NATIONAL SUPERCONDUCTING CYCLOTRON LABORATORY
PROPOSAL FOR EXPERIMENT

Date Submitted: October 22, 2002 Experiment # ____________________
(Assigned by NSCL)

TITLE: Breakup of the rp-Process Nuclei ^{69}Br and ^{73}Rb

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Is this a thesis experiment? (Yes) No If yes, for whom? Brian Nett

OTHER EXPERIMENTERS: (please spell out first name)

Name	Organization	Check, if applicable Grad	Sr. Grad
Robert Charity	Washington University		
Romualdo de Souza	Indiana University		
William Lynch	NSCL		
Michael Mocko	NSCL		X
Brian Nett	NSCL	X	
Hendrick Schatz	NSCL		
Brad Sherrill	NSCL		
Wanpeng Tan	NSCL		X
Betty Tsang	NSCL		
Lee Sobotka	Washington University		
Giusseppe Verde	NSCL		
Mark Wallace	NSCL		X
Daniel Bazin	NSCL		
Arialdo Moroni	INFN Milano		
Fabiana Gramegna	INFN Legnaro		

REQUEST FOR CURRENT PERIOD: BEAM ON TARGET (either primary or rare-isotope; for the latter, please specify the desired primary beam from the Beam List)

	Beam on target Nuclide E/A (MeV)	Current (pps)	Desired beam purity (%)	Hours on target	Primary beam Nuclide E/A (MeV)
a)	^{70}Br 65 MeV/A	3000	>97%	48	^{78}Kr 140 MeV/A
b)	^{75}Rb 65 MeV/A	1000	>80%	120	^{78}Kr 140 MeV/A } OR
c)	^{75}Rb 65 MeV/A	6000	>80%	48	^{92}Mo 140 MeV/A } OR

TOTAL REQUESTED HOURS: 192 (Calculated as per item 4. of the Notes for PAC26 in the Call for Proposals)

Will further time be requested for a subsequent PAC? If so, estimate additional hours: ____________

HOURS APPROVED: ____________

HOURS RESERVED: ____________

SET UP TIME: (before start of beam):

Access to:	Experimental Apparatus	240	hrs
	Electronics Set-up Area	168	hrs (Be realistic--affects scheduling)
	Data Acquisition Computer	168	hrs

TAKE DOWN TIME: (After beam, include all calibrations, etc.):

Access to:	Experimental Apparatus	96	hrs
	Electronics Set-up Area	96	hrs (Be realistic--affects scheduling)
	Data Acquisition Computer	96	hrs

WHEN WILL YOUR EXPERIMENT BE READY TO RUN? 03 / 15 / 2003

DATES EXCLUDED: ____________________

EXPERIMENTAL EQUIPMENT (CHECK WHICH OF THESE DEVICES WILL BE USED):

X	A1900		Beta Counting System
	4pi Array		Beta-NMR Apparatus
	92" Chamber		Neutron Walls
X	S800 Spectrograph		Modular Neutron Array
	Sweeper Magnet		SuperBall Neutron Calorimeter
	Segmented Ge Array	X	High Resolution Array
	NaI Array		Neutron Emission Ratio Observer
	Other (give details)		

TARGETS: ^{9}Be primary target ~265 mg/cm^2; Secondary Target: ^{9}Be 10 mg/cm^2

RARE-ISOTOPE BEAM REQUIREMENTS: (please specify any special requirements)

BEAM TRACKING: (Yes) No ______ Position only __X__ Position and angle

Comments ____________________

BEAM TIMING: (Yes) No

Comments ____________________

PARTICLE-BY-PARTICLE MOMENTUM: (Yes) No

Comments Plastic Scintillators for TOF Measurements

OTHER SPECIAL REQUIREMENTS: (Safety related items are listed separately on following pages.)

SUMMARY (no more than 200 words)

The HiRA array will be used in an experiment for accurate measurements of the (p,γ) Q-values of the astrophysically interesting nuclei ^{73}Rb and ^{69}Br, which are important waiting point nuclei in the rp-process. Measurements will provide insight into the progress of the rp-process and its effect on the rp-process site, thought to be associated with X-ray bursts. The information will be useful to calculations of light curves of an X-ray burst for comparison to data taken with new X-ray observatories. The proposed measurements are complementary to the proposal of Wallace et al. (submitted to this PAC) for the mass measurements of waiting point nuclei in this isotopic region.

DESCRIPTION OF EXPERIMENT
(no more than 4 pages of text - 1 1/2 spaced, 12pt; no limit on figures or tables)

Please organize material under the following headings or their equivalent:

1. Physics justification, including background and references.
2. Goals of proposed experiment
3. Experimental details—apparatus (enclose sketch); what is to be measured; feasibility of measurement; count rate estimate (including assumptions); basis of time request (include time for calibration beams, test runs and beam particle or energy changes); technical assistance or apparatus construction required from the NSCL.

