I. Project Objectives:

One of the future directions in FRIB physics is to understand the "nature of neutron stars and dense nuclear matter" [LRP07], a goal that requires understanding the Equation of State (EoS) for neutron-rich matter. The nuclear EoS is a fundamental property of nuclear matter that describes the relationships between the energy, pressure, temperature, density and isospin asymmetry $\delta=(\rho_n-\rho_p)/\rho$ for a nuclear system [Dan02]. It can be divided into a symmetric matter contribution that is independent of the isospin asymmetry and a symmetry energy term, proportional to the square of the asymmetry [Lat01, Lat04]. This second term describes the dependence of the EoS on asymmetry. Investigations that provide an improved understanding of this term will also provide an improved understanding of masses [Dan03], fission barriers, energies of isovector collective vibrations [Kli07, Dan03], the thickness of the neutron skins of neutron-rich nuclei [Bro00], and an improved understanding of the role of isovector modes in fusion and strongly damped collisions.

Macroscopic quantities of asymmetric nuclear matter exist over a wide range of densities in neutron stars and in type II supernovae [Lat01]. Experimental information about the EoS can help to provide improved predictions for neutron star observables such as stellar radii and moments of inertia, crustal vibration frequencies [Lat04,Vil04], and neutron star cooling rates [Lat04,Ste05] that are currently being investigated with ground-based and satellite observatories. For many of these observables, the absence of strong constraints on the symmetry energy term of the EoS engenders major theoretical uncertainties. Consequently, the goal of determining the EoS has been a major motivation for many X-ray observations of neutron stars including the proposed International X-ray Observatory [Ixo08]. For example, recent X-ray observations with the XMM-Newton X-ray telescope have been interpreted as requiring an unusually repulsive equation of state for neutron matter [Oze05]. While these observations and their interpretation have not been confirmed, the proposed investigations outlined here are urgently needed to check whether similar conclusions in the future can be supported by laboratory measurements.

The proposed project meets the criteria set forth in the 10 CFR Part. 605.10 (d):

- **Scientific and/or technical merit of the project:** The proposed measurements meet the goal of determining the EoS of neutron rich matter, which is key to the LRP goal of "understanding the nature of neutron stars and dense nuclear matter" [LRP07]. Colliding neutron rich nuclei provide the only means to compress neutron-rich matter in the laboratory and determine its EoS. The expected constraints are described in Sections II - IV.
- **Appropriateness of the proposed method or approach:** This project aims to measure all observables that have been identified as being sensitive to the EoS of neutron-rich matter at supra-saturation densities. The proposed measurements, described in Sections III and IV, will be performed at the world's best facilities for such studies, using the most appropriate measurement techniques.
- **Competency of the applicant's personnel and adequacy of the proposed resources:** The international experimental team includes top experts in this field. This team and the technical resources at the NSCL and RIKEN, described in Section VI, are capable of developing the SAMURAI dipole and its Time Projection Chamber, described in Section V.
- **Reasonableness and appropriateness of the proposed budget:** The budget is justified in Sections VI and VII. The requested sum is modest in accomplishing one of the goals set forth in the LRP of understanding the "nature of neutron stars and dense nuclear matter" [LRP07].

Currently the U.S. PI's are leading in this research area in terms of providing the best sets of experimental data and some of the first constraints in the sub-saturation density region. To maintain this lead, U.S. scientists need the opportunities to run experiments using high energy beams and beams with largest asymmetry difference available. The proposed project will provide the U.S. scientists opportunities to use the unique neutron-rich beams at Riken and at GSI. The proposed experiments in these two facilities will not be possible in other existing facilities. The project will provide the opportunity for a leading role by U.S. participants both in the forefront technology to build a Time-Projection Chamber, to conduct experiments in determining the constraints on the density dependence of the symmetry energy at the premier radioactive ion beam facilities in the world and to provide guidance to the U.S. scientists the research direction at FRIB in this research topic. This investment is vital to maintain U.S. scientific leadership in the study of dense asymmetric matter.

II. Constraints on the density dependence of the symmetry energy from heavy ion collisions

The total energy per nucleon (i.e. the Equation of State (EoS)) of cold nuclear matter can be written as the sum of a symmetry energy term and the energy per nucleon of symmetric matter,

$$E(\rho, \delta) = E_0(\rho, \delta{=}0) + E_\delta;\ E_\delta = S(\rho)\delta^2, \qquad (1)$$

where the asymmetry $\delta = (\rho_n - \rho_p)/\rho$, ρ_n, ρ_p and ρ are the neutron, proton and nucleon number densities, and $S(\rho)$ describes the density dependence of the symmetry energy term, E_δ. Measurements of isoscalar collective vibrations, collective flow and kaon production in energetic nucleus-nucleus collisions have constrained the equation of state for symmetric matter, $E_0(\rho, \delta{=}0)$, for densities ranging from saturation density to five times saturation density [Dan02, Fuc06, You97]. The extrapolation of the EoS to neutron–rich matter depends on $S(\rho)$, which has few experimental constraints [Bro00] until recently.

Many recent efforts to constrain the density dependence of the symmetry energy have focused on its behavior near saturation density. There, one may expand the symmetry energy, $S(\rho)$, about the saturation density, ρ_o,

$$S(\rho) = S_0 + \tfrac{L}{3}\left(\frac{\rho-\rho_o}{\rho_o}\right) + \tfrac{K_{sym}}{18}\left(\frac{\rho-\rho_o}{\rho_o}\right)^2 + \ldots \qquad (2)$$

where L and K_{sym} are slope and curvature parameters at ρ_o. The slope parameter, L, is related to p_o, the pressure from the symmetry energy for pure neutron matter at saturation density as follows:

$$L = 3\rho_0 \left| dS(\rho)/d\rho \right|_{\rho_0} = [3/\rho_0] p_0. \qquad (3)$$

The symmetry pressure, p_o, provides the baryonic contribution to the pressure in neutron stars at saturation density [Ste05], where the energy of symmetric matter, $E_0(\rho, \delta{=}0)$, contributes no pressure, and it is also related to the neutron skin thickness (δR_{np}) of neutron rich heavy nuclei including ^{208}Pb [Hor01,Typ01]. In the last few years, measurements of collective structures such as the Giant Monopole Resonance [Li07] and the Pygmy Dipole Resonance [Kli07] in neutron-rich nuclei, and measurement of reaction observables such as isospin diffusion [Tsa04], neutron/proton emission [Fam06], and fragment isotopic ratios [Tsa01, Igl06] have provided initial constraints on the density dependence of the symmetry energy at sub-saturation densities [Li08, Tsa08].

Fig. 1 compares constraints obtained from different analyses of experimental data. The plotted quantities, L and S_0 are the slope and symmetry energy at saturation density that parameterize the density dependence of the symmetry energy in Eq. (2). The lower box centered at S_0 = 32 MeV depicts the range of p_o values (right axis) from analyses of Pygmy Dipole Resonance data [Kli07].

The upper box centered at S_0 = 32.5 MeV depicts the range of L and S_0 values reported in Ref. [Dan08] from the analyses of mass dependence of nuclear symmetry energies. The vertical dot-dashed line at S_0 = 31.6 MeV depicts the range of L values obtained from the comparisons of Boltzmann-Uehling-Uhlenbeck (BUU) transport model IBUU04 calculations [Li05], to the measured isospin diffusion data of Ref. [Tsa04]. The dashed, dot-dashed and solid lines centered around S_0=30.1 MeV represent L values obtained by comparing Improved Quantum Molecular Dynamics (ImQMD) model calculations [Tsa08] to the neutron-proton spectral ratios published in Ref. [Fam06], the isospin diffusion data in Ref. [Tsa04] and the rapidity selected isospin diffusion data from the collisions of Sn isotopes of Ref. [Liu07].

The dot-dashed lines at S_0 = 30.1 and 31.6 MeV represent constraints obtained by comparison of IBUU04 [Li05] and ImQMD [Tsa08] models to the same isospin diffusion data of Ref. [Tsa04]. While the two constraints in L overlap, there is a model-dependence to the extracted L values that can be partly attributed to the different values of S_0 adopted in the two calculations. To illustrate this sensitivity, ImQMD calculations were performed using the parameterization of the symmetry energy

$$S(\rho)=12.5\left(\frac{\rho}{\rho_0}\right)^{2/3}+\frac{C_{s,p}}{2}\left(\frac{\rho}{\rho_0}\right)^{\gamma_i}, \qquad (4)$$

By varying $C_{s,p}$ and γ_i, different values of S_0 and L are obtained and used in ImQMD calculations. The shaded region in Fig. 1 represents the boundaries in the S_0 and L plane that satisfy a 2σ criterion in a χ^2 analysis that compares ImQMD calculations to the isospin diffusion data [Tsa08]. This region overlaps the other constraints, from heavy ion collisions, nuclear masses and nuclear structure.

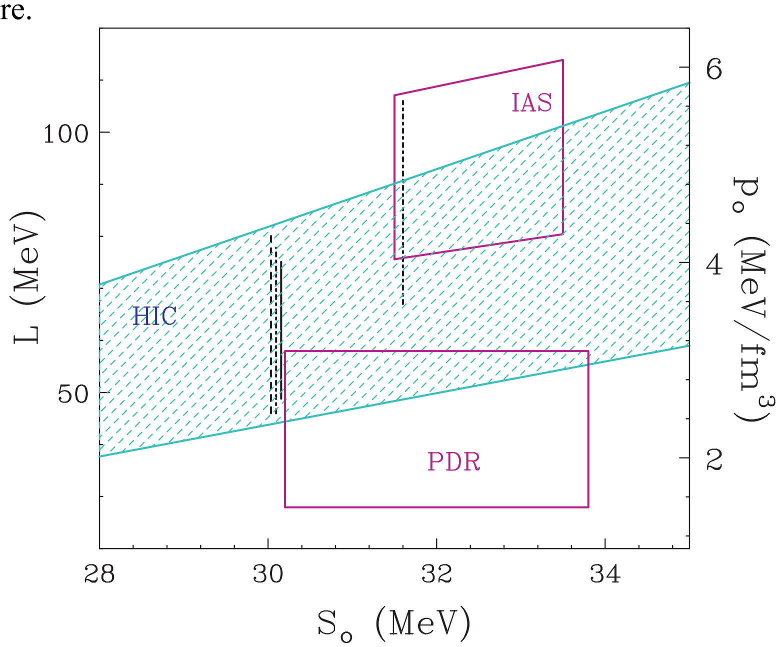

Fig. 1: Representation of the density dependence of the symmetry energy in the S_0 and L parameter space of Eq. (2). The shaded region satisfies the 2σ criterion in the χ^2 analysis of the isospin diffusion data of Ref. [Tsa04]. The dash, dotdashed and solid vertical linse at S_0 =30.1 are obtained from the neutron/proton double yield ratios data of Ref. [Fam06], isospin diffusion data for Z=1-8 fragments from Ref. [Tsa04] and isospin diffusion data from mirror nuclei of ^{7}Li and ^{7}Be of Ref. [Liu07], respectively. The vertical line at S_0 =31.6 MeV represents the constraints from Ref. [Li07]. The lower box is formed by the constraints from Pygmy dipole resonance data [Kli07] and the upper box is from symmetry energy analysis in nuclei [Dan08]. The right axis corresponds to the symmetry pressure at saturation density assuming $\rho_0 \sim 0.16$ fm^{-3}.

