National Superconducting Cyclotron Laboratory
Proposal Form - PAC 39

By submitting this proposal, the spokesperson certifies that all collaborators listed have read the Description of Experiment and have agreed to participate in the experiment.

Title

Probing the momentum dependence of the isovector mean field potential

Spokespeople

	Primary Spokesperson	**Backup Spokesperson**
Name	William Lynch	Zbigniew Chajecki
Address	NSCL Michigan State University 640 S. Shaw Lane E. Lansing, MI	2228 Everett Tower Western Michigan University Kalamazoo, MI 49008
Phone	(517) 908-7319	(269) 387-4911
E-Mail	lynch@nscl.msu.edu	Zbigniew.Chajecki@wmich.edu
Organization	NSCL & MSU Dept. of Physics and Astronomy	Physics Department, Western Michigan University
Position	Senior Researcher	Senior Researcher

Experimenters

Name	**Organization**	**Position**	**Name**	**Organization**	**Position**
Manyee (Betty) Tsang	NSCL/MSU	Senior Researcher	TadaAki Isobe	RIKEN	Senior Researcher
Jack Winkelbauer	NSCL/MSU	Graduate Student	Zachary Kohley	NSCL/MSU	Senior Researcher
Juan Manfredi	NSCL/MSU	Graduate Student	Giuseppe Verde	IPN Orsay, France	Senior Researcher
Suwat Tangwancharoen	NSCL/MSU	Graduate Student	Byungsik Hong	Korea University, Korea	Senior Researcher
Jon Barney	NSCL/MSU	Graduate Student	Genie Jhang	Korea University, Korea	Graduate Student
Justin Estee	NSCL/MSU	Graduate Student	Junwoo Lee	Korea University, Korea	Graduate Student
Sean Sweany	NSCL/MSU	Graduate Student	Fengfeng Cheng	Beijing Normal University, China	Senior Researcher
Corinne Anderson	NSCL/MSU	Undergraduate	Yao Feng Zhang	Beijing Normal University, China	Senior Researcher
Ben Brophy	NSCL/MSU	Undergraduate	Gong Xiaohui Chen	Western Michigan University	Undergraduate
Han Setiawan	NSCL/MSU	Undergraduate			
Pierre Morfouace	NSCL/MSU	Postdoctoral Associate			
Yassid Ayyad	NSCL/MSU	Postdoctoral Associate			
Lee Sobotka	Washington University	Senior Researcher			
Robert Charity	Washington	Senior Researcher			

	University	
Kyle Brown	Washington University	Graduate Student
Cole Pruitt	Washington University	Graduate Student
Dan Hoff	Washington University	Graduate Student
Demetrios Sarantites	Washington University	Senior Researcher
Walter Reviol	Washington University	Senior Researcher
Andrew Rogers	University of Massachusetts Lowell	Senior Researcher
Hiu Ching (Jenny) Lee	Hong Kong University	Senior Researcher
Jerzy Lukasik	IFJ-PAN Krakow, Poland	Senior Researcher
Piotr Pawlowski	IFJ-PAN Krakow, Poland	Senior Researcher
Zhigang Xiao	Tsinghua University	Senior Researcher
Tetsuya Murakami	Kyoto University	Senior Researcher

Location & Equipment Details

Location	S2 Vault
Equipment	53" Chamber High Resolution Array

	Setup Time (Days)	Take Down Time (Days)
Experimental Vault	28	14
Data Acquisition	21	7
Electronics	21	7

Preferred Experiment Start Date	4/4/2016
Dates Excluded	Please note that the setup and takedown times could be shared between this experiment and E14030 if these were run back to back.

Summary

We propose to probe the momentum dependence of the isovector mean field potential by comparing the energy spectra (i.e. radial flow) of neutrons vs. protons in ^{40,48}Ca+^{112,124}Sn collisions at E/A=35, and 120 MeV. Such mass asymmetric collisions are relatively more sensitive to the momentum dependence and less sensitive to the density dependence of the nuclear mean field potential than are collisions with mass symmetric systems such as ^{112,124}Sn + ^{112,124}Sn [Pan93]. Combining these data with data on light mass symmetric ^{40,48}Ca+^{40,48}Ca and heavy mass symmetric ^{112,124}Sn + ^{112,124}Sn collisions, we will be able to clearly distinguish between the influence of the momentum and density dependences of the isovector mean field (i.e. symmetry) potential and obtain strong constraints on both.

