The nuclear caloric curve: Temperatures of simulated quasi-projectiles

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The equation of state describes the bulk quantities of matter, and how they relate to each other. These quantities include the temperature, composition, density, pressure, volume and energy of the system. In the nuclear system there is still theoretical uncertainty in how strongly the asymmetry of the nucleus impacts the nucleus's thermodynamic quantities. One area requiring experimental constraints is the difference between "ays-stiff" and "ays-soft" equations of state, which have important astrophysical implications. In order to help constrain these theoretical models, various experiments were performed with NIMROD (Neutron Ion Multidetector for Reaction Oriented Dynamics) in (year of experiments) including the ^{70}Zn+^{70}Zn , ^{64}Ni+^{64}Ni, and ^{64}Zn+^{64}Zn systems at 35 MeV/u [1]. The charged particles produced in these reactions were detected, along with the neutron multiplicity. These runs would prove to be a rich data set, and were used to determine temperatures of reconstructed quasiprojectiles (QP) [2,3]. Analysis showed a dependence on the nuclear caloric curve based on the asymmetry of the reconstructed QP. The more neutron rich QPs had lower temperatures at the same excitation energy and this trend was seen in multiple kinetic and chemical probes. The purpose of this project is to use anti-symmetrized molecular dynamics (AMD) [4] and Gemini[5, 6] to attempt to reproduce and test the trends seen experimentally, and to see if there is a dependence between ays-stiff and ays-soft interactions on the nuclear caloric curves.

In the original data set roughly 10000 AMD-DS events were run by Z. Kohley to a time of 300fm/c for each system. Afterwards, Gemini was used to de-excite the nuclides, with each AMD event used as a starting point for Gemini 20 times. In addition to this data set, another 40000 AMD-DS events were generated for each system in 2019-2020. In 2021 an additional 227,400 AMD-DS data was run for the ^{70}Zn on ^{70}Zn system with the gogny stiff interaction, and 193,882 for the gogny soft system. If we allow ourselves to run each AMD event through Gemini 20X times we can greatly increase the apparent statistics, however this complicates the evaluation of the statistical error as now each event is not completely independent from others. These new events have been processed. These events were then subjected to the same event selection cuts used to shift through the data collected in the experiment. See paper for details on the event selection, as well as how these temperatures are calculated [2,3].

A weak dependence is seen between the gogny stiff and gogny soft interaction for the MQF temperatures calculated using protons as the probe. This is seen in Fig.1. A more noticeable dependence is seen using the (H/He) Albergo chemical probe (See Fig.2). Both seem to indicate that the stiff interaction is hotter than the soft interaction. While this is encouraging, there are challenges to comparing the AMD+Gemini results to the experimental data. Using the same AMD primary event 20 times to make different AMD+Gemini events may cause the statistical error bars to be too small, as each event is no longer completely independent of each other. This problem can be remedied by only using Gemini once for each AMD primary event and we can compensate for the loss of counts by running more AMD primary events. To reassure ourselves that the trend is robust to this effect, the H/He Albergo

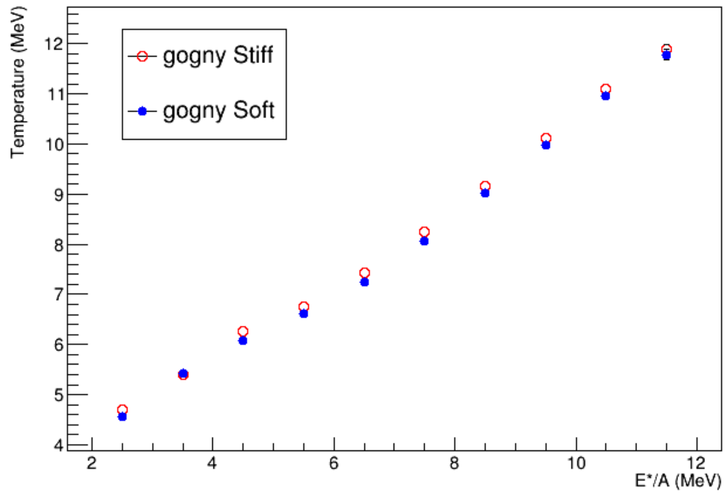

Fig. 1. Temperature of QP calculated using the MQF of protons as a function of excitation energy per nucleon. A weak difference is seen between the gogny stiff and gogny soft interaction, with the stiff having slightly higher temperatures.

