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Rapid Communications

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Thermal equilibrium in strongly damped collisions

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Energy division between colliding nuclei in damped collisions is studied in the statistical nucleon exchange model. The reactions $^{56}Fe+^{165}Ho$ and $^{56}Fe+^{238}U$ at incident energy of 465 MeV are considered for this purpose. It is found that the excitation energy is approximately equally shared between the nuclei for the peripheral collisions and the systems slowly approach equilibrium for more central collisions. This is in conformity with the recent experimental observations. The calculated variances of the charge distributions are found to depend appreciably on the temperature and are in very good agreement with the experimental data.

The stochastic nucleon exchange model[1] has been found to be very successful in explaining the various important characteristics of strongly damped collisions like inclusive and exclusive charge and mass distributions,[2] total energy and angular momentum loss,[3] angular momentum misalignment,[4,5] etc. The calculations have usually been done in the zero-tempetature approximation, and in cases where temperature dependence of the reaction process is taken into account, it is assumed that both the reacting fragments have equilibrated in energy and therefore have the same temperature. Earlier experimental data on the energy distribution of the evaporated neutrons from the reacted fragments are suggestive of such a thermal equilibrium established between the colliding nuclei.[6] A simplistic dynamical calculation in the nucleon exchange model by Randrup[5] however indicated that for very asymmetric systems, thermal equilibrium is not reached for small and moderate energy losses.

The recent experimental measurements[7] of charge distributions in the reaction with ^{58}Ni at 15.3 MeV/nucleon incident energy bombarded on ^{197}Au suggest an equal division of excitation energy between the two nuclei rather than in proportion to their masses (equal temperature). A similar conclusion is reached, at least for low energy losses, from the analysis[7] of the neutron multiplicity data for the reaction $^{56}Fe+^{165}Ho$ at 465 MeV (Ref. 8) incident energy. From the measurement of the mass asymmetry of the fission fragments of the heavier nucleus in the reaction $^{56}Fe+^{238}U$ at 476 MeV, Vandenbosch *et al.*[9] also observe that for low to intermediate energy losses (30–70 MeV), the excitation energies are shared more nearly equally. Model calculations done very recently by Feldmeier and Spangenberger[10] are in agreement with such a conclusion. The energy division between the colliding partners thus seems to be an open question. This motivates us towards a fully dynamical calculation in the framework of the model of stochastic transfer of single nulceons for the study of energy partitioning between the two interacting nuclei.

If the driving force for neutron and proton transfer is neglected, the nuclei would exchange an equal number of nucleons between them resulting initially in an equal amount of excitation in both. For asymmetric systems, the lighter one would, therefore, have a higher temperature. A temperature gradient would thus be established towards the heavier partner causing a larger energy transport, on the average, from the lighter to the heavier nucleus until equilibrium is established between them. The proper accounting of temperature is therefore crucial for the calculation of energy partitioning. The occupation functions are also temperature dependent and thus temperature regulates the flow of nucleons between the closely interacting nuclei. In this Rapid Communication we report on whether equilibrium is established between these strongly interacting partners in the stochastic nucleon exchange model and, in passing, also study the role of temperature on the mass or charge flow. The effect of temperature dependent Pauli-restricted exchange, the dyanmics of the nuclei, the effect of driving force, and penetration of Coulomb and nuclear barriers are taken into account.

Each nucleon transfer through the neck or window established between the dynamically evolving nuclei generates a hole excitation in the donor nucleus and a particle excitation in the recipient nucleus. The hole excitation energy is given by

$$\Delta E_h = E_F - \tfrac{1}{2} m v_f^2 \tag{1}$$

and the particle excitation energy is given by

$$\Delta E_p = \tfrac{1}{2} m (\mathbf{v}_f + \mathbf{v}_{\rm rel})^2 - (E_F - \omega) \ . \tag{2}$$

