Intermediate Mass Fragment Production in Central Collisions of Intermediate Energy Heavy Ions

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We present Z distributions for fragments with $1 \leq Z \leq 12$ from central collisions of $^{40}Ar+^{45}Sc$ at incident energies ranging from 35 to 115 MeV/nucleon. We find that the Z distributions can be described by a power law or an exponential and steepen with increasing incident energy. Over the range of incident energies studied, the average number of intermediate mass fragments decreases while the average number of particles increases. When combined with previous results for the charge distributions, a minimum is observed in the extracted power-law parameter.

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The observation and characterization of a liquid-gas phase transition in nuclear matter will provide valuable information concerning the nuclear equation of state (EOS). Nuclear matter exists in a liquidlike state in its ground state. When nuclear matter is heated to excitations high compared to its binding energy it behaves like a classical gas. So far no unambiguous experimental evidence for the liquid-gas phase transition in nuclear matter exists. In this Letter we report charge distributions, $\sigma(Z)$, for ^{40}Ar-induced reactions on a ^{45}Sc target at incident energies of 35 to 115 MeV/nucleon where fragments with $1 \leq Z \leq 12$ were observed with the Michigan State University (MSU) 4π array. By selecting central collisions in this nearly symmetric system, we reduce the contribution of spectator matter and create a system with known excitation energy and number of participant particles. We find that the charge distributions from central collisions become steeper as the beam energy is increased from 35 to 115 MeV/nucleon corresponding to excitation energies ranging from 8 to 29 MeV/nucleon assuming that preequilibrium particle emission is not important.

The critical point of the liquid-gas phase diagram has been predicted to occur in infinite nuclear matter at an excitation energy as low as 15 MeV/nucleon [1] and as high as 330 MeV/nucleon [2]. Scaling theories [3] suggest that the cluster size distribution near the critical point in the phase diagram follows a scaling function

$$n(A_f,p)=A_f^{-\tau}f(A_f^{\sigma}(p-p_c)) , \qquad (1)$$

where p is the order parameter with $f(0)=1$ at the critical value of the order parameter ($p=p_c$). [In the Fisher droplet model [4], $f(x) \propto e^{-x}$.]

Several experimental studies involving the production of intermediate mass fragments (IMFs) have produced information relating to the liquid-gas phase transition [5]. The production of IMFs ($3 \leq Z \leq 14$) has been studied by 80 to 350 GeV protons incident on a Xe target [6] and by 1 to 19 GeV protons incident on a Xe target [7]. Recently the production of intermediate mass fragments from the reaction of 600 MeV/nucleon Au incident on a variety of targets has been investigated [8,9]. Production of IMFs has also been examined in reactions of $^{3}He+Ag$ from 160 to 1200 MeV/nucleon [10,11]. In all these experiments the cross sections of emitted fragments were observed to have a power-law dependence on the charge of the fragment.

In the light-ion-induced work, the extracted power-law parameter τ decreases with increasing beam energy and appears to reach a plateau at around 2. Whether this effect is due to a constancy in the decay mechanism or a saturation in the amount of excitation energy deposited in the target nucleus is still an open question. In the proton-induced work [7] the results were consistent with a modified version of the Fisher model incorporating a liquid-gas phase transition. However, the authors made no selection on impact parameter or amount of excitation energy deposited which implies that a large distribution of excitation energies was possible at each proton energy [1]. In the Au-induced reactions [8,9], the authors do observe first a flattening of the charge distributions with increasing excitation energy up to about 8 MeV/nucleon and then a steepening. However, the quoted excitation energy and the number of participant nucleons were dependent on a model calculation. In contrast, the use of symmetric system Ar+Sc in the present work removes many of the questions involved with determining the excitation energy and number of participant nucleons.

The present measurements were carried out with the MSU 4π array [12] at the National Superconducting Cyclotron Laboratory (NSCL) using beams from the K1200 cyclotron. The 4π array consists of a main ball of 170 phoswich counters covering angles from 23° to 157° and a forward array of 45 phoswich counters covering from 7° to 18°. In addition there were 30 Bragg curve counters [13] operated with a pressure of 500 torr of P5 gas (95% argon, 5% methane). The Bragg counters were used in ion chamber mode. The anodes of the five most forward Bragg counters were segmented to provide a total of 55 separate gas ΔE counters. The fast plastic scintillator of the main ball phoswiches served as the E counter for particles that stopped in the fast plastic. Thus the array was capable of detecting charged fragments from $Z=1$ to $Z=12$ with the lower energy threshold for protons being 17 MeV. The lower energy threshold for $Z=3$ fragments was 3 MeV/nucleon while for $Z=12$ fragments the lower threshold was 5 MeV/nucleon. The target consisted of 1.6 mg/cm^2 Sc. The beam intensity was approximately 100 electrical pA of ^{40}Ar. The data were taken with two different multiplicity triggers, $m\geq 2$ and $m\geq 5$, where m is the number of detectors firing out of the 215 phoswich detectors of the 4π array. Central collisions were selected using midrapidity charge $Z_{\rm mr}$, total transverse momentum $p_\perp$, and charged particle multiplicity N_c. The impact parameter was selected to be less than or equal to 25% of the sum of the radii of the projectile and target nuclei by selecting central collisions taking

