# Correlated charge and mass distributions from reactions of $^{56}Fe$ with $^{58}Ni$, $^{64}Ni$, and $^{122}Sn$

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First and second moments of the projectilelike fragment distributions in the $NZ$ plane have been measured for the reactions of $^{56}Fe$ with $^{58}Ni$ at 315 and 461 MeV, with $^{64}Ni$ at 464 MeV, and with $^{122}Sn$ at 320 and 460 MeV bombarding energy. Results are compared as a function of energy loss to predictions of theoretical transport calculations which include effects of the deexcitation of the excited fragments by particle evaporation. Comparisons involve no adjusted parameters. Theoretical and experimental results for second moments are in good agreement for all cases. First moments agree well with theory for $^{58}Ni$ and $^{64}Ni$ cases, but for $^{122}Sn$ the experimental data show a drift toward higher masses that is less rapid than predicted. It is concluded that a theory employing statistical single nucleon exchange as the dominant mechanism in energy damping can generally reproduce the results of these experiments.

[NUCLEAR REACTIONS Heavy ions. Measured isotopic distributions versus energy loss for $^{56}Fe + ^{58,64}Ni$, $^{122}Sn$. Compare to predictions from transport theory.]

## INTRODUCTION

One of the primary subjects in the study of heavy ion reaction properties has been the attempt to understand the fundamental nature of the energy loss process in deeply inelastic collisions.[1–3] In the past several years a large number of macroscopic and microscopic models have been developed emphasizing radically different physical processes which may be important in various stages of the energy loss process. At the extremes of the current models are those based on transport theories[4–7] which consider primarily the effects of the exchange of single nucleons between the two heavy ions during the collision process and those which deal primarily with the dissipation of energy via excitation of collective surface and giant resonance modes[2,8] in the two impinging nuclei and the subsequent irreversible damping of these modes into other degrees of freedom. The relative importance of these two energy dissipation mechanisms has been a subject of considerable debate, but until recently most comparisons between experiment and theory have been of a qualitative nature and have yielded ambiguous conclusions on the fundamental nature of the energy damping process.[1,2]

Following the original attempts by Nörenberg[4] to apply transport theory to the problem of heavy ion collisions, Randrup[6] has developed a transport theory which incorporates energy damping nucleon exchanges using a one body dissipation approach. An important feature of this model is that it incorporates effects due to the blocking of transfers to occupied states around and below the Fermi surface because of the Pauli principle. This model has been compared to experimental mass and charge variances[9–12] and yields good quantitative agreement for relatively heavy systems. In addition, it gives quantitative predictions for average deflection functions and properties of angular momentum transfer to the outgoing particles.[13] In most cases a good quantitative agreement was obtained between the experimental data and theoretical predictions of average properties of the outgoing particles. In most cases deviations could be at least partially ascribed to the neglect of the deexcitation process for the excited fragments.

In this paper we present a detailed comparison of calculations using this transport theory with experimental data for the systems $^{56}$Fe + $^{58}$Ni at bombarding energies of 315 and 461 MeV, $^{56}$Fe + $^{64}$Ni at 464 MeV, and $^{56}$Fe + $^{122}$Sn at 320 and 460 MeV. Moments and correlation coefficients of the $Z$ and $N$ distributions of the projectilelike reaction fragment are compared with theoretical values as a function of total energy loss. Quantitative comparisons are obtained by using theoretical final fragment distributions determined from the initial theoretical distribution by means of a Monte Carlo evaporation cascade calculation.

