NATIONAL SUPERCONDUCTING CYCLOTRON LABORATORY
PROPOSAL FOR EXPERIMENT

Date Submitted: ____________________ Experiment # ____________________
(Assigned by NSCL)

TITLE: Transfer reaction mass measurements of astrophysical rp process nuclei

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Is this a thesis experiment? [✓ Yes] No If yes, for whom? Mark Wallace

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OTHER EXPERIMENTERS: (please spell out first name)

Name	Organization	Grad	Sr. Grad
D.Bazin	NSCL		
R.R.C. Clement	NSCL		XXX
M.Famiano	NSCL		
M.J. van Goethem	NSCL		
M. Mocko	NSCL	XXX	
B. Sherrill	NSCL		
H. Schatz	NSCL		
L.G. Sobotka	Washington University of St.Louis		
R. de Souza	Indiana University		
M.B. Tsang	NSCL		
G.Verde	NSCL		

(Check, if applicable: Grad, Sr. Grad)

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)	^{66}As	1.8×10^4	Mixed Beam	72	^{78}Kr 140 MeV/u
b)	^{73}Kr	1.4×10^4	Mixed Beam	168	^{78}Kr 140 MeV/u
c)					
d)					

TOTAL REQUESTED HOURS: 288 (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? ___February___ / ___15___ / __2003___

DATES EXCLUDED: ____________________

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

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

TARGETS: C_2H_4 (polyethelyne)

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

BEAM TRACKING: [✓ Yes] No __________ Position only ____XX__ Position and angle

Comments ____________________

BEAM TIMING: [✓ Yes] No

Comments ____________________

PARTICLE-BY-PARTICLE MOMENTUM: [✓ Yes] No

Comments ____________________

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

SUMMARY (no more than 200 words)

We propose to use (p,d) reactions for high precision mass measurements and energy levels above the ground state. By determining the proton separation energies of the “waiting point nuclei” starting with ^{64}Ge and ending at ^{72}Kr, we can eliminate major uncertainties in rp-process calculations in the mass region A=64 to 74. These experimentally measured masses will be useful for theory, as they will serve as tests of mass models predictions near the proton dripline, and especially the N=Z nuclei.

DESCRIPTION OF EXPERIMENT

Physics justification

Type I X-ray bursts are thermonuclear explosions on the surface of an accreting neutron star [1, 2]. Burst observations can yield crucial information about neutron star properties like rotation or magnetic fields if the underlying nuclear physics of the rapid proton capture process (rp process) [3] powering X-ray bursts is sufficiently well understood [4]. The goal of this proposal is to provide the necessary nuclear physics data to remove some of the biggest uncertainties in rp process calculations.

Accurate modeling of the rp process is also needed to determine the crust composition of accreting neutron stars in X-ray bursters and X-ray pulsars [5]. This is crucial to find solutions to some of the most important open questions raised by recent observations: (1) Can electron captures deform the neutron star crust so much that the rotating neutron star emits potentially detectable gravitational radiation [6](2)? Can electron captures heat the crust of old neutron stars sufficiently to account of the radiation observed during the off state in transient bursters? This could be used as a criterion to differentiate between neutron star and black hole systems [7]. (3) What causes magnetic fields of neutron stars to change over time leading to the observed two distinct classes of X-ray binaries - bursters and pulsars [8]?

It has been found recently that the rp process on accreting neutron stars can reach a SnSbTe cycle and that the energy production associated with processing beyond Ni is directly responsible for extended X-ray burst tails [9]. This could explain X-ray bursts with tail timescales of more than 100 s, and leads to an important relation between burst duration and the amount of hydrogen available at burst ignition. All these conclusions are based on assumptions on the properties of nuclei along the proton drip line and therefore are subject to large uncertainties. Currently, the most critical problem in rp process calculations is the unknown processing timescale through ^{64}Ge, ^{68}Se and ^{72}Kr. Based on current nuclear physics knowledge, these nuclei serve as a bottleneck in the rp process and are the origin of most of the burst tailing [9]. Fig.1 shows the rp process path in the Ge-Kr mass region. While the β decay half-lives are well known, the total lifetime during the rp process is also determined by the effective proton capture rate, which depends exponentially on the unknown proton capture Q-values [2] (see Fig 2). For reliable rp process calculations, the proton capture Q-values have to be known with an accuracy of kT, which is typically of the order of 80 keV during the tail of an X-ray burst. The (p, γ) Q-values are needed regardless of whether the reaction produces a proton bound or unbound nucleus.

