Fast $A/Z$ Equilibration and Correlated Nucleon Exchange in Damped Collisions of $^{56}$Fe Ions with $^{209}$Bi

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Recently published data on mass and charge distributions in interactions of $^{56}$Fe with $^{209}$Bi are reexamined. Both the average mass-to-charge ratio and the relationship between the variances of the mass and charge distributions were found to depend on the degree of energy damping. This was reported to present evidence for long interaction times required for charge equilibration and for the evolution of correlations in the exchange of neutrons and protons. We show that the dependence of the equilibrated mass-to-charge ratios on energy loss is the combined result of i) the mass drift in the $^{56}$Fe + $^{209}$Bi reaction and ii) the steep gradients of the potential energy surface which lead to a strong dependence of the mass-to-charge ratios on mass asymmetry. Also, the ratios of the variances of mass and charge distributions are shown to reflect the varying slope of the potential energy valley. It is concluded that the $^{56}$Fe + $^{209}$Bi data are consistent with fast charge equilibration and fully correlated nucleon exchange in agreement with the behaviour of other systems.

I. Introduction

Insight into important aspects of the reaction mechanism for damped collisions between heavy nuclei can be gained by studying the correlation between neutron and proton numbers of the final fragments. From the average charges at fixed mass asymmetry measured in a number of systems [1–6] one can conclude that the mass-to-charge equilibration is complete after a few tens of MeV of kinetic energy are dissipated. In equilibrium the average mass-to-charge ratios $\langle A/Z \rangle$ minimize the potential energy of the composite system. The relevance of pairing corrections and of shell effects for the potential energy in the exit channels has recently been demonstrated [5]. Thus it appears that the most important factors determining $\langle A/Z \rangle$ at fixed mass asymmetry are the $Z$-dependence of i) the symmetry energy of the liquid drop model, ii) pairing corrections, and iii) shell corrections. All these contributions depend on the actual mass $A$ of the final fragment and, therefore, $\langle A/Z \rangle$ is a non-linear function of $A$. As a consequence, the simple assumption of a uniform charge density (UCD) where the fragment $\langle A/Z \rangle$ ratios for all mass asymmetries are given by the total mass and charge of the combined system as $(A_1 + A_2)/(Z_1 + Z_2)$ is in error.

Variance $(\sigma^2_A)^2$ of charge distributions at fixed $A$ have been measured in a number of systems [2, 4, 6–8] and have been found to be remarkably narrow. These results on first and second moments of charge distributions at fixed mass asymmetry are consistent with a reaction mechanism where – after the initial entrance channel charge asymmetry is relaxed – the ratios $\langle A/Z \rangle$ are sensitively determined by the highest available density of states in the exit channels and where neutron and proton exchanges are highly correlated. Further information on the degree of correlation between neutron and proton exchanges can be obtained from the variances $\sigma^2_A$, $\sigma^2_Z$, and $\sigma^2_N$ of the integral mass-, charge-, and neutron number distributions at fixed values of the dissipated energy $E_{\text{loss}}$. The correlation coefficient $\rho$ is defined by

$$\sigma_A^2 = \sigma_A^2 + \sigma_N^2 + 2 \rho \sigma_A \sigma_N$$

with $-1 \leq \rho \leq 1$. For uncorrelated exchange of neu-
trons and protons, $\rho = 0$ and

\[ \sigma_n^2 = (1 + N/Z) \sigma_z^2 = (A/Z) \sigma_z^2 \]

(2)

where $N$, $Z$, and $A$ refer to the combined system. For fully correlated exchange, $\rho = 1$ and

\[ \sigma_n^2 = (1 + dN/dZ)^2 \sigma_z^2, \]

(3)

where $dN/dZ$ represents the slope of the potential energy valley in the $N-Z$ plane, averaged over the particular mass range under consideration. On the basis of what has been discussed above $dN/dZ$ is not constant but depends on the mass asymmetry. Only in the limit of the UCD-assumption, $dN/dZ$ equals $(N_1 + N_2)/(Z_1 + Z_2)$ and relation (3) is approximated [9] by

\[ \sigma_n^2 = (A/Z)^2 \sigma_z^2. \]

(4)

