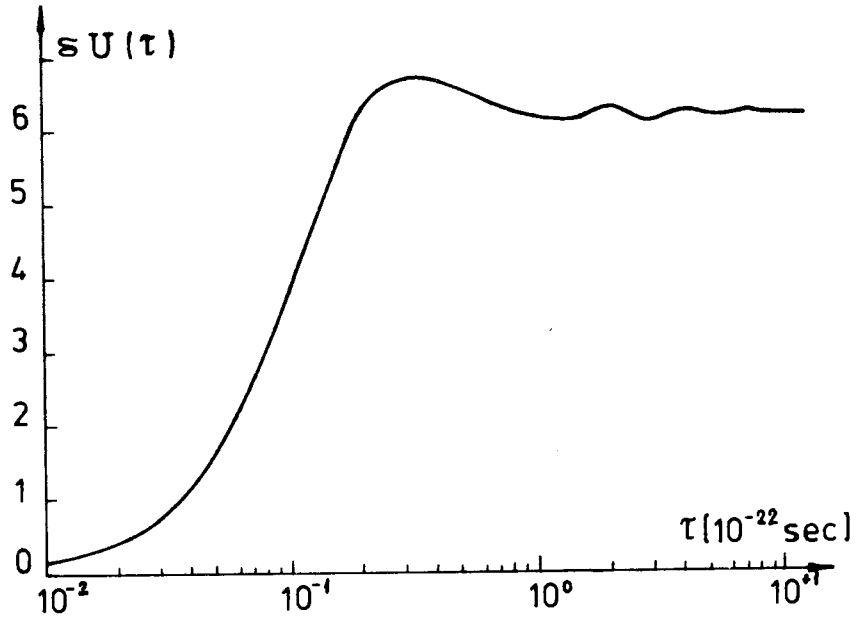

Fig. 1. Dependence on time of the additional potential $\delta U(R,t)$. (arbitrary units).

to investigate the kinetic energy damping mechanism it is necessary to conserve the time dependence of δU. So, we cannot include δU into the static potential U. The time dependence of δU is a source of the dissipation of the relative motion energy. The ideology of the linear response corresponds more to the relatively slow processes such as fission /15/.

3. Dissipation of the kinetic energy

Let us start from the consideration of frictional forces which are traditionally included in the phenomenological models. The coefficient of radial friction calculated by us is significantly

smaller (by 50 - 100 times) than it is required for the explanation of the experimental results only by the frictional forces.

It contradicts the usual assumptions. Thus it is necessary to investigate the contribution to the energy damping of the additional potential δU . Usually, this effect was not taken into account /13/ because of neglect of δU time dependence[2].

Neglecting in (6') the frictional forces and integrating this equation from $t=0$ (the moment when nuclear forces begin to act) up to $t=\tau_{int}$, where τ_{int} is the collision time, we get the following expression for the excitation energy of the interacting nuclie $E^*(\tau)$ (i.e.,for the kinetic energy loss):

$$E^*(\tau) = \int_0^{\tau} \frac{\partial U(R,t)}{\partial t}\, dt . \qquad (8)$$

In this work we will not perform detailed trajectory calculations, but confine ourselves to qualitative estimates. To this end in the right-hand side of (8) we change the relative distance between the colliding nuclei R , by the average distance $\langle R\rangle$. Taking into account (7), we get from (8):

$$E^*(\tau) = \delta U(\langle R\rangle, \tau) = \sum_{n\ell m} \frac{|\tilde{\delta}_{n\ell m}(\langle R\rangle)|^2}{4 f_{in}\, \rho_0^2(0)\, \mathcal{N}_{n\ell}} \frac{d\rho_0(0)}{d\epsilon_F} \times$$

$$\times \left(1 - \exp\left(-\frac{1}{2}\Gamma_{n\ell} t\right)\left(\cos\Omega_{n\ell} t + \frac{\Gamma_{n\ell}}{2\Omega_{n\ell}} \sin\Omega_{n\ell} t\right)\right) .$$

As is seen from fig. 1 the dependence of δU on τ has a threshold character and δU takes an asymptotic value at $\tau \approx 10^{-22}$ sec. This value of δU determines the maximum value of the kinetic energy loss, which can be explained using the investigated mechanism.

[2] It is necessary to mention the paper /6/ devoted mainly to the nuclear Cherankov effect, in which the threshold dependence of δU on time was pointed out.

