National Superconducting Cyclotron Laboratory Proposal Form - PAC 38

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 effective mass dependence of the symmetry energy via particle ratios in 40,48Ca+40,48Ca collisions at E/A=35 and 120 MeV.

Spokespeople

	Primary Spokesperson	Backup Spokesperson
Name	Zbigniew Chajecki	Betty Tsang
Address	National Superconducting Cyclotron Laboratory Michigan State University 640 S. Shaw Lane, East Lansing, Michigan 48824-1321	National Superconducting Cyclotron Laboratory Michigan State University 640 S. Shaw Lane, East Lansing, Michigan 48824-1321
Phone	15179744029	5179087386
E-Mail	chajecki@nscl.msu.edu	tsang@nscl.msu.edu
Organization	NSCL/MSU	NSCL/MSU
Position	Postdoctoral Associate	Senior Researcher

Experimenters

Name	Organization	Position	Name	Organization	Position
John Barney	MSU/NSCL	Graduate	Demetrios Sarantites	Washington University	Senior Researcher
Justin Estee	MSU/NSCL	Graduate	Walter Reviol	Washington University	Senior Researcher
WIlliam Lynch	MSU/NSCL	Senior Researcher	Zach Kohley	MSU/NSCL	Senior Researcher
Betty Tsang	MSU/NSCL	Senior Researcher	Corinne Anderson	MSU/NSCL	Undergraduate
Zbigniew Chajecki	MSU/NSCL	Postdoctoral Associate	David Witalka	MSU/NSCL	Undergraduate
Juan Manfredi	MSU/NSCL	Graduate	Kyle Brown	Washington University	Graduate
Rachel Showalter	MSU/NSCL	Graduate	Cole Pruitt	Washington University	Graduate
Rebecca Shane	MSU/NSCL	Postdoctoral Associate			
Suwat Tangwancharoen	MSU/NSCL	Graduate			
Jack Winkelbauer	MSU/NSCL	Graduate			
Laura Francalanza	INFN-Catania	Graduate			
Lee Sobotka	Washington University	Senior Researcher			
Robert Charity	Washington University	Senior Researcher			
Jerzy Lukasik	IFJ-PAN Krakow, Poland	Senior Researcher			
Giuseppe Verde	INFN-Catania	Senior Researcher			

Andy Rogers	NSCL	Senior Researcher
Tetsuya Murakami	Kyoto University	Senior Researcher
TadaAki Isobe	RIKEN	Senior Researcher
Yao Feng Zhang	Beijing Normal University	Senior Researcher
Feng Feng Cheng	Beijing Normal University	Senior Researcher
Zhigang Ziao	Tsing Hua University	Senior Researcher
Piotr Pawlowski	IFJ-PAN Krakow, Poland	Senior Researcher
Noritsugu Nakatsuka	Kyoto University	Graduate
Romualdo deSouza	Indiana University	Senior Researcher
Sylvie Hudan	Indiana University	Senior Researcher

Location & Equipment Details

Location	S2 Vault
Equipment	53" Chamber High Resolution Array
Additional Equipment	Washington University Microball

	Setup Time (Days)	Take Down Time (Days)
Experimental Vault	30	14
Data Acquisition	30	0
Electronics	30	14

Preferred Experiment Start Date	3/1/2015
Dates Excluded	

Summary

Nucleus-nucleus collisions provide the only means to experimentally probe neutron-rich nuclear matter and its Equation of State (EoS) at supra-saturation and sub-saturation densities. It is essential to find the constraints on the density and the momentum dependence of the symmetry energy using observables from heavy ion collisions and use them to extrapolate to higher nuclear matter densities. The physics is relevant to properties of neutron stars. We propose to measure impact parameter selected particle spectra for protons, deuterons, tritons, helium-3 and alphas emitted from 40Ca+40Ca and 48Ca+48Ca collisions at E/A=35 and 120 MeV. In order to extend the energy range of measured tritons as well as other light clusters, we will upgrade the HiRA telescopes for the proposed experiment by installing longer CsI crystals. Recently we developed a method to extract neutron spectra from these light charged particles spectra. From the extracted n- and measured p- spectra, we can construct precise single and double coalescence-invariant neutron to proton yield ratios as a function of the nucleon kinetic energy. Comparison of data to transport models will allow us to place stringent constraints on the momentum dependence of the symmetry potential albeit the effective nucleon masses.

Special Requirements

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

Requirements that are outside the current NSCL operating envelope:

Reaction targets at the experimental station:

Breaks required in the schedule of the experiment:

Non-standard resources:

Other special requirements:

Proposal Elements

PAC38_CaCa_final.pdf

LISE++ Files

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

Description of Experiment

I. Physics Justification

Introduction: Nucleus-nucleus collisions provide the only means to experimentally probe neutron-rich nuclear matter and its Equation of State (EoS) at both supra-saturation and sub-saturation densities. One of the most compelling questions concerns the density and momentum dependence symmetry energy and its mean field potential, which governs the extrapolation of the EoS to neutron matter. This momentum dependence leads to different values of the neutron and proton effective masses that strongly influence the thermal properties of neutron-rich systems and the magnitude of shell effects in nuclei far from stability [1,2,3].