By combining the constraints on S_0 = 30.2 to 33.8 MeV from the Pygmy Dipole Resonance (PDR) data [Kli07], we can obtain tentative bounds on the allowed symmetry energy at sub-saturation density represented by the enclosed region in Fig. 2. Currently there is very little data in the supra-saturation density region. The dotted curve from $\rho \sim 0.4$ *to* $0.5/fm^{-3}$ represents the symmetry energy consistent with a recent theoretical analysis [Xia08] of the π^+/π^- yield ratio data for Au+Au reactions from Ref. [Rei07]. These analyses suggest that the symmetry energy at $\rho/\rho_0 \geq$ 2.5 is much smaller than it is at saturation density and that the symmetry energy must reach a maximum between 1-2 times the saturation density. This conclusion, however, is based on the comparison to a single set of data that has not been optimally chosen to constrain the symmetry energy at supra-saturation densities as discussed in Sections III and IV.

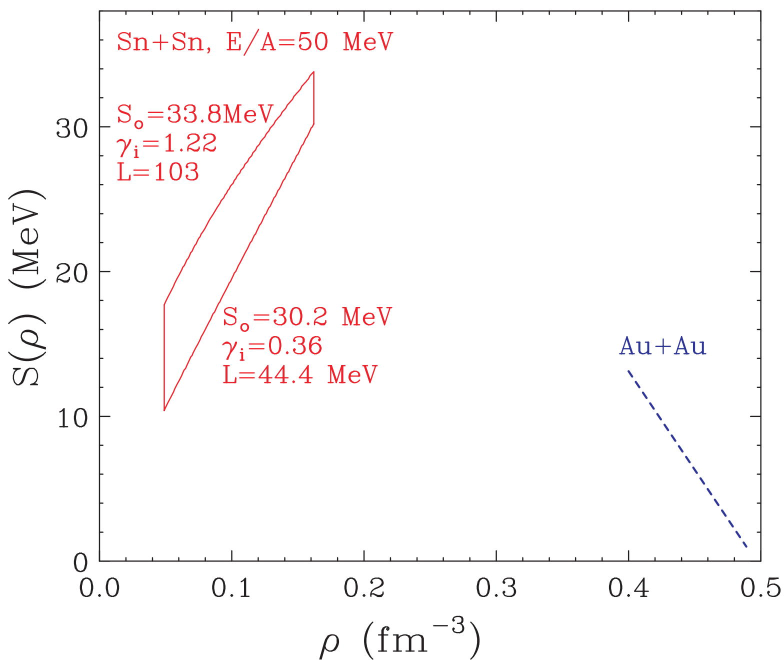

Fig. 2: Density dependence of the symmetry energy obtained from heavy ion reactions. The limits to the enclosed region at sub-saturation nuclear matter density are obtained from Sn+Sn collision data assuming S_o=30.1 and 33.8 MeV. The dotted line in supra-saturation density region represents initial constraints obtained from the measurements of π^+/π^- yield ratio data from Au+Au collisions [Xia08, Rei07].

The bounded regions in Figs. 1 and 2 represent the current status of a rapidly evolving field where new measurements and calculations will have a considerable impact and changes and improvements in such constraints will be expected. In section IV, we discuss measurements of isospin diffusion and neutron-proton double ratios with rare isotope beams that will allow improved experimental precision and a reduction of the model dependence in the constraints at sub-saturation density. The tentative constraints obtained using π^+/π^- yield ratio data from Au+Au collisions [Xia08,Rei07] can be significantly improved by the measurements at MSU, RIKEN and GSI discussed in Sections III and IV of this proposal.

Constraints on the symmetry energy at supra-saturation density from the proposed measurements can be highly relevant to neutron stars, and may be more relevant to calculations of neutron star radii than the difference between the neutron and proton matter radii of ^{208}Pb, a quantity that probes the symmetry energy at sub-saturation densities [Hor01]. Fig. 3 compares the correlation between the baryonic pressure at saturation density (left panel) or twice saturation density (right panel) and the neutron star radius [Lat01]. For neutron star radii in the region of R=9-13 km, the correlation between the neutron star radius and the pressure at saturation density is relatively weak. In contrast, the correlation at twice saturation density is much sharper; constraints on the EoS at supra-saturation densities can have a significant influence on predictions of neutron star radii.

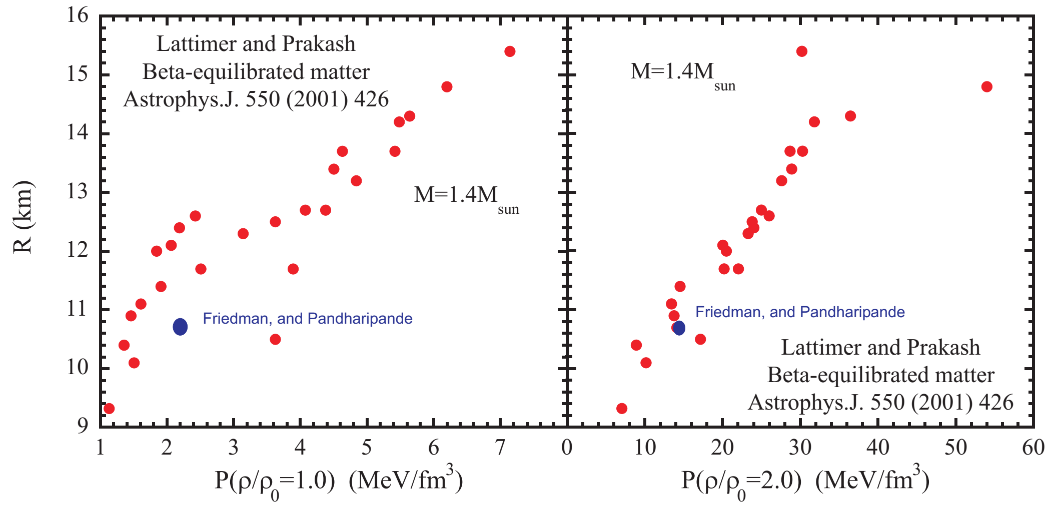

Fig. 3: Correlation between the neutron star radius and the baryonic pressure at saturation density (left panel) or twice saturation density (right panel). Adapted from Ref. [Lat01].

This proposal focuses mainly on obtaining constraints on the symmetry energy at supra-saturation density, where nucleus-nucleus collisions provide the only means to probe the symmetry energy. The proposed RIKEN measurements in Section III explicitly address the density dependence at $\rho \approx 2\rho_0$ where no constraints exist. In Section IV, we also propose complementary measurements at MSU and GSI by the collaboration to map out the density dependence of the symmetry energy from $0.4\rho_0 \leq \rho \leq 3\rho_0$ in the next decade. The major focus of the instrumentation request in this proposal is to provide the Time Projection Chamber (TPC) needed for the measurements at RIKEN and to do experiments with this TPC. Travel funds are also requested for U.S. researchers to do important complementary experiments at GSI.

III. Experimental Probes using the SAMURAI TPC

The main focus of the present section will be on the measurements that can be performed at the RIBF facility at RIKEN using the proposed TPC. In addition to pions, the TPC also detects and identifies light charged particles such as proton, tritons and ^{3}He. When the TPC is coupled with a highly efficient neutron detector, such as the proposed NEBULA array, at RIKEN, it will be possible to measure neutron-proton spectral double ratios. In this section, we discuss measurements of pion production [Li02], neutron vs. proton emission and differential flow [Li02] and triton and ^{3}He emission, that can provide significant constraints on the density dependence of the symmetry energy, the neutron-proton effective mass splitting and the isospin dependence of the in-medium nucleon-nucleon cross-sections at supra-saturation density. The observables discussed below probe a range of densities that can be controlled by selecting the incident energy and impact parameter of the collision. The proposed studies will pave the way to precise measurements of density dependence of the symmetry energy that would be performed at FRIB and at FAIR to explore the density dependence of the symmetry energy when these future facilities become available. It will enable U.S. researchers to remain at the forefront of the research on Equation of State of neutron-rich matter in the upcoming decade.

III.a) Pion and kaon production

Investigations of pion production in nucleus-nucleus collisions provide unique opportunities to establish meaningful constraints on the density dependence of the symmetry energy at high densities $\rho>\rho_0$. Calculations predict that the relative concentrations of neutrons and protons in the dense interior of a central nucleus-nucleus collision reflect the pressure of the symmetry energy, which is greater for a "stiffer" symmetry energy term with stronger density dependence [Li97, Bar01]. The left side of Fig. 4 shows the ratio of the neutron/proton central densities for $^{132}Sn+^{124}Sn$ collisions at E/A = 400 MeV. It decreases with time for strongly repulsive symmetry energy, while increasing in time for much softer symmetry energy. This decrease stems from the larger repulsive potential energy of the stiff symmetry energy at larger density. Fig. 4 shows that the larger ρ_n/ρ_p for much less repulsive symmetry energies (left panel) results in larger $Y(\pi^-)/Y(\pi^+)$ yield ratios [Yon05] (right panel).