Special Requirements

Detail any modifications needed to the standard configuration of the device used:

These proposed measurements will require the same setup and beams as approved Experiment 14030. If these experiment run back to back, we do not need the additional calibration and setup time listed on the scheduling constraints page.

Requirements that are outside the current NSCL operating envelope:

There are no special requirements.

Reaction targets at the experimental station:

self supporting 112Sn and 124Sn 5 mg/cm^2

Breaks required in the schedule of the experiment:

No breaks are needed if experiment is scheduled back to back the Exp 14030.

Non-standard resources:

HiRA and Microball. Both of these are in the custody of the collaborators.

Other special requirements:

none.

Proposal Elements

PAC39ca_sn_final.pdf

LISE++ Files

48Ca120MeV.lpp
48Ca35MeV.lpp
40Ca35MeV.lpp
40Ca120MeV.lpp

Fast Beam Worksheet 1

Primary Beam

Beam Type	Developed
Isotope	40Ca
Energy	140 MeV/nucleon
Intensity	50 pnA
Tuning Time	12 hrs

Beam-On-Target

Isotope	40Ca
Energy	120 MeV/nucleon
Rate at Experiment	1 pnA
Total A1900 Momentum Acceptance	0.5 %
Purity at Experiment	100 %
Rare-Isotope Delivery Time Per Table	0 hrs
Tuning Time to Vault	3 hrs
Total beam preparation time	15 hrs
Is a plastic timing scintillator required at the A1900 focal plane for providing a timing start signal?	No
Is event-by-event momentum correction from position measured at the A1900 Image 2 position required?	No
Experimental Device	Other - HiRA, WU uBall
Experimental Device Tuning Time	0 hrs
On-Target Time Excluding Device Tuning	72 hrs
Total On-Target Time	72 hrs
Total Beam Preparation Time	87 hrs

Fast Beam Worksheet 2

Primary Beam

Beam Type	Developed
Isotope	40Ca
Energy	140 MeV/nucleon
Intensity	50 pnA
Tuning Time	0 hrs

Beam-On-Target

Isotope	40Ca
Energy	35 MeV/nucleon
Rate at Experiment	1 pnA
Total A1900 Momentum Acceptance	0.5 %
Purity at Experiment	100 %
Rare-Isotope Delivery Time Per Table	0 hrs
Tuning Time to Vault	3 hrs
Total beam preparation time	3 hrs
Is a plastic timing scintillator required at the A1900 focal plane for providing a timing start signal?	No
Is event-by-event momentum correction from position measured at the A1900 Image 2 position required?	No
Experimental Device	Other - HiRA, WU uBall
Experimental Device Tuning Time	0 hrs
On-Target Time Excluding Device Tuning	72 hrs
Total On-Target Time	72 hrs
Total Beam Preparation Time	75 hrs

Fast Beam Worksheet 3

Primary Beam

Beam Type	Developed
Isotope	48Ca
Energy	140 MeV/nucleon
Intensity	80 pnA
Tuning Time	12 hrs

Beam-On-Target

Isotope	48Ca
Energy	120 MeV/nucleon
Rate at Experiment	1 pnA
Total A1900 Momentum Acceptance	0.5 %
Purity at Experiment	100 %
Rare-Isotope Delivery Time Per Table	0 hrs
Tuning Time to Vault	3 hrs
Total beam preparation time	15 hrs
Is a plastic timing scintillator required at the A1900 focal plane for providing a timing start signal?	No
Is event-by-event momentum correction from position measured at the A1900 Image 2 position required?	No
Experimental Device	Other - HiRA, WU uBall
Experimental Device Tuning Time	0 hrs
On-Target Time Excluding Device Tuning	72 hrs
Total On-Target Time	72 hrs
Total Beam Preparation Time	87 hrs

Fast Beam Worksheet 4

Primary Beam

Beam Type	Developed
Isotope	48Ca
Energy	140 MeV/nucleon
Intensity	80 pnA
Tuning Time	0 hrs

