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Proposal for Nuclear Physics Experiment at RI Beam Factory

(RIBF NP-PAC-02, 2007)

Title of Experiment : Constraining the density dependence of the symmetry energy via isospin diffusion

[x] NP experiment [ ] Detector R&D [ ] Construction

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Experimental Device:

[ ] GARIS [ ] CRIB [ ] RIPS [x] BigRIPS /ZD

Beam Time Request Summary

Tuning with beam	1	Days
DATA RUNS	4.9	Days
Total	**5.9**	**Days**

Primary Beam

Particle ^{124}Xe, ^{136}Xe Energy 200 (A MeV) Intensity 100 pna

Sheet for an experiment with RI beam

[ ] CRIB

[ ] RIPS

[x] BigRIPS

RI Beams			Beam-On-Target Time for DATA RUN
isotope	Energy(MeV/A)	Intensity(/s)	hours
^{108}Sn	50	6.50E+05	36
^{112}Sn	50	1E+06	52
^{124}Sn	50	8.50E+05	45
^{136}Xe	200	$5x10^7$	8

Estimated date ready to run the experiment **June 2008**

Dates which should be excluded, if any **none at present**

Summary of Experiments:

We propose to measure the isotopic distribution of projectile residues from the collisions of Sn isotopes, which differ in their isospin asymmetry. Such measurements potentially offer a uniquely direct comparison to transport theory because they suffer no ambiguities concerning the particle production mechanism or the reaction timescale. For the first time, we will use a rare isotope beam, e.g. ^{108}Sn, to probe the symmetry energy. This allows us to increase the asymmetry difference between projectile and target and thereby increases the diffusion rate between the two nuclei. It will also double the number of measurements of diffusion that have been obtained so far and provide more stringent constraints on the density dependence of the symmetry energy.

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Detailed Description of the proposed experiment

Goals and methods of the proposed experiment:

The nuclear Equation of State (EOS) describes the relationships between the energy, pressure, temperature, density and isospin asymmetry $\delta=(\rho_n-\rho_p)/\rho$ for a nuclear system [Dan02]. The symmetry energy term, which governs the asymmetry dependence of the EOS, also governs many properties of neutron stars, such as stellar radii and moments of inertia, maximum masses [Lat01, Lat04, Ste05], crustal vibration frequencies [Wat06], and neutron star cooling rates [Yak04, Ste05]. Measurements have constrained the equation of state for symmetric matter for densities ranging from saturation density to five times saturation density [Dan02, Fuc06, Gar05]. Until recently, constraints on the density dependence of the symmetry energy have been rather weak [Bro00].

Methods: In this proposal we outline a set of measurements of isospin diffusion [Tsa04] that can provide significant constraints on the density dependence of the symmetry energy at sub-saturation densities, $\rho/\rho_0 \approx 0.5$-1 [Shi03, Tsa04, Che05]. Such studies usually compare A+B collisions of a neutron-rich nucleus (A) and a proton-rich nucleus (B) to symmetric collisions involving two neutron-rich nuclei (A+A) and two proton-rich (B+B) nuclei under the same experimental conditions [Tsa04]. When the collision involves projectile and target nuclei (A+B or B+A) with different isospin asymmetries, $\delta=(N-Z)/A$, the symmetry energy enhances the diffusion rate that drives the system towards isospin equilibrium so that the difference between neutron and proton densities is minimized. When the collision involves symmetric projectile and target nuclei (A+A or B+B) with the same isospin asymmetries, the measurements provide reference values for the projectile-like residues of neutron rich systems A+A and proton rich systems B+B in the limit of vanishing diffusion. These reference values allow one to extend isospin diffusion measurements to more asymmetric systems achievable with rare isotope beams, as we discuss below.

The most important quantity to determine is the asymmetry of the projectile-like residue immediately after the collision and prior to secondary decay because this is the quantity that is calculated in transport theory [Shi03, Tsa04, Che05]. To do this, one can measure an observable X that is linearly dependent on the residue asymmetry, i.e. $X = a\cdot\delta+b$, and construct the corresponding isospin transport ratio $R_i(X)$

$$R_i(X) = 2\frac{X-(X_{A+A}+X_{B+B})/2}{X_{A+A}-X_{B+B}} \qquad (1)$$

Then, trivial substitution provides that $R_i(X)=R_i(\delta)$ and one dispenses with most of the uncertainty associated with determining δ from measurements of X. This technique is very precise but one must experimentally demonstrate that the observable X varies linearly with δ.

