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Asymmetry dependence of the nuclear caloric curve

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ABSTRACT

A basic feature of the nuclear equation of state is not yet understood: the dependence of the nuclear caloric curve on the neutron–proton asymmetry. Predictions of theoretical models differ on the magnitude and even the sign of this dependence. In this work, the nuclear caloric curve is examined for fully reconstructed quasi-projectiles around mass $A = 50$. The caloric curve extracted with the momentum quadrupole fluctuation thermometer shows that the temperature varies linearly with quasi-projectile asymmetry $\frac{N-Z}{A}$. An increase in asymmetry of 0.15 units corresponds to a decrease in temperature on the order of 1 MeV. These results also highlight the importance of a full quasi-projectile reconstruction in the study of thermodynamic properties of hot nuclei.

1. Introduction

The relation between the temperature and the excitation energy of a system (the caloric curve) is of fundamental importance in a wide variety of physical systems. Since the application of the concept of a caloric curve to atomic nuclei [1,2], several "thermometers" have been used to elucidate properties of excited nuclei including the transition from evaporative-type decay to nuclear multifragmentation (see [3,4], and references therein). Recently, a clear mass-dependence of the caloric curve for finite nuclei has been demonstrated [5].

The dependence of the nuclear caloric curve on the neutron/proton asymmetry, $\frac{N-Z}{A}$, remains uncertain due to conflicting predictions from theoretical calculations and the relatively small body of experimental data on the subject. Some theoretical approaches predict that critical temperatures or limiting temperatures would be higher for neutron-poor systems [6,7]; others predict higher temperatures for neutron-rich systems [8–10]. Inclusion (or intentional omission) of a "gas" phase that interacts with the bulk system is expected to impact the asymmetry dependence of the temperature of the bulk system [7,8]. The observation of an asymmetry dependence may support the physical picture of a nuclear liquid interacting with its vapor [7], or may allow insight into the driving force of nuclear disassembly [11]. Studies in recent years [12–14] have sought to probe the asymmetry energy in the nuclear equation of state by examining the fragments produced in heavy-ion reactions. Since these studies often assume the temperature is independent of the asymmetry, observation and characterization of an asymmetry-dependence of the caloric curve would allow a refined interpretation of fragment yield data (e.g. in the statistical interpretation of isoscaling). Moreover, characterization of this asymmetry dependence may offer the opportunity to probe the asymmetry energy in a new way; this is discussed below. Experimentally, temperatures have shown either a small dependence [11,15] or no discernible dependence [16,17] on the asymmetry of the initial system.

Motivation for an asymmetry dependence of the nuclear temperature may be seen in the following argument based on Landau theory [18–20]. We consider a fragmenting nuclear source, and write the free energy per nucleon of each fragment produced by the source as

$$\left(\frac{F}{A}\right)_f = \left(\frac{F}{A}\right)_{f,0} + Hm_f + V_c Z_s Z_f + \frac{3}{2}T \quad (1)$$

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where $(\frac{F}{A})_{f,0}$ is the free energy per nucleon of the fragment in isolation and T is the temperature of the system. The asymmetry of the fragment $m_f = \frac{N_f - Z_f}{A_f}$ increases the free energy in proportion to H, the conjugate variable of m_f [20,21]. The quantity $H = c_{asy} m_s$ is the asymmetry field due to the source where c_{asy} is the asymmetry energy coefficient in the nuclear equation of state and $m_s = \frac{N_s - Z_s}{A_s}$ is the asymmetry of the source [19]. The Coulomb interaction between the charged fragment of interest (Z_f) and the remainder of the source (Z_s) is described by the V_c term. Consider two identical fragments produced from two sources with the same mass and excitation energy but different asymmetry. Taking the difference in the free energy for these two fragments, $(\frac{F}{A})_{f,0}$ cancels exactly. This gives a linear dependence of temperature on the source asymmetry:

$$\Delta T = \Delta m_s\left(\frac{1}{3}V_c A_s Z_f - \frac{2}{3}m_f c_{asy}\right) + \frac{2}{3}\Delta\left(\frac{F}{A}\right)_f. \qquad (2)$$

In the present work, we demonstrate such an asymmetry dependence of nuclear temperatures exists.

2. Experiment and event selection

To investigate the dependence of the nuclear caloric curve on asymmetry, heavy-ion collisions at intermediate energy were studied. Charged particles and free neutrons produced in reactions of ^{70}Zn + ^{70}Zn, ^{64}Zn + ^{64}Zn, and ^{64}Ni + ^{64}Ni at $E/A = 35$ MeV [22,23] were measured with excellent isotopic resolution in the NIMROD-ISiS 4π detector array [17,24]. The quasi-projectile (QP, the primary excited fragment that exists momentarily after a non-central collision) was reconstructed, including determination of the QP *composition* (both A and Z). Excitation energies above $E^*/A = 2$ MeV are well measured with this setup.