Calculations using Landau-Fermi liquid theory [4] and the non-relativistic Brueckner-Hartree-Fock [5] approach predict that $m^*_n > m^*_p$ in neutron-rich matter, while some relativistic mean field (RMF) and relativistic Dirac-Brueckner calculations [6-8] predict that $m^*_n < m^*_p$. Analyses of nucleon-nucleus elastic scattering somewhat prefers $m^*_n > m^*_p$ [9], but the uncertainties are large. Consequently, the sign and magnitude of this isospin dependent effective mass splitting are not well constrained - especially for $\rho \neq \rho_0$.

Recent reviews of the symmetry energy constraints [10,11] have shown that constraints on the symmetry energy at sub-saturation densities obtained from isospin diffusion measurements in heavy-ion collisions are consistent with those extracted from nuclear-structure. While effective masses splitting does not strongly influence isospin diffusion [12], it does influence the ratio of neutron over proton spectra and other probes of the density dependence of the symmetry energy at supra-saturation densities [13]. Constraints on the effective mass splitting of neutrons and protons are therefore urgently needed.

In a neutron-rich system, the symmetry mean field potential repels neutrons and attracts protons; the magnitude of this effect depends strongly on the splitting of nucleon effective masses [14,15]. We investigated this recently by measuring $^{112,124}Sn+^{112,124}Sn$ collisions at E/A=50 MeV and 120 MeV. We constructed theoretical and experimental coalescence-invariant primordial neutron and proton spectra by combining free nucleons at a given velocity with those bound in light nuclei (clusters) moving at the same velocity. In Figure 1, we plot the double-ratio of the coalescence-invariant neutron to proton spectra defined as

$$DR(n/p) = R_{n/p}(A)/R_{n/p}(B) = \frac{dM_n(A)/dE_{cm}}{dM_p(A)/dE_{cm}} / \frac{dM_n(B)/dE_{cm}}{dM_p(B)/dE_{cm}} \qquad (1)$$

where A and B represent the neutron-rich (e.g. $^{124}Sn+^{124}Sn$) reaction and the neutron-deficient (e.g. $^{112}Sn+^{112}Sn$) systems, respectively, and dM_x/dE_{cm} is the differential multiplicity of the particle (e.g. neutron, proton,…) as a function of the nucleon energy.

Comparisons of data to Improved Quantum Molecular Dynamic (ImQMD_sky) calculations using two different Skymre interactions (SLy4 with $m_n^*<m_p^*$, upper red and SkM* with $m_n^*>m_p^*$, lower blue in Fig. 1) show the data lie between the two calculations at E/A=50 MeV, and very close to the SLy4 at E/A=120 MeV. At the present time, this is the only theoretical calculation with sufficient precision to explore the influence of effective mass splitting for this system. In comparison, constraints obtained by analyzing fitted nucleon-nucleus optical potentials, weakly prefer $m_n^*>m_p^*$ over $m_n^*<m_p^*$, [9]. If both the Sn+Sn double ratios and the optical model fits are correct, this may mean that the effective mass splitting evolves from $m_n^*>m_p^*$ to $m_n^*<m_p^*$ with increasing temperature or density. Additional data and theoretical studies with a wider range of transport models are urgently needed to resolve this issue.

The report of the 2013 International Collaborations in Nuclear Theory (ICNT) workshop on the Symmetry Energy at NSCL/FRIB emphasizes the importance of obtaining "theoretical error bars" for constraints on different aspects of the symmetry energy, and for reactions, specifically, the importance of a better understanding and treatment of cluster production [11]. To facilitate this, it is advantageous to measure small systems such as $^{40,48}Ca+^{40,48}Ca$, that allow extensive calculations with nearly all transport models. This allows extensive Antisymmetried Molecular Dyanmics (AMD) transport calculations that reproduce the production of hydrogen and helium isotopes and the ratio of triton to ^3He spectra ratios quantitatively by explicitly including cluster-cluster and cluster nucleon cross sections [16].

Careful analyses of the light-particle spectra in central $^{124,112}Sn+^{124,112}Sn$ and $^{40,48}Ca+^{40,48}Ca$ reveals a form of chemical potential scaling governing the spectra of light particles when they are plotted as a function of E_{cm}/u (the energy per nucleon in the center of mass) [17]. Some of this could be anticipated from isoscaling where the yield ratios $R_{21}(N,Z)$, of an isotope with neutron number N and proton number Z from two reactions, 1 and 2, can be described as

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

However, this new scaling goes beyond isoscaling to demonstrate equivalence of various products and ratios of spectra, e.g., that the $t/^3He$ double ratio should be exactly equivalent to the n/p double ratio and also equivalent to a double ratio of $Y_2(d)/Y_2(p)^2/\{Y_1(d)/Y_1(p)^2\}$. Moreover, in the limit that the Coulomb barrier effects are small, as in the case of total disintegration, the chemical potential scaling predicts that the product of the measured triton over helion spectra times the measured proton spectra provides a "pseudo" neutron spectrum.

$$Y(n)=Y(p)*Y(t)/Y(^3He) \quad (3)$$

A somewhat similar procedure has also been proposed in Ref. [20]. We demonstrated this method in Figure 2 [17] where the extracted neutron spectra (open crosses) compare well to the measured neutron spectra (green solid circles). This opens the possibility of extracting the 'n/p' spectral ratios without measuring neutrons. As the systematic uncertainties for neutrons are typically 10%, one may expect better accuracy measuring carefully the light particles to high kinetic energies in the center of mass. This reduces the equipment and setup time requirements that made the neutron measurements in Sn+Sn experiments very challenging for the experimenters and for the CCF as in e09042.

