

## Observed suppression of fermionic fluctuations in heavy-ion reactions

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Recently Zheng and Bonasera have proposed a new temperature and density calculation to be used for nuclear fragmentation studies [1, 2]. This thermometer treats the quantum nature of the system distinguishing it from the classically based methods previously available. The calculation uses the particle quadrupole fluctuations and normalized variance of the particle multiplicity per event to calculate the temperature. Full details of the calculation can be found in the above references. The necessity of a quantum treatment, however, can be shown experimentally through effects on the normalized variance used in the temperature calculation.

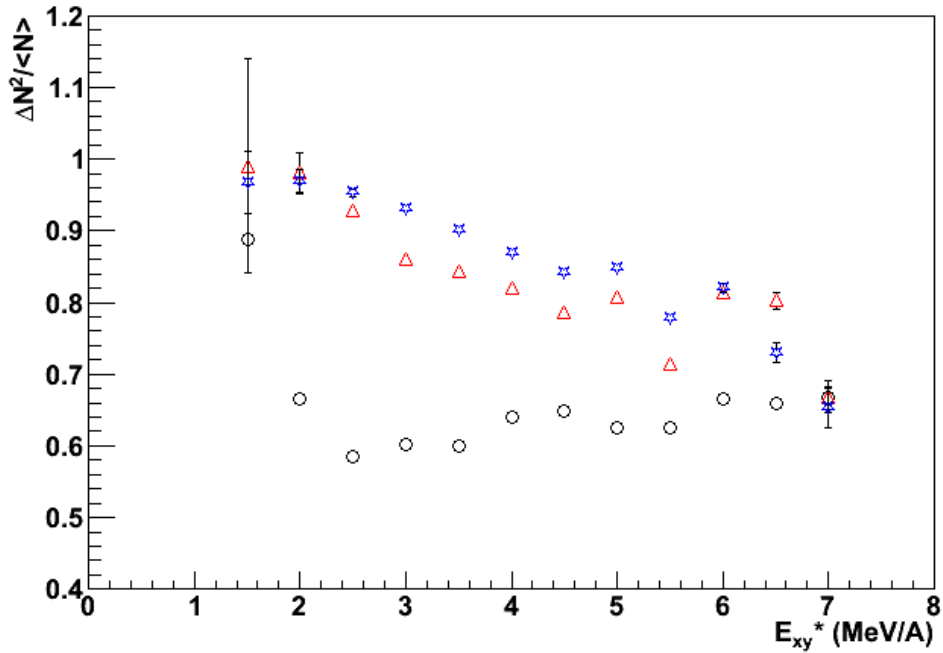
Data was used from the 2005-2006 FAUST campaign [3]. The 45 MeV/A  $^{32}\text{S} + ^{112}\text{Sn}$  reaction system was chosen because it has the highest statistics. FAUST is a forward array of 68, 300  $\mu\text{m}$  Silicon / 2.5 cm CsI (TI) telescopes [4]. The thickness of the silicon detectors bias the data toward fragments emitted from the projectile like source in peripheral reactions. Projectile like sources were selected by summing the charge of each particle detected in each event and selecting events with a sum charge equal to that of the incident beam ( $Z=16$ ). Events with particles that could not be fully isotopically identified were excluded. An event selection requiring the sum of the mass number of the detected fragments to be equal to the incident beam has been performed. This keeps the size of the fragmenting system constant.

The excitation energy was calculated through calorimetry as defined in Equation 1. Notice that only the portion of the kinetic energy transverse to the beam direction is used in this calculation to reduce any dynamic contribution to the kinetic energy from the interaction with the target. The resulting sum kinetic energy is then multiplied by 3/2. In effect this estimates the Z-axis contribution to the sum kinetic energy as the average of the other two axes.

$$E_{xy}^* / A = \left( \frac{3}{2} \right) \frac{\sum_{i=0}^{CP_{mult}} KE_{xy} - Q_{rxn}}{\sum_{i=0}^{CP_{mult}} A_{fragment}} \quad (1)$$