We employ a model which deduces the number of free neutrons emitted by the QP from the measured number of total neutrons, background, and the efficiencies for measuring neutrons produced from QP and QT (quasi-target) sources [25]. The uncertainty in the composition arises mainly from the free neutron measurement, which arises from the efficiency (70%) of the neutron detector; the background in the neutron detector was measured online and contributes a negligible amount to the uncertainty. The efficiency of the detector was investigated through detailed simulations [25,26]. The efficiency increases the width of the "true" QP neutron distribution of at most 9% (at the highest excitation energies). Therefore, the "true" distribution is only modestly perturbed by the efficiency. The excitation energy was deduced using the charged particle kinetic energies, the Q-value of the breakup, the measured free neutron multiplicity, and the average neutron kinetic energy. The average neutron kinetic energy is determined using the Coulomb-shifted proton energy distribution; as a check, the Coulomb shift provides a good transformation between the ^{3}H and ^{3}He energy distributions. We have investigated the magnitude of the autocorrelation between the neutron contribution to the excitation energy and the observed asymmetry dependence of the caloric curve. The asymmetry dependence is robust for any physically reasonable values of neutron average kinetic energy and neutron multiplicity. The uncertainty in the neutron measurement does not impact the QP composition or excitation enough to significantly bias the results presented in this Letter.

Building on previous work [14,16,17,27], three cuts are made to select equilibrated QP sources. To exclude fragments that clearly do not originate from an equilibrated QP source, the fragment velocity in the beam direction v_z, relative to the velocity of the heavy residue $v_{z,PLF}$, is restricted. The accepted window on $\frac{v_z}{v_{z,PLF}}$ is 1 ± 0.65 for $Z = 1$, 1 ± 0.60 for $Z = 2$, and 1 ± 0.45 for $Z \geqslant 3$. The mass of the reconstructed QP is required to be $48 \leqslant A \leqslant 52$. To select QPs that are equilibrated, it is required that the QP be on average spherical. This is achieved with a selection on the longitudinal momenta p_z and transverse momenta p_t of the fragments comprising the QP: $-0.3 \leqslant \log_{10}(Q_{shape}) \leqslant 0.3$ where $Q_{shape} = \frac{\sum p_z^2}{\sum \frac{1}{2} p_t^2}$ with the sums extending over all fragments of the QP. Since the shape degree of freedom is slow to equilibrate, these QPs that are on-average spherical should be thermally equilibrated. Over the range of excitation energies presented in this work, the typical QP is comprised of one large fragment, several light particles ($Z \leqslant 2$) and one IMF ($3 \leqslant Z \leqslant 8$).

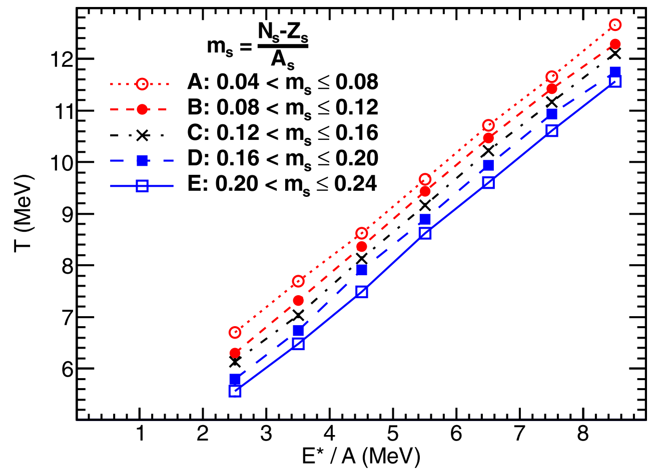

Fig. 1. (Color online.) Caloric curves for isotopically reconstructed sources with mass $48 \leqslant A \leqslant 52$, extracted with the momentum quadrupole fluctuation method. Each curve corresponds to a narrow range in source asymmetry, m_s.

The temperatures of the QPs are calculated with the momentum quadrupole fluctuation method [28], which has been previously used to examine temperatures of nuclei [16,17,29–32]. The momentum quadrupole is defined as $Q_{xy} = p_x^2 - p_y^2$ using the transverse components p_x and p_y of the particle's momentum in the frame of the QP source. Assuming a Maxwell–Boltzmann distribution, the variance of Q_{xy} is related to the temperature by $\langle\sigma_{xy}^2\rangle = 4m^2T^2$ where m is the probe particle mass [16,28]. For this analysis, protons, which are abundantly produced in the collisions, are used as the probe. Since p_z is potentially impacted by the velocity cut which was imposed to exclude fragments which do not originate from an equilibrated QP source, we make use of only the transverse components in the determination of the temperature and excitation. The effects of secondary decay on this thermometer should be small [16]: the thermal energy in the primary clusters is significantly less than that in the QP, so the width of the momentum quadrupole is dominated by the QP breakup.

3. Results and discussion

Fig. 1 shows the temperature as a function of excitation energy per nucleon (E^*/A) of the QP as determined with the momentum quadrupole fluctuation thermometer using protons as the probe particle. Data points are plotted for 1 MeV-wide bins in excitation energy per nucleon. For clarity, the points are connected with lines to guide the eye. The error bars correspond to the statistical uncertainty and where not visible are smaller than the points. The temperature shows a monotonic increase with excitation energy. At $E^*/A = 2.5$ MeV, the temperatures are around 6 MeV; by $E^*/A = 8.5$ MeV, the temperatures have risen to around 12 MeV. Each curve corresponds to a narrow selection in the asymmetry of the source, $m_s = \frac{N_s - Z_s}{A_s}$, as indicated in the legend. The average