Date Submitted: April 6, 2001          Experiment # ________________________________
(Assigned by NSCL)

TITLE: Investigating the Density Dependence of the Asymmetry Term of the EOS

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Is this a thesis experiment? Yes No         If yes, for whom? New Graduate Student

OTHER EXPERIMENTERS: (please spell out first name) Check, if applicable
Name                 Organization                    Grad     Sr. Grad
Robert Charity       Washington University
Demetrios Sarantites Washington University
Walter Reviol       Washington University
Konrad Gelbke       Michigan State University
Wanpeng Tan         Michigan State University
Man-Yee B. Tsang    Michigan State University
Marc-Jan Van Goethem Michigan State University
Giuseppe Verde      Michigan State University

REQUEST FOR CURRENT PERIOD: BEAM ON TARGET (either primary or rare-isotope)

<table>
<thead>
<tr>
<th>Particle</th>
<th>E/A(MeV)</th>
<th>Current (pps)</th>
<th>Desired beam purity (%)</th>
<th>Hours on target</th>
</tr>
</thead>
<tbody>
<tr>
<td>112Sn</td>
<td>50</td>
<td>6x10^8 p/s</td>
<td>100%</td>
<td>96</td>
</tr>
<tr>
<td>124Sn</td>
<td>50</td>
<td>6x10^8 p/s</td>
<td>100%</td>
<td>72</td>
</tr>
<tr>
<td>c)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

TOTAL REQUESTED HOURS: 168 (Calculated per note on beam list. Include time for test runs, for calibration of beams, and for particle/energy changes)

Will further time be requested for a subsequent PAC? If so, estimate additional hours: Experiment is self contained

HOURS APPROVED: _____________________
HOURS RESERVED: _____________________
SET UP TIME: (before start of beam):
Access to: Experimental Apparatus __________ 200 hrs
Electronics Set-up Area __________ 200 hrs (Be realistic—affects scheduling)
Data Acquisition Computer __________ 200 hrs

TAKE DOWN TIME: (After beam, include all calibrations, etc.):
Access to: Experimental Apparatus __________ 96 hrs
Electronics Set-up Area __________ 72 hrs (Be realistic—affects scheduling)
Data Acquisition Computer __________ 72 hrs

WHEN WILL YOUR EXPERIMENT BE READY TO RUN? __________ August __________ / ____ / 2001
DATES EXCLUDED: __________ September __________ 10-30 2001

EXPERIMENTAL EQUIPMENT (CHECK WHICH OF THESE DEVICES WILL BE USED):
__________ A1900 ___________ A1900
__________ 4pi Array ___________ NaI Array
__________ 92" Chamber ___________ Beta-Decay Station
__________ RPMS* ___________ x Neutron Walls (in S800 vault)
__________ S800 Spectrograph ___________ SuperBall
__________ Irradiation Station ___________ Other (give details)

*The RPMS is being refurbished and is not expected to be available for experiments till the beginning of 2002.

TARGETS: __________ 112Sn, 124Sn

SPECIAL REQUIREMENTS: (e.g., shipping RADIOACTIVE targets or sources, toxic gases, etc.)

NOTE: Shipping radioactive materials requires permission of both your institution and MSU. For information, contact Kristin Erickson (517)355-5008, ERICKS30@MSU.EDU.

SUMMARY (no more than 200 words)

The density dependence of the asymmetry term of the nuclear EOS is a property of nuclear matter that is key to the description of very asymmetric nuclear systems ranging from the surfaces of weakly bound neutron-rich nuclei to the interiors of neutron stars. Transport theory has made definite predictions concerning how the density dependence of the asymmetry term influences differently the transport of neutrons and protons in a nuclear collision. We propose to measure and contrast neutron and proton observables that have been singled out as especially sensitive to the asymmetry term. These are flow and the pre-equilibrium energy spectra. The experiment will be performed using the reaction version of the WU MICROBALL in conjunction with A NEUTRON ARRAY.
DESCRIPTION OF EXPERIMENT