$$C=[(Z_{\rm mr}/Z_{\rm tot})(p_\perp/p_{\rm proj})(N_c/N_{\rm max})]^{1/3}$$

as the centrality condition where $Z_{\rm tot}$ is the total charge, $p_{\rm proj}$ is the incident projectile momentum, and $N_{\rm max}$ is the maximum number of charged particles.

In Fig. 1 the charge distributions $(1\leq Z\leq 12)$ for central collisions of Ar+Sc are shown as a function of the incident energy. The solid histograms are the cross sections for production of fragments without any correction. The circles stand for the cross sections corrected for the acceptance of the 4π array. This correction was carried out using a Monte Carlo simulation filtered through the acceptance of the array. The simulated observables included light charged particle multiplicity, IMF multiplicity, Z distributions and fragment energy spectra. The filter included geometric acceptance, kinetic energy cuts, multiple hits, particle misidentification, and shadowing by the target frame.

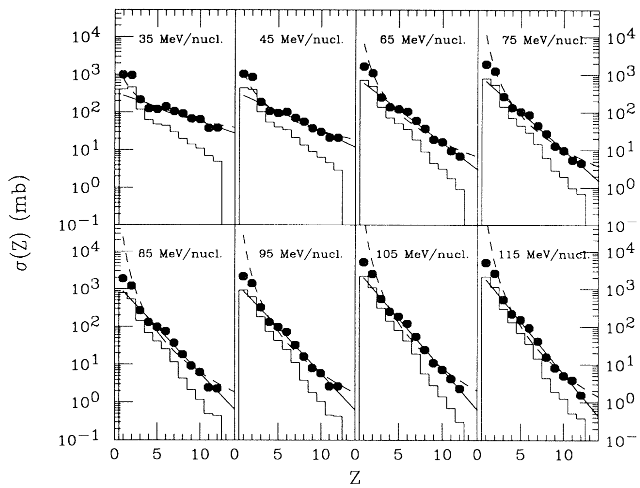

FIG. 1. Charge distributions for central collisions of Ar+Sc. The histogram represents data uncorrected for acceptance. The circles stand for the data corrected for acceptance. The dashed line is a power-law fit and the solid line is an exponential fit.

The dashed line is a power-law fit for $3\leq Z\leq 12$ to the corrected cross sections of the form $\sigma(Z)=C_\tau Z^{-\tau}$, where C_τ is a normalization factor. The straight lines represent exponential fits for $3\leq Z\leq 12$ of the form $\sigma(Z)=C_\lambda e^{-\lambda Z}$, where C_λ is a normalization factor. The power-law fits have the lower χ^2 at 35 MeV/nucleon while the exponential fits have the lower χ^2 at 115 MeV/nucleon. However, in both cases the χ^2 values are significantly larger than 1 per degree of freedom. Part of this lack of agreement may be due to binding energy effects on the fragment production cross sections which are not included in the simple model.

In Fig. 2(a) the power τ extracted from the Z distributions $(3\leq Z\leq 12)$ is given as a function of the incident energy. In Fig. 2(a) the filled circles represent the data corrected for acceptance and the open circles show the uncorrected data. One can see that τ increases from a value around 1.2 at 35 MeV/nucleon to around 4 at 115 MeV/nucleon. The measured incident energies correspond to excitations for the combined system of 8 MeV/nucleon for 35 MeV/nucleon up to 29 MeV/nucleon at 115 MeV/nucleon assuming that preequilibrium emission is not important. Also plotted in Fig. 2(a) are the results of the Au-induced reactions [8] shown by open squares. The excitation energies given in Ref. [8] are scaled by a kinematic factor to compare with the present beam energy assuming the data for Ar+Sc represent completely inelastic collisions. The two experiments are in qualitative agreement although the emitting system was larger in the Au-induced reactions. The values of τ extracted from the present work clearly demonstrate the steepening of the charge distributions as the beam energy is increased above 35 MeV/nucleon.

