Dynamic Evolution and the Caloric Curve for Medium Mass Nuclei

J.Cibor, R. Wada, K. Hagel, M. Lunardon, N. Marie, R. Alfaro, W. Shen, B. Xiao, Y. Zhao, J. Li,
M. Murray, J. B. Natowitz, Z. Majka* and P. Staszel *
Institute of Physics, Jagellonian University, ul. Reymonta 4, 30-059 Krakow, Poland

In pursuit of better understanding the behavior of nuclear systems at non-normal densities we carried out a study of the reactions $^{12}C+^{116}Sn$, $^{22}Ne+^{108}Ag$, $^{40}Ar+^{100}Mo$, $^{64}Zn+^{89}Y$ all at 47 AMeV projectile energy [1].

The choice to study this particular series of collisions was guided by QMD transport model calculations performed with the computer code CHIMERA [2] using a "soft" equation of state, K=200 (see Figure 1—solid lines with small dots). The calculations indicate that the degree of compression and the excitation energy increase monotonically with increasing projectile mass. The combined thermal and compressional energies that are deposited lead to increasing expansions of the composite nuclei. The first light particles are emitted at ~50fm/c after contact, prior to the time that global thermal equilibrium is achieved. These and subsequent pre-equilibrium particles remove both mass and energy from the expanding composite nuclei. The nuclei reach their minimum densities near ~100 fm/c, at which point thermal equilibrium appears to be essentially established as indicated by Q_{zz}, the second moment of the nucleon momentum distribution. At these minimum densities the expanded nuclei are predicted to have mass numbers approximately the same but, as seen in Figure 1, excitation energies which range from 3 to 8 MeV/u and densities which range from slightly below normal density, $\sim 0.8\rho_0$, to $\sim 0.4\rho_0$. For the heavier projectiles entrance into the spinodal region is indicated [3] and multifragment production is observed in the simulation. To show sensitivity of these calculations to the incompressibility of the nuclear matter we also present in Figure 1 trajectories computed with a "hard" equation of state, K=380 (dashed lines).

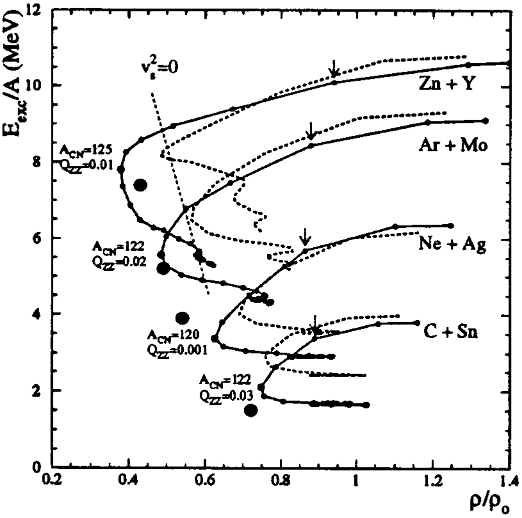

Figure 1. QMD calculated trajectories in the excitation energy per nucleon-normalized density plane for central collisions for the four different systems studied. The trajectories start at the time of maximum density. The small dots mark time increments of 10 fm/c. Arrows indicate the time of first emission of particles (near 50 fm/c after contact). Both masses and Qzz values are indicated at the minimum calculated density. To the left of the dashed line is the spinodal region. The solid points represent the excitation energy-density values derived from coalescence model analyses (see text). Solid lines with dots - calculation with incompressibility parameter K=200 MeV (soft EOS), dashed lines - K=380MeV (hard EOS).

Additionally the QMD calculations suggest an approximate relationship between Coulomb corrected velocity of the light charged particle, v_{surf}, and the time at which this particle was emitted. For the reactions studied it turns out that particles with v_{surf} = 7 cm/ns are on average emitted at 80 fm/c after contact, whereas particles velocities v_{surf} = 4 cm/ns are associated with emission times around 105 fm/c. Thus focusing at different v_{surf} one can sample different emission times.

To analyze our data we employed the Coulomb corrected coalescence model by Awes [4]. In this model the yields, energy spectra and angular distributions of ejected light composite particles are directly related to those of the ejected nucleons. The phase space correlations which lead to these relationships are parameterized in terms of P_0, the radius of the momentum space volume within which the correlations exist. P_0 in turn is directly related to the size of the emitting system in the thermal coalescence model of Mekjian [5].

A comparison of the data from the different reactions indicates that at the lowest velocities results of the coalescence analysis are significantly influenced by increasing contributions from late stage evaporative decay of the target-like source or secondary decay from light fragments. We have attempted to remove those contributions by extracting P_0 values for isotopes of Z=1 and Z=2 from observed experimental yields from which the target-like-source yields, obtained in multi-source fit procedure, have been subtracted.

For the four systems studied we present, in Figure 2, the values of P_0 and the corresponding equivalent sharp cut-off radii (assuming a spherical volume), R, derived at v_{surf} = 7 cm/ns and 4 cm/ns for triton emission observed in the angular range of 38° to 52° in the laboratory. This selection of angular range minimizes the relative contributions from secondary evaporative decay of projectile-like or target-like sources. The calculations indicate that global thermal equilibrium is not completely established when the first particles are emitted. Thus the temperatures at high v_{surf} should be considered only as approximations. For temperatures T>5 MeV, however, the radii derived from the measured P_0 values are relatively insensitive to T.

