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Evidence of critical behavior in the disassembly of nuclei with $A\sim36$

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A wide variety of observables indicate that maximal fluctuations in the disassembly of hot nuclei with $A\sim36$ occur at an excitation energy of 5.6 ± 0.5 MeV/nucleon and temperature of 8.3 ± 0.5 MeV. Associated with this point of maximal fluctuations are a number of quantitative indicators of apparent critical behavior. The associated caloric curve does not appear to show a flattening such as that seen for heavier systems. This suggests that, in contrast to similar signals seen for liquid-gas transitions in heavier nuclei, the observed behavior in these very light nuclei is associated with a transition much closer to the critical point.

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Most efforts to determine the critical point for the expected liquid-gas phase transition in finite nucleonic matter have focused on examinations of the temperature and excitation energy region where maximal fluctuations in the disassembly of highly excited nuclei are observed [1–4]. A variety of signatures have been employed in the identification of this region [1–11] and several publications [6–11] have reported the observation of apparent critical behavior. Fisher droplet model analyses have been applied to extract critical parameters [6–10] which are very close to those observed for liquid-gas phase transitions in macroscopic systems [12]. Data from the EOS [13] and ISiS [14] collaborations have been employed to construct a coexistence curve for nucleonic matter [9]. Those analyses have proceeded under the assumption that the point of apparent critical behavior was the true critical point of the system [6,7]. However, some recent theoretical treatments suggest that apparent signals of critical behavior may be encountered well away from the actual critical point [15,16] and applications of Δ-scaling analyses have suggested that the observation of scaling and power-law mass distributions [17,18] are not sufficient to identify the true critical point. Recently, several of the present authors suggested that disassembly for heavier systems occurs within the coexistence region, at temperatures well below the critical temperatures [19]. It was further suggested that the decreasing importance of Coulomb effects makes the lightest nuclei the most favorable venue for investigation of the critical point.

In this Rapid communication we report results of an extensive investigation of nuclear disassembly in nuclei of $A\sim36$ excited to energies as high as 9 MeV/nucleon. We find that the maximum fluctuations occur at an excitation energy of 5.6 ± 0.5 MeV and a temperature of 8.3 ± 0.5 MeV. At this same point, a number of indications of apparent critical behavior are seen. While this does not guarantee that the critical point has been reached, we also find that the caloric curve does not exhibit a plateauing at the point of maximum fluctuations, in contrast to experimental results for heavier systems [11]. These observations suggest that the critical point for these very light nuclei may have been reached.

Using the TAMU NIMROD detector [20] and beams from the TAMU K500 superconducting cyclotron, we have probed the properties of excited quasi-projectile-like fragments (QP) produced in the reactions of 47 MeV/nucleon ^{40}Ar+^{58}Ni. Earlier work on systems at energies near the Fermi energy have demonstrated the essential binary nature of such collisions, even at relatively small impact parameters [21]. As a result, these collisions prove to be very useful in preparing highly excited light nuclei [22].

The charged particle detector array of NIMROD includes 166 individual CsI detectors arranged in 12 rings in polar angles from $\sim3°$ to $\sim170°$. In these experiments each forward ring included two Si-Si-CsI telescopes and three Si-CsI telescopes to identify intermediate mass fragments (IMF). The NIMROD neutron ball, which surrounds the charged particle array, was used to determine the neutron multiplicities for selected events. The correlation of the charged particle multiplicity and the neutron multiplicity was used to select violent collisions. In this work, we developed a new method to reconstruct the QP source. We first carry out three source (QP, quasitarget, and a midrapidity source) fits to the observed energy spectra and angular distributions of the light charged particles (LCP). We then employ the parameters of these fits to control the *event−by−event* assignment of individual LCP to one of the sources using Monte Carlo sampling techniques. We associate IMFs with $Z\geqslant4$ with the QP