Alternatively, one can simply calculate $R_i(X)$ from $R_i(\delta)$ with a residue decay theory, for each of the values of δ predicted by transport theory for the various density dependent symmetry terms [Tsa04]. This suffers due to the model dependencies and limited statistical precision of residue decay calculations [Tsa04].

In our published data, we used the isoscaling parameter ($X=\alpha$) from collisions involving the asymmetric ^{124}Sn+^{112}Sn (A+B) and ^{112}Sn+^{124}Sn (B+A) systems and the two symmetric systems ^{124}Sn+^{124}Sn (A+A) and ^{112}Sn+^{112}Sn (B+B) [Tsa04]. The neutron isoscaling parameters α and the proton isoscaling factor β are typically obtained from the ratios of isotopic yields from two reactions that differ essentially in their isospin compositions:

$$R_{21}(N,Z)=Y_2(N,Z)/Y_1(N,Z)= C exp(\alpha N+\beta Z). \quad (2)$$

Here, $Y_i(N,Z)$ is the yield of the measured fragments with neutron number N and proton number Z emitted in reaction i (i=1,2), and C is the normalization constant obtained by fitting the isotope yield ratios to Eq. (2). In the experiments, yields from the ^{124}Sn+^{112}Sn (A+B), ^{112}Sn+^{124}Sn (B+A) ^{124}Sn+^{124}Sn (A+A) and ^{112}Sn+^{112}Sn (B+B) were each divided by the yields from the ^{112}Sn+^{112}Sn (B+B) reaction to obtain the isoscaling parameter. Relations between α, β, and α-β and δ have been obtained for evaporative and multifragment decays of an excited projectile-like fragment and both theories predict a linear dependence of α, β, and α-β on the residue asymmetry δ [Bot02,Tsa01]:

$$\begin{aligned}
&\alpha = \Delta\mu_n / T = 2C_{sym}(\Delta\delta)(1-\overline{\delta})/T, \\
&\beta = \Delta\mu_p / T = -2C_{sym}(\Delta\delta)(1+\overline{\delta})/T, \\
&and \\
&\alpha - \beta = (\Delta\mu_n - \Delta\mu_p)/T = 4C_{sym}(\Delta\delta)/T,
\end{aligned} \quad (3)$$

where $\Delta\delta=\delta_2-\delta_1$ and $\overline{\delta}=(\delta_2+\delta_1)/2$ are the differences and the mean of the asymmetries of the emitting source, and C_{sym} is the coefficient of the symmetry energy term in the nuclear Gibbs free energy.

The linear dependence of the isoscaling parameters α, β, and α-β on δ, has been experimentally demonstrated for central collisions. In the upper panel of Figure 1, we compare the values for α, β, and α-β obtained at mid-rapidities for central ^{112}Sn+^{112}Sn (δ= 0.107), ^{112}Sn+^{124}Sn (δ= 0.153) and ^{124}Sn+^{124}Sn (δ= 0.194) collisions as a function of the total asymmetry using the data of ref. [Liu04]. Figure 1 clearly establishes the linear dependence of the isoscaling parameters on δ for central collisions, independent of theory. We have an approved experiment at the NSCL to determine the dependence of the isoscaling parameters on δ for peripheral collisions and this test will be completed prior to this proposed measurement.

The quantity α-β can be related to the ratios of yields of mirror nuclei Y(N,Z) and Y(Z,N) (where |N-Z|=1), providing additional diffusion observables. From these ratios, one obtains:

