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Effect of trajectory fluctuations on nucleon drift and diffusion in deep inelastic heavy ion collisions

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The role of trajectory fluctuations on the first and second moments obtained in the mean trajectory approximation for the proton and neutron distributions of the projectile-like fragments produced in deep inelastic heavy ion collisions has been studied in the framework of stochastic transfer of single nucleons. At each instant of time the neutron and proton numbers of the colliding nuclei are considered to be given by dynamically evolving Gaussian distributions generating trajectory fluctuations. The first moments calculated in this method differ considerably from those obtained in the mean trajectory approximation for the systems with strong gradient in the driving force around the point of injection. The second moments, however, do not change appreciably for all the systems studied.

The model of stochastic transfer of single nucleons between two colliding heavy ions[1] has been found to be very successful in explaining varied experimental data on strongly damped collisions like inclusive and exclusive charge and mass distributions of the projectile-like fragments, energy and angular momentum loss from relative motion into intrinsic excitations,[2,3] misalignment of angular momentum,[4,5] etc. All these calculations have been performed in the mean trajectory approximation (MTA). Recent analyses of experimental data for highly asymmetric target-projectile combinations amply show[6-8] that the MTA is inadequate to explain the evolution of average neutron and proton numbers of the projectile-like fragments with energy loss when the driving force (to be more precise, the gradient of the driving force) is relatively strong around the injection point in the N-Z plane.

This naturally raises the question of the validity of the MTA. The work of Brosa *et al.*[9] has shown that a global moment approach is not appropriate to deep inelastic collisions and that the use of a local moment approach is a better approximation. In this Brief Report we study in a simple way the effect of the trajectory fluctuations generated through the finite widths of the instantaneous nucleon distributions within the interacting nuclei on the quantities related to the proton and the neutron distributions of the projectile-like fragments produced in strongly damped collisions. The basic formalism employed for this purpose is the same as in Ref. 10. However, it is well known that the large energy loss observed for relatively central collisions cannot be explained unless the appropriate shape degrees of freedom are included in the calculations. For this purpose we have considered the neck degree of freedom, the treatment being the same as in Ref. 11. For the sake of completeness, only the basic equations employed in our calculations are given in the following; the details may be found in Refs. 10 and 11.

The collective degrees of freedom whose time evolutions have been studied 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 orientations of the projectile and the target, the neck radius, and the neutron and proton number of the projectile, respectively. The random exchange of nucleons between the two colliding ions occurs when they come in proximity and the transfer of a single nucleon induces a hole excitation ΔE_h in the donor nucleus and particle excitation ΔE_p in the recipient nucleus, which 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 in the donor nucleus having the finite-temperature Fermi-Dirac distribution, $\mathbf{V}_{\rm rel}$ is the instantaneous relative velocity between the colliding nuclei, and the quantity ω represents the macroscopic driving force calculated in the liquid drop model which corresponds to the change of the total potential energy (including rotational energy) of the dinuclear complex for the transfer of a single nucleon.

The transfer of nucleons also induces rotational motion in the donor and the recipient nuclei. The expressions for the transfer-induced angular momenta may be found in Ref. 12. 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 result being close to that of average proximity friction.[13] The neck motion is damped through the one-body wall dissipation as given in Ref. 11. The total one-way particle current from nucleus A to B under the MTA is given by

$$N_{AB} = \frac{3}{4\pi V_F^3} \int d\mathbf{A} \int d\mathbf{V}_f f(\epsilon_A, T_A)[1 - f(\epsilon_B, T_B)] \mathcal{N}(|\mathbf{V}_f + \mathbf{V}_{\rm rel}|_x) \mathcal{T} . \tag{3}$$

Here the integrations are over the neck area A and the intrinsic velocities of the nucleons in the donor nucleus. This integral is evaluated by employing the Monte Carlo simulation technique. The size and position of the neck are taken to

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be the same as in Ref. 11; they are changing dynamically. The quantities ϵ_A and ϵ_B are the energies of the transferred nucleon in nucleus A and B, respectively, $f(\epsilon,T)$ is the Fermi occupancy of the single-particle state for energy ϵ and temperature T, $\mathcal{N}(|\mathbf{V}|_x)$ is the particle flux with x along the instantaneous dinuclear axis, and $\mathcal{T}$ is the barrier (Coulomb plus nuclear) penetration factor which is operative beyond the neck region. The particle current in the direction B to A (N_{BA}) can be evaluated in a similar way. The proton and neutron currents are obtained with the use of the appropriate flux $\mathcal{N}$. Then $N_{AB}(\bar{Z})-N_{BA}(\bar{Z})$ gives us the proton drift under the MTA.

