Signatures of the liquid-gas phase transition from fermionic quantum fluctuations

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Heavy-ion collisions at the Fermi scale are dominated by nuclear fragmentation, the breakup of a nuclear system into several intermediate sized pieces, and are often used to explore the phase diagram of nuclear matter. Because of the van der Waals nature of the nucleon-nucleon interaction, it is believed that nuclear matter is likely to exhibit a liquid-gas phase transition [1–3]. However, unlike van der Waals fluids, nuclei are finite two-component systems. Most of the divergences usually linked to a phase transition in macroscopic systems are washed out in these small systems [4]. Also, the additional degree of freedom which is related to proton and neutron concentrations makes phase transitions more complex [5]. The phase transition should therefore manifest itself through different signals. Several attempts were made in the past to investigate the relationship between multifragmentation and a liquid-gas phase transition. For example, caloric curves were examined [2, 6], critical exponents were determined [7] and negative heat capacities were observed [8]. However, because of the assumptions made in these studies the system could not be located in pressure-density-temperature space [9]. In the present study, the experimental temperatures and densities of the fragmenting systems are determined using a new quantum method presented in Ref. [10, 11]. Experimental pressures are extracted making use of the grand partition function of Fisher's droplet model [12].

The experiment was performed at the Texas A&M University Cyclotron Institute. Beams of ^{64}Zn, ^{64}Ni and ^{70}Zn at 35 MeV/nucleon were incident on ^{64}Zn, ^{64}Ni and ^{70}Zn targets, respectively [13]. Charged particles and neutrons were measured using the NIMROD-ISiS 4π detector array [14]. 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 experimental information on the 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. [15] 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.

The temperatures and densities of the selected *QP's* have been extracted from the momentum quadrupole and multiplicity fluctuations with protons as a probe particle. Full details of the calculations are reported in Refs. [10, 11]. The corresponding pressures were calculated by making use of the grand partition function from Fisher's droplet model described in Ref. [12]. In Fig.1 (left panel), the critical exponent β which describes the nature of singularity in density (ρ) and temperature (T) at the critical point is determined by fitting $1-\rho/\rho_c$ versus $1-T/T_c$. The critical values ρ_c and T_c for each m_s bin are determined using Guggenheim's equation [9] to fit ρ versus T curves. Calculated 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).

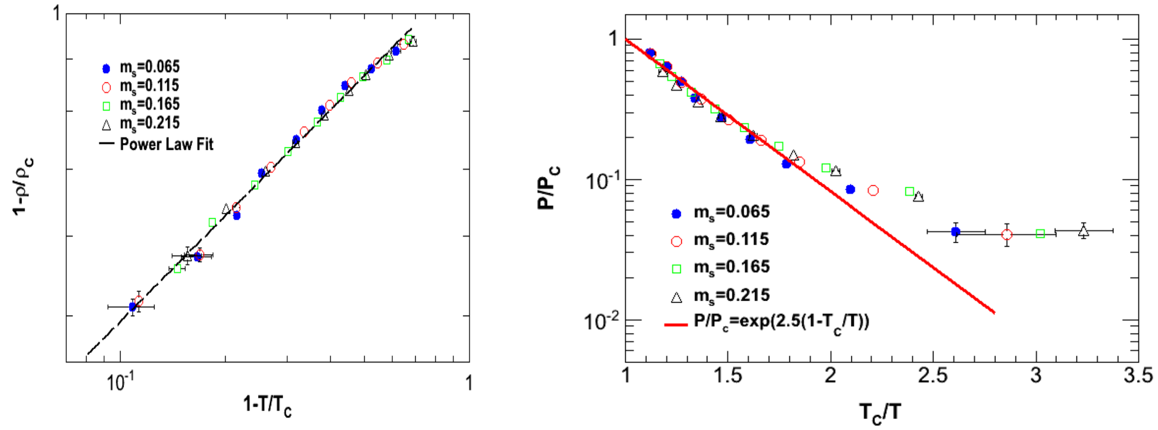

FIG. 1. (Left panel) The extraction of the critical exponent β. The dash line represents a fit to a power law. (Right panel) The reduced pressure as a function of the inverse of the reduced temperature. The solid line shows a fit to the Clausius-Clapeyron equation [9].

The temperature, the density and the pressure of the selected fragmenting sources and the corresponding critical values have shown a dependence on the source asymmetry. The extracted critical exponent $\beta = 0.355 \pm 0.014$ is in the range of extracted experimental values from a variety of systems [9]. Calculated critical compressibility factor values ($P_c /\rho_c T_c$) have shown an increase when increasing m_s and are very close to those for several fluids [9]. These results provide strong evidence for a signature of a nuclear liquid-gas phase transition.

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