In order to understand the processing of the elements in this region of the rp-process one needs as nuclear physics inputs the proton separation energies at these “waiting points”, as well as resonant state information. For nuclei in the vicinity of the rp-process penning trap measurements provide accurate ground state masses as well as possible isomeric state information for many of the nuclei of interest here, however this alone in insufficient to solve this problem. Using the technique of (p,d) reactions one can get ground state masses of nuclei with short half lives and proton unbound nuclei as well as energy levels for resonant reactions. This makes reaction experiments an essential addition to penning traps measurements for studies of rp-process nucleosynthesis.

This experiment, along with another experiment proposed for this PAC "Breakup of ^{69}Br and ^{73}Rb", will remove the largest uncertainty in rp process calculations by providing accurate proton separation energies for ^{65}As, ^{69}Br, and ^{73}Rb.

^{65}As has been observed as a β emitter and has therefore a proton binding energy of more than –250 keV [10]. On the other hand, the non-observation of ^{69}Br [11, 12] and ^{73}Rb [13, 14] in radioactive beam experiments indicates that these nuclei are short-lived proton emitters with proton separation energies of less than -450 keV and ≈ -500 keV respectively. Recently, Lalleman et al. [15] reported first experimental results for the mass of ^{68}Se indicating strong deviations from the expected mass systematic [16]. Furthermore, if the new ^{68}Se mass value is used together with the Audi and Wapstra 1995 [16] prediction for ^{69}Br, one finds that ^{69}Br is proton bound by 1.5 MeV in disagreement with the previous experiments. Such a change would have drastic consequences for X-ray burst calculations. This is illustrated in Fig. 3, which compares calculations using proton separation energies of +1.5 MeV for ^{65}As, ^{69}Br, and ^{73}Rb (assuming similar deviations from the systematic for the other waiting points) with a calculation using proton separation energies from Schatz et al. [2] (-80 keV, -450 keV, and –590 keV respectively). Better mass data and a re-measurement of the mass of ^{68}Se are clearly needed to resolve these discrepancies and to put rp process calculations on a more solid basis. Improved mass data on heavy N=Z nuclei would also be important to study the role of proton-neutron pairing in N=Z nuclei at the transition into the strongly deformed ^{76}Sr - ^{80}Zr region [17, 18].

Goals of the Experiment

We propose to carry out mass measurements via Q-value measurements of (p, d) transfer reactions in inverse kinematics. Recent tests have shown that we can achieve better then 10 keV accuracy for ground state as well as excited state energies as shown in figure (4). This is a figure of the deuteron spectrum from a ^{36}Ar(p,d)^{35}Ar reaction performed in July 2002 using the S800 to measure the deuterons. From this preliminary figure we see a FWHM for the ground state of about 50 keV with an uncertainty less then 1 keV. This gives us the proof that one can make very accurate measurements using (p,d) reactions. We will measure ground state masses along with excited state energies for astrophysically important ^{65}As, ^{64}Ge, ^{68}Se, ^{69}Br, and ^{72}Kr applying the same technique except we will use the HIRA detector with it's larger angular acceptance along with the S800 to achieve similar uncertainties then those shown in figure (4).

In order to determine masses to the full capability of this method we will measure many additional isotopes simultaneously. We can compare these with known results, and future results proposed using penning traps, to reduce any systematic uncertainties. In order to accomplish this large number of measurements, with relatively low beam intensities we will be using the HiRA detector with the S800 to significantly increase the angular acceptance.

