INFORMATION SHEET
(2004)

Experiment at	**TANDEM [ ]**	**CYCLOTRON [x]**	**EXCYT [ ]**
Technical test [ ]	**New experiment [x]**	**Continuation of approved experiment [ ]**	

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EXPERIMENT IS SUPPORTED BY THE CHIMERA/ISOSPIN COLLABORATION AT CATANIA	INFN LNS and INFN Sezione di Catania

Beam	Energy (A MeV)	Intensity (pnA)	Beam line	BTU	Excluded dates
^{112}Sn	35	0.02	cyclope	9	
^{124}Sn	35	0.02	cyclope	9	

Special requirements (targets, sources, beam timing, vacuum, electronics …)	CHIMERA APPARATUS Vacuum ≈ 10^{-6} torr. Beam timing ≈ 1ns $\Delta T \sim 100$nsec

Isospin dyamics and the isospin dependent EOS

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ABSTRACT: Nuclear collisions with beams and targets of varying isospin provide the opportunity to investigate the isospin dependence of the nuclear EOS and of the in-medium cross sections. The asymmetry term contains the relevant isospin information of the EOS and is therefore key to the description of very asymmetric nuclear matter in systems ranging from the surfaces of weakly bound neutron-rich nuclei to the interiors of neutron stars. Theory has identified observables that are sensitive to the asymmetry term; some experimental investigations have been performed at higher incident energies. We propose to examine these issues using the Chimera array, which is well suited for such studies.

EXPERIMENTAL MOTIVATION: Investigations of the equation of state (EOS), of nuclear matter have primarily focused upon the EOS for symmetric matter. Such analyses [1] have ruled out both very soft equations of state as well as models with very stiff equations of state like those predicted initially by relativistic mean field theories. Data in this continually advancing field appear to be bracketed by predictions for Skyme effective interactions with incompressibilities in the range of K_{inf}=180-310 MeV, and it is anticipated that these constraints on the EOS for symmetric matter will be further improved [1].

Such analyses have not addressed the asymmetry dependence of the EOS, which makes the dominant contribution at the large asymmetries typical of neutron star matter. For example, the asymmetry term supplies all of the nuclear contributions to the pressure supporting a neutron star at $\rho=\rho_0$ and up to 70% of the pressure at $\rho=2\rho_0$. While ground state masses constrain $E_{sym}(\rho)$ near saturation density, the density dependence of $E_{sym}(\rho)$ and the asymmetry contribution to the pressure, $P_{asym}=\rho^2 \cdot(d\, E_{sym}(\rho)/d\rho)\cdot\beta^2$, are not well constrained by existing data [2-4]. A range of density dependences for $E_{sym}(\rho)$ are presently theoretically allowed, leading to a wide range of predictions for the internal structure, the mass - radius relationship and the moments of inertia of neutron stars[4].

Because the forces generated by the asymmetry term are of opposite sign for protons and neutrons, tracking the movements of neutrons and protons via measurements of isotropically resolved yields and energy spectra provide special sensitivity to the asymmetry term [2,5,6]. Observables sensitive to the asymmetry term, however, are often also sensitive to the isospin dependence of nucleon-nucleon cross-sections and other factors that influence the transport of isospin throughout the collisions. Constraints on the isospin dependence of the EOS therefore require a better understanding of isospin transport in general.

In peripheral and mid impact parameter collisions, calculations predict a more rapid isospin transfer to occur between projectile and targets of differing isospin when the asymmetry term has weaker density dependence [7]. This issue has been explored at higher incident energies by constructing ratios of isotopic yields $R_{21}(N,Z)=Y_2(N,Z)/Y_1(N,Z)$ for specific pairs of reactions with different total isotopic composition. Such ratios follow an isoscaling relationship [8]

$$R_{21}(N,Z)=Y_2(N,Z)/Y_1(N,Z)= C\exp(\alpha N+\beta Z), \qquad (1)$$

where α and β are the isoscaling parameters for the chosen pair of reactions. The left panel of Fig. 1 shows measured values for $R_{21}(N,Z)$ at incident energies of E/A=50 MeV, assuming ^{124}Sn +^{124}Sn collisions as reaction 2 and ^{112}Sn+^{112}Sn collisions as reaction 1 in Eq. 1. The solid and dashed lines show the fit to Eq. 1. Fits to the other systems

(^{124}Sn +^{112}Sn, and ^{112}Sn+ ^{124}Sn) though not shown are of similar quality. In the right panel of Fig. 1, we plot the best fit values for the isoscaling parameter, α, versus the overall isospin asymmetry of the colliding system: $\delta_O = (N_O - Z_O)/(N_O + Z_O)$, where N_O and Z_O are the corresponding total neutron and proton numbers. The solid and open points denote data for ^{124}Sn and ^{112}Sn projectiles, respectively.

