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Is thermal equilibrium in strongly damped collisions only apparent?

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The dependence of excitation-energy sharing on the direction of the net transfer of mass, observed by Viola and co-workers, is interpreted in terms of the participant-spectator model of Wilczynski and Wilschut. It is demonstrated that the division of the excitation energy in fully damped collisions (proportional to the mass numbers of the fragments) is a natural consequence of the participant-spectator kinematics and therefore it does not necessarily imply temperature equilibration prior to scission.

One of the most important questions in the present studies of the deep-inelastic reactions between complex nuclei is whether or not statistical equilibrium between the interacting fragments is attained during a rather short contact time before reseparation of the system. In attempts to obtain an answer to this question, the partition of excitation energy had been measured for several heavy systems. In the early studies (see, e.g., Ref. 1) it has been found that the excitation energy divides approximately in proportion to the mass numbers of the primary fragments, i.e., as one can expect assuming that the two fragments attain the thermal equilibrium before scission. In further investigations Awes *et al.*[2] and Vandenbosch *et al.*[3] demonstrated however that for some moderate energy losses the excitation energy divides more nearly equally than predicted by the thermal-equilibrium models. Recent studies[4-6] seem to indicate that the partition of the excitation energy evolves gradually from nearly equal division in quasielastic collisions to the division scaled by the mass ratio of the fragments for fully damped reactions. Such a general trend is predicted by the dynamical transport model of Randrup,[7] although the experimental results show significant deviations from the predictions of the model. Specifically, some of the experimental results indicate that the partition of the excitation energy does depend on the direction of the net nucleon flow. This effect has been demonstrated most clearly in a work reported by Viola *et al.*[8] and Płaneta *et al.*[9] The transport model of Randrup[7] does not predict such a dependence.

In this work, the energy dependence of the excitation-energy partition, reported by Viola *et al.*[8] and Płaneta *et al.*[9] for selected primary fragments, is explained in terms of the participant-spectator model of the excitation-energy sharing proposed by Wilczynski and Wilschut.[10] In addition, it is demonstrated that the *complete* damping of kinetic energy (within the participant-spectator mechanism) always results in the partition of the excitation energy proportionally to the mass numbers of the primary fragments, *independently* on the degree of thermal equilibration of the system. Therefore the observed sharing of the excitation energy for the completely damped events (proportional to the mass numbers) does not necessarily mean that the colliding system has indeed attained thermal equilibrium before scission.

The model of Wilczynski and Wilschut[10] gives a prescription for the partition of the excitation energy within the participant-spectator scheme underlying the optimum Q-value model of Siemens *et al.*[11] According to this scheme, the excitation energy generated in a process of the unidirectional transfer is entirely deposited in the receptor nucleus. In a general case of exchange reaction $A(a,b)B$ in which n nucleons are transferred from the projectile a to the target A, and m nucleons from the target to the projectile, the bidirectional process can be viewed as simultaneous occurrence of two unidirectional-transfer reactions:

$$A(a,b)B \leftrightarrows A'(a,a')B + A(a',b)A' , \tag{1}$$

where $A' = A - m$ and $a' = a - n$. The excitation energy generated in the $A'(a,a')B$ subprocess is located in nucleus B, and excitation energy generated in the $A(a',b)A'$ subprocess goes to the nucleus b. Thus, for the combined reaction $A(a,b)B$ at its optimum Q value,[11] the partition is given as shown in Ref. 10,

$$E^*(B) = Q_{gg1}(R) + \frac{n(A-m)}{\mu B}[E - U_{aA}(R)] , \tag{2}$$

$$E^*(b) = Q_{gg2}(R) + \frac{m(a-n)}{\mu b}[E - U_{aA}(R)] . \tag{3}$$

Here E is the bombarding energy (in the c.m. system), $\mu = aA/(a+A)$ the reduced mass number of the colliding system, and $Q_{gg1}(R)$ and $Q_{gg2}(R)$ are the threshold energies of the two subprocesses, calculated at the interaction distance R:

$$Q_{gg1}(R) = (M_{A'} + M_a - M_{a'} - M_B)c^2 + U_{aA'}(R) - U_{Ba'}(R) , \tag{4}$$

$$Q_{gg2}(R) = (M_A + M_{a'} - M_b - M_{A'})c^2 + U_{Aa'}(R) - U_{bA'}(R) . \tag{5}$$

(The ground-state Q values, representing the energy thresholds for $r=\infty$, are corrected for the change of the potential energy of the system at the contact configuration $r=R$.) The subscripts at the symbol U in Eqs. (2)–(5) denote the respective subsystem, for which the Coulomb-plus-nuclear potential energy U is calculated.