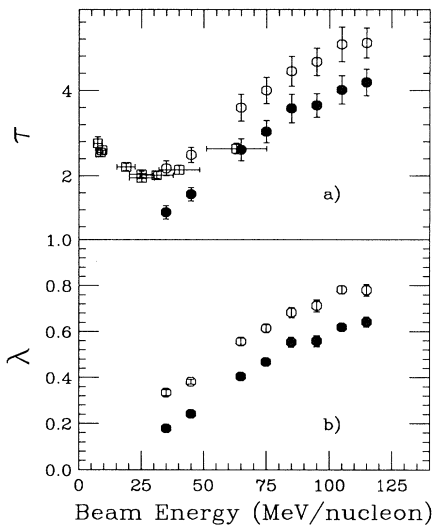

FIG. 2. Parameters extracted from fits to the charge distributions. Filled circles stand for data corrected for acceptance while open circles stand for uncorrected data. (a) Power-law parameter τ extracted from power-law fits. The open squares represent results from 600 MeV/nucleon Au+C, Al, and Cu from Ref. [8]. (b) Slope parameter λ extracted from exponential fits to the charge distributions.

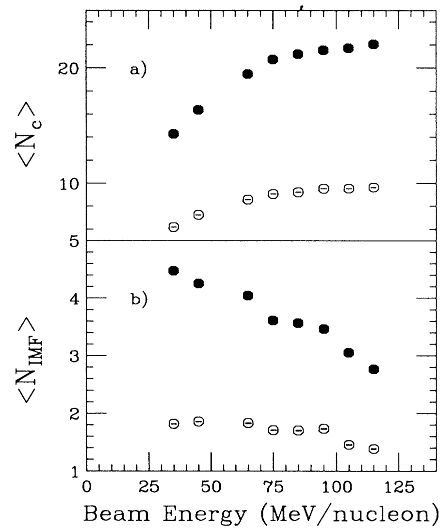

FIG. 3. (a) Average number of charged particles $\langle N_c \rangle$ emitted from central collisions of Ar+Sc. (b) Average number of IMFs, $\langle N_{\rm IMF} \rangle$, from central collisions of Ar+Sc. In both panels the filled circles stand for data corrected for acceptance while open circles stand for uncorrected data and the error bars are smaller than the symbols.

When the extracted values for τ from the Au-induced reactions [8] are combined with the present data, a clear minimum in τ as a function of incident energy is observed. A similar observation was made in Ref. [14] where the authors observed a minimum in τ versus apparent temperature in many different reactions which was interpreted by the authors as evidence for the liquid-gas phase transition. The minimum observed in the combined data for τ in Fig. 2(a) occurs around 35 MeV/nucleon, corresponding to an excitation energy of about 8 MeV/nucleon which is close to nuclear binding energy. The fact that our data are systematically lower than the data of [8,9] could be due to the fact that we are using a nearly symmetric projectile-target combination which deposits much larger compressional energy and radial flow in the system. Fragment emission has been shown to be sequential for Ar+V central collisions at 35 MeV/nucleon [15,16]. Above that energy, fragment emission is consistent with multifragmentation. Thus one could interpret this apparent minimum as a critical point below which the system is undercritical and emits fragments sequentially and above which the system is overcritical and multifragmentation takes place.

The parameter λ extracted from the Z distributions ($3 \leq Z \leq 12$) is shown in Fig. 2(b) as a function of incident energy where the filled circles stand for corrected data and the open circles show the uncorrected data. This parameter, like the τ parameter, increases with incident energy indicating that the slope of the charge distribution associated with IMF production also steepens as the beam energy is increased. It is seen from Fig. 2 that regardless of the functional form used to fit the data, the present charge distributions get steeper as the beam energy is increased.

In Fig. 3(a) the average number of charged particles emitted from central collisions of Ar+Sc, $\langle N_c \rangle$, is plotted as a function of incident energy. The open circles represent the data before the acceptance correction and the filled circles show the data after correction. The value of $\langle N_c \rangle$ increases and then begins to saturate at an incident energy of 85 MeV/nucleon. In Fig. 3(b) the average number of IMFs, $\langle N_{\rm IMF} \rangle$, is shown as a function of incident energy. Again the open circles are the raw data and the filled circles are the data corrected for acceptance. These values decrease with beam energy and agree qualitatively with the Au-induced results [8].

In conclusion we have measured the production of fragments with $1 \leq Z \leq 12$ from central collisions of Ar+Sc and we observe a steepening of the charge distributions as the beam energy is increased from 35 to 115 MeV/nucleon. When these charge distributions are fitted with a power law and combined with previous results [8] we observe a minimum in τ at an excitation energy of around 8 MeV/nucleon which may be related to the liquid-gas phase transition in nuclear matter. Further we find that the average number of IMFs decreases slightly with incident energy while the total multiplicity of fragments increases with energy.

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