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Transport and evaporation model calculation of N and Z distributions for damped nuclear reactions

D.-K. Lock and R. Vandenbosch
Department of Chemistry and Nuclear Physics Laboratory, University of Washington, Seattle, Washington 98195

Jørgen Randrup
Nuclear Science Division, Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720

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A nucleon exchange model calculation followed by an evaporation model calculation has been used to predict the various parameters of the N and Z distributions for the reactions 465 MeV ^{56}Fe+^{56}Fe, ^{238}U. Comparison with the recent results of Breuer *et al.* shows overall good agreement, with the correlation coefficients particularly well reproduced. However, the neutron and proton drift in the asymmetric system is poorly reproduced.

The Z, N, and A distributions and their correlations provide important information about the mechanism of quasielastic and deeply inelastic nuclear reactions. The variances of the distribution are related to the number of nucleon exchanges during the reaction. The mean values are a measure of the difference between the number of particles transferred in each direction. The correlation coefficient is related to the $N-Z$ dependence of the underlying potential energy surface. The distributions of most interest from a theoretical viewpoint are the primary distributions prior to particle evaporation. The measured secondary distributions include the effect of particle evaporation at a later stage of the reaction process.

Two experiments were performed recently which enable a unique confrontation of experimental data with theoretical models. Breuer *et al.*[1] have measured the Z and A distributions as a function of energy loss for several systems, including ^{56}Fe + ^{56}Fe and ^{56}Fe + ^{238}U. The symmetric ^{56}Fe + ^{56}Fe system is of particular interest because there will not be any average net charge or mass drift between the two nuclei, and thus the $\langle N\rangle$ and $\langle Z\rangle$ values of the primary distribution from this reaction are known. Also the average excitation energy of the two fragments will be equal. Comparison of the observed $\langle N\rangle$ and $\langle Z\rangle$ values with the calculated values provides a test of the validity of the evaporation calculations used to transform the theoretically calculated primary distributions to secondary distributions which can be compared with experiment.

The ^{56}Fe + ^{238}U reaction data allow a test of the nucleon exchange model for a very asymmetric system. The principal difficulty in making such a test in the past has been the paucity of experimental data on the dependence of the division of the total excitation energy between the two fragments on total kinetic energy loss. A recent experiment[2] determined the energy division for intermediate energy losses, and showed that the division is far from the equal temperature limit often assumed.

The theoretical model we have used to calculate the primary N and Z distributions and their dependence on energy loss is the transport model of Randrup.[3] The classical equations of motion are solved by integration along a trajectory determined by the initial orbital angular momentum and the Coulomb and nuclear forces. A proximity potential is used for the latter, augmented by corrections for a cylindrical neck which is allowed to develop once the nuclei are in contact. Stochastic exchange of nucleons accounts for the drift in the mean value and the width of the particle number distributions, and for the conversion of kinetic energy of relative motion into internal excitation energy.

The evaporation effects were handled in the same way as described in Ref. 4. Briefly, the evaporation code PACE (Ref. 5) was used to calculate the evaporation residue yield from each nuclide produced in significant yield at a particular energy loss for a given system. These results were used to generate a transformation matrix to convert the primary yields from the nucleon exchange model into secondary yields which can be compared with experiment.

The results of the calculations are compared with experiment in Table I and in Fig. 1. We emphasize that there are no adjustable parameters in the transport model and that we have taken standard or default values in the evaporation calculation. We first consider the Fe + Fe system. The comparison of the $\langle N\rangle$ and $\langle Z\rangle$ values for this system are insensitive to the transport model and therefore provide an important test of the evaporation calculation, particularly the ratio of proton emission to neutron emission. The agreement of the calculated post-evaporation values with experiment is gratifying. The variances of the N and Z distributions, on the other hand, are relatively insensitive to evaporation effects and test the transport model. The variances are underestimated somewhat, perhaps due to the neglect of fluctuations about the mean trajectory in the model. The correlation coefficient, which is sensitive to the ratio of the variances of the N and Z distributions, is reproduced quite well after evaporation effects are taken into account. The calculated isobaric variances are somewhat too small, for reasons that are not apparent.

We turn now to a discussion of the Fe + U system. All of the calculated properties are in reasonable agreement

TABLE I. Comparison of preevaporation distribution parameters from nucleon exchange model (pre), post-evaporation distribution parameters (post), and experimental distribution parameters (exp) as a function of total kinetic energy loss (TKEL).

