**TITLE:** Transfer reaction mass measurements of astrophysical rp process nuclei at and beyond the proton dripline

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**OTHER EXPERIMENTERS:** (please spell out first name)  
<table>
<thead>
<tr>
<th>Name</th>
<th>Organization</th>
<th>Grad</th>
<th>Sr. Grad</th>
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<tr>
<td>D. Bazin</td>
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<td>R.R.C. Clement</td>
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<td>S. Hudan</td>
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<td>A. Moroni</td>
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<td>M. Weischer</td>
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**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)

<table>
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<tr>
<th>Nuclide</th>
<th>E/A (MeV)</th>
<th>Current (pps)</th>
<th>Desired beam purity (%)</th>
<th>Hours on target</th>
<th>Primary beam Nuclide</th>
<th>E/A (MeV)</th>
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<tr>
<td>a) $^{66}$As</td>
<td>$1.8 \times 10^4$</td>
<td>Mixed Beam</td>
<td>72</td>
<td>$^{78}$Kr 140 MeV/u</td>
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<tr>
<td>b) $^{73}$Kr</td>
<td>$1.4 \times 10^4$</td>
<td>Mixed Beam</td>
<td>168</td>
<td>$^{78}$Kr 140 MeV/u</td>
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<td>c)</td>
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**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: _________________
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 the major uncertainties in rp-process calculations in the mass region $A=64$ to 72. 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.
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 $\beta$ decay half-lives are well known, the total lifetime during the rp process is also determined by the effective proton capture rate, which could shorten the processing time for these waiting point nuclei. The capture rate 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 $(p, \gamma)$ 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 the locations of excited states through which proton captures can proceed. While penning trap measurements provide accurate masses for ground states and long-lived isomers, such information is 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 the relevant energy levels. 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 and the locations of excited states and proton capture resonances.

$^{65}$As has been observed as a $\beta$ 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 $\approx$ -500 keV respectively. Recently, Lalleman et al. [15] reported first experimental results for the mass of $^{68}$Se that deviate strongly from the expected mass systematics [16]. Furthermore, if the new $^{68}$Se mass value is used in conjunction with the Audi-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 has 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). Mass measurements for $^{65}$As, $^{69}$Br, and $^{73}$Rb and mass a re-measurement of the mass of $^{68}$Se are clearly needed to resolve these discrepancies. That and knowledge of the excited states, including proton resonances are needed 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 indicate that we can achieve accuracies of better than 10 keV for the energies of ground and excited states. This is shown in figure (4), where a deuteron energy spectrum from the $^{36}$Ar(p,d)$^{35}$Ar reaction, measured in a July 2002 test run, was reported. For this run the S800 was used to measure the deuterons. A FWHM for the ground state of about 52 keV was achieved corresponding to an uncertainty in the centroid of about 2 keV, even though the analysis is not yet fully optimized for resolution. This gives us the proof that one can make very accurate measurements using (p,d) reactions. Using (p,d) reaction, we propose to measure ground state masses and excited state energies to an accuracy of less than 10 keV for astrophysically important $^{65}$As, $^{64}$Ge, $^{68}$Se, $^{69}$Br, and $^{72}$Kr nuclei by employing the HIRA detector, which has a solid angle 60x larger than the S800 spectrometer, to measure the deuterons.

We plan to measure many additional isotopes with both known and unknown masses simultaneously in order to optimize our efficiency and to have an internal calibration of the setup. The heavy reaction partner
As in the case of $^{65}\text{As}(p,d)\ ^{65}\text{As}$ reaction) will be detected in the S800 spectrograph in order to identify which rare isotope in the beam is inducing the reaction and to reduce the background from reactions on carbon nuclei in the secondary target (CH$_2$). In the case of the $^{70}\text{Br}(p,d)\ ^{69}\text{Br}$ reaction, we will detect $^{68}\text{Se}$ in the S800, but this should not create ambiguities because the beam contains no $^{69}\text{Br}$ ions.

Simulations suggest that we can measure the masses and structure of $^{69}\text{Br}$ and $^{73}\text{Rb}$ with higher rates and statistics using breakup reactions on a beryllium target by a decay spectroscopy technique involving the measurements of the relative momentum of the decay proton and heavy residual nucleus. This is proposed in a separate proposal. We note that $^{69}\text{Br}$ and $^{73}\text{Rb}$ can decay to excited $^{68}\text{Se}$ and $^{72}\text{Kr}$ nuclei respectfully; the excited state energies of $^{68}\text{Se}$ and $^{72}\text{Kr}$ will be helpful for clarifying the decay spectrum of these nuclei. The decay spectroscopy technique is also not feasible for lifetimes much in excess of 10 ns, so the transfer reaction technique is preferable for measurements of ground state masses when the rates allow.

**Experimental Details**

The HiRA array consists of 20 Silicon-Silicon-CsI(Tl) telescopes, each composed of a 65 µm thick silicon strip detector ($\Delta E_1$), a 1.5 mm thick silicon strip detector ($\Delta E_2$), and a 4 cm thick CsI(Tl) scintillators (E) read out by PIN diodes. 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 $6^\circ \leq \theta_{\text{lab}} \leq 37^\circ$ 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 the 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 $(50 \text{ keV})$. The kinematic broadening should contribute about $(70 \text{ keV})$ FWHM to the resolution. With contributions from the target and beam we anticipate having a
resolution about 100 keV FWHM. With anticipated statistics this should lead to an uncertainty in the energy of 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 for $^{64}$Ge, 2953 for $^{68}$Se, and 154 for $^{69}$Br, and 561 for $^{72}$Kr. Many excited state should also have similar yields. Calibration nuclei closer to stability will have even better statistics.

References

15. A.-S. Lalleman, private communication, 2000
Figures

Figure #1

(Network calculations of nuclei abundance flows in X-ray Burst)
Figure #2

$\beta^+$ and (p,\gamma) half-life of $^{68}$Se

Figure #3

Luminosity erg/g/s

time (s)
Figure #4

G.S.  
FWHM = 52 keV in excitation energy

1\textsuperscript{st}: 1.18 MeV in excitation energy

3 MeV

2.68

Figure #5

Cross Section of 66As(p,d)65As

at 40 MeV/\text{u}
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:  _____Mark Wallace____________________________________

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 ITEM.