Asymmetry Energy Effects on Reaction Break-up Mechanisms Near the Fermi Energy

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Abstract. Heavy Ion Collisions play an important role in probing the density dependence of the asymmetry energy by providing a unique tool to probe nuclear interactions away from saturation. Lower energy reactions (\(\sim 10-15\)A MeV) provide a means of probing around and below normal nuclear density. In particular, these collisions can provide a sensitive means of probing the interaction and possibly the asymmetry terms of the nuclear Equation of State. Simulations of \(^{124}\)Sn+\(^{64}\)Ni using Constrained Molecular Dynamics and Stochastic Mean Field calculations, at different asymmetry energies, have been used to study the asymmetry energy dependence of projectile-like fragment break-up channels as well as the mass correlations of the heaviest fragments. The results of these simulations present the possibility of developing an experimental probe for measuring the density dependence of the asymmetry energy using picosecond time resolution time of flight spectroscopy in a multi-detector array.

1. Introduction

The nuclear Equation of State (EoS) poses a great challenge to the field of nuclear science. The EoS plays a fundamental role in describing nuclear and astrophysical phenomena. The behavior of the EoS in symmetric matter has been well studied and is constrained well, specifically at the saturation point where \(E/A=-16\) MeV/nucleon and \(\rho_0 \sim 0.16\) fm\(^{-3}\) \cite{1, 2}. However, the behavior of the EoS in asymmetric matter is not well understood in regions far from normal nuclear density \((\rho/\rho_0=1)\). At low densities \((\rho/\rho_0 \leq 1)\), understanding the behavior of the asymmetry term of the EoS is essential for the understanding and study of neutrons skins of heavy elements, nuclear structure at the drip lines and the formation of neutron stars \cite{3, 4} where as high densities lends itself to the understanding of neutron star mass-radius relation, cooling, and hybrid structure \cite{5, 6}.

Nuclear reactions just below the Fermi energy present a unique opportunity for probing the dynamics of nuclear matter below normal nuclear density using shape fluctuations, angular momentum, and relative multiplicities of the resulting fragments. Competition between fusion and quasi-fission in semi-peripheral collisions and deep-inelastic transfer (multiplicity\(\geq 2\)) mechanisms in peripheral collisions dominate the exit channels. However, composite systems resulting from semi-peripheral collisions may exhibit prolate (elongated) shapes with a large associated angular momentum. More neutron-rich nuclear reactions are expected to be more
sensitive to the density dependence of the asymmetry energy via dynamical ternary/quaternary break-up and angular alignment of the most massive fragment [4, 7–18]. We present simulation results using Constrained Molecular Dynamics (CoMD)[19, 20] and Stochastic Mean Field (SMF) (using the TWINGO code) [21–26] and a brief description of the experimental design proposed to measure these effects.

2. Results of Theoretical Simulations
Simulations using the TWINGO code have been used to calculate the fluctuations in quadrupole and octupole moments in momentum space. This is to facilitate prediction of the relative expected ternary (quaternary) breaking of the system. Specifically, we have looked at the fluctuations based on the quadrupole and octupole moments of the projectile-like fragment (PLF) resulting from semi-peripheral interactions of heavy nuclei just below the Fermi energy to predict the probability of secondary break-up. Using $^{124}\text{Sn}+^{64}\text{Ni}$ at 15 MeV/nucleon, Figures 1 and 2 show the extracted PLF deformations from TWINGO resulting from mean field interactions.

These events are divided by impact parameter (6, 7 and 8 fm respectively) at time $t=450$ fm/c. The events were accepted if there were two or more large particles in the event. In this way, we can see that there are noticeable differences in the quadrupole and octupole fluctuations with respect to the asymmetry energy.

![Figure 1](example.png)

**Figure 1.** Quadrupole fluctuations of the Projectile-Like Fragment (PLF) in Momentum Space from TWINGO. The selected fluctuations are at time=450 fm/c and impact parameter 6 fm(a), 7 fm(b), and 8 fm(c). Events were selected where the number of particles per event were greater than 1.

In addition, to gain an insight into the observables expected to be pertinent to the experimental observables on longer time scales, CoMD has been used. In this case, the same system and incident energy has been studied out to 3000 fm/c in order to allow the reaction products to begin to cool dynamically. In Figure 3, we can see there is a noticeable difference in the impact parameter distribution with respect to the multiplicity of the $Z\geq3$ fragments. Statistical decay methods (such as SMM [27] or GEMINI [28]) were not used to speed computational time because the phenomena of interest, including deformation and large angular momentum effects, would not be seen by cooling the reaction products at shorter times back to more spherical nuclei (esp. in the case of GEMINI) via statistical emission of nucleons and light charged particles. Additionally, codes such as GEMINI used to statically decay reaction products expect the products to be nearly spherical at the input. In this case we expect, and can see from Figures 1 & 2, the products in these types of reactions are expected to be largely non-spherical.
Figure 2. Octupole Fluctuations of the Projectile Like Fragment (PLF) in Momentum Space from TWINGO. The selected fluctuations are at time=450 fm/c and impact parameter 6 fm(a), 7 fm(b), and 8 fm(c). Events were selected where the number of particles per event were greater than 1.

