**Using break-up mechanisms in heavy ion collisions at low energies to constrain the symmetry energy at low nuclear density**

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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, spin and relative multiplicities of the resulting fragments. The results of these interactions are theorized to be dependent upon and sensitive to the symmetry energy. Composite systems resulting from semi-peripheral collisions may exhibit prolate (elongated) shape with a large associated angular momentum. More neutron-rich nuclear reactions are expected to have a greater sensitivity to the density dependence of the symmetry energy through observing ternary or quaternary breaking after re-separation [1].

Using the results from DiToro *et al.* [1] (Fig. 1) as motivation, simulations using TWINGO code [2-7] (a stochastic mean field approach) have been used to calculate the fluctuations in quadrupole and octupole moments in momentum space. This was done in order to facilitate the prediction of

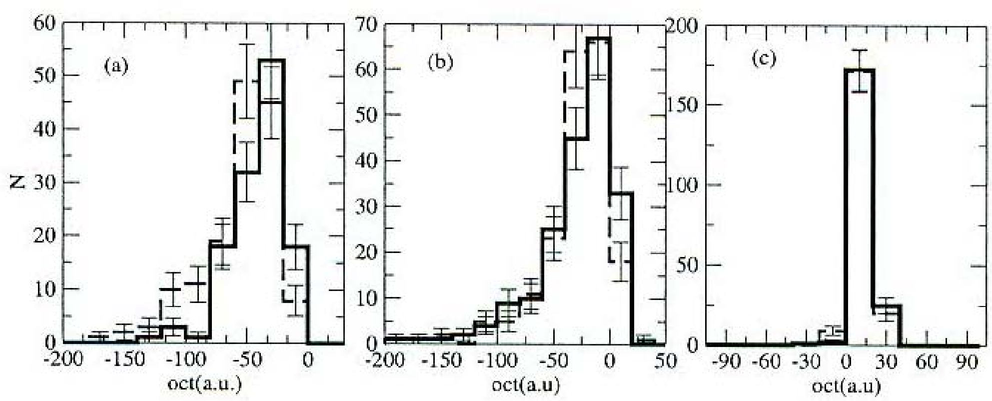


**FIG. 1.** Octupole fluctions of the primary fragmets (in position space) for $^{132}$Sn+$^{64}$Ni at 10A MeV. In dashed = asy-stiff, solid= asy-soft [1]. (a) b = 6 fm (b) b = 7 fm (c) b = 8fm.

the relative expected ternary (quaternary) breaking of the PLF (and TLF) resulting from semi-peripheral interactions of heavy nuclei below the Fermi energy. Using $^{124}$Sn+$^{64}$Ni at 15A MeV, Fig. 2 shows the cluster identified results of TWINGO resulting from the mean field interaction. ln this way we can see that there are noticeable differences in the quadrupole and octupole fluctuations with respect to the symmetry energy. It is expected that reactions using $^{124,136}$Xe instead of $^{124}$Sn should exhibit the same signatures. In addition, to gain an insight into the observables pertinent to the experiment on long time scales, CoMD (Const rained Molecular Dynamics [8, 9]) has been used. In Fig. 3, we can see there is a noticeable difference in the multiplicity of the Z ≥ 3 fragments.

