Capability of studying N-Z equilibration using FAUST

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In heavy-ion collisions (HICs) near the Fermi energy, the formation of atypical nuclear matter affords methods of probing the nuclear equation of state (nEOS), an outstanding question in the field of nuclear science that legislates the nature of both intrinsic and extrinsic properties of nuclear matter. The nEOS, comprised of several interrelated components, suffers from associated uncertainties, of which the density dependence of the asymmetry energy remains the least constrained.

Observation of nucleon exchange between reaction participants led to the development of a method that uses the preferential migration of nucleons within a system to constrain the asymmetry energy dependence, a process known as neutron-proton (N-Z) equilibration. Studying angular and isospin correlations between the fragments produced in HICs can provide insight into the length and strength of the interaction; observing this across systems of varying isospin content can then provide information about the nature of the asymmetry energy of the nEOS. A more comprehensive discussion regarding the phenomenon is provided by [1] and references therein.

N-Z equilibration was previously studied at Texas A&M University (TAMU) using the near-4π Neutron Ion Multidetector for Reaction Oriented Dynamics (NIMROD) for all beam and target permutations of ^{70}Zn and ^{64}Ni at 35 MeV/u [2-5] in which equilibration was characterized for subsystems of varying Z compositions [5]. Equilibration is characterized by observing the relationship between the N-Z composition of the heaviest and second-heaviest fragments originating from the projectile-like fragment (PLF) in an event and their corresponding alignment angle, α, defined as

$$\alpha \equiv \mathrm{acos}\left(\frac{\vec{v}_{CM} \cdot \vec{v}_{rel}}{\|\vec{v}_{CM}\| \cdot \|\vec{v}_{rel}\|}\right) \quad ; \quad \vec{v}_{rel} = \vec{v}_{HF} - \vec{v}_{LF}. \tag{1}$$

In these equations, v_{CM}, v_{rel}, v_{HF}, and v_{LF} refer to the velocity of the center-of-mass of the (reconstructed) PLF, the relative velocity between the heavy fragment (HF) and light fragment (LF), the laboratory velocity of the HF, and the laboratory velocity of the LF, respectively. The full results for each aforementioned study are summarized in the respective references; the purpose of this report is to investigate whether N-Z equilibration can be studied with the Forward Array Using Silicon Technology (FAUST) at TAMU. FAUST is a position-sensitive charged particle array that covers most of 1.6-45.5° of forward angles via 68 ΔE-E telescopes. FAUST, despite significantly less overall angular coverage in comparison to NIMROD, possesses excellent position and angular resolution unachievable by NIMROD (in its current state) consequent of the dual-axis duo lateral (DADL) position-sensitive silicon detectors serving as the ΔE of the telescopes.

To understand the capacity of N-Z equilibration in FAUST, simulations of Heavy-Ion Phase Space Exploration (HIPSE) coupled with statistical de-excitation afterburner were produced for systems of ^{70}Zn + ^{70}Zn, ^{40}Ca + ^{40}Ca, and ^{48}Ca + ^{40}Ca at 35 MeV/nucleon and filtered using simulated filters for both FAUST and NIMROD. The zinc system was simulated as a "standard" for N-Z studies; the calcium systems were simulated because a) the relative isospin magnitude for ^{48}Ca is greater than any participant in a zinc or nickel-based system, and b) the lesser total Z of the system takes advantage of FAUST's lighter-particle isotopic resolution. The near mass symmetry of all systems considered means that the products are less forward focused on average, and thus concerns for FAUST geometry become significant (Fig. 1a). However, as the HF and LF originate from the PLF which is moving forward of mid-velocity, these components will be forward focused enough that FAUST geometry is sufficient (Fig. 1b). The diagrams provided as example are the smallest Z LF and HF that are traditionally gated on in these analyses [5]. Higher Z components are increasingly forward focused; by LF Z = 6, nearly 100% of the distribution is forward of $\theta_{lab} = 45°$.

In the interest of furthering this study, analyses similar to those conducted in experiment (see, for

