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PARTITION OF EXCITATION ENERGY BETWEEN REACTION PRODUCTS IN HEAVY ION COLLISIONS

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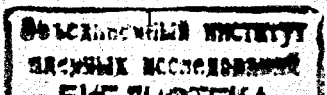
1. Introduction

The large value of the kinetic energy losses is an inherent feature of deep inelastic heavy ion collisions [1]. Energy distributions of the reaction products, correlations of the dissipated energy with other observables , especially the one that characterizes nucleon exchange have been investigated in a number of experiments (see in [1,2]).

Originally, the results of several early experiments were consistent with the assumption of a very rapid set-in of the thermal equilibrium in a dinuclear system. In this case the excitation energy is divided approximately proportionally to the fragment masses. However, later experiments [3,4] demonstrated that this assumption is not correct. Moreover, in the reactions $^{52}Cr+^{208}Pb$ [5], $^{238}U+^{124}Sn$, ^{110}Pd [6] a large part of the excitation energy is concentrated in the light fragments even for a large range of total energy losses. Nearly equal sharing of the excitation energy has been observed in the reactions $^{58}Ni + ^{197}Au$ [4], $^{56}Fe+^{165}Ho$ [7-9] and $^{74}Ge+^{165}Ho$ [10-13] for relatively large values of the total kinetic energy losses . With increasing total kinetic energy loss the division of the excitation energy approaches but never reaches the thermal equilibrium limit. Thus, these new experiments generated great interest in the problem of kinetic energy dissipation. It is important also to know how the excitation energy is distributed between the fragments for the reconstruction of the primary reaction product yields from measured yields of evaporation residues and for the calculations of the exotic nuclei production cross section.

In the theoretical models proposed for the description of deep inelastic collisions [14] the relative motion of nuclei is treated classically and the frictional forces are introduced to describe the kinetic energy dissipation. The calculation of frictional coefficients requires explicit formulation of the microscopical model including the coupling of relative motion to the intrinsic degrees of freedom [14-27]. These models are distinguished by intrinsic excitations to be considered: collective surface vibrations, giant resonances, non-coherent particle-hole excitations or nucleon exchange between nuclei. It is clear that the structure of excited states, the strength of the coupling of different excitation modes with a relative motion will influence excitation energy distribution between fragments.

In the present work the microscopic model which is based on the assumption that the average fields of the colliding nuclei are not disturbed drastically during the collision [28-30] is applied to the description of excitation energy division between the reaction products. The main effect of the nuclear average fields is the multinucleon



transfer between fragments and inelastic processes (particle-hole excitations) in fragments. The method allows us to compare the relative role of the particle-hole excitations and nucleon exchange in the process of the kinetic energy dissipation and to calculate the correlations between the characteristics of the nucleon exchange and the total excitation energy of nuclei. The results of calculations of the excitation energy distribution between nuclei will be shown for different projectile-target combinations and bombarding energies.

2. Model

The model is based on the assumption that the colliding nuclei moving approximately along the classical trajectories conserve mainly their individual properties at the kinetic energies under consideration. Each nucleus is presented by a potential well (Woods-Saxon potential) with nucleons in it. During the interaction time both potential wells act on the nucleons in each nucleus causing transitions of nucleons between single-particle states. The transitions taking place in every nucleus are particle-hole excitations while those occurring between partner-nuclei are nucleon exchanges. Thus, in the proposed model the single-particle mechanism is considered as the main mechanism of excitation and dissipation. The two-body nucleon collisions are taken into account only through the temperature-dependent occupation number of the single-particle states. Such effects as excitations of high- and low-lying collective states of the interacting nuclei and of the combined system connected with the effective residual forces are neglected. Although the contribution to dissipation can come from easily excited surface vibrations the adiabaticity of a relative motion with respect to these vibrations decreases their effect.

The total Hamiltonian of a dinuclear system $\hat{H}$ is taken in the form

$$\hat{H} = \hat{H}_{rel} + \hat{H}_{in} + \hat{V}_{int}. \qquad (1)$$

The Hamiltonian of a relative motion

$$\hat{H}_{rel} = \frac{\hat{\mathbf{P}}^2}{2\mu} + \hat{U}(\hat{\mathbf{R}})$$

consists of the kinetic energy and nucleus-nucleus interaction potential $\hat{U}(\hat{\mathbf{R}})$. Here $\hat{\mathbf{R}}$ is a relative distance between the center of mass of fragments, $\hat{\mathbf{P}}$ is a conjugate momentum, μ is a reduced mass of the system. The last two terms in (1) describe the intrinsic motion of nuclei and the coupling between relative and intrinsic motion.

Employing the Ehrenfest theorem it is easy to obtain from (1) the classical limit of equations of motion for the macroscopic collective variables $\mathbf{R}$ and $\mathbf{P}$:

$$\dot{\mathbf{R}} = \nabla_P(H_{rel} + < t|\hat{V}_{int}|t >), \qquad (2)$$

$$\dot{\mathbf{P}} = -\nabla_R(H_{rel} + < t|\hat{V}_{int}|t >), \qquad (3)$$

where $< t|...|t >$ means the averaging over the intrinsic state at the moment of t. It is clear that a relative motion of nuclei additionally depends on the nonconservative and nonstationary coupling potential $< t|\hat{V}_{int}|t >$ which can be calculated by solving the equation of motion for the single-particle density matrix.

