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Heat partition in damped reactions

S. Chattopadhyay and D. Pal
Saha Institute of Nuclear Physics, 92 Acharya Prafulla Chandra Road, Calcutta 700 009, India
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The effect of driving force on the division of excitation energy between the asymmetric colliding partners in deep inelastic heavy-ion collisions is studied in the nucleon-exchange model. For this purpose an event by event analysis using Monte Carlo simulation technique is performed. It is seen that the fraction of the total excitation energy carried by the projectile-like fragment is sensitive to the mass drift. The model is also applied to analyze the correlation between fragment mass and excitation energy for a given total energy loss and significant correlation is found. The reactions induced by ^{56}Fe at 9 MeV/nucleon and ^{74}Ge at 8.5 MeV/nucleon on ^{165}Ho are considered in our analysis and the calculated correlations are in good agreement with the results obtained from the kinematic coincidence experiments.

In recent years, considerable effort has been made[1-3] in the experimental study of the division of the excitation energy between two asymmetric colliding heavy ions with the hope that this will enable us to understand the underlying reaction mechanism pertaining to strongly damped processes. It is now generally accepted that the excitation energy is shared almost equally by the two colliding partners for small energy losses which evolves towards a division according to masses (equal temperature) for high-energy losses where the reaction time is longer. A few theoretical attempts[4,5] using stochastic single nucleon exchange model have been made in this direction within the mean trajectory approximation (MTA) which reproduce the experimental trend. Recently the measurement of excitation energy of the projectile-like fragment (PLF) as a function of its mass for a fixed total kinetic-energy loss shows a considerable correlation between the two quantities. However, it has been claimed by Tôke, Schröder, and Huizenga[6] that the finite resolution of the experimental setup may have artificially induced the correlation. They have further demonstrated that the experimental data of Ref. 1 are consistent with an assumption of no correlation if uncertainties resulting from finite resolution of the kinematic coincidence measurements are considered. To resolve this dilemma, we undertake a Monte Carlo simulation of the classical trajectory with stochastic exchange of single nucleons. The above-mentioned correlation cannot be studied under MTA for obvious reasons and an event by event analysis is performed to study this correlation. As this does not involve any kinematic coincidence, the simulation experiment we perform is free from the finite resolution problem of the real experiment.

The basic formalism employed for simulation of the deep inelastic trajectory is the same as that of Ref. 5. However, it is well known that the large energy loss observed for the relatively central collisions cannot be explained unless the appropriate shape degrees of freedom are included. For this purpose we have considered the neck degree of freedom, the treatment being the same as in Ref. 7. We briefly outline below the basic reaction mechanism and the relevant expressions.

The dynamical variables[8] are R, Θ, Θ_P, Θ_T, C, N, and Z, which represent the distance between the ion centers, the angle made by the line joining the ion centers with the beam direction, the orientation angles of the projectile and the target, the neck radius, and the instantaneous neutron number and proton number of the projectile-like fragment, respectively. When the colliding nuclei are in proximity, a window is opened up at the interface through which stochastic exchange of single nucleons take place. The transfer of a single nucleon induces hole (ΔE_h) and particle (ΔE_p) excitations in the donor nucleus and in the recipient nucleus, respectively. They are given by

$$\Delta E_h = E_F - \tfrac{1}{2} M V_f^2 , \tag{1}$$

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

Here M is the nucleon mass, E_F is the Fermi energy, $\mathbf{V}_f$ is the intrinsic velocity of the transferred nucleon given by finite-temperature Fermi distribution, $\mathbf{V}_{\rm rel}$ is the relative velocity between the colliding nuclei, and ω represents the macroscopic driving force obtained in the liquid drop model which corresponds to the change of the total potential energy for the transfer of a single nucleon. However, it will be seen shortly that the liquid-drop-model driving force is unable to reproduce the observed mass and charge drifts for the Fe and Ge induced reactions on Ho, which are studied in this work. This may be attributed to various reasons such as shell effect, deformation of the system, and temperature dependence of the liquid drop energy which are not included due to their involved character. For simplicity, we scale the model driving force and it is expected that this scaling factor will be, in general, different for the neutron and proton and also depend on the system. This scaling procedure reproduces the observed drifts fairly well. However, it may be emphasized that our main intention is not to reproduce the drifts but to study the correlation between drifts and the fraction of excitation energy shared by the PLF.