The experimental information about the dependence of the kinetic energy loss on the interaction time can be obtained analyzing correlations between the energy loss and the number of transferred nucleons or the angle of emission.

Such an analysis requires additional assumptions about the reaction mechanism, thus introducing new uncertainties of the results. In /16/ the correlations between the kinetic energy losses and the widths of charge distributions of the reaction products σ_z^2 have been analyzed.

Considering nucleon transfer as a diffusion process and describing this process by the Fokker-Planck equation, we get a linear relation between σ_z^2 and the interaction time τ (if diffusion coefficient D_z is a constant):

$$\sigma_z^2 = 2 D_z \tau$$

So, by measuring the dependence of the kinetic energy loss on the width of charge distribution, it is possible to obtain a dependence of the energy loss on the interaction time. An experimental dependence of $E^*(\tau)$ on τ is qualitatively the same as in fig. 1.

In order to estimate quantitatively the scale of the energy loss which can be explained by the investigated mechanism, we calculate the excitation energy of Th - E^* ($\tau \approx 10^{-22}$sec) in the reaction A_2+Th (E_{lab} =388 MeV) /14/ as a function of $\Delta R = R_1 + R_2 - R$. The results are shown in fig. 2. When ΔR =2,5-3,0fm that corresponds to the maximum value of ΔR in the classical trajectory calculations based on equation (6'), the energy losses are of an order of (70 - 100) MeV. The maximum energy losses found in this reaction experimentally are (120-140) MeV. But they include nuclear deformation (what is important for the exit channel

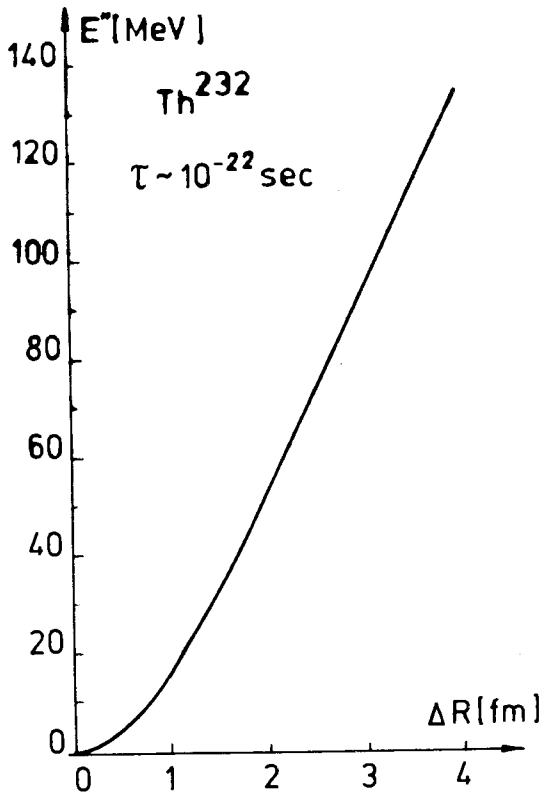

Fig. 2. Dependence of Th excitation energy E^* ($\tau \approx 10^{-22}$ sec) in the reaction $Ar + Th$ (E_{lab} = 388 MeV) on $\Delta R = R_1 + R_2 - R$.

potential), Ar excitation energy and the rotational energy losses due to the dissipation of the relative angular momentum.

The coefficient of tangential friction appeared to be large enough in our calculations and close to the value used in phenomenological models. If the relative angular momentum ℓ is of the order $\ell \approx 90$ the rotational energy losses due to tangential friction are $\sim$ 30 MeV.

Thus, the significant part of the kinetic energy losses can be explained by the mechanism investigated in this paper.

In the following paper we shall perform detailed trajectory calculations of heavy-ion deep inelastic collisions on the basis of equation (6').

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If the nucleon-nucleon potential is given by the expression [11]:

$$v_{12}(\vec{r}_1-\vec{r}_2) = f_{in} \left(\frac{d\rho_0(0)}{d\epsilon_F}\right)^{-1} \delta(\vec{r}_1-\vec{r}_2),$$

where f_{in} is the constant of the effective interaction of nucleons in nucleus and $d\rho_0(0)/d\epsilon_F$ is the derivative of the density with respect to the Fermi energy, then $\tilde{\gamma}_{n\ell m}$ takes the form

$$\tilde{\gamma}^{(1)}_{n\ell m}(\vec{R}) = \rho_0(0) \left(\frac{d\rho_0(0)}{d\epsilon_F}\right)^{-1} f_{in}\, A_{(1)}\, F_{n\ell}(R)\, Y_{\ell m}(\vec{R}/R).$$

In the last expression the form factor $F_{n\ell}$ includes the parameters characterizing the size of the interacting nuclei, and $A_{(1)}$ is the number of nucleons in the target nucleus.