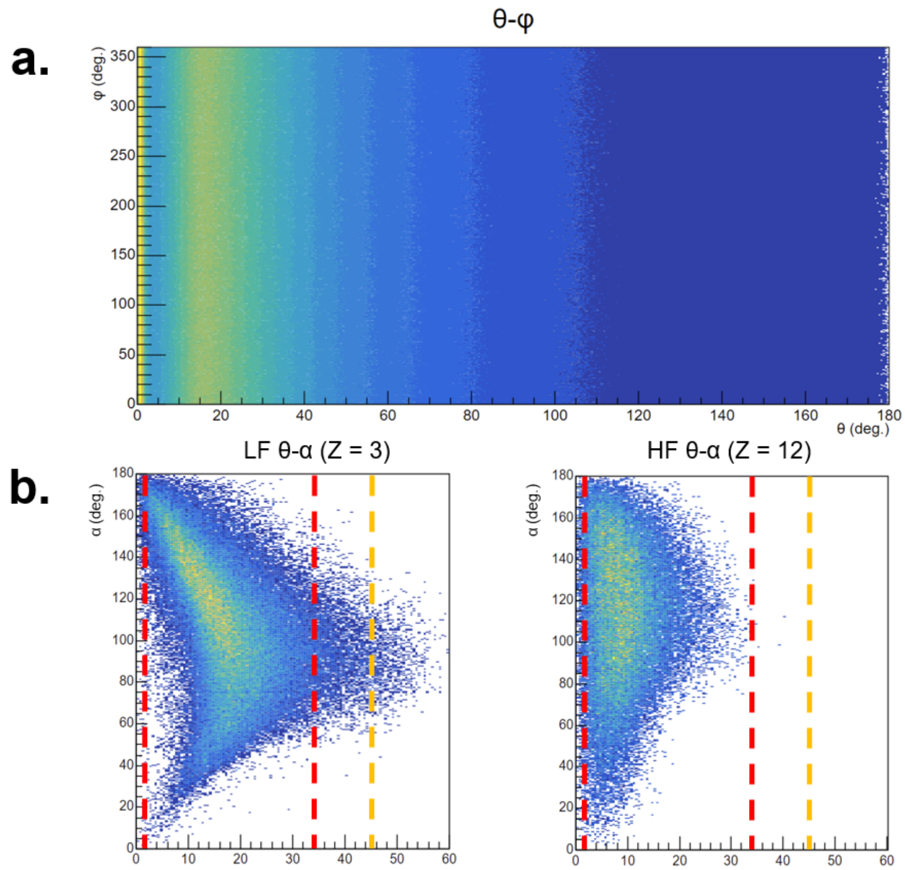

Fig. 1. (a) Laboratory θ-φ distribution of particles from simulated $^{70}Zn + ^{70}Zn$ @ 35 MeV/nucleon. This distribution illustrates that while most particles are forward of $\theta_{lab} = 90°$, a significant amount are present backward. (b) Laboratory θ-α distribution of particles identified as the LF and HF in an event based on particle Z and velocity conditions. For each diagram, the red dashed lines enclose the region of θ_{lab} that is effectively covered by FAUST geometry, while the orange dashed line designates the maximum θ_{lab} in FAUST. Coverage in this intermediate region reduces approximately exponentially. See discussion in text.

example, [5]) were replicated for the unfiltered and filtered HIPSE data. Fig. 2 summarizes results for distributions of α (therein provided as cos(α)) and Fig. 3 summarizes results for Δ vs. α (therein provided as α) for all permutations of systems and filters. These distributions were produced using an overall velocity cut on the LF of 0.2c; this imposed velocity gate accounts for differing isotopes have differing velocity thresholds for detection. Particle velocities are highly correlated to the measured α; neutron-rich fragments, possessing lower velocity thresholds than their corresponding neutron-poor isotopes, would contribute disproportionately and lead to a more neutron-rich LF on average for small α without a velocity cut. Ideally, cuts would be made on a Z basis to best utilize the available statistics, but a generalized cut was used here in the interest of efficiently probing the potential for further studies.

In Fig. 2, the excess in the cos(α) distributions leading to asymmetry about zero would indicate the presence of a non-statistical decay contribution, but comparing these to an experimental equivalent [5] shows that the distributions are inverted about zero. This suggests that the present trend is instead an

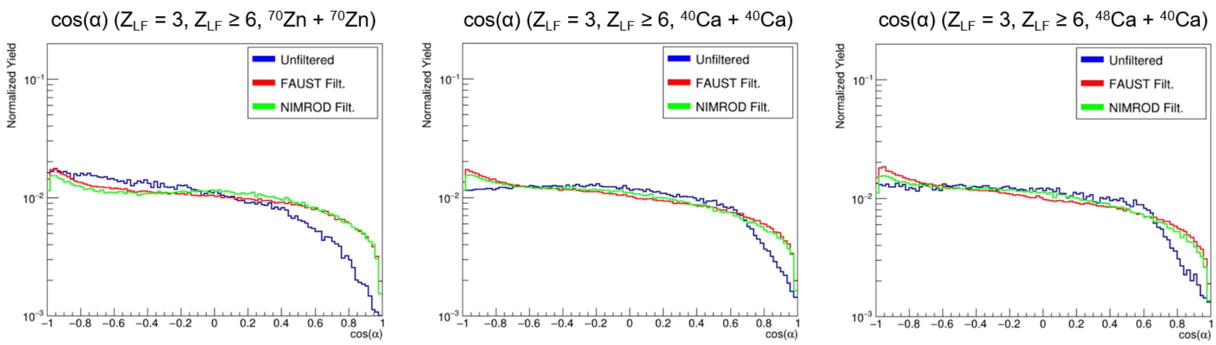

Fig. 2. cos(α) distributions for systems of ^{70}Zn + ^{70}Zn (left), ^{40}Ca + ^{40}Ca (middle), and ^{48}Ca + ^{40}Ca (right). These distributions compare normalized yield between unfiltered (blue), FAUST filtered (red), and NIMROD filtered (green) HIPSE.