The dynamical neck area at time t is given by

$$A = \pi C^2 + 2\pi \bar{R}(s - s_{\max}) \equiv \pi R_e^2 , \tag{3}$$

where $\bar{R}$ is the reduced radius, s is the surface separation, and s_{max} is taken to be 3.2 fm, beyond which no neck exists. The effective neck radius R_e is constrained to be less than or equal to $R_<$, the radius of the lighter colliding partner. The probability that a nucleon will be transferred in the time interval t to $t+\Delta t$ from the nucleus A to the nucleus B is given by

$$\Delta P_{AB} = Af(e_A,T_A)[1-f(e_B,T_B)] \times N(|\mathbf{V}_f+\mathbf{V}_{rel}|_x)\Gamma\Delta t\,, \qquad (4)$$

where Δt is made sufficiently small so that $\Delta P_{AB}<1$. The position of the nucleon on the effective circular neck of radius R_e [cf. Eq. (3)] through which it is exchanged and its velocity vector $\mathbf{V}_f$ are generated randomly, where $\mathbf{V}_f$ is given by Fermi distribution function $f(e,T)$. The quantity $N(|\mathbf{V}|_x)$ is the neutron or the proton flux with x along the instantaneous dinuclear axis, and Γ is the barrier (Coulomb plus nuclear) penetration factor. At each time step (mesh size $\Delta t \approx 0.1$–0.5 fm/c) ΔP_{AB} and ΔP_{BA} are calculated both for neutron and proton. A random number is then generated for each ΔP_{AB} or ΔP_{BA} and if the random number is less than ΔP only then a nucleon is allowed to transfer in the appropriate direction. The transfer of nucleons also induces rotational motion in the donor and in the recipient nucleus. The expressions for the transfer induced angular momenta may be found in Ref. 9. The intrinsic excitations generated through particle transfer will damp the kinetic energies associated with the coordinates R and Θ, which are calculated in a self consistent way. The neck motion is damped through the one body wall dissipation as given in Ref. 7. For conservative force we take nuclear proximity[10] and Coulomb forces which are adjusted whenever a particle transfer occurs. A trajectory is numerically integrated with the above dissipative and conservative forces. The excitation energy of nucleus A is given by

$$E_A^* = \sum_i \Delta E_h^A(i) + \sum_j \Delta E_p^A(j) + E_w^A\,, \qquad (5)$$

where i and j summations correspond to transfer of nucleons from A to B and from B to A, respectively. The quantity E_w^A is the excitation energy generated through wall dissipation for which we shall consider two prescriptions: equal sharing, i.e., $E_w^A = E_w^B$ and sharing proportional to the respective radius. The excitation energy E_B^* can also be calculated in a similar way. This allows us to determine the pre-evaporated mass and charge numbers and the respective excitation energies of the interacting nuclei.