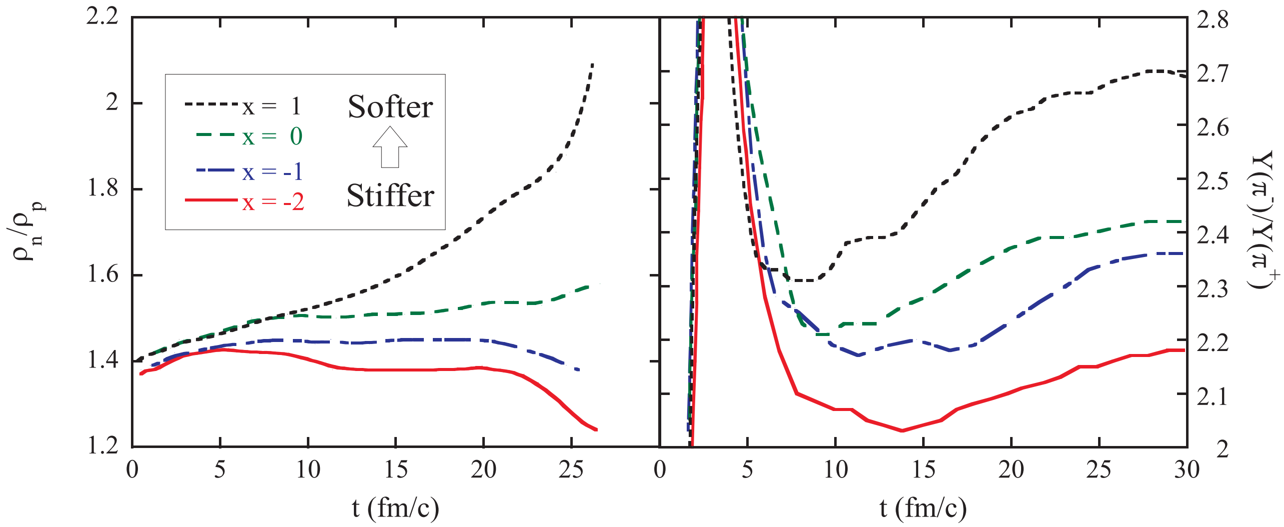

Fig. 4: (Left panel) The dashed and solid lines show the predicted ratio of neutron over proton densities at $r_{cm}=0$ as a function of time for symmetry energies that range from weakly repulsive (x = -2) to strongly repulsive (x = 1). (Right panel) The dashed and solid lines show the corresponding pion single ratios $Y(\pi^-)/Y(\pi^+)$ [Li02].

Pions are largely produced at these incident energies by Δ resonance production and decay. Consequently, π^- and π^+ production rates are strongly correlated with the p-p and n-n collision rates at maximum density, respectively. Detailed calculations indicate that (1) the pion production rate increases with incident energy [Har87], and (2) the sensitivity of that rate to the symmetry energy decreases with incident energy [Qin05,Bar05,Bic08]. In addition, pion absorption and rescattering reduce the sensitivity of pion production with incident energy. Calculated sensitivities of pion production to the symmetry energy are significant at energies E/A $\leq$ 0.5 GeV below the free nucleon-nucleon production threshold [Qin05, Bar05]. Therefore, measurements of the yield double ratio

$$R(\pi^-/\pi^+)= [Y(\pi^-;^{132}Sn+^{124}Sn)\cdot Y(\pi^+;^{112}Sn+^{112}Sn)] \ / \ [Y(\pi^+;^{132}Sn+^{124}Sn)\cdot Y(\pi^-;^{112}Sn+^{112}Sn)] \quad (5)$$

are feasible [Yon05]. Both reactions in this ratio have the same number of protons; the ratio is designed for first order removal of Coulomb effects. It also reduces the sensitivity of the single π^- to π^+ ratios in Fig. 4 to differences in the detection efficiencies for negative and positive pions [Yon05]. Predictions for this ratio, shown in Fig. 5, display a strong sensitivity to the density dependence of the symmetry energy [Yon05].

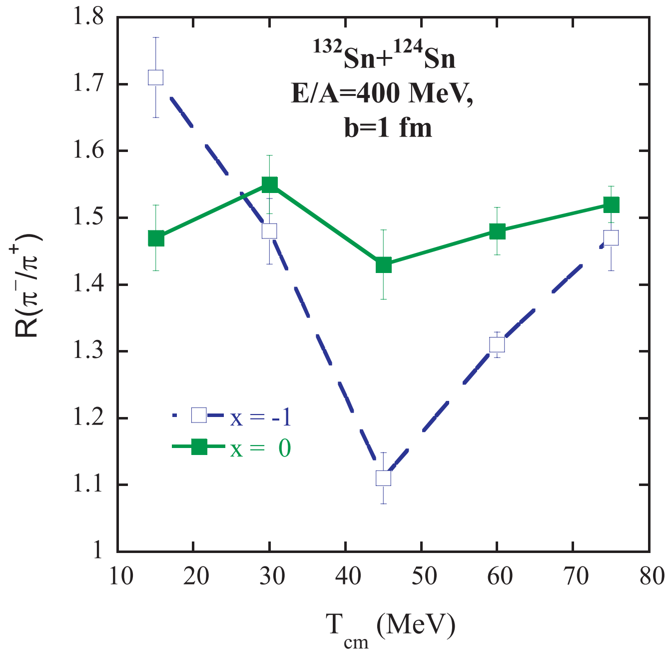

Fig. 5: The solid and open squares show the predicted pion double ratio, $R(\pi^-/\pi^+)$, as a function of the pion center of mass kinetic energy, for weakly and strongly density dependent symmetry energies [Yon05].

The tentative constraint from the π^- to π^+ ratios shown as dotted line in Fig. 2 comes from the experimental measurements of one system, Au+Au at incident energy at 0.4 to 1.2 GeV and is very sensitive to Coulomb effects and to differences between the π^- to π^+ detection efficiencies. The Au+Au system has both large symmetry and Coulomb mean field potentials. The Coulomb "effect" on the relative production of positive and negative pions has been clearly demonstrated [Fra85]; thus, it is essential to unambiguously distinguish the effects of Coulomb and symmetry potentials. This can be accomplished by explicitly comparing pairs of reactions with the same total charge but very different isospin asymmetries. With such reaction pairs, one can remove the Coulomb effects and remove differences in the detection efficiencies for negative and positive pions by constructing pion double ratios as in Eq. 5.

The neutron-rich and neutron-deficient rare isotope beams of the RIBF facility at RIKEN provide an excellent opportunity to perform such studies. We envision using the TPC to measure excitation functions for pion production in ^{132}Sn+^{124}Sn, ^{105}Sn+^{112}Sn, ^{52}Ca+^{40}Ca and ^{36}Ca+^{40}Ca collisions at E/A = 200-300 MeV at the RIBF facility. The range of asymmetry δ=(N-Z)/A of these beams allows the influence of the symmetry energy, which scales as the square of the asymmetry of the total system, to be clearly isolated. To reduce the uncertainties in the predictions for pion production, these measurements will be embedded in a broader set of measurements of the collective flows of nucleons and light clusters at RIKEN, MSU and GSI. These other measurements will provide much needed information about transport properties such as the nucleon effective masses and in-medium cross sections that also influence the pion production [Bar05].

To enable these studies, partial funds to build a TPC for pion measurements was included in the recently funded SAMURAI Dipole Spectrometer proposal [Sam05]. The TPC will be able to detect and identify light charged particles such as protons, tritons and ^{3}He concurrently. The allocated funding is not sufficient to build and implement a modern TPC. As RIKEN has no infrastructure for development of the TPC chamber, we request funds to design and build the TPC chamber and pad plane in the U.S. at Michigan State University. The magnet, laser calibration system, gas-handling system, mounting structure, ancillary trigger detectors and other equipment required for these measurements will be provided by our Japanese collaborators. Details of this technical development are provided in Section V. In addition, we request travel funds to install the TPC in the SAMURAI magnet and to commission the TPC system at RIKEN. We envision a program of subsequent experiments with the TPC that would occur at RIKEN after the end date of this proposal. Some of the goals of these subsequent programs are also discussed in Sections III and IV of this proposal. The SAMURAI-TPC design is optimized to measure pions at incident energies higher than 200 MeV per nucleon where the pion multiplicities are of order unity. If the FRIB driver is upgraded to E/A=400 MeV, we would propose to move the SAMURAI TPC to FRIB, install it in a large gap dipole and utilize it for definitive EoS investigations with the unique extremely asymmetric rare isotope beams that will become available at FRIB.

Calculations suggest that the K^{+}/K^{0} yield ratio may provide sensitivity at the higher densities $\rho>2\rho_0$ attainable at GSI-FAIR [Fer06]. While comparisons of the K^{+}/K^{0} ratio measured for ^{96}Zr+^{96}Zr collisions to that for ^{96}Ru+^{96}Ru collisions at E/A=1.5 GeV have not provided significant constraints on the symmetry energy [Lop07], recent calculations [Fer06] suggest that measurements of ^{132}Sn+^{124}Sn at E/A = 800-1000 MeV may be better suited for such studies. Additional theoretical calculations are needed to verify this and to identify suitable observables for probing densities of $\rho\geq3\rho_0$ at FAIR. When such observables are better understood, we envision an experimental program at FAIR that may involve the SAMURAI TPC to extend the constraints on the symmetry energy obtained at RIKEN to higher densities.

III.b) Neutron - proton ratios and differential flows

In this section, we discuss future studies of neutron to proton (n/p) ratios and differential flows, at RIKEN and elsewhere. We note that investigations of the symmetric matter EoS required measurements of a variety of observables to obtain independent constraints on the symmetric matter EoS, on the nucleon-nucleon cross-sections and on the momentum dependence of the mean field [Dan02]. Similarly, a range of measurements, including pion *and nucleon* observables, will be required to obtain independent constraints on the symmetry energy, the neutron and proton effective masses and the isospin dependence of the nucleon-nucleon cross sections.

Neutron to proton (n/p) ratios and differential flows [Fam06, Li97, Li05] strongly reflect the symmetry energy. At E/A=50 MeV, measurements of (n/p) spectral ratios in heavy ion reactions provide constraints on the symmetry energy at sub-saturation densities [Fam06, Tsan08], and measurements of neutron to proton (n/p) ratios and differential flows at higher energies can provide constraints on the symmetry energy at supra-saturation densities. The open geometry of the proposed SAMURAI TPC enables coincident measurements of neutrons in highly efficient neutron detection arrays and therefore, measurements of neutron to proton (n/p) ratios and differential flows at higher incident energies.

