Temperature Measurements in Low Excitation Energy Reactions to Probe a Possible Phase Transition

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Abstract. Several methods have been used to determine the temperatures of systems formed in multifragmentation reactions. From these temperatures, caloric curves can be constructed and possible nuclear phase transitions can be explored. This work presents a previously observed, low temperature phase transition predicted by a theoretical simulation, and an experimental proposal to observe this transition. The proposed experiment will explore what types of reactions produce fragments near the phase transition temperature, and expand the range of fragments that can be detected in this low temperature region.

1. Introduction
Improved measurements of the temperature of systems formed in multifragmentation reactions has advanced the understanding of nuclear phase transitions. Plotting the temperature versus excitation energy produces a caloric curve [1]. Flattening, or backbending, in this caloric curve is a signature of a phase transition [2, 3]. Phase transitions observed from these caloric curves can aid in understanding how a system will fragment and describes some of the fundamental properties of nuclei [4]. This work will provide a way to observe a phase transition signature that has been predicted in models at low temperature by using a new detector arrangement that bridges a large range of relevant excitation energies.

2. Temperature and Density
A recently developed quadrupole momentum fluctuation thermometer [5, 6] has been used to derive nuclear temperatures, especially at low excitation energy. This thermometer is based on the quantum fluctuation of fermions and is derived using a Fermi-Dirac distribution. This differs from the classical quadrupole momentum fluctuation thermometer [7] which uses a Maxwell-Boltzmann distribution. The quantum thermometer has been applied to results from Constrained Molecular Dynamics (CoMD) [8] simulations of \(^{40}\text{Ca}+^{40}\text{Ca}\) and \(^{16}\text{O}+^{16}\text{O}\) at energies ranging from 4 MeV per nucleon to 100 MeV per nucleon at a fixed impact parameter of 1 fm [5] and to experimental results from the reaction of \(^{32}\text{S}+^{112}\text{Sn}\) at 45 MeV per nucleon.
detected in the Forward Array Using Silicon Technology (FAUST) \cite{9, 10}. To calculate the temperatures using these thermometers, a quasi-projectile (QP) must be reconstructed from the detected fragments. The QP is a spherical source with a charge and mass similar to the projectile that is reconstructed from the experimental data. From the reconstructed QP, the resulting quantum temperature value that corresponds to various energy densities through the equation

$$\epsilon = \frac{\langle E_{th} \rangle}{A} \rho$$

where \(\epsilon\) is the energy density of the system, \(E_{th}\) is the event excitation energy, \(A\) is the mass of the particle being used to probe the temperature, and \(\rho\) is the density of the system derived from the momentum quadrupole fluctuations and the Fermi energy \cite{9}. Details on the derivation of the temperature and density of a selected QP is given in Refs \cite{5, 6, 9}. The energy density is then plotted as a function of temperature as shown in Figure 1.

In Figure 1, the temperatures above \(3-4\) MeV steadily increase with increasing energy density. Below \(3-4\) MeV, the temperatures remain fairly constant, while the energy density decreases rapidly. This change in the trend of the temperature with energy density is a signature of a phase transition. This transition signature is evident in the \(^{40}\text{Ca} + ^{40}\text{Ca}\) and \(^{16}\text{O} + ^{16}\text{O}\) simulations in the top panel of Figure 1 and may be observed in the \(^{32}\text{S} + ^{112}\text{Sn}\) reaction in the bottom panel of Figure 1. Only one data point exists in this constant temperature region.

At low temperature, statistics are limited in the experimental data due to a lack of detection efficiency of low excitation energy events in FAUST thus limiting the observation of the phase transition in the experimental data.

Excitation energies from the experimental data were recorded down to \(1\) MeV per nucleon. From the excitation energies, the temperature and energy density were calculated to produce Figure 1. The lower limit of the excitation energy determines the lower limit of the calculated temperature, so extending the excitation energy to lower values, and having more statistics at those lower values, would produce the temperature values needed to observe the phase transition. Exploring the properties of these low excitation energy events can further the ability...
to experimentally detect them, and lead to an experimental investigation of the proposed phase transition region.