In Fig. 1 we display the average charge and mass drift from the projectile by the open box using the normal liquid-drop driving force along with the experimental data for the reaction ^{56}Fe+^{165}Ho at bombarding energy 9 MeV/nucleon. In Fig. 2 the same is shown for the reaction ^{74}Ge+^{165}Ho at 8.5 MeV/nucleon. It is seen that the calculated results are significantly different from the experimental data and it can be easily realized that the neutron drift for the Ge induced reaction is even in the wrong direction. Though the use of the trajectory fluctuations could explain drifts for some of the reactions[8] where MTA failed, the drifts for these two reactions cannot be explained even with the inclusion of trajectory fluctuations. As mentioned earlier, that reasonably good fit to the drift can be obtained with the scaled driving force as shown by the solid box in Figs. 1 and 2. The scaling factors used for the Fe induced reaction are 2 and 0.5 for the proton and neutron, respectively; the corresponding factors for the Ge induced reaction are 2 and −0.3. The average fraction of excitation energy $f_p = \langle E^*_{PLF}/E^*_{TOT}\rangle$ carried by the PLF for the Fe induced reaction[1] as a function of energy loss is shown in Fig. 3(a) by the open box and the solid box which correspond to the normal liquid-drop driving force and the scaled force, respectively. Here equal sharing for the wall dissipation E_w is considered. It is seen that there is a definite correlation between the mass drift (Fig. 1) and the excitation energy fraction of the PLF. Figure 3(b) gives the fraction f_p for the same reaction using E_w proportional to the radius of the colliding ions and the fit to the experimental data is seen to improve a little. In the rest we consider E_w to be shared proportional to the radius of the colliding ion. In Fig. 3(c)

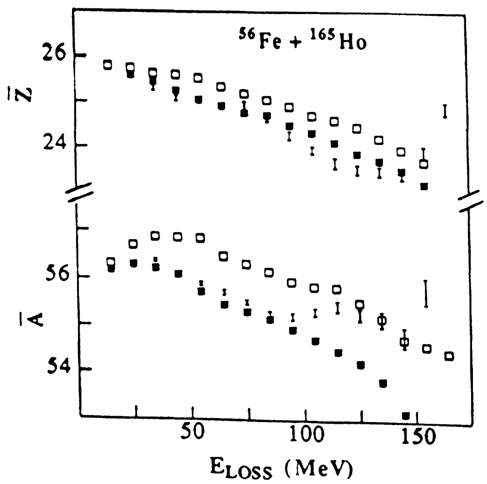

FIG. 1. Average charge and mass drifts as a function of total kinetic-energy loss (TKEL) for the reaction induced by 9 MeV/nucleon ^{56}Fe on ^{165}Ho. The bars indicate experimental results and for the other symbols see the text.

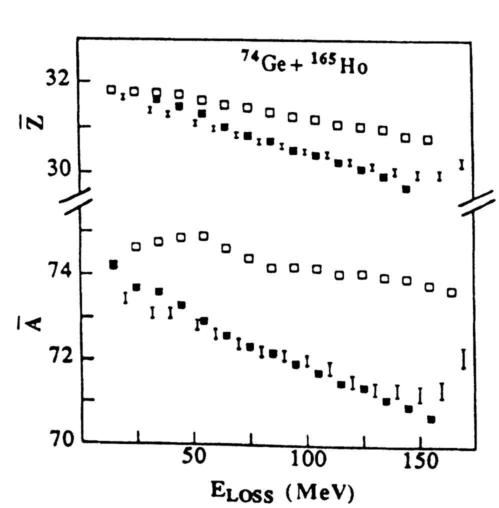

FIG. 2. Same as in Fig. 1 for the reaction induced by 8.5 MeV/nucleon ^{74}Ge.