In addition to the dependence on the symmetry energy, however, comparisons of neutron-proton spectral ratios display a strong sensitivity to the difference between the neutron and proton effective masses and to the isospin dependent in-medium nucleon-nucleon cross sections. The π^{+} to

π^- ratios also display sensitivity to the effective masses and cross sections [Bar05]. We plan to combine both pion and neutron-proton data to disentangle the symmetry energy effects from those of neutron-proton effective masses and isospin dependent in-medium cross sections and obtain independent constraints on all three quantities.

We illustrate the sensitivity of the neutron-proton measurements to the effective masses with some recent predictions for ^{132}Sn+^{124}Sn collisions at E/A=100 MeV. Fig. 6 shows predictions for the ratio of the neutron and proton transverse momentum spectra for nucleons emitted with center of mass rapidities y_{cm} of $|y_{cm}/y_{beam,cm}|<0.3$ in central ^{132}Sn+^{124}Sn collisions at E/A=100 MeV [Riz05]. (In the non-relativistic limit, the rapidity of a particle is proportional to the component of its velocity parallel to the beam.) Calculations for $m_p^* > m_n^*$ (blue squares) are compared to those for $m_p^* < m_n^*$ (red circles) in each panel; the left and right panels show calculations assuming weak and strong density dependencies of the symmetry energy, respectively [Riz05]. These ratios for the highest momentum nucleons ($p_t \geq 300$ MeV/c) display a strong sensitivity to the effective masses. A similar sensitivity may be expected in the ratios of ^{3}H and ^{3}He spectra at high transverse momentum [Che04]. Spectral ratios like this can be accurately measured at RIKEN, MSU, GSI and FRIB and used to investigate the effective neutron and proton masses. Currently, data from such experiments have only been reported for stable beams at lower incident energies, which limits their sensitivities.

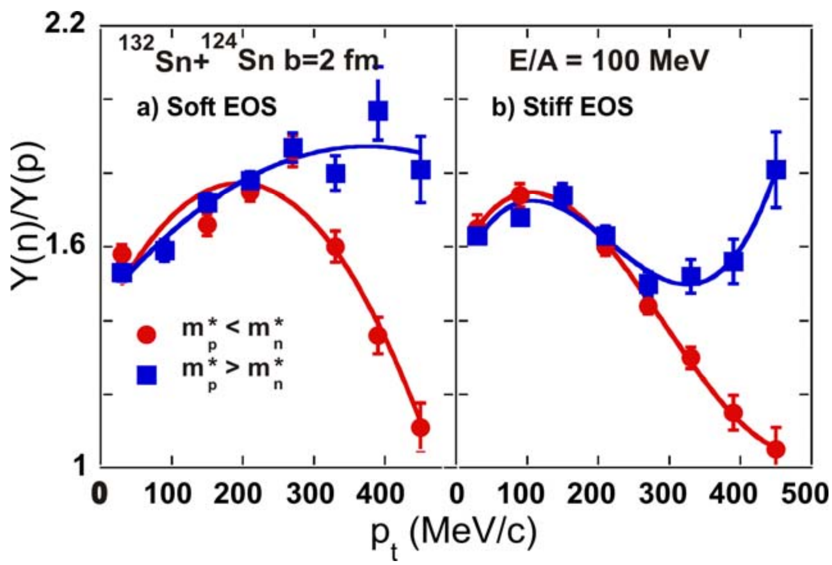

Fig. 6: Ratio of neutron and proton spectra calculated for central ^{132}Sn+^{124}Sn collisions utilizing soft (left panel) and stiff (right panel) symmetry energy dependences. The squares and circles indicate calculations assuming $m_p^* > m_n^*$ and $m_p^* < m_n^*$, respectively. The lines are drawn to guide the eye. Adapted from [Riz05].

To illustrate what has been learned thus far, Fig. 7 shows double yield ratios of the neutron and proton spectra from the central ^{124}Sn +^{124}Sn and ^{112}Sn+^{112}Sn collisions at E/A=50 MeV. Such double ratios have been defined as

$$DR(n/p) = R_{n/p}(A)/ R_{n/p}(B) = \frac{dM_n(A)/dE_{c.m.}}{dM_p(A)/dE_{c.m.}} \cdot \frac{dM_p(B)/dE_{c.m.}}{dM_n(B)/dE_{c.m.}}, \qquad (5)$$

and constructed by measuring the energy spectra, $dM/dE_{C.M}$, of neutrons and protons for two systems A=^{124}Sn+^{124}Sn and B=^{112}Sn+^{112}Sn. The double ratios reduce experimental and theoretical systematic uncertainties. The data, represented by the star symbols, and the calculations, represented by the lines and the cross-hatched regions, are coalescence invariant double ratios

DR(n/p) constructed in the center of mass by including all neutrons and protons emitted at a given velocity, regardless of whether they are emitted free or emitted within a light cluster.

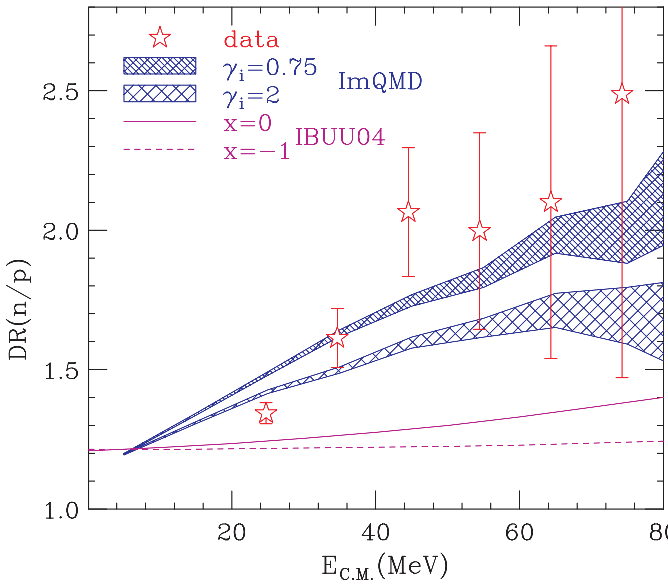

Fig. 7: The open stars denote coalescence invariant neutron proton double ratios as a function of kinetic energy of the nucleons. The shaded regions are calculations from the ImQMD simulations at b=2 fm [Tsa08] with soft (top shaded region) and stiff (lower region) density dependence of the symmetry energy. The solid and dashed lines denote IBUU04 calculations for the soft (x=0) and stiff (x=1) symmetry energies [Li05].

The shaded regions in the Fig. 7 shows the predicted double ratios *DR(n/p)* for the ImQMD Quantum Molecular Dynamics model of Ref. [Zha08] for two different density dependencies of the symmetry potential energy: γ_ι=0.75 (soft symmetry energy, upper shaded region) and γ_ι=2 (stiff symmetry energy, lower shaded region) as defined in Eq. 4. The solid and dashed lines denote calculations for the Boltzmann-Uehling-Uhlenbeck Equation (IBUU04) model of Ref. [Li05]. If one optimizes the agreement between experiment and the ImQMD calculations, the value γ_ι~0.7 is somewhat favored, which provides a density dependent symmetry energy similar to that for IBUU04 calculations labeled x=0. Both the IBUU04 with x~-1 and ImQMD calculations with γ_ι≈0.75 describe the isospin diffusion data satisfactorily [Li05, Tsa08]. The differences between the predictions of two calculations for the n/p ratios may arise from the assumption in the ImQMD model of equal neutron and proton effective masses, unlike the IBUU04 predictions that assumed $m_n^* > m_p^*$. As shown in Fig. 6, the latter choice decreases the slopes of the neutron spectra relative to the proton spectra, a trend that is not observed experimentally [Fam06]. As the effective masses depend on density and on nucleon momenta, high quality comparisons between neutron and proton spectra ratios at several incident energies will be required to determine how the difference between neutron and proton effective masses depends on the density and nucleon momentum.

At higher incident energies where supra-saturation densities are probed, IBUU04 calculations predict larger double ratios for calculations with stiffer symmetry energies [Li07]. Fig. 8 shows IBUU04 predictions for the spectral double ratios for the systems A=^{132}Sn+^{124}Sn and B=^{112}Sn+^{112}Sn. Provided that a highly efficient neutron detector, such as the proposed NEBULA array, is available at RIKEN, it should be possible to measure neutron-proton spectral double ratios, at the RIBF facility of RIKEN, during the same excitation function experiments for ^{132}Sn+^{124}Sn, ^{105}Sn+^{112}Sn, ^{52}Ca+^{40}Ca and ^{36}Ca+^{40}Ca collisions at E/A = 200-300 MeV that we proposed for measurements of pion emission.

Recent calculations of elliptical neutron and proton flow using the IBUU04 [Li01] and Ultra-relativistic Quantum Molecular Dynamics models [Li08b] suggest a measurable sensitivity of the v_2 elliptical flow observable to the density dependence of the symmetry energy at supra-saturation densities. We propose to explore this at RIKEN concurrently with the measurement of neutron-proton double ratios discussed above. Preliminary results from the analysis of the v_2 from existing Au+Au data at E/A=400 MeV has been reported [Rus08]. A proposal to measure neutron and proton elliptical flow in ^{124}Sn+^{124}Sn and ^{112}Sn+^{112}Sn collisions at E/A=400,600 and 800 MeV using the FOPI and LAND detectors at GSI will be submitted to the GSI PAC [Lem08]. Funds are requested in this proposal for participation in this experiment.

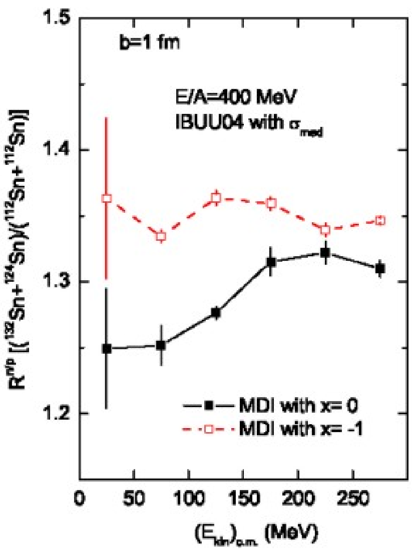

Fig. 8: The open stars denote coalescence invariant neutron proton double ratios measured for ^{132}Sn+^{124}Sn and ^{112}Sn+^{112}Sn as a function of kinetic energy of the nucleons. The solid and dashed lines denote IBUU04 calculations for the soft (x=0) and stiff (x=1) symmetry energies [Li05].