In experiment e03045, we measured central $^{40}Ca+^{40}Ca$ and $^{48}Ca+^{48}Ca$ collisions with the HiRA array and the MSU 4-pi array [21]. The experiment was designed to measure the two-proton correlations. Since neutrons were not measured, we extracted the pseudo neutron spectra for this reaction using Eq. (3). Figure 3 shows the measured energy spectra of p, d, t, ^3He, ^4He as well as the pseudo neutron spectra for $^{40}Ca+^{40}Ca$ system. The pseudo neutron and coalescence invariant spectra stop at E/A=40 MeV due to the angular coverage and the limited range of the tritons using the 4 cm long HiRA CsI crystals. This in turn limits the comparisons of the double ratios to energies in the middle panel of Figure 4 where the SLy4 and SkM* predictions agree.

We propose to study this system at two energies E/A= 35 and 120 MeV with 10 cm long CsI crystals and an angular coverage optimized for higher center of mass energies. This will allow us to probe, with a theoretically tractable system, the effective mass splitting as a function of incident energy and density and test whether this splitting changes $m_n^*>m_p^*$ to $m_n^*<m_p^*$ with incident energy as suggested by the available data. For completeness, the calculated double ratios for the proposed systems at E/A= 35 and 120 MeV are included in Figure 4 (top and bottom panel).

Goals of the proposed experiment

The principal goal of this experiment is to measure particle spectra for protons, deuterons, tritons, helium-3 and alphas to obtain precise single and double coalescence-invariant neutron to proton ratios for $^{40}Ca+^{40}Ca$ and $^{48}Ca+^{48}Ca$ collisions at E/A=35 and 120 MeV in order to place stringent constraints on the density and momentum dependence of the symmetry energy with upgraded HiRA telescopes. The spectra also can be used to benchmark the reliability of transport models which are needed to extract effective mass constraints.

II. 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 5. 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 16 telescopes positioned at azimuthal angles of 30^0-70^0 in the laboratory (~90^0-110^0 in the center-of-mass frame) to measure the energy spectra of the light fragments emitted from ^{48}Ca+^{48}Ca and ^{40}Ca+^{40}Ca collisions at E/A=120 and 35 MeV. To be able to measure those fragments at higher energies we propose to replace the current 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 6, we also increase the number of CsI crystals of each telescope to 9 to better accommodate multiple hits. Figure 7 and 8 show the angle and energy coverage for tritons (which are our limiting particles in the construction of pseudo neutrons spectra) in both the laboratory and center of mass frame for E/A=120 and 35MeV.

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 e05045 (Ca+Ca collisions at E/A=80MeV). The energy spectra drops exponentially as shown in Figure 3. 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 45 MeV/u with the same amount (2 days) of beam time as experiment E05045. To extend the energy spectra of the tritons to 60 MeV/u Ca+Ca, we would request an extra day of beam time which should give us energy spectra with adequate statistics for constructing the double ratios at high energy. This amounts to 6 days of data taking with two different reactions: ^{48}Ca+^{48}Ca and ^{40}Ca+^{40}Ca for E/A=120MeV. Following the analogous estimates for Ca+Ca collisions at E/A=35MeV we will need 4 days of ^{40}Ca beam and 4 days of ^{48}Ca beam on target. We will need 24 hours of beam time to debug the Microball and HiRA 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.

We should be ready to run the experiment in the spring of 2015 after we upgrade the HiRA telescopes.

III. Supplemental Information (Figures, Tables, References, etc., including one figure that depicts the layout of the experimental apparatus)

References:

[1] J.A. Pons, S. Reddy, M. Prakash, J.M. Lattimer, and J.A. Miralles, The Astrophysical Journal 513, 780 (1999).

[2] H. A. Bethe. Supernova mechanisms. Rev. Mod. Phys., 62:801–866, Oct 1990.

[3] J. Dobaczewski. Structure of nuclei at extreme values of the isospin. Acta Physica Polonica B, 30:1647, 1999.

[4] O. Sjberg, Nuclear Physics A, 265(3):511 – 516, 1976.

bruekner hf

[5]W. Zuo, I. Bombaci, and U. Lombardo. Asymmetric nuclear matter from an extended brueckner-hartree-fock approach. Phys. Rev. C, 60:024605, Jul 1999.

[6] F. Hofmann, C. M. Keil, and H. Lenske. Density dependent hadron field theory for asymmetric nuclear matter and exotic nuclei. Phys. Rev. C, 64:034314, Aug 2001.

[7] B. Liu, V. Greco, V. Baran, M. Colonna, and M. Di Toro. Asymmetric nuclear matter: The role of the isovector scalar channel. Phys. Rev. C, 65:045201, Mar 2002.

[8] V. Greco, M. Colonna, M. Di Toro, and F. Matera. Collective modes of asymmetric nuclear matter in quantum hadrodynamics. Phys. Rev. C, 67:015203, Jan 2003

[9] E. Bauge, J. P. Delaroche, and M. Girod, Phys. Rev. C, 63, 024607 (2001).

