Dependence of Isobaric Charge Distributions on Energy Loss and Mass Asymmetry in Damped Collisions

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Yields for specific Z and A have been measured for projectilelike fragments produced in the reaction of 8.3-MeV/u ^{56}Fe ions with targets of ^{56}Fe, ^{165}Ho, and ^{238}U. Variances of the isobaric charge distributions $\sigma_Z^2(A)$ reveal a saturation value of $\sigma_Z^2(A) \approx 0.8$, reached within the first 30–50 MeV of energy loss depending on target. Variances of the isotopic mass distributions saturate at a value of $\sigma_A^2(Z) \approx 2–4$, which is reached after about 60–80 MeV of energy loss. The data are compared with N/Z equilibration models.

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In order to gain a more microscopic understanding of the processes whereby energy is dissipated in collisions between very heavy nuclei, yields of individual projectilelike fragments have been measured as a function of energy loss for ^{56}Fe-induced reactions. A series of target nuclei ranging from ^{56}Fe to ^{238}U has been studied, thus providing information on the effects of mass asymmetry and target-projectile N/Z ratios in the entrance channel. Such data ($d^3\sigma/dA\,dZ\,dE$) provide a much more detailed view of the evolution of the nucleon exchange process than previously possible. Of particular current interest is the explanation of the fragment isobaric charge distributions, which define the charge equilibration (N/Z) degree of freedom. This process is believed to be one of the fastest relaxation modes in damped collisions.[1] Hence, from studies of this type one hopes to derive a clearer picture of the very early stages of the target-projectile interaction mechanisms which subsequently evolve toward statistical equilibrium.

Recently the subject of isobaric charge distributions has received considerable attention, both experimentally[2,3] and theoretically.[4-11] Because of uncertainties in correcting the experimental distributions for particle emission from the primary fragments, the principal focus of these investigations has been on the variances of the distributions, which are only slightly sensitive to these effects. Two sets of experimental data for systems in which damped collisions dominate the total reaction cross section have been reported prior to the present work. In counter studies of a nearly mass-symmetric system, 430-MeV ^{86}Kr + ^{92,98}Mo, Berlanger *et al.*[2] found that the variances in the isobaric charge distributions, $\sigma_Z^2(A)$, increased rapidly with increasing energy loss up to $E_{loss} \approx 30$ MeV and then remained constant at a value of $\sigma_Z^2(A) \approx 0.8$ thereafter. In these measurements a mass resolution of only 1.5 u was attained, leaving some uncertainties in the derivation of the experimental variances for individual mass numbers. In contrast, a radiochemical study by Poitou *et al.*,[3] involving the mass-asymmetric 890-MeV ^{132}Xe + ^{197}Au system produced quite different results. The variances were reported to increase monotonically up to an excitation energy of 150 MeV and in addition the data were characterized by smaller values of $\sigma_Z^2(A)$ ($\approx 0.2–0.8$). Despite the definite Z and A identification in these experiments, their interpretation is complicated by the problems of energy resolution and the assumptions employed in the complex data-reduction procedures required to unfold the $d^3\sigma/dA\,dZ\,dE$ data.

In this Letter we present isobaric charge distribution data obtained with counter techniques which provided discrete Z and A identification of all projectilelike fragments. The measurements were performed at the Lawrence Berkeley Laboratory SuperHILAC accelerator with 8.3-MeV/u ^{56}Fe ions incident on targets of ^{56}Fe, ^{165}Ho, and ^{238}U. Hence, we have studied target-projectile systems ranging from symmetric to very asymmetric combinations under identical experimental conditions. In each case the energy in excess of the Coulomb barrier, $E_{\text{c.m.}} - V_C$, is the same within 10%. Fragment mass and charge distributions were measured at angles near the grazing angle with a ΔE-E time-of-flight counter telescope; data on the gross features of the ^{56}Fe, ^{165}Ho, and ^{209}Bi reactions with ^{56}Fe have been reported previously.[12] In the most recent measurements a Z resolution (full width at half maximum) of ≤ 0.8 u and an A resolution of ≤ 0.7 u were obtained for the fragments over a 200-MeV range in E_{loss}.