## EXPERIMENTAL PROCEDURE

Details of the experimental setup and procedures will be given elsewhere.[14] The experiments used beams of $^{56}$Fe from the LBL Super HILAC to bombard targets of $^{58}$Ni ($\sim$0.8 mg/cm$^2$) at energies of 315 and 461 MeV, $^{64}$Ni ($\sim$0.6 mg/cm$^2$) at an energy of 464 MeV, and $^{122}$Sn ($\sim$1 mg/cm$^2$) at 320 and 460 MeV. Outgoing projectilelike fragments were detected by a time-of-flight system (TOF) followed by a $\Delta E$-$E$ measurement so that both the mass and charge of the detected particle could be deduced for each event. The TOF system used two chevron microchannel plate systems[15] in which pulses were generated by means of secondary electron emission. The secondary electrons were obtained from foils of 40 $\mu$g/cm$^2$ polypropylene coated with a 20 $\mu$g/cm$^2$ Al layer. The flight path between the two detectors was $\sim$1.6 m and the intrinsic time resolution obtained was $\sim$80 ps. A gas ionization detector[16] backed by a semiconductor detector was used for the $\Delta E$-$E$ measurement. After analysis, typical resolutions were $\Delta Z/Z \sim 1/50$ and $\Delta A/A \sim 1/85$. The experimental energy resolution (5–7 MeV FWHM) was limited primarily by the Super HILAC beam energy spread.

In the region near $^{56}$Fe the data were easily resolved into individual $M, Z$ bins over the kinetic energy loss (i.e., $Q$ value) region of interest in this paper. The data were converted event by event from $E$, $\Delta E$, TOF, to $E$, $Z$, $A$. The total kinetic energy loss was then deduced using binary kinematics. The $Z$,$A$ distributions were characterized by first and second moments in two different representations; $Z$, $N$ and $N$-$Z$, $A$. The yields for $^{55-57}$Fe and the yields at forward angles and small energy losses of $^{56,57}$Co were obtained by interpolation following the trends in the Mn spectra. This was necessary because of elastic spillover from $^{56}$Fe to the neighboring isotopes and because of the presence of a small slit scattered energy degraded beam component. The contribution to experimental errors from statistics was negligible in the first and second moments. Systematic errors were estimated by comparing results derived from the raw data and results using the Co and Fe interpolated yields as described above. Overall errors on average quantities are estimated as less than 0.2 u and less than 0.2 u or 10% for standard deviations.

## THEORETICAL CALCULATIONS

The details of the theoretical calculations have been described elsewhere[6,7] and the calculated results have been compared to experimental measurements.[9,13] In this section we will give only an outline of the important features of the theory and the method for making a quantitative comparison to the experimental data.

In this theory it is assumed that the dominant factor in converting kinetic energy to excitation energy comes from the exchange of single nucleons between the two nuclides when they are in close proximity. The effects of this exchange are calculated in a one-body dissipation limit where the single particle exchanges damp the kinetic energy by moving between the two parts of a dinuclear complex that is characterized by a potential with the shape of two spheres connected with a small cylindrical neck. The transfers are driven by the available phase space determined using a liquid drop formula for the potential energy and finite-temperature Fermi-Dirac statistics for the nucleons.

The calculations use a Fokker-Planck equation to follow the dynamical evolution of the probability $P(N,Z;t)$ of finding $N$ neutrons and $Z$ protons in one reaction fragment at a given time $t$. Using this approach, collisions from a given impact parameter result in a final distribution $P(N,Z,E_{\rm loss})$ at the time of scission. In addition, the average value of the excitation energy $E_i^*$, in each fragment and $\sigma_{Ei}^{2*}$ can be obtained. The results show $\langle E_i^* \rangle$ to be approximately proportional to the masses, $A_i$, of the fragments and $\sigma_{Ei}^{2*} = 2\tau E_{\rm loss}$, where $\tau$ is an effective temperature.

The major difficulty in comparing quantitatively to experimental data is that the calculations yield the distribution $P(N,Z)$ at the moment the reaction fragments separate, whereas the experiments measure $P'(N,Z)$ which results after the fragments have dissipated their excitation energy. In a general case, it is very difficult to derive $P(N,Z)$ from $P'(N,Z)$ in an unambiguous way. For this reason, previous comparisons have involved asymmetric systems and heavy targets so that the projectilelike fragment gets little excitation and decays primarily by neutron emission. A much more direct method to compare to experimental data is to derive $P'(N,Z)$ from the calculated $P(N,Z)$ using a suitable evaporation calculation. In our comparison we have used a modified version of the Monte Carlo code JULIAN[17] to derive $P'(Z,N)$ from $P(Z,N)$. In this calculation the starting distribution is given by $Z,N,\sigma_Z{}^2,\sigma_N{}^2,\sigma_{NZ}$ from the theoretical calculations and $\sigma_{Ei}^{2*}$ is taken as $2E_{\mathrm{loss}}\tau$, with $\tau = 1$ MeV. This is an adequate representation since it is found that changes of a factor of 2 in $\sigma_{Ei}^{2*}$ do not significantly affect the results. The calculated average spins for the fragments are also taken as starting points, but again the final distributions are not very sensitive to the spins assumed. The resultant $P'(Z,N)$ distribution is then characterized by its first and second moments for comparison to the experimental results.