[1] In $\alpha_{n\ell m}$ we omit the indices referring them to one of the colliding nucleus and suppose H_{int} contains the terms pertaining to both interacting nuclei.

The expression for H_{int} can be obtained also in the another more phenomenological way. To this end let us use the fact that the parameters of the potential $U(R)$ such as nuclear radii $R_{1,2}$ are in principle the dynamical variables depending on α :

$$R_{1,2}(\vartheta,\varphi) = R_{1,2}\left(1 + \sum_{n\ell m} (K_{n\ell} R_{1,2})^{-1} j_\ell'(K_{n\ell} R_{1,2})\, \alpha_{n\ell m}\, Y^*_{\ell m}(\vartheta,\varphi)\right). \quad (3)$$

Substituting (3) in the expression for $U(R)$, expanding it in powers of $\alpha_{n\ell m}$ and taking into account only the first order terms in α , we get:

$$H_{int} = \sum_{n\ell m} \tilde{\gamma}_{n\ell m}(\vec{R})\, \alpha_{n\ell m} ,$$

$$\tilde{\gamma}_{n\ell m}(\vec{R}) = R_{1,2} \frac{\partial U}{\partial R_{1,2}} \sum_{n\ell m} j_\ell'(K_{n\ell} R_{1,2}) \cdot (K_{n\ell} R_{1,2})^{-1}\, Y^*_{\ell m}(\vec{R}/R).$$

Let us get the equations of motion for $\vec{R}$ and $\alpha_{n\ell m}$:

$$i\hbar\, \dot{\vec{R}} = [H, \vec{R}] = -\frac{\hbar^2}{M} \vec{\nabla}_R ,$$

$$-\hbar^2 \ddot{\vec{R}} = [H,[H,\vec{R}]] = \frac{\hbar^2}{M}\left(\vec{\nabla} U(R) + \sum_{n\ell m} \vec{\nabla} \tilde{\gamma}_{n\ell m}(\vec{R}) \cdot \alpha_{n\ell m}\right). \quad (4)$$

And for $\alpha_{n\ell m}$

$$-\hbar^2 \ddot{\alpha}_{n\ell m} = \hbar^2 \omega_{n\ell}^2 \alpha_{n\ell m} + \hbar^2 \Gamma_{n\ell} \dot{\alpha}_{n\ell m} + \frac{\hbar^2 \omega_{n\ell}^2}{2 f_{in} \rho_0^2(0) \mathcal{N}_{n\ell}} \frac{d\rho_0(0)}{d\epsilon_F} \tilde{\gamma}_{n\ell m}(\vec{R}), \quad (5)$$

where $\mathcal{N}_{n\ell} = \int_0^{R_1} z^2\, dz\, j_\ell^2(K_{n\ell} z)$.

In deducing equation (5), the harmonic approximation for the density vibrations has been used. Moreover, the damping $\Gamma_{n\ell} \dot{\alpha}_{n\ell m}$ has been included into this equation to describe effectively the coupling of the density vibrations with the other nuclear degrees of freedom not included in the Hamiltonian. The equation analogous to (5) but for the variable describing longitudinal nuclear deformation in fission has been analyzed in /12/.

Solving (5) with respect to $\alpha_{n\ell m}$ and substituting the result into (4), we get:

$$M\ddot{\vec{R}} + \vec{\nabla} U(\vec{R}) = \frac{2}{\hbar} \sum_{n\ell m} \vec{\nabla} \tilde{\gamma}_{n\ell m}(\vec{R}) \frac{\hbar\omega_{n\ell}\, d\rho_0(0)/d\epsilon_F}{4 f_{in} \rho_0^2(0) \mathcal{N}_{n\ell}} \cdot \frac{\omega_{n\ell}}{\Omega_{n\ell}} \times$$

$$\times \int_0^t \exp\left(-\tfrac{1}{2}\Gamma_{n\ell}(t-t')\right) \sin \Omega_{n\ell}(t-t') \cdot \tilde{\gamma}^*_{n\ell m}(\vec{R}(t'))\, dt' , \quad (6)$$

where $t = 0$ is the moment when nuclear forces begin to act, and $\Omega_{n\ell}^2 = \omega_{n\ell}^2 - \tfrac{1}{4}\Gamma_{n\ell}^2$.