[10] M. B. Tsang, J. Stone, F. Camera, P. Danielewicz, S. Gandolfi, et al., Phys.Rev. C86, 015803 (2012).

[11] C. J. Horowitz, E. F. Brown, Y. Kim, W. G. Lynch, R. Michaels, A. Ono, J. Piekarewicz, M. B. Tsang, H. H. Wolter, arXiv:1401.5839 (2014).

[12] Lie-Wen Chen, Che Ming Ko, and Bao-An Li, Phys. Rev. Lett. 94, 032701 (2005).

[13] M. Di-Toro, V. Baran, M. Colonna, and V. Greco, J. Phys. G Nucl. Part. Phys. 37 08001, (2010).

[14] Y. Zhang et al, to be published. .

[15] J. Rizzo, M. Colonna, and M. Di Toro, Phys. Rev. C 72, 064609 (2005).

[16] Z. Chajecki, A. Ono, et al, in preparation.

[17] Z. Chajecki, et al, submitted for publication, to appear on arXiv Feb 24, 2014

[18] D. Coupland et al, in preparation.

[19] Y. Zhang, Z. Chajecki, private communication.

[20] K. Hagel, R. Wada, J. Cibor, M. Lunardon, N. Marie et al., Phys.Rev. C62, 034607 (2000), J. Natowitz, R. Wada, K. Hagel, T. Keutgen, M. Murray, et al., Phys.Rev. C65, 034618 (2002).

[21] V. Henzl, M. A. Kilburn, Z. Chajecki, D. Henzlova, W. G.Lynch, et al., Phys.Rev. C85, 014606 (2012).

[22] Z. Kohley, S. J. Yennello, Heavy-ion Collisions: Direct and indirect probes of the density and temperature dependence of Esym, arXiv:1401.5533 (2014)

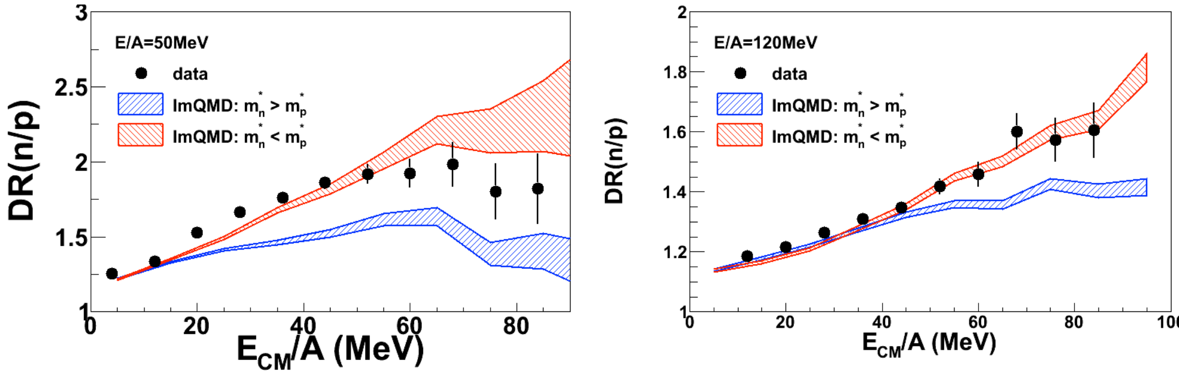

Figure 1: *Coalescence invariant neutron to proton double ratio (Eq. 1) for ^{112,124}Sn+^{112,124}Sn collisions at 50 MeV/u (left panel) and 120 MeV/u (right panel). The black points represent the recent experimental data [17,18].*