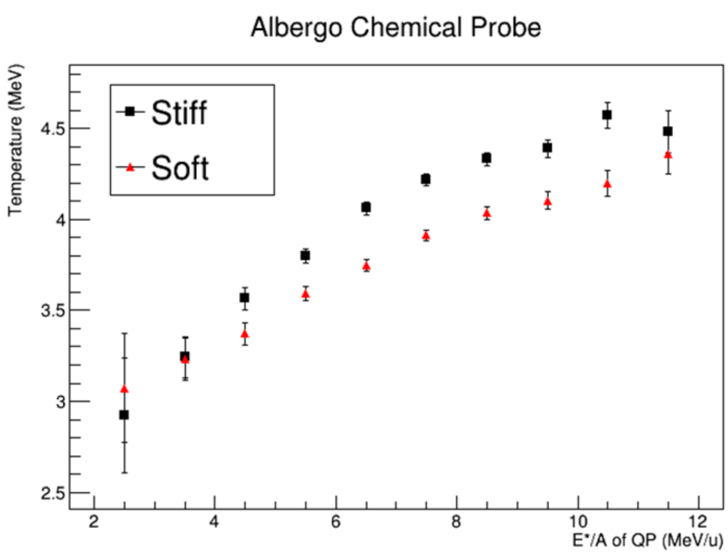

Fig. 2. Temperature of the QP calculated using H/HE Albergo temperature probe as a function of excitation energy per nucleon. A significant difference is seen between the two interactions.

temperatures were re-evaluated when only de-exciting the AMD primary event once in Gemini (see Fig. 3). From this test it looks like there is indeed a statistically significant difference between stiff and soft interaction on the H/He Albergo chemical probe. Even with a better understanding of the statistical error bars, there would still be the concern of systematic difference between AMD+Gemini and the real experimental reaction. For instance, while the calculated Albergo temperatures from AMD+Gemini appear to line up well with the experimental ones, the MQF temperatures appear lower than seen in the experiment. In addition, for the MQF case there are differences in the ordering of which particle probe is hotter than what is seen in the experiment. These systematic differences complicate a direct comparison with experimental results.

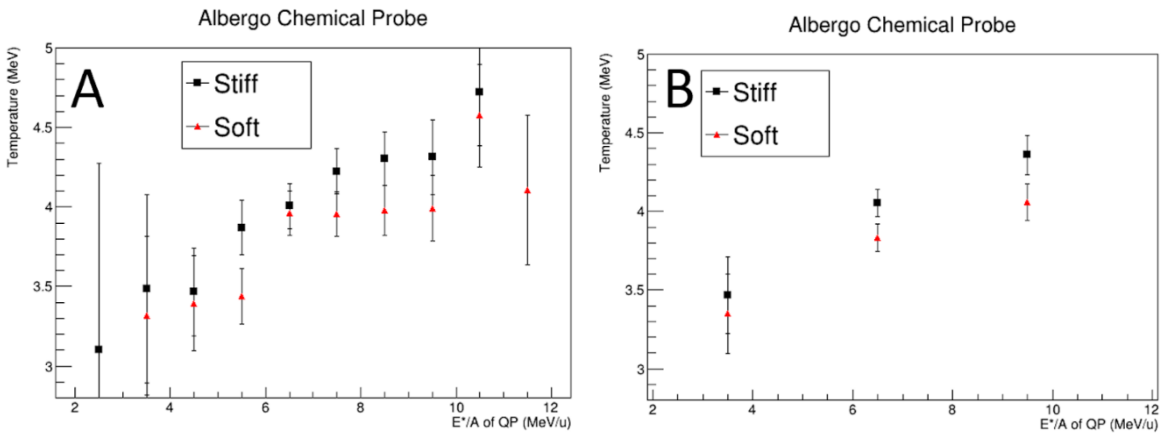

Fig. 3. A) Same as Figure 2, but with the data set only deexciting each AMD primary event once through Gemini. Error bars are quite large. B) Same as A) but re-binned, two points show a statistically significant difference between Stiff and Soft, with Stiff appearing to be hotter.

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