The nuclear caloric curve: Temperatures of simulated quasiprojectiles

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The equation of state describes the emergent physical properties of matter. Experimental data is needed to help constrain the equation of state for nuclear matter. These constraints can help determine between a “ays-stiff” and a “ays-soft” equation of state, which has important astrophysical implications. For example, the proton-neutron makeup of neutron stars, and thus the cooling of neutron stars by the direct Urca process[1]. How temperature and the asymmetry of the nuclear matter interact has important implications for the strength of the asymmetry term.

The physical experimental data was taken on NIMROD (Neutron Ion Multidetector for Reaction Oriented Dynamics) [2]. The experiment ran a number of systems, ^{70}Zn+^{70}Zn , ^{64}Ni+^{64}Ni, and ^{64}Zn+^{64}Zn at 35 MeV/u [3]. The charged particles produced in these reactions were detected, along with the neutron multiplicity.

These runs proved to be a rich data set, which was analyzed to determine temperatures of the reconstructed quasiprojectiles(QP) [4]. As seen in Fig. 1, the temperatures increase as expected with excitation energy per nucleon. However, when the Quasi-projectile’s asymmetry was used to further separate the data, a clear trend was observed. As the asymmetry of the quasi projectile increased the temperature as a function of excitation energy is shifted to lower temperature. This trend proved to be robust for multiple temperature probes using both momentum quadrupole fluctuations (kinetic) and the Albergo chemical thermometer. This phenomenon is consistent with the thermal Thomas-Fermi model.

The purpose of this research is to use antisymmetrized molecular dynamics (AMD) [5] coupled

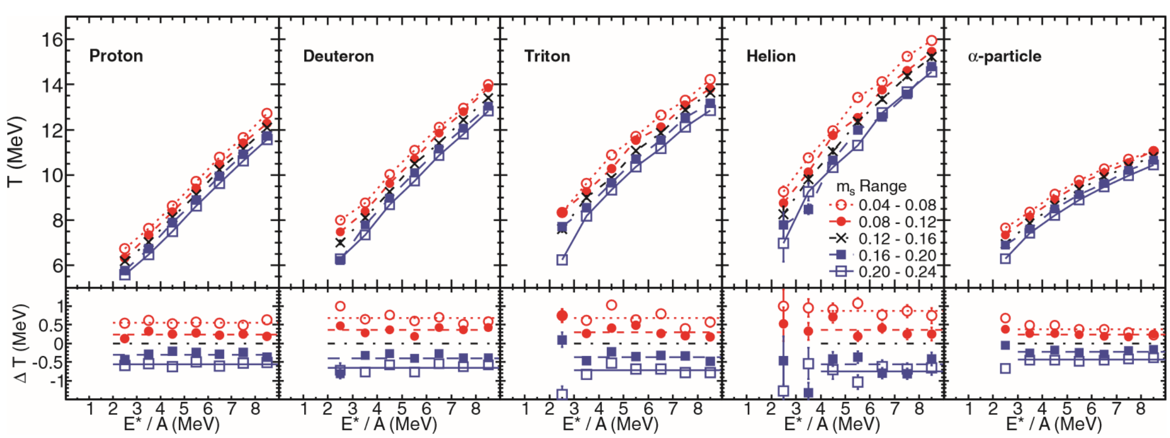

FIG. 1. Temperatures calculated as a function of excitation energy per nucleon. The different asymmetry values of the quasiprojectile(QP) are shown with different colors and marking according to the legends. The temperatures were determined by momentum quadrupole method. The temperature probes used are indicated on the top left of each curve. Taken from reference[4].

to GEMINI afterburner [6,7] to reproduce the trends seen with the experimental data. Once this is achieved, the effects of the imperfect nature of NIMROD can be removed, to see if the trend is preserved. Additionally, further alterations to the assumptions made in the model could be used to explore how the asymmetry interacts with this affect. The focus of this analysis was on the $^{70}Zn+^{70}Zn$ system, as it was the data set with the most statistics. 10000 AMD-DS events where run by Z. Kohley to a time of 300fm/c, afterwards Gemini was used to deexcite the nuclides, with each AMD event used as a starting point for Gemini 20 times[3]. These events where then subjected to the same event selection cuts used to select the experimental data. First, these events were run through the NIMROD filter, in order to mimic the detector effects. The first gate was that the parallel velocity of the particle detected must be within a certain range of the projectile like fragment (PLF) (the largest fragment detected). This is done to remove particles that are more likely to have been emitted from the excited target like fragment (too little parallel velocity), and fast pre-equilirium particles (too much parallel velocity). The velocity conditions depend on the Z of the particle detected. For hydrogen particles the ratio range was from 35% to 165% of the PLF parallel velocity. Helium particles range was from 40% to 160% and for all other charged particles the range was 55% to 145%. Those particles that pass this condition where then combined with the neutrons detected from the neutron ball to reconstruct the quasi projectile. The event was only used for further analysis if the quasi projectile had a mass number between 48 and 52. The QP velocity could then be calculated from the momentum and masses of the particles emitted from it.