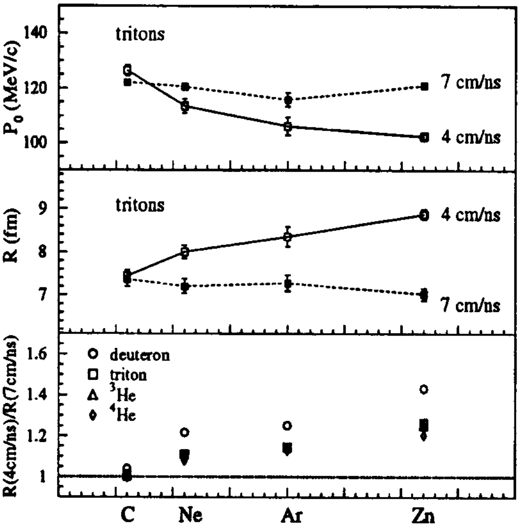

Figure 2. Radii and relative radii derived from the coalescence model analyses for all four systems at v_{surf}=4 cm/ns and 7 cm/ns. Top panel - P_0 values derived from triton data. Middle panel - radii derived from triton data. Bottom panel - relative radii for all four particles.

At 7 cm/ns the extracted radii are observed to be 7 fm - 7.4 fm, for all four systems. At 4 cm/ns the radii increase with projectile mass, indicating progressively larger sizes at later emission times. Results for other Z=1 and Z=2 particles show very similar trends to those seen for the tritons, but the absolute values of the radii are larger for deuterons and smaller for alpha particles, apparently reflecting the very different binding and spatial extent of these clusters. In relative terms, i.e., $R(v_{surf}=4cm/ns)/R(v_{surf}=7cm/ns)$ the size increase is found to be essentially the same for tritons, ^{3}He and ^{4}He but appears larger for deuteron emission (Figure 2, bottom panel).

Using the radii derived from the triton and ^{3}He data and taking the mass of the emitter to be that in the entrance channel system minus mass emitted from the projectile-like and intermediate sources we find that the densities sampled at $v_{surf}=4$ cm/ns are $0.70\rho_0$, $0.52\rho_0$, $0.47\rho_0$, and $0.41\rho_0$ for the ^{12}C, ^{22}Ne, ^{40}Ar and ^{64}Zn induced reactions, respectively. Our results are shown by the solid points in Figure 1. The excitation energies are determined from linear momentum transfer using the target-like fragment velocities from multi-source fits [6,7].

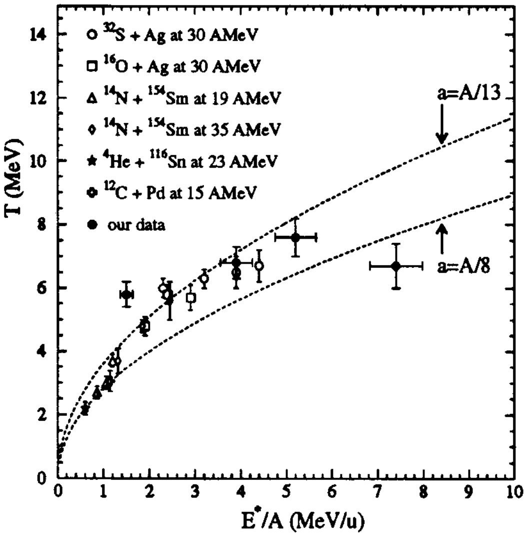

Figure 3. Caloric curve for medium mass nuclei. Double isotope yield ratio temperatures derived in the present work are combined with results reported previously by Wada *et al.* [7]. Dashed lines indicate trends of a Fermi gas model calculation with two different choices of level density parameter.

We present in Figure 3 the double isotope yield ratio temperatures at 4.0 cm/ns plotted against excitation energy. The results indicate a nearly flat caloric curve with temperature T≈7 MeV at excitation energies from 3 to 8 MeV/u. The errors on the excitation energy reflect the uncertainties in the velocity determinations. These temperatures near 7 MeV which result for the expanded low density systems are significantly higher than those derived from integrated isotope yields. They are also essentially identical to that derived in our earlier work on the caloric curve for A≈125 nuclei in which we found a temperature of 6.8±0.5 MeV at 4.3 MeV/u excitation energy [7]. This observation, coupled with the more detailed understanding of the particle emission dynamics and system evolution obtained from the coalescence model analysis, may indicate that the temperature limit of thermally equilibrated nuclei produced in these collisions results from binding energy limitations, i.e., the unbound nucleons with high kinetic energies stream out of the expanding system creating a natural limit to the excitation energy of the remaining nucleus [8].

Thomas-Fermi calculations predicting a lowering of the temperature when radial flow is present may explain the possible decrease for the ^{64}Zn projectile. This would suggest that the ^{22}Ne or ^{40}Ar induced collisions lead to systems near the “balance point" of nuclear matter.

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