Recently, mean values of $A/Z$ and variances $\sigma_n^2$ and $\sigma_z^2$ of mass and charge distributions as a function of $E_{\text{loss}}$ were published by Breuer et al. [10] for interactions of $8.3 \text{ MeV/u}^{56}\text{Fe}$ ions with $^{56}\text{Fe}$, $^{155}\text{Ho}$ and $^{209}\text{Bi}$. The data have been corrected for particle evaporation [10]. For the latter two systems both the $A/Z$ ratio and the relationship between the variances of the mass- and charge distributions for Fe-like fragments were found to depend on the degree of energy damping. The authors of Ref. 10 concluded that, for very asymmetric systems, an equilibrium in $A/Z$ and correlated nucleon exchange are not achieved until the reactions are almost totally damped. This conclusion is at variance with previous evidence [1–8].

The purpose of this paper is to reexamine the $^{56}\text{Fe} + ^{209}\text{Bi}$ data of Ref. 10 and to demonstrate that the data are consistent with an early achievement of $A/Z$ equilibrium and of fully correlated nucleon exchange. Moreover, this paper intends to stress the importance of nuclear structure for the path of mass and charge flow in damped heavy-ion collisions.

II. Results

We have started our considerations by calculating the most probable charge $\langle Z \rangle$ at each mass asymmetry near $^{56}\text{Fe}$ by minimizing the potential energy for two touching spherical fragments using the method described in Ref. 5. The minimum potential energy concept is justified by phase space considerations relating the most probable charge $\langle Z \rangle$ at a given mass asymmetry to the highest available density of states in the exit channels. The highest level density is associated with the maximum available energy $\Delta E^*$ in the dinuclear system. The available energy $\Delta E^*$ as a function of $Z$ at fixed $A$ is expressed as

\[ \Delta E^* = Q_{\text{gs}} - \delta_n - \delta_p + \Delta V_C(R) + \Delta V_N(R) + \Delta V_V(R) \]

where $Q_{\text{gs}}$ is the ground state $Q$-value calculated from experimental mass excesses thus including shell effects for two separated fragments. \( \delta_n \) and \( \delta_p \) represent corrections of $Q_{\text{gs}}$ due to the breaking of pairs in the diffusion process [1], and $\Delta V_C$, $\Delta V_N$ and $\Delta V_V$ are the changes in the Coulomb, the nuclear and the centrifugal potentials between entrance and exit channel. The contribution of the centrifugal potential differences was found to vary insignificantly between $l = 0$ and $l = 100$ and was therefore ignored. For the shell-corrected calculations of the available energy $\Delta E^*$ we used the interaction radii $R = 1.16 (A_1^{1/3} + A_2^{1/3} + 2)$ fm.

Another choice of $R$ (e.g. the half-density radii) does not sensitively change the results. Alternatively, for large values of $E_{\text{loss}}$ where shell effects were assumed to be washed out, we calculated $Q_{\text{gs}}$ from binding energies of the liquid drop model without shell corrections. Here, half density radii were used. The same static potential energy calculations have been shown to reproduce quantitatively the experimental average $\langle A/Z \rangle$ ratios in the reactions of Xe-ions with $^{197}\text{Au}$ [5].

The resulting values for the equilibrium ratios of $\langle A/Z \rangle$ as a function of mass asymmetry in the $^{56}\text{Fe} + ^{209}\text{Bi}$ reaction are shown in Fig. 1 where neutron

\[ \begin{align*}
N_n &= 28, & N_l &= 126, & \text{UCD} \\
MPE &\text{ without } SC \\
MPE &\text{ with } SC \\
Z_l &= 28, & Z_n &= 82 \\
\langle A/Z \rangle &\text{ versus } A
\end{align*} \]

Fig. 1. Predictions of equilibrium mass-to-charge ratios $\langle A/Z \rangle$ at fixed mass asymmetry for $^{56}\text{Fe}$-like fragments in the $^{56}\text{Fe} + ^{209}\text{Bi}$ system. The minimum potential energy prediction including pairing and shell corrections is represented by the solid line, the minimum potential energy prediction with pairing but without shell corrections by the dashed line, and the $A/Z$-ratio of the combined system (UCD-rule) by the dotted line. The entry point ($^{56}\text{Fe}$) is marked as encircled cross. Closed shells in the light and heavy fragment are also indicated.