The measured isoscaling parameters increase with the overall isospin asymmetry δ_O. Statistical calculations suggest an approximately linear dependence of α on the value for δ of the emitting source [9]. We note that the measured value for the ^{124}Sn projectile (solid point) is much larger than the value for the ^{112}Sn projectile (open point) at $\delta_O = 0.153$ indicating that isospin equilibrium is not achieved in these asymmetric systems. Indeed, the timescale for isospin diffusion appears to be comparable to the collision timescale [7]. BUU calculations suggest that isospin equilibrium would be approximately achieved if the asymmetry term had a sufficiently soft density dependence; the present observations are more comparable to the results calculated for an asymmetry term with strong density dependence [7]. We are interested to see whether the values for α for the two mixed systems will become more equal at E/A=35 MeV, where the collision timescales will be longer, and whether the comparisons of data at E/A-35 MeV to transport theory will lead to similar or different conclusions about the asymmetry term.

We are also very interested in the isospin dynamics of central collisions. In such collisions, the relative emission rate of neutrons and protons and the asymmetry of fragments resulting from bulk disassembly at low density depends strongly on the density dependence of the asymmetry term, providing sensitivity to it [11,12]. The incident energy of E/A=35 MeV is close to the multi-fragmentation threshold. The system is expected to spend a relatively long time at low-density as it proceeds to a multi-fragment disassembly; this has served to justify equilibrium interpretations of the fragmentation process including those involving the extraction of negative heat capacities [10]. There are a wide range of studies that will be undertaken if we are given time to measure central collisions; however, space permits us to only provide one example. Specifically, comparisons of isotopically resolved fragment mean energies and energy spectra provide sensitive information about the importance of surface emission as opposed to bulk equilibrium emission as a source of fragment production. The left panel of Figure 2 shows mean fragment kinetic energies <KE> measured in ^{112}Sn+^{112}Sn collisions at E/A=50 MeV [13]. Instead of the nearly linear dependence of <KE> on fragment mass expected from equilibrium models, the mean energies for the most neutron deficient fragment are higher, a trend that can be reproduced by the EES model that assumes surface emission of the fragments (right panel). By this simple measurement, the validity of equilibrium emission models for slowly expanding and multi-fragmenting systems can be sensitively tested.

GOALS OF PROPOSED MEASUREMENT: The principal goals of the experiment will be the precision measurement of isotopically resolved spectra of light particles and intermediate mass fragments over as wide an angular range as possible. Measurements at forward angles will easily allow determination of isospin diffusion to and from the projectile. Combining the measurements of the four combinations of ^{112}Sn and ^{124}Sn as projectiles and targets will enable one to establish isotopically resolved emission patterns over the full rapidity range from projectile to target. This will enable detailed exploration of isospin dynamics in these collisions and will provide information important to the goal of determining the density dependence of the asymmetry term of the nuclear EOS.

EXPERIMENTAL DETAILS: This experiment measures collisions of ^{112}Sn and ^{124}Sn beams and ^{112}Sn and ^{124}Sn targets with the Chimera array in its standard running configuration. Isotopic resolution will be obtained via the Si-

CsI(Tl) telescopes of the array at all angles where the particles penetrate the silicon detectors [14]. By combining the data from the four reactions, it will be possible to obtain the spectra at all angles for Z=1-5. For larger Z values there will be a region at low center of mass energy and angles about $\theta_{cm}\approx 90^o$, where data will not be available but it should be possible to interpolate this data with some uncertainty from the other angles.

Coverage for isotopic identification near projectile rapidities needed for measurements of isospin diffusion will be close to ideal. This angular coverage will also be excellent for the application of isospin tracing techniques to very central collisions [15,16], in which the isotopic distributions at forward angles are examined in order to assess the difference between forward emission when a ^{124}Sn beam bombards a ^{112}Sn target and the reverse condition when a ^{112}Sn beam bombards a ^{124}Sn target. The coverage for isotopic resolution of particles emitted at central rapidities will be good enough to address many if not most of the important questions, especially since the isoscaling parameters are to first order element independent.

BEAM TIME REQUEST: Our beam time estimate is based upon the following considerations. The experimental data-taking rate will be limited by the data acquisition to about 1000 events/s. Based on our experience, we estimate that it will take one day (three BTU's) to measure each of the four beam – target combinations. One day will be needed to change from ^{112}Sn to ^{124}Sn and one day will be needed with the ^{112}Sn beam at the beginning of the experiment to check that the Chimera detectors are all functioning properly. In addition, calibration beams will be needed. We would like this experiment to be scheduled in a campaign mode with other Chimera experiments so as to be able to use the standard Chimera calibration that involves Tandem beams. We also request two BTU's of a low energy (≈22 MeV/A) ^{4}He-H molecular ion beam and a CH_2 target in order to have a calibration of the CsI(Tl) crystals in our running configuration. If this molecular beam proves difficult to produce, we could use the lowest energy ^{4}He beam that can be produced by the cyclotron, instead. Including three BTU's for the development of the ^{4}He-H molecular ion beam, we request a total of (2+18+3 = 23 BTU's). (see calibration proposals submitted by A.Pagano).