Simulations suggest that we can measure the masses and structure of ^{69}Br and ^{73}Rb with higher statistics using breakup reactions on a beryllium target by measuring the relative momentum of the proton and heavy nucleus instead of transfer reactions. This is therefore proposed in a separate proposal. As ^{69}Br and ^{73}Rb can decay to excited ^{68}Se and ^{72}Kr nuclei respectfully, the excited state energies of ^{68}Se and ^{72}Kr may be needed to clarify the decay spectrum of these nuclei.

Experimental Details

The HiRA array consists of 20 Silicon-Silicon-CsI(Tl) telescopes, each composed of a 65 μm thick silicon strip detector (ΔE_1), a 1.5 mm thick silicon strip detector (ΔE_2), and a 4 cm thick CsI(Tl) scintillator (E) read out by a PIN diode. These thicknesses are sufficient to isotopically resolve the deuterons and stop them in the 1.5 mm silicon detectors. Energetic particles that punch through both silicon detectors will be vetoed by the CsI(Tl) detectors.

For this experiment the 20 telescopes will be arranged to cover $6° \leq \theta_{lab} \leq 37°$ as shown in the diagram of experimental setup. Due to the kinematics and forward focusing of the reaction this covers the total solid angle in the center of mass frame. The HiRA detector will be used to measure the energy and angle of the deuteron created in the CH_2 target. The S800 focal plane will be used to detect the heavy fragment in coincidence with the deuteron, providing information about with beam species reacted with the target, and clearing up background from carbon in the target. The intermediate image of the S800 will be equipped with two new high rate beam tracking PPAC's. There will also be a PPAC at the object of the S800. With these PPAC's one can determine the momentum for each particle. This can also be used to determine the angle the beam particle is incident on target, which is needed for calculating the actual scattering angle

A detailed simulation of the experiment, taking into account uncertainties in beam energy, angle on target, reaction angle, target thickness, and detector resolutions, was performed. For the reactions being considered, kinematic broadening and the intrinsic resolution of the telescopes will be the dominant contributions to the total energy resolution of the transfer reaction peaks. The energy resolution of the telescope for these deuterons is expected to be (50 keV). The kinematic broadening should contribute about (70 keV) in the fwhm. With contributions from the target and beam we anticipate having a fwhm resolution about 100 keV overall. With anticipated statistics this should lead to an uncertainty in the energy less then 10 keV. Calculations of the cross section for cases of interest were done using DWBA and a sample is shown in figure (5). All cross sections calculations gave results on the order of 1 mb/sr. Lise++ was used to estimate beam rates. Using these rates and calculated cross sections we anticipate having 452 ground state events for ^{65}As, 838 ^{64}Ge, 2953 ^{68}Se, and 154 ^{69}Br, and 561 ^{72}Kr ground state events. Many excited state should also have similar yields. Calibration nuclei closer to stability will have even better statistics.

References

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Figures

Figure #1

(Network calculations of nuclei abundance flows in X-ray Burst)

