

## Critical scaling of excited nuclear systems from quantum fluctuations

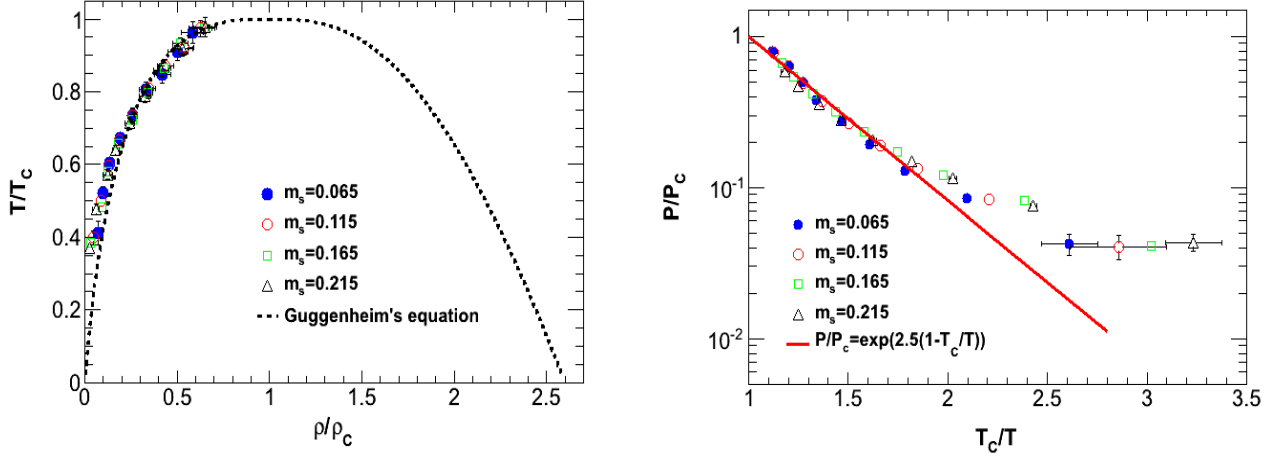
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The idea that nuclear systems may show some evidence for the occurrence of critical behavior related to a liquid-gas phase transition, stimulated by the van der Waals nature of the nucleon-nucleon interaction, has been a subject of many investigations [1-3]. Experimentally, heavy-ion reactions around the Fermi energy dominated by nuclear fragmentation are explored to investigate this possibility. To date, various experimental evidences have been observed which seem to be related to the nuclear phase transition. Some of these observations include the plateau of the nuclear caloric curve [2, 4] in a certain excitation energy range, the extraction of critical exponents in the charge or mass distribution of the multifragmentation system [5] and the negative branch of the heat capacity experimentally observed in nuclear fragmentation [6]. These signals and many others [7, 8] were only qualitative, giving information on the phase space region reached by the system but not on the detailed trajectory (pressure, volume, temperature) followed by the system to pass from one phase to the other. However, in previous works of Elliott *et al.* [9, 10] the systems studied were located in pressure-density-temperature space. In this current study we extend the work by Elliot *et al.*, adding the asymmetry degree of freedom of the fragmenting source to experimentally establish the dependence of the nuclear equation of state on this quantity.

We report the experimental temperatures and densities of the fragmenting system calculated by the quantum fluctuation method for protons presented in [11, 12]. In addition, pressures calculated through the grand partition function of Fisher's droplet model [13] are also presented. Since the protons represent the vapor part of the system, the derived densities and temperatures refer to the vapor branch of the 'liquid-gas'-like instability region. It is shown that the present data contain a signature of a liquid-gas phase transition. Scaling of physical observables to their critical values displays universality, i.e. independence from the proton-neutron asymmetry of the source.