analytic artifact. However, in Fig. 3, the evolution of Δ as a function of increasing α for the ^{70}Zn and ^{48}Ca systems also suggests that dynamical contribution may be present in the simulation data, albeit suppressed as a consequence of statistics. This is further reinforced by the comparative *lack* of evolution in the ^{40}Ca system; this system, possessing N = Z overall, is not affected by a driving force for nucleon migration

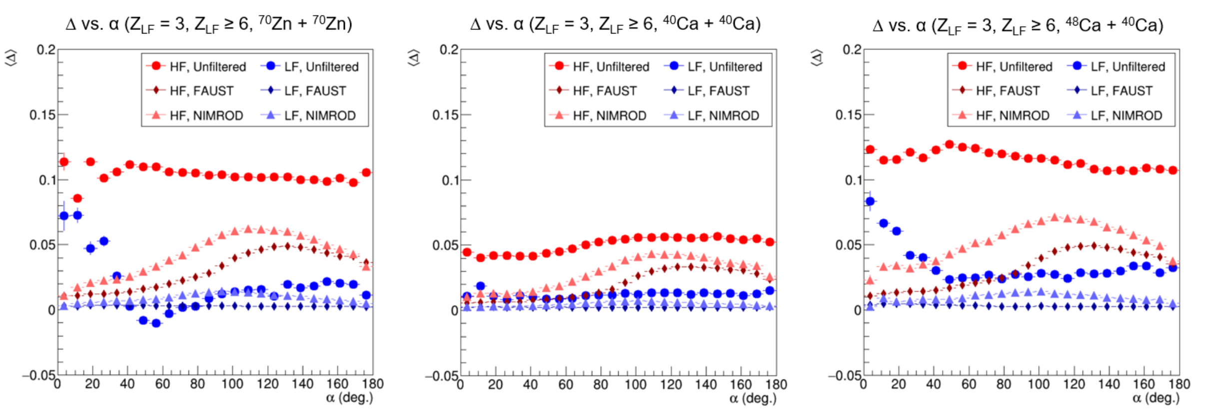

Fig. 3. Δ vs. α distributions for systems of ^{70}Zn + ^{70}Zn (left), ^{40}Ca + ^{40}Ca (middle), and ^{48}Ca + ^{40}Ca (right). Both the ^{70}Zn and ^{48}Ca show distinguishable features with the evolution of α, while the ^{40}Ca does not. In consideration of the nature of ^{40}Ca + ^{40}Ca, this may suggest that some of the dynamical nature of N-Z equilibration is captured by HIPSE simulations. It is important to note that the abnormal behavior of these plots is due to a combination of limited statistics and the nature of HIPSE simulation.

during the initial collision (as there is no asymmetry penalty to mitigate) and thus no potential for equilibration afterward (beyond native fluctuation). Because the $^{40}Ca + {}^{40}Ca$ Δ versus α is essentially featureless in comparison to the other two systems, further analysis to understand the discrepancy in the $\cos(\alpha)$ is needed as well as review of the HIPSE framework to determine if observing N-Z trends in simulation is reasonable. Comparison between the filters for each system reveals that FAUST performance in relation to NIMROD in the context of N-Z studies is plausible – the result of filtering raw HIPSE leads to the same general conclusion in terms of evolution of the trend. While a more comprehensive study is desired to support these conclusions, preliminary results suggest that conducting an N-Z experiment with FAUST would be doable from a geometric acceptance and resolution standpoint and should be considered further in the future of the FAUST research campaign. Finally, concerning the plausibility of N-Z studies for a smaller system such as $^{40}Ca + {}^{40}Ca$, a recent experiment conducted with the INDRA-VAMOS charged particle array-spectrometer and the beam/target combinations discussed herein was able to demonstrate equilibration [6]. With this in mind, further investigation into these reaction systems with differing experimental conditions may be of interest to comprehensively understand the dynamics at play.

[1] A.B. McIntosh and S.J. Yennello. Prog. in Part. and Nuc. Phys. **108**, 103707 (2019).
[2] A. Rodriguez Manso *et. al.* Il Nuovo Cimento C **5**, 188 (2018).
[3] A. Rodriguez Manso *et. al.* Phys. Rev. C **100**, 044612 (2019).
[4] A. Hannaman *et. al.* Phys. Rev. C **101**, 034605 (2020).
[5] A. Jedele, Ph. D. Thesis, Texas A&M University, 2020.
[6] Q. Fable, *et. al.* Phys. Rev. C, **106** 024605 (2022).