The presence of the integral term in (6) means that the character of the relative motion at the moment t is determined by the whole preceding motion along the trajectory.

In principle equation (6) can exactly be solved numerically, but for the comparison with the phenomenological models it is usefull to expand the quantity $\tilde{\gamma}_{n\ell m}(\vec{R}(t'))$ under the integral in (6) in powers of $(t-t')$:

$$\tilde{\gamma}_{n\ell m}(\vec{R}(t')) = \tilde{\gamma}_{n\ell m}(\vec{R}(t)) - \dot{\vec{R}} \vec{\nabla} \tilde{\gamma}_{n\ell m}(\vec{R}(t)) \cdot (t-t') + \ldots$$

In fact it will be the expansion in powers of the velocity $\dot{\vec{R}}(t)$ and of higher derivatives of $\vec{R}(t)$. Such an expansion has sense if the velocity of the relative motion is small in comparison with the characteristic velocities of inner motion or the widths $\Gamma_{n\ell}$ are large so that $\tilde{\gamma}_{n\ell m}$ is changed (slightly) during the time $\sim \frac{\hbar}{\Gamma_{n\ell}}$.

As a result the integro-differential equation (6) becomes differential equation. The first term in the right-hand side of (6) independent of time derivatives of $\vec{R}(t)$ $-\delta U(R,t)$ is the renormalization of the potential U . It is necessary to stress that this term is generated by the excitation of nuclei and depends on time. The second term is proportional to $\dot{\vec{R}}(t)$ and can be interpreted as a frictional force. The subsequent term proportional to $\ddot{\vec{R}}(t)$ is the renormalization of the reduced mass and so on. In the present work we consider only the first two terms. In such an

approximation equation (6) can be rewritten in the following way:

$$M\ddot{\vec{R}} + \vec{\nabla} U(R) = \sum_{n\ell m} \frac{\vec{\nabla}\,|\tilde{\gamma}_{n\ell m}(\vec{R})|^2}{\hbar\omega_{n\ell}} \cdot \frac{\hbar\omega_{n\ell}}{4\ell_{in}\rho_0^2(0)\mathcal{N}_{n\ell}} \frac{d\rho_0(0)}{d\epsilon_F} \times$$

$$\times\left(1-\exp\left(-\tfrac{1}{2}\Gamma_{n\ell}t\right)\left(\cos\Omega_{n\ell}t + \frac{\Gamma_{n\ell}}{2\Omega_{n\ell}}\sin\Omega_{n\ell}t\right)\right) -$$

$$-\sum_{n\ell m} \frac{?}{\hbar\omega_{n\ell}^3} \vec{\nabla}\tilde{\gamma}^{*}_{n\ell m}(\vec{R})\cdot(\vec{R}\cdot\vec{\nabla})\tilde{\gamma}_{n\ell m}(\vec{R}) \frac{\hbar\omega_{n\ell}}{4\ell_{in}\rho_0^2(0)\mathcal{N}_{n\ell}} \frac{d\rho_0(0)}{d\epsilon_F} \times$$

$$\times\left(\Gamma_{n\ell} - \exp\left(-\tfrac{1}{2}\Gamma_{n\ell}t\right)\left(\left(\Gamma_{n\ell}+\omega_{n\ell}^2 t\right)\cos\Omega_{n\ell}t -\right.\right.$$

$$\left.\left.-\left(1-\tfrac{1}{2}\Gamma_{n\ell}t\right)\frac{\omega_{n\ell}^2}{\Omega_{n\ell}}\sin\Omega_{n\ell}t - \frac{\Gamma_{n\ell}^2}{2\Omega_{n\ell}}\sin\Omega_{n\ell}t\right)\right).$$

The dependence of the additional potential δU and the form-factor of the frictional force on time is a consequence of the memory of the system about the history of the collision process. Disregard of this effect is equivalent to changing of the low limit of integration in (6) from $t=0$ to $t\to-\infty$, as in linear response theory[13]. In this case the additional potential δU and the form factor of friction force are independent of time and take asymptotic values.