Beam-On-Target

Isotope	48Ca
Energy	35 MeV/nucleon
Rate at Experiment	1 pnA
Total A1900 Momentum Acceptance	0.5 %
Purity at Experiment	100 %
Rare-Isotope Delivery Time Per Table	0 hrs
Tuning Time to Vault	3 hrs
Total beam preparation time	3 hrs
Is a plastic timing scintillator required at the A1900 focal plane for providing a timing start signal?	No
Is event-by-event momentum correction from position measured at the A1900 Image 2 position required?	No
Experimental Device	Other - HiRA WU uBALL
Experimental Device Tuning Time	0 hrs
On-Target Time Excluding Device Tuning	72 hrs
Total On-Target Time	72 hrs
Total Beam Preparation Time	75 hrs

Spectrograph Worksheet

No Spectrograph Worksheet is required.

Sweeper Worksheet

No Sweeper Magnet Worksheet is required.

Safety Information Worksheet

Contact: William Lynch

Yes	**Radioactive sources required for checks or calibrations**	228Th, 241Am
No	**Transport or send radioactive materials to or from the NSCL**	
No	**Transport or send? to or from the NSCL?chemicals or materials that may be considered hazardous or toxic**	
No	**Generate or dispose of chemicals or materials that may be considered hazardous or toxic**	
No	**Mixed Waste (RCRA) will be generated and/or will need disposal**	
No	**Flammable compressed gases needed**	
No	**High-Voltage equipment (Non-standard equipment with > 30 Volts)**	
No	**User-supplied pressure or vacuum vessels, gas detectors**	
No	**Non-ionizing radiation sources (microwave, class III or IV lasers, etc.)**	
No	**Biohazardous materials**	
No	**Lifting or manipulating heavy equipment (>500 lbs)**	

I. Physics Justification

Measurements of isoscalar collective vibrations, collective flow and kaon production in energetic nucleus-nucleus collisions have constrained the Equation of State (EoS) for symmetric matter at densities ranging from saturation density to five times saturation density, ρ_0 [Dan02, Fuc06, You97]. Laboratory constraints on the symmetry energy and EoS of cold neutron rich matter have emerged at $\rho<\rho_0$ [Tsa12, Hor14], and efforts are underway to constrain them at $\rho>>\rho_0$ [Sha14, Hor14]. This proposal aims to improve constraints on the momentum dependence of the isovector mean field potential [Zha14, Xie14], which is highly relevant to the transport of nucleons within nucleus-nucleus collisions and to the thermal properties of the EoS and symmetry energy of neutron-rich matter in laboratory systems [pon99, Bet90, Dob99], and in neutron stars [Lat04] and to the radiative cooling of both [Ste05].

Nucleons in dense matter experience strong momentum-dependent interactions that "appear" to reduce their inertial masses to lower "effective mass" or "k-mass" values [Mah85, Van05]. These reductions can arise from exchange (Fock terms), other non-localities, Lorentz properties of the N-N interaction, and higher-order terms [Mah85, Li04, Liu02, Dob99, Zou02, Hof01, bru55, Bla81, Bau01, Dan00, Bet90, Pon99]. In deeply bound nuclear states [Mah85], nucleon-nucleus elastic scattering [Bau01] and in relativistic nucleus- nucleus collisions [Dan00] these k-mass values can be reduced in symmetric matter at $\rho=\rho_0$ to ~ 70% of their vacuum values. These neutron (m_n^*) and proton effective masses (m_p^*), however, can differ [Mah85] in neutron rich environments, with larger differences in systems with larger neutron/proton asymmetries or larger densities or both. Such differences strongly influence the symmetry energy [Mah85, Hof01] and equation of state [Bet90], the magnitude of shell effects in nuclei far from stability [Dob99, Hof01], the thermal properties of neutron-rich nuclei, core-collapse supernovae [Bet90], neutron stars [Pon99, Bal14], and neutron star cooling by neutrino emission [Bal14].

Calculations using Landau-Fermi liquid theory [Sjo76] and the non-relativistic Brueckner-Hartree-Fock [Zou02] theory have predicted that $m_n^* > m_p^*$ in neutron rich matter, while other calculations using relativistic mean field (RMF) theory and relativistic Dirac-Brueckner theory [Liu02, Hof01] predict that $m_n^* < m_p^*$. Analyses of nucleon-nucleus elastic scattering somewhat prefer $m_n^* > m_p^*$ [Li04], but their uncertainties are large. Moreover, the sign and magnitude of the effective mass splitting are poorly constrained at densities far from saturation density.