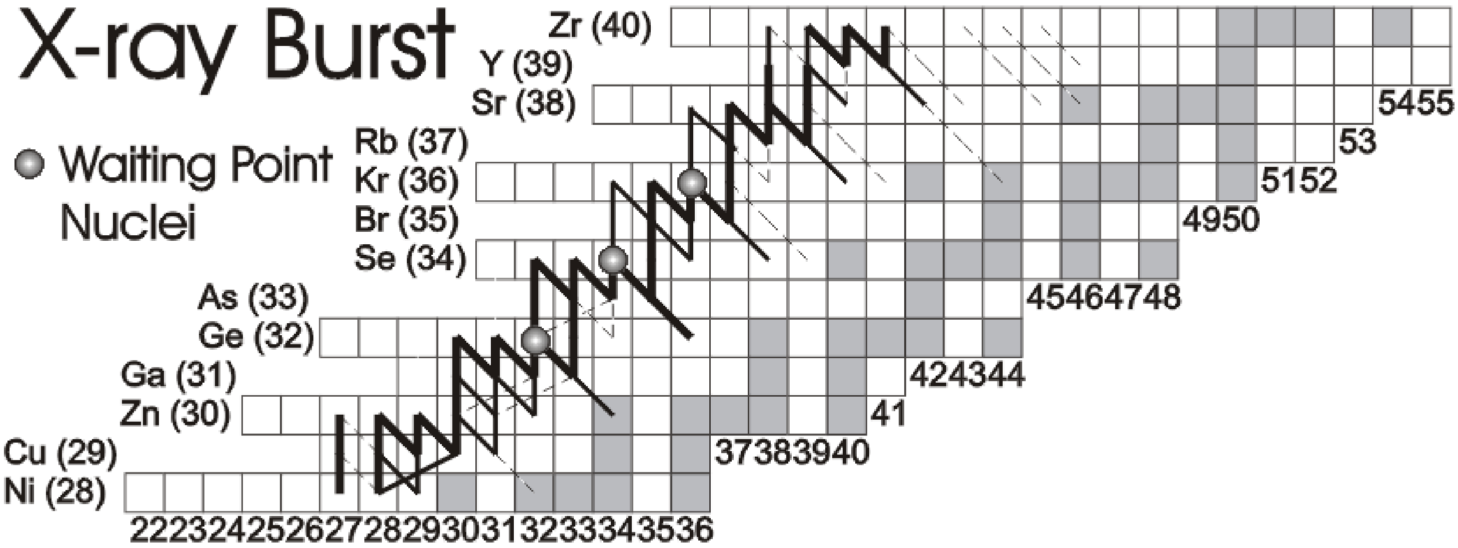


Figure #2

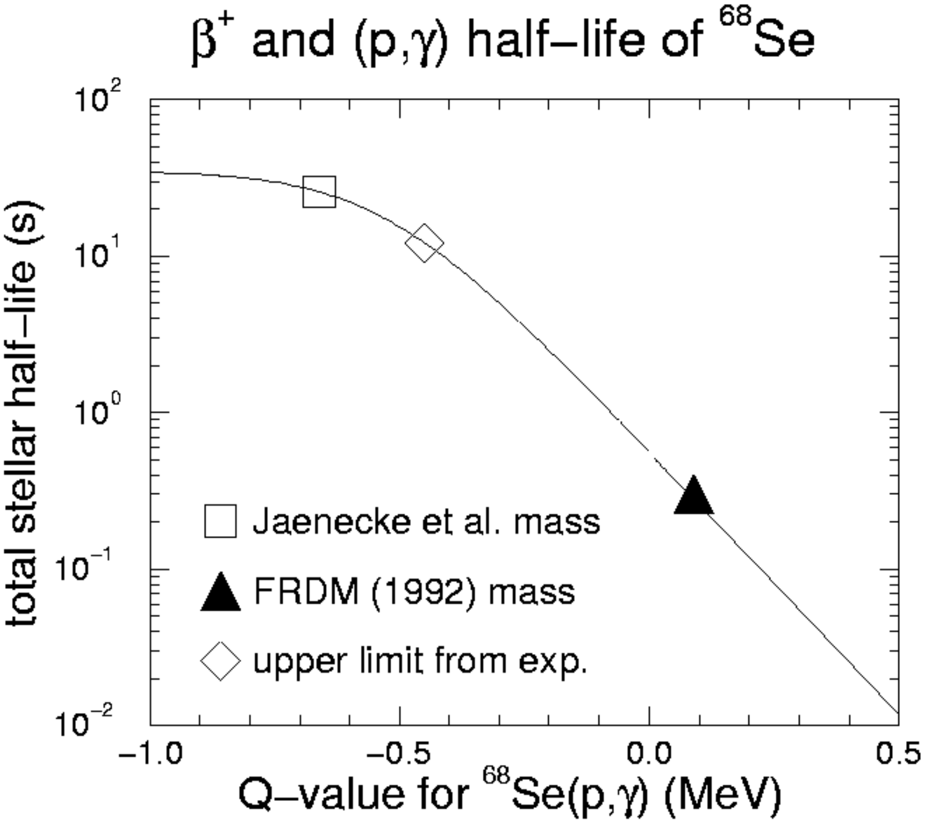

β⁺ and (p,γ) half-life of ⁶⁸Se
total stellar half-life (s)
10²
10¹
10⁰
10⁻¹
10⁻²
Jaenecke et al. mass
FRDM (1992) mass
