Using light charged particles to probe the asymmetry dependence of the caloric curve

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The nuclear equation of state (EoS) relates the thermodynamic parameters of the nuclear system: temperature, density, pressure, excitation energy, mass and asymmetry. The EoS directly impacts the physics of heavy ion reactions at all energies, nuclear structure (e.g., collective excitation), the processes at play in supernova explosions (including supernova nucleosynthesis), and many properties of neutron stars. Typically, the equation of state is investigated by examining the correlation between two thermodynamic parameters. Here, we study how the relation between temperature and excitation energy per nucleon depends on the neutron-proton asymmetry.

Excited quasi-projectile (QP) sources are isotopically reconstructed using charged particles and free neutrons measured with the TAMU NIMROD-ISiS array for collisions of ^{70}Zn+^{70}Zn, ^{64}Zn+^{64}Zn, and ^{64}Ni+^{64}Ni at E = 35MeV/nucleon. Equilibrated QP sources are selected by means of three successive cuts on particle and event characteristics (see [1, 2] and references therein). The largest uncertainty in the composition of the QP, and also in its excitation energy, arises from the free neutron measurement. Detailed simulations of the TAMU Neutron Ball have been performed [3]. The efficiencies are found not to depend on the model employed nor the neutron excess of the system under study. We have carefully analyzed the impact of the efficiency and the background signals in the Neutron Ball. Combined, these sources of uncertainty introduce an 11% uncertainty in neutron multiplicity. This corresponds to an uncertainty of 0.11MeV in excitation energy, and a maximum uncertainty of only up to 0.02 units in asymmetry (N-Z)/A. Our results below are robust with respect to these uncertainties.

The temperature of the QP is extracted using the momentum quadrupole fluctuation MQF thermometer [4], using five independent light charged particles (LCP) as probes (protons, deuterons, tritons, helions, and α-particles). The caloric curves are extracted for narrow selections in the neutron-proton asymmetry of the source, $m_s=(N_s-Z_s)/A_s$. These curves are shown in the top row of Fig. 1. With increasing asymmetry, the caloric curve shifts to lower temperatures. This is observed across all excitation energies for all MQF probes of the temperature. The magnitude of the shift is on the order of 1MeV between the two most extreme m_s bins. In the lower row of Fig. 1, the temperature difference is plotted between each curve and the central curve ($0.12<m_s<0.16$), used as a reference. This difference shows no dependence on excitation, with the exception of the small trend for alpha particles at low excitation. Also of note is the ordering of the caloric curves by particle type: protons and alphas have the lowest temperatures, followed by deuterons, tritons, and helions. Protons and alphas are relatively cheap to emit (Q~10MeV), deuterons more expensive (Q~15), and tritons and helions are the most expensive (Q~20). This temperature ordering observed is consistent with an emission-time-ordering of the particles due to their Q-value of emission.

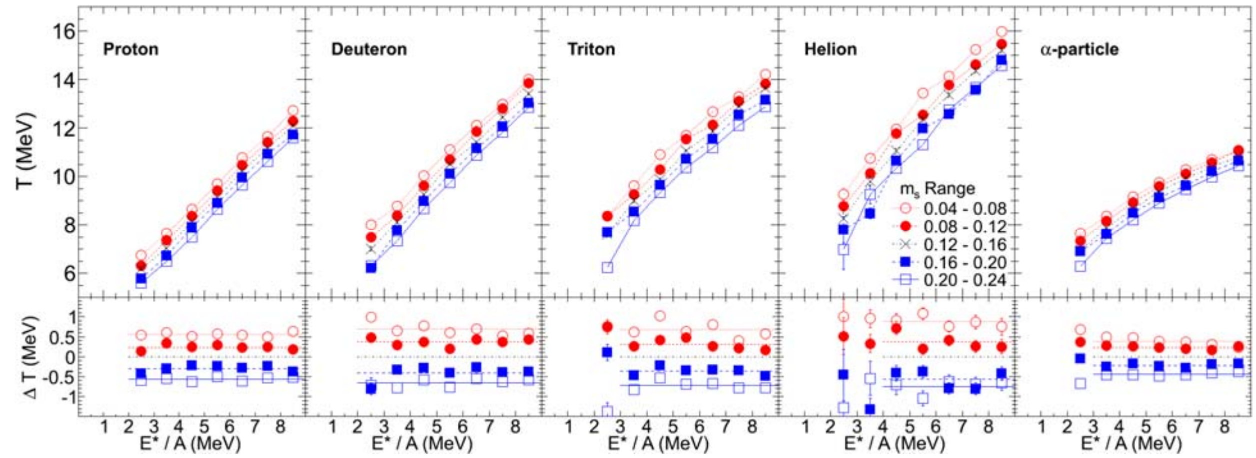

FIG. 1. (Top Row) Caloric curves for light charged particles, selected on source asymmetry (m_s=(N-Z)/A). (Bottom Row) Temperature difference between each caloric curve and the middle caloric curve ($0.12 \leq m_s \leq 0.16$), which is used as a reference. The horizontal lines correspond to the average difference over the indicated range in excitation. Error bars represent statistical uncertainties.