Figure 3. Impact parameter distributions with respect to the multiplicity of the event extracted from CoMD gating only on particles with Z≥3 in ternary events (involving three particles all with Z≥3). The simulation was allowed to dynamically equilibrate to t=3000 fm/c in order to preserve asymmetry energy effects. The x-axis labeled “BIMP” is the impact parameter in fm.

Differences in mass partitioning were also looked at for the same system using CoMD. We notice, as shown in Figure 4, that there appears to be an asymmetry energy dependence in the mass partitioning of the reaction products. For the case of a binary separation of the PLF and target-like fragment (TLF), there appears to be no significant difference between the two asymmetry energies used. However, ternary events (with three fragments (Z≥3)) we begin to observe the beginnings of a difference in the observed masses (Figure 4b). In the case of the quaternary events (multiplicity=4 for particles with Z≥3), the ability to make a clear determination as to the asymmetry energy effects on mass partitioning are limited by low statistics. Each of the plots in Figure 4 represent the specifically mentioned events over all impact parameters from 0 to 10.
Figure 4. Mass partitioning from CoMD gating only on particles with $Z \geq 3$. The simulation was allowed to dynamically equilibrate to $t=3000$ fm/c in order to preserve asymmetry energy effects. In these cases, each of the figures show the spread in $A$ for binary (a), ternary (b), and quaternary (c) events over all impact parameters from 0 to 10. The events were selected based on having 2, 3, or 4 particles with $Z \geq 3$ (for binary, ternary, and quaternary respectively).

3. Experimental Design

Based on the theoretical results outlined above, it may be possible to probe the fragmentation mechanism competition of the primary nuclei and neck fragmentation at low-intermediate energies using heavy, asymmetric systems. This can be done by looking at the angular alignment of IMFs and primary fragments (from the PLF), velocity correlations of the fragments, mass partitioning of the fragments, multiplicity of ternary and quaternary breaking as compared to theoretical calculations, quasi-reconstruction of the PLF based on measured masses of fragments, isospin content measurement and iso-scaling of the dynamical neck fragments (IMFs). These distributions can be compared to CoMD simulations, results from CHIMERA, and other experiments that have observed this alignment at slightly higher energies [29–33]. Finally, using the IMFs emitted from the neck and secondary breakings, isotopic ratios can be used to characterize the interaction potential present in these reactions. Using $\Delta E$-$E$ techniques will allow for good isotopic resolution to facilitate these measurements.

We plan to upgrade the Forward Array Using Silicon Technology (FAUST)[34], shown in Figure 5, to have Time-of-Flight (ToF) capabilities to measure the mass of the heaviest fragments in order to include identification of PLF. ToF measurements would require the installation of a fast timing micro-channel plate detector (MCP[35]) upstream of the current target assembly to provide time resolution in the range of $\sim 130-150$ ps, facilitating mass resolution of the largest fragments expected in binary (statistical) fission events to within 1-5 mass units (depending on the lab frame angle of detection). With this level of mass resolution, it should be possible to resolve the smaller masses involved with the dynamical fission events (ternary/quaternary breakings and dynamic IMFs with $Z \geq 3$). Each charge sensitive preamplifier motherboard must be retrofitted/redesigned to include a fast timing pick-off to gain the timing signature for the desired mass resolution. The timing pick-off amplifier is essential for use with detectors whose charge collection time greater than to 10ns (such as Si surface barrier detectors)[36].

In addition, FAUST can already be used to measure IMFs ($Z \geq 3$). This, in conjunction with the mass measurements mentioned previously, should make it possible to make coincidence co-
relations in the angular distribution of the heaviest fragments. The IMFs from the dynamical fission events should have sufficient energy to be elementally resolved with the current detector setup. Providing correlations between the density dependence of the associated IMFs to the reaction mechanism competitions suggested above would provide a deeper insight into the density dependence of the nuclear EoS. By looking at the isospin content (and possibly the iso-scaling parameters) of the associated IMFs, it may be possible to determine the asymmetry energy and draw correlations from the reaction mechanism to help constrain the density dependence of the asymmetry energy below normal nuclear density.

Experimental tests have been performed using both an accelerated beam of $^{129}$Xe and alphas from a $^{228}$Th source to measure the expected time and energy resolution of the timing pre-amplifier and silicon surface barrier detector combination expected to be used in the proposed series of experiments. The beam experiment was used to simulate the upper bound of the time resolution for the experiment with the alphas as a lower bound. In this way, it was possible to facilitate the estimation of the time resolution for the detector array proposed in this experiment. It has been demonstrated (Figure 6) that the detectors are at least capable of a time resolution of $\sim 135$ ps (FWHM) corresponding to a mass resolution of $\sim 1$ mass unit (or less for lighter particles).

This beam data was collected using a BC-408 thin film (10 $\mu$m) scintillator combined with a 2 cm x 2 cm, 300 $\mu$m, single-sided silicon detector and time pick-off amplifier (LBL 21X742). Using a MCP as a time-zero detector should only enhance the results seen in the initial beam experiment. With respect to timing resolution extrapolation from the source data to the beam data, it is reasonable to expect the timing to be better for heavier, higher energy particles of interest as has been reported previously[35].

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Figure 6. Time resolution of 2 cmx2 cm, 300 µm single sided Si detector with timing pick-off amplifier combined with thin film (10 µm) BC-408 scintillator (coupled to a photomultiplier tube).

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