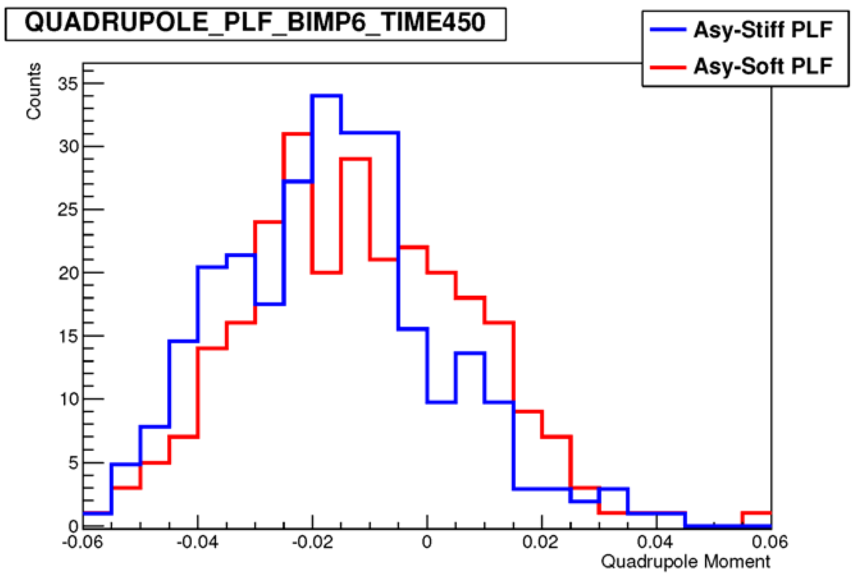


**FIG. 2.** Quadrupole fluctuation of the projectile-like-fragment (PLF) via TWINGO code.

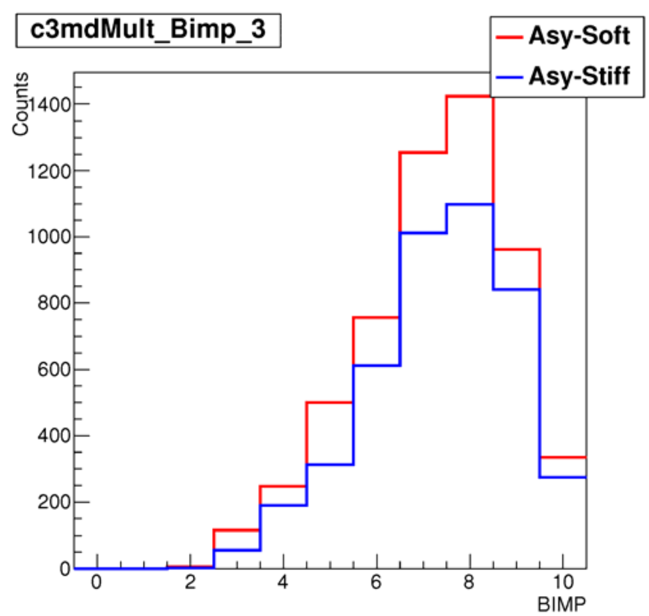


**FIG. 3.** CoMD events shown where the multiplicity = 3 for $Z \geq 3$ particles as a function of impact parameter and symmetry energy.

In order to probe these fluctuations in octupole and quadrupole moments and their effects on the breaking of the projectile-like-fragment (PLF), an experiment must be designed to specifically cater to the lower energy reaction products typically produced in the subsequent (dymanic) fission of the PLF. One of the observables, dependent on the multiplicity distribution from CoMD mentioned above, is a mass partitioning of the products emanating from the breakup of the PLF. Therefore, it will be necessary to measure the mass of the fragments via time-of-flight techniques in this lower energy regime. Time-of-flight methods are necessary as Z identification will not be feasible using standard *ΔE-E* methods. To this end, we have conducted experimental tests using an accelerated beam of $^{129}Xe$ to measure the expected time and energy resolution of the timing pre-amplifier and silicon detector combination. Using the Forward Array Using Silicon Technology (FAUST) [10] in combination with the timing pick-off preamplifiers and a fast time zero detector (micro-channel plate detector), we expect to measure the symmetry energy dependence of the dynamic fission of the PLF. We have demonstrated (Fig. 4) that we were able to achieve a time resolution of 135ps (FWHM) corresponding to a mass resolution of 1 mass unit. In combination with the Si timing-pick off amplifiers, a micro-channel plate time-zero detector should provide the timing resolution to detect the mass of the expected heavy ions [11]. The retrofit upgrade of FAUST for Time-of-Flight (ToF) capabilities, with excellent timing resolution (100's of pico-seconds) is currently underway and is expected to be completed by mid-fall 2012.

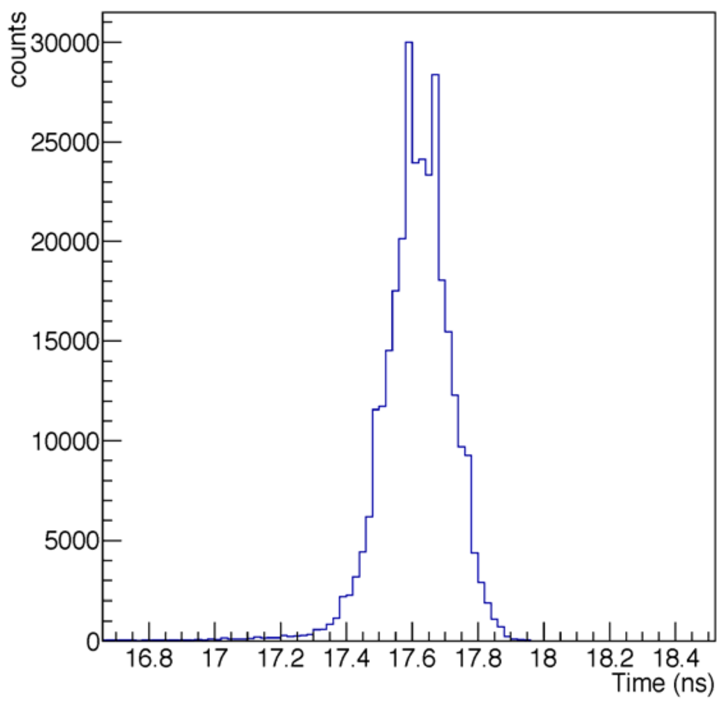


**FIG. 4.** Time resolution of the 300μm Si detector with timing pick-off.

Based on the experimental and theoretical results, probing the fragmentation mechanism competition of the primary nuclei and neck fragmentation at low-intermediate energies in heavy, asymmetric systems could provide additional constraints on the symmetry energy at low nuclear density. Initial simulations have been performed using CoMD and TWINGO (a stochastic mean field simulations) to predict the prevalence of the reaction observables. However, because of the time intensive nature of the computations, more statistics are needed to enhance the effects of the symmetry energy.

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