## RESULTS

For orientation the differential cross sections, $d\sigma^2/d\Omega\, dE_{\mathrm{loss}}$, are shown in Figs. 1 and 2 for the $^{56}$Fe bombardment of $^{58}$Ni and $^{122}$Sn at the two bombarding energies and at several laboratory an-

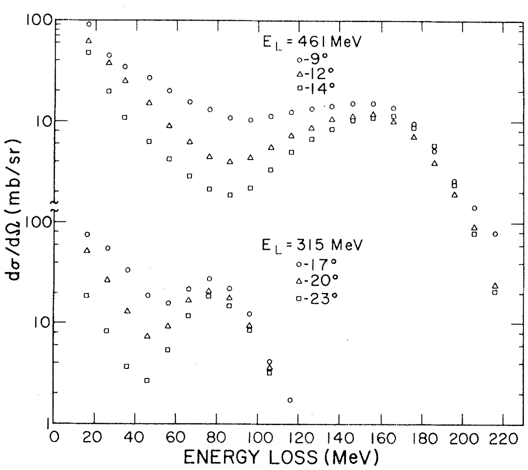


FIG. 1. Differential cross sections $d\sigma/d\Omega\, dE_{\mathrm{loss}}$ for the projectilelike products for the $^{56}$Fe bombardment of $^{58}$Ni.

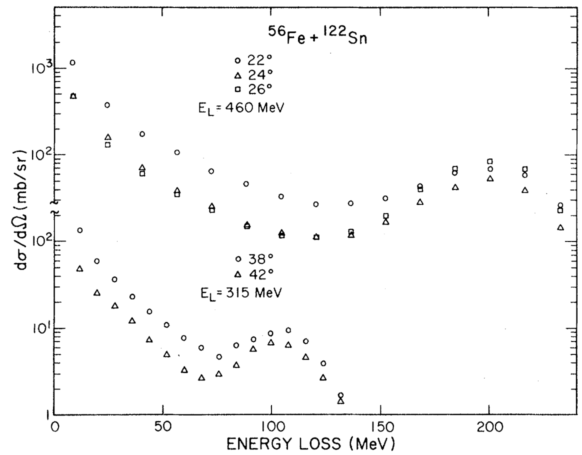


FIG. 2. Differential cross sections $d\sigma/d\Omega\, dE_{\mathrm{loss}}$ for the projectilelike products for the $^{56}$Fe bombardments of $^{122}$Sn.

