Coulomb corrections to the extraction of the density and temperature in non-relativistic heavy ion collisions

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The properties of the Nuclear Equation of State (NEOS) can be investigated by means of Heavy Ion Collisions. In the microscopic system formed in the collision, non-equilibrium effects could be dominant. As a consequence, the derivation of quantities needed to constrain the NEOS like density, pressure and temperature is not an easy task. To determine densities and temperatures of colliding systems we have recently suggested a method based on fluctuations of quantities such as the light particles multiplicity and quadrupole momentum [1-5]. In particular, in Refs. [2-3] the method takes into account the quantum statistical nature of nuclear particles and clusters obeying to the Fermi-Dirac statistics, while in Ref. [4] the same procedure is applied for Boson clusters like deuterons and alpha particles. The choice of fluctuations, particularly along the perpendicular direction to the beam axis, is motivated by their relation to the temperature as it is stated by the fluctuation-dissipation theorem. We expect fluctuations to give the closest possible determination of the "temperature" of the system, even though it could be chaotic but non-ergodic. In the classical limit [1], Quadrupole momentum Fluctuations (QF) can be easily connected to the temperature. Of course, if the system is classical and ergodic, the temperature determined from QF and, say from the slope of the kinetic distribution of the particles should be the same. In the ergodic case, the temperature determined from isotopic double ratios should also give the same result. This is, however, not always observed, which implies that the system is non-ergodic, or non-classical. We can go beyond the classical approximation. When we are dealing with fermions, in such a case it is not possible to disentangle the 'temperature' from the Fermi energy, thus the density [2-3]. For bosons case, we have similar situation, even more complicated because of the possible Bose-Einstein Condensate (BEC). Because we have two unknowns, we need another observable, which depends on the same physical quantities. In [2-4] we have proposed to look at multiplicity fluctuations (MF) which, similarly to QF, depends on T and ρ of the system in a way typical of fermions [2-3] or bosons, such as alpha particles [4]. The application of these ideas in experiments has produced interesting results such as the sensitivity of the temperature from the symmetry energy [6], fermion quenching [7] and the critical T and ρ in asymmetric matter [8]. Very surprisingly, the method based on quantum fluctuations [8] gives values of T and ρ very similar to those obtained using the double ratio method and coalescence and gives a good determination of the critical exponent β. This stresses the question on why sometimes different methods give different values, including different particles ratios, while in other cases the same values are obtained.

In Ref. [1] the classical temperature derived from QF gave different values for different isotopes. Clearly the Coulomb repulsion of different charged particles can distort the value of the temperature obtained from QF, which depends on kinetic values. Also the obtained values, say of the critical temperature and density, might be influenced by Coulomb as well as by finite size effects. For these reasons, it is highly needed to correct for these effects as best as possible. In Refs. [9, 10] we proposed a method to correct for Coulomb effects in the exit channels related to the emitted charged clusters (Fermions and Bosons respectively). In order to support our findings, we will compare our results to the neutron case, which is of course independent, at least not directly, from the Coulomb force. Of course, neutron distributions and fluctuations are not easily determined experimentally, thus we will base our considerations on theoretical simulations using the CoMD model.

In Fig. 1, we plot T and ρ versus excitation energy per nucleon respectively. As we can see the derived T of protons are much closer to the neutrons. The good agreement for the obtained temperatures suggests that thermal equilibrium in the transverse direction is nearly reached. The modification to the density due to Coulomb is very small which implies that the MFs are not so much affected by Coulomb.