The particle current depends on the instantaneous charge number Z and the neutron number N of the projectile (those for the target are automatically fixed from the total number of neutrons and protons), and Eq. (3) is evaluated at $Z=\bar{Z}(t)$, $N=\bar{N}(t)$ where the average proton number $\bar{Z}$ and the neutron number $\bar{N}$ at time t are obtained by averaging over many trajectories for each relevant impact parameter. In reality one should consider a dynamical distribution for N and Z, and the proton drift then reads as

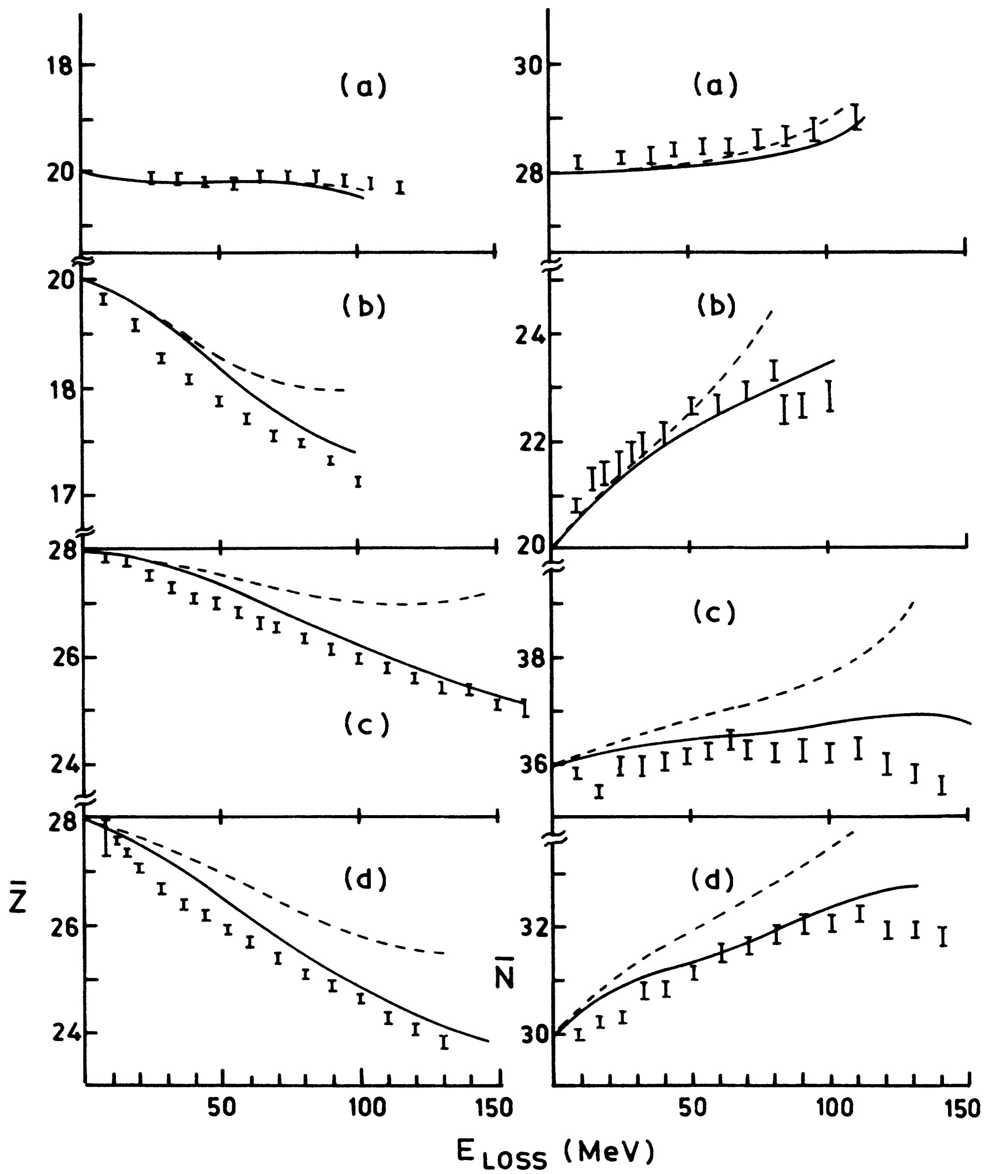

FIG. 1. Average charge number $\bar{Z}$ and neutron number $\bar{N}$ vs energy loss for the reactions induced by (a) ^{48}Ca, (b) ^{40}Ca, (c) ^{64}Ni, and (d) ^{58}Ni on ^{238}U. The dashed lines correspond to the MTA and the solid lines refer to calculations including the fluctuations.

$$\frac{d\bar{Z}}{dt}=\int[N_{AB}(Z)-N_{BA}(Z)]P(N,Z,t)dN\,dZ\ , \tag{4}$$

where for the distribution function $P(N,Z,t)$ we have used a bivariate distribution given by[14]

$$P(N,Z,t)=C\frac{1}{2\pi\sigma_N(t)\sigma_Z(t)}\exp\left[-\frac{1}{2}\left\{\frac{Z-\bar{Z}(t)}{\sigma_Z(t)}\right\}^2-\frac{1}{2}\left\{\frac{N-\bar{N}(t)}{\sigma_N(t)}\right\}^2-\alpha(N-\beta Z)\right]\ , \tag{5}$$

where C is the normalization constant. The last term in the argument of the exponential introduces correlation in the neutron-proton by forcing N towards βZ where β is given[14] as the ratio of the total number of neutrons to protons of the dinuclear complex. The correlation coefficient ρ can be expressed[14] in terms of the parameters α and β and the variances. It is clear that for $\alpha=0$ one has $\rho=0$ and $\alpha=\infty$ corresponds to $\rho=1$. The proton diffusion coefficient is given by