The single-particle basis is constructed from the asymptotical single particle state vectors of noninteracting nuclei: for projectile "P" $|P >$ and target "T" $|T >$ in the form

$$|\tilde{P} >= |P > -\frac{1}{2}\sum_T |T >< T|P >,$$

$$|\tilde{T} >= |T > -\frac{1}{2}\sum_P |P >< P|T > .$$

The orthogonality condition for the given basis is fulfilled up to the second order of the overlapping integral $< P|T >$ [30].

The single-particle Hamiltonian of a dinuclear system $\hat{\mathcal{H}}$ is as follows

$$\hat{\mathcal{H}}(\mathbf{R(t)}) = \sum_{i=1}^{A}\left(\frac{-\hbar^2}{2m}\Delta_i + \hat{U}_P(\mathbf{r}_i - \mathbf{R}(t)) + \hat{U}_T(\mathbf{r}_i)\right), \qquad (4)$$

where m is the nucleon mass, $A = A_P + A_T$ is the total number of nucleons in the system. The average single-particle potentials of projectile U_P and target U_T include both the nuclear and Coulomb fields.

In the second quantization form the Hamiltonian (4) can be rewritten as

$$\begin{aligned}
&\hat{\mathcal{H}}(\mathbf{R}(t)) = \hat{H}_{in}(\mathbf{R}(t)) + \hat{V}_{int}(\mathbf{R}(t)),\\
&\hat{H}_{in}(\mathbf{R}(t)) = \sum_i \tilde{\varepsilon}_i(\mathbf{R}(t))\mathrm{a}_i^+\mathrm{a}_i = \sum_P \tilde{\varepsilon}_P(\mathbf{R}(t))\mathrm{a}_P^+\mathrm{a}_P + \sum_T \tilde{\varepsilon}_T(\mathbf{R}(t))\mathrm{a}_T^+\mathrm{a}_T, \qquad (5)\\
&\hat{V}_{int}(\mathbf{R}(t)) = \sum_{i\neq i'} V_{ii'}(\mathbf{R}(t))\mathrm{a}_i^+\mathrm{a}_{i'}\\
&= \sum_{P\neq P'} \chi_{PP'}^{(T)}(\mathbf{R}(t))\mathrm{a}_P^+\mathrm{a}_{P'} + \sum_{T\neq T'} \chi_{TT'}^{(P)}(\mathbf{R}(t))\mathrm{a}_T^+\mathrm{a}_{T'} + \sum_{T,P} \mathrm{g}_{PT}(\mathbf{R}(t))(\mathrm{a}_P^+\mathrm{a}_T + h.c.).
\end{aligned}$$

Up to the second order in $< P|T >$

$$\tilde{\varepsilon}_P(\mathbf{R}(t)) = \varepsilon_P + < P|U_T(\mathbf{r})|P >,$$

$$\tilde{\varepsilon}_T(\mathrm{R}(t)) = \varepsilon_T + < T|U_P(\mathrm{r}-\mathrm{R}(t))|T >,$$
$$\chi^{(T)}_{PP'}(\mathrm{R}(t)) = < P|U_T(\mathrm{r})|P' >,$$
$$\chi^{(P)}_{TT'}(\mathrm{R}(t)) = < T|U_P(\mathrm{r\text{-}R}(t))|T' >, \qquad (6)$$
$$\mathrm{g}_{PT}(\mathrm{R}(t)) = \frac{1}{2} < P|U_P(\mathrm{r\text{-}R}(t)) + U_T(\mathrm{r})|T > .$$

In the expression (6) $\varepsilon_{P(T)}$ are single-particle energies of nonperturbed states in the projectile (target) nucleus. These states are characterized by the set of quantum numbers $P \equiv (n_P, j_P, l_P, m_P)$ and $T \equiv (n_T, j_T, l_T, m_T)$. The diagonal matrix elements $< P|U_T|P >$ and $< T|U_P|T >$ determine the shifts of the single-particle energies of the projectile nucleus caused by the target mean field. The corresponding nondiagonal matrix elements $\chi^{(T)}_{PP'}$ and $\chi^{(P)}_{TT'}$ generate particle-hole transitions in the same nucleus. The matrix elements g_{PT} correspond to the nucleon exchange between the reaction partners due to the nonstationary mean field of a dinuclear system. The contributions of noninertial recoil effects to the matrix elements are neglected since they are small [21].