I. **Physics Justification**

While the general origin of the elements has undergone intense scrutiny over the past 45 years,[1] significant uncertainties still exist. In particular, nucleosynthesis processes involving nuclei far from stability (i.e., the rp- and r-processes) remain largely untested. A small fraction of proton-rich nuclei heavier than iron cannot be attributed to production via the neutron capture processes. Theoretical descriptions of the processes that produce these nuclei rely heavily on complex reaction networks involving hundreds of nuclei and thousand of interactions. However, only a handful of the rates have been studied near A=100.[2-4] This is believed to be the termination point of the rp-process. The heaviest p-process nuclei are expected to be produced instead via photospallation reactions on heavier seeds. Indeed, if the rp-process make a significant contribution to stellar abundances, it must be terminated to prevent overproduction of these nuclei.[5,6]

The rp-process is expected to progress in a hot (T_9~0.5-1), proton-rich environment, where successive proton captures on seed nuclei progress faster than the β^+ rates of the resulting nuclei. Progression up the rp-process path is typically very close to the proton drip line (Fig. 1).[5] A successful model of an rp-process site depends heavily on knowledge of nuclear masses, β^+ decay rates, and proton capture rates. These nuclear properties dictate the environment necessary for a successful rp-process. However, because of the expected low level density of the nuclei involved in the rp-process, statistical rate calculations such as those based on the Hauser-Feshbach formalism are not as accurate as in the cases of the neutron-rich nuclei. Currently, theoretical predictions of Q-values vary by amounts greater than the temperature of rp-process environment,[7-9] making experimental validation of the rp-process nuclei necessary.

Explosive hydrogen burning in X-ray bursts from accreting neutron stars has been proposed as a possible site of the rp-process, and the interdependency of the nuclear properties of rp-process nuclei and conditions on the surface of the accreting neutron star has been explored.[5] While it is unclear how much material is ejected from a burst, the light curve of the associated X-ray burst can be directly determined by understanding the dynamics of the rp-process and then compared with results on X-ray bursts from X-ray observatories. That is, the burst luminosity and its duration are both dictated by the initial amount of hydrogen accreted onto the neutron star and the rate at which it is consumed. Calculations predict that processing to A~100 may be responsible for bursts with timescales of several hundred seconds. Additionally, the shape of the light curve is determined by the rate of processing. Processing dominated by

β-decay due to low (p,γ) rates will cause a "bottleneck" in the rp-processing, directly affecting the X-ray burst luminosity and lengthening the burst in time. Knowing these factors can help to understand the dynamic of the neutron star crust, its composition, rotation, and its magnetic field.[5,10,11]

For reasonable analyses of the rp-process environment, Q-values and masses should ideally be known to within ~50 keV. Additionally, it is thought that 2p capture is possible in the rp-process, meaning that progression through proton-unbound nuclei is possible.[5,11] Two important experiments include accurate mass measurements of nuclei near the so-called "waiting points" (where most of the processing time is spent) and (p,γ) Q-values of the proton-unbound nuclei involved in the rp-process. The experimenters propose to measure the latter – for ^{69}Br and ^{73}Rb as well as the resonances relevant to proton capture on neighboring nuclei. Recent measurements have lead to the conclusion that ^{69}Br is unbound by at least 450 keV[12], and ^{73}Rb is unbound by 590 keV[13]. However, both are largely inconclusive in that they relied on the non-observance of their respective nuclei of interest. Similarly, only one unbound resonance may exist in ^{69}Br at 3.95 MeV. Passage of the rp-process through these nuclei can be greatly slowed due to the negative binding energies of these nuclei. However, if one or more low-lying resonance exists, the "bottleneck" may be circumvented by successive proton captures. Ultimately, if X-ray bursts are the rp-process site as currently believed, modeled light curves will depend heavily on what is known about the breakup of ^{73}Rb and ^{69}Br. Clearly, the passage of the rp-process through these nuclei will be determined by an accurate measurement.

This experiment complements the experiment "Transfer Reaction Mass Measurements of Astrophysical rp-Process Nuclei at and Beyond the Proton Drip Line" proposed by Wallace et al. for the current PAC. It provides a direct measurement of the proton breakup spectrum of ^{69}Br and ^{73}Rb, both of which are important to the astrophysical rp-process. An ancillary benefit of the present proposal will be measurements of proton resonances in neighboring nuclei that are important to the proton capture rates in the rp-process. If both proposals are approved, the major nuclear structure uncertainties will be removed from the rp-process calculations in this mass regions, enabling not only better analyses of the rp-process, but also better constraints on its site.