					Fe + Fe ($E_{\rm lab}$=465 MeV)				
TKEL		σ_N^2			σ_Z^2			ρ	
	pre	post	exp	pre	post	exp	pre	post	exp
40	1.48	1.29	2.38	1.06	1.03	1.54	0.21	0.41	0.52
80	2.61	2.93	5.62	1.97	2.26	3.51	0.53	0.77	0.81
100	4.10	4.80	8.90	3.01	3.40	5.71	0.70	0.86	0.89
TKEL		$\sigma_Z^2(A)$			$\langle Z \rangle$			$\langle N \rangle$	
	pre	post	exp	pre	post	exp	pre	post	exp
40	0.49	0.34	0.45	26.0	25.7	25.6	30.0	29.2	29.4
80	0.53	0.29	0.41	26.0	24.6	24.6	30.0	28.0	28.0
100	0.52	0.28	0.39	26.0	24.2	24.1	30.0	27.5	27.3
					Fe + U ($E_{\rm lab}$=465 MeV)				
TKEL		σ_N^2			σ_Z^2			ρ	
	pre	post	exp	pre	post	exp	pre	post	exp
40	2.36	1.85	1.71	0.96	0.91	0.93	0.18	0.18	0.18
100	4.44	3.57	3.98	2.47	2.50	2.61	0.54	0.56	0.58
140	11.0	8.64	8.25	5.11	4.73	4.69	0.83	0.84	0.77
TKEL		$\sigma_Z^2(A)$			$\langle Z \rangle$			$\langle N \rangle$	
	pre	post	exp	pre	post	exp	pre	post	exp
40	0.57	0.51	0.50	25.6	25.5	25.0	31.8	31.0	30.4
100	0.74	0.65	0.66	24.9	24.8	23.6	34.0	32.0	29.5
140	0.61	0.50	0.70	24.7	24.7	22.7	34.9	32.0	28.8

with experiment for this system except for the $\langle N \rangle$ and $\langle Z \rangle$ values. The agreement of the calculated variances and correlation coefficient is remarkably good.

The question arises whether the nucleon exchange model prediction for the variances depends strongly on $\langle N \rangle$ and $\langle Z \rangle$ since the transport model did a poor job in reproducing the latter quantities. In trying to answer this, we performed model calculations on the ^{56}Cr + ^{238}U and ^{56}Ti + ^{238}U systems at the same bombarding energy as for the ^{56}Fe + ^{238}U system. The results of the calculation for the variances are very similar to the Fe + U reaction. This shows that the calculated variances are not sensitive to the mean value of N and Z about which the fluctuations are occurring. It is perhaps not difficult to understand that the variances can be calculated with greater confidence than the mean values: The rate of change in the mean charge, say, is given by $d\langle Z \rangle/dt = N_Z^+ - N_Z^-$, where N_Z^+ (N_Z^-) is the instantaneous current of protons into (out of) the projectilelike reaction partner, while the variance grows according to $d\sigma_Z^2/dt \approx N_Z^+ + N_Z^-$. Thus, the mean drift is governed by the relatively small *difference* between the two directed currents while the variance is governed by their *sums*. In consequence, the former quantity depends rather delicately on details of the dinuclear energetics while the latter is more robust.

Let us now discuss the discrepancy between the calculated $\langle N \rangle$ and $\langle Z \rangle$ values. The projectilelike fragment is predicted to pick up neutrons from the neutron-rich ^{238}U target and to give up protons. This tendency is observed experimentally, but not nearly to the extent predicted by the transport model. (The experimental $\langle N \rangle$ values decrease slightly with increasing energy loss, but when evaporation is taken into account the implicit primary distribution $\langle N \rangle$ is larger than the $N = 30$ value of the projectile.) The potential energy surface determining the drift coefficients in the transport model calculation is based on the liquid drop model and neglects shell effects. We have performed an exploratory calculation to see if the discrepancy in the $\langle N \rangle$ and $\langle Z \rangle$ values might arise from shell effects. We used the Myers-Swiatecki[6] shell correction method to generate the corrections to liquid drop model driving forces. Since these shell corrections are based on noninteracting fragments we introduced these shell corrections into a simpler transport model which neglects the neck degree of freedom in the calculation of the drift coefficients (but not in the determination of the mean trajectory). The effect of adding the shell correction is illustrated in Fig. 2, where we compare the preevaporation $\langle N \rangle$ and $\langle Z \rangle$ values with and without shell corrections. The calculated shell effects are very modest, in the right direction for $\langle Z \rangle$, but in the wrong direction for $\langle N \rangle$. (The values shown for no shell corrections in this figure differ slightly from those shown in Fig. 1 due to the neglect of correction terms for the neck degree of freedom.) We thus conclude that unless shell effects are strongly modified by deformation they are unlikely to be the cause of the discrepancy between the observed and calculated neutron and proton drift.