The equation of motion for the single-particle density-matrix $\hat{n}(t)$ is

$$i\hbar\frac{\partial\hat{n}(t)}{\partial t} = [\hat{\mathcal{H}}(\mathrm{R}(t)), \hat{n}(t)]. \qquad (7)$$

In the matrix representation it takes the form

$$i\hbar\frac{dn_i(t)}{dt} = \sum_k \left[V_{ik}(\mathrm{R}(t))n_{ki}(t) - n_{ik}(t)V_{ki}(\mathrm{R}(t))\right], \qquad (8)$$

$$i\hbar\frac{dn_{ik}(t)}{dt} = \hbar\tilde{\omega}_{ik}(\mathrm{R}(t))n_{ik}(t) + V_{ki}(\mathrm{R}(t))[n_k(t) - n_i(t)], \qquad (9)$$

where the following notations $\tilde{\omega}_{ik}(\mathrm{R}(t)) = [\tilde{\varepsilon}_i(\mathrm{R}(t)) - \tilde{\varepsilon}_k(\mathrm{R}(t)]/\hbar$, $n_{ik}(t) = < t|\mathrm{a}^+_i\mathrm{a}_k|t >$, $n_i(t) = n_{ii}(t) = < t|\mathrm{a}^+_i\mathrm{a}_i|t >$ are used. In the equation (9) we have done the following approximation

$$\sum_{k'} V_{k'i}(\mathrm{R}(t))n_{k'k}(t) - \sum_{i'} V_{ki'}(\mathrm{R}(t))n_{ii'}(t) \approx V_{ki}(\mathrm{R}(t))\left[n_k(t) - n_i(t)\right]. \qquad (10)$$

Substituting the solution of (9)

$$n_{ik}(t) = \frac{1}{i\hbar}\int_{t_0}^{t} dt' V_{ik}(\mathrm{R}(t'))\exp\left\{i\int_{t'}^{t} dt''\tilde{\omega}_{ki}(\mathrm{R}(t''))\right\}[n_k(t') - n_i(t')] \qquad (11)$$

into (8) we obtain equations for the dynamical occupation numbers $n_i(t)$

$$\frac{dn_i(t)}{dt} = \sum_k \int_{t_0}^{t} dt' \Omega_{ik}(t,t')[n_k(t') - n_i(t')] \qquad (12)$$

where $\Omega_{ik}(t,t') = \frac{2}{\hbar^2}\mathrm{Re}\left\{V_{ik}(\mathrm{R}(t))V_{ki}(\mathrm{R}(t'))\exp\left[i\int_{t'}^{t} dt''\tilde{\omega}_{ki}(\mathrm{R}(t''))\right]\right\}$.

The equation (12) contains memory effects. In Markovian approximation equation (12) can be rewritten in a master-equation form

$$\frac{dn_i(t)}{dt} = \sum_k w_{ik}(t,t_0)[n_k(t) - n_i(t)], \qquad (13)$$

where

$$w_{ik}(t,t_0) = \int_{t_0}^{t} dt' \Omega_{ik}(t,t').$$

The equation (13) can be solved by the successive iteration procedure

$$n_i(t+\Delta t) = n_i(t) + \sum_k \overline{W}_{ik}(\mathrm{R}(t),\Delta t)[n_k(t) - n_i(t)],$$
$$\overline{W}_{ik}(\mathrm{R}(t),\Delta t) = |V_{ik}(\mathrm{R}(t))|^2 \frac{\sin^2\left(\frac{\Delta t}{2}\tilde{\omega}_{ki}(\mathrm{R}(t))\right)}{\left[\frac{\hbar}{2}\tilde{\omega}_{ki}(\mathrm{R}(t))\right]^2}. \qquad (14)$$

The initial values of the occupation numbers are equal to 1 for occupied states and zero for unoccupied one. A magnitude of the time step Δt used in the calculations is $(0.3 \div 0.7)\cdot 10^{-22} s$.

The equation (13) describes irreversible evolution of the system. Using this equation and the definition of entropy $S(t)$

$$S(t) = -k\sum_i \left[n_i(t)\ln n_i(t) + \bar{n}_i(t)\ln\bar{n}_i(t)\right], \qquad \bar{n}_i(t) = 1 - n_i(t),$$

we can obtain the time derivative of the entropy

$$\frac{dS(t)}{dt} = \frac{k}{2}\sum_{i,k} w_{ik}(\mathrm{R}(t),\Delta t)\left[n_i(t)\bar{n}_k(t) - n_k(t)\bar{n}_i(t)\right]\ln\left[\frac{n_i(t)\bar{n}_k(t)}{\bar{n}_i(t)n_k(t)}\right] \qquad (15)$$

where k is the Boltzmann constant. It is seen that the entropy derivative is larger than or equal to zero. This irreversibility is a consequence of the assumptions that the distribution of the phases of the nondiagonal matrix elements of $\hat{V}$ and $\hat{n}$ is chaotic (eq. 10). The stationary solution of equation (13) does not coincide with the temperature-dependent occupation numbers for the Fermi gas because the residual interaction between nucleons was not taken into consideration. The inclusion of the residual forces

results in the well-known two-body collision term [31, 32] in the right-hand side of equations (12) and (13) additional to the one-body term

$$\sum_{jkl}\int_{t_0}^{t} dt' \Omega^{res}_{ijkl}(t,t')[\bar{n}_i(t')\bar{n}_j(t')n_k(t')n_l(t') - n_i(t')n_j(t')\bar{n}_i(t')\bar{n}_j(t')],$$

$$\Omega^{res}_{ijkl}(t,t') = \frac{1}{\hbar^2}\mathrm{Re}\left\{V^{res}_{ijkl}(\mathbf{R}(t))V^{res}_{lkji}(\mathbf{R}(t'))\exp\left[i\int_{t'}^{t} dt''\tilde{\omega}_{lkji}(\mathbf{R}(t''))\right]\right\},$$