The results of calculations of the potential $\delta U(R,t)$:

$$\delta U(R,t) = \sum_{n\ell m} \frac{|\tilde{\gamma}_{n\ell m}(R)|^2}{4\ell_{in}\rho_0^2(0)\mathcal{N}_{n\ell}} \frac{d\rho_0(\omega)}{d\epsilon_F}\left(1-\exp\left(-\tfrac{1}{2}\Gamma_{n\ell}t\right)\times\right. \qquad (7)$$

$$\left.\times\left(\cos\Omega_{n\ell}t + \Gamma_{n\ell}/2\Omega_{n\ell}\times\sin\Omega_{n\ell}t\right)\right)$$

are shown in fig. 1 for the reaction $Ar+Th$ [14]. It is seen that δU takes an asymptotic value at $t \sim 10^{-22}$ sec.

According to the estimates made in the phenomenological analysis of the deep inelastic collisions of heavy ions, this time is of the same order as the kinetic energy loss time. Consequently,

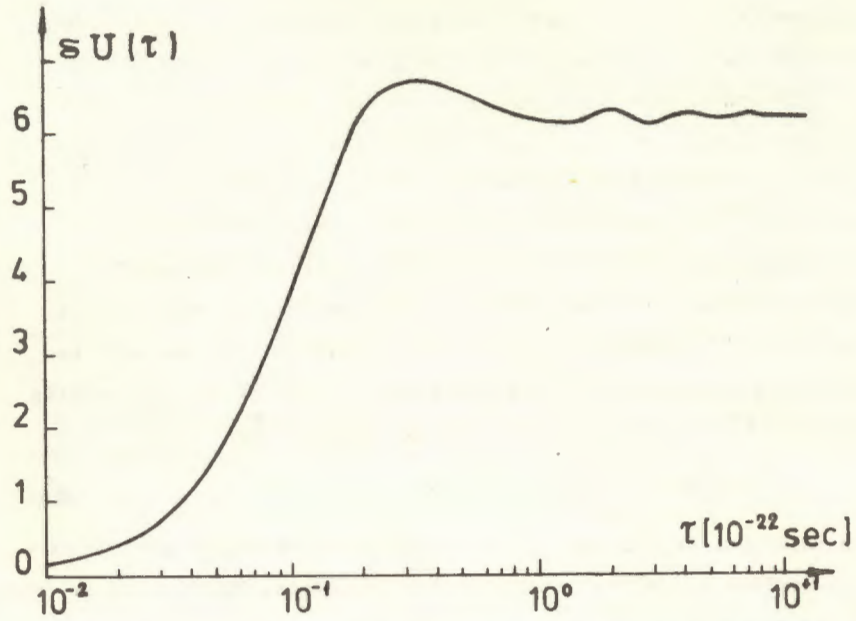

Fig. 1. Dependence on time of the additional potential $\delta U(R,t)$. (arbitrary units).

to investigate the kinetic energy damping mechanism it is necessary to conserve the time dependence of δU. So, we cannot include δU into the static potential U. The time dependence of δU is a source of the dissipation of the relative motion energy. The ideology of the linear response corresponds more to the relatively slow processes such as fission[15].

3. Dissipation of the kinetic energy

Let us start from the consideration of frictional forces which are traditionally included in the phenomenological models. The coefficient of radial friction calculated by us is significantly

smaller (by 50 - 100 times) than it is required for the explanation of the experimental results only by the frictional forces.

It contradicts the usual assumptions. Thus it is necessary to investigate the contribution to the energy damping of the additional potential δU . Usually, this effect was not taken into account /13/ because of neglect of δU time dependence[2].

Neglecting in (6') the frictional forces and integrating this equation from $t=0$ (the moment when nuclear forces begin to act) up to $t=\tau_{int}$, where τ_{int} is the collision time, we get the following expression for the excitation energy of the interacting nuclie $E^*(\tau)$ (i.e.,for the kinetic energy loss):

$$E^*(\tau) = \int_0^{\tau} \frac{\partial U(R,t)}{\partial t}\, dt . \qquad (8)$$

In this work we will not perform detailed trajectory calculations, but confine ourselves to qualitative estimates. To this end in the right-hand side of (8) we change the relative distance between the colliding nuclei R , by the average distance $\langle R\rangle$. Taking into account (7), we get from (8):

$$E^*(\tau) = \delta U(\langle R\rangle, \tau) = \sum_{n\ell m} \frac{|\tilde{\delta}_{n\ell m}(\langle R\rangle)|^2}{4 t_{in}\, \rho_0^2(0)\, \mathcal{N}_{n\ell}} \frac{d\rho_0(\omega)}{d\epsilon_F} \times$$

$$\times \left(1 - \exp\left(-\frac{1}{\hbar}\Gamma_{n\ell} t\right)\left(\cos\Omega_{n\ell} t + \frac{\Gamma_{n\ell}}{\hbar\Omega_{n\ell}} \sin\Omega_{n\ell} t\right)\right).$$

As is seen from fig. 1 the dependence of δU on τ has a threshold character and δU takes an asymptotic value at $\tau \approx 10^{-22}$ sec. This value of δU determines the maximum value of the kinetic energy loss, which oan be explained using the investigated mechanism.