$$X_A = ln(Y_2(N,Z)/Y_1(Z,N)) = \alpha-\beta+ ln(C) \quad (7)$$

where A=N+Z and C is a constant. The bottom panel of Figure 1 shows that X_7 and X_{11} also depend linearly on δ. The rapidity dependence of the isospin transport ratio $R_7 \equiv R_i(X_7)$ in our previous experiment is shown by the data points in Figure 2 [Liu06]. R_7 is nearly flat near the projectile and the target rapidity regions before dropping to zero around mid-rapidity. This indicates that these fragments observables are not very sensitive to details of the fragment rapidity gate. Other analyses also indicate that the dependence on the transverse momenta of the detected fragments is small as well. The shaded boxes in Figure 2 show the published isospin transport ratio analyses using $R_i(X=\alpha)$, which yielded values of 0.47±0.05 at y/y_{beam} = 0.7-1.0 (from $^{124}Sn+^{112}Sn$ collisions) and -0.45±0.05 at y/y_{beam}=0-0.3 (from $^{112}Sn+^{124}Sn$ collisions) at an impact parameter gate of $0.8 \leq b/b_{max} \leq 1$ (b≈6 fm) [Tsa04]. In the overlap region of rapidities, $R_i(X_7)$ obtained from the $Y(^7Li)/Y(^7B)$ mirror nucleus ratio and $R_i(\alpha)$ obtained from isoscaling parameters are consistent within experimental uncertainties.

The scientific potential of the isospin transport ratio measurements to place constraints on the density dependence of the symmetry energy is illustrated by Figure 3. In this figure, the circles show corresponding values for R_i [Tsa04] calculated with the Bolzmann-Euhling-Uhlenbeck (BUU) equation at an impact parameter of b≈6 fm for symmetry energy terms with different density dependencies [Che05]. These calculations are arranged from left to right in the order of increasing stiffness of the density dependence; the intersection of theoretical and experimental values provides some indication of the range of density dependencies for which the data and calculations are consistent. The figure also summarizes model calculations [Che05, Li06, Ste05], with the same symmetry energies, of the radii of 1.4 solar mass neutron stars (upper axis) and of the difference between neutron and proton radii for ^{208}Pb (lower axis). While the constraints shown in Figure 3 are preliminary, the figure illustrates relationships that exist between these quantities, which all depend sensitively on the symmetry energy.

In the proposed experiment, we will obtain the isospin transport ratios from the cross sections of residues detected in the zero degree spectrometer. These fragments come directly from residue decay and their isospin transport ratios $R_i(X)$ are unambiguously related to the isospin asymmetry of the projectile residue. Present theoretical calculations assume that the projectile-like residue emits fragments whose yields are involved in the computation of $R_i(X)$ after the two residues separate. While this is certainly true for many of the fragments included in the previous isospin diffusion measurement, it may not be true for all. Fragments that are emitted before the residues separate will reflect the asymmetry δ at an earlier stage of the reaction when the diffusion is less complete. This concern will be eliminated in the proposed measurement.

The residue cross sections are larger than the cross sections for the fragments with $3 \leq Z \leq 8$ that were measured in the previous study. This permits us to extend our measurements to unstable beams and increase the asymmetry difference between projectile and target by colliding ^{108}Sn projectiles with a ^{124}Sn target. We propose to measure six reactions $^{108}Sn+^{112}Sn$, $^{108}Sn+^{124}Sn$, $^{112}Sn+^{124}Sn$, $^{124}Sn+^{112}Sn$, $^{112}Sn + ^{112}Sn$ and $^{124}Sn+^{124}Sn$. This allows us to define 4 isospin transport ratios. Predictions using the BUU transport equation for the time dependence of the collisions of $^{108}Sn+^{124}Sn$ isospin transport ratios are shown in Figure 4 for two different assumptions about the density dependence of the symmetry energy. The red and black points correspond to the predictions for symmetry energies with strong and weak density dependencies, respectively.

The current proposal is an important first step towards the exploration of isospin diffusion and the symmetry energy with rare isotope beams. It will double the number of constraints on the symmetry energy that were obtained in the first experimental work and should make the final constraints on the symmetry energy much more stringent.

Goals: The primary goals are to improve the constraints on the symmetry energy provided by measurements of the isospin transport ratios for peripheral collisions at an impact parameter of about 6 fm. More specifically we will:

1) Determine the isospin transport ratios $R_i(X)$ for fragments that come unambiguously from residue decay.