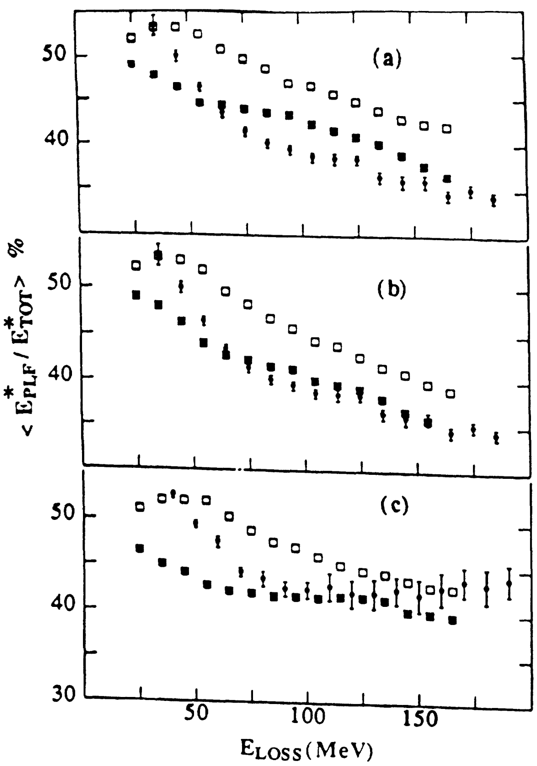

FIG. 3. The percentage of the total excitation energy carried by the PLF as a function of TKEL for the reactions induced by (a) and (b) ^{56}Fe and (c) ^{74}Ge.

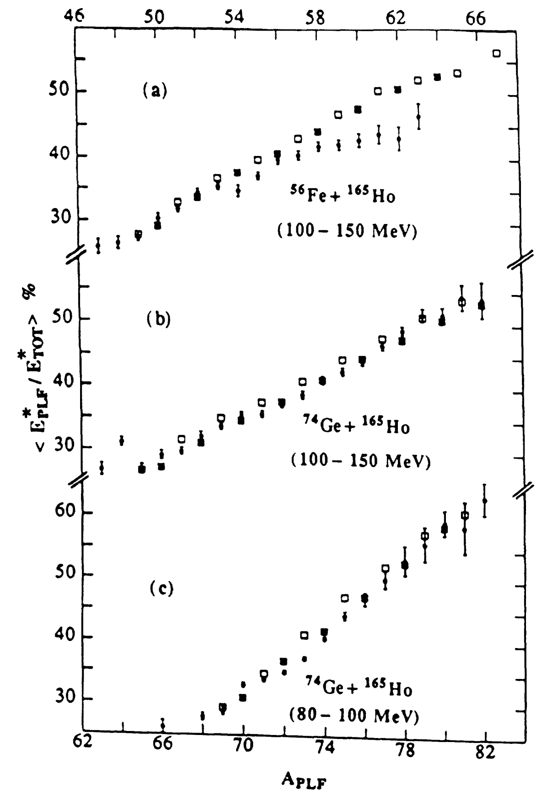

FIG. 4. Correlation between percentage of total excitation energy carried by PLF with its mass number for reactions and TKEL bins as indicated in the figure.

the ratio f_p is shown for the Ge induced reaction[2] and the same correlation between drift and excitation energy is found. In Fig. 4(a) we present the correlation between f_p and the mass number of the PLF for the total kinetic-energy loss between 100–150 MeV for the Fe induced reaction where the solid and open boxes correspond to scaled and normal liquid-drop driving forces, respectively. The same correlations are shown for the Ge induced reaction in Figs. 4(b) and 4(c) corresponding to the total kinetic-energy loss 100–150 MeV and 80–100 MeV, respectively. It is observed that the simulated correlations are very close to those obtained in the kinematic coincidence experiments.[1,2] The claim of Ref. 6 that in deep inelastic collisions the fraction f_p is expected to be independent of PLF mass is approximately true only when the drift is small compared to diffusion. The particle diffusion around 125 MeV energy loss for these reactions is ≈ 20 and the maximum drift (mass range) occurring in Fig. 4 is also of similar magnitude. Since the hole excitation ΔE_h is significantly smaller than the particle excitation ΔE_p, it is expected that the ion-losing particle will have less excitation. This fact is reflected in the results displayed in Figs. 3 and 4.

In summary, we conclude that the drift has a significant role in the division of excitation energy in deep inelastic heavy-ion collision. Further, there exists significant correlation between the excitation energy and the mass of PLF for a given total kinetic-energy loss. This correlation obtained from the kinematic coincidence experiment and from the present simulation study are in good agreement.

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