[2] It is necessary to mention the paper /6/ devoted mainly to the nuclear Cherankov effect, in which the threshold dependence of δU on time was pointed out.

The experimental information about the dependence of the kinetic energy loss on the interaction time can be obtained analyzing correlations between the energy loss and the number of transferred nucleons or the angle of emission.

Such an analysis requires additional assumptions about the reaction mechanism, thus introducing new uncertainties of the results. In /16/ the correlations between the kinetic energy losses and the widths of charge distributions of the reaction products σ_z^2 have been analyzed.

Considering nucleon transfer as a diffusion process and describing this process by the Fokker-Planck equation, we get a linear relation between σ_z^2 and the interaction time τ (if diffusion coefficient D_z is a constant):

$$\sigma_z^2 = 2 D_z \tau$$

So, by measuring the dependence of the kinetic energy loss on the width of charge distribution, it is possible to obtain a dependence of the energy loss on the interaction time. An experimental dependence of $E^*(\tau)$ on τ is qualitatively the same as in fig. 1.

In order to estimate quantitatively the scale of the energy loss which can be explained by the investigated mechanism, we calculate the excitation energy of Th - E^* ($\tau \approx 10^{-22}$sec) in the reaction A_2+Th (E_{lab} =388 MeV) /14/ as a function of $\Delta R = R_1+R_2-R$. The results are shown in fig. 2. When ΔR =2,5-3,0fm that corresponds to the maximum value of ΔR in the classical trajectory calculations based on equation (6'), the energy losses are of an order of (70 - 100) MeV. The maximum energy losses found in this reaction experimentally are (120-140) MeV. But they include nuclear deformation (what is important for the exit channel

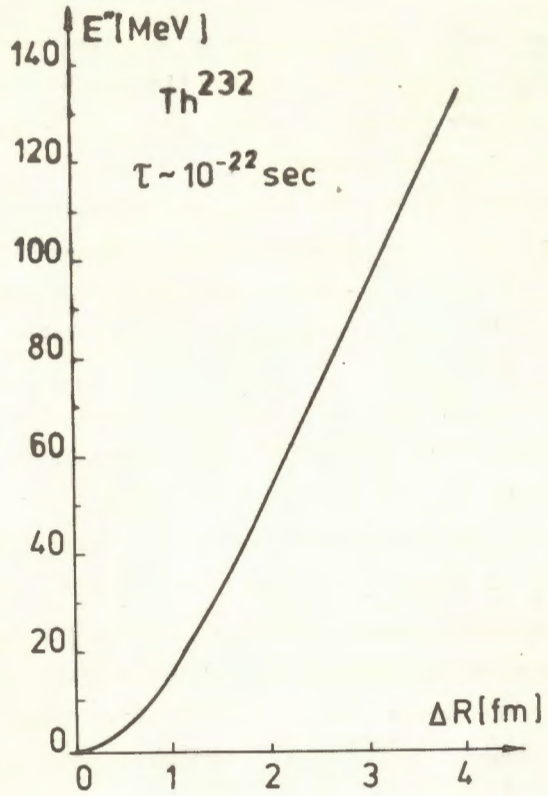

Fig. 2. Dependence of Th excitation energy E^* ($\tau \approx 10^{-22}$ sec) in the reaction $Ar + Th$ (E_{lab} = 388 MeV) on $\Delta R = R_1 + R_2 - R$.

potential), Ar excitation energy and the rotational energy losses due to the dissipation of the relative angular momentum.

The coefficient of tangential friction appeared to be large enough in our calculations and close to the value used in phenomenological models. If the relative angular momentum ℓ is of the order $\ell \approx 90$ the rotational energy losses due to tangential friction are ~ 30 MeV.

Thus, the significant part of the kinetic energy losses can be explained by the mechanism investigated in this paper.

In the following paper we shall perform detailed trajectory calculations of heavy-ion deep inelastic collisions on the basis of equation (6').

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