II. Goals of the Experiment and its Relation to the Proposal of Wallace et al.

The breakup of ^{69}Br, ^{73}Rb and neighboring rp-process nuclei will be studied via correlations between the energetic proton and the heavy residual nucleus. The proposed measurement of ^{73}Rb is currently the only way to obtain the separation energy of this important waiting point nucleus. If the proposal of Wallace et al. is approved, a mass measurement of ^{69}Br will be obtained by the ^{70}Br(p,d) reaction. The proposed measurement will then provide an independent measurement of the proton separation energy for ^{69}Br and an important cross-check between the two techniques. Together, the two measurements will remove the major nuclear structure uncertainties in this mass region.

III. Experimental Details

The breakup reaction in this experiment will proceed by producing 7pnA primary beam of ^{78}Kr at an energy of 140 MeV/u. A 376 mg/cm^2 Be primary target will be used to produce secondary beams of ^{75}Rb and ^{70}Br. ^{73}Rb and ^{69}Br will be produced by colliding the secondary beams (mainly ^{75}Rb and ^{70}Br) at E/A≈65 MeV with a secondary Be target of thickness 10 mg/cm^2 in the scattering chamber of the S800. Beam purity will be improved with the use of an Al wedge in the dispersive focal plane so as to limit the counting rate in the S800 focal plane detector. Breakup protons from the secondary target will be studied in the HiRA telescope, while the heavy residual nuclei will be detected in the focal plane detectors of the S800 spectrograph.

One of the HiRA telescopes is shown in Figure 2. Each telescope consists of a 65 μm Si strip detector, a 1.5 mm double-sided silicon strip detector (DSSD), and four CsI scintillator detectors arranged about the longitudinal axis as shown in the figure. The modular design of the HiRA telescopes allows for the employment of up to 20 units in various arrangements.

The experimental setup is diagrammed in Figure 3. Eight telescopes will be used for positive proton identification and energy determination at an angular coverage of $5° < \theta < 16°$, covering nearly the entire phase space of the emitted proton, as shown in Figure 4. The residual ^{72}Kr and ^{68}Se will be strongly forward scattered into the S800 for detection. Examination of Figure 4 reveals that small differences in the proton separation energies become large differences in the laboratory proton energy. At large angles, they will be of the order of 75 keV and dominated by the angular resolution of the HiRA detectors, ±0.15° at 35 cm. At small angles, they will be of the order of 150 keV and scale linearly with the target thickness. Figure 5a shows a decay spectrum for $^{8}B \rightarrow p + ^{7}Be$, measured in ref. [16] by the same technique. Depending on the final beam intensity and the state separations observed on line, we plan to reduce or increase the secondary target thickness to balance rate against resolution. It will also be possible to separate the decay peaks from ground and excited states of ^{73}Rb, ^{69}Br and other rp-process nuclei that are of the order of 100 keV apart or more, none of which have been experimentally measured. Thus, resonant states above the proton threshold can be measured. Particle ID plots for the HiRA telescope are shown in Figure 5b, demonstrating that proton identification will not be a problem.

This experiment has been simulated using the LISE++ code (v6.0.43).[17] A beam purity greater then 97% for the secondary beam is expected, and count rates have been calculated to be about 2800 d^{-1} and 710 d^{-1} for excited ^{69}Br and ^{73}Br respectively. Assuming a detection efficiency of about 70% (governed largely by geometrical coverage), we expect a counting rate of about 2000d^{-1} and 500d^{-1} for the decays of excited ^{69}Br and ^{73}Br, respectively. The background of ^{72}Kr and ^{68}Se from the secondary beam in the S800 can be reduced to negligible values using an Al wedge degrader in the dispersive focal plane. For this reason, five days with the A1900 optimized for ^{75}Rb and two days with the A1900 optimized for ^{70}Br, will allow a Q-value measurement with an accuracy of about 10 keV. In practice, Q-values for the nuclei of interest can be measured with only a single change in the A1900 rigidity settings between 2.3 Tm and 2.1 Tm (after the wedge). However, it should be noted that the Rb experiment may be better with a ^{92}Mo primary beam, which would produce the ^{75}Rb secondary beam with a factor of six higher intensity. This would allow a reduction in the beam time by about three days even while an additional day to change the primary beam is included. Finally, calibration of the HiRA CsI detectors during setup will be done by changing the rigidity of the A1900 to produce secondary protons (using the same ^{78}Kr primary beam and target configuration) and scattering these from a gold foil in place of the secondary target. For a 30 mg/cm^2 foil, proton count rates in the HiRA detectors are expected to be about 1000 counts per hour, so that calibration can be accomplished in with about 1 shift of beam time. In practice, this means that the data time for the ^{73}Rb will be one shift less than 5 days. Finally we include 24 hours for the beam change from the ^{70}Br to ^{75}Rb secondary beams.

