Temperature Measurements in Central Collisions

M.B. Tsang and H.F. Xi

National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824, USA

At incident energies in excess of about E/A=50 MeV, a rapid collective expansion of the combined system may occur during the later stages of a central collision between heavy nuclei. The emission of the observed particle species occurs after initial overlap and before the density of the system passes below about 0.1ρ∞, corresponding to an expansion rate dependent on the total emission time which is less than 100 fm/c. The short emission times motivate the description of such collisions via dynamical models or via statistical models which assume equilibrium at a single breakup density and temperature. This latter class of models includes bulk multifragmentation models such as the Statistical Multifragmentation Model (SMM) which displays a phase transition in sub-saturation density [1]. Calculations predict enhanced heat capacities for finite nuclear systems at temperatures of the order of 4-6 MeV due to the transformation from the Fermi liquid which can be found in the interior of large nuclei in their ground and low excited states to a gas phase consisting of free nucleons and light clusters.

Temperatures extracted from the isotopic abundances of helium and lithium fragments [2] produced by the fragmentation of Au projectiles display a "caloric curve" consistent with the hypothesis of a mixed phase equilibrium. Temperatures for hot nuclear systems formed in nucleus-nucleus collisions have been extracted from ratios of isotopic yields, Tiso, and excited state populations, TAE [3,4].

While consistent values of Tiso and TAE, have been obtained for central Au+Au collisions at incident energies E/A ≤ 50 MeV [3,4], temperatures from the two methods diverge for E/A>50 MeV. Values for Tiso(He, Li) using yields of 3,4He and 5,7Li isotopes increase with incident energy but values for TAE using yields of highly excited states of 4He, 5Li and 8Be nuclei do not [4]. This discrepancy has been argued to be the result of a suppression of the numbers of highly excited fragments within the disintegrating nuclear medium [5] which would lower the values of TAE. On the other hand, as the most common method to extract TAE relies on the isotopic yield ratios of ( 3He, 4He), early emission of 3He [5] could elevate the Y(3He)/Y(4He) ratio and raise the values of TAE.

In the present work, we determine Tiso and TAE in Kr + Nb and Ar+Sc central collision from E/A=35 to 150 MeV. Details of the experiment can be found in ref. [6]. In the left panel of Fig. 1, we present temperatures TAE obtained from the relative populations of
widely separated states in emitted \(^4\text{He}\), \(^5\text{Li}\) and \(^8\text{Be}\) nuclei. Extracted values of \(T_{\Delta E}\) are plotted as a function of incident energy. The extracted temperatures \(T_{\Delta E}\) are of the order of 4 MeV and show little variation with incident energy, a trend also observed for central Au+Au collisions [4].

Fig 1: Dependence of \(T_{\text{iso}}\) (left panel) and \(T_{\Delta E}\) (right panel) upon the incident energy.

Fig. 2: Differential Multiplicities for \(d, t, ^3\text{He}\), \(^\alpha\) particles. Closed circles are data and solid lines are predictions from SMM model (see text).

Values of \(T_{\text{iso}}\) were also obtained over the range of incident energies shown in the right hand panel of figure 1. Values for \(T_{\text{iso}}(\text{CLi})\) (closed circles) obtained from the yields of \(^6\text{Li}\) and \(^{11,12}\text{C}\) vary little with incident energy, similar to the trends exhibited by the temperatures \(T_{\Delta E}(\text{Li})\), \(T_{\Delta E}(\text{He})\), and \(T_{\Delta E}(\text{Be})\) extracted from excited states populations shown in the left panel. In contrast, values of \(T_{\text{iso}}(\text{He-Li})\) (closed squares) obtained from the yields of \(^6,7\text{Li}\) and \(^3,4\text{He}\) isotopes increase monotonically with incident or excitation energy [4].

Some corrections to the measured apparent temperatures can be expected due to the secondary decay of heavier isotopes that feed the isotope yields used to extract \(T_{\text{iso}}\)[3]. Secondary decay calculations, however, predict the corrections to be relatively small for apparent temperatures of the order of 4.5 MeV [3,7]. Moreover, the secondary decay corrections to \(T_{\Delta E}(\text{He})\) and \(T_{\text{iso}}(\text{He-Li})\) should be nearly identical for all source temperatures [8] because both are affected primarily by the feeding contributions to the ground state yield of \(^4\text{He}\). Thus the discrepancies observed between different thermometers cannot be explained by secondary decays.