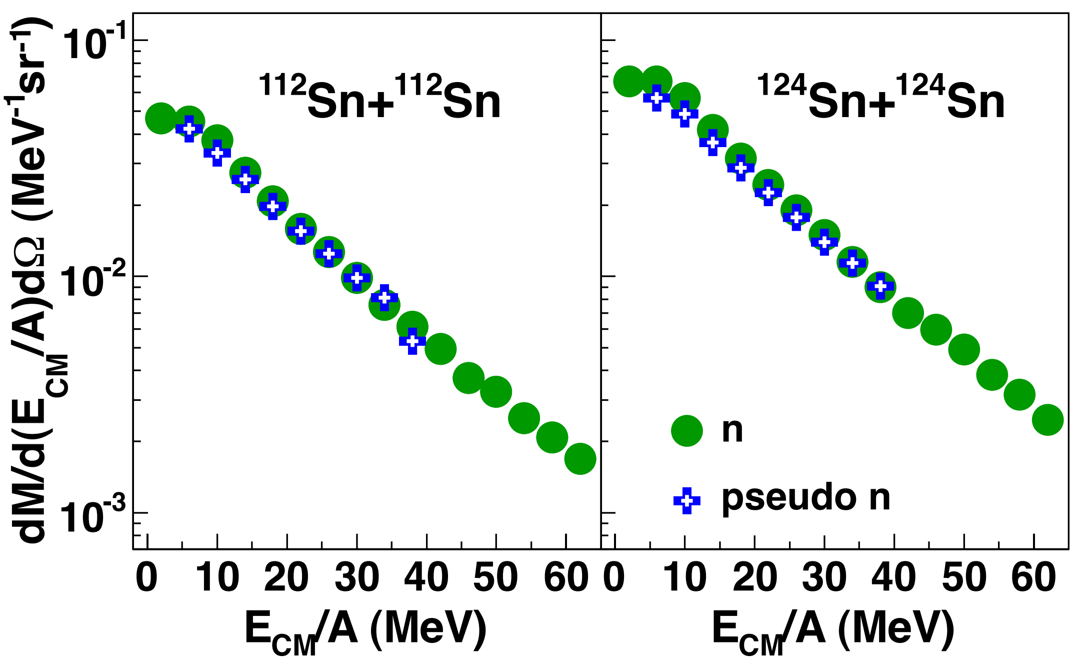

Figure 2: *Measured (solid circles) and pseudo (open crosses) neutron spectra from ^{124}Sn+^{124}Sn (left panel) and ^{112}Sn+^{112,124}Sn collisions (right panel) at E/A=50 MeV [17,18].*

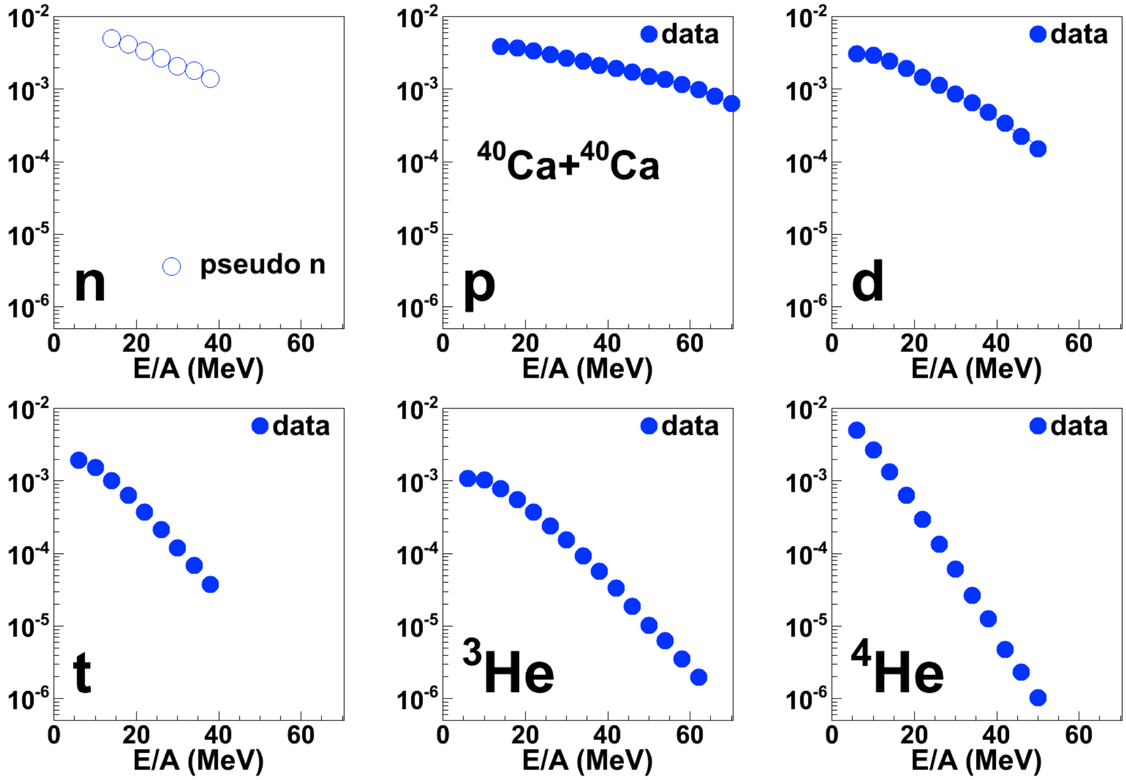

Figure 3: *Energy spectra of pseudo neutrons, protons, deuterons, tritons, 3He and 4He from 40Ca+40Ca at E/A=80MeV [17].*