To address these issues in experiment E09042, we compared the spectra of neutrons emitted to 90 degrees in the center of mass to corresponding proton spectra for both central ^{124}Sn+^{124}Sn collisions and central ^{112}Sn+^{112}Sn collisions at E/A=50 and 120 MeV. Transport calculations predict fast neutrons to come from the compressed participant region and experience a more repulsive potential and a higher acceleration for $m_n^* < m_p^*$, than do fast protons at the same momentum, resulting in an enhanced ratio of neutron over proton (n/p) spectra at high energies [Riz05, Zha14, Xie13]. In contrast, calculations for $m_n^* > m_p^*$ predict that the effective masses enhance the acceleration of protons relative to neutrons resulting in a lower n/p spectral ratio [Riz05, Zha14, Xie13].

Sensitivity to the symmetry energy can be enhanced and isoscalar dynamics suppressed by dividing the proton and neutron energy spectra for a reaction to obtain the n/p spectral ratio $R_{n/p}$ defined by

$$\mathrm{R_{n/p}}(^{124}\mathrm{Sn}+^{124}\mathrm{Sn})=\frac{dM_n}{dE_{cm}d\Omega_{cm}}/\frac{dM_p}{dE_{cm}d\Omega_{cm}}$$

where $\frac{dM_n}{dE_{cm}d\Omega_{cm}}$and $\frac{dM_p}{dE_{cm}d\Omega_{cm}}$ are the neutron and proton spectra at 90° in the center of mass [Cou14]. We further enhance the symmetry energy effects by constructing the double ratio.

$$DR(n/p) = \frac{\mathrm{Rn/p(124Sn + 124Sn)}}{\mathrm{Rn/p(112Sn + 112Sn)}}$$

Calculations indicate that DR(n/p) is independent of the isoscalar mean-field potential, the isoscalar nucleon effective mass and the isoscalar in-medium nucleon-nucleon cross sections [Zha12, Cou11]. Moreover, the double ratio minimizes sensitivities to the charge distributions at breakup, to the neutron detection efficiencies, reaction losses in the particle detectors and the neutron and proton energy calibrations. Each of these instrumental corrections can be of the order of 10%.

At present, most transport model calculations do not accurately predict the relative abundances of neutrons, protons and other light particles due to the inaccurate description of the binding energies of light clusters, most importantly, the alpha particle. To compensate for this deficiency, we calculated double ratios of the Coalescence Invariant (CI) spectra. These spectra are constructed from light particle spectra by counting the numbers of free protons or neutrons and combining them with neutrons or protons emitted within bound clusters moving at the same velocities [Cou14]. The solid black points in top and bottom panels of Figure 1 indicates the double ratios constructed from the CI neutron and proton spectra at $E_{beam/A}$ = 50 and 120 MeV, respectively. At E/A>50 MeV, where the free (not shown) and CI double ratios agree, the measured points lie between the calculated trends for the SLy4 interaction with $m_n^* < m_p^*$ and the trends for the SkM* interaction with $m_n^* > m_p^*$. At lower energies, the trend is closer to that of the SLy4 interaction. Thus the entire trend is not described by either interaction, which may indicate inaccurate description of the momentum dependence or of the density dependence of the symmetry energy.

This choice of equal mass projectiles and target maximizes the compression achieved in the collision and the role of the density dependence. One can reduce the role of the density dependence while retaining the momentum dependent effects by exploring mass-asymmetric collisions; shown by Pan and Danielewicz [Pan93].