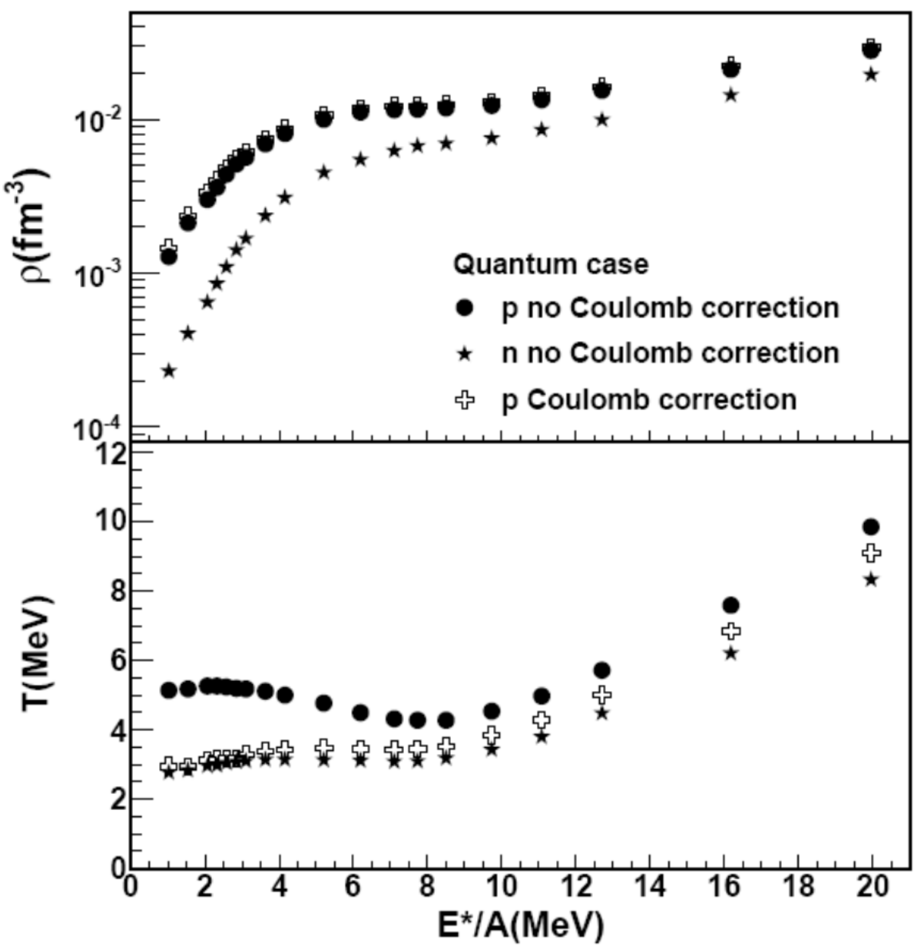

FIG. 1. (Top panel) Densities extracted from CoMD simulated data versus excitation energy per nucleon E*/A. (Bottom panel) Temperatures versus E*/A. Solid circles and solid stars refer to p and n obtained from quantum fluctuations without Coulomb correction respectively; open crosses refer to p-case obtained from quantum fluctuations with Coulomb correction.

In Fig. 2, we plot reduced density $\tilde{\rho} = \rho/\rho_0$ where ρ_0 is the nuclear ground state density and T vs excitation energy respectively obtained from CoMD simulations. The neutron case is also included. As we see the densities derived from d and alpha observables with Coulomb correction are very close to each other and to those derived from the neutron observables. There is a large difference between the cases with Coulomb correction and without Coulomb correction which demonstrates the crucial role of adding the Coulomb repulsion between bosons. For completeness we also include the results for bosons from Landau's O (m^6) approach [4] which is close to the results without Coulomb corrections. The derived T of d and alpha with Coulomb correction are also much closer to the neutron values. The good agreement for the obtained temperatures and densities suggests that thermal equilibrium is nearly reached for particles emitted in the transverse direction, similar to the fermions case.

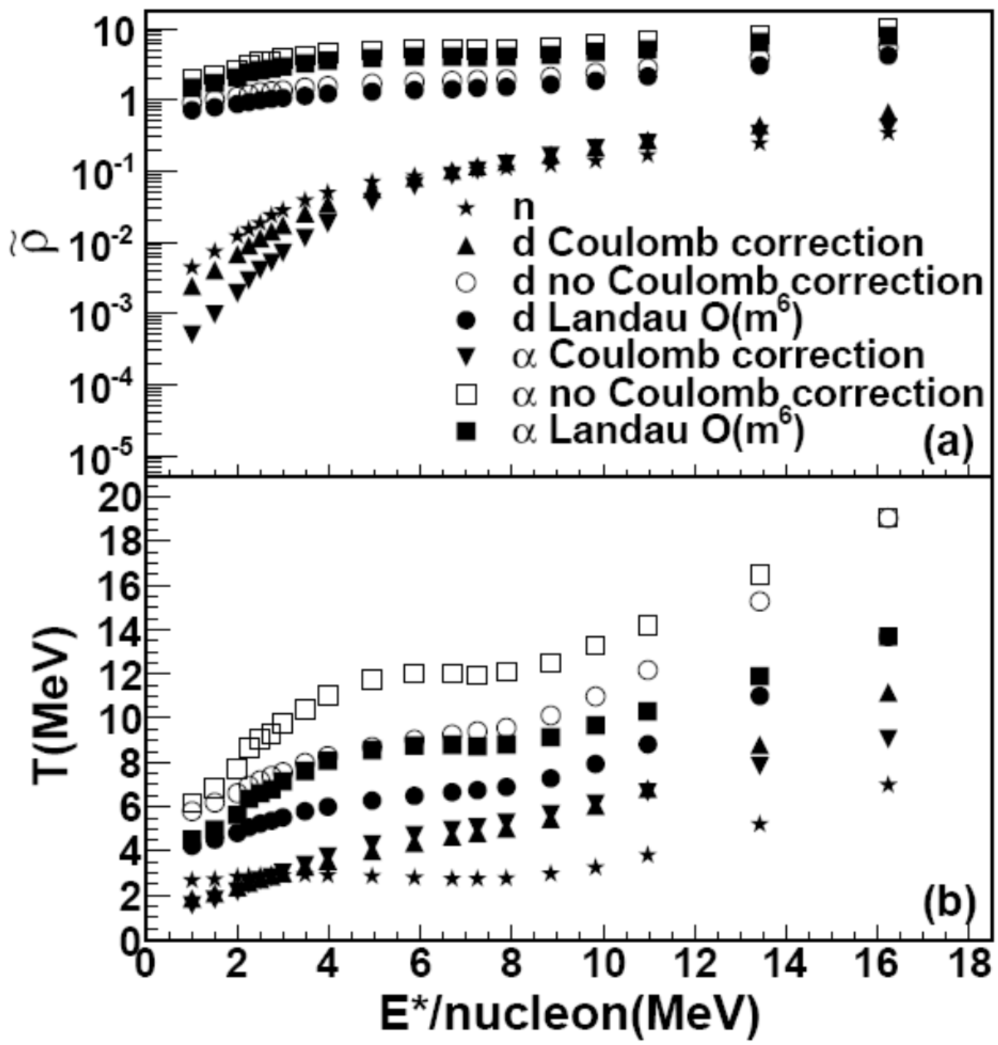

FIG. 2. The reduced density (a) and temperature (b) versus E*/nucleon of d and alpha from CoMD simulations. Three methods, with Coulomb correction, without Coulomb correction and Landau's O(m^6) theory, are used to calculate the density and temperature. The corresponding results for neutrons are also included as a reference.

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