Here, $\mathbf{v}_f$ is the intrinsic Fermi velocity of the transferred nucleon in the donor nucleus given by the finite temperature Fermi-Dirac distribution, $\mathbf{v}_{\mathrm{rel}}$ the relative velocity of the nuclei, m the nucleon mass, E_F the Fermi energy of the donor nucleus, and ω is the macroscopic driving force taken from the liquid drop model in this calculation. The sum of the hole and particle excitation energies is the total excitation in the dinuclear complex due to a single nucleon transfer which is equal to the energy loss from the relative motion. The total particle excitation energy in nucleus B due to transfer of nucleons from nucleus A in a certain specified reaction time is given by

$$E_p^B = \int dt\, N_{AB} \Delta E_p \quad . \tag{3}$$

The one way particle current N_{AB} is

$$N_{AB} = \frac{3}{4\pi v_F^3} \int d\mathscr{A} \int d\mathbf{v}_f\, f(\epsilon_A, T_a)[1 - f(\epsilon_B, T_B)] \times \mathscr{N}(\mathbf{v}_f + \mathbf{v}_{\mathrm{rel}}) \mathscr{T} \quad . \tag{4}$$

In a similar way, an expression for the hole excitation energy can be obtained. In Eq. (4) the integrals are over the neck area $\mathscr{A}$ and the intrinsic velocities of the nucleons in the donor nucleus. This integral is evaluated in the Monte Carlo method as in Ref. 11. The quantity $\mathbf{v}_F$ is the Fermi velocity, ϵ_A and ϵ_B are the energies of the transferred nucleon in systems A and B, $f(\epsilon, T)$ is the occupancy for a single particle state at energy ϵ and at temperature T, $\mathscr{N}(\bar{v})$ is the particle flux, $\mathscr{T}$ is the barrier (nuclear[1,11] + Coulomb) penetration factor, and ΔE_p is given by Eq. (2). The window area is calculated with the prescription given in Ref. 11. The barrier is approximated to be parabolic and the penetration factor is calculated using the Hill-Wheeler formula. For the evolution of the dynamical trajectory, we have followed the prescription of Ref. 12 with soft Coulomb and proximity force and proximity friction. The temperature of each fragment is calculated as

$$T_{A,B} = \left(\frac{10 E_{A,B}^*}{M_{A,B}} \right)^{1/2} \quad , \tag{5}$$

where M is the mass number of either nucleus. Here $E_{A,B}^*$ is the excitation energy of either nucleus A or B barring their collective rotational energies which we calculate from the angular momenta poured in A or B from particle exchange.

The particle current N_{BA} from nucleus B to nucleus A can be obtained analogous to Eq. (4). One can then obtain the drift and diffusion in both charge and mass once the relevant currents are evaluated. If the differences in Fermi energies and temperatures of the two nuclei are small compared with the mean Fermi energy and the relative velocity is small compared with the Fermi velocity v_F, the currents can be linearized in these quantities and expressions for drift and diffusion can be obtained as given by Feldmeier *et al.*[10] In our calculation, however, we have used the full expression through the Monte Carlo simulation technique.

The nuclear barrier is a function of the ratio between the surface separation and the surface diffuseness. As recently shown by Campi and Stringari,[13] the diffuseness increases very little at moderate temperatures and thus the decrease in the nuclear barrier is not significant. Since this effect does not change much the quantities of interest, this temperature dependence on the barrier has been ignored in our calculation.