upper limit from exp.
−1.0
−0.5
0.0
0.5
Q−value for ⁶⁸Se(p,γ) (MeV)

Figure #3

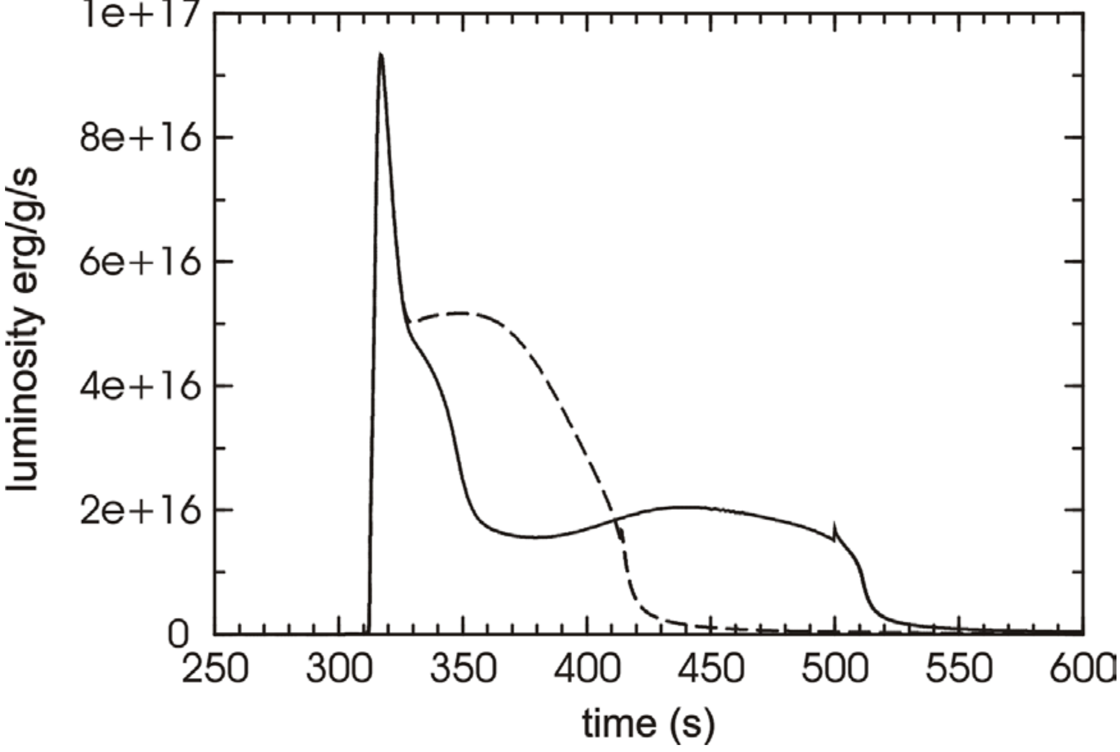

1e+17
8e+16
6e+16
4e+16
2e+16
0
luminosity erg/g/s
250
300
350
400
450
500
550
600
time (s)