In summary, we have compared the results of a nucleon-exchange model calculation coupled to an evaporation calculation with experimental data for a symmetric and a quite asymmetric system. The overall agreement was quite good. In particular for the very asymmetric system, the theoretical calculation did very well in

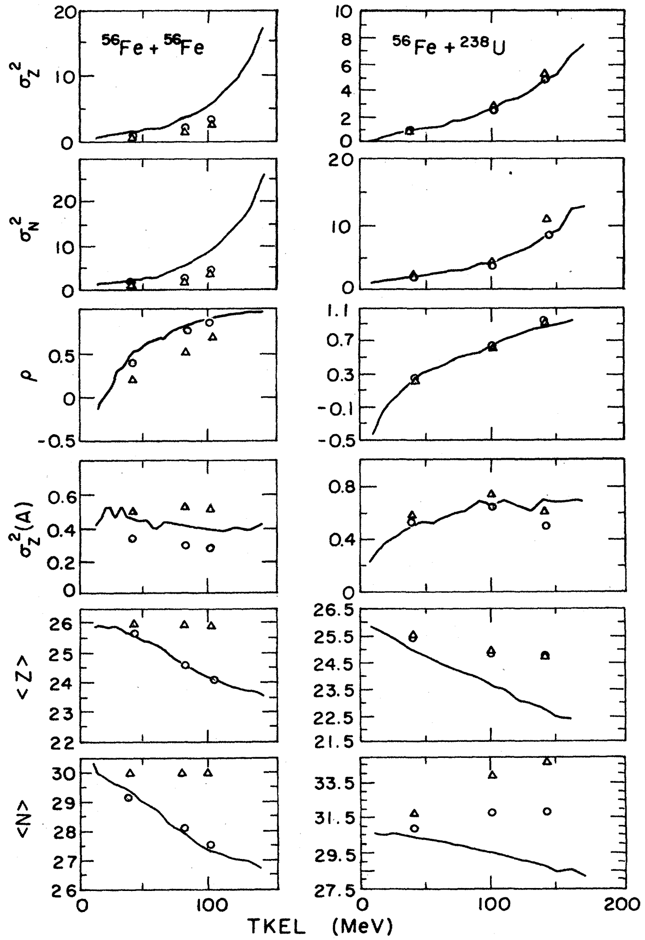

FIG. 1. Comparison of distribution parameters from the nucleon exchange model before (△) and after (○) evaporation corrections. The full curves give the trends of the experimental data of Breuer *et al.*

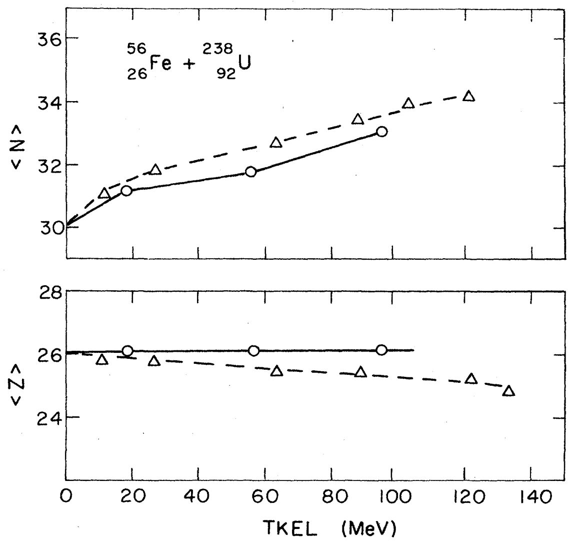

FIG. 2. Effect of shell corrections on the preevaporation calculated $\langle N \rangle$ and $\langle Z \rangle$ values. The values indicated by circles do not include shell corrections and the values indicated by triangles include shell corrections.

accounting for the variances and correlation coefficient. This supports the suggestion that the fundamental process of stochastic exchange of nucleons between the two nuclei is a dominant dissipation mechanism in damped nuclear reactions. Finally, the nucleon-exchange model did poorly in predicting the drift in $\langle N \rangle$ and $\langle Z \rangle$ values for the asymmetric system.

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