Investigations of the pressure-density-temperature relationship, i.e., equation of state (EOS), of nuclear matter have primarily utilized “collective flow” observables constructed from the momenta of particles accelerated from the high-pressure, high-density region. Analyses of such observables 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 are presently bracketed by predictions for Skyme effective interactions with incompressibilities in the range of $K_{\text{inf}} = 180-310$ 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. The EOS has a quadratic dependence on the asymmetry, $E_{\text{sym}}(\rho) \beta^2$, where $\beta = (\rho_n - \rho_p) / (\rho_n + \rho_p)$. This dependence makes the asymmetry contribution dominant at the large asymmetries typical of neutron star matter. For example, the asymmetry term supplies all of 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 $E_{\text{sym}}(\rho)$ near saturation density, the density dependence of $E_{\text{sym}}(\rho)$ and the asymmetry contribution to the pressure, $P_{\text{asym}} = \rho^2 \cdot (dE_{\text{sym}}(\rho)/d\rho) \cdot \beta^2$, are not well constrained by existing data [2-4]. A range of density dependences for $E_{\text{sym}}(\rho)$ 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].

Sensitivity to the asymmetry term has been predicted for a number of observables that could be measured in nucleus-nucleus collisions. Because the forces generated by the asymmetry term are of opposite sign for protons and neutrons, comparisons of neutron and proton transverse collective flow provide special sensitivity to the asymmetry term. This feature is illustrated for collisions at $E/A=50$ MeV in Fig. 1, where predictions for the mean proton and mean neutron transverse momenta in the reaction plane are compared as a function of the rapidity [5]. The upper and lower panels show predictions for EOS’s with a more repulsive “asy-stiff” and a less repulsive “asy-soft” asymmetry term, respectively. In these lower energy collisions, the flow is sensitive to the density dependence of the asymmetry below saturation density. At these low densities in this parameterization, the “asy-soft” mean field potential is more attractive for protons than the “asy-stiff” mean field potential, counterbalancing the repulsive momentum transfers due to Coulomb and residual nucleon-nucleon interactions. Thus the “asy-stiff” with its less attractive overall interaction for protons leads to a larger partial pressure for protons than for neutrons and thus a larger flow signal for protons than for neutrons (see upper frame.)

In addition to flow, other comparisons of neutron and proton observables are predicted to be sensitive to the density dependence of the asymmetry term. For example, larger relative emission rates and
energies are predicted for neutrons than protons from n-rich system with a density dependence of the EOS described by the “asy-soft” parameterization. These effects are reduced with the “asy-stiff” EOS. These differences are shown in Fig. 2 where that ratio of the angle averaged neutron energy spectrum divided by the angle averaged proton energy spectrum for central (b< 5 fm) are shown for Sn+Sn collisions for the two different asymmetry dependences of the EOS [2]. There is a clear enhancement for the emission of energetic neutrons with an asy-soft EOS for the neutron rich systems. This clearly observable effect disappears for neutron deficient systems or if the “asy-stiff EOS” represents nature.

While the comparisons in Figs. 1 and 2 are for neutrons and protons, similar effects are predicted for comparisons of triton and $^3$He observables [6]. Due to the low efficiencies of neutron detectors, it is preferable to measure the density dependence of the asymmetry term via triton and $^3$He measurements if one can cross-calibrate the triton vs. $^3$He observables against their n vs. p counterparts.

**Goals of the proposed measurements**

Due the difficulty of performing neutron measurements with high efficiency, we propose to perform our initial measurements using asymmetric and symmetric collisions of stable $^{124}$Sn and $^{112}$Sn nuclei. The symmetric collisions this will allow us to cross-calibrate the triton vs. $^3$He observables against their n vs. p counterparts and to place first constraints upon the density dependence of the asymmetry term. The asymmetric collisions will provide important information about the transport of charge during the collision and allow important tests of the transport theoretic description of these collisions.

Using the information derived from the cross-calibrations, we plan to propose sensitive measurements utilizing rare isotope beams from the CCF to improve the constraints upon the asymmetry term derived from our initial stable beam measurements. For example, we plan to propose measurements of triton and $^3$He flow observables for systems like $^{130}$Sn+$^{124}$Sn and $^{107}$Sn+$^{112}$Sn that are experimentally feasible at CCF intensities and allow variations in N/Z ranging from 1.19 to 1.54.