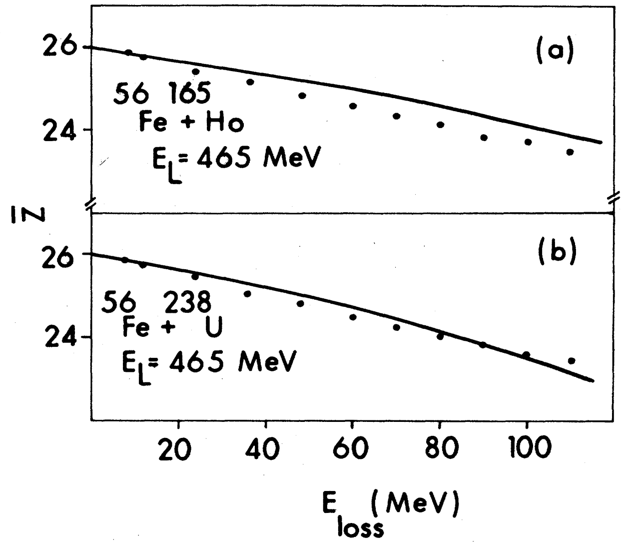

FIG. 1. The centroids of the charge distributions of the systems (a) ^{56}Fe + ^{165}Ho and (b) ^{56}Fe + ^{238}U plotted against energy loss. The solid lines correspond to calculated results and the dots represent the experimental data points.

We have studied two systems in this paper, namely, ^{56}Fe + ^{165}Ho and ^{56}Fe + ^{238}U, both at an incident energy of 465 MeV. In Fig. 1, the centroids of the charge distributions are plotted against energy loss for these systems. For these asymmetric systems, it is expected that due to the large Coulomb pressure experienced by the proton single-particle orbitals of the lighter nucleus, protons would be driven towards the heavier nucleus and that effect is correctly reproduced. We however find that the calculated

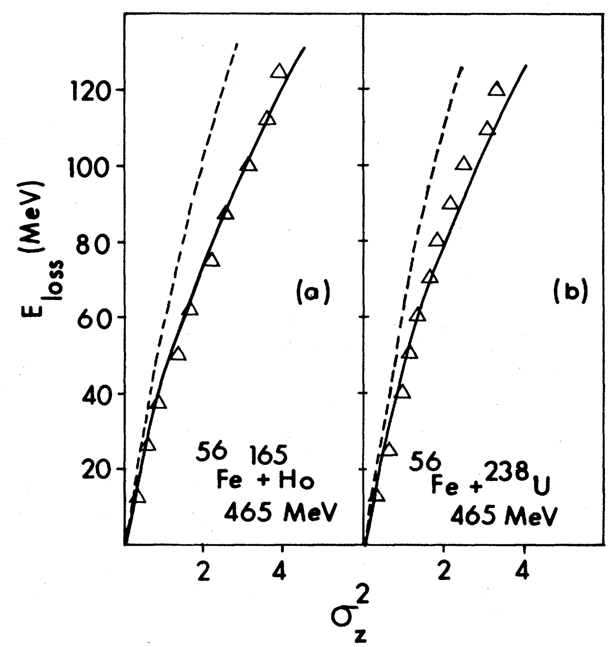

FIG. 2. The charge variances against the energy losses for the systems studied. The open triangles refer to the experimental data. The full lines correspond to finite temperture calculations and the dotted lines correspond to zero-temperature calculations.

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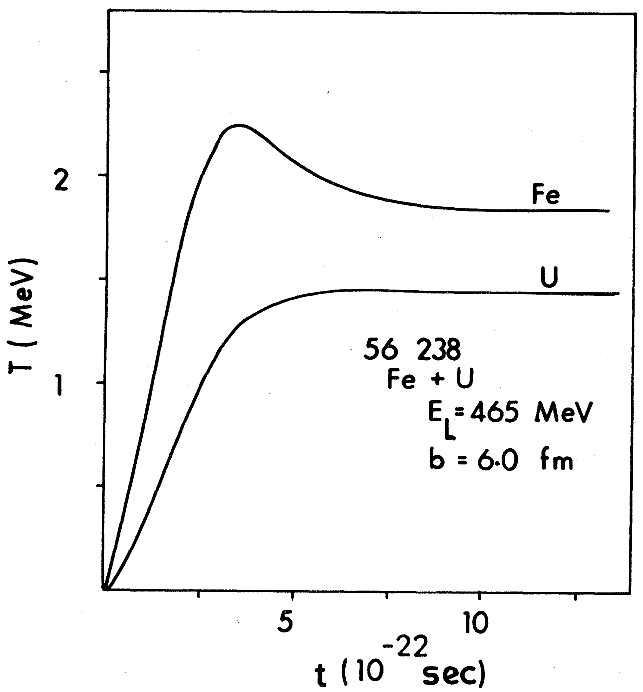

FIG. 3. Time evolution of the temperatures of ^{56}Fe and ^{236}U nuclei at a fixed impact parameter ($b = 6$ fm).