2) Improve the constraints on the symmetry energy from isospin diffusion by using rare isotope beams. The combination of the ^{108}Sn projectile with the ^{124}Sn target represents the largest asymmetry difference between projectile and target that has been achieved experimentally. Measurements of ^{108}Sn+^{124}Sn and ^{108}Sn+^{112}Sn collisions will double the number of diffusion observables that can be used to constrain the density dependence of the symmetry energy. This is the first test of the use of rare isotope beams to expand the sensitivity to the symmetry energy; it paves the way towards more sensitive future measurements with ^{132}Sn and ^{104}Sn beams with even larger asymmetry differences.

In addition to the diffusion observable, these measurements will provide isotopically resolved measurements of fragment production as a function of impact parameter and overall system asymmetry. Such information will help to constrain models for the fragmentation process that are currently used to predict rare isotope beam intensities and the yields of fragments needed for experimental studies of nuclear structure and nuclear astrophysics.

Experimental Details and beam time request:

The experimental equipment will consist of the WU *Reactions* Microball, the LASSA silicon strip detector array, a microchannel plate tracking detector and the ZeroDegree spectrometer. A schematic layout of the experiment in Figure 5 shows selected rings of the Microball in a 1 m^3 cubic scattering chamber along with the LASSA array and a microchannel plate tracking detector. We have a fully instrumented 1 m^3 scattering chamber that can be used for these measurements if there is no suitable chamber in Riken.

The secondary ^{108}Sn, ^{112}Sn and ^{124}Sn beam intensities were simulated using LISE and assuming 100 pna primary ^{124}Xe (for ^{108}Sn, ^{112}Sn) and ^{136}Xe (for ^{124}Sn) beams at E/A=200 MeV. The predicted intensities of the ^{108}Sn, ^{112}Sn, and ^{124}Sn beams are listed in Table 1. The predicted impurities of the ^{108}Sn, ^{112}Sn, and ^{124}Sn beams are <0.3% for all three beams. The beam phase spot, was constrained to be less than 1.2 mm in diameter. Even though the purities are predicted, we anticipate that the close geometry in the chamber may make it necessary to track the beam particles individually to determine their trajectories. We have therefore limited the beam intensity to $1x10^6$ /s in calculating the data rates.

The multiplicities and transverse energies of charged particles detected by the Microball and the LASSA will be used to determine the impact parameter. Similar set ups were used to measure the previous isospin diffusion shown in Figures 1-4 [Liu06]. The *Reactions* Microball is a small

4π array of 98 CsI(Tl) scintillators [Sar96]. At angles of less than about 28^0, the Microball detectors will be remove to allow passage of charged particles, which will be detected in the LASSA Silicon-CsI(Tl) strip detector array, consisting of nine Silicon-CsI strip detector telescopes [Dav01]. In this experiment, eight out of the nine LASSA telescopes will be arranged in a rectangular 3X3 array centered at 0 degrees, with the center telescope removed to allow the passage of the beam. Isospin transport ratios for fragments with $3 \leq Z \leq 4$ will be measured with LASSA to cross check them with the isospin transport ratios from residue decay fragments measured with the ZeroDegree Spectrometer.

We have simulated the response of the spectrometer to these fragments using LISE. Most of the fragments will be emitted at angles of less than 2.5^0, inside the acceptance of the spectrometer. With momentum and focal aperture settings chosen to avoid beam charge states, it is possible to obtain the residue fragments data with 5-6 magnetic settings.

Our simulations indicate that accurate measurements can be obtained using 50 mg/cm^2 ^{112}Sn and ^{124}Sn targets. Even with such thick targets, the counting rates will be low. The ^{112}Sn beam has the highest intensity; even for ^{112}Sn, we don't expect the event rates to exceed 100 events/sec. At this event rate, we expect that dead time should not be an issue. We need six different reactions: ^{124}Sn+^{124}Sn, ^{124}Sn+^{112}Sn, ^{112}Sn+^{124}Sn, ^{112}Sn+^{112}Sn, ^{108}Sn+^{124}Sn and ^{108}Sn+^{112}Sn, to construct the four possible isospin transport ratios. The construction of each isospin transport ratio, as defined in Eq. 3, requires the measurement, for all reactions, of the yields of the isotopes that enter into the ratio. Typical values were be simulated by calculating the production of As isotopes with A=70-74, Fe isotopes with A=54-58, and Zr isotopes with A=86-90. The rates of some of the low statistics ratios and the corresponding beam times for these isotopes are listed in Table 1. This time request includes 3 hours to change the rigidity of the ZeroDegree Spectormeter during these measurements. In addition we request 24 hours of beam time to set up the Microball, LASSA and Zero-degree spectrometer and to check the trigger condition. For convenience, we add the debugging time to the request for ^{112}Sn beam. (^{124}Sn beam is also acceptable.)

