Limiting Temperatures and the Equation of State of Nuclear Matter

J. B. Natowitz, K. Hagel, Y. Ma, M. Murray, L. Qin, R. Wada, and J. Wang

In a recent paper, measurements of nuclear specific heats from a large number of experiments were employed to construct caloric curves for five different regions of nuclear mass [1]. Within experimental uncertainties, each of these caloric curves exhibits a plateau region at higher excitation energy, i.e., a "limiting temperature" is reached. The results employed in Ref. 1 were based upon temperature determinations derived from double isotope yield ratios and from slope measurements of particle spectra. More recently, the TAPs Collaboration has reported temperatures determined from a new technique, observations of "second chance" bremsstrahlung gamma ray emission for a series of reactions which span a wide range of mass [2, 3]. There are not yet sufficient data of this latter type to construct caloric curves for relatively narrow mass regions as was done for the previous temperature data. However, in each case studied with this technique, the collisions lead to excitation energies which are above those identified as the starting points of the plateau regions identified in Ref. 1. Thus, it is reasonable to compare the temperatures determined from the thermal bremsstrahlung measurements with the earlier limiting temperature values. As seen in Fig. 1,

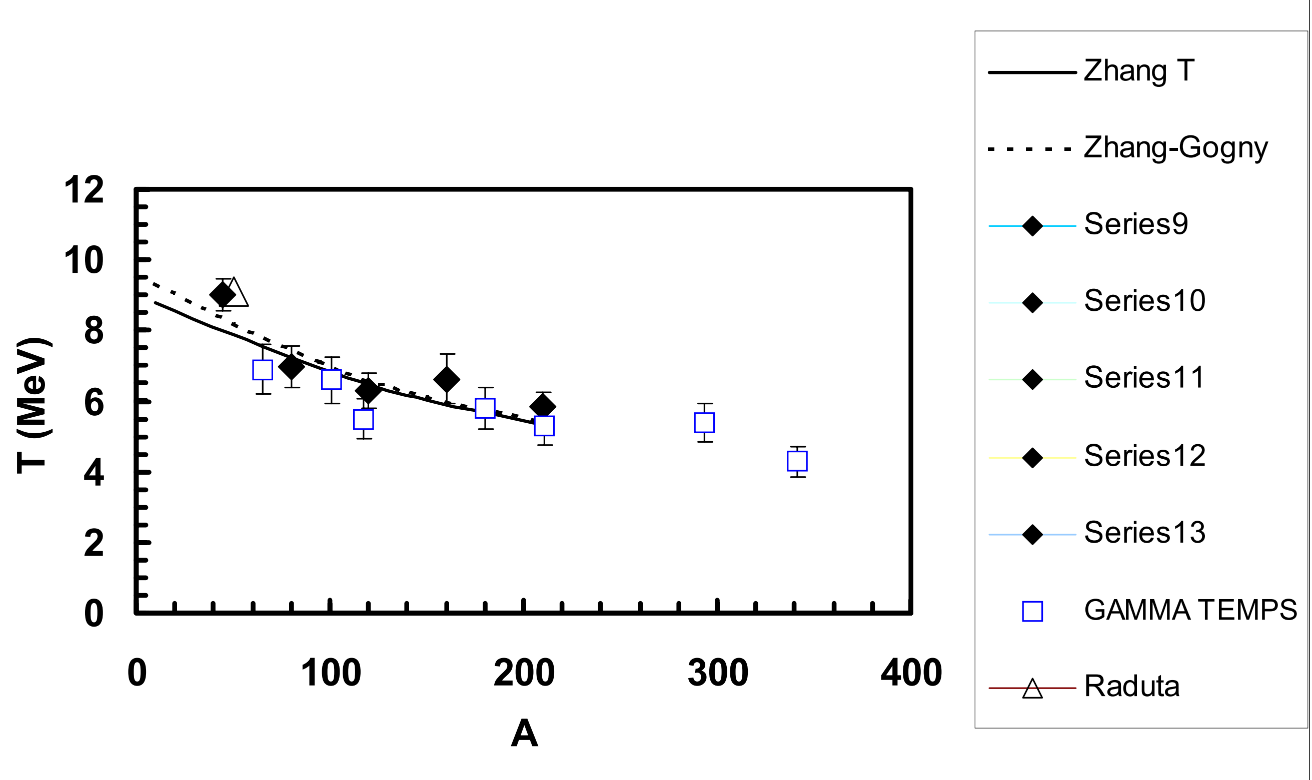

Figure 1: Limiting Temperatures vs Mass. Limiting temperatures derived from double isotope yield ratio measurements are represented by solid diamonds. Temperatures derived from thermal bremsstrahlung measurements are represented by open squares. Lines represent limiting temperatures calculated using interactions proposed by Gogny dashed and Furnstahl.

the reported second chance gamma temperatures and their mass dependence are in excellent agreement with the earlier results. We take this agreement as an independent confirmation of the earlier results and note that the new results extend the determination of the mass dependence to significantly higher mass.

The limiting temperatures plotted in Figure 1 are well below typical calculated critical temperatures of semi-infinite nuclear matter (nuclear matter with a surface). This difference reflects finite size effects, Coulomb effects, and isospin asymmetry effects for the finite nuclei studied. Employing a variety of Skyrme type interactions, Song and Su have previously noted a mass dependent scaling of the Coulomb Instability temperatures with the critical temperature of nuclear matter [see Fig. of Ref. 4]. These calculations were performed for nuclei along the line of beta stability. A similar scaling exists when other model interactions are employed. We have employed the mean variation of T_{Lim}/T_C with A (Fig. 2), determined from a variety of microscopic theoretical calculations, together with the five experimental limiting temperatures reported in reference 1, to extract the critical temperature of nuclear matter. The results are presented in Fig. 3. Averaging the individual results, we find 16.6 ± 0.86 MeV.

