Coulomb corrections to experimental temperatures and densities in Fermi-energy heavy-ion collisions

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Understanding the behavior of nuclear matter at various densities and temperatures is one of the main goals of the study of heavy-ion reactions. The determination of nuclear parameters (temperature, density, pressure, free energy, etc) that characterize the nuclear equation of state (NEOS), essential in understanding a number of important issues in astrophysics, remains a difficult task despite a wide body of available experimental data. A number of methods can be found in the literature that have been developed and applied to the study of thermodynamic properties of highly excited nuclear systems. These include the slope thermometer from kinetic energy distributions of emitted particles [1–4], the population of excited states thermometer [5–7] and the double isotopic yield ratio method [3, 4, 7–9] to extract the density and temperature of the system. All these methods were derived from a classical approach. However, a coalescence approach was also developed to estimate the density [9, 10]. The densities obtained using a coalescence approach were found to be higher than those from a double ratio densitometer. This is undoubtedly due to the coalescence parameter that might mimic important quantum effects [11] resulting in relatively high densities.

Another method for measuring temperatures was proposed by Wuenschel *et al.* [12] based on quadrupole momentum fluctuations of fragments using a classical Maxwell-Boltzmann distribution. Within the same framework but for a Fermi-Dirac distribution or a Bose-Einstein distribution, a new method for extracting simultaneously both density and temperature of the system was suggested in Refs. [13–15]. A proper treatment of the quantum statistical nature of particles produced during heavy-ion reactions is taken into account in this newly proposed method. In such an approach, particle multiplicity fluctuation is used in addition to quadrupole momentum fluctuation to infer a temperature and density of the system. Also, important quantum effects, such as Fermion Quenching or Bose-Einstein Condensation (BEC) [16–19], can be traced when fermions and bosons are treated differently. In subsequent works [20–22], this method has been further modified by taking explicitly into account Coulomb corrections.

In the present study, we extend our previous analysis [23–25] which used protons as the probe particle. We provide additional results from the same experimental data set by Coulomb correcting the density and temperature. The experiment was performed at the K-500 superconducting cyclotron facility at Texas A&M University. ^{64,70}Zn and ^{64}Ni beams were used to respectively irradiate ^{64,70}Zn and ^{64}Ni targets at 35 MeV/nucleon. Charged particles and free neutrons were detected with the NIMROD-ISiS 4π detector array [26]. Further details of the experiment may be found in Refs. [27, 28]. The excellent energy resolution achieved allowed isotopic resolution of charged particles up to Z=17 and elemental resolution up to the charge of the beam. The quasi-projectile (QP), the large, excited, primary fragment of the projectile following a non-central collision with the target, was reconstructed from events in which all charged particles were isotopically identified. The Neutron Ball [29] provided event-by-event

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experimental information on the free neutrons emitted during a reaction. The number of free neutrons emitted by the QP was deduced from the total measured number of neutrons, background and efficiencies for measuring neutrons produced from QP and quasi-target sources [12]. The excitation energy was deduced using the transverse kinetic energy of the charged particles, the neutron multiplicity and the energy needed for the breakup (Q-value). This method of reconstruction has previously been fully described in Refs. [12, 30]. Using the three reaction systems, we selected a QP mass range not too far from the projectile mass ($54 \leq A \leq 64$) and a span in neutron-proton asymmetry (m_s) with sufficient statistics.

The temperatures of reconstructed QPs and nucleon densities are obtained with the quadrupole momentum and multiplicity fluctuation method fully reported in Refs [13–15, 20]. Protons have been used as the probe particle. In Refs. [20, 21], Zheng *et al.* addressed the issue of correcting for Coulomb effects in the determination of densities and temperatures of hot sources produced in heavy-ion collisions. This method borrowed from electron scattering was adopted and applied to classical as well as to quantum systems. The Coulomb field is taken to be the Fourier transform of the Coulomb potential of the source. In this way, the equations of quadrupole momentum fluctuation, the average multiplicity, as well as the multiplicity fluctuation containing the Coulomb field term, were numerically solved to derive the temperature (T), the density (ρ) and the volume of the system (V). Using model calculations, the authors of Refs. [20, 21] showed that derived temperatures of protons and neutrons are very similar whereas densities are largely not affected by Coulomb effects. The same behavior was also observed for composite fermions in the classical case. We have applied the same procedure to our experimental data.

In Fig. 1 (top panels), we present QP temperatures as a function of the excitation energy per nucleon using protons as the probe particle. These caloric curves show a monotonic rising behavior for both cases (without and with Coulomb corrections). A weak dependence on m_s is observed for temperatures extracted without and with Coulomb correction. It is also observed that Coulomb corrections lower the temperature value by almost 2 MeV.

The densities of QP regions probed by protons versus the excitation energy per nucleon are shown in bottom panels of Fig. 1. The left and right panels correspond to results without and with Coulomb corrections, respectively. As protons refer to the gas component (low-density) region of the system in the liquid/gas-type phase transition, we observe that the density rises as the excitation energy increases. In fact, as the excitation energy increases more protons leave the liquid phase and enter the gas phase thus creating a larger density of protons in the gas phase. A clear dependence on m_s is seen in each panel for the four density curves: the larger the asymmetry, the lower the density. In our previous studies [25, 31, 32], a strong dependence of temperatures on m_s has been shown within a classical treatment. However, in the present treatment where we extract simultaneously both temperature and density, the dependence on m_s is rather strongly exhibited in the density. We also note that Coulomb corrections have, in general, a small effect on the derived densities as was shown for model calculations reported in Refs. [20, 21].