In ref. [9], high values for \(T_{\text{iso}}(\text{He-Li})\) and low values for \(T_{\Delta E}(\text{Li})\) have been predicted within a common statistical framework by assuming that the radius of the unstable \(T_{\Delta E}(\text{Li})\) nuclei is equal to the sum of radii of its decay products whereby excited \(^5\text{Li}\) nuclei are 3.1
times larger in volume than ground state $^5\text{Li}$ nuclei. The yield of excited $^5\text{Li}^*$ is consequently suppressed due to the constraint that its size imposes upon the size of the remaining system. In contrast, the volume of $^8\text{Be}^*(17.6 \text{ MeV})$ is 0.95 times the volume of $^8\text{Be}^*(3 \text{ MeV})$. Since the radii of $^8\text{Be}^*(17.6 \text{ MeV})$ and $^8\text{Be}^*(3 \text{ MeV})$ are nearly the same, $T_{\Delta E}(^8\text{Be})$ should not be suppressed. The expected values for $T_{\Delta E}(^8\text{Be})$ should therefore be much higher than the observed values for $T_{\Delta E}(^5\text{Li})$ at high incident energies - an effect not observed experimentally. Thus the method described in ref. [9] to reconcile excited state and isotope temperatures is not supported by the present data.

The overall picture provided by the present data suggests that the temperatures deduced from the $^3\text{He}$ yields are inconsistent with all other cases investigated. This discrepancy may reflect differences in the emission environments of $^3\text{He}$ as compared to the emission environments for fragments and alpha particles.

To investigate this possibility, we consider how well the experimental observed light cluster multiplicities can be self consistently described within a statistical model assuming a single freezeout picture. The data points in Fig. 2 show the observed multiplicity $dM/d\Omega_{\text{CM}}$ at $\theta_{\text{CM}} = 90^\circ$ for $^2\text{d}$, $^2\text{t}$, $^3\text{He}$ and $^4\text{He}$ particles. Consistent with the trends deduced from inclusive data, the extracted $^2\text{d}$, $^2\text{t}$ and $^3\text{He}$ multiplicities increase with beam energy over this energy range while multiplicity of $^4\text{He}$ remains approximately constant.

The solid lines in Fig. 2 shows the corresponding calculated multiplicities of deuterons, tritons, $^3\text{He}$'s and $^4\text{He}$'s as a function of incident energy using the Statistical Multifragmentation Model (SMM) which has been widely used to describe the emission of intermediate mass fragments (IMF's) at intermediate energies. In a typical SMM calculation, the emission of light particles and IMF's is calculated by assuming an equilibrated breakup configuration at density of about 1/3 to 1/6 saturation nuclear density. Some reductions in the size and excitation energy of the equilibrated system below the values characteristic of the total system in its center of mass are frequently assumed in such calculations to account for the mass and energy removed by non-equilibrium emission prior to breakup. We adjust the excitation energy of the source to reproduce the previously measured IMF charge distribution and adjust the source nucleon number to reproduce the previously measured IMF multiplicity. We further assumed values for the radial flow velocity given by the systematics of ref [10].

For $^4\text{He}$ particles, the calculated and measured multiplicities are in relatively close agreement above 70 MeV. In contrast, the calculated multiplicities of deuterons, tritons, and $^3\text{He}$ particles are only about half of the yields observed experimentally. To achieve consistency with the SMM model predictions, one must assume that the remainder of the deuteron, triton, and $^3\text{He}$ yields are emitted prior to the freeze-out stage for which the $^4\text{He}$ and IMF yields can be simultaneously modeled by the SMM. This interpretation is also consistent with the assumption of a source size for central collisions which is only about 50% of the size of the total system.
This suggests a hierarchy of emission time scales in which light particles are emitted earlier than heavy fragments. Investigations of fragment-fragment correlations [11] and fragment charge distributions have reported evidence for a hierarchy of time scales whereby light particle emission precedes fragment emission rendering the two processes out of equilibrium. Such a hierarchy is qualitatively consistent with the expectations of rate equation models based upon decay rates derived from detailed balance [12]. The result is also consistent with the Boltzmann Uehling Uhlenbeck (BUU) equation, obtained using the numerical code and cluster production mechanics[13]. The precise degree to which light particle emission during the early stages of the collision is further enhanced by statistical emission of predominantly light particles at very high initial temperature depends on the time scale for thermalization and requires further experimental and theoretical investigations. Qualitatively, however, both effects will cause a divergence of temperatures derived from poorly bound light particles such as d, t, \(^{3}\)He from those derived from strongly bound fragments such as \(^{4}\)He, \(^{12}\)C nuclei observed in the present work. As \(^{3}\)He and \(\alpha\) particles are emitted at different times, they should not be used in the isotope thermometer measurements.

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REFERENCES: