National Superconducting Cyclotron Laboratory
Proposal Data Form—PAC 30

TITLE: Precise study of the diffractive components in two-proton knockout reactions

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

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OTHER EXPERIMENTERS: (Please spell out first name and indicate Graduate Students (GS), Undergraduate students (UG) and Postdoctoral Associates (PD))

Last name, First name	**Organization**	**Last name, First name**	**Organization**
Tostevin, Jeff	University of Surrey	Rogers, Andrew (GS)	NSCL
Lynch, Bill	NSCL	Henzlova, Daniela (PD)	NSCL
Tsang, Betty	NSCL	Henzl, Vladimir (PD)	NSCL
Famiano, Michael	Western Michigan	Lukyanov, Sergei	JINR - Dubna
McDaniel, Sean (GS)	NSCL	Mocko, Michal (PD)	NSCL
Obertelli, Alexandre	CEN Saclay	Lee, Jenny (GS)	NSCL
Charity, Robert	Washington University	Sobotka, Lee	Washington University
Hudan, Sylvie	Indiana University	DeSouza, Romualdo	Indiana University

REQUEST FOR PRIMARY BEAM SEQUENCE INCLUDING TUNING, TEST RUNS, AND IN-BEAM CALIBRATIONS: (Summary of information provided on Beam Request Worksheet(s). Make separate entries for repeat occurrences of the same primary beam arising from user-requested interruptions to the experiment.)

	Isotope	Energy (MeV/nucl.)	Minimum Intensity (particle-nanoampere)	Sum of Beam Preparation Times (Hours)	Sum of Beam-On-Target Times (Hours)
Beam 1	**^{40}Ar**	**140**	**50**	**18**	**84**
Beam 2					
Beam 3					
Beam 4					

ADDITITIONAL TIME REQUIREMENTS THAT REQUIRE USE OF THE CCF (e.g. modification of the A1900 standard configuration, development of optics, … Obtain estimates from the A1900 Device Contact.)

Additional CCF use time:

Total Hours: **18** | **84**

TOTAL TIME REQUEST (HOURS): **102**

(Calculated as per item 4. of the Notes for PAC 30 in the Call for Proposals)

HOURS APPROVED: ________________

HOURS RESERVED: _____________________

NSCL PAC 30 – Proposal Data Form

		SET UP TIME (before start of beam)	TAKE DOWN TIME
Access to:	Experimental Vault	20 days	8 days
	Electronics Set-up Area	same	same
	Data Acquisition Computer	same	same

WHEN WILL YOUR EXPERIMENT BE READY TO RUN? Winter 2007

DATES EXCLUDED: none

EXPERIMENTAL LOCATION:

___ Transfer Hall (in the A1900)
___ Transfer Hall (downstream of the A1900)
___ N3 vault (with 92” chamber)
___ N3 vault (92” chamber removed)
___ N4 vault (Gas stopping line)
___ N4 vault (Sweeper line)
___ N4 vault (User line)
___ S1 vault (Irradiation line)
___ S2 vault
x S3 Vault

EXPERIMENTAL EQUIPMENT:

___ A1900
___ Beta Counting System
___ Beta-NMR Apparatus
___ 92" Chamber
___ Sweeper Magnet
___ Neutron Walls
___ Modular Neutron Array
___ Neutron Emission Ratio Observer
x High Resolution Array
___ APEX NaI Array
___ Segmented Ge Array [ ] classic [ ] mini [ ] beta [ ] delta [ ] plunger [ ] barrel [ ] other
x S800 Spectrograph [**x**] with [ ] without scattering chamber
___ Other (give details)

DETAIL ANY MODIFICATION TO THE STANDARD CONFIGURATION OF THE DEVICE USED, OR CHECK NONE: [**x**] NONE

DETAIL ANY REQUIREMENTS THAT ARE OUTSIDE THE CURRENT NSCL OPERATING ENVELOPE, OR CHECK NONE (Examples: vault reconfiguration, new primary beam, primary beam intensities above what is presently offered, special optics, operation at unusually high or low rigidities): [**x**] NONE

TARGETS: ^{9}Be, 94 mg/cm^{2}

LIST ALL RESOURCES THAT YOU REQUEST THE NSCL TO PROVIDE FOR YOUR EXPERIMENT BEYOND THE STANDARD RESOURCES OUTLINED IN ITEM 11. OF THE NOTES FOR PAC 30 IN THE CALL FOR PROPOSALS.

LIST ANY INTERRUPTIONS REQUIRED IN RUNNING YOUR EXPERIMENT: (Examples of why an experiment might need an interruption: to change the experimental configuration; to complete the design of an experimental component based on an initial measurement.)