IV. References

[1] Wallerstein et al., Rev. Mod. Phys, 69 (1997).

[2] Chloupek F.R. et al., Nucl. Phys. A, 652, 391(1999).

[3] Somorjai, E. et al., A&A, 333, 1112 (1998).

[4] Woosley, S.E. & Howard, W.M., ApJS, 36, 285 (1978).

[5] Schatz, H. et al., Phys. Rep., 294, 167 (1998).

[6] Ozkan, N. et al., Nucl. Phys. A, 710, 469 (2002).

[7] Iliadis, C. et al., ApJ, 524, 434 (1999).

[8] Jose, J., Coc, A., & Hernanz, M., ApJ, 560, 897 (2001).

[9] Descouvemont, P., ApJ, 543, 425 (2000).

[10] Schatz, H., Bildsten, L., & Cumming, A., ApJ, 524, 1014 (1999).

[11] Rembges, F., et al., ApJ, 484, 412 (1997).

[12] Blank, B. et al. Phys. Rev. C 74, 4611 (1995).

[13] Xu, X.J. et al., Phys. Rev. C 55, R553 (1997).

[14] Pfaff, R. et al., Phys. Rev. C 53, 1753 (1996).

[15] Clement, R.C., private communication, and the proposal by Wallace, M. et al.

[16] T.K. Nayak, et al., Phys. Rev. C 45, 132 (1992)

[17] Tarasov, O. & Bazin, D., LISE++ v6.0.43, http://groups.nscl.msu.edu/lise

Figure 1 –An example of the rp-Process path. Paths may change depending on T_9 and accumulated accretion, as well as the nuclear physics input.[7]

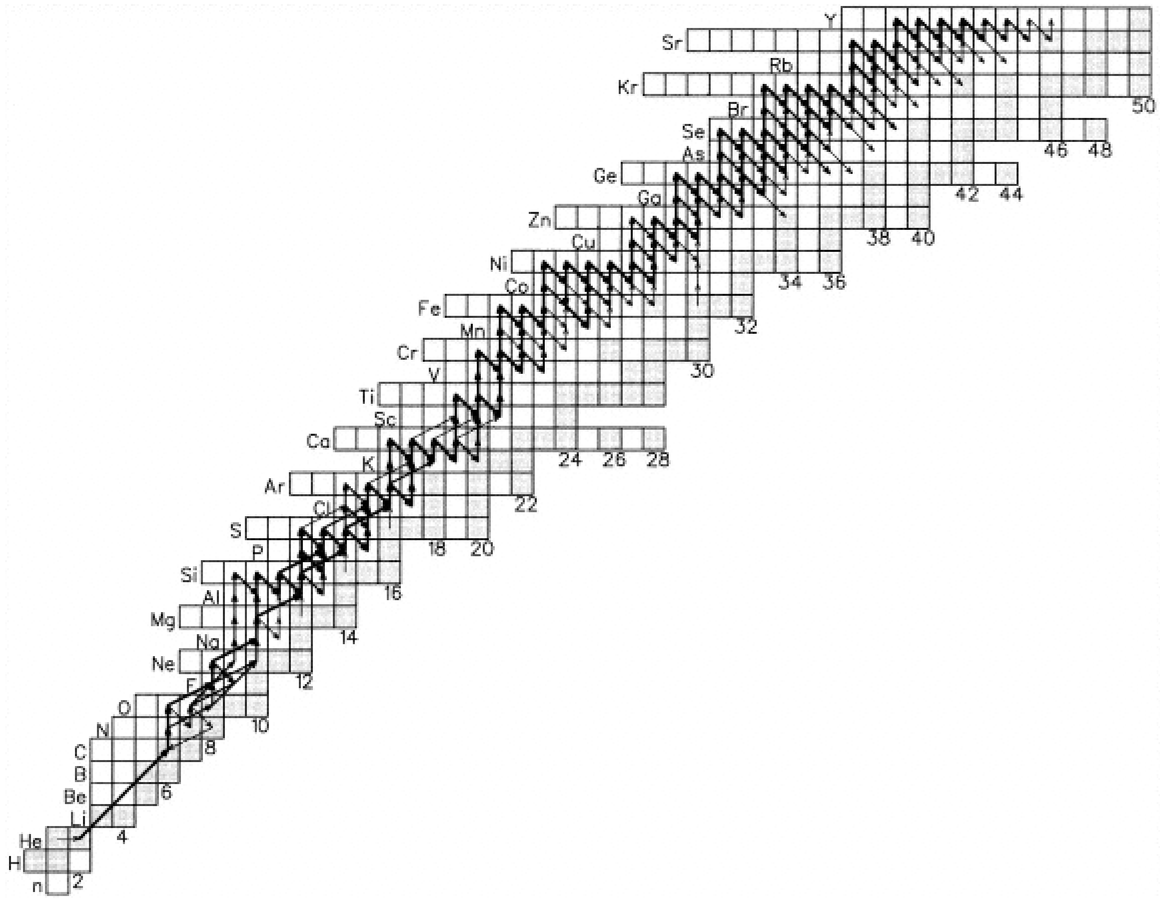


Figure 2 – HiRA Telescope, showing the four CsI detectors, the light guides, and the Si strip detectors.