Figure #4

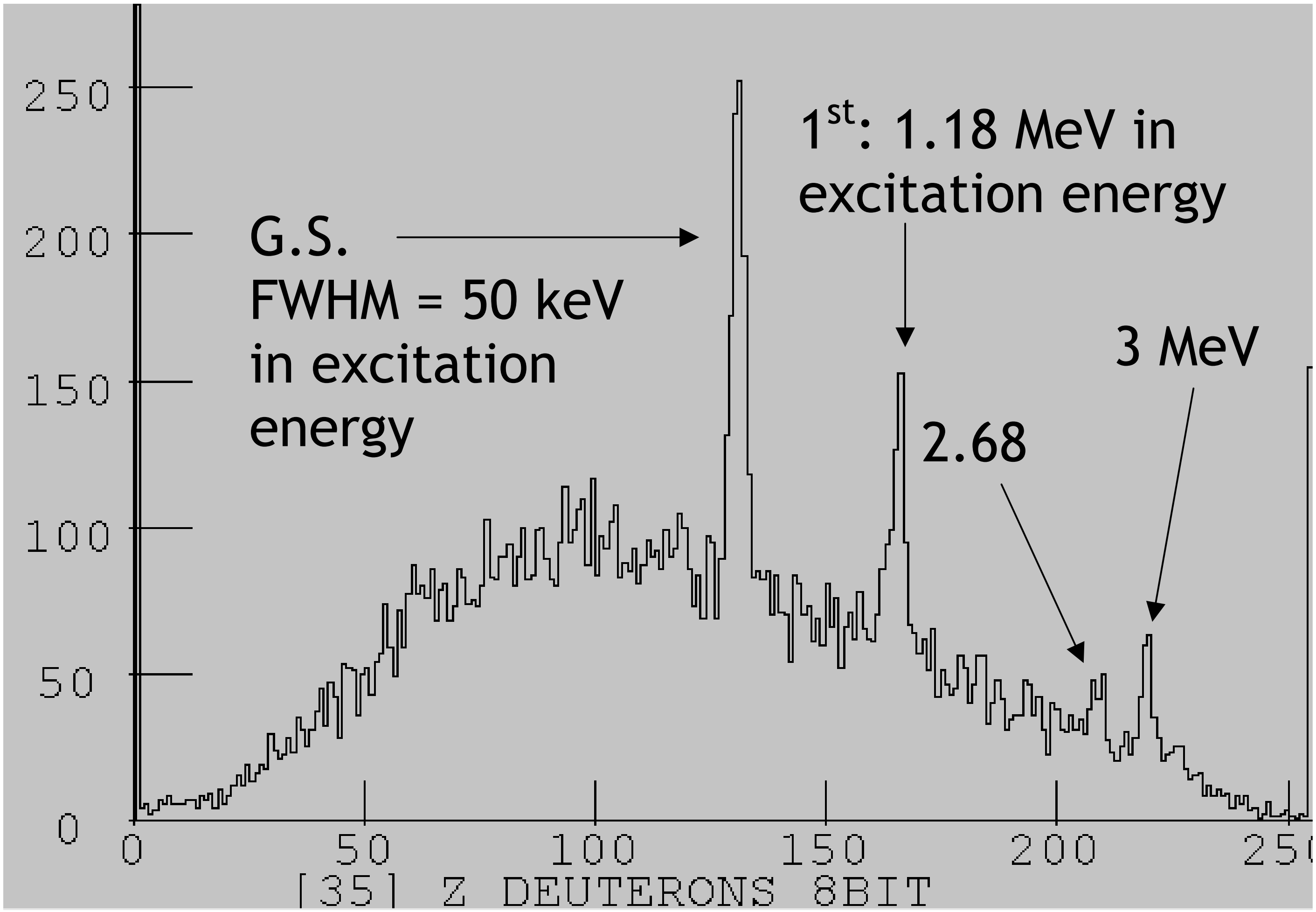
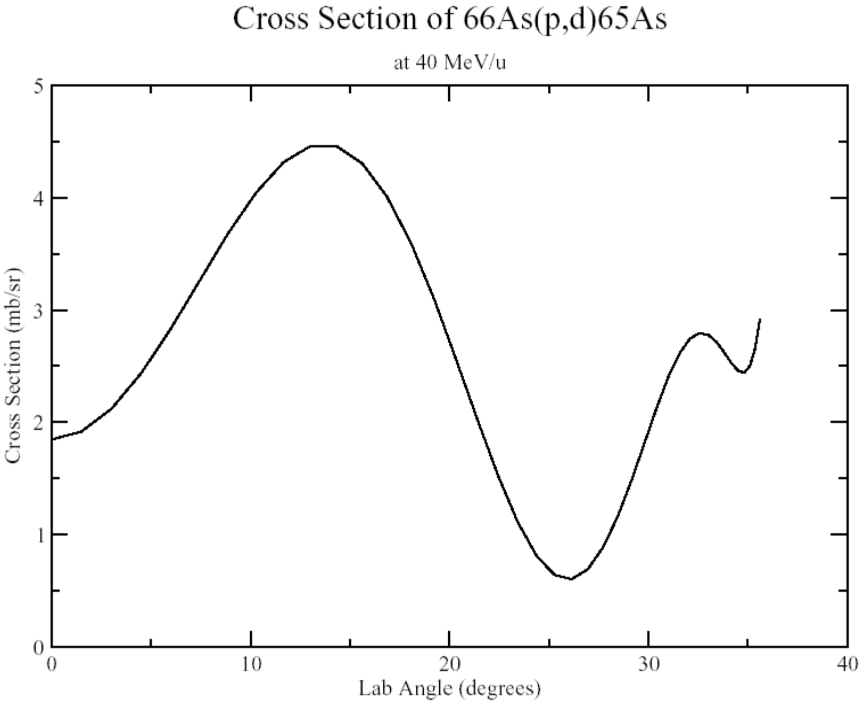
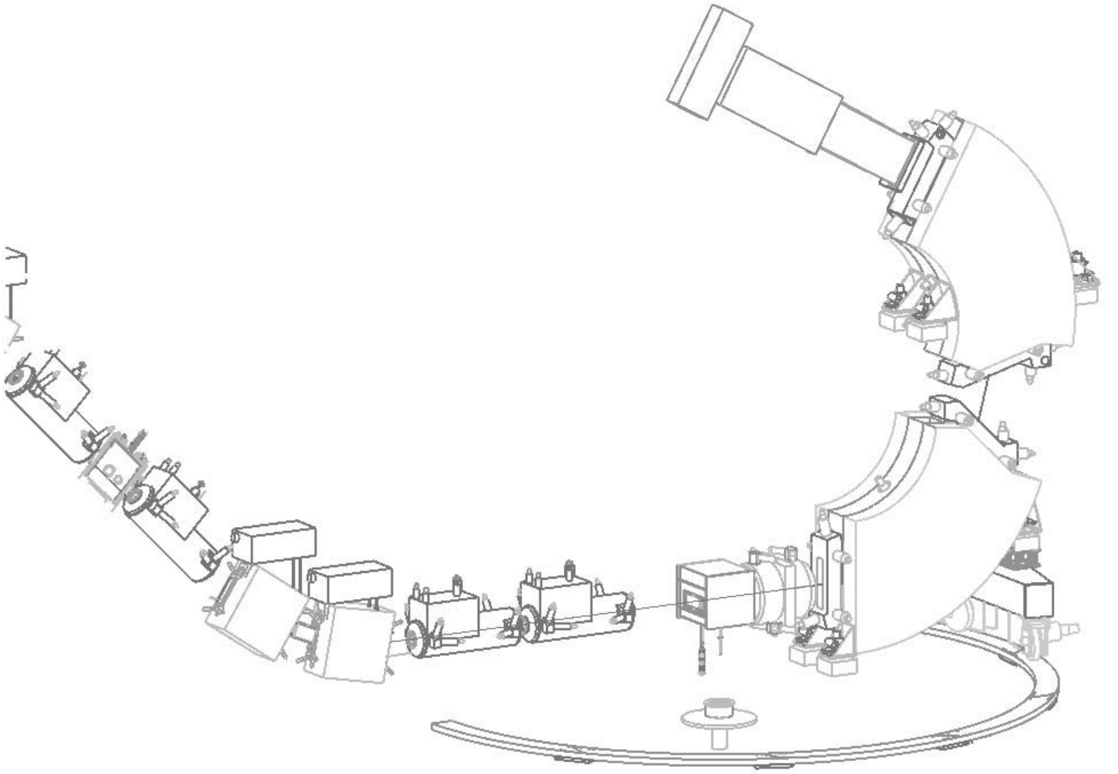