In Fig. 1 the isobaric charge variances are shown for two systems at 8.3 MeV/u bombarding energy: (1) ^{56}Fe + ^{56}Fe for all masses from $A = 52$ to 58 and (2) ^{56}Fe + ^{165}Ho for all masses from $A = 52$ to 57. Similar results are found for the ^{238}U target. The data shown in Fig. 1 are for the fragments observed in the detectors without corrections for particle emission or detector resolution. If corrections are made for particle evaporation from the primary fragments, assuming division of the excitation energy according to A_1/A_2, the values of $\sigma_Z{}^2(A)$ remain essentially unchanged. However, no information is available on the spread in excitation energy about this average excitation energy. If this spread is large, somewhat smaller values of $\sigma_Z{}^2(A)$ may result for the primary fragments. It should be pointed out that for the projectilelike fragments observed with Ho and U targets, the observed most probable mass for each element lies on the neutron-rich side of β stability. Hence, for the primary fragments only neutron emission is important. For the ^{56}Fe + ^{56}Fe system charged-particle emission is also possible; we estimate this effect on the data will decrease the $\sigma_Z{}^2(A)$ values by less than 10%.

The significant result of this study is that all the isobaric charge distributions are very similar and nearly independent of target-projectile mass asymmetry (A_1/A_2) or total mass ($A_1 + A_2$). The