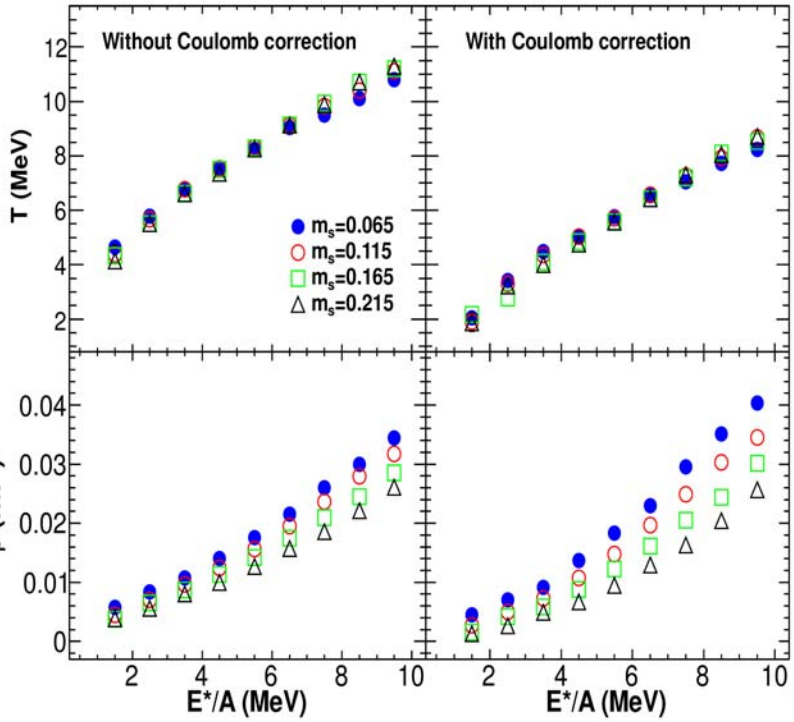

FIG. 1. Temperatures (top panels) and densities (bottom panels) of the gas phase for QPs that differ in neutron-proton asymmetry (m_s) as a function of the excitation energy per nucleon. Protons are used as the probe particle. Left and right panels correspond respectively to results without and with Coulomb correction. Statistical errors are smaller than the symbols.

The correlation between the density and the temperature, as probed by protons, is presented in the left panel of Fig. 2 for the four different source asymmetries. All curves display a rising behavior. It is also interesting to notice that as the system temperature increases, the spacing between the proton density values for different asymmetries increases. These features may be attributed to the competing roles of symmetry and Coulomb energies. From the values of density and excitation energy, we examine in the right panel of Fig. 2 the energy density $\varepsilon=(E^*/A)\rho$ against the temperature. It is observed that ε monotonically increases as T increases and the differences between curves seen in the left panel of Fig. 2 are less noticeable.

To summarize, we have presented and discussed temperatures and densities of hot sources produced in heavy-ion collisions near Fermi energies determined with the very recently established quantum fluctuation method. Coulomb corrections applied to derived temperatures and densities using protons as the probe particle have shown to lower temperature values by almost 2 MeV compared to non-corrected results while little effect is shown on derived densities. The results of energy density versus temperature have shown a small dependence on the neutron-proton asymmetry of the system.

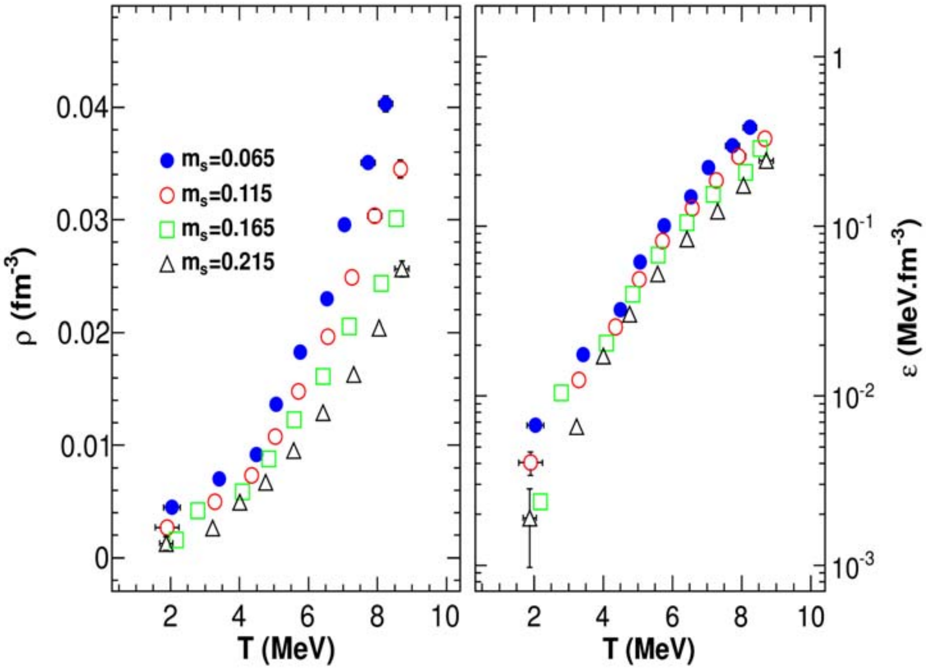

FIG. 2. Left panel: Correlation between the density and the temperature of the system as probed by protons. Right panel: Energy density versus temperature. All quantities are corrected for Coulomb. Statistical errors are shown by the bars and are not shown when smaller than the symbols.

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