where $\tilde{\omega}_{lkji}(\mathbf{R}(t)) = [\tilde{\varepsilon}_l(\mathbf{R}(t)) + \tilde{\varepsilon}_k(\mathbf{R}(t)) - \tilde{\varepsilon}_j(\mathbf{R}(t)) - \tilde{\varepsilon}_i(\mathbf{R}(t))]/\hbar$, $V^{res}_{ijkl}(\mathbf{R}(t))$ are matrix elements of a residual interaction. Then, the time derivative of the entropy can be calculated including the two-body collision term

$$\begin{aligned}\frac{dS(t)}{dt} &= \frac{k}{2}\Big\{\sum_{i,k} w_{ik}(\mathbf{R}(t))(n_i\bar{n}_k - n_k\bar{n}_i)\ln\left[\frac{n_i\bar{n}_k}{n_k\bar{n}_i}\right] \\ &+\frac{1}{2}\sum_{ijkl} w^{res}_{ijkl}(\mathbf{R}(t))[n_in_j\bar{n}_k\bar{n}_l - \bar{n}_i\bar{n}_jn_kn_l]\ln\left[\frac{n_in_j\bar{n}_k\bar{n}_l}{\bar{n}_i\bar{n}_jn_kn_l}\right]\Big\}, \qquad (16)\end{aligned}$$

where for the brevity following notations $n_i = n_i(t)$, $\bar{n}_i = 1 - n_i(t)$ and

$$w^{res}_{ijkl}(\mathbf{R}(t)) = \int_{t_0}^{t} dt' \Omega^{res}_{ijkl}(t,t')$$

are used. It is well known that the stationary solution of (16) corresponds to the statistical equilibrium with the temperature-dependent Fermi-Dirac occupation numbers with the same temperature ($T_P = T_T$), and Fermi energy ($\varepsilon_{F_P} = \varepsilon_{F_T}$) for nuclei in contact. The explicit account of the residual interaction requires a large volume of calculations. The linearization of the two-body collision integral simplify the consideration. In the relaxation time approximation [33]:

$$i\hbar\frac{\partial\hat{\tilde{n}}(t)}{\partial t} = [\hat{\mathcal{H}}, \hat{\tilde{n}}(t)] - \frac{i\hbar}{\tau}[\hat{\tilde{n}}(t) - \hat{\tilde{n}}^{eq}(\mathbf{R}(t))], \qquad (7')$$

where τ is the relaxation time, $\tilde{n}^{eq}(\mathbf{R}(t))$ is a local quasiequilibrium density matrix at fixed value of the collective coordinate $\mathbf{R(t)}$ which is determined by the excitation energy of each nucleus. Analogously to the expressions (8), (9), (11) and (12), the following equations are obtained

$$i\hbar\frac{d\tilde{n}_i(t)}{dt} = \sum_k [V_{ik}(\mathbf{R}(t))\tilde{n}_{ki}(t) - V_{ki}(\mathbf{R}(t))\tilde{n}_{ik}(t)] - \frac{i\hbar}{\tau}[\tilde{n}_i(t) - \tilde{n}^{eq}_i(\mathbf{R}(t))], \qquad (8')$$

$$i\hbar\frac{d\tilde{n}_{ik}(t)}{dt} = \hbar\left[\tilde{\omega}_{ik}(\mathbf{R}(t) - \frac{i}{\tau}\right]\tilde{n}_{ik}(t) + V_{ki}(\mathbf{R}(t))[\tilde{n}_k(t) - \tilde{n}_i(t)], \qquad (9')$$

$$\tilde{n}_{ik}(t) = \frac{1}{i\hbar}\int_{t_0}^{t} dt' V_{ik}(\mathbf{R}(t'))\exp\left\{i\int_{t'}^{t} dt''\left[\tilde{\omega}_{ki}(\mathbf{R}(t'') + \frac{i}{\tau}\right]\right\}[\tilde{n}_k(t') - \tilde{n}_i(t')], \qquad (11')$$

$$\frac{d\tilde{n}_i(t)}{dt} = \sum_k\int_{t_0}^{t} dt'\Omega_{ik}(t,t')\exp\left(\frac{t'-t}{\tau}\right)[\tilde{n}_k(t') - \tilde{n}_i(t')] - \frac{1}{\tau}[\tilde{n}_i(t) - \tilde{n}^{eq}_i(\mathbf{R}(t))] \qquad (12')$$

A formal solution of equation (12') is

$$\begin{aligned}\tilde{n}_i(t) &= \exp\left(\frac{t_0-t}{\tau}\right)\Big\{\tilde{n}_i(t_0) + \sum_k\int_{t_0}^{t} dt'\int_{t_0}^{t'} dt''\Omega_{ik}(t',t'')\exp\left(\frac{t''-t}{\tau}\right)[\tilde{n}_k(t'') - \tilde{n}_i(t'')] \\ &+\int_{t_0}^{t} dt'\tilde{n}^{eq}_i(\mathbf{R}(t'))\exp\left(\frac{t'-t_0}{\tau}\right)\Big\}. \qquad (17)\end{aligned}$$