Rachel Hodges-Showalter recently completed the analysis of experiment E05049 (proposed by Michael Famiano), which measured mass-asymetric Ca+Sn collisions at E/A=120 MeV. After constraining the in-medium cross sections with this data, Rachel explored the sensitivity of the single ratio $R_{n/p}(^{48}Ca+^{124}Sn)$ for CI invariant neutrons and protons emitted at mid rapidity shown in the upper panel of Figure 2 and the corresponding double ratio

$$DR(n/p)=\frac{\mathrm{Rn/p(48Ca+124Sn)}}{\mathrm{Rn/p(48Ca+112Sn)}}$$

shown in the lower panel of Figure 2, below. The trend of the single ratio in upper panel of Figure 2 favors the SkM* calculation with $m_n^* > m_p^*$. Such single ratios are much more sensitive to systematic uncertainties in the efficiencies, energy calibrations and reaction losses than the double ratio. While the statistical precision of the double ratios do not allow one to unambiguously rule out either effective interaction, the new measurements proposed here will enable such distinctions to be made.

II. Goals of the proposed experiment

The principal goal of this experiment is to measure “pseudo-neutron” and particle spectra for protons, deuterons, tritons, helium-3 and alphas to obtain precise single and double coalescence-invariant neutron to proton ratios for ^{40}Ca+^{124}Sn, ^{40}Ca+^{112}Sn, ^{48}Ca+^{124}Sn and ^{48}Ca+^{112}Sn collisions with the upgraded HiRA telescopes. Because of the densities achieved, the Pauli blocking and the momentum dependence of the mean fields evolve with incident energy, we believe that at least two incident energies, E/A ≈ 35, and 120 MeV, will be needed to map this behavior and to permit a more accurate extrapolation to the higher-densities. The results will be used to benchmark the reliability of transport models which are needed to extract symmetry energy and effective mass constraints. The same two beam energies have been approved for experiment e14030. Set up time and calibrations effort can be shared and thus reduce the beam time needed for calibrations and debugging if the present experiment and the e14030 can run in a campaign mode.

III. Experimental Details

The experimental equipment will consist of the Washington University Microball array and the HiRA silicon strip detector array. Both arrays will be placed in the S2 scattering chamber as shown on the schematic layout of the experiment in Figure 3. Multiplicity of the charged particles detected by the Microball will be used to determine the impact parameter of the collisions. The HiRA array consists of 14 telescopes positioned at azimuthal angles of 30-70 deg. in the laboratory to measure the energy spectra of the light fragments emitted from ^{40}Ca+^{124}Sn, ^{40}Ca+^{112}Sn, ^{48}Ca+^{124}Sn and ^{48}Ca+^{112}Sn collisions at E/A=35, and 120 MeV. We propose to run this experiment together with e14030 which will also use HiRA upgrade array currently under construction. A brief note on HiRA upgrade: We propose to replace the current HiRA CsI crystals that are 4cm long with 10cm-long CsI crystals. This will extend the energy range of measured p, d, t, ^{3}He, ^{4}He up to 190, 130, 105, 230 and 190 MeV/u respectively. In the upgraded design shown in Figure 4, we also increase the number of CsI crystals of each telescope to 9 to better accommodate multiple hits. We have received internal funding from the laboratory starting April 1, 2015 to build 10 upgrade telescopes. Our Chinese collaborators at Beijing Normal University will provide 4 more upgraded CsI arrays. Since we are buying the packaged CsI arrays directly from a manufacturer there will be minimal in-house R&D effort. We expect to finish the HiRA upgrade by the end of this year.

Based on our recent experiences running experiments with the WashU Microball at MSU as well as in RIKEN, we anticipate we will be event rate limited at about 400 events/sec, corresponding to an incident beam intensity of about $3x10^{8}$ pps, similar to the rate achieved in experiment e05049 (Ca+Sn collisions at E/A=140 MeV). The transverse momentum spectra drop exponentially as shown in Figure 5. With the HiRA upgrade and assuming the high energy tritons have similar fall off as the alpha particles, we should be able to measure the energy spectra of tritons up to 45 MeV/u with the same amount (2 days) of beam time as experiment E05049. To extend the energy spectra of the tritons to 60 MeV/u, we would request an extra day of beam time which should give us energy spectra with adequate statistics for constructing the single and double ratios at high energy. We will need 6 days of ^{40}Ca beam and 6 days of ^{48}Ca beam on target. We also ask 24 hours of beam time to debug the Microball and HiRA-upgrade array setup and to verify the trigger condition. To calibrate the HiRA telescopes with proton particles, we request 32 hours to scatter recoil protons from CH2 target using two degraded ^{16}O beams of 15 and 30 MeV per nucleon. These calibration beam time can be much shortened or eliminated if the experiment is scheduled back to back with experiment e14030.