Finally, we request 8 hours to calibrate the CsI(Tl) detectors of the LASSA array by measuring the pulse heights of hydrogen ions that penetrate though the CsI(Tl) detectors using the primary ^{124}Sn beam at E/A=200 MeV. For this, it is only necessary to have a high-energy beam; other beams such as O, Ni or Ca can serve the same purpose. (The silicon detectors will be measured with an alpha source.) It would be very useful to have access to a multi-peak ^{228}Th source for this purpose.

The total beam time request is 141 hours. At present, the RIBF facility is the only facility where this experiment is feasible. It has the highest ^{108}Sn intensity in the world, over 6 times larger than the available intensities at the NSCL, according to the available information.

Beam	^{108}Sn	^{108}Sn	^{112}Sn	^{112}Sn	^{124}Sn	^{124}Sn
Intensity	6.50E+05	6.50E+05	3.90E+06 (limit to $1x10^6$)	3.90E+06 (limit to $1x10^6$)	8.50E+05	8.50E+05
Tgt (50 mg/cm^2)	^{112}Sn	^{124}Sn	^{112}Sn	^{124}Sn	^{112}Sn	^{124}Sn
typical rates (s^{-1})	0.21	0.19	0.28	0.26	0.15	0.18
time to achieve 2% precision	17.5 hrs	18.5 hrs	13.5 hrs	14.5 hrs	24.5 hours	20.5 hours

Table 1: Beams, targets and times required of the taking the primary data for the proposed measurements. In addition to these times, 24 hours of ^{112}Sn beam are needed to set up the electronics and beam line, 8 hours of ^{124}Sn beam are needed for calibrating the CsI(Tl) scintillators, and 3 hours are needed to change the rigidities of the ZeroDegree Spectrometer.

Readiness: The Microball, channel plate, LASSA and their electronics exist. The 50 mg/cm^2 ^{112}Sn and ^{124}Sn targets would need to be made. We believe that it is technically feasible to begin mounting this experiment in May 2008 at the earliest.