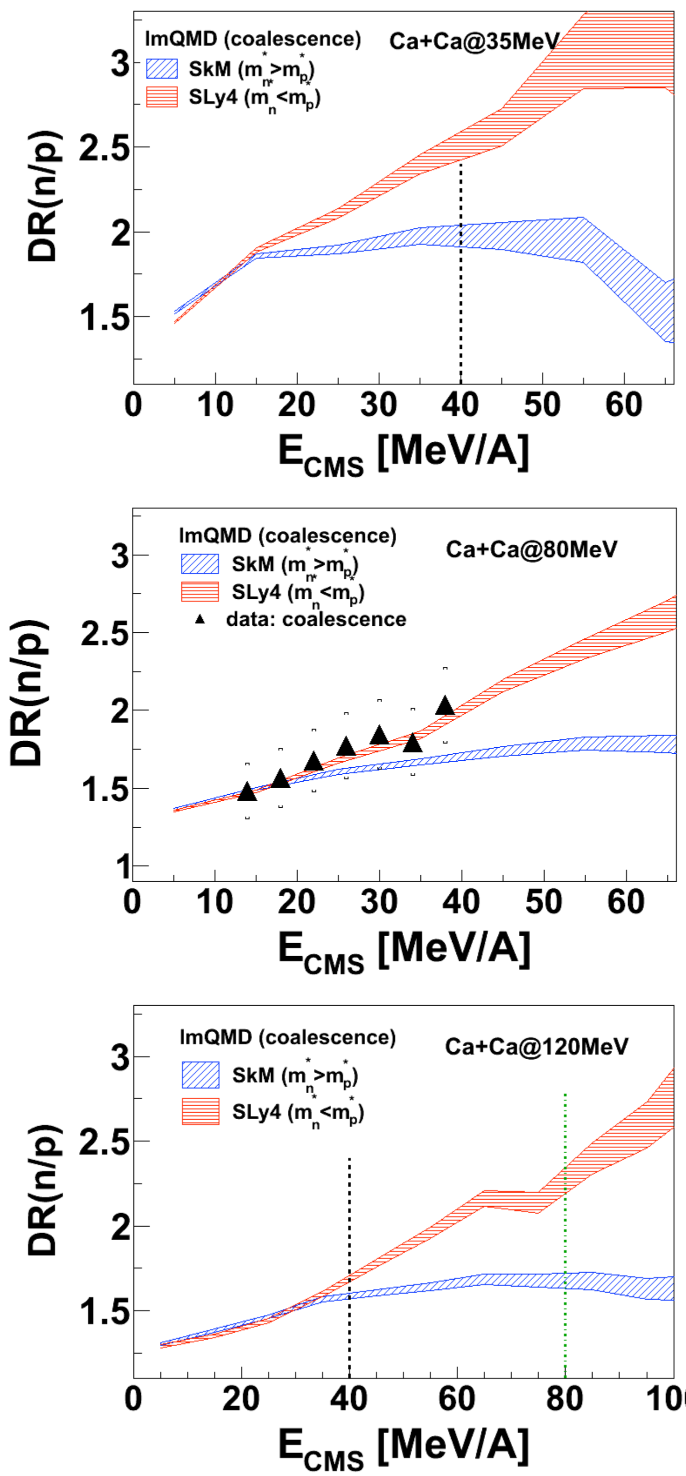

Figure 4: *Coalescence neutron to proton double ratio (Eq. 1) from* $^{48}Ca+^{48}Ca$ *and* $^{40}Ca+^{40}Ca$ *collisions at E/A=35MeV (top), E/A=80 MeV (middle) and 120 MeV (bottom) from ImQMD(sky) simulations using two Skyrme parameterizations of the nuclear potential SLy4 (*$m^*_n<m^*_p$*; red shaded region) and SkM*(*$m^*_n>m^*_p$*; blue shaded region) . The black points represent the experimental data from E/A=80MeV collisions [16]. The black vertical dotted line represents the maximum energy of tritons (in the center-of-mass frame) measured using the existing HiRA telescopes with 4cm CsI crystal. The green hashed-dotted line presents the maximum triton energy that can be measured using 10cm CsI crystals.*

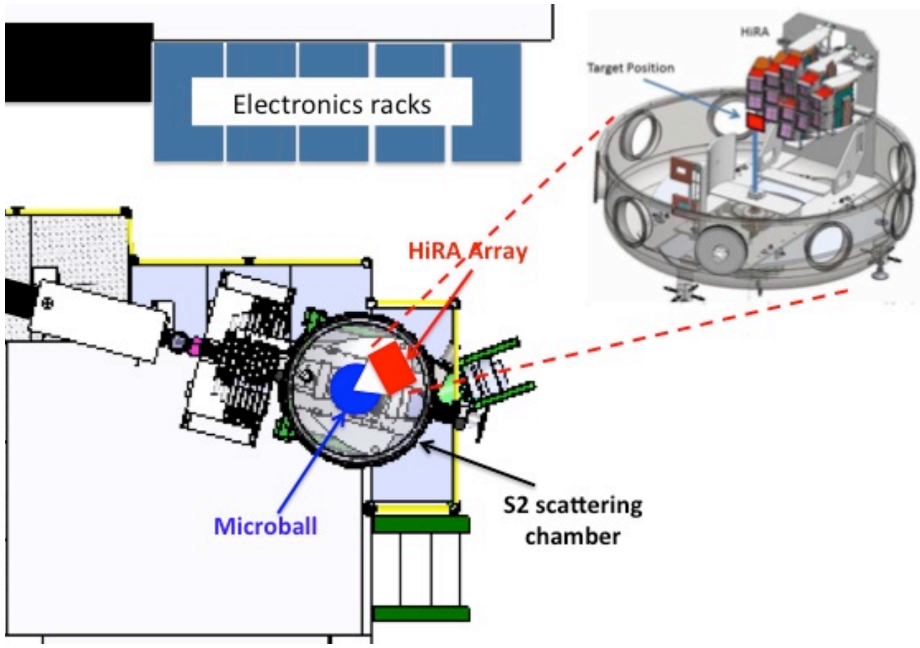

Figure 5: *Overhead view of the setup in the S2 vault involving Microball, HiRA Array mounted in the S2 scattering chamber.*