We should be ready to run the experiment in March of 2016 after we upgrade the HiRA telescopes.

IV. Supplemental Information

V. References:

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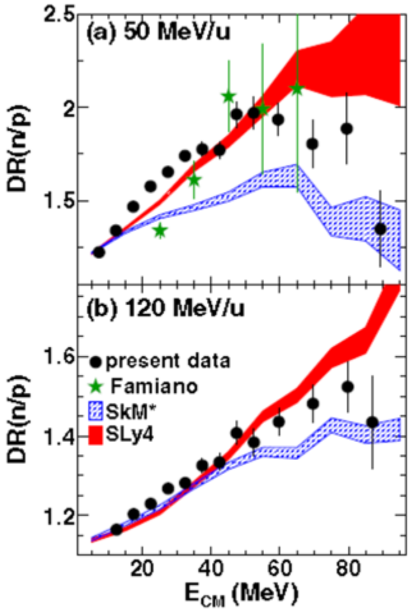

Figure 1: Coalescence invariant double ratios for Sn+Sn collisions at E/A=50 MeV (upper panel) and 100 MeV (lower panel). The solid points are the current data and the shaded regions are ImQMD calculations.

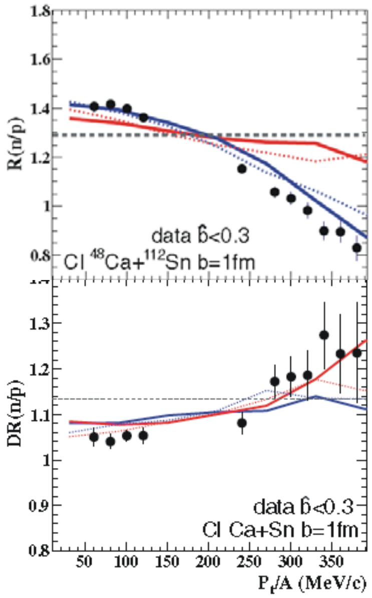

Figure 2: Coalescence invariant single ratios for ^{48}Ca+^{124}Sn collisions (upper panel) and double ratios (lower panel) for ^{48}Ca+^{124}Sn over ^{48}Ca+^{112}Sn collisions.

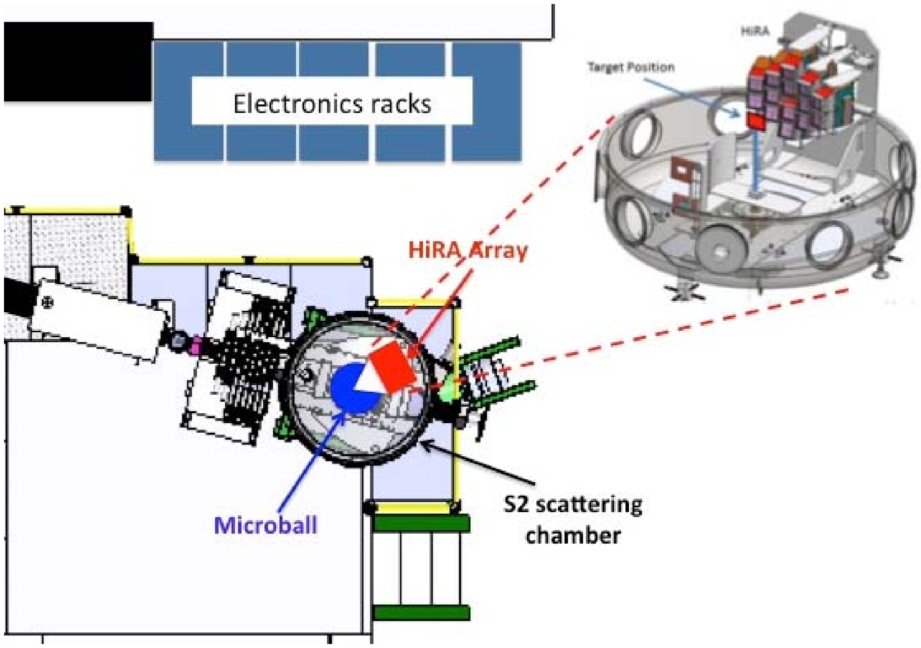

Figure 3: *Overhead view of the setup in the S2 vault involving Microball, HiRA Array mounted in the S2 scattering chamber*