We denote by n_0 and m_0 the *minimum* numbers n and m, respectively, that are necessary to produce the final fragments B and b in the reaction $A(a,b)B$. Such a net-transfer reaction characterized by the numbers n_0 and m_0 can be accompanied by an exchange of k pairs of neutrons or protons. By replacing in (2) and (3),

$$n=n_0+k,\ m=m_0+k\ , \tag{6}$$

we obtain expressions representing the excitation-energy spectra of the fixed products B and b, as a function of the number of exchanged nucleons k. Obviously, the sum $E^*=E^*(B)+E^*(b)$ represents then the total spectrum of the excitation energy. Note that the energy thresholds $Q_{gg1}(R)$ and $Q_{gg2}(R)$ do not depend on k because the combined energy threshold for the reaction $A(a,b)B$ is totally determined by the properties of the system in the initial $(a+A)$ and final $(b+B)$ channels. (Each exchange of a pair of neutrons or protons does not influence the potential energy of the system.) Therefore the fragments A' and a' in Eqs. (4) and (5) have to be taken as for the net-transfer reaction: $A'=A-m_0$ and $a'=a-n_0$.

The interpretation of the energy spectra in terms of Eqs. (2) and (3) with notation (6) implies that various parts of the energy spectrum of a given reaction $a+A\rightarrow b+B$ result from different numbers of exchanged pairs of nucleons k (in addition to the fixed net transfer determined by n_0 and m_0). The smallest excitation energy corresponds to the optimum Q value in the net-transfer process, $k=0$. With increasing number of exchanged nucleons the reaction becomes more and more inelastic. This interpretation agrees conceptually with other one-body dissipation models, although the dynamical consequences of the assumed participant-spectator mechanism are quite different from the predictions of the existing nucleon-exchange models, such as the model of Randrup.[7] It should be noted however that the proposed participant-spectator nucleon-exchange mechanism has not been built into a complete transport model. Therefore by using Eqs. (2), (3), and (6) alone one cannot predict relative yields of different net-transfer channels and other interchannel characteristics of the deep-inelastic reactions, but one can easily predict the partition of the excitation energy for fixed net-transfer channels, the important quantity that is very sensitive to the assumed reaction mechanism.

The predictions based on Eqs. (2), (3), and (6) can be compared with the results reported by Viola *et al.*[8] and Płaneta *et al.*[9] on the ^{74}Ge+^{165}Ho reaction at 8.5 MeV/nucleon. The authors of Refs. 8 and 9 have reconstructed the average excitation energies of the primary fragments (as a function of the total kinetic-energy loss) for selected mass numbers of these fragments. As seen from Fig. 1, there is a distinct difference in the observed[8,9] partition of the excitation energy between the stripping-type reactions (A_{PLF}=65–67 and 71–73), zero-net transfer (A_{PLF}=74), and pickup-type reactions (A_{PLF}=78–80). The most striking differences are observed for small energy losses. As reported in Refs. 8 and 9, these effects cannot be explained with the transport model of Randrup.[7] On the other hand, predictions of the present model [Eqs. (2), (3), and (6)], shown by solid lines in Fig. 1, reproduce the main trends in the $\langle R\rangle=\langle E^*_{PLF}/E^*_{tot}\rangle$ ratio quite well. Specifically, for low energy losses (small k) the ratio $\langle R\rangle$ is determined mostly by the net transfer of nucleons (n_0 and m_0), and therefore the observed trends for the $E_{loss}=0$ limit coincide with the following predictions: $\langle R\rangle\cong 0$ for stripping-reaction products, $\langle R\rangle\cong 1$ for pickup products, and $\langle R\rangle\cong 0.5$ for zero-net-transfer reactions. With increasing number k of exchanged nucleons, the asymmetry in the partition of the excitation energy (caused by the net transfer) becomes less pronounced as a result of a more equal sharing of the excitation energy generated by the exchange processes.