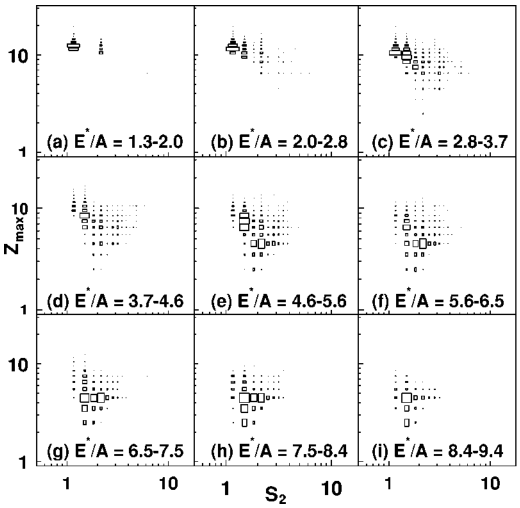

FIG. 1. Campi plots in different E^*/A windows.

source if they have rapidity $>0.65 y_p$, where y_p is the beam rapidity. For the present analysis we have selected reconstructed QP events with total charge number $Z_{QP} \geqslant 12$ from violent collisions. Although the detector coverage is $\sim 85\%$ of 4π (NIMROD has limited Si detector coverage and a low effective efficiency only about $\sim 4\%$ for the selected events. With this technique of source selection the particles emitted in the source frame exhibit symmetric emission, a necessary condition for equilibrium emission.

The QP source velocity was determined from momentum conservation of all QP detected particles. The distribution of QP source excitation energy for the selected events was deduced using the energy balance equation [23] where the kinetic energies of charged particles, mass excesses, and average neutron contributions were considered. Using results of the source fits we have also evaluated (on the average) small corrections for undetected mass and energy (mostly as protons), in the sampled events. We have observed that, up to the transition point discussed later in this paper, the excitation functions of the mean multiplicities of light ejectiles are in good agreement with those calculated using the GEMINI statistical code [24]. This observation provides further evidence for QP source equilibration in these events.

Campi plots of the natural log of the largest cluster charge, $\ln Z_{max}$, versus the natural log of the normalized second moment, $\ln S_2$, ($S_2 = \Sigma_{Z_i \neq Z_{max}} Z_i^2 \cdot n_i / \Sigma_{Z_i \neq Z_{max}} Z_i \cdot n_i$, where n_i is the multiplicity of QP clusters with atomic number Z_i), are very instructive in searches for critical behavior [1,7]. In Fig. 1 we present such plots for nine selected excitation energy bins. In the low excitation energy region the upper (liquid phase) branch is strongly evidenced. In the range of E^*/A near 5.6 MeV/nucleon, the liquid branch and the lower Z_{max} (gas-phase) branch are populated essentially equally. At the higher E^*/A the gas-phase branch dominates the plot. These results indicate that the region of maximal fluctuations signaling a transition between the two phases is to be found near 5.6 MeV/nucleon.

To further explore this region we have investigated other proposed observables commonly related to fluctuations and critical behavior. Since we wish to compare our results with several model calculations which are based upon specification of the initial temperature of the excited system, we first turn to a determination of the caloric curve for these $A=36$ nuclei. We have used two different techniques to derive "initial temperatures" from the observed apparent temperatures. The first consisted of fitting the kinetic energy spectra for different LCPs in nine different bins in E^*/A with Maxwellian distributions to obtain the slope temperatures. To derive the initial temperatures it is necessary that the experimentally observed slope temperatures be corrected for effects due to secondary decay. We therefore employed the measured excitation energy dependence of the multiplicity for the ejectile under consideration to determine initial temperatures [25,26]. The second technique employed results of a quantum statistical model (QSM) calculation to correct the observed double isotope, H-He, ratio temperatures for secondary decay effects [27,28]. For this work we employed the QSM model described in Ref. [28]. The first technique employing observed spectral slopes assumes sequential evaporation of the ejectiles from a cooling compound nucleus source [25,26] while the second assumes simultaneous fragmentation of a reduced density equilibrated nucleus and subsequent secondary evaporation from the primary fragments [27,28]. Given that the discussion above suggests an important transition from liquid to gas dominance at 5.6 MeV/nucleon excitation energy, the first method should not be appropriate above that energy and the second method is not appropriate below that energy. The data points in Fig. 2 represent the initial temperature values determined from cascade corrected slopes (solid squares) and H-He isotope ratios (solid circles), each determined in its appropriate region of applicability. The two techniques lead to reasonable agreement in the transition region. We note that the caloric curve, defined in this manner, exhibits no obvious plateau. The temperature at 5.6 MeV excitation is 8.3 ± 0.5 MeV. The quoted error is a statistical estimate based on the results of translated polynomial fits to the full set of data points.