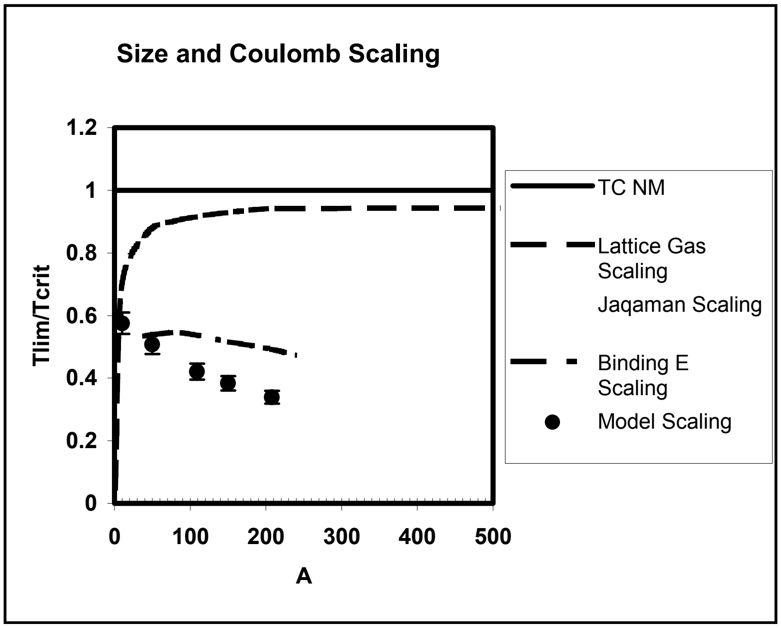

Figure 2: Theoretical variation of the ratio T_{lim}/T_c with mass along the line of beta stability. The solid line indicates the reference value of T_c. The long dashed line shows the effect of finite size scaling derived from a lattice gas model. The line with alternating short and long dashes depicts the ratio of the nuclear binding energy per nucleon to the bulk binding energy per nucleon, 16 MeV.

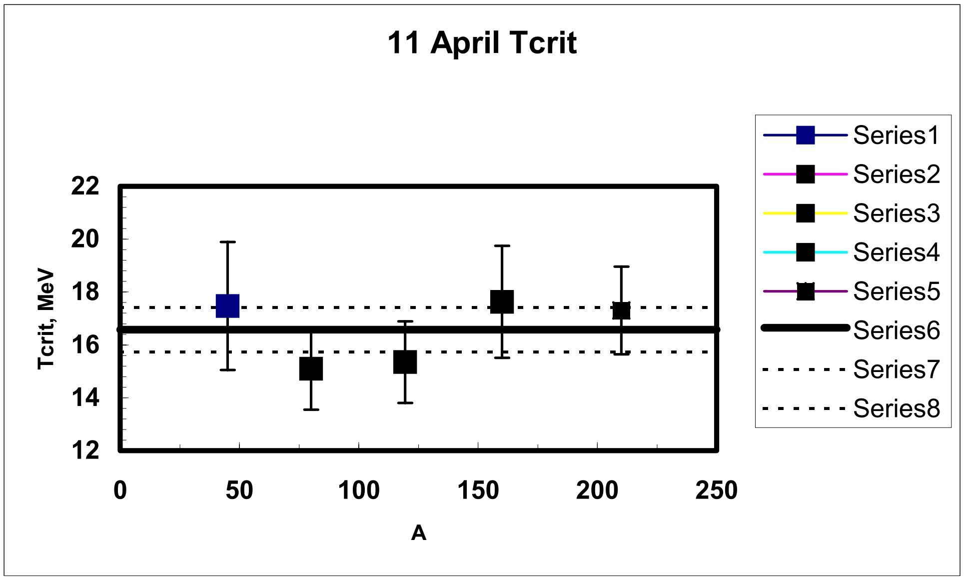

Figure 3: Derived values of the critical temperature of symmetric nuclear matter. Values derived from data in five different mass regions are presented. The mean value of 16.6 MeV is indicated by the horizontal solid line. The range corresponding to ± one standard deviation from this mean value is shown by the thin dashed lines.

Lattimer and Swesty [6, 7] have pointed out that correlations between parameters used to describe nuclear matter are such that a relationship between the critical temperature, T_c, the incompressibility, K, the effective mass, m* (= $m_{eff.}/m$ where $m_{eff.}$ Is the nucleon effective mass and m is the nucleon mass) and the saturation density, Δ_s, may be written as:

$$T_c = C_T \ (K/m^*)^{1/2} \Delta_s^{-1/3}$$

In this formulation, which includes a constant, C_T, to be determined, we see that the quantity determined by the critical temperature measurement is not K but rather $(K/m^*)^{1/2} \rho_s^{-1/3}$. Thus, to extract K, the relation to the other parameters must be understood.

The model values of Δ_s, calculated with the different interactions, show little variation. K and m* are not independent variables but are correlated. For Skyrme interactions, the ratio K/m* depends on the choice of Φ, the parameter controlling a density dependent term. Fixing the saturation density at 0.16 fm^{-3} would lead to K~235 MeV. We are currently exploring the best way to take the density dependent term into account in a determination of K. With radioactive beams it should be possible to employ caloric curve measurements to determine the critical parameters for quite asymmetric nuclei, thus testing the isospin dependence of the equation of state. Caloric curve measurements should continue to be an important tool for probing the equation of state.

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