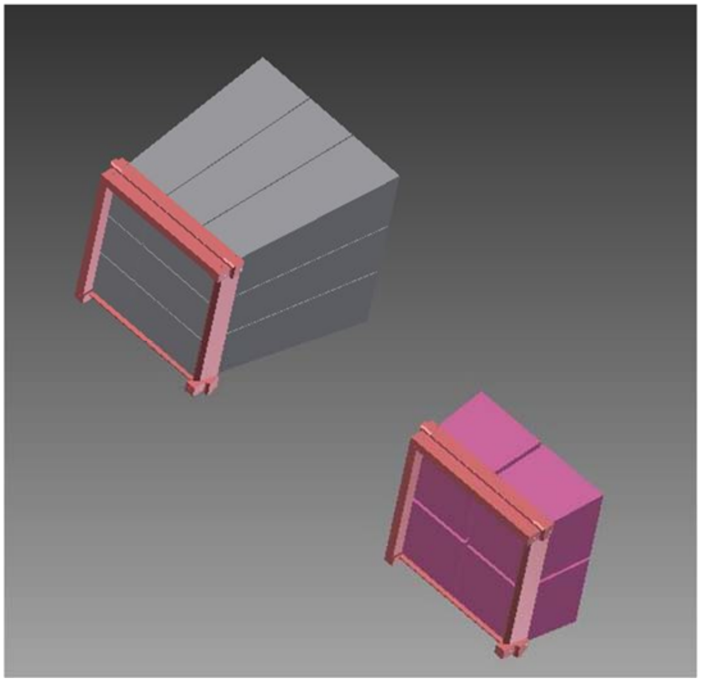

Figure 4: *Schematic drawings of one HiRA telescope with 4 c m CsI crystals (right, current setup), and 10 cm CsI crystals (left, proposed upgrade).*

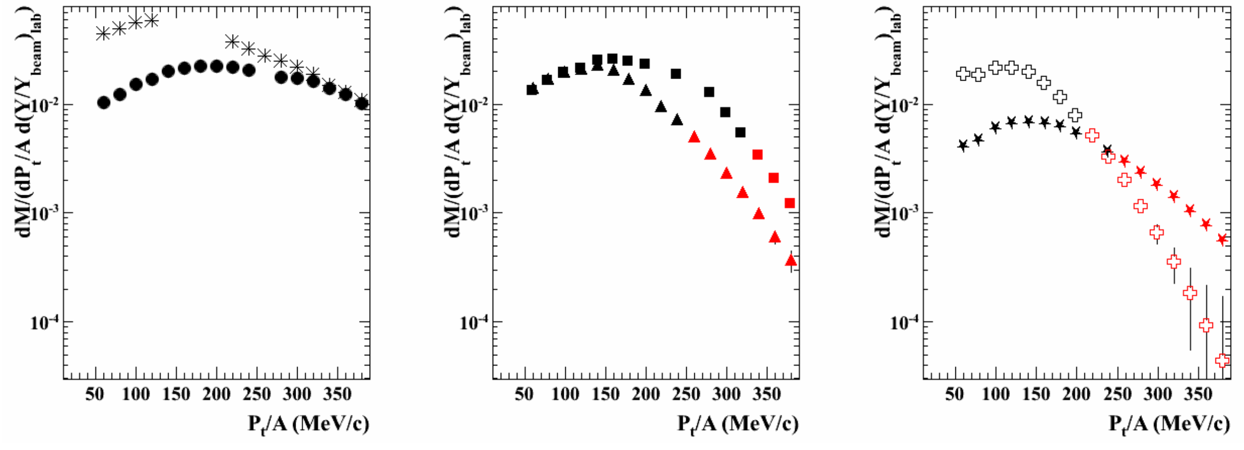

Figure 5: *Free particle Pt/A spectra (black points) and extended spectra (red points) for the 48Ca+124Sn reaction within the mid-rapidity region. The extended spectra are obtained by fitting the last 3-4 points of the measured spectra. Left panel: star represent n and solid circles represent p. Middle Panel: squares represent d and triangle represent t. Right Panel: crosses represent 4He and star represent 3He.*

Status of Previous Experiments

Results from, or status of analysis of, previous experiments at the CCF listed by experiment number. Please indicate publications, invited talks, Ph.D.s awarded, Master's degrees awarded, undergraduate theses completed.