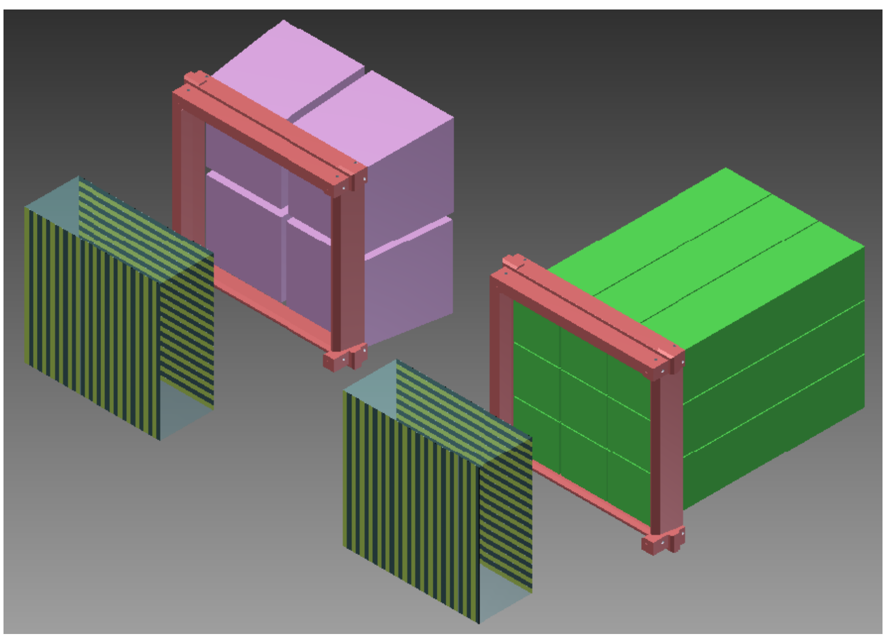

Figure 6: *Schematic drawings of one HiRA telescope with 4 cm CsI crystals (left, current setup), and 10 cm CsI crystals (right, proposed upgrade).*

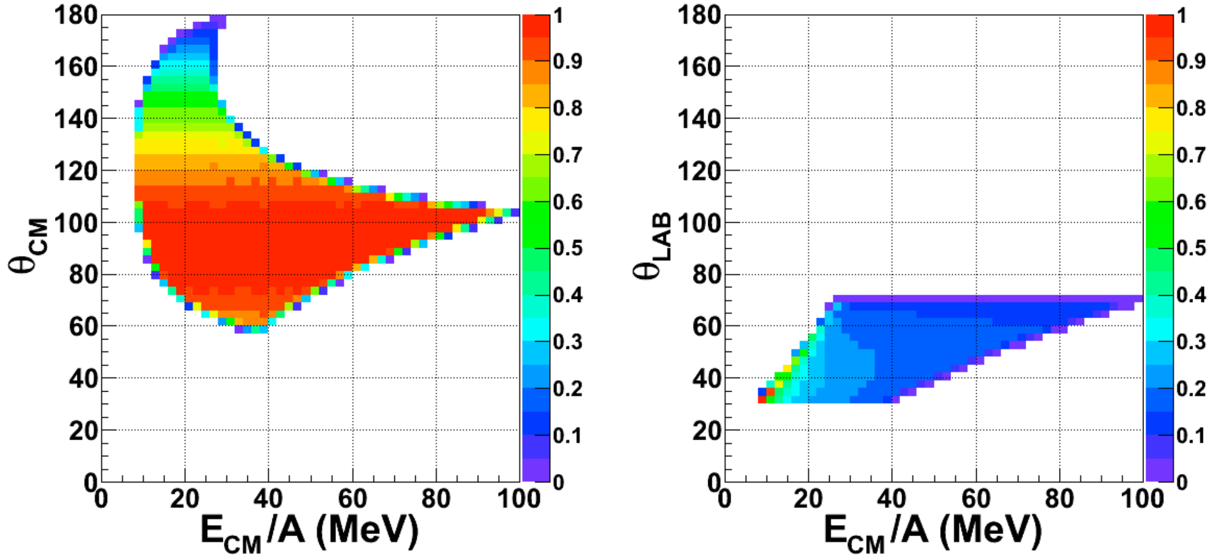

Figure 7: *θ angle in the center-of-mass frame (left panel) and laboratory frame (right frame) plotted versus the center-of-mass kinetic energy of tritons from $^{40}Ca+^{40}Ca$ at E/A=120 MeV emitted at $\theta_{LAB}=(30^0,70^0)$ with maximum kinetic energy in the lab frame $E_{lab}/A<105MeV$ (the punch-through energy for tritons in 10 cm CsI crystals).*