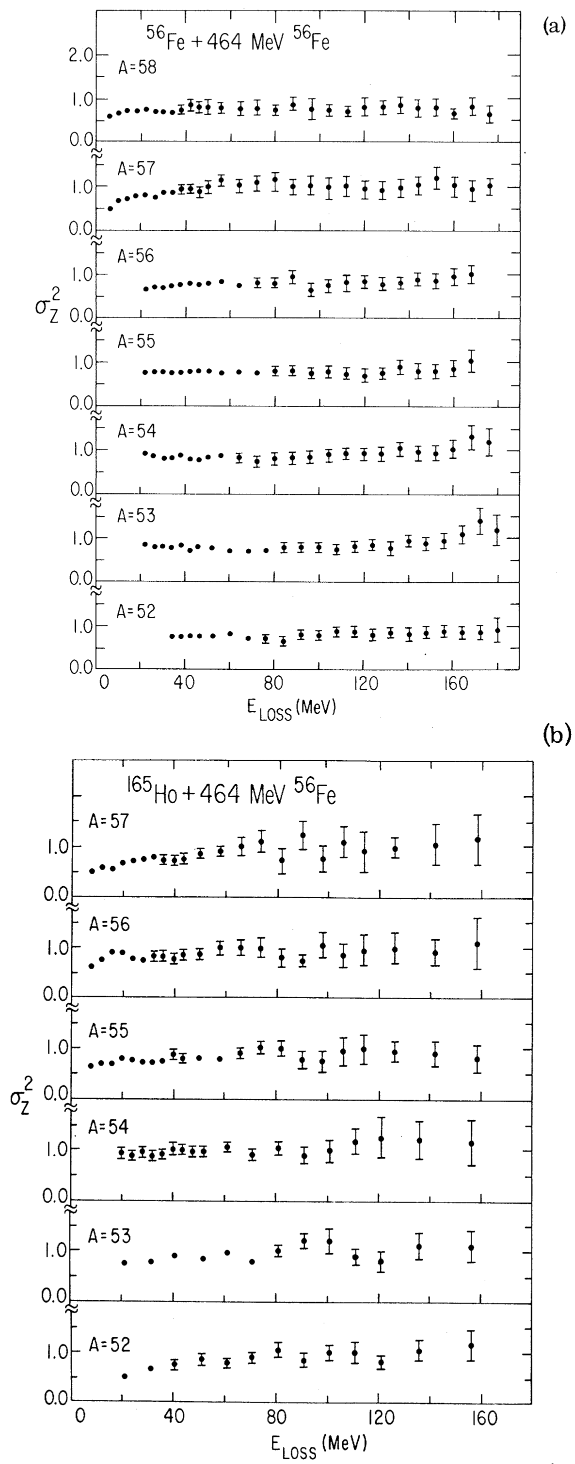

FIG. 1. Plot of isobaric charge variances for (a) ^{56}Fe + ^{56}Fe for $A = 52$–58 and (b) ^{56}Fe + ^{165}Ho for $A = 52$–57 as a function of E_{loss}.

variances are observed to saturate within the first 30–50 MeV of energy loss and thereafter re-

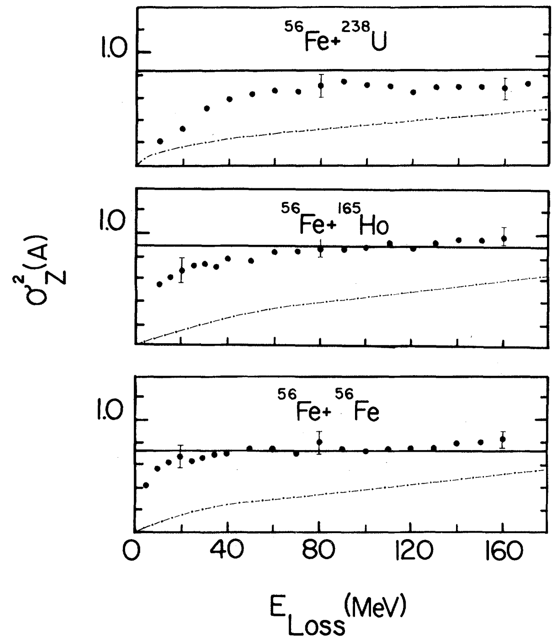

FIG. 2. Comparison of average $\sigma_Z^2(A)$ values for data in Fig. 1 and ^{238}U, corrected for experimental resolution, as a function of E_{loss} with predictions of theory for quantal fluctuations (solid line) and statistical fluctuations (dashed line) as described in text.

main constant at $\sigma_Z^2(A) \approx 0.8$ up to energy losses in excess of 150 MeV. As an example of the similarity in the variances, if one averages all experimental $\sigma_Z^2(A)$ values for each isobar over an energy range from 50–150 MeV for the data of Fig. 1 and corrects for the experimental resolution, an average value of $\sigma_Z^2(A) = 0.75 \pm 0.08$ is found for the ^{56}Fe target, $\sigma_Z^2(A) = 0.85 \pm 0.10$ for the ^{165}Ho target, and $\sigma_Z^2(A) = 0.72 \pm 0.10$ for the ^{238}U target. The average slope $\sigma_Z^2(A)$ vs E_{loss} is found to be consistent with zero for energy losses greater than 50 MeV. In this respect our data are similar to those of Berlanger *et al.*,[2] but show an energy-loss dependence different from that reported by Poitou *et al.*[3]

Examination of the first 50 MeV of energy loss in Fig. 2 suggests that the approach to saturation in the variances depends on the system studied. Although this feature of the data is less well defined, it indicates that the amount of energy dissipation required to reach the saturation value for $\sigma_Z^2(A)$ increases with increasing Z and A of the composite system. Such an effect, which may reflect the temperature of the system, may provide a self-consistent explanation for the differences between the data reported here and in Ref. 2 and those of Ref. 3; however, more extensive data as a function of bombarding (excitation) energy are needed before a rigorous comparison of all these systems can be made.

Analysis of the isotopic mass variances, $\sigma_A^2(Z)$, produces similar results. For charges near that of the projectile, all systems yield a saturation value of $\sigma_A^2(Z) \approx 2$–4, which is reached, however, only after an energy loss of about 60–80 MeV. Thus it appears that approximately twice as much energy must be dissipated in order to saturate the variances for the mass degree of freedom as for the charge degree.