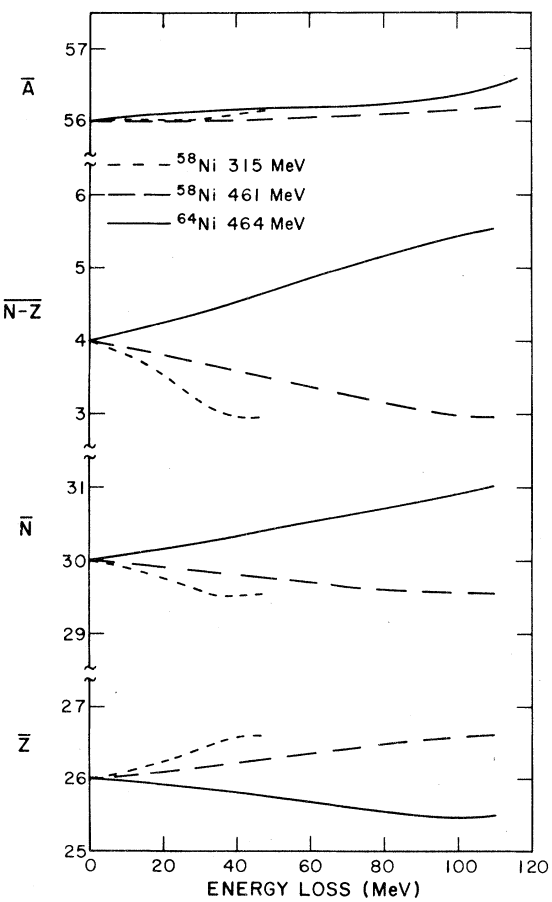


FIG. 3. Calculated means for the initial distributions for various reactions as a function of energy loss.

gles. In each case the middle angle is close to the classical grazing angle and the largest angle close to the quarter point angle. The results are typical of this type of reaction, showing a monotonic decrease in $d\sigma^2/d\Omega\, dE_{\rm loss}$ with increasing energy loss followed by a peak corresponding to the fully damped events at a $Q$ value well below that corresponding to a final kinetic energy equal to the Coulomb barrier for two touching spheres.

Calculations for the first moments of the initial projectilelike fragment are shown in Fig. 3 in the two representations, $(A,N-Z)$ and $(N,Z)$, for the $^{58}$Ni and $^{64}$Ni cases. Calculations are shown only up to kinetic energy losses which correspond to a final kinetic energy equal to the Coulomb barrier between touching spheres because of the geometric constraint in the theory. It can be seen that the most informative coordinate system is $A,N-Z$ which shows that $A$ stays close to 56 independent of target or bombarding energies while $N-Z$ shows the effects of changing $N-Z$ of the target from 2 to 8. In addition, it can be seen that the equilibrium of $N-Z$ occurs for a smaller energy loss at the lower bombarding energy. Figure 4 shows calculated initial distributions for $\sigma_N$, $\sigma_Z$, and

$$NZ_{\rm corr} \equiv \sigma_{NZ}/\sigma_N\sigma_Z$$

for the $^{64}$Ni case. The open points correspond to calculated results for the final fragment distribution (i.e., after evaporation). It can be seen that evaporation does not significantly change $\sigma_N$ or $\sigma_Z$, a result that was taken as an assumption by previous authors in comparing experimental to theoretical results. The theoretical $NZ$ correlation function, however, is significantly changed by the evaporation process, and comparisons between theory and data that ignore the evaporation corrections could lead to the conclusion that the neutron and proton transfers are more correlated than is in fact the case. In the $(A, N-Z)$ representation, it was found that $\sigma_{N-Z}$ actually became narrower due to the focusing effect of decay into the valley of $\beta$ stability.

Figures 5–8 show the experimental results for the $^{58}$Ni, $^{64}$Ni cases compared to the theoretical predictions including evaporation effects in the two different representations. The experimental results have been averaged over the three angles shown in

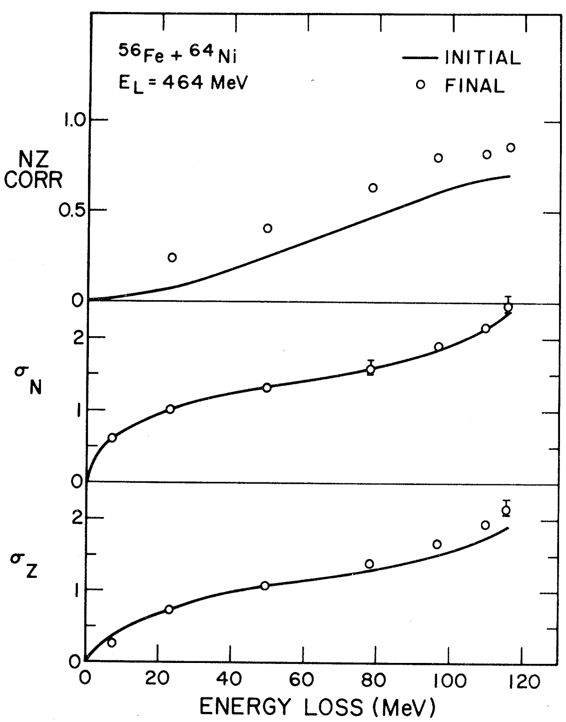


FIG. 4. Calculated second moments for initial and final distributions as a function of energy loss. Final values are results following the deexcitation cascade as described in the text. Error bars show result of change in the dispersion in the fragment excitation energies, $\sigma^2(E^*)$, by $\pm$ a factor of 2.