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

NSCL PAC 30 – Proposal Data Form

SUMMARY (no more than 200 words):
Two-nucleon knockout reactions may be a powerful tool for exploring the nature of the wave function of nuclei farthest from stability. So far, published comparisons of experimental cross sections are with reaction calculations of only the stripping mechanism, where both nucleons interact inelastically with the target. It is expected, however, that diffraction mechanisms, where at least one nucleon is removed by an elastic collision with the target, will also play a very significant role. A theoretical estimate puts this at to 42% of the total cross section for the proposed case. In parallel with these reaction theory developments it is essential to identify the contributions of the stripping and diffractive removal mechanisms experimentally. Such validation is key to obtaining spectroscopic information using such reactions. We thus propose to perform a first measurement of the diffractive-removal contributions to the two-proton knockout from ^{28}Mg in a coincidence experiment using the S800 spectrograph in combination with the HiRA detector array. The absolute cross sections and the full momentum vector of all detected particles will be measured to isolate the diffractive components of the reaction. The analysis of the first coincidence experiment, on the one-proton knockout from ^{9}C (exp. 05038), is now in progress, and demonstrates the feasibility of detecting proton-proton-residue triple coincidences with this setup as required in this proposal.

Description of Experiment

I. Physics Justification

Reactions in which two-nucleons are knocked out of fast radioactive projectiles by a light target, such as ^{9}Be, have been shown to be direct when removing two protons from neutron-rich nuclei or two neutrons from proton-rich nuclei [Baz03]. Although the intrinsic two-nucleon removal cross sections are smaller than for one-nucleon knockout reactions, these reactions extend the study of single-particle structure towards the drip line nuclei, as was recently shown for ^{42}Si [Fri05].

The eikonal reaction theory framework used to calculate single-particle cross sections in one-nucleon knockout reactions can also be developed for the case of two-nucleon knockout, but with the added feature that the structure and reaction aspects of the reaction no longer factorize in expressions for the cross sections. Instead, the calculations must combine the shell-model two nucleon wave functions with the eikonal theory at the spectroscopic amplitude level. Such calculations were first performed [Tos04] only for the stripping part of the cross section where both removed nucleons interact inelastically with the target (inelastic breakup). However, more complete calculations now suggest that the diffractive part of the cross section may be of about the same magnitude. This result includes the three terms for the diffraction at least one of the nucleons: two ways of diffracting one while stripping the second, and the one term from diffracting both. The theory of these two-nucleon diffractive contributions is presently being developed and refined. These complete calculations of both the stripping and diffractive components will permit quantitative comparisons with experimental results, yielding spectroscopic information on the correlated two-particle structures.

For such comparisons to be valid, it is essential to study the relative contributions from the different reaction mechanisms using a dedicated experiment. We thus propose to perform a coincidence experiment on the two-proton knockout from ^{28}Mg, using the S800 spectrograph to characterize the ^{26}Ne heavy residue and the HiRA detector array to detect the fast diffracted protons. The choice of ^{28}Mg is motivated by our earlier very successful (but mechanism insensitive) results for this reaction [Baz03], from which the feeding to the various final states of

^{26}Ne are known and were well reproduced by the eikonal model predictions of the stripping component [Tos04].

II. Goals of the proposed experiment

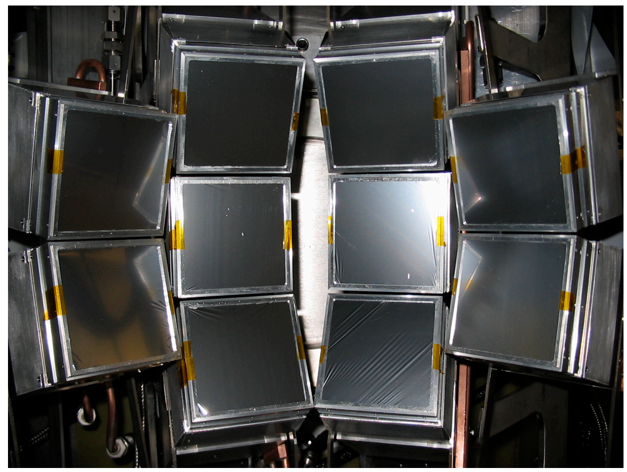
The primary goal of the experiment is to make the first measurement to establish the separate contributions of the stripping and diffractive reaction mechanisms to the cross section for two-proton removal from ^{28}Mg by a ^{9}Be target. The three component cross sections are from i) inelastic collisions of both protons with the target, ii) diffraction of one proton and an inelastic collision of the second, and iii) diffractive removal of both protons. The HiRA detector array will identify the fast diffracted protons and measure their angular distribution as well as their kinetic energies. The forward focused ^{26}Ne heavy residues will be collected in the large acceptance S800 spectrograph, which provides particle identification as well as full momentum vector reconstruction.

^{26}Ne State	(i) Strip^2	(ii) Diff/Strip	(iii) Diff^2	Sum	Exp
0^+	0.543	0.389	0.070	1.002	0.70(15)
2^+	0.159	0.093	0.014	0.266	0.09(15)
4^+	0.524	0.296	0.042	0.862	0.58(9)
2^+_2	0.229	0.135	0.020	0.384	0.15(9)
Inclusive	1.455	0.913	0.145	2.514	1.50(10)

Table 1: calculated and measured cross sections in ^{28}Mg two-proton knockout. See text for details.