It is convenient to solve the eq.(17) step by step dividing time interval $(t - t_0)$ into parts: t_0, $t_0 + \Delta t$, $t_0 + 2\Delta t$, etc. Then eq. (17) can be rewritten approximately for $\Delta t < \tau$ as

$$\begin{aligned}\tilde{n}_i(t) &= \tilde{n}^{eq}_i(\mathbf{R}(t))\left[1 - \exp\left(\frac{-\Delta t}{\tau}\right)\right] + f_i(t)\exp\left(\frac{-\Delta t}{\tau}\right), \\ f_i(t) &= \tilde{n}_i(t-\Delta t) + \sum_k \overline{W}_{ik}(\mathbf{R}(t),\Delta t)[\tilde{n}_k(t-\Delta t) - \tilde{n}_i(t-\Delta t)], \qquad (18)\end{aligned}$$

where $\overline{W}_{ik}$ is defined in (14). The dynamic $f_i(t)$ (eq. 14) and quasiequilibrium $\tilde{n}^{(eq)}_i(\mathbf{R}(t))$ occupation numbers are calculated at every time step. The temperature characterizing Fermi-Dirac occupation numbers $\tilde{n}^{eq}_i(\mathbf{R}(t))$ is determined by the excitation energy of each nucleus. The relaxation time τ specifies relative contributions of the single-particle and two-particle components.

The present model allows us to calculate the average number of protons $< Z_{P(T)} >$ or neutrons $< N_{P(T)} >$, their variance σ^2_Z or σ^2_N and to determine the intrinsic excitation energies $E^*_{P,T}(t)$ for every nucleus:

$$\begin{aligned}< Z_{P(T)} > (t) &= \sum_{P(T)}^{Z}\tilde{n}_{P(T)}(t), \qquad (19)\\ < N_{P(T)} > (t) &= \sum_{P(T)}^{N}\tilde{n}_{P(T)}(t), \qquad (20)\\ \sigma^2_{Z(N)}(t) &= \sum_{P}^{Z(N)}\tilde{n}_P(t)[1 - \tilde{n}_P(t)], \qquad (21)\\ E^*_{P(T)}(t+\Delta t) &= E^*_{P(T)}(t) \\ &+ \sum_{P(T)}[\tilde{\varepsilon}_{P(T)}(\mathbf{R}(t)) - \varepsilon_{F_P(F_T)}(\mathbf{R}(t))][\tilde{n}_{P(T)}(t+\Delta t) - \tilde{n}_{P(T)}(t)], \qquad (22)\end{aligned}$$

where $\varepsilon_{F_P(F_T)}(\mathbf{R}(t))$ is the Fermi energy of a projectile-like nucleus "P" or target-like nucleus "T". The top index $Z(N)$ of sum restricts the summation over the proton(neutron) single-particle levels. It is seen from (22) that the fragment excitation energy is calculated step by step along the time scale. The variations of the occupation numbers which are described by the equations (18) are determined by the $\overline{W}_{ik}$. It is seen from (14) and (5) that at every time step the contributions from the p-h excitation and the nucleon exchange to the variations of the occupation numbers are separated since only the squares of the matrix elements $\chi^{(T)}_{PP'}$, $\chi^{(P)}_{TT'}$, g_{PT} contribute to $\overline{W}_{ik}$.

Substituting (11′) into equation (3) we obtain also the following integro-differential equation describing a relative motion

$$\frac{d}{dt}\left[\mu(\mathbf{R}(t))\dot{\mathbf{R}}(t)\right] = -\nabla_{\mathbf{R}}U(\mathbf{R}(t)) - \frac{2}{\hbar}\mathrm{Im}\left\{\sum_{i\neq k}\nabla_{\mathbf{R}}V_{ki}(\mathbf{R}(t))\tilde{n}_{ik}(t)\right\}. \quad (23)$$

The second term on the right-hand side of (23) contains a contribution of the effective forces. This term depends explicitly not only on $\mathbf{R}(t)$ but also on the current time t. If the characteristic time of the collective motion is larger than the relaxation time,we can derive the equation which is local in time expanding the matrix elements $V_{ki}(\mathbf{R}(t'))$ at $t' = t$ in a series of $(t'-t)$. This equation contains the renormalizations of nucleus-nucleus potential. We get also radial and tangential friction coefficients.

3. Model calculations

Partitions of the internal excitation energy between two collision partners are calculated for the reactions ^{58}Ni + ^{197}Au [4], ^{238}U + ^{124}Sn , ^{238}U + ^{110}Pd [6],^{56}Fe(505 MeV) + ^{165}Ho [7, 9] and ^{74}Ge + ^{165}Ho [12]. We investigated also the role of the nucleon exchange and the particle-hole excitation mechanism in a conversion of the relative motion kinetic energy into the internal excitation energy. The theoretical and experimental results for the ratio of the projectile excitation energy to the total excitation energy $R_P = E^*_P/(E^*_P + E^*_T)$ are presented in Figs. 1a, 2a. The theoretical results for reactions with projectile-nucleus ^{238}U (Figs. 3a, 4a) can be compared with the averaged experimental values of the discussed ratio taken from [6]. For the reactions with target-nucleus ^{124}Sn or ^{110}Pd the averaged experimental ratio is about 0.4. For the reaction ^{58}Ni(880 MeV) + ^{197}Au [4] it is only known that this ratio closed to 0.5. The experimental data show that the excitation energy is distributed approximately equally between the fragments rather than proportionally to the masses of the fragments. Even in the reactions with ^{238}U a lighter fragment gets more excitation energy than the heavier one. The results of calculations qualitatively agree with the experimental data. Relative

role of the nucleon exchange $R^{(ex)}_P = E^{*(ex)}_P/(E^{*(ex)}_P + E^{*(ex)}_T)$ and the p-h mechanisms $R^{(ph)}_P = E^{*(ph)}_P/(E^{*(ph)}_P + E^{*(ph)}_T)$ in the ratio of the projectile-like nucleus excitation energy to the total excitation energy is illustrated in Figs. 1b, 2b, 3b, 4b, 5b. Here $E^{*(ex)}_{P(T)}$ and $E^{*(ph)}_{P(T)}$ are the contributions in $E^*_{P(T)}$ from the nucleon exchange and the p-h excitation, respectively.

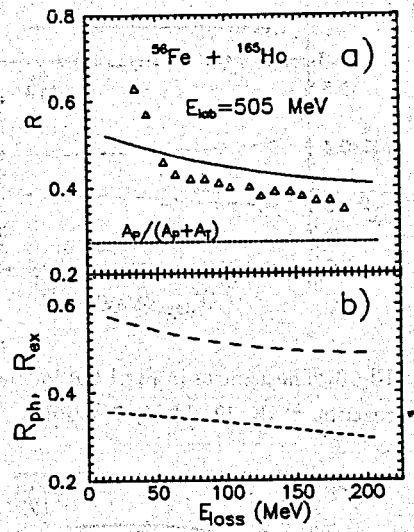


Fig.1. **a)** Ratio R_P of the projectile-like fragment excitation energy (E^*_P) to the total excitation energy for reaction ^{56}Fe(505 MeV) + ^{165}Ho as a function of the total excitation energy $E_{loss} = E^*_P + E^*_T$. Triangles mark the experimental data. Solid line presents the theoretical result of our model. Dotted line corresponds to thermal equilibrium ($E^*_P/E_{loss} = A_P/(A_P + A_T)$).
b) Calculated ratios $R^{(ex)}_P = E^{*(ex)}_P/(E^{*(ex)}_P + E^{*(ex)}_T)$, $R^{(ph)}_P = E^{*(ph)}_P/(E^{*(ph)}_P + E^{*(ph)}_T)$ for the reaction ^{56}Fe(505 MeV) + ^{165}Ho as a function of total excitation energy E_{loss} are presented by long dashed line and short dashed line, respectively

The theoretical results for the ratio of the part of total excitation energy produced by the p-h excitation $E^{(ph)}_{loss} = E^{*(ph)}_P + E^{*(ph)}_T$ to the part produced by the nucleon exchange $E^{(ex)}_{loss} = E^{*(ex)}_P + E^{*(ex)}_T$ are shown in Table 1.

Reaction	E_{lab} (MeV)	L	$E^{(ph)}_{loss}/E^{(ex)}_{loss}$
^{238}U + ^{110}Pd	1398	57	0.70
^{238}U + ^{124}Sn	1468	50	0.67
^{238}U + ^{124}Sn	1468	100	0.60
^{58}Ni + ^{197}Au	880	240	0.18
^{74}Ge + ^{165}Ho	629	169	0.30
^{56}Fe + ^{165}Ho	505	175	0.31

Table 1. Ratio of excitation energy produced by inelastic (p-h) excitation $E^{(ph)}_{loss} = E^{*(ph)}_P + E^{*(ph)}_T$ to that produced by nucleon exchange $E^{(ex)}_{loss} = E^{*(ex)}_P + E^{*(ex)}_T$ for different reactions and trajectories

It is seen that in the reactions with ^{58}Ni, ^{74}Ge and ^{56}Fe the main role in the kinetic energy dissipation plays the nucleon exchange. In the reactions with heavier partners with $A > 100$ the role of the p-h excitation mechanism increases.