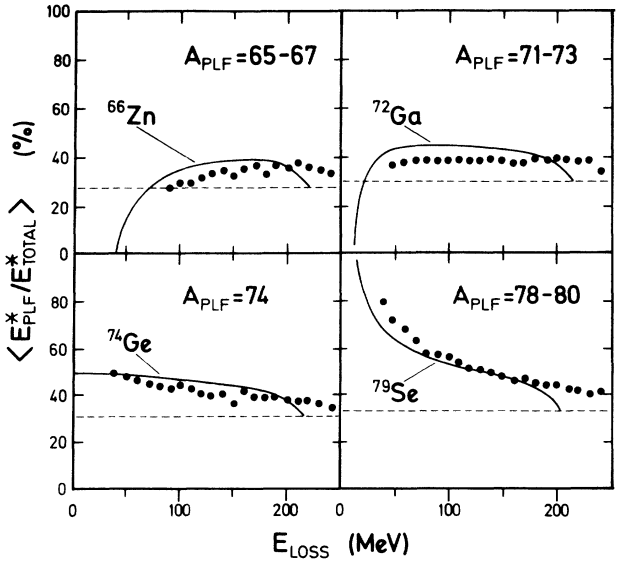

FIG. 1. Average ratio of excitation energy in projectilelike fragments (PLF) to total available excitation energy as a function of energy loss in the ^{74}Ge+^{165}Ho reaction at E/A=8.5 MeV per nucleon. The data are taken from Refs. 8 and 9. The results for four primary mass bins, A_{PLF}=65–67, 71–73, 74, and 78–80, are compared with the model predictions for the following assumed primary PLF's: ^{66}Zn, ^{72}Ga, ^{74}Ge, and ^{79}Se, respectively.

There is an interesting consequence of the proposed nucleon-exchange mechanism for completely damped reactions. Assume, for simplicity, that the net transfer is negligible ($n_0\cong 0$, $m_0\cong 0$). Then $B\cong A$, $b\cong a$, and for large numbers of exchanged nucleons $Q_{gg1}(R)$ and $Q_{gg2}(R)$ can be neglected in Eqs. (2) and (3):

$$E^*(B\cong A)\cong\frac{k(A-k)}{\mu B}[E-U_{aA}(R)]\ , \tag{7}$$

$$E^*(b\cong a)\cong\frac{k(a-k)}{\mu b}[E-U_{aA}(R)]\ . \tag{8}$$

One can see that the number of exchanged pairs of nucleons necessary to totally dissipate the available kinetic

energy, $E-U_{aA}(R)$, is

$$k_{\text{damped}} \cong \frac{bB}{b+B} = \mu_f . \tag{9}$$

By inserting this result into Eqs. (7) and (8), one can check that for the *completely* damped events, $k = k_{\text{damped}}$, the excitation energy is divided proportionally to the mass numbers of the fragments:

$$\frac{E^*_{\text{damped}}(B)}{E^*_{\text{damped}}(b)} \cong \frac{B}{b} . \tag{10}$$

The limit corresponding to the division of the excitation energy in the proportion to the mass numbers is indicated in Fig. 1 by horizontal dashed lines. The calculated ratios $\langle R \rangle$ approach this limit as soon as the available kinetic energy totally dissipates. Note that the experimental points extend to still larger values of E_{loss}. This clearly indicates for the lowering of the exit-channel barrier, probably due to substantial deformations in the exit channel which are not considered in the present model.

It should be emphasized that the result given by Eq. (10) does *not* imply thermal equilibrium. In the present model, the division of the excitation energy proportionally to the mass numbers always results when the available kinetic energy gets totally dissipated via the participant-spectator nucleon-exchange mechanism. Certainly, this prediction is *independent of the time scale* of the exchange process and the degree of thermal equilibration.

In conclusion, the proposed participant-spectator nucleon-exchange mechanism well explains the energy dependence of the excitation-energy division in the whole range of energy losses, as well as the dependence on the direction of the net transfer of mass at small energy losses. Therefore this mechanism is quite plausible and, consequently, the scenario of the processes that lead to the observed partition of excitation energy may substantially differ from that generally believed at present. In this alternative scenario, even *nonequilibrium* multinucleon exchange processes inevitably lead to the partition of excitation energy proportional to the mass numbers, provided that the available kinetic energy is totally dissipated. This *primary* (proportional to the mass numbers) partition is independent of the degree of thermal equilibration of the system. Both fragments have enough time *after scission* to equilibrate their respective portions of the excitation energy generated in the primary process.

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