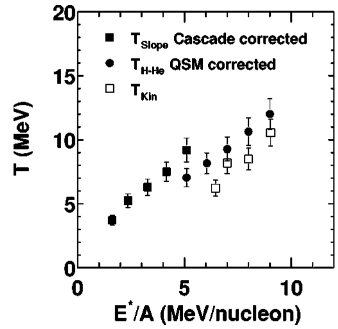

FIG. 2. Caloric curve. See text for details.

This temperature of 8.3 ± 0.5 MeV is in quite reasonable agreement with the limiting value of 9.0 ± 1.2 MeV derived from caloric curves of low mass nuclei ($A=30-60$) in Ref. [11]. In that reference it is also pointed out that the point of flattening and rapid departure of the caloric curve from the Fermi-gas-like behavior corresponds well with the point identified as the critical point by the Fisher scaling analysis. The present temperature is also in excellent agreement with the (interpolated) limiting temperature of 8.2 MeV derived

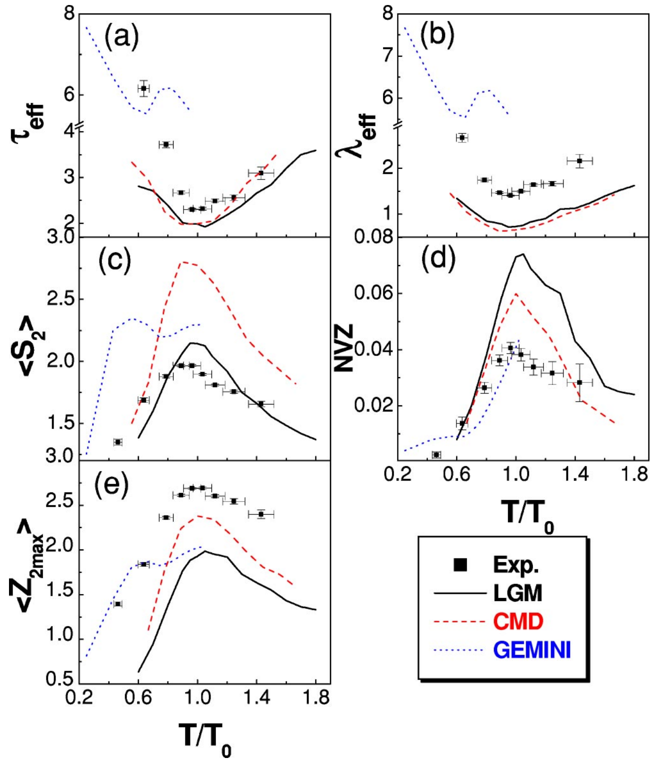

FIG. 3. Color online. The effective Fisher-law parameter (τ_{eff}) (a), the effective exponential law parameter (λ_{eff}) (b), $\langle S_2 \rangle$ (c), NVZ fluctuation (d), the mean charge number of the second largest fragment $\langle Z_{2max} \rangle$ (e). Solid squares with the error bars are experimental data and the lines are different model calculations as illustrated in right bottom corner. For data, T_0=8.3 MeV, for the LGM calculation T_0=5.0 MeV and for the CMD calculation T_0=4.5 MeV. See details in text.