To be more quantitative about the asymmetry dependence of the caloric curve, we examine the decrease in temperature ΔT that occurs for a given increase in asymmetry Δm_s. To obtain this, we construct the difference between every pair of m_s-selected curves (10 total, for 5 curves). We have already seen that ΔT is essentially independent of excitation (Fig. 1, lower row). The excitation-averaged ΔT is linear as a function of Δm_s. This is true for all 7 probes of the temperature (5 MQF, and 2 Albergo).

The slopes of the $\Delta T/\Delta m_s$ correlations for the MQF thermometer follow an ordering. From smallest to largest they are ordered α, p, d, t, h. This ordering is reminiscent of the ordering of the temperatures seen in Fig. 1. This is consistent with an emission-time ordering scenario, where the composition of the QP must change with each particle emission. Thus the particles that are emitted early (high Q-value helions and tritons) are sensitive to the initial asymmetry of the QP, which we deduce. The particles emitted later on average (the low Q-value protons and alphas) are sensitive to the asymmetry at the time of their emission, which has changed somewhat from the deduced, initial value. If these two observations - the ordering of the temperatures and the ordering of the $\Delta T/\Delta m_s$ correlations - have a common origin as discussed, there should be a scaling. Therefore we examine in Fig. 2 the $\Delta T/\langle T\rangle$ vs Δm_s. The data for the MQF p, d, t, h collapse onto a single line. This suggests that we are sensitive to the emission-time ordering of the LCPs. The alphas do not quite follow this scaling, which may indicate differences in the production mechanism of alphas as compared to the other LCPs, such as production from regions of different density, or differences in coalescence. The correlations corresponding to the Albergo temperatures also do not scale to the other curves. This may be a manifestation of the differences in the methods (chemical vs kinetic) used to extract the temperature, and the fact that the Albergo temperature relies on multiple particle species which precludes conclusions about sensitivity to differences in the emission time for this thermometer.

In summary, we have reported a clear dependence of the nuclear caloric curve on the neutron-proton asymmetry. The dependence is observed for five probes of the temperature using the MQF thermometer. A sensitivity of the average emission order is observed in the temperatures and in the magnitude of the asymmetry dependence. These two quantities exhibit a scaling. The observation is enabled by the excellent resolution and 4π character of the TAMU NIMROD-ISiS array which allows isotopic reconstruction of the excited quasi-projectiles.

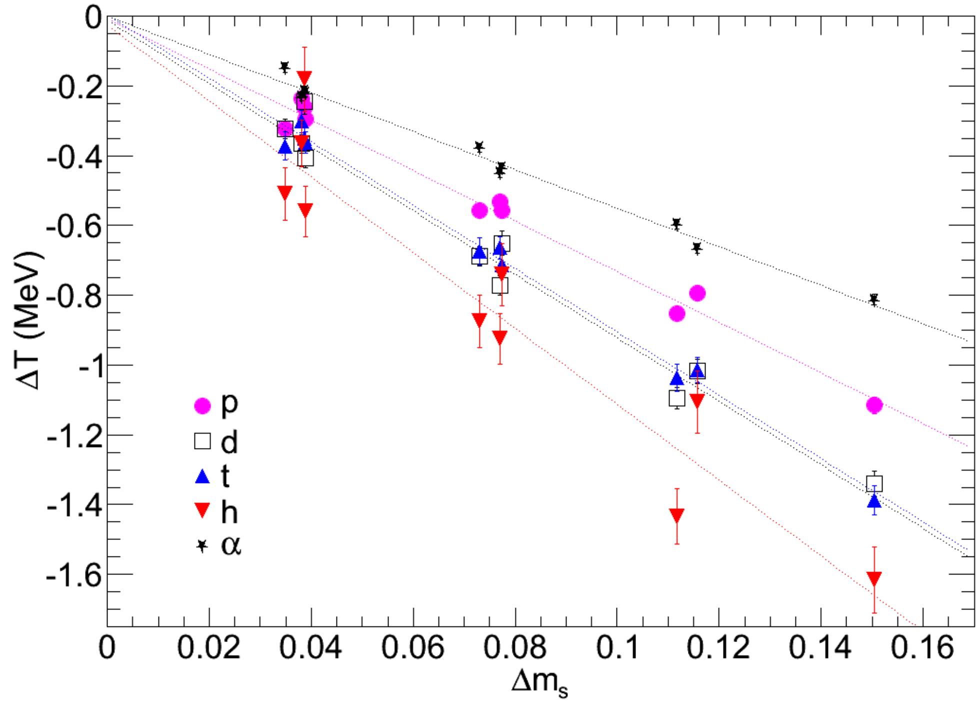

FIG. 2. Scaled change in temperature $\Delta T/\langle T\rangle$ with changing asymmetry Δm_s.

[1] A.B. McIntosh *et al.,* Phys. Lett. B **719**, 337 (2013).

[2] A.B. McIntosh *et al.*, Phys. Rev. C **87**, 034617 (2013).

[3] P. Marini *et al.*, Nucl. Instrum. Methods Phys. Res. **A707**, 80 (2013).

[4] H. Zheng and A. Bonasera. Phys. Lett. B **696**, 178 (2011).