$$\frac{d\sigma^2}{dt}_Z=\int[N_{AB}(Z)+N_{BA}(Z)]P(N,Z,t)dN\,dZ\ . \tag{6}$$

It may be pointed out that for the fully correlated ($\rho=1$) neutron and proton exchanges, the correlation inducing term in Eq. (5) reduces to a one-dimensional integral. Integrating Eqs. (4) and (6) and their counterparts for neutrons, one gets the first and second moments for proton and neutron distributions of the projectile-like fragments.

The calculations of average values for proton and neutron numbers and their variances have been performed for the reactions ^{58}Ni and ^{64}Ni at 8.5 MeV/nucleon (Ref. 7), ^{40}Ca at 8.5 MeV/nucleon (Ref. 6), and ^{48}Ca at $E_{\rm lab}=425$ MeV,[8] on ^{238}U. It is well known that the correlation coefficient generally increases from the value zero to the value unity with the increase of the energy loss. We have considered these two extreme limits $\rho=0$ and 1 and found that our results are insensitive to the value of ρ. So we present in the following results pertaining to the uncorrelated case. The results for $\bar{Z}$ and $\bar{N}$ as a function of energy loss are displayed in Fig. 1. We observe that barring the reaction induced by ^{48}Ca, in all other cases the drift in neutron and proton numbers is very poorly reproduced in the MTA and the numerical values of the calculated drift coefficients are significantly smaller for proton drift and larger for neutron drift than those of the measured values (neutron corrected for evaporation), particularly for higher energy losses. The driv-

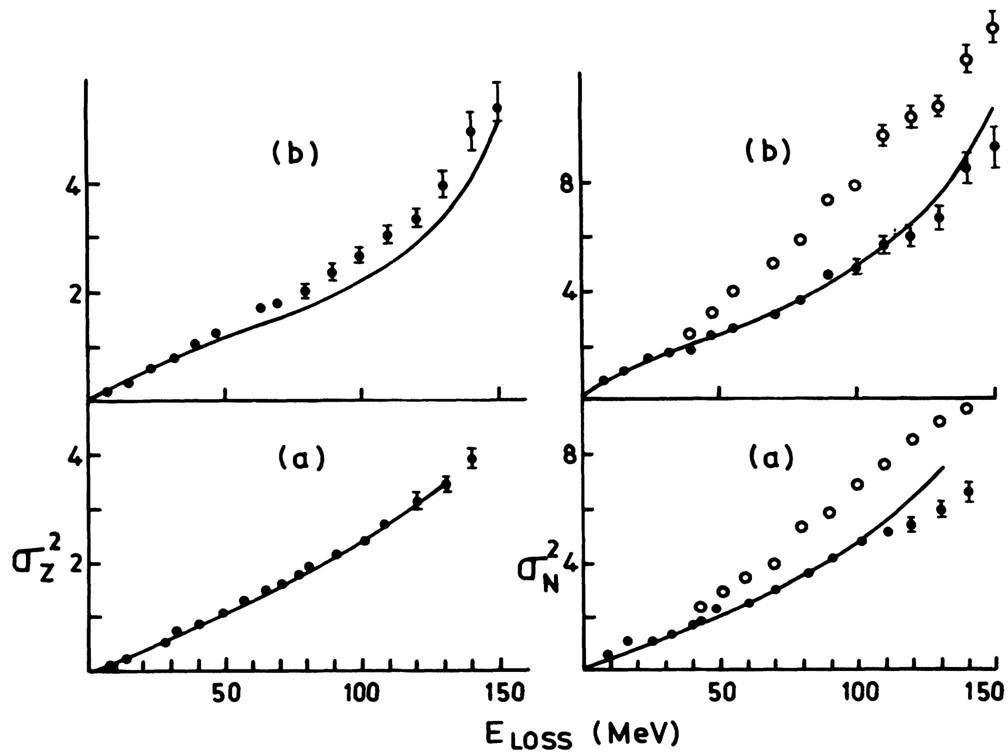

FIG. 2. Proton and neutron variances as a function of energy loss for the reactions induced by (a) ^{58}Ni and (b) ^{64}Ni on ^{238}U. The open and the filled circles correspond to experimental data with and without evaporation corrections, respectively. The solid lines refer to calculations with the MTA, and the results including the fluctuations are indistinguishable from it.

ing force as well as its gradient in the N-Z plane are negligible for the $^{48}Ca+^{238}U$ system around the injection point,[8] whereas those are rather appreciable[6] for the rest of the systems considered. This clearly demonstrates that the MTA is not adequate to explain the observed drifts for systems having large values of driving forces at the injection point. The calculated drifts with the inclusion of the effect of fluctuations as given by Eq. (4) are also shown in the figure, and we note that the agreement with the experimental data is fairly good. The increasing differences with energy loss of the MTA drifts and those calculated with the fluctuations may be understood due to large values of variances at higher energy losses and relatively long reaction times. It is also observed that at low energy losses, the percentage error between the predicted values of $\bar{N}$ and $\bar{Z}$ with the data is not negligible. This may be attributed to (a) the structure effect and (b) the memory effect.[15]

In Fig. 2 we have plotted proton variances (σ_Z^2) and neutron variances (σ_N^2) versus energy loss for ^{58}Ni- and ^{64}Ni-induced reactions. The measured neutron variances corrected for evaporation are also displayed. It has been found that the calculated σ_Z^2 and σ_N^2 with and without fluctuations are very close, and both of them are represented by the solid lines in Fig. 2. The particle current in the absence of a driving force is practically the same in either direction, and hence the drift is sensitive to the driving force. On the other hand, the diffusion is mainly controlled by the total particle flux, and therefore the fluctuations have little role to play. We find that the calculated proton variances are also in good agreement with the measured values (evaporation has a small effect on proton variances). However, it may be noted that the calculated neutron variances at high $E_{\rm loss}$ somewhat underestimate the deduced primary values, and we are unable to explain any definite reason for this.

In summary, we have shown that for systems having a large gradient in driving forces around the injection points, the MTA is inadequate to explain the drift of neutrons and protons at considerable energy loss. The inclusion of the trajectory fluctuations improves the results significantly. The variances are found to be insensitive to the fluctuations for all the systems studied.

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