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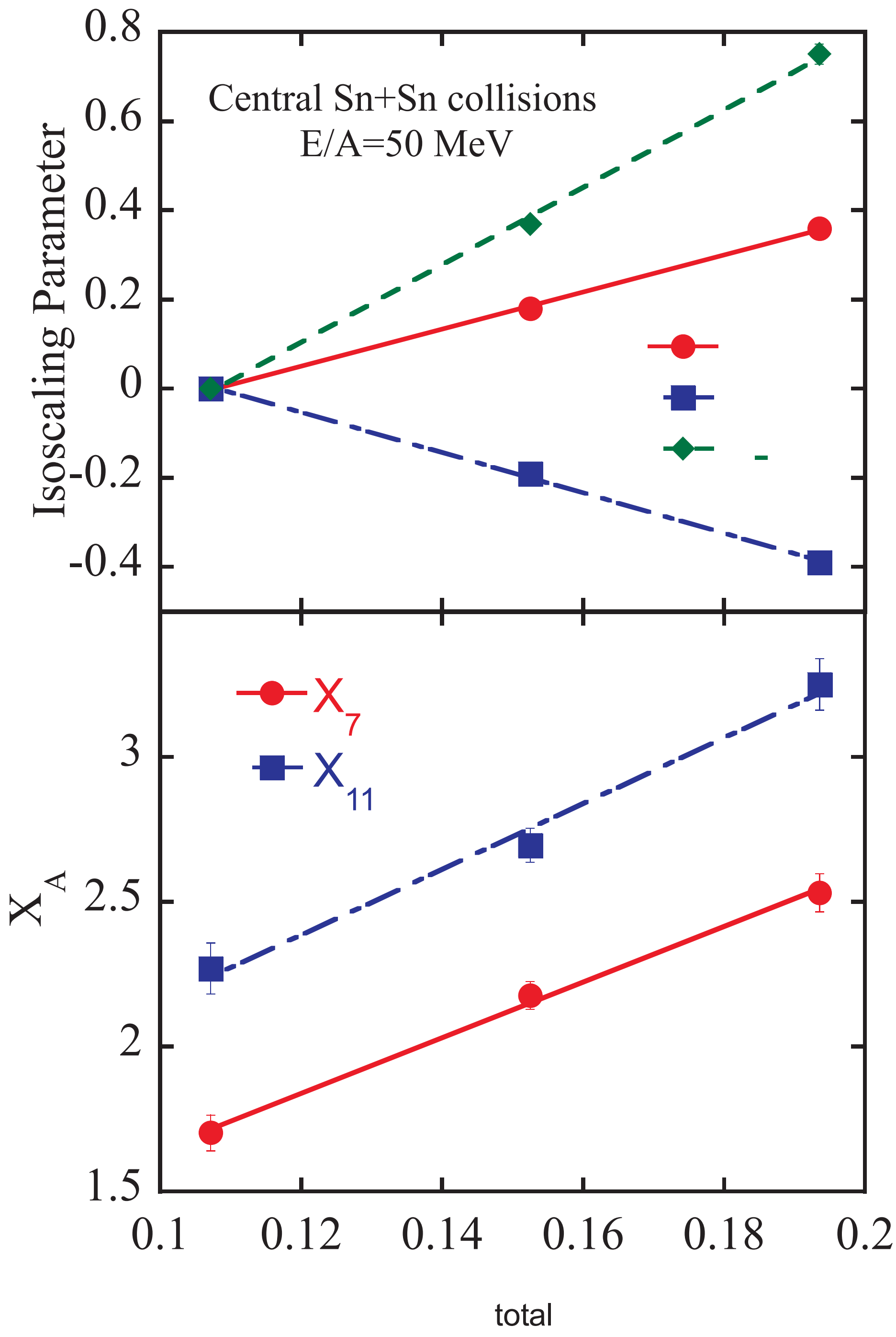

Figure 1: Upper panel: The circles, squares and diamonds show the experimental data for α, β and α-β, respectively, that have been measured for central Sn+Sn collisions. The x axis corresponds to the isospin asymmetry of the combined system. Lower panel: The solid circles, and solid squares show the experimental data for X_7 and X_{11}, respectively, for the same reactions shown in the upper panel.