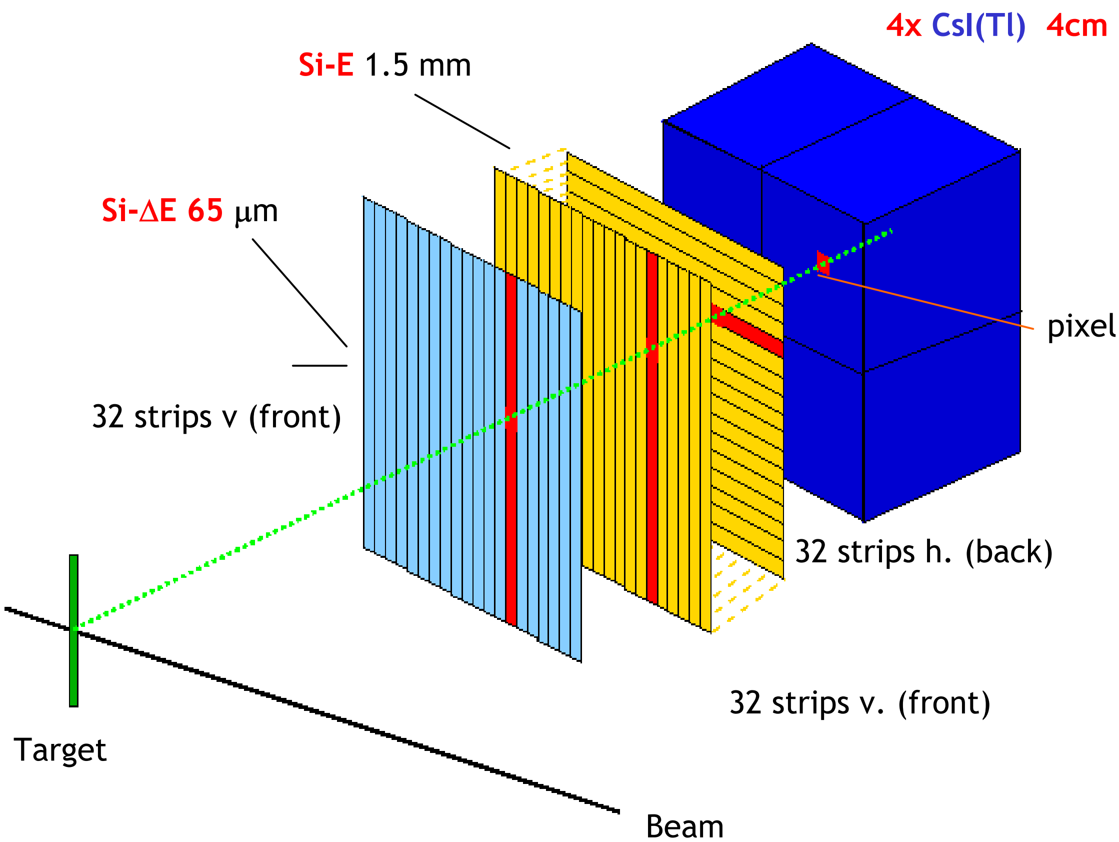


Figure 3 – Experimental setup showing 8 telescopes.