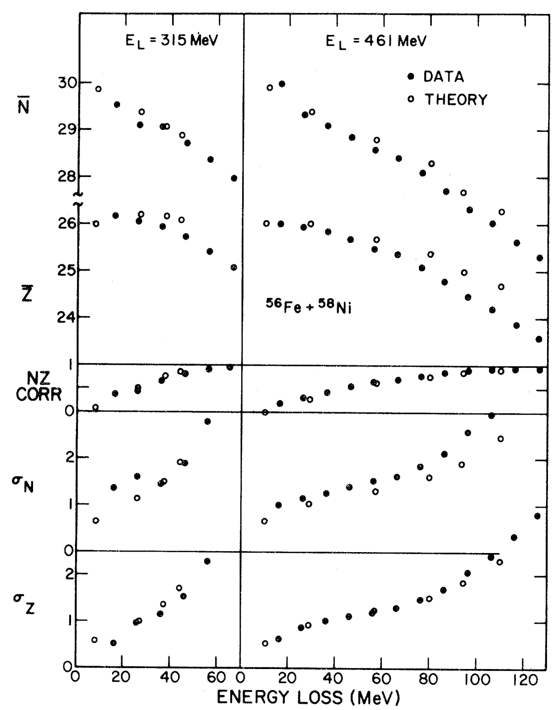


FIG. 5. Comparison of experimental and theoretical first and second moments of the distributions of projectilelike fragments as a function of energy loss for $^{56}$Fe bombardments of $^{58}$Ni.

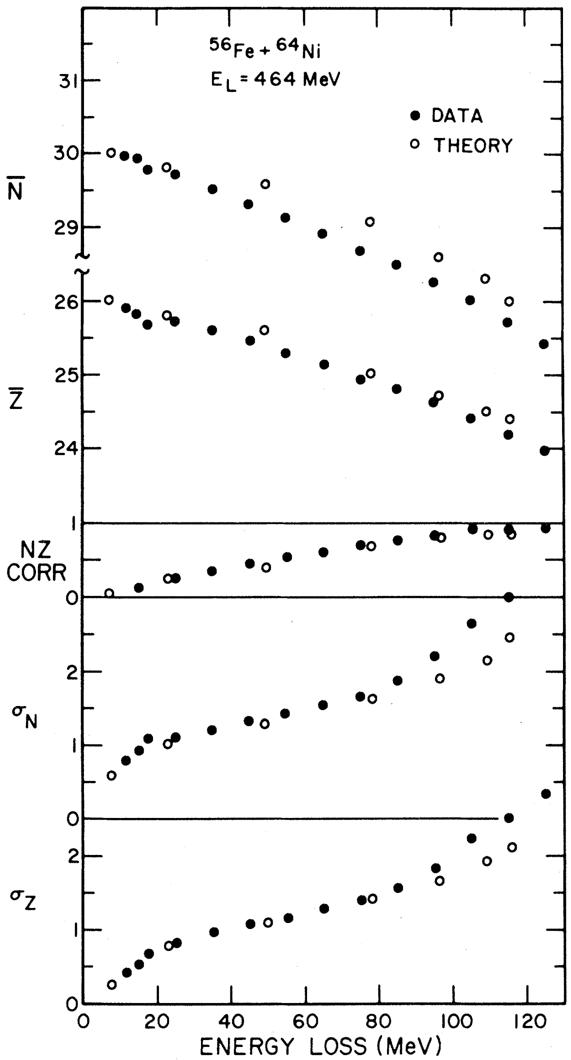


FIG. 6. Comparison of experimental and theoretical first and second moments of the distributions of projectilelike fragments as a function of energy loss for $^{56}$Fe bombardment of $^{64}$Ni.