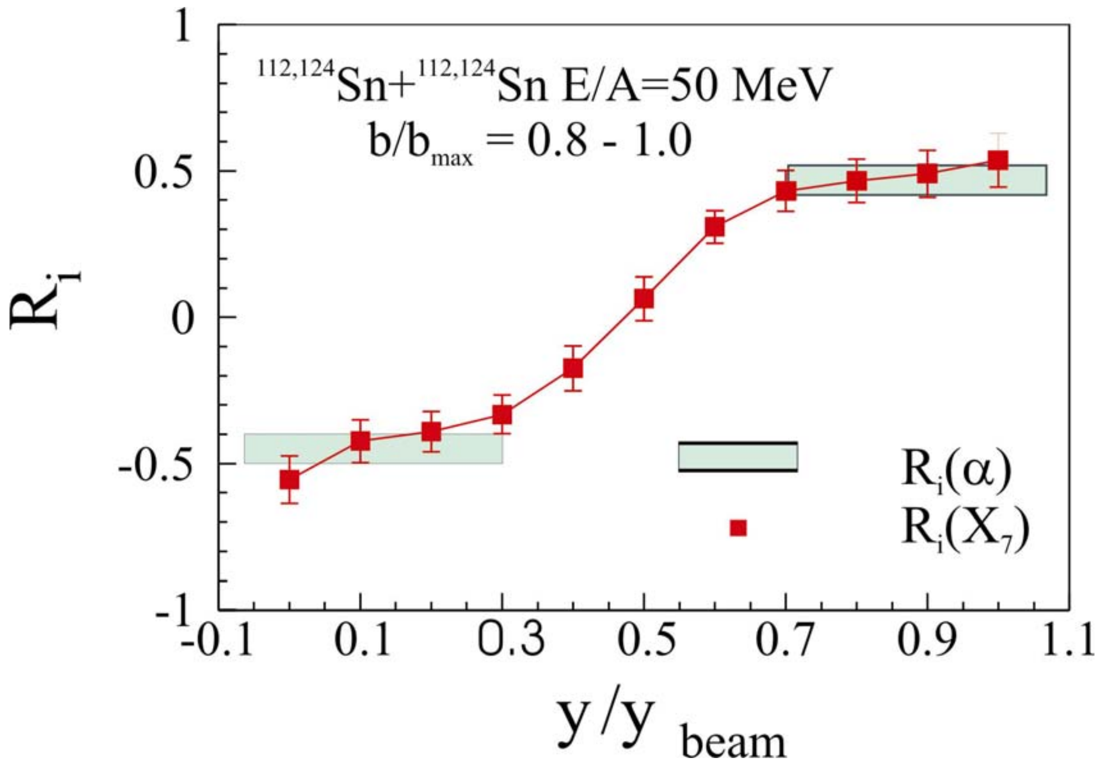

Figure 2: The shaded rectangles at $0 < y/y_{beam} < 0.3$ and $0.7 < y/y_{beam} < 1.0$ show the values of $R_i(\alpha)$ measured for the ^{124}Sn+^{112}Sn and ^{112}Sn+^{124}Sn systems, respectively [Tsa04]. The data points show the values of $R_i(X_7)$ measured for A=7 mirror nuclei in peripheral ^{124}Sn+^{112}Sn collisions as a function of rapidity.

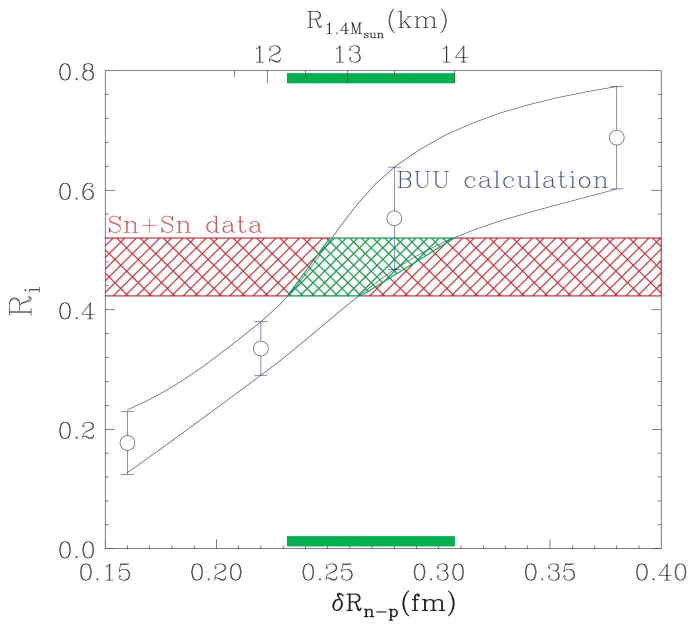

Figure 3: Comparison of measured [Tsa04] (red crosshatched region) and calculated [Li06] (solid points) values for the isospin transport ratio R_i. The theoretical error bars represent the statistical uncertainties of the theoretical simulations. The top and bottom scale summarize model calculations [Li06] for radii of 1.4 solar mass neutron stars (top scale) and for the difference between neutron and proton radii of ^{208}Pb (bottom scale) for those symmetry energy functions that were used in calculating the isospin transport ratio.