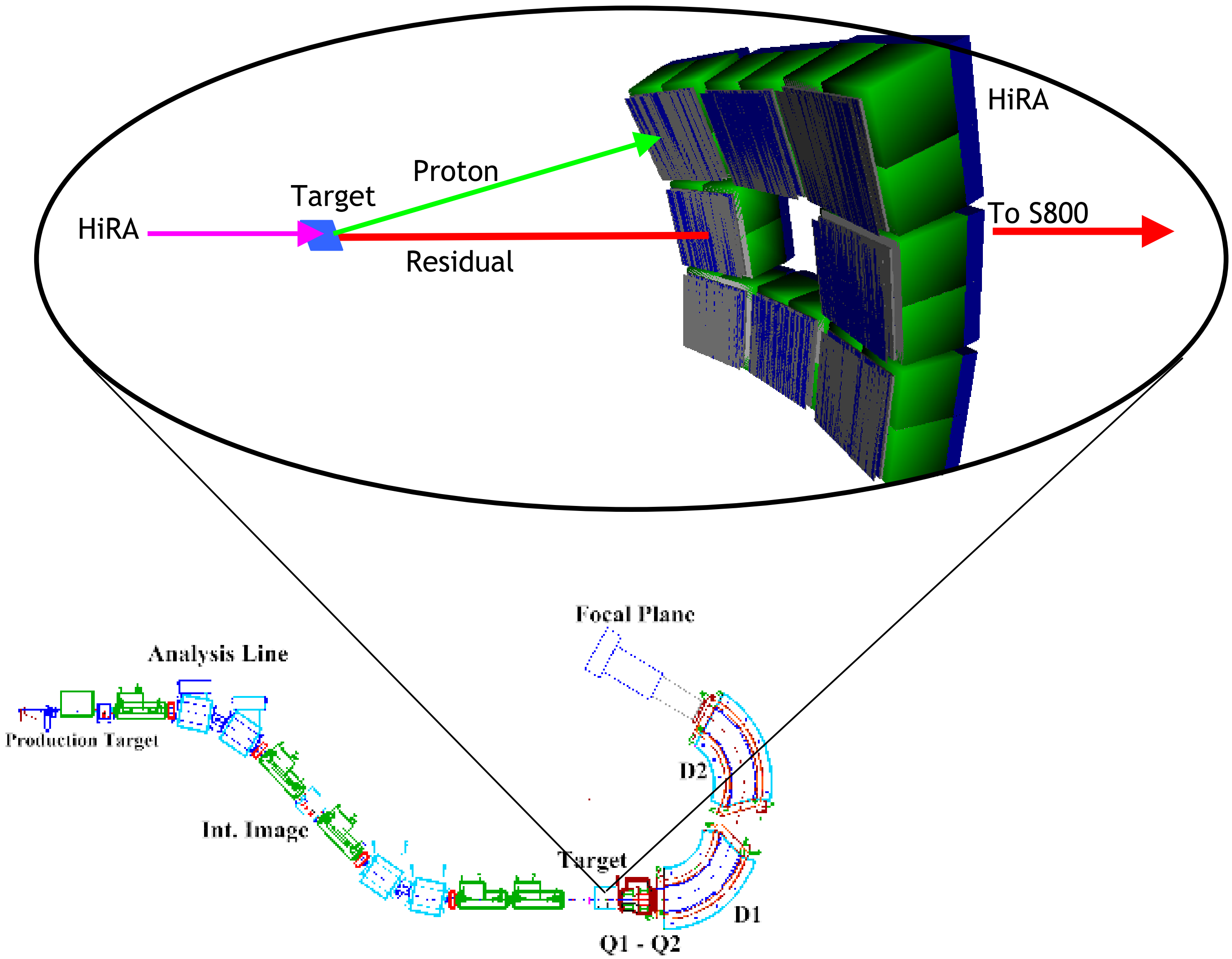


Figure 4 – Proton kinematic plots for ^{69}Br breakup. The kinematic plots for the ^{73}Rb breakup are very similar.