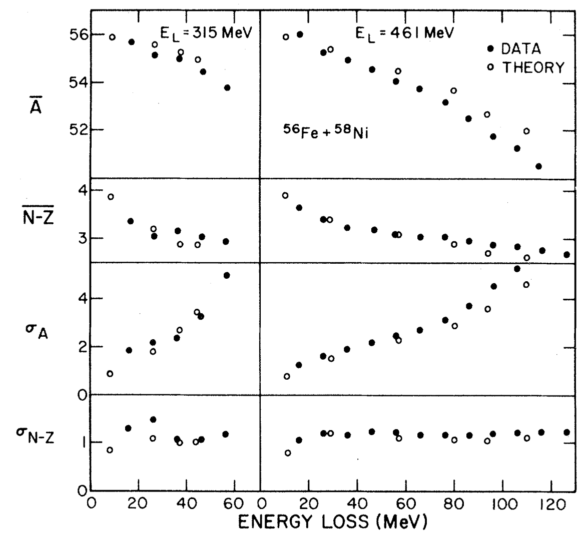


FIG. 7. Comparison of experimental and theoretical first and second moments of the distributions of projectilelike fragments as a function of energy loss for $^{56}$Fe bombardments of $^{58}$Ni.

Fig. 1 except for the 10–20 MeV region in the $^{64}$Ni case where only the back two angles were used. It is seen that there is good absolute agreement between the $^{58,64}$Ni data and the theoretical predictions for $E_{\rm loss} > 10$ MeV. The agreement is even more remarkable since no parameters were adjusted in the theoretical transport calculation. At the highest energy losses there is a trend for the calculated $\sigma_A$ (or $\sigma_N$, $\sigma_Z$) to be lower than experimental values. These energy losses correspond to the region where the geometrical model of two spheres connected by a cylindrical neck is expected to begin to become inadequate. Table I shows $\sigma_A$ for various scattering angles for the $^{64}$Ni case. It is seen that the data taken at different scattering angles show $\sigma_A$ to be independent of angle up to $E_{\rm loss} \sim 100$ MeV, whereas for $E_{\rm loss} > 100$ MeV there is a discernible angular dependence with $\sigma_A$ varying smoothly from 6.1 to 7.7 for $\theta$ varying from 6° to 16° at $E_{\rm loss} = 135$ MeV. Then at the highest energy losses $\sigma_A$ again becomes independent of scattering angle. These results are typical of all cases.

Figures 9 and 10 show results for the $^{122}$Sn target at 320 and 460 MeV bombarding energies. The experimental results have been averaged over the angles shown in Fig. 2. In these cases, the theoretical calculations both before and after particle evaporation are shown. As in the Ni cases, the second moments agree very well with the theoretical calculations. However, at the largest energy losses in the quasielastic region there seem to be significant deviations in the average quantities ($A$,$N-Z$ or $N$,$Z$) after particle evaporation has been taken into account. These deviations ($\sim 1-2$) could in principle be due to a combination of three factors: (1) inaccuracies in the evaporation calculations, (2) deviations from the assumption that the excitation energies are divided in proportion to fragment mass, or (3) too large a mass drift in the theoretical calculations. The good agreement for average quantities in the Ni cases (Figs. 5–8) suggests that uncertainties in the evaporation calculations should not contribute more than $\sim 0.3$ to the observed deviation. To get an experimental/theoretical agreement by changing the division of excitation energy with