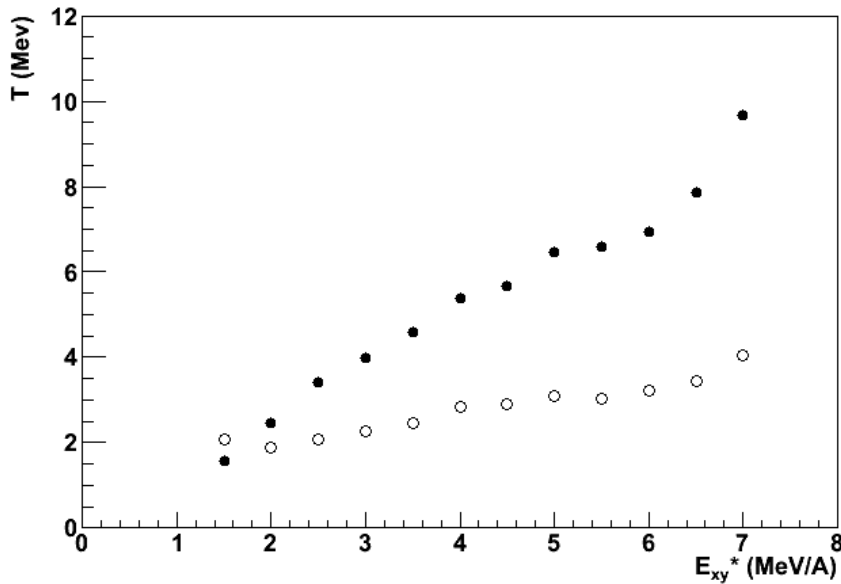
The data was broken in to 12  $E_{xy}^*$  bins of 0.5 MeV/A. The central values of these bins ranged from 0.5 to 7 MeV per nucleon. Figure 1 shows the normalized variance of the fragment multiplicity per event for three different fermionic particles for each of the above excitation energy bins.

The reduction of the normalized variance below 1 is expected for fermions and is the result of Pauli blocking. This effect is most pronounced for the protons and reduced for the two  $A=3$  fragments. This is also understood, as Pauli blocking should be reduced for composite particles. In a classical system, we would expect the normalized variance to be equal to 1 across all excitation bins. The trend observed in figure 1 agrees qualitatively with the model calculations of Zheng and Bonasera although their calculations were performed for a different reaction system.



**FIG. 1.** Normalized variance by particle type versus excitation per nucleon. The open circles, triangles, and stars represent the protons, tritons, and  $^3\text{He}$  respectively. The excitation has been calculated using the transverse kinetic energy as discussed in the text. Statistical error on the normalized variance is plotted. The  $E_{xy}^*$  bins are 0.5 MeV/A in width.

Another temperature calculation based on event particle quadrupole fluctuations, but classically derived, was previously proposed by Wuenschel and Bonasera [5]. For comparison the proton



**FIG. 2.** Proton temperature calculated with both a classical (closed circles) and quantum (open circles) calculation. Notice the significant reduction in the calculated temperature of the quantum calculation over that of the classical, particularly at high excitation. Statistical error for the temperature is plotted (though the error bars remain smaller than the individual points). The  $E_{xy}^*$  bins are 0.5 MeV/A in width.

temperature from each calculation is plotted with the above event selection in figure 2. The classical and quantum temperatures are the closed and open circles respectively. There is a significant decrease in the temperature calculated by the quantum method over that of the classical, especially at higher event excitation.

Together the results suggest the importance of a quantum treatment of temperature for heavy ion reactions. Future work will include the expansion of the project to include the investigation of bosons type fragments as well as direct comparison with the CoMD model used in references [1,2].

- [1] Hua Zheng and Aldo Bonasera, *Phys. Lett. B* **696**, 178 (2011).
- [2] Hua Zheng and Aldo Bonasera, arXiv: 1105.0563v1; Hua Zheng and Aldo Bonasera, *Progress in Research*, Cyclotron Institute, Texas A&M University (2010 – 2011), p ??-??.
- [3] B.C. Stein *et al.*, *Progress in Research*, Cyclotron Institute, Texas A&M University (2007 – 2008), p II-30.
- [4] F. Gimeno-Nogues *et al.*, *Nucl. Instrum. Methods Phys. Res.* **A399**, 94 (1997).
- [5] S. Wuenschel *et al.*, *Nucl. Phys.* **A843**, 1 (2010).