**Experimental Details**

Both of the signals mentioned above will be investigated in the proposed experiment. A sketch of the setup is shown in Fig. 3. The required pieces of apparatus are:

1) Charged particle telescopes with sufficient depth to obtain the full spectra for mid-rapidity emission.
2) Neutron detectors also capable of extracting spectra over a wide angular range.
3) A device capable of impact parameter determination and capable of being used, in conjunction with the charged particle telescopes and neutron detectors, for the determination of the directed transverse flow as described below.

These tasks will be performed using the following tools:

1) The Si-CsI telescopes of LASSA that are located at 10 to 60 deg (relative to the beam axis) in the laboratory and view the target through an opened slice of the multiplicity device (see below).
2) The neutrons will be detected with the MSU neutrons walls [7] and about 10 discrete neutron detectors. All detectors will be placed at distances ranging from 4-6 m from the target and at angles so as to provide good coverage over polar angles ranging from 10° to 60° and asymuthal angles consistent with the removal of one microball element per ring. The discrete neutron detectors are 3” deep and 5” in diameter; they are owned by the WU group.

3) The reaction MICROBALL [8]. This heavy weight brother of the ball used for spectroscopy is still thin by intermediate energy reaction standards (3.5 mm to 9 mm CsI(Tl) back to front). However when calibrated beyond the punch through energies (MeV*A = 29 to 50 MeV back to front) is adequate for impact parameter determination and will allow the necessary angular coverage to complement the neutron detectors and LASSA telescopes in the determination of the mean transverse momenta of particles detected in those devices as described below. This device also has the advantage of being easy to use and, most crucially, presents a minimum of material for neutron in-scattering. Even with the very thin detectors and chamber in this experimental design, of the order of 10% of the neutrons will be scattered in the chamber, detectors and mounting structure. Thicker detectors would make the modeling of neutron scattering inside the chamber very problematic.

4) The experiment will be performed with the WU thin-walled neutron chamber, which will be mounted at the end of the S800 beam line, with the S800 spectrograph rotated to large scattering angles.

5) A time of flight start signal will be provided by an annular CsF start detector subtending angles of 80° ≤ θlab ≤ 100°

Let us examine the two experimental objectives.

**Relative spectra:**

A multiplicity selection on the MICROBALL will serve as an impact selector. The n and p spectra will be collected with the neutron detectors and the LASSA detectors respectively. The limited efficiency of the neutron detectors makes the neutron count rate the limiting factor the ratio of the energy spectra. We aim to achieve a total count \( N_{100} \) at least 100 neutrons/MeV at \( E_{CM} = 100 \text{ MeV} \) and \( 80° ≤ θ_{CM} ≤ 100° \).

**Relative flow:**

The mean transverse momenta of neutrons and light particles will be obtained via the techniques of Ref. [9] wherein the inner product \( I_{νμ} ≡ p_{ν}^+(y_ν) \cdot p_{μ}^+(y_μ) \) between the transverse momentum \( p_{ν}^+(y_ν) \) of a particle of type ν at rapidity \( y_ν \) and the transverse momentum \( p_{μ}^+(y_μ) \) of a particle of type μ at rapidity \( y_μ \) is averaged over the transverse momenta of the two particles. Random fluctuations of the transverse momenta about the collective mean values then average to zero in this approach, leaving only the collective mean values. Choosing a coordinate system in which the nonvanishing mean collective transverse momenta lie along the x
axis, this average inner product becomes [9,10] \( I_{\nu\mu} \approx \langle p_\nu^+(y_\nu) \rangle \langle p_\mu^+(y_\mu) \rangle \), which is a matrix that can be diagonalized to obtain \( \langle p_\nu^+(y_\nu) \rangle \). This procedure will provide accurate values for the mean transverse momenta in our experiment as long as one of the two particles used to construct \( I_{\nu\mu} \) is measured in the neutron detectors or the charged particle telescopes over a wide energy range [11]. We have extensive experience with this approach [10,12], which also provide rigorous procedures to correct for anisotropies in the detection apparatus and other effects.