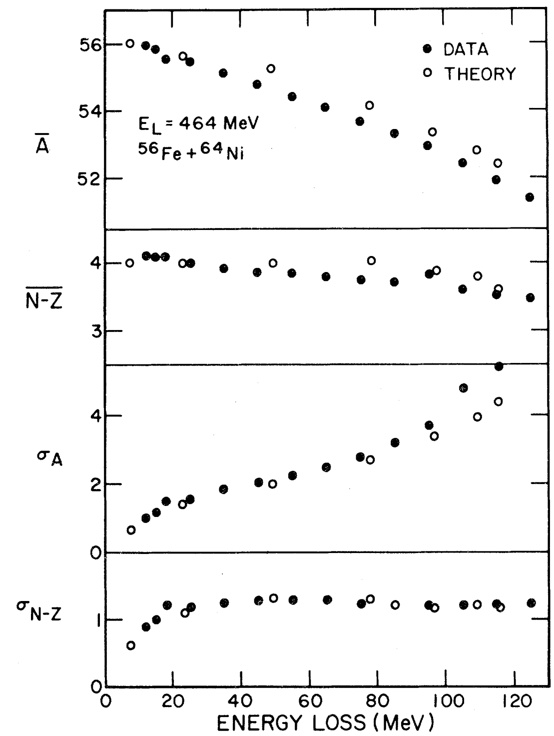


FIG. 8. Comparison of experimental and theoretical first and second moments of the distributions of projectilelike fragments as a function of energy loss for $^{56}$Fe bombardment of $^{64}$Ni.

TABLE I. $\sigma_A$ for the $^{56}$Fe + $^{64}$Ni reaction at 464 MeV.

| $E_{loss}$ (MeV) | $\theta_{lab}$ 6° | 9° | 12° | 14° | 16° |
|---|---|---|---|---|---|
| 15 | 0.9 | 1.1 | 1.3 | 1.1 | 1.1 |
| 25 | 1.7 | 1.5 | 1.6 | 1.5 | 1.4 |
| 35 | 1.9 | 1.7 | 1.9 | 1.8 | 1.7 |
| 45 | 2.1 | 2.0 | 2.1 | 2.0 | 2.0 |
| 55 | 2.3 | 2.3 | 2.3 | 2.2 | 2.3 |
| 65 | 2.6 | 2.6 | 2.5 | 2.5 | 2.4 |
| 75 | 3.0 | 2.9 | 2.8 | 2.7 | 2.7 |
| 85 | 3.2 | 3.2 | 3.2 | 3.2 | 3.4 |
| 95 | 3.7 | 3.8 | 3.9 | 3.9 | 4.4 |
| 105 | 4.2 | 4.4 | 4.8 | 5.1 | 5.4 |
| 115 | 4.8 | 5.0 | 5.4 | 5.7 | 6.1 |
| 125 | 5.4 | 5.8 | 6.3 | 6.4 | 6.8 |
| 135 | 6.1 | 6.7 | 7.2 | 7.4 | 7.7 |
| 145 | 7.1 | 7.8 | 8.5 | 8.7 | 8.9 |
| 155 | 8.7 | 9.5 | 9.8 | 10.2 | 10.4 |
| 165 | 10.7 | 11.2 | 11.6 | 11.9 | 11.9 |
| 175 | 12.5 | 13.2 | 13.4 | 13.4 | 13.6 |
| 185 | 14.9 | 15.2 | 15.5 | 15.4 | 15.5 |
| 195 | 16.6 | 17.7 | 17.9 | 17.8 | 17.6 |
| 205 | 18.9 | 19.9 | 20.6 | 18.9 | 18.5 |

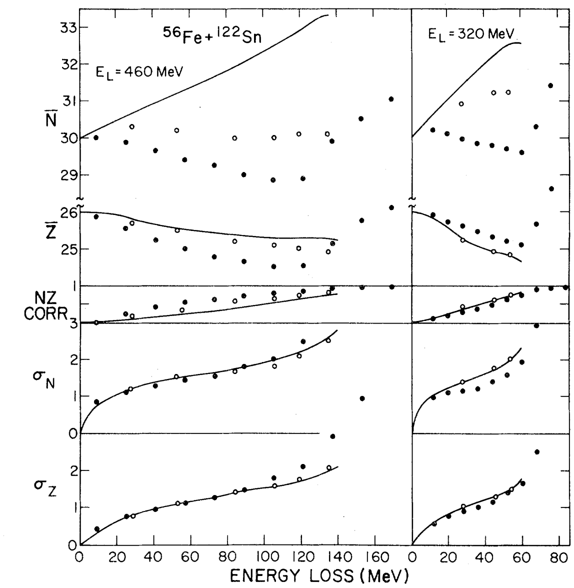


FIG. 9. Comparison of experimental and theoretical first and second moments of the distributions of projectilelike products as a function of energy loss for $^{56}$Fe bombardments of $^{122}$Sn. Solid lines give theoretical predictions of initial distributions. Open and closed points are theoretical and experimental final values, respectively.