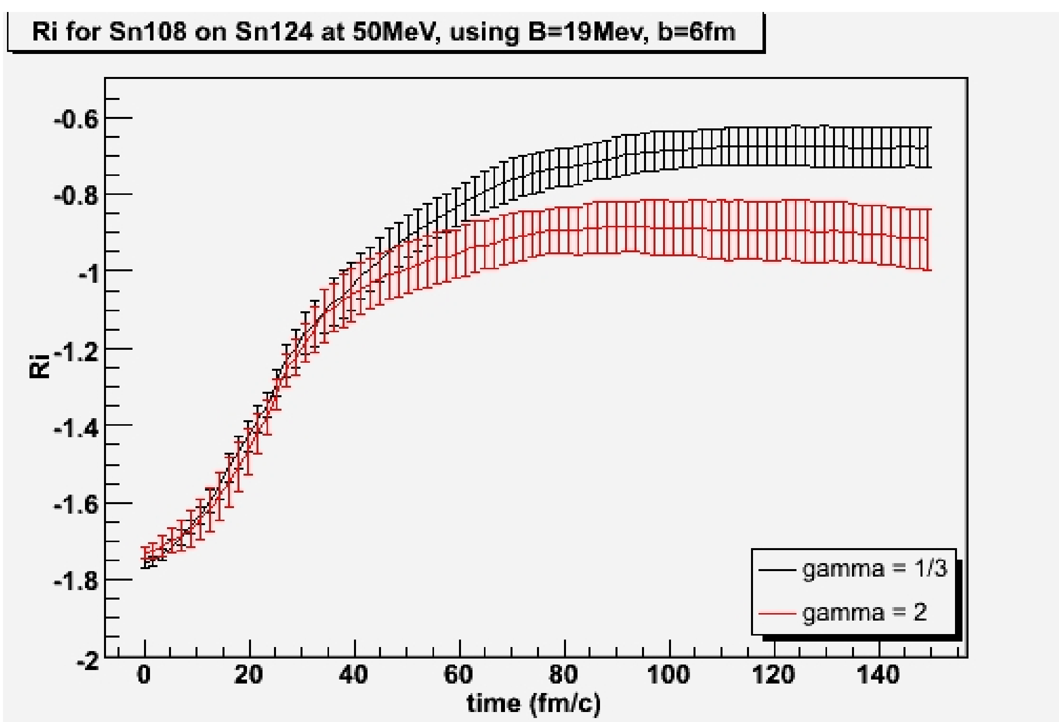

Figure 4: Theoretical isospin transport ratios.

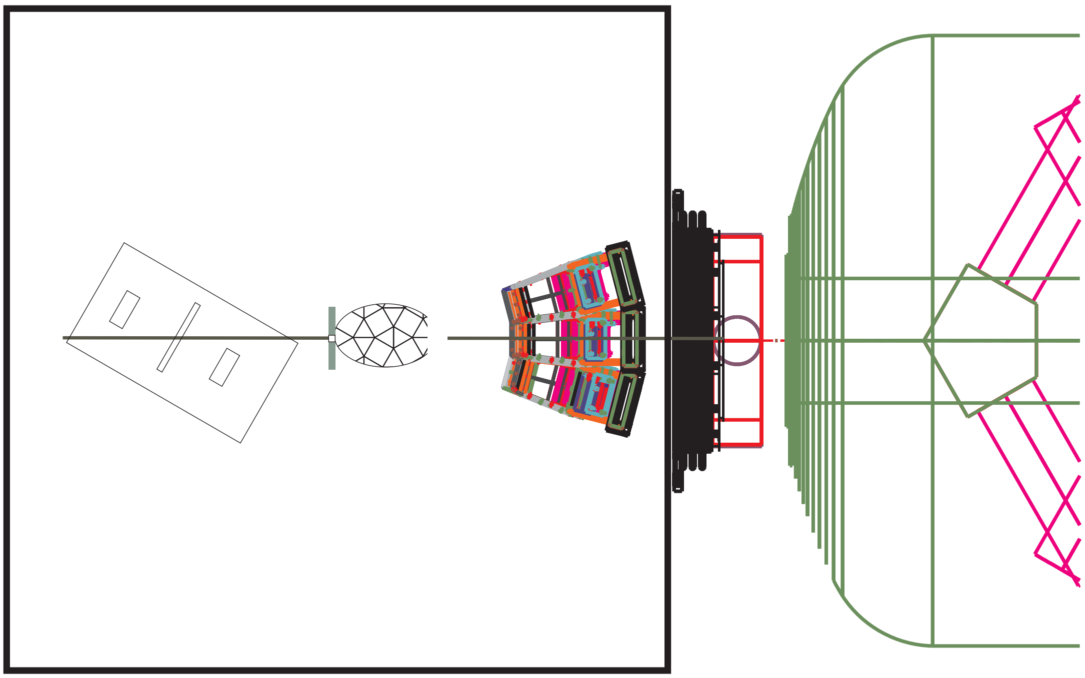

Figure 5: Overhead view of the experimental setup involving the channel plate tracking detector, the Microball, and LASSA (at forward angles) inside the scattering chamber.