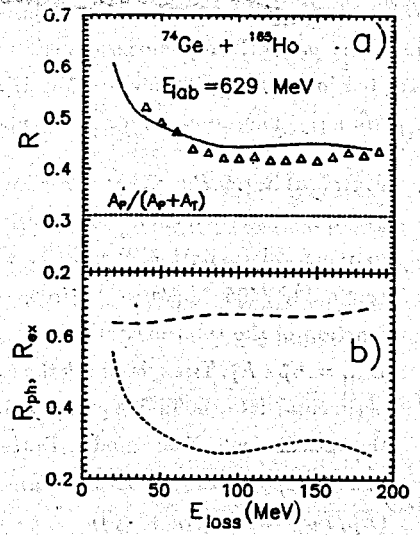


Fig.2. The same as in Fig.1 but for the reaction ^{74}Ge(629 MeV) + ^{165}Ho

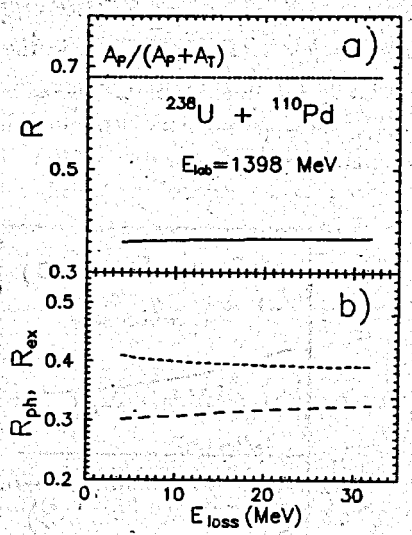


Fig.3. The same as in Fig.1 but for the reaction ^{238}U(1398 MeV) + ^{110}Pd

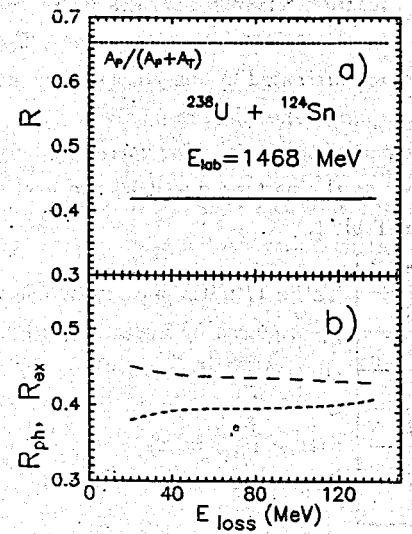


Fig.4. The same as in Fig.1 but for the reaction ^{238}U(1468 MeV) + ^{124}Sn

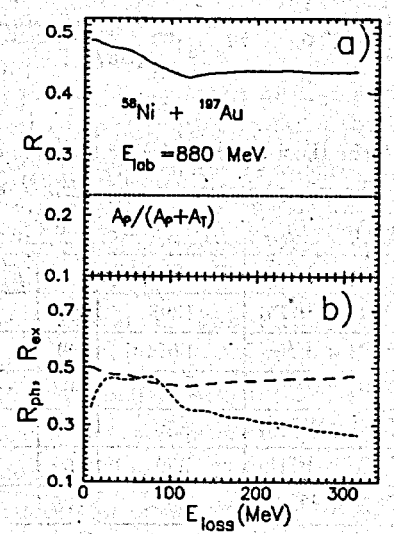


Fig.5. The same as in Fig.1 but for the reaction ^{58}Ni(880 MeV) + ^{197}Au

The values of charge (mass) drift and the variances of charge (mass) distributions are shown on Figs. 6–12. A good description of the experimental data has been obtained.

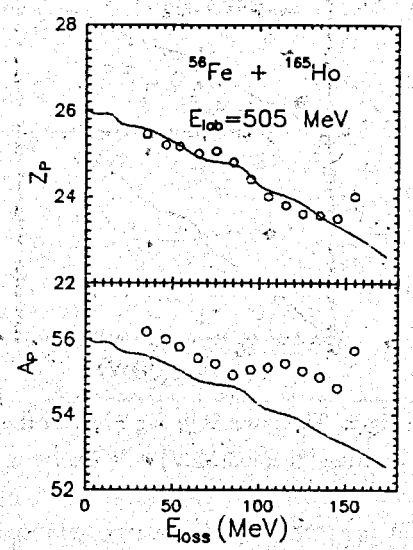


Fig.6. Centroids of the Z_P, A_P distributions for projectile-like fragments of the reaction ^{56}Fe(505 MeV) + ^{165}Ho as a function of the total excitation energy E_{loss}. Circles give the primary values, dashed lines present results of the nucleon exchange transport model [18] and solid line is our model predictions of the primary distributions

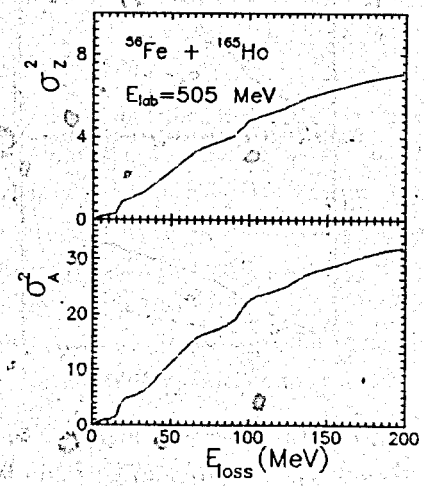


Fig.7. Variances of the Z_P, A_P distributions for projectile-like fragments of the reaction ^{56}Fe(505 MeV) + ^{165}Ho as a function of energy loss E_{loss}. Symbols are the same as in Fig.6