3. Constrained Molecular Dynamics Simulation
A Constrained Molecular Dynamics (CoMD) simulation of $^{64}\text{Ni}^{+}{^{27}}\text{Al}$ was performed at an energy of 25 MeV per nucleon, using a triangular distribution of impact parameters from 0 to 10 fm, to a time of 3000 fm/c. This reaction is different from the $^{32}\text{S}^{+}{^{112}}\text{Sn}$ reaction above in that it uses inverse kinematics, a smaller system, and a lower energy in order to produce fragments at low excitation energy. In this simulation most of the fragments had less than 3 MeV per nucleon of excitation energy. Because of the inverse kinematics, the fragments were forward focused and most were concentrated over an angular range within 15° of the beam axis. In addition to the excitation energy and angular distribution of the fragments, the charge distribution of the fragments also helps to characterize the event and the determination of the temperature of the QP. Figure 2 shows the charge of the fragments produced with their corresponding angle.

![Figure 2](image)

**Figure 2.** Charge of fragments vs their angle relative to the beam axis for $^{64}\text{Ni}^{+}{^{27}}\text{Al}$ at 25 MeV per nucleon.

At very small angles relative to the beam axis, there is a large concentration of fragments that are of a similar charge to the projectile. These fragments are considered to be projectile-like fragments (PLF) and make up a large portion of the total charge of the reaction. The detection of these PLFs is very important since they are produced at low excitation energies near the phase transition. For the experimental results shown in Figure 1, the mass of the reconstructed QP was required to be equal to the mass of the projectile, meaning that only events where every fragment from the reaction was detected were considered. PLFs that were not detected due to lack of angular coverage were not included in the reconstruction or temperature calculation. Detection of these PLFs is an important step in calculating temperatures at low excitation energy near the phase transition.

4. FAUST- Quadrupole Triplet Setup
The results from the CoMD simulation show that the reaction of $^{64}\text{Ni}^{+}{^{27}}\text{Al}$ at 25 MeV per nucleon produces many fragments at a low angles and similar in size to the projectile. It is important to detect as many particles as possible in these events to accurately reconstruct these events. One way to accomplish this is via the coupling of the FAUST detector array to the quadrupole triplet separator. FAUST detects fragments at larger angles while the triplet detects
fragments at smaller angles. By coupling FAUST to the quadrupole triplet magnet setup we propose to be able to fully detect multifragmentation events over a broad range of excitation energies.

FAUST is comprised of 68 Si-CsI telescopes arranged in 5 square rings projected onto a sphere and has an angular coverage of 71% from 1.64°-2.31°. 90% from 2.31°-33.63°, and 25% from 33.63°-44.85°. The quadrupole triplet is composed of three quadrupole magnets placed one behind another and rotated 45° from each other. It has an angular coverage of 3°, followed by a 2.5 m beam pipe. The triplet will be used to focus fragments onto a Si-Si telescope that will give isotopic resolution via the $\Delta$E-E technique. Two Parallel Plate Avalanche Counters (PPAC) will be placed before and after the triplet in order to determine the time-of-flight of the heavy fragments in order to achieve good isotopic resolution.

The addition of the quadrupole triplet after FAUST provides a way to detect heavy fragments and PLFs that normally pass through the center of the array at small angles. Detection of these heavy fragments should correspond to detection of events with a low excitation energy. This will allow for extension of the temperature calculations shown in Figure 1 to lower temperatures, which can experimentally confirm the phase transition observed in simulation.

5. Conclusion
The FAUST-Triplet setup should allow for detection of fragments resulting from higher excitation energy events normally detected in arrays down to lower excitation energy fragments which can be detected in a separator. The expanded angular coverage and fragment detection of this new detector setup will allow for the probing of a temperature region that has a signature of a phase transition. This setup will also allow for detection of fragments at temperatures and energy densities above and below the phase transition region, allowing for a more complete observation of the phase transition expected around $T = 3$-4 MeV.

Acknowledgements
Thank you to the SJY Research Group, the Cyclotron Institute, and Texas A&M University. Thank you to Aldo Bonasera, and Hua Zheng for use and implementation of CoMD. This work supported by grants from: Department of Energy Grant # DE-FG03-93ER40773, Welch Foundation #A-1266.
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