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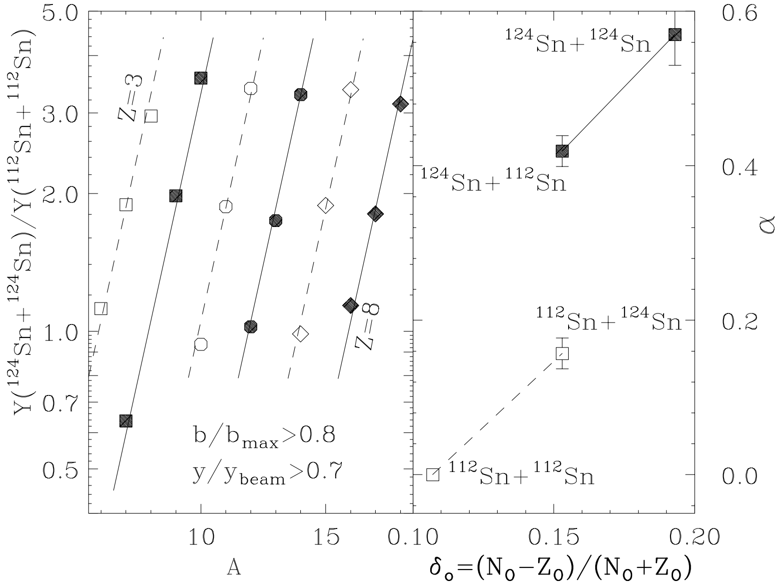

Fig. 1: Left panel: Measured values for $R_{21}(N,Z)= Y_{124+124}(N,Z)/Y_{112+112}(N,Z)$ (points) and fits with Eq. 1 (lines). The solid line and points represent even Z=4,6,8 isotopes while the dash lines and open points represent odd Z=3,5,6 isotopes. Right panel: Best fit values for α as function of δ_O. The lines serve to guide the eye. The reactions are labelled next to the data points. δ_O = 0.107 and 0.194 for the symmetric systems of ^{124}Sn+^{124}Sn and ^{112}Sn+^{112}Sn respectively. The two mixed systems have the same δ_O = 0.153. Solid points denote ^{124}Sn as the projectile and open points denote ^{112}Sn as the projectile.

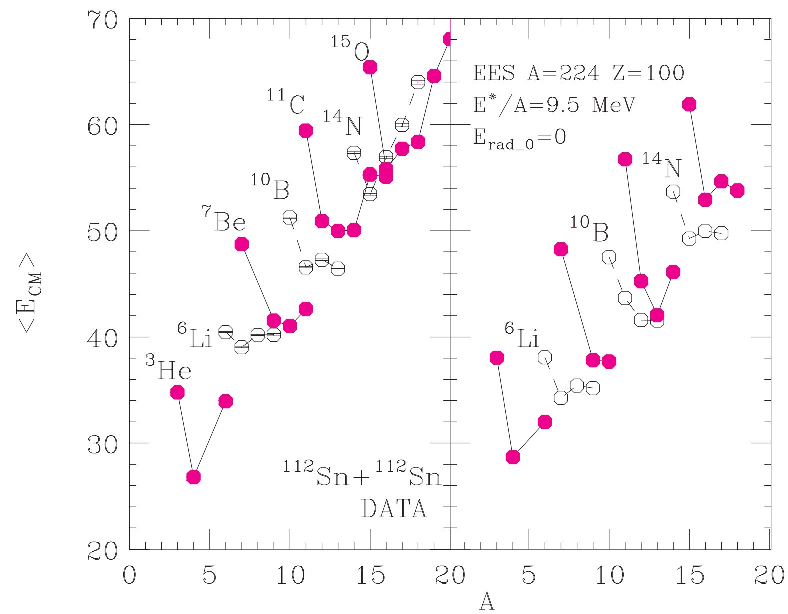

Fig. 2: Left panel: Measured values for the mean kinetic energies of fragments emitted near θ_{CM}=90° in central ^{112}Sn+^{112}Sn collisions at E/A=50 MeV. The experimental data deviate significantly from the expectations $\langle E_{c.m.}\rangle \approx \langle E_{thermal}\rangle + Z\cdot e\langle\Phi_{Coul}\rangle + A\cdot\frac{1}{2}m_N\langle v_{coll}^2\rangle$ for equilibrium emission. Right panel: Mean kinetic energies for fragments calculated with EES model, which assumes surface emission from an expanding emitting source.