III.c) Neutron and proton rapidity distributions

The isospin dependence of in-medium nucleon-nucleon (NN) cross sections in asymmetric matter is also important. In free space, σ_{np}/σ_{pp} decreases from about 2.5 to 1.5 as the energy of the incident nucleon is increased from 50 MeV to 200 MeV. Some calculations predict σ_{np}/σ_{pp} inside the nuclear medium to decrease with density [Sam06], while others predict opposite trends [Qin00]. Theoretical studies have recently revealed a strong sensitivity of the rapidity dependence of the asymmetry δ=(Y(n)-Y(p))/(Y(n)+Y(p)) of light particles emitted in central collisions to the isospin dependence of the in-medium cross section [Li05b]. Precise constraints on the isospin dependent in-medium cross sections will be obtained by comparing systems in which the projectile mass remains constant, e.g. ^{100}Zr+^{40}Ca and ^{100}Ag+^{40}Ca, at RIKEN or ^{96}Ru+^{40}Ca and ^{96}Zr+^{40}Ca at MSU and GSI, as well as systems in which the number of protons remains constant, e.g. ^{107}Sn+^{40}Ca and ^{127}Sn+^{40}Ca at RIKEN or ^{112}Sn+^{40}Ca and ^{124}Sn+^{40}Ca at MSU and GSI. Thus, the mean free path for transmission of target neutrons and protons through the projectile can be measured as a function of the numbers of projectile and target nucleons and the isospin dependence of the in-medium cross sections can be determined. Measurements would be performed at E/A=50 and 150 MeV at MSU, E/A=300 MeV at RIKEN and E/A=800 MeV at GSI. We propose to perform the RIKEN measurements using travel funds from this proposal.

III.d) t and ^{3}He Ratios

Experimentally, neutrons are more difficult to measure and the efficiencies of neutron detectors are low. To minimize systematic errors arise from the difference in the efficiencies of different types of detectors, double ratios, such as Eq. (3) are adopted in the data analysis. As an alternative to measuring the neutron and protons emitted in collisions, it is possible to use A=3 mirror nuclei of t and ^{3}He, which are detected and identified with the TPC. To avoid influence of sequential decays and cluster effects, both theoretical studies [Zha08] and experimental measurements [Fam06] of the neutron to proton yield ratios suggest that we need to detect high energy particles with E_{kin}/A>40 MeV. These studies, which are difficult at E/A=50 MeV, become more straightforward at RIKEN and GSI where the incident energies (>200 MeV) lead to the production of high energy t and ^{3}He particles in much higher abundances [Wes82]. Measurements of t and ^{3}He yields will be obtained in the SAMURAI TPC concurrently with the pion measurements.

IV. Overall experimental program to study the density dependence of symmetry energy – International collaboration

To achieve the scientific objective of determining the constraints to the equation of state of neutron matter, we propose to conduct a series of experiments at unique facilities based in the U.S. (NSCL at Michigan State University), Japan (the RIBF at Riken) and Germany (GSI). Each facility enables the exploration of a different density range. To conduct and interpret these experiments, we have formed a strong international experimental and theoretical team of scientists; the required manpower or expertise does not reside at a single laboratory or in a single country. Members of the experimental team are listed on the first page of this narrative. Theoretical input is essential to these efforts. Many theoreticians that have committed to constraining the equation of state of neutron matter have joined this collaboration and are also listed on the front page of this proposal. In addition to regular video conferences, the collaboration will meet once a year to present and discuss the most up to date experimental and theoretical results and monitor and plan the progress of this effort. Recognizing that broad participation at these meetings is essential for success, we have included a request for funds to facilitate collaborative travel for US. scientists. Some of this will be used to support the travel of young scientists and students to collaboration meetings. We envision also using some funds to support the travel of consultants on this project.

This proposal requests funds for construction of a TPC to be installed and commissioned within the SAMURAI dipole magnet at the RIBF facility in RIKEN, one experiment to probe the symmetry energy at $\sim 2\rho_0$ with this setup at RIKEN, and one complementary measurement at GSI to probe higher densities $2\rho_0 \leq \rho \leq 3\rho_0$.

The upper two rows in Table 1 indicate a scenario for the timeline, and the reactions and observables to be explored for these two of measurements. Assuming work on the SAMURAI TPC begins in FY2010, the TPC commissioning experiment would run near the beginning of FY2013. This experiment together with the three following experiments in 2015 to 2017, which occur after the ending date of this proposal, are designed to obtain initial constraints on three quantities: 1) the density dependence of the symmetry energy at $\sim 2\rho_0$, 2) the difference between neutron and proton effective masses and 3) the isospin dependence of the in-medium cross sections. We envision the first experiment to involve comparisons of ^{132}Sn+^{124}Sn to ^{105}Sn+^{112}Sn collision and ^{52}Ca+^{48}Ca to

$^{36}Ca+^{40}Ca$ collisions. The experiments will place constraints on the symmetry energy at ~ $2\rho_0$ using the sensitivities discussed in Section III.a) and displayed in Figs. 4-5, for example, and on the difference between neutron and proton effective masses using the sensitivity discussed in Section III.b) and displayed in Fig. 6, for example. Measurements of the rapidity dependence of neutron and proton emission in central asymmetric collisions, such as $^{100}Zr+^{40}Ca$ and $^{100}Ag+^{40}Ca$, (discussed in Section III.c) will place constraints on the isospin dependence of the in-medium nucleon-nucleon cross sections, for example. Other observables will be measured in these collisions and will also provide constraints on these three quantities; for the virtue of clarity, we do not try to discuss all known sensitivities here. We also note that future calculations will be performed before these proposed experiments run and will refine our approach further. Our experimental design is flexible enough to accommodate new theoretical developments.

To extend these studies to higher densities, we also request travel funds for U.S. participation in an international collaborative effort at GSI in FY2011 led by our European collaborators, R. Lemmon and P. Russotto [Lem08]. This proposed experiment will probe the symmetry energy and the difference between neutron and proton effective masses at higher densities, $2\rho_0 \le \rho \le 2.5\rho_0$ via comparisons of neutron and proton observables in $^{124}Sn+^{124}Sn$ and $^{112}Sn+^{112}Sn$ collisions at E/A=400, 600 and 800 MeV. Current plans for these measurements combine the LNS Catania CHIMERA and MSU MINIBALL arrays to measure the impact parameter and reaction plane, the LAND detector at GSI and its veto paddle to measure the neutron and proton spectra. We note that these efforts will help to define the constraints on the symmetry energy at higher densities that will be achievable later at the FAIR facility.

Site	Probe	Device	E_{lab}/A MeV	Main Focus	Reactions	$?	FY	density
RIBF RIKEN	$\pi^+\pi^-$,p, n,t,^{3}He	TPC NEBULA	200-300	E_{sym} m_n^*, m_p^*	$^{132}Sn+^{124}Sn$, $^{105}Sn+^{112}Sn$, $^{52}Ca+^{48}Ca$, $^{36}Ca+^{40}Ca$	Y	2013 -2014	$\approx 2\rho_0$
RIBF RIKEN	$\pi^+\pi^-$ p, n,t,^{3}He	TPC NEBULA	200-300	σ_{nn}, σ_{pp}, σ_{np}	$^{100}Zr+^{40}Ca$, $^{100}Ag+^{40}Ca$, $^{107}Sn+^{40}Ca$, $^{127}Sn+^{40}Ca$	N	2015-2017	$\approx 2\rho_0$
GSI	p,n	LAND, FOPI, Miniball CHIMERA	400-800	E_{sym} m_n^*, m_p^*, σ_{nn}, σ_{pp}, σ_{np}	$^{124,112}Sn+^{124,112}Sn$	Y	2011	2.5-3ρ_0
NSCL	$\pi^+\pi^-$	AT-TPC	120-170	E_{sym}	$^{124,112}Sn+^{124,112}Sn$	N	2014-2016	1-1.7ρ_0
NSCL	p,n	LASSA N-wall	50-150	E_{sym} m_n^*, m_p^*, σ_{nn}, σ_{pp}, σ_{np}	$^{124,112}Sn+^{124,112}Sn$, $^{96}Ru+^{40}Ca$, $^{96}Zr+^{40}Ca$, $^{112}Sn+^{40}Ca$, $^{124}Sn+^{40}Ca$	N	2009 -2012	0.5-1.6ρ_0
NSCL RIBF RIKEN TAMU GANIL LNS	isotope yields, isospin diffusion		35-70	E_{sym}	$^{124,112}Sn+^{124,112}Sn$, $^{108,112,124,132}Sn+^{124,112}Sn$ $^{56,58,64,68}Ni+^{58,64}Ni$ $^{40,48}Ca+^{40,48}Ca$	N	2009 -2012	~0.3-1ρ_0

Table 1: Partial overview of reactions investigations of the density dependence of the symmetry energy.

To provide a more comprehensive scenario, the next two rows of the table list other investigations of the symmetry energy at the NSCL **that will be done by members of this**

collaboration, but for which no funding is requested. To address the density dependence at supra-saturation densities of $\rho_0 \leq \rho \leq 1.7\rho_0$, we believe it is important to measure pion production at the NSCL and later, at FRIB. Even though the pion multiplicities are small at energies of E/A=200 MeV and below, which are available at the NSCL and FRIB, calculations predict that their sensitivity to the symmetry energy remains high and actually increases as the energy is lowered. Proposals to fund an Active Target - Time Projection Chamber (AT-TPC) for experiments at the NSCL and ultimately FRIB have been submitted to the DOE and to the NSF. This device, which is designed to provide maximal luminosity for high resolution reaccelerated beam experiments, has also the optimal properties for pion detection at E/A<200 MeV, where the multiplicities are small. Its solenoidal design allows higher beam intensities because it confines the beam induced ionization both geometrically and magnetically better than can be achieved in a dipole design such as the SAMURAI TPC, so it would be better suited to the pion measurements that would be possible with the 200 MeV driver LINAC with the present FRIB project.