As seen in Fig. 2, the projectile appears aligned with the direction of the beam as expected for a

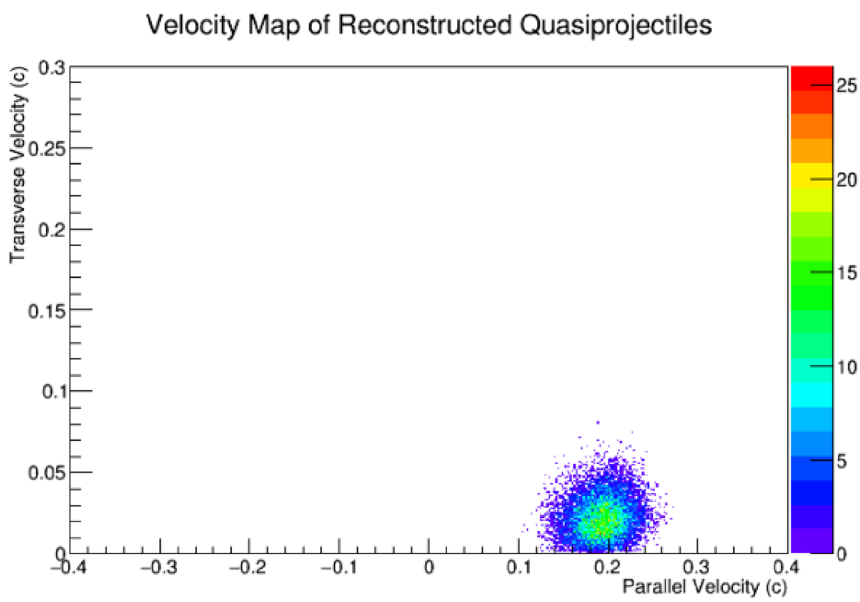

FIG. 2. The velocity map for the reconstructed QP. The velocity map for the reconstructed QP. The velocity in the transverse direction is plotted on y axis, it is an absolute value as it is taken from the vector addition of the velocity in the x direction and the y direction. The parallel velocity is plotted on the x axis. All the velocities are in unit c. This is plot is with the velocity cut and mass cut.

heavy fragment produced by the projectile. This fact suggests that the cuts give a reasonable reconstruction of the quasi projectile.

Once this was done the momentum quadrupole moment (Q) was calculated in the quasi projectile frame in order to gate on the sphericity of the particle emission.

$$Q = \frac{\Sigma p_{Z,i}^{2}}{\frac{1}{2}\Sigma p_{T,i}^{2}} \qquad (1)$$

Where $p_{Z,i}^2$ is the momentum parallel to the beam in the QP frame of reference and $p_{T,i}^2$ is the momentum in the transverse direction.

In Fig. 3, a comparison between the sphericities of the simulated and the physical events is made. As shown in the figure on the right the sphericity cut is between log10(Q) values of -.3 and .3. These constraints gate on roughly spherical decompositions. Gating on the spherical events selects for thermally equilibrated QPs.

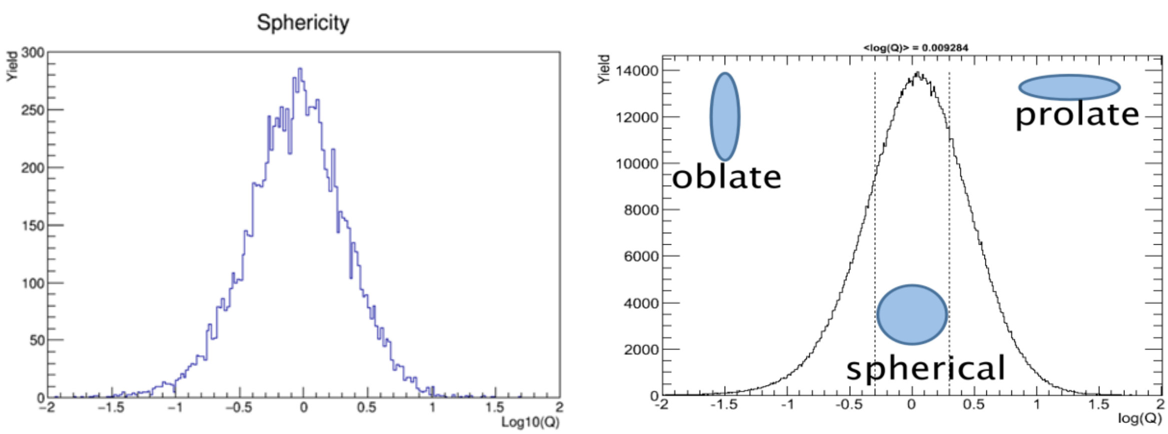

FIG. 3. On the left: the log of the momentum quadrupole for the events that pass both the nimrod filter, the velocity cut, and the mass cut is plotted for the simulated events. On the right: The analogous plot using the physical data, taken from reference[8]. While the statistics are lower than for the experimental data, the general shape is preserved. There is a however a slight tendency for more oblate momentum quadrupole moments than in the experiment data.

With the basic cuts and QP reconstruction now working the next step is to correctly reconstruct the excitation energy of the QP. Afterwards temperatures will be extracted from the momentum quadruple fluctuation method and slope method. Further statistics may also be necessary, especially for probes that use rarer particles.

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