using the Gogny force as reported by Zhang *et al.* [29]. As the interactions employed in the lattice gas model (LGM) and classical molecular 29 dynamics (CMD) calculations are much simpler interactions then those which reproduce ground state nuclear properties, they should not be expected to quantitatively reproduce the observed results for nuclei. However scaled by T_0, the calculations and experimental results show very similar behaviors as a function of excitation energy. Note also that the y axis scales in Fig. 3 do not begin at zero. The comparison of T_0 obtained with the LGM and CMD calculations suggest that in the $A \sim 36$ region the Coulomb energy may lower the transition point 10%. In LGM calculations we also find a systematic shift of T_0 with A_{source} consistent in sign with the trend expected for neutral drops of changing size. In the calculation a 10% shift in A_{source} leads to a corresponding 10% shift of T_0 in the same direction.

If the vapor phase may be characterized as an ideal gas of clusters [12], then, at and above T=8.3 MeV, this should be signaled by a kinetic temperature, $T_{\rm kin}=\frac{2}{3}E_{\rm kin}^{\rm th}$, where $E_{\rm kin}^{\rm th}$ is the Coulomb corrected average kinetic energy of primary fragments. Secondary decay effects make it difficult to test this expectation. However, in an inspection of the average kinetic energies for the different species observed, we find that, *for each* E^*/A *window*, the average kinetic energy of ^{3}He isotropically emitted in the projectilelike frame, is higher than those of other species. This together with simple model estimates indicates that the ^{3}He spectra are the least affected by secondary decay. Kinetic temperatures for ^{3}He, defined as $\frac{2}{3}(\overline{E_k}-B_c)$, where $\overline{E_k}$ is the average kinetic energy and B_c is the Coulomb energy, are plotted as open squares in Fig. 2. No cuts were made in kinetic energy spectra. The Coulomb barrier corrections were extracted from spectral fits in each excitation energy bin. Above T=8.3 MeV the kinetic temperatures show a similar trend to the chemical temperatures but are approximately 1.5 MeV lower. While not perfect this approximate agreement provides additional evidence for disassembly of an equilibrated system.

Returning to the characterization of the apparent transition at E^*/A=5.6 MeV, we plot in Fig. 3(a) the effective Fisher-law parameter τ_{eff} extracted from power law fits for $Z=2-7$ of the QP charge distributions in the different E^*/A windows. The results are plotted as a function of T/T_0, where T_0 is 8.3±0.5 MeV temperature derived for E^*/A =5.6 MeV. As seen in Fig. 1, at low E^*/A a large residue always remains, i.e., the nucleus is basically in the liquid phase accompanied by some light particles. When $T/T_0 \sim 1$, the charge distribution shows a near power-law distribution with $\tau_{eff} \sim 2.3$. This value is close to the critical exponent of the liquid-gas phase transition [12]. As T continues to increase, the charge distribution becomes steeper which indicates that the system tends to vaporize. The observed minimum in τ_{eff} is rather broad. For comparison to the experimental data we also display, in Fig. 3(a), the variation of τ_{eff} predicted by three different models: standard statistical sequential decay as modeled by the code GEMINI [24], the isospin dependent LGM of Gupta *et al.* (using A=36 and Z =16 particles in a cubic lattice with 64 sites) [5,30] and CMD with Coulomb forces [30]. The last, without Coulomb, has been shown to give results essentially the same as the LGM which is known to have a liquid-gas phase transition. Thus the addition of Coulomb interactions to that model is argued to be equivalent to the more difficult task of inclusion of Coulomb interactions in the LGM. In order to compare all parameters on a T/T_0 scale, T_0 for the GEMINI calculation is taken as 8.3 MeV. For the LGM and CMD calculations T_0 is taken as the associated phase transition temperature for A =36 and Z=16. For the potential employed Ref. [30] these are, respectively, T_0=5.0 MeV and T_0=4.5 MeV. Scaled in this way, the LGM and CMD results exhibit a variation of τ_{eff} vs T/T_0 that is very similar to that seen in the experiment while the GEMINI calculation shows dramatically different behavior.