We also plan comparisons of neutron and proton observables in ^{124}Sn+^{124}Sn, ^{112}Sn+^{112}Sn, ^{112}Sn+^{40}Ca and ^{124}Sn+^{40}Ca collisions at E/A=50-150 MeV at the NSCL, which will provide the necessary information about the differences between neutron and proton effective masses and the isospin dependence of the nucleon-nucleon cross sections that are needed to definitively isolate the density dependence of the symmetry energy over densities ranging from 0.3-1.6ρ_0.

The final entry concerns measurements of fragment isotope distributions and isospin diffusion that probe the symmetry energy at sub-saturation densities, $\rho/\rho_0 \approx 0.3$-1 [Tsa08]. Isospin diffusion investigations involve comparisons between "mixed" collisions of a neutron-rich nucleus and a neutron-deficient nucleus to "symmetric" collisions of two neutron-deficient nuclei or two neutron-rich nuclei [Tsa04]. This comparison allows one to probe the symmetry energy dependent diffusion rate between the two nuclei, which can be modeled dynamically for different density dependencies of the symmetry energy [Tsa04, Li05]. The blue bounded region on Fig. 1 and the red bounded region at low density in Fig. 2 were provided by isospin diffusion data. We note that the width of the shaded region at fixed S_o corresponds to a variation in the skin thickness of ^{208}Pb of ±0.04 fm. This can be compared to the estimated uncertainties of ±0.05 fm in the proposed direct measurement of the neutron radius in the ^{208}Pb nucleus [PRE06]. Additional measurements of isospin diffusion have been performed at LNS Catania and GANIL. New measurements of isospin diffusion are approved with stable and radioactive beams at the NSCL and RIKEN. More sensitive measurements can be performed at FRIB to further constrain the symmetry energy at sub-saturation densities.

Combining isospin diffusion with additional constraints from nuclear structure such as giant resonances, masses, polarizabilities and neutron and proton radius differences, we expect that the constraints on the symmetry energy at subsaturation densities provided by FRIB will be relatively stringent. For this reason, we believe that high priority should be given to measurements that we are proposing to extend such constraints to $\rho \approx 2\rho_0$ and beyond.

Measurements at RIKEN will provide initial constraints on the symmetry energy at supra-saturation densities that would be considerably improved by measurements at FRIB. While pion multiplicities are small below E/A=200 MeV, calculations predict that their sensitivity to the symmetry energy remains high and actually increases as the energy is lowered. While the dipole design of the SAMURAI TPC is ideally suited to the RIKEN facility where it allows easy integration of ancillary devices such as the NEBULA neutron time of flight walls that are much needed for its experimental program, it is not as well suited to low multiplicity pion measurements below E/A=200 because beam induced ionization limits the beam intensities that can be used with it. A solenoidal TPC at FRIB would allow such measurements but would preclude coincident neutron time of flight measurements. When a later 400 MeV upgrade to the FRIB driver is funded, one should install the SAMURAI TPC in a dipole magnet at the upgraded FRIB facility for experiments at E/A>200 MeV with the unique new rare isotope beams that FRIB will provide.

V. Development of the SAMURAI Time Projection Chamber (TPC):

The Japanese government has funded the SAMURAI dipole magnetic spectrometer in Riken. The determination of the EoS of neutron rich matter via measurement of the ratio of negative to positive pion multiplicities in central heavy ion collisions is included in the SAMURAI proposal and is part of its scientific agenda [Sam05].

V.a) SAMURAI Dipole

Bids from vendors have been requested for the SAMURAI dipole. Table 2 contains the technical parameters of the magnet that was included in the bid package. The specifications of the final magnet should be close to the ones given below. With a pole diameter of 2 m and magnet gap of 80 cm, the SAMURAI dipole is somewhat smaller than the HISS magnet (2.1m pole diameter and 1 m magnet gap) that housed the EOS TPC at the LBL Bevalac [Wie91]. The magnet can be rotated to optimize detection of particles at nearly any polar angle.

SAMURAI Dipole Specifications	
Magnet Type	H
Maximum Rigidity	7 Tm
Pole Diameter	2m
Return Yoke Dimensions Top and Bottom	6.8m x 3m x 1.4 m
Return Yoke Dimensions Sides	1.7m x 0.7m x 1.88m
Central Field	0.4-3 T (at the center)
Magnet Gap	0.88 m – 0.8 m with vacuum chamber
Mounting	Rotatable Base
Total Weight	630 T

Table 2: Parameters of the SAMURAI Dipole.

The current SAMURAI design includes a vacuum chamber with a large thin window to allow the detection of neutrons and energetic light charged particles. The rotatable base allows the center of the window to be rotated to different detection angles. Fig. 9 shows schematic drawings of the dipole. The vacuum chamber is designed to maximize the available interior space in the gap.

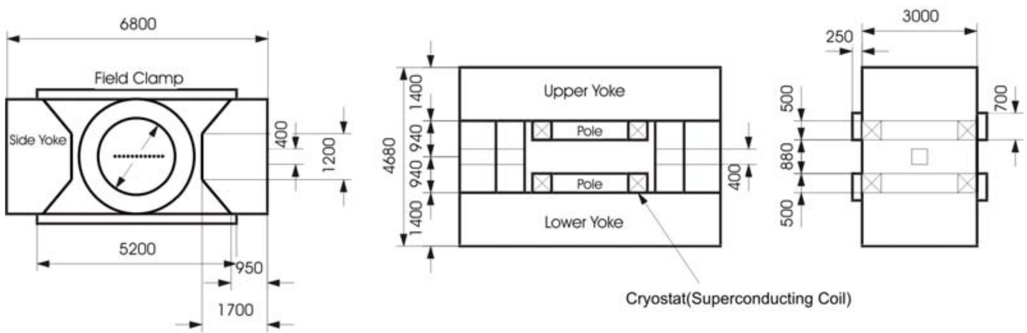

Fig. 9: Schematic design drawings showing three views of the SAMURAI dipole. All dimensions are in mm.

V.b) SAMURAI TPC

The TPC and the surrounding chamber will be at atmospheric pressure during normal TPC operation. With its pole diameter of 2 m and available magnet gap of 80 cm, the SAMURAI dipole is somewhat smaller than the HISS magnet (2.1m pole diameter and 1 m magnet gap) that housed the EOS TPC at the LBL Bevalac [Wie91]. Table 3 lists the relevant parameters of the proposed SAMURAI TPC.

SAMURAI TPC Parameters	
Pad Plane Area	1.3 m x 0.9 m
Number of pads	11664 (108 x 108)
Pad size	12 mm x 8 mm
Drift distance	55 cm
Pressure	1 atmosphere
Gas composition	90% Ar+10% CH_4
Gas gain	3000
E field	120 V/cm
Drift velocity	5 cm/μs
dE/dx range	Z=1-8, π, p, d, t, He, Li-O
Two track res.	2.5 cm
Multiplicity limit	200

Table 3: Parameters of the SAMURAI TPC.

The Electric drift field in the TPC is vertical and will be provided by a field cage with vertical panels that are set 5 cm back from the pad plane. The 55 cm drift distance considers the space required within the 80 cm gap for the electronics and various mechanical structures, and for the anode structure. Fig. 10 shows a schematic representation of the TPC (in blue), with the electronics boards (yellow) and an I-beam structure mounted on the top of the TPC to keep the pad-plane flat and rigid.

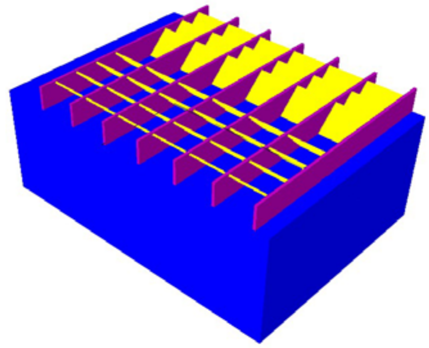

Fig. 10: Schematic design of the SAMURAI TPC the gas containment volume (blue) the GET ASIC electronics boards (yellow) and I-Beam support structure (violet).

The current design assumes a TPC wire and anode structure similar to that employed by the EOS TPC [Rai90]. This design allows the possibility for some sections of anode wires to operate at lower potentials for the analysis of tracks from heavier and more strongly ionizing particles. A test chamber has been developed at MSU to evaluate the suitability of various anode structures, including wires, GEM's [Car05] and Micromegas [Col04]. Following these tests, we will finalize the design of the anode structure.

Based on the performance of the EOS TPC and the Star TPC, we expect excellent particle identification for the light particles that are especially relevant to placing constraints on the EoS at supra-saturation densites. Fig. 11 shows a simulation of the expected performance of a TPC for collisions at typical incident energies that would be probed with the SAMURAI TPC. Pions and light particles can be accurately identified.

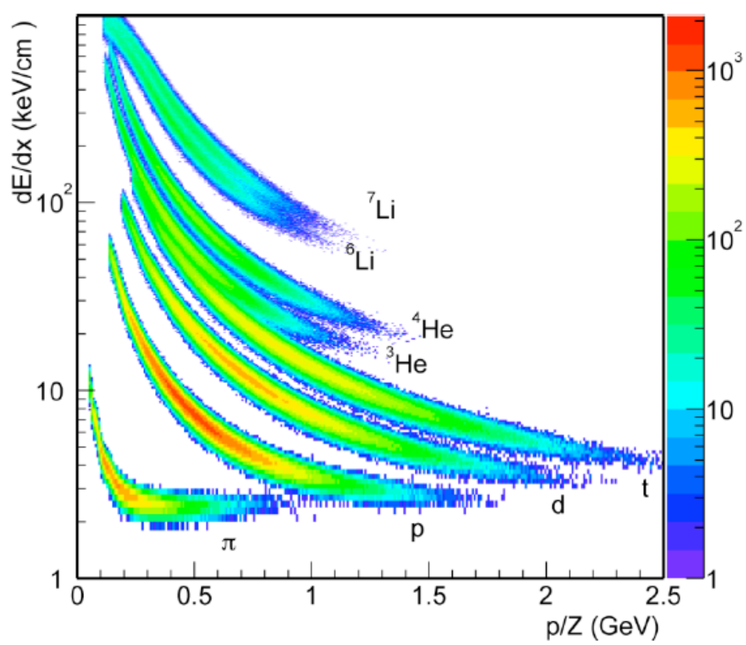

Fig. 11 Simulated PID of the TPC based on the performance of the STAR TPC. Comparable performance was achieved in the EOS detector and would be achieved with the SAMURAI TPC.