The experiment was performed at the Texas A&M University Cyclotron Institute. Beams of  $^{64}\text{Zn}$ ,  $^{64}\text{Ni}$  and  $^{70}\text{Zn}$  at 35 MeV/nucleon were incident on  $^{64}\text{Zn}$ ,  $^{64}\text{Ni}$  and  $^{70}\text{Zn}$  targets, respectively [14]. Charged particles and neutrons were measured using the NIMROD-ISiS  $4\pi$  detector array [15]. The granularity and excellent isotopic resolution provided by the array enabled the reconstruction of the quasi-projectile ( $QP$ ), the hot projectile-like source produced in the early stage of the collision, in both  $Z$  and  $A$ . The NIMROD-ISiS charged particle array is housed inside the TAMU Neutron Ball. The Neutron Ball provides event-by-event multiplicity of free neutrons emitted during a reaction. The  $QP$  source was selected by means of event-by-event cuts on the experimental data as in Ref. [16] with its mass restricted to be in the range  $54 \leq A \leq 64$ . Its excitation energy was deduced using the measured free neutron multiplicity, the charged particle kinetic energies, and the Q-value of the breakup. Data were sorted into four different source asymmetry ( $m_s = (N - Z)/A$ ) bins ranging from 0.04 to 0.24 with bin width of 0.05. In addition, effects of  $QP$  excitation energies on the thermodynamic quantities were investigated by gating the data into nine bins of 1 MeV in the range of 1-10 MeV/nucleon.

Figure 1 (left panel) shows the temperatures and densities of the selected  $QP$  of mass in the range  $54 \leq A \leq 64$  plotted in the scaled values. The critical values  $\rho_c$  and  $T_c$  for each  $m_s$  bin were determined using Guggenheim's equation [17] to fit  $\rho$  versus  $T$  curves. It is shown that all the experimental data falls on the same curve. The extracted critical exponent  $\beta = 0.35 \pm 0.01$  that defines the universality class of the system is in the range of extracted experimental values from a variety of systems [18]. Calculated



**FIG. 1.** (Left panel) Reduced temperature-reduced density coexistence curve. The dashed line shows a fit to Guggenheim's equation. (Right panel) The reduced pressure as a function of the inverse of the reduced temperature. The solid line shows a fit to the Clausius-Clapeyron equation where the value of 2.5 is the average of the  $\Delta H/T_c$  values extracted from different  $m_s$  bins.

pressures ( $P$ ) normalized to the critical values ( $P_c$ ) are plotted versus the inverse of the reduced temperature ( $T_c/T$ ) in Fig.1 (right panel). The values of  $P_c$  for different  $m_s$  bins are extracted using the Clausius-Clapeyron equation ( $P/P_c = \exp[\Delta H/T_c(1 - T_c/T)]$ ) which describes several fluids up to  $T_c$  [19]. The quantity  $\Delta H$  is the enthalpy of emission of a fragment from the liquid. The slope of the coexistence lines  $\Delta H/T_c = 2.5$  is in agreement with the one obtained in Refs. [9, 10], but a factor of 2 lower than the values of macroscopic systems reported by Guggenheim in Ref. [19]. The experimental critical parameters ( $T_c$ ,  $\rho_c$  and  $P_c$ ) and the critical compressibility factor for each  $m_s$  bin are listed in Table I. The critical temperatures  $T_c$  and pressures  $P_c$  are observed to increase when increasing  $m_s$  while  $\rho_c$  decreases with increasing  $m_s$ . The critical compressibility factor values ( $P_c/\rho_c T_c$ ) are very close to those of real gases reported in [20] and are observed to increase with  $m_s$ . Strong evidence for a signature of a liquid-gas

**Table I.** Critical values and thermodynamic quantities for the four  $m_s$  bins.

$m_s$	$T_c$ (MeV)	$\rho_c$ ( $fm^{-3}$ )	$P_c$ (MeV/ $fm^3$ )	$P_c/\rho_c T_c$	$\Delta H/T_c$
0.065	$12.12 \pm 0.39$	$0.070 \pm 0.006$	$0.211 \pm 0.002$	$0.25 \pm 0.02$	$31.50 \pm 1.01$
0.115	$12.51 \pm 0.35$	$0.066 \pm 0.005$	$0.209 \pm 0.001$	$0.25 \pm 0.02$	$32.51 \pm 0.90$
0.165	$13.11 \pm 0.30$	$0.064 \pm 0.004$	$0.232 \pm 0.001$	$0.27 \pm 0.02$	$31.46 \pm 0.71$
0.215	$13.39 \pm 0.21$	$0.061 \pm 0.002$	$0.258 \pm 0.002$	$0.31 \pm 0.01$	$32.13 \pm 0.50$

phase transition in two-component systems has been found. These results provide a means to establish the

proton-fraction dependence of the nuclear equation of state in systems with large neutron excess such as neutron stars.

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