Since the Monte Carlo technique mixes contributions from different sources, we have used results of the LGM calculations boosted into the laboratory frame and mixed with particles from an assumed intermediate velocity component to estimate the effects of this mixing. These model events were then treated in the same fashion as the data and results for various observables were compared to results from the analysis of the unmixed LGM events. For the quantities plotted in Figs. 3(a)–3(e) our results indicate that the positions of the observed transition temperatures, signaled by the minima in Figs. 3(a) and 3(b) and the maxima in Figs. 3(c)–3(e) may shift ±0.2 to 0.3 MeV. The absolute magnitudes of the values of the plotted quantities may change by 5–10%.

In a LGM investigation of scaling and apparent critical behavior, Gulminelli *et al.* have pointed out that, in finite systems, the size distribution of the maximum cluster, i.e., the liquid, might overlap with the gas cluster distribution in such a manner as to mimic the critical power-law behavior with $\tau_{eff} \sim 2.2$ [15]. They further note, however, that at that point the scaling laws are satisfied [15]. We find that removal of the heaviest cluster from the distribution leads to distributions which are exponential in nature over the entire energy range sampled. In Fig. 3(b) the resultant exponential slope parameters, λ_{eff}, are also plotted against excitation energy. A minimum is seen in the same region where τ_{eff} exhibits a minimum. Once again the LGM and CMD models show similar behavior while the GEMINI calculation leads to very different predictions.

For a further comparison we present in Figs. 3(a)–3(e) experimental and calculated results for (c) the mean normalized second moment, $\langle S_2 \rangle$, from Fig. 1, (d) the normalized variance in Z_{max}/Z_{QP} distribution, NVZ $=\sigma^2_{Z_{max}/Z_{QP}}/\langle Z_{max}/Z_{QP}\rangle$ [31], (e) $\langle Z_{2max}\rangle$—the average atomic number of the second largest fragment [32]. For these additional parameters, which are often used to characterize a region of maximum fluctuations, the data show maxima at $T/T_0=1$. The LGM and CMD calculations show very similar behavior with some difference in absolute value. (Note suppressed zero points on y axes of the plots in Fig. 3.) The GEMINI results are very different in each case.

To recap, in our measurements for the disassembly of a small nucleus with $A\sim 36$ maximal fluctuations are observed at 5.6 ± 0.5 MeV/nucleon excitation energy and $T=8.3\pm 0.5$ MeV. The fragment topological structures suggest the onset of a phase change. Comparisons with results of LGM and CMD (with Coulomb) calculations suggest that the critical point may have been reached. As pointed out in the introduction, recent theoretical treatments suggest that apparent signals of critical behavior may be encountered well away from the actual critical point [15–18], and therefore most of the parameters investigated, in Figs. 1 and 3 may not be sufficient by themselves to identify the true critical point of the system. What differentiates the present work from previous identifications of points of critical behavior in nuclei, in addition to the fact that these are the lightest nuclei for which a detailed experimental analysis has been made, is the comportment of the caloric curve. For heavier systems the points identified as the critical points appear to occur at excitation energies very close to those at which the onset of significant flattening in the caloric curves are observed [11]. The reason for this flattening is still under discussion. It may reflect expansion and/or spinodal decomposition inside the coexistence region [16,33,34]. In contrast no quasiplateau region in the caloric curve is apparent in the present study. Further, above the point of maximal fluctuations, the kinetic temperatures of ^{3}He ejectiles, thought to represent early emission with little contamination from secondary decay, show a similar trend to that of the chemical temperatures. While this difference in caloric curves certainly needs to be probed in greater detail, a possible interpretation is that the transition is occurring at, or extremely close to, the critical point of this equilibrated small system.

Finally, we believe it is worth noting that the significance of the event topology in the $T=8.3$ MeV region is also indicated in a Zipf's law test (not shown) as proposed in Ref. [35]. Moreover, the analysis of Δ scaling of Z_{max} distribution, the fluctuation of total kinetic energy of QP and critical exponents also support the occurrence of a significant transition around $E^*/A\sim 5.6$ MeV [36].

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