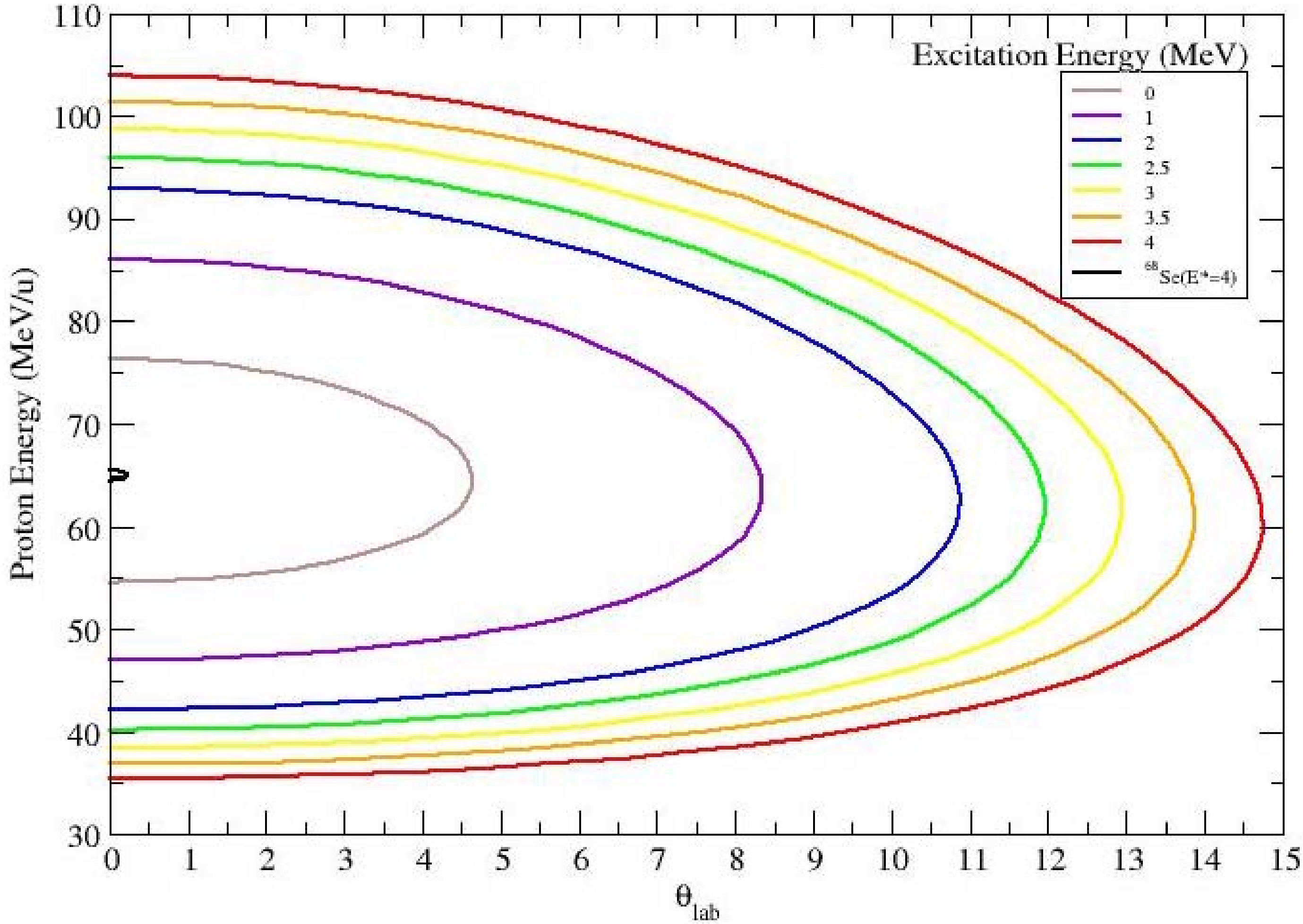
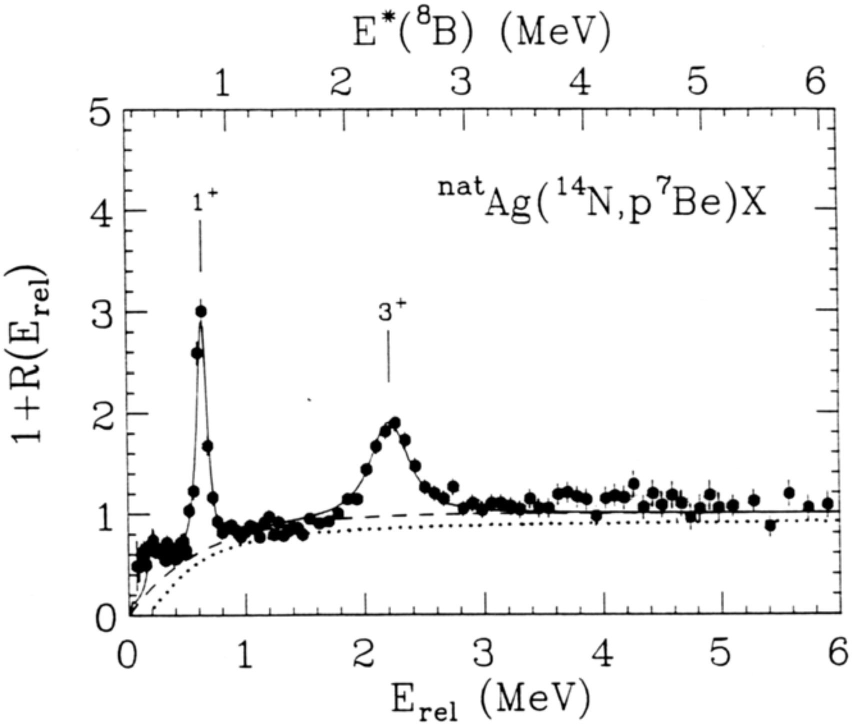
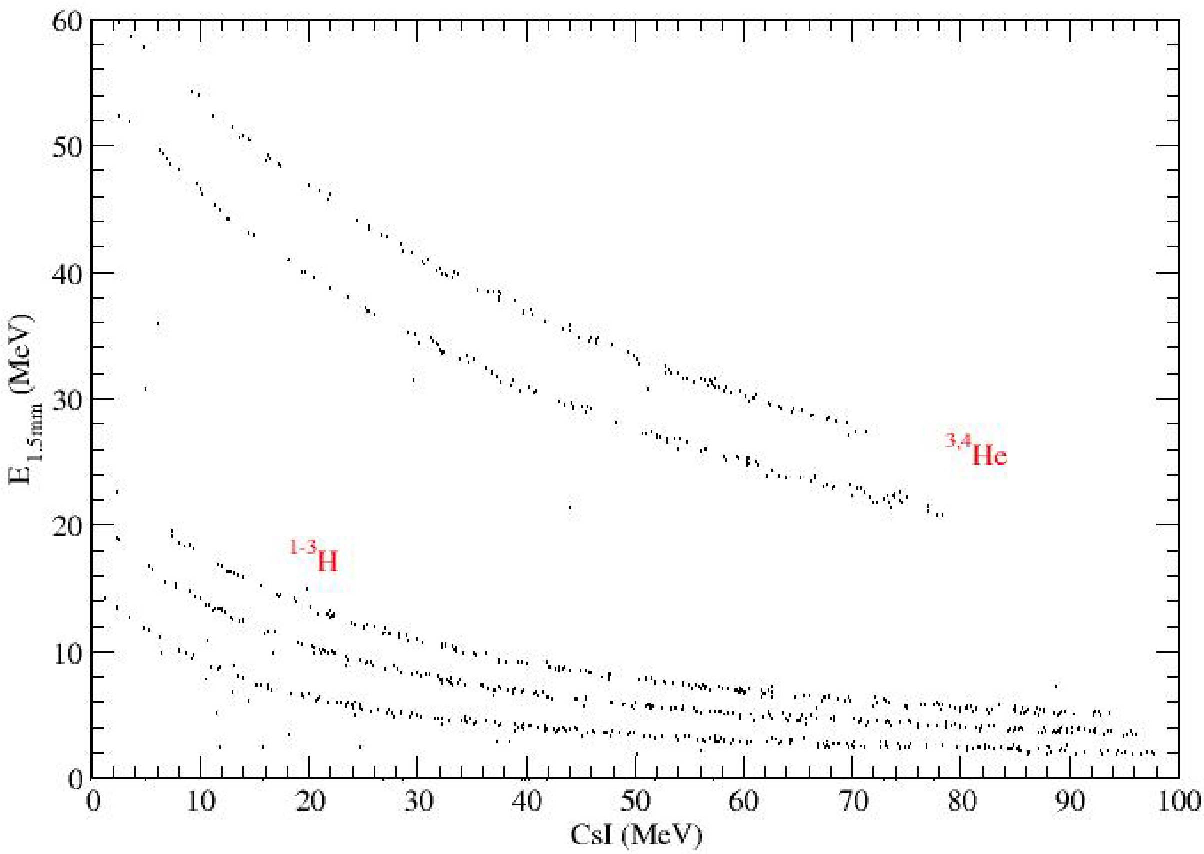