We will place an optical bench for a laser calibrations system for the SAMURAI TPC upstream of the drift volume. This system will split the beam of a Nd-YAG laser into multiple beams, which will provide a Cartesian reference grid that will allow the determination of corrections for magnetic field non-uniformities. This laser can be pulsed to monitor variations in the electron drift velocity with time.

V.c) TPC electronics:

The SAMURAI TPC will measure ions ranging from pions to oxygen, corresponding to a wide range of stopping powers and, consequently, a wide range of induced signals on the pads. This wide dynamic range can be partly compensated by biasing different anode sections to different voltages. The STAR collaboration has agreed to allow the NSCL to take ownership of the STAR electronics, and details of the transfer are currently being arranged. STAR readout electronics will be employed during initial testing, development and first commissioning of the SAMURAI TPC.

Longer term, we will employ readout electronics with a 12 bit ADC instead of STAR electronics with its 10 bit ADC's. MSU is a member of the ACTAR collaboration, which is developing new 12 bit TPC readout electronics suitable for Active Target TPC's. We presently plan to use these new electronics for the final SAMURAI TPC readout. The TPC electronics will be purchased by RIKEN. It will be built largely at SACLAY and will be based on the GET ASIC, which is a revised version of the AFTER ASIC used for the TPC in the T2K neutrino experiment [T2k07]. Table 4 lists some of the specifications of the GET ASIC and associated readout electronics.

The current time line for GET electronics development has prototyping of the electronics completing in 2012 and final production in 2013. Under this time line, a complete set of GET electronics would not be available for testing at MSU or for the first commissioning experiment at RIKEN. We propose to design the pad plane to accept the GET electronics, and route the signals from the pad plane to STAR electronics for the testing at MSU and the commissioning experiment at RIKEN. Under this plan, the GET electronics would be installed at RIKEN during FY2014 between the commissioning experiment and the second RIKEN run. As a alternative solutions, we have also ordered several T2k FEM boards for testing. The T2k boards have a 12 bit ADC and a suitable dynamics range. We will test the T2k boards to see whether it is possible to read data from them in excess of 200 events/s. If so, we will investigate adaptations of the T2k electronics to the SAMURAI TPC, which may provide a final electronics solution before the commissioning experiment in FY2013.

Parameter	**Value**	**Parameter**	**Value**
Power consumption	< 10 mW / channel	**Trigger**	
Number of channels	72 per readout board	**Discriminator solution**	L.E.D
Number of channels	72 per readout board	**Dynamic range**	5% of input charge range
Input dynamic range	120 fC; 1 pC; 10 pC	**I.N.L**	< 5%
I.N.L of the charge measurement	< 2%	**Threshold value**	4-bit DAC/channel + (3-bit + polarity bit) common DAC
Resolution (Charge range: 120fC; Peaking Time: 200ns; Cin < 30pF)	< 850 e-	**Minimum threshold value**	≥ noise
Peaking time value	50 ns to 1 μs	**Readout**	
Number of SCA Time bins	511	**Readout frequency**	20 MHz to 25 MHz
Sampling Frequency	1 MHz to 100 MHz	**Counting rate**	< 1 kHz

Table 4: Some specifications of the GET ASIC and associated readout electronics.

V.d) Trigger and ancillary detectors:

A 100 x 100 cm^2 plastic scintillator wall will be constructed by our Japanese collaborators. This wall will be centered about the beam at the edge of the SAMURAI dipole field to provide fast first level centrality trigger based in the forward going charged particle multiplicity. The specification for the GET ASIC and its readout electronics allows a maximum first level trigger rate of about 1 kHz. An FPGA in the TPC readout chain will provide information about the number of tracks in the TPC and can function as a second level trigger. The specifications of the TPC electronics allows for instantaneous rates of up to 1 kHz, but the actual data will be a few hundred Hz for events that satisfy all the trigger requirements.

A large-area neutron detector (NEBULA) is being developed at the RIBF facility for invariant mass measurements using the SAMURAI TPC. The current specifications for NEBULA describe a neutron detector composed of 120 scintillator bars with dimensions of 180(h)x12(w)x12(t) cm^3 [Mur08]. Charge particles will be vetoed by 12 veto scintillators of 190(h)x32(w)x1(t) cm^3. (Here the designations (h), (w) and (t) follow the height, width and thickness, respectively of the scintillator bars.) Current plans have NEBULA arranged in four layers of 30 bars each, which will provide an efficiency of about 40% for 250 MeV neutrons and typical angular and velocity resolutions of 5 mrad and 0.6%, respectively. It will be available for neutron measurements with the SAMURAI TPC.

VI. Project Performance Sites, division of responsibilities and resources required:

Construction and initial testing of the SAMURAI TPC chamber will be carried out primarily at the NSCL of Michigan State University, which has a well-instrumented detector laboratory with experience in multi-wire drift chambers, ion chambers and TPC's. RIKEN and our Japanese collaborators will also be responsible for the procurement of the SAMURAI dipole, the TPC laser calibration system, the TPC gas handling system, TPC mounting and transportation hardware, the target, the beam tracking, the TPC electronics and data acquisition and the ancillary trigger scintillation array.

Experiments will be performed during this proposal at RIKEN, GSI, and NSCL to constrain the EoS for asymmetric matter. The principal request during the experimental phase of this proposal is for travel funds for one experiment at GSI and for the commissioning experiment at RIKEN. The managements of both facilities are aware of our plans and have agreed that the proposed measurements at their facilities will be feasible.

VI.a) Project performance sites, division of responsibilities and resources required for the SAMURAI TPC construction and development.

The project leader for the development, construction and testing of the SAMURAI TPC will be William Lynch. The design of the SAMURAI TPC is based upon the EOS TPC, which was commissioned in 1992 and has been used in experiments at the LBL BEVALAC, the BNL AGS and currently in the MIPP experiment at FERMILAB. The manpower requirements and cost estimate for the development of the SAMURAI TPC are based upon the EOS design, for which a set of design drawings exists.

The NSCL has a well-instrumented detector laboratory with experience in multi-wire drift chambers, ion chambers and TPC's. Modifications to the EOS design to accommodate the smaller drift volume allowed by the SAMURAI dipole and modifications to the pad plane to interface with the readout electronics will be the responsibility of the NSCL. Tests of alternative GEM or Micromegas anode structures should be completed at the NSCL in FY2009. If a GEM or Micromegas structure is selected, the corresponding design modifications to the SAMURAI TPC would also be the responsibility of the NSCL. The design of the gas containment vessel and support structure for testing outside of the SAMURAI magnet volume will be the responsibility of the NSCL as well. The design of the mounting and insertion structures within the SAMURAI dipole will be the responsibility of our Japanese collaborators.

The conceptual design of LASER pulser system will be the responsibility of the group at Western Michigan University and the mechanical design necessary for implementing the laser system within the TPC volume will be the responsibility of the NSCL. The laser and optical components will be purchased by our Japanese collaborators and delivered to MSU for incorporation in the TPC itself. The gas handling system will allow a mixing of up to three gas components. It will be purchased by our Japanese collaborators.

The TPC will be constructed and tested at MSU prior to shipping to RIKEN. The responsibility for assembling and testing the TPC at MSU will be the responsibility of the U.S. collaborators from Michigan State University, Western Michigan University (WMU) and Texas A&M University (TAMU). Funding is requested for the detector lab personnel, design and fabrication staff, as well as electrical engineering support needed at MSU during development and testing stages. Funding is also requested for a postdoc (1/2 time) and for graduate students from WMU and TAMU, who will be stationed at MSU while engaged in the development and testing of the TPC. Additional scientific manpower will be provided by the research grants of the members of the collaboration including the research group of Professors Betty Tsang and William Lynch, the co-spokespersons of this proposal.

Installation and commissioning of the TPC will occur at RIKEN. The overall project leader for the SAMURAI TPC project will be Tetsuya Murakami, who will lead the Japanese efforts. Our Japanese colleagues will be responsible for all other aspects of the project, such as the mating of the TPC to the SAMURAI magnet and to the data acquisition system at RIKEN.

Testing and commissioning the SAMURAI TPC system at RIKEN will be the responsibility of the U.S. group in conjunction with our Japanese and European colleagues, who are named on this collaborative proposal. During the testing and commissioning period, a transfer of technology and responsibility to our Japanese colleagues will occur that will enable them to maintain the TPC between experimental campaigns. Acquiring the GET electronics will be the responsibility of our Japanese colleagues. The electronics reconfiguration in FY2014 will be a joint effort.

The total materials and technical manpower direct cost of $825k for the TPC design, construction, testing and commissioning is discussed in Section VII. This cost includes TPC construction materials, technical and engineering support during the TPC design, construction and testing stages, three years of post-doctoral support (1/2 time) and for four years support of a graduate student from Western Michigan University and a graduate student from Texas A&M University.

VI.b) Project performance sites, division of responsibilities and resources required for the SAMURAI TPC electronics

The overall project leader for the SAMURAI TPC system is Tetsuya Murakami. Our Japanese colleagues will have the responsibility to acquire the TPC electronics and to integrate this electronics with the data acquisition environment at RIKEN.

Initial testing will utilize STAR TPC electronics. The implementation of STAR TPC electronics during these tests will be the responsibility of the U.S. team, principally from the NSCL.

The NSCL already uses the STAR TPC electronics for the readout of the focal plane detector of the S800 spectrograph and the readout of the NSCL PPAC beam line tracking detectors [Yur99].

Longer term, we plan to employ new 12 bit TPC readout electronics, instead of the 10 bit STAR electronics. MSU is a member of the ACTAR collaboration, which designing suitable electronics for this purpose. Both MSU and RIKEN have been engaged in negotiations with other members of the ACTAR collaboration over a MOU that assigns responsibilities in the design process for a new TPC readout system called GET. It is anticipated that the MOU will be finalized in the near future. Design of the GET ASIC has begun at SACLAY. A. Chbihi from GANIL will assist as local liaison to the French engineering effort. Work on the ASAD (which contains the ASICS), the Trigger Card and the Protection Circuit is planned to commence at the beginning of calendar year 2009. Under the proposed MOU, MSU has responsibility for the CoBo, which services, strips zeros and formats data from the ASAD boards and sends it to the data acquisition. RIKEN will be involved in testing the final GET electronics, will purchase the final SAMURAI TPC electronics and will provide the data acquisition hardware and computer environment for successful operation of the SAMURAI TPC at RIKEN.