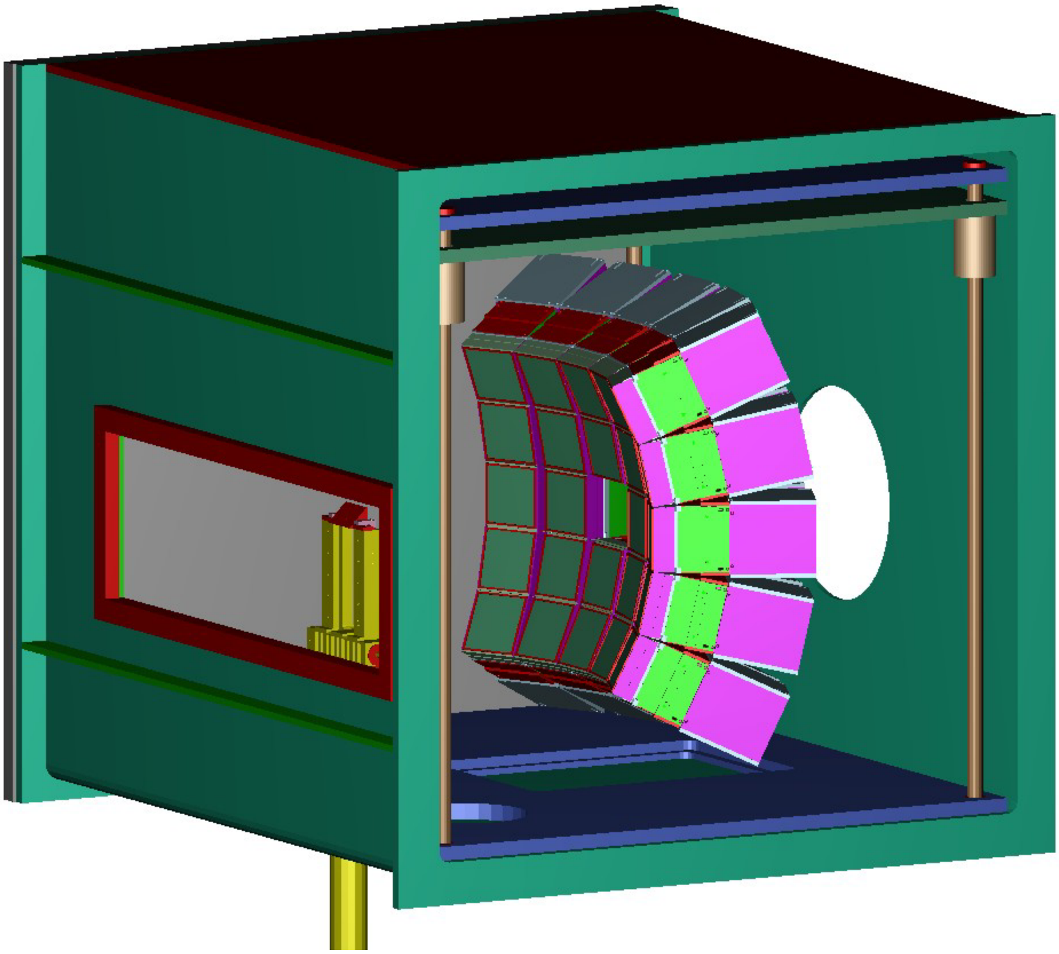


Figure #5



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





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: ____

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

___________ 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 ITEM.