Figure 5 – a) Example of the relative energy spectrum for the astrophysically interesting nucleus ^8B. b) Simulated HiRA PID plots





LIST OF EQUIPMENT REQUIRING NSCL DEVELOPMENT AND
DIAGRAM OF EXPERIMENTAL APPARATUS (include for all experiments)

(See Figure 3 of proposal)

SAFETY INFORMATION

It is an important goal of the NSCL that users perform their experiments safely, as emphasized in the Director's Safety Statement. Your proposal will be reviewed for safety issues by committees at the NSCL and MSU who will provide reviews to the PAC and to you. If your experiment is approved, a more detailed review will be required prior to scheduling.

SAFETY CONTACT FOR THIS EXPERIMENT: ___Michael Famiano____

HAZARD ASSESSMENTS (CHECK ALL ITEMS THAT MAY APPLY TO YOUR EXPERIMENT):

______x___	Radioactive sources required for checks or calibrations.
__________	Transport or send radioactive materials to or from the NSCL.
__________	Transport or send— to or from the NSCL—chemicals or materials that may be considered hazardous or toxic.
__________	Generate or dispose of chemicals or materials that may be considered hazardous or toxic.
__________	Mixed Waste (RCRA) will be generated and/or will need disposal.
__________	Flammable compressed gases needed.
__________	High-Voltage equipment (Non-standard equipment with > 30 Volts).
__________	User-supplied pressure or vacuum vessels, gas detectors.
__________	Non-ionizing radiation sources (microwave, class III or IV lasers, etc.).
__________	Biohazardous materials.

PLEASE PROVIDE BRIEF DETAIL ABOUT EACH CHECKED