Funds are requested for 0.5 FTE of an electrical engineer to support the testing of the TPC, and the testing of the GET prototype electronics at MSU. These funds are included in the TPC development and construction budget discussed in Sections VI and VII.

VI.c) Project performance sites, division of responsibilities and resources required for trigger, beam tracking and ancillary detectors

The overall project leader for the SAMURAI TPC system is Tetsuya Murakami. Our Japanese colleagues will have the responsibility to implement the trigger, beam tracking and ancillary detectors.

VI.d) Project performance sites, division of responsibilities and resources required for the experimental program.

During next decade, RIKEN will provide unique high intensity rare isotope beams that can be used to probe the EoS of asymmetric matter at twice saturation density. A total of $85k is requested to support travel to RIKEN by the U.S. collaborators from MSU, WMU and TAMU on this project. Since this travel occurs before the electronic reconfiguration is complete, this amount is included in the Total TPC Project budget of $825k. The timescale for this work and basis for this budget is discussed in greater detail in Section VII. The physics program at RIKEN is discussed in Sections III and IV.

During this period, GSI will provide unique high energy stable beams that can be used to probe the EoS of asymmetric matter at densities of $\rho>2\rho_0$. A total of $25k is requested to support travel to one experiment at GSI by the U.S. collaborators from MSU, WMU and TAMU on this project. This timescale for this work and basis for this budget is discussed in greater detail in Section VII. The physics program at GSI is discussed in Sections III and IV.

Analyses of the experimental data and its theoretical interpretation will be performed at the home institutions of the collaboration members under their individual research grants. Travel funds ($35k) are requested for U.S. collaborators for travel between institutions to facilitate experimental planning and attendance at an annual collaboration workshop, where future experiments, analyses and theoretical ideas to constrain the EoS of neutron-rich matter will be discussed. More information about this budget request is given in VII.

VII. Duration of project and budget:

The total budget requested is $1,200k for a project starting on October 1, 2009 and ending on September 30, 2014. This includes direct costs and indirect costs on salaries and travel. The breakdown of the direct costs is given in Table 5 below. In this section we give a brief overview of the major component of the budget before breaking it down further in Sections VII.a)-VII.d).

TPC materials	$59k
TPC technical manpower	$195k
Postdoc (3y, ½ time)	$106k
2 Graduate students (4y)	$379k
TPC Project Travel	$85k
Total TPC Project budget	**$825k**
Collaboration travel	$35k
GSI Experimental travel	$25k
Supplies, services, shipping	$51k
Total Project budget	**$934k**

Table 5: Break-down of direct charges for the construction of SAMURAI TPC and for the experimental program.

The TPC materials and technical manpower budgets, listed in Table 5, provide the funds for construction of the TPC. The post-doc and graduate student funds are needed to provide the necessary scientific manpower during the design, testing and commissioning stages of the project. The post-doc will be stationed at the NSCL. Two graduate students, one from Western Michigan University under the guidance of Prof. Michael Famiano and another one from Western Michigan University under the guidance of Prof. Sherry Yennello, will be involved in the project and will work at MSU for much of the project. Additional scientific manpower will be provided by the research grants of the members of the collaboration including the research group of Professors Betty Tsang and William Lynch, the co-spokespersons of this proposal.

In addition to the TPC itself, we request travel funds to allow the formation of the international collaboration and funds for foreign travels for U.S. experimentalists. Included in the collaboration travel fund request ($35k) are funds for U.S. collaborators to attend an annual collaboration workshop for planning and discussing the experimental and theoretical projects undertaken by the collaboration to constrain the EoS of neutron-rich matter. Such meetings are important to insure progress on both the experimental and theoretical frontiers. We also request funds for the commissioning experiment in Riken and one experiment in GSI during the five year period of the grant.

The main focus of the proposal is on the measurements that can only be performed at the RIBF facility at RIKEN using the proposed TPC. The proposed studies will pave the way to precise measurements of density dependence of the symmetry energy that would be performed at FRIB in the U.S. and at FAIR in Germany to explore the density dependence of the symmetry energy when these future facilities become available. The investment is modest considering the resulting opportunity to maintain U.S. scientific leadership in the study of dense asymmetric matter, one of the scienticific areas of research in FRIB.

VII.a) TPC development time table

ID	Task Name
0	**SAMURAI TPC SYSTEM**
1	**SAMURAI TPC**
2	**Chamber design and construction**
3	Design
4	Procurement and fabrication
5	Assembly
6	**Detector design and construction**
7	Design
8	Procurement and fabrication
9	Installation of detector in TPC chamber
10	Testing
11	contingency
12	Shipping
13	Installation and testing at RIKEN
14	Commisioning at RIKEN
15	Gas Handling System
16	Laser Calibration System
17	TPC electronics and data acquisition
18	Trigger Scintillation Array
19	SAMURAI Dipole Magnet
20	Electronics reconfiguration

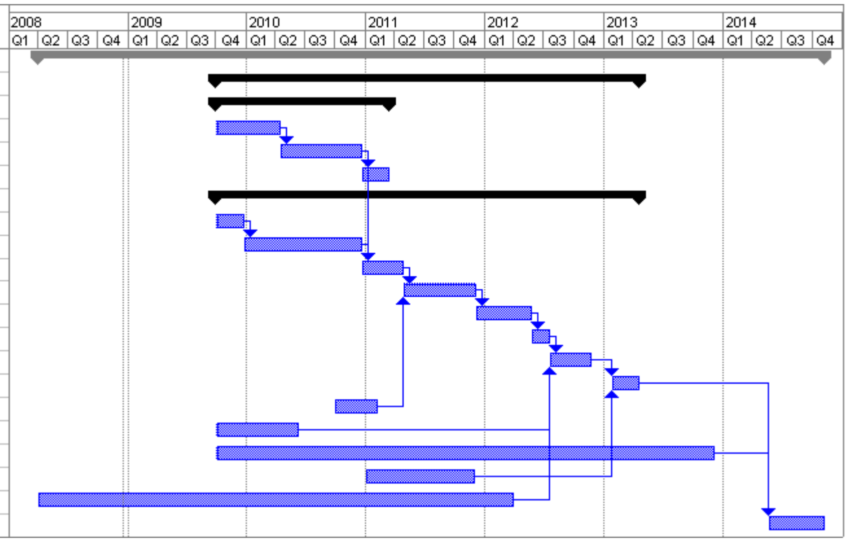

Table 6: Timeline for the design and construction of the SAMURAI TPC

The time line for the construction and installation of the SAMURAI TPC is shown in Table 6. Design of the chamber will start in the first half of year 1. Once the design is finalized, procurement and fabrication of the device will start in the second half of year 1. We plan to assemble the parts in the second year. In parallel with the design and construction of the chamber, the design and construction of the detector will proceed in similar schedule. By the second half of the second year, we will start testing the detector in the chamber. At the conclusion of the testing, the chamber with the detector will be shipped to Riken for installation during the second quarter of year 3. Under this time scale, the TPC would be constructed, tested and shipped to RIKEN for experiments within a time span of 2.7 years after the initiation of the project. By the time the TPC is shipped to Riken, the other parts of the project such as the dipole magnet, scintillation array, and data acquisition would have been ready. These systems will be merged with the TPC chamber/electronics in the second half of the third year. Starting year four we should be able to schedule commission runs of the TPC and proceed to the first of a series of experiments to study the density dependence of the symmetry energy at supra-saturation density at Riken.

VII.b) TPC development and commissioning budget

In this section, we discuss the expenditures that are directly related to the materials and manpower costs for developing the SAMURAI TPC. The cost estimate for the development of the SAMURAI TPC is based upon the EOS design, for which a set of design drawings exists. Table 6 and the upper part of Table 5 lists tasks, timelines and estimated costs, for the TPC design and construction. The line labeled "Total TPC Project Budget" in Table 5 lists the total materials and technical manpower direct costs (\$825k) for the TPC design, construction, testing and commissioning. This cost includes \$59k for TPC construction materials, \$195k for TPC technical and engineering support during the TPC design, construction and testing stages, \$106k for three years of post-doctoral support (1/2 time) and \$379k for four years support of a graduate student at Western Michigan University and a graduate student at Texas A&M University. The final (GET) TPC electronics, laser calibration system, high voltage supplies, gas handling system, dipole magnet, trigger array, beam tracking counters and ancillary detectors will be purchased by RIKEN and are not included in this budget. Funds will also be required for travel between institutions prior to completion, for the installation, testing and commissioning of the TPC at RIKEN. The funds are discussed in Section VII.c)..

VII.c) Experiment schedule, collaborative travel schedule and budget

An overview of the travel schedule, provided by Table 7, lists the travel request. The travel budget for a given experiment reflects an estimate of the total travel time on site that is required to prepare or conduct the relevant experiment. In addition, funds are requested for trips to the collaboration meetings, and to facilitate experimental and analysis coordination and theoretical interpretation. The total budget for collaborative travel assumes $1000 per domestic trip and $2000 per overseas trip. In FY2012, $25k is also requested to ship the TPC to RIKEN and $10k is requested to ship the Miniball to GSI and back. In addition, we request $3k per year as a materials and supplies budget, adjusted for inflation.

Year	Experiment	total	Collaboration	total
FY2010	none		7 trips	$8k
FY2011	Experimental preparation	$12k	6 trips	$6.3k
FY2012	GSI exp.: RIKEN TPC installation	$43k	6 trips	$6.6k
FY2013	TPC commissioning: 5 trips	$35k	6 trips	$6.9k
FY2014	Electronics reconfiguration: 5 trips	$20k	6 trips	$7.3k

Table 7: Proposed experiment and collaboration travel

VIII. Project Management

TPC design and construction will be directed by Prof. William Lynch, who has extensive experience in the development of new scientific instruments [Wal07,Dav01,Des90]. The overall project director will be Dr. Betty Tsang. The project director will be responsible to monitor the progress of the project including the cost and schedule supported by the infra-structure of the NSCL in effort reporting. Dr. Tsang has had extensive experience managing international collaborations. Upon the completion of the installation and commissioning of the TPC at RIKEN, the project will enter the phase of experimentation at RIKEN. To ensure that the best scientific ideas and results will come out of the experiments, the collaboration plans to elect a scientific director whose tenure will rotate among the collaborators to oversee the scientific direction of the collaboration.