Status of experiments associated with Betty Tsang and Bill Lynch
(not including users' experiments, see Charity's, Wousma's and Bazin's proposals)
Nearly 20 papers have been published on experiments using the HiRA array.

Expt #	date completed	PhD student	Year graduate	Responsible person	presentation	publication
1032	Jun-03			Famiano	numerous	Phys.Rev.Lett. 97, 052701 (2006)
				Tsang		Phys.Rev.Lett. 102, 122701 (2009).
				Tsang		Phys.Rev.C 86,015803 (2012)
1036	Jun-04	M. Mocko	2006	Mocko	numerous	Phys. Rev. C **74**, 054612 (2006)
				Mocko		Phys. Rev. C **76**, R067601 (2007)
				Mocko		Phys. Rev. C **76**, 041302 (2007)
				Tsang		Europhysics Letters, **79** (2007) 12001
				Mocko		Nucl.Phys.**A813**:293(2008)
				Mocko		Phys. Rev. C **78**,024612(2008)
				Winkelbauer		Phys. Rev. C **88**,044613(2013)
3031	May-05			Lukyanov		PRC 80, 014609 (2009).
2026	Oct-05	Wallace	2005	Wallace	numerous	NIMA 583, 302 (2007)
2023	Aug-05	Rogers	2009	Rogers	numerous	PRL106, 252503 (2011).
3045	Dec-06	M. Kilburn	2009	Henzl, Henzlova	numerous	PRC 85, 014606 (2011).
				Chajecki		Submitted to PRL
				Chajecki		Paper in preparation
5133	Dec-07	Jenny Lee	2010	Lee	numerous	PRL 102,062501 (2009)
				Lee		PR C83, 014606 (2011)
				Tsang		PR C88, 017604 (2013).
				Rogers		NIMA 707, 64 (2013)
06035	Dec-07	Sanetullaev	2010	Tsang	numerous	PLB 736, 137 (2014).
			2010	Rogers		arXiv:1309.2745Submitted to NIMA
07038	Jun-11	Winkelbauer		Winkelbauer	numerous	Data being analyzed

05049	May-09	Showalter	2014	Showalter	numerous	Paper in preparation (Famiano’s experiment)
09042	Nov-09	Coupland	2012	Coupland	numerous	Paper in preparation
09042	Nov-09	Coupland	2012	Coupland	numerous	Paper in preparation
09042	Nov-09	Coupland	2012	Coupland	numerous	Paper in preparation
		M. Youngs	2013	M. Youngs		Paper in preparation
10015	Dec-15			A. Rogers		Data being analyzed
09084	Nov-15	J. Manfredi		J. Lee		Data being analyzed
12014				Chajecki		Experiment not scheduled
14030				Chajecki		Experiment not scheduled

Educational Impact of Proposed Experiment

If the experiment will be part of a thesis project, please include the total number of years the student has been in graduate school, what other experiments the student has participated in at the NSCL and elsewhere (explicitly identify the experiments done as part of thesis work), and what part the proposed measurement plays in the complete thesis project.

This experiment will form part of the thesis for Sean Sweany, he will finish his first year as a physics graduate student at MSU. He worked as a RA at NSCL last summer and worked on repairing the damaged CsI detectors. Due partly to his effort, the CsI array was ready for experiments 10015 and 09084 last November and December. He is doing well in his academic classes and is awarded a research assistant this term. Currently he is working on the design of the HiRA upgrade project. Thus he should have no trouble setting up and carrying out the proposed experiment. The HiRA array has provided many opportunities to train undergraduate students. Currently, an MSU undergraduate, Corinne Anderson is helping with the design of the upgrade. Through her work on the repair of the CsI array, setting up experiments 10015 and 09084, she has developed into a very skillful experimentalist and has presented many posters on the work.

This project would also actively engage other undergraduate and graduate students as well as postdocs from NSCL and Washington University.