In an attempt to explain these results a simple model has been proposed that is based on treatment of the neutron-excess $(N - Z)$ degree of freedom in terms of an harmonic-oscillator analogy.[2,4,5] This oscillator (assumed to have a constant collective frequency ω) is coupled to the intrinsic degrees of freedom of the system which are assumed to constitute a heat bath of temperature T. Two extreme predictions for $\sigma_Z^2(A)$ arise from this model, depending on the relative magnitude of the oscillator phonon energy $h\omega$ compared to T: (1) If $\hbar\omega \gg T$, then $\sigma_Z^2(A)$ is predicted to be a constant related to the stiffness coefficient derived from the liquid-drop mass formula,[4] C, of the mode by $\sigma_Z^2(A) = \hbar\omega/2C$. In this case, the charge fluctuations are of the quantal type and ω represents the frequency of the underlying collective mode. (2) If $\hbar\omega \ll T$, then $\sigma_Z^2(A)$ varies directly with the nuclear temperature $\sigma_Z^2(A) = T/C$. In this case, one is dealing with statistical fluctuations.

The ^{86}Kr + ^{92,98}Mo results have been interpreted[2] in terms of a quantal picture with $\hbar\omega \approx 8.5$ MeV. On this basis the authors of Ref. 2 have suggested that the out-of-phase vibration of the neutron and proton distributions, i.e., the giant isovector dipole resonance, is an important factor in determining N/Z equilibration and energy damping in the early phase of damped collisions. On the other hand, the ^{132}Xe + ^{197}Au data[3] support a model based on statistical fluctuations which then readily couple to the slower degrees of freedom, well known to be described by statistical transport models.[13] By modifying the quantal fluctuation model to include dynamical considerations,[4,6] a slightly better fit to both of the above sets of data can be obtained; however, this cannot be achieved with self-consistent values of $\hbar\omega$ for the two pairs of target-projectile combinations. Another suggested interpretation[5] of these data is that mass-symmetric systems exhibit quantal fluctuations and asymmetric systems behave statistically. Our data show no evidence for such behavior.

In order to compare these data with the predictions for quantal and statistical fluctuations, in Fig. 2 we have plotted the average of the isobaric charge variances for the data of Fig. 1 at each energy loss as a function of $E_{\rm loss}$. The theoretical curves have been calculated with[4] $\hbar\omega = 78/(A_1^{1/3}+A_2^{1/3})$ MeV and $C = 7.1$, 4.8, and 4.2 MeV for the ^{56}Fe + ^{56}Fe, ^{165}Ho + ^{56}Fe, and ^{238}U + ^{56}Fe systems, respectively. The agreement of the saturation values with the quantal fluctuation extreme is good for both the ^{165}Ho + ^{56}Fe and ^{56}Fe + ^{56}Fe systems. However, before attributing this correspondence to the isovector giant dipole resonance, it should be cautioned that the underlying feature of this theory is the liquid-drop mass equation, for which the parabolic dependence on Z for a given set of isobars is well known. Hence, these experimental results may simply be a consequence of liquid-drop energetics. In addition, it should be noted that the initial increase of the variances with energy loss is inconsistent with instantaneous increase predicted by the simple quantal model discussed above. More realistic quantal calculations[9] qualitatively reproduce the observed energy dependence of $\sigma_Z^2(A)$ for the earlier data of Refs. 2 and 3. Recently, Brosa and Gross[10] have suggested that the data of Refs. 2 and 3 can be described with a single-particle model, while Samaddar and Sobel[11] have attempted to explain the rapid equilibration of the N/Z ratio in damped collisions in terms of both a diffusion and a collective model. Thus, although the data presented here are consistent with the quantal calculations, this agreement does not necessarily confirm the existence of quantal fluctuations.[10] It would be interesting to have a quantitative prediction of these widths based on a macroscopic transport theory.

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