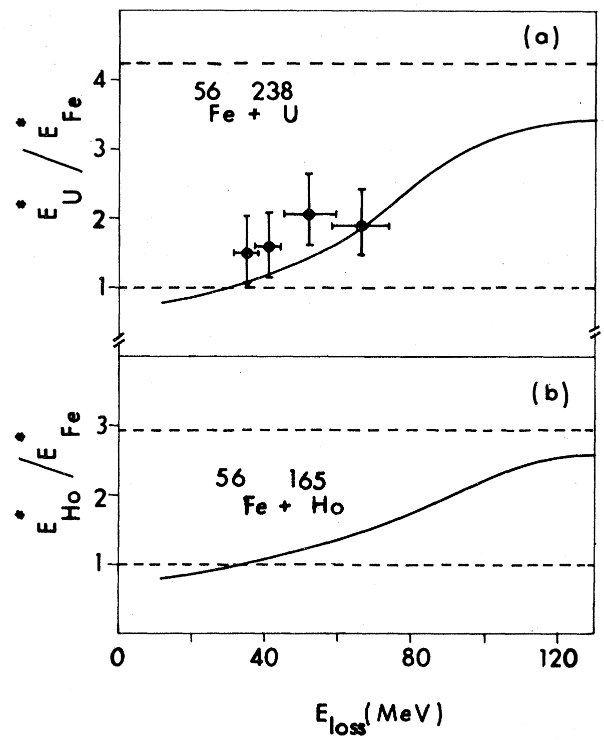

FIG. 4. The ratios of the thermal excitation energies of the target-like and projectile-like fragments for the systems studied vs energy loss. In (a) the experimental points are taken from Vandenbosch *et al.* (Ref. 9).

values, particularly for the ^{56}Fe + ^{165}Ho system (above 50 MeV energy loss) are larger than the experimental values by approximately 0.5 units. It is probably a reflection of the inadequacy of the macroscopic liquid drop driving force.

In Fig. 2, we plot the charge variances for the abovementioned systems against energy loss. We find that the variances obtained from the zero-temperature approximation are underestimated; proper accounting of the temperatures of the nuclei increases the variances and reproduce the experimental data very well. The variances obtained from the Monte Carlo calculations correspond to uncorrelated proton-neutron transfer, isospin-correlation[2] affects the proton or neutron variances very little. The first and second moments of the charge and the neutron distributions have been calculated for many other systems and are found to be in good agreement with the data indicating the validity of the model. This would be reported elsewhere. To see the effect of the temperature gradient on the mass (or charge) asymmetry and the mass or charge variances, we repeated the calculations by forcing the temperatures of both the fragments to be the same. It is found that the thermal feedback[14] has no significant effect on the drift in the cases we have studied. The effect of the temperature gradient on the variances is also found to be very small (at most around five percent).

In Fig. 3 we show how the temperatures of the nuclei evolve as a function of the interaction time for a typical impact parameter ($b = 6.0$ fm) for the Fe + U system; this corresponds to an energy loss of 80 MeV. We find that the temperatures of both the nuclei rise very quickly in the initial phase. It is partly because, in the initial phase, the energy loss per particle transfer is larger, partly because the neck area increases rather quickly allowing for large flux of nucleons in a short time. The temperature of the lighter fragment rises faster, reflecting the fact that energy is not divided in the ratio of the masses. After a time $\sim 3.5 \times 10^{-22}$ sec, the temperature of the lighter nucleus drops because it delivers more energy to the cooler heavy nucleus than it gets through particle diffusion. The energies of the nuclei remain almost constant after $t \sim 7.0 \times 10^{-22}$ sec. Here, in the exit channel the nucleon exchange is inappreciable and therefore the temperatures saturate. The final temperature of the nuclei differ by ~ 0.4 MeV which shows that energy is not completely equilibrated even for this trajectory with appreciable energy loss.