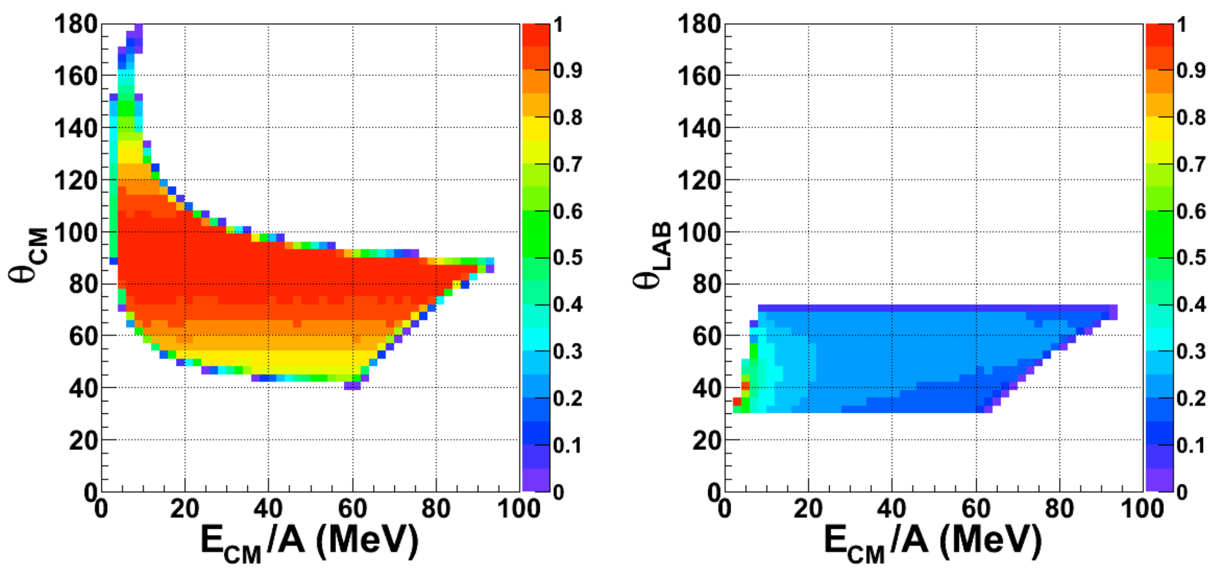

Figure 8: *Same as Figure 7 but for E/A=35 MeV.*

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)

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	arXiv:1309.2745PLB (2014) accepted
			2010	Rogers		arXiv:1309.2745Submitted to NIMA
07038	Jun-11	Winkelbauer		Winkelbauer	numerous	Data being analyzed
05049	May-09	Showalter		Showalter	numerous	Data being analyzed

						(Famiano's experiment)
09042	Nov-09	Coupland	2012	Coupland	numerous	Paper in preparation
		M. Youngs	2013	M. Youngs		Paper in preparation
12014				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 Juan Manfredi, a second year physics graduate student at MSU. He has been working as a research assistant at the NSCL since Aug 2012. He has been involved extensively with the setup and execution of experiments 11001, 10001 and 10011. The HiRA telescope in the proposed experiment will have the set up similar to these experiments. Thus he should have no trouble setting up and carrying out the proposed experiment. An MSU undergraduate, David Witalka is working on the design of the upgrade while Corinne Anderson will install and test the new CsI detectors.

This project would also actively engage undergraduates, graduate students and postdocs from NSCL and Washington University.

Fast Beam Worksheet 1

Primary Beam

Beam Type	Developed
Isotope	16O
Energy	150 MeV/nucleon
Intensity	175 pnA
Tuning Time	12 hrs

Beam-On-Target

Isotope	16O
Energy	15 MeV/nucleon
Rate at Experiment	3e8 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 + Microball
Experimental Device Tuning Time	0 hrs
On-Target Time Excluding Device Tuning	16 hrs
Total On-Target Time	16 hrs
Total Beam Preparation Time	31 hrs

Fast Beam Worksheet 2

Primary Beam

Beam Type	Developed
Isotope	16O
Energy	150 MeV/nucleon
Intensity	175 pnA
Tuning Time	0 hrs

Beam-On-Target

Isotope	16O
Energy	10 MeV/nucleon
Rate at Experiment	3e8 pnA
Total A1900 Momentum Acceptance	0.5 %
Purity at Experiment	100 %
Rare-Isotope Delivery Time Per Table	0 hrs
Tuning Time to Vault	0 hrs
Total beam preparation time	0 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 + Microball
Experimental Device Tuning Time	0 hrs
On-Target Time Excluding Device Tuning	16 hrs
Total On-Target Time	16 hrs
Total Beam Preparation Time	16 hrs

Fast Beam Worksheet 3

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	3e8 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 + Microball
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	40Ca
Energy	140 MeV/nucleon
Intensity	50 pnA
Tuning Time	0 hrs

Beam-On-Target

Isotope	40Ca
Energy	35 MeV/nucleon
Rate at Experiment	3e8 pnA
Total A1900 Momentum Acceptance	0.5 %
Purity at Experiment	100 %
Rare-Isotope Delivery Time Per Table	0 hrs
Tuning Time to Vault	0 hrs
Total beam preparation time	0 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 + Microball
Experimental Device Tuning Time	0 hrs
On-Target Time Excluding Device Tuning	96 hrs
Total On-Target Time	96 hrs
Total Beam Preparation Time	96 hrs

Fast Beam Worksheet 5

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	3e8 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 + Microball
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 6

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	3e8 pnA
Total A1900 Momentum Acceptance	0.5 %
Purity at Experiment	100 %
Rare-Isotope Delivery Time Per Table	0 hrs
Tuning Time to Vault	0 hrs
Total beam preparation time	0 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 + Microball
Experimental Device Tuning Time	0 hrs
On-Target Time Excluding Device Tuning	96 hrs
Total On-Target Time	96 hrs
Total Beam Preparation Time	96 hrs

Spectrograph Worksheet

No Spectrograph Worksheet is required.

Sweeper Worksheet

No Sweeper Magnet Worksheet is required.

Safety Information Worksheet

Contact: Zbigniew Chajecki

Yes	**Radioactive sources required for checks or calibrations**	we will need alpha source (228Th) to calibrate HiRA Silicon Array
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)**	