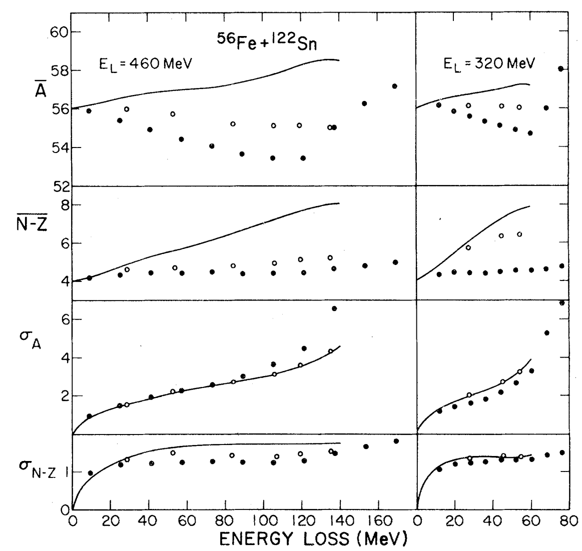


FIG. 10. Comparison of experimental and theoretical first and second moments of the distributions of projectilelike products as a function of energy loss for $^{56}$Fe bombardments of $^{122}$Sn. Solid lines give theoretical predictions of initial distributions. Open and closed points are theoretical and experimental final values, respectively.

mass, it would be necessary to assume equal excitation energies in the two fragments, and this would conflict with several experimental results obtained in similar reactions.[18–20] On this basis it seems most reasonable to assume that the theoretical calculations are giving too large a rate of mass drift. This could happen because the theory employs a liquid drop potential energy surface and takes no account of shell effects. For the nearly symmetric Fe + Ni systems the calculated mass drifts are very small and possible shell effects on this drift cannot be tested. However, for Fe + Sn, a substantial drift rate is calculated and the data indicate a decreased drift rate. This effect is qualitatively consistent with the extra stability expected in the Fe and Sn regions.

## SUMMARY

In this paper, we have attempted to quantitatively test the predictions of a single particle transport model of heavy ion collisions by comparison to the first and second moments of the projectilelike fragment $NZ$ distributions as a function of total kinetic energy loss. The model employs single nucleon exchange mechanisms with inclusion of Pauli blocking effects but neglects possible perturbations due to direct excitation of collective surface or giant resonance modes. In order to compare quantitatively to experimental results it was essential to accurately take into account the particle evaporation from the excited projectilelike fragment following the collision. This was done by combining the Monte Carlo evaporation calculation of the fragment deexcitation with the transport model calculation of the collision. Then a detailed comparison can be made for theoretical and experimental $NZ$ distribution for the projectilelike fragment after deexcitation.

Comparisons for near symmetric projectile-target combinations ($^{56}$Fe + $^{58,64}$Ni) and an asymmetric projectile-target combination ($^{56}$Fe + $^{122}$Sn) at two energies shows good agreement for second moments of the distributions ($\sigma_N$,$\sigma_Z$,$\sigma_{NZ}$) as a function of energy loss for all cases. For the near symmetric systems where very little mass drift is predicted in the first moments, postevaporation values ($\bar{N}$,$\bar{Z}$) agree well suggesting that the deexcitation calculations used are reasonably reliable. For the asymmetric case ($^{56}$Fe + $^{122}$Sn) the calculations yield a more rapid mass drift than indicated from the experimental data. This discrepancy is qualitatively consistent with the expected effects due to the neglect of nuclear shells in the theoretical transport model. The proximity of shells in the region of Fe and Sn will tend to inhibit a net drift in $N$ and $Z$ as compared to liquid drop estimates at the relatively low temperatures involved in these experiments. The comparisons suggest that the first moments ($\bar{N}$,$\bar{Z}$) are more sensitive for the observation of these shell effects than the second moments.

The fact that the theoretical/experimental comparison involves no adjusted parameters and yields good agreement supports the conjecture that single particle transfer is dominant in the energy loss mechanism for heavy ion collisions in this energy region.

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