**Count rate Estimates:**

Our count beam time estimate is based upon the following considerations. Our previous experience [10] has indicated the necessity for about \( 2 \times 10^6 \) central and mid-impact parameter events in order to obtain directed flow measurements of the necessary quality. The efficiency for neutron detection will be the major factor limiting our count rate. We use the 2m x 2m neutron walls in conjunction with 10 discrete neutron detectors with about 0.5 msr solid angle each, distributed so as to equalize the counting rate as a function of rapidity. The relative efficiency of this setup is about \( 7 \times 10^{-3} \) relative to a device with \( 4\pi \) neutron detection efficiency. The overall rate for Sn+Sn collisions is as follows:

<table>
<thead>
<tr>
<th>beam</th>
<th>intensity</th>
<th>target</th>
<th>cent. coll.</th>
<th>neutron rt</th>
<th>events/day</th>
<th>#days</th>
<th>total events</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{124})Sn 0.1 pna</td>
<td>(^{124})Sn 5mg</td>
<td>(5 \times 10^3 /s)</td>
<td>30 /s</td>
<td>(3 \times 10^6)</td>
<td>1</td>
<td>(3 \times 10^6)</td>
<td></td>
</tr>
<tr>
<td>(^{124})Sn 0.11 pna</td>
<td>(^{112})Sn 5mg</td>
<td>(5 \times 10^3 /s)</td>
<td>30 /s</td>
<td>(3 \times 10^6)</td>
<td>0.5</td>
<td>(1.5 \times 10^6)</td>
<td></td>
</tr>
<tr>
<td>(^{112})Sn 0.1 pna</td>
<td>(^{112})Sn 5mg</td>
<td>(5 \times 10^3 /s)</td>
<td>30 /s</td>
<td>(3 \times 10^6)</td>
<td>1</td>
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<td>(3 \times 10^6)</td>
<td>0.5</td>
<td>(1.5 \times 10^6)</td>
<td></td>
</tr>
</tbody>
</table>

In addition to the time for data taking, one needs roughly two days of beam to assess and control the neutron background due to scattering from the walls, floor, etc; most of this time will be devoted to measurements with shadow bars in front of the neutron detectors. In addition we request 16 hours for setup and 8 hours for calibration using recoil protons from a polyethylene target. Including 24 hours for a beam change from \(^{124}\)Sn to \(^{112}\)Sn, we request a total of seven days of beam time.
References


11. For example, this technique can be used to get the neutron transverse momenta from the inner product of neutron and alpha particle transverse momenta by forming the inner product of neutron transverse momenta at one rapidity bin with the alpha transverse momenta at a variety of rapidity bins. Because the alphas are measured at all azimuthal angles (backwards of $60^{\circ}$) the average over relative azimuthal angle of these inner products can be obtained. If there are six alpha rapidity bins, for example, the combination of the neutron-alpha inner product averages and the alpha-alpha inner product averages makes a 7x7 square matrix that can be diagonalized to provide the mean neutron and alpha transverse momenta averaged over the respective rapidity intervals and over the transverse momentum acceptance of their respective detectors. Clearly this analysis can be extended to provide the mean transverse momenta for neutrons detected at any rapidity and transverse momentum where there is neutron data.

Figure 1: BUU calculations for the mean transverse momenta of protons and neutrons for symmetric $^{124}$Sn collisions at E/A=50 MeV assuming an “asy-stiff” asymmetry term (upper panel) and an “asy-soft” asymmetry term (lower panel).

Figure 2: Ratio of neutron spectra averaged over scattering angle to proton spectra averaged over scattering angle as a function of the energy in the center of mass. The upper panel is for $^{124}$Sn+$^{124}$Sn and the lower panel is for $^{112}$Sn+$^{112}$Sn. In each panel, the upper curve corresponds to the calculations with the asy-soft EOS. The lower curve corresponds to the asy-stiff EOS. The middle curve corresponds to an EOS with a density dependence of the asymmetry term that is intermediate between the other two.

Figure 3: Schematic setup (not to scale) showing the UW microball, LASSA detectors and neutron detectors.