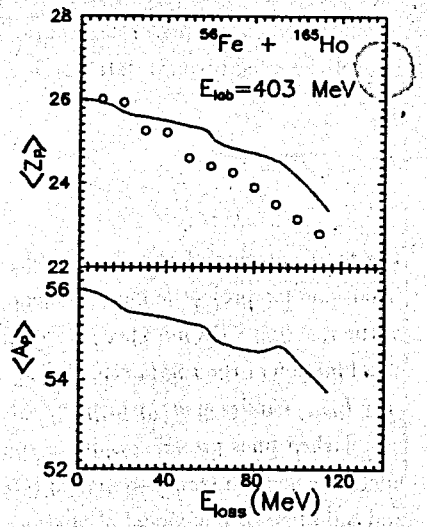


Fig.8. The same as in Fig.6 but for the reaction ^{56}Fe(403 MeV) + ^{165}Ho

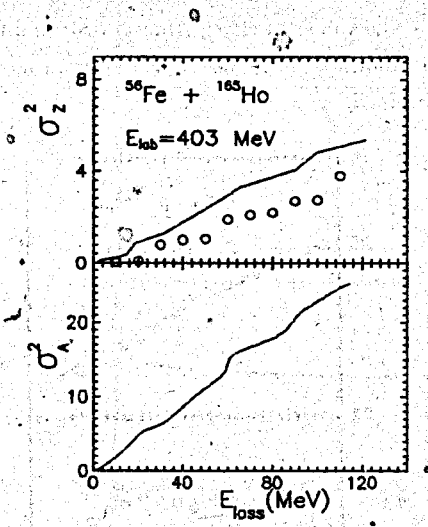


Fig.9. The same as in Fig.7 but for the reaction ^{56}Fe(403 MeV) + ^{165}Ho

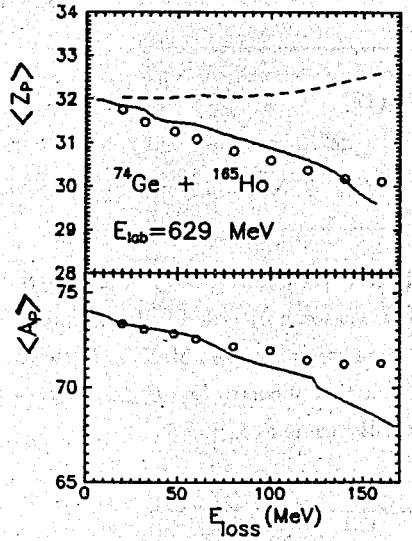


Fig.10. The same as in Fig.6 but for the reaction ^{74}Ge(629 MeV) + ^{165}Ho

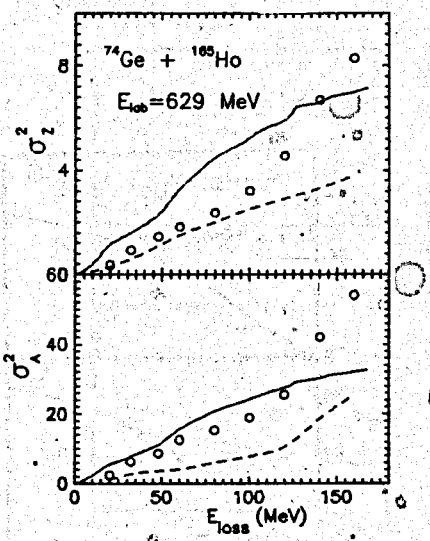


Fig.11. The same as in Fig.7 but for the reaction ^{74}Ge(629 MeV) + ^{165}Ho

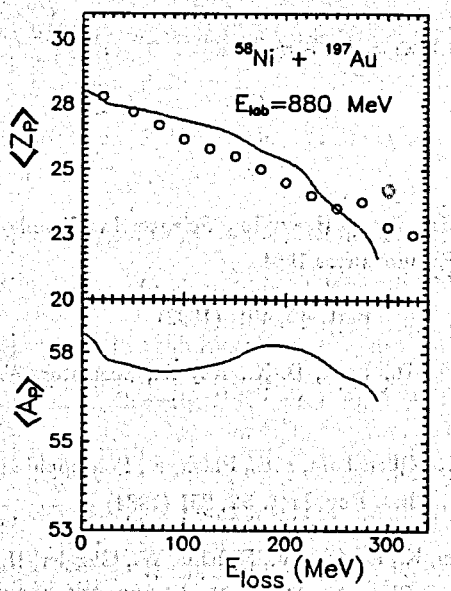


Fig.12. The same as in Fig.6 but for the reaction ^{58}Ni(880 MeV) + ^{197}Au

The trajectory of colliding nuclei was determined as in [28, 34]. Single-particle matrix elements $\chi^{(P)}_{TT'}$, $\chi^{(T)}_{PP'}$ and g_{PT} have been calculated in the approach described in [35, 36]. The calculations show that the variations of τ values from $5 \cdot 10^{-23}$ s to $25 \cdot 10^{-22}$ s don't change the results considerably. All the calculations are performed at $\tau = 15 \cdot 10^{-22}$ s.

4. Conclusion

The model described in section 2 is capable to explain both the multinucleon transfer data and the distribution of the excitation energy between the primary fragments in deep inelastic collisions. The results obtained show that the redistribution of the excitation energy takes place during the whole interaction time, not only at the initial stage. Nucleon exchange, particularly, neutron exchange is a dominant mechanism of energy dissipation. However, for the heavy dinuclear systems it seems that the p-h excitations become as important as nucleon exchange. Influence of the shell structure of the interacting nuclei on the nucleon transfer and the partition of excitation energy is significant.

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