In Fig. 4, the ratios of the excitation energies for the two systems against the total energy loss are displayed. For low energy loss, the lighter fragment is somewhat more excited than the heavier one. The macroscopic driving force drives more protons from the lighter to the heavier nucleus due to the Coulomb pressure; however, it caused preferential transfer of neutrons from the heavier to the lighter nucleus. The larger relative weight of the latter is reflected in the larger excitation energy of the lighter fragment for small energy losses. With increasing energy loss, the relative excitation of the heavier nucleus increases. Though the longer interaction time drives the system towards thermal equilibrium, the limit corresponding to complete equilibration is not reached for the systems studied. The more asymmetric system Fe + U is farther away from equilibrium as one would expect. In this particular case, the experimental data obtained by Vandenbosch *et al.*[9] for energy division are also shown in the figure. The calculated results are found to be in fair agreement with the data. For the system Fe + Ho, the neutron multiplicity data indicate a gradual transition[7] from equal partitioning of energy to equal temperature with increasing energy loss. Such a gradual evolution from nonequilibrium to equilibrium is also obtained in our calculations.

To summarize, we find from the stochastic nucleon exchange model that for very asymmetric systems, the reaction fragments are in thermal nonequilibrium for noncentral collisions and gradually evolve towards equilibrium for more central (deeply inelastic) collisions. This is supported by the experimental data. This observation, coupled with the nice reproduction of the experimental charge centroids and variances, brings out the dominant nature of the stochastic nucleon exchange process in the heavy ion collisions.

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[1]J. Randrup, Nucl. Phys. A **327**, 490 (1979).
[2]S. S. Kapoor and J. N. De, Phys. Rev. C **26**, 172 (1982).
[3]J. N. De and D. Sperber, Phys. Lett. **72B**, 293 (1978); W. U. Schroder, J. R. Huizenga, and J. Randrup, *ibid.* **98B**, 355 (1981); H. C. Britt *et al.*, Phys. Rev. C **26**, 1999 (1982).
[4]J. N. De, S. K. Samaddar, and K. Krishnan, Phys. Rev. Lett. **48**, 81 (1982).
[5]J. Randrup, Nucl. Phys. **A383**, 468 (1982).
[6]D. Hilscher *et al.*, Phys. Rev. C **20**, 576 (1979); B. Tamain *et al.*, Nucl. Phys. **A330**, 253 (1979); Y. Eyal *et al.*, Phys. Rev. C **21**, 1377 (1980).
[7]T. Awes *et al.*, Phys. Rev. Lett. **52**, 251 (1984).
[8]H. Breuer *et al.*, Phys. Rev. C **28**, 1080 (1983).
[9]R. Vandenbosch *et al.*, Phys. Rev. Lett. **52**, 1964 (1984).
[10]H. Feldmeier and H. Spangenberger, in *Conference on Theoretical Approaches to Heavy Ion Reaction Mechanism,* Paris, 1984 [Nucl. Phys. A (in press)]; H. Feldmeier, in *Nuclear Structure and Heavy-Ion Dynamics,* Varenna Lecture Course LXXXVII, edited by L. G. Moretto and R. Ricci (North-Holland, Amsterdam, 1984), p. 274.
[12]J. P. Bondorf, M. I. Sobel, and D. Sperber, Phys. Rep. **15C**, 83 (1974).
[13]X. Campi and S. Stringari, Z. Phys. A **309**, 239 (1983).
[14]L. Moretto, Z. Phys. A **310**, 61 (1983).