Table 1 shows the measured and calculated cross sections for this reaction. The trends measured in the population of the ^{26}Ne final states [experiment 01013] are very well reproduced by the calculations. The two-proton stripping cross sections, (i) above, were calculated in Ref. [Tos04]. The diffraction/stripping cross sections (ii) require that one proton is absorbed while the second scatters elastically from the target and remains unbound to the heavy residue, e.g. [Tos06, Yon06]. The predicted two-proton diffraction cross section (iii) is presently an estimate based on the calculated ratio between the two-proton stripping and the diffraction/stripping cross sections. It assumes that the reduction in the cross section calculated when diffracting just one proton is also applied when the second proton is diffracted [Tos06,Yon06]. The total contribution from the two distinct diffraction mechanisms, (ii) and (iii), amounts to 42% of the total cross section, the weakest channel being the two-proton diffraction which is estimated to carry only 6% of the total. The best estimate of the expected experimental cross section for this channel, based on the already measured inclusive cross section, is therefore 0.086(6) mb. The biggest challenge of the experiment is therefore to identify and measure this channel via a triple coincidence, with sufficient statistics.

III. Experimental Details



The geometry of the HiRA detector array used for this experiment will be the same as the one designed for experiment 05038 studying diffraction in one-proton knockout on ^{9}C. The photo shows the geometrical configuration of the 10 HiRA telescopes used in experiment 05038. Each telescope is composed of two Silicon strip detectors (65 μm and 1.5 mm) followed by a 4 cm thick CsI scintillator crystal. The punch-through energy for protons is around 110 MeV [Goe04], therefore the CsI scintillator should cover the full range of the diffracted protons at an incident energy less than 100 MeV. As in experiment 05038, the thin 65 μm Silicon strip detectors will not be used in this experiment (the thick Silicon detectors have strips on both sides and therefore provide the complete angular information). The identification of the protons will be performed via energy loss - total energy measurements. Figure 1 shows a typical identification spectrum for one of the telescopes, taken during experiment 05038. The lines corresponding to protons, deuterons and tritons are easily identified. The angular coverage and efficiency of the array in this

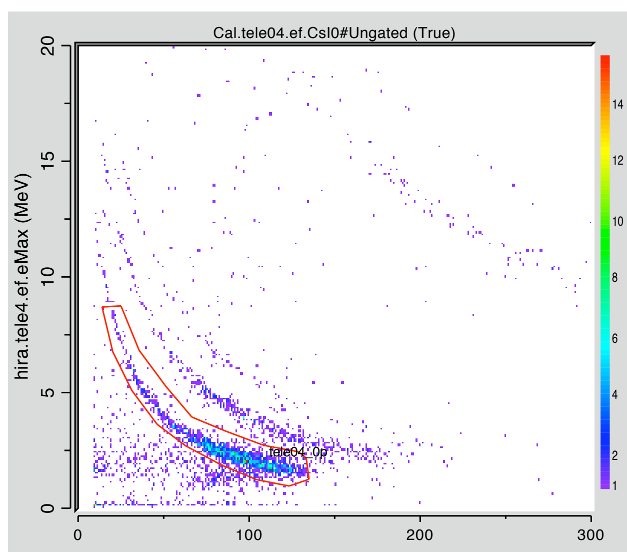


Figure 1: typical identification spectrum from one of the HiRA telescopes taken during experiment 05038. The gate is set on the proton line.

geometry is shown in figure 2, with an estimate of the proton angular distribution. The average efficiency over the covered angular range is 33%, therefore the efficiency for detecting the two diffracted protons in coincidence is about 10%. The angular resolution in this close geometry is about 0.3°.

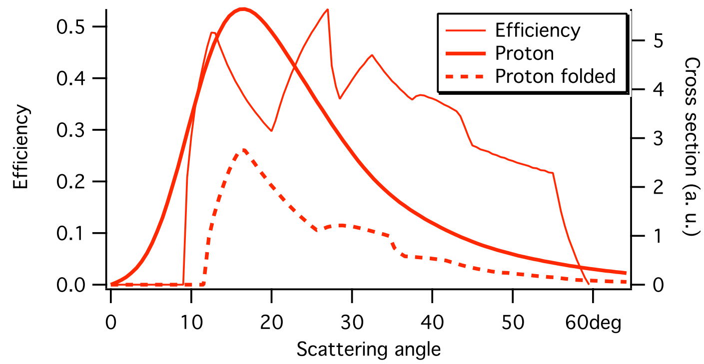


Figure 2: efficiency of the HiRA detector array as a function of proton scattering angle. Also shown are the proton angular distributions with and without folding from the efficiency curve.

Table 2 shows a preliminary analysis of the proton multiplicity observed in experiment 05038 for the one- and two-proton knockout reactions on ^{9}C. For the one-proton knockout reaction, hardly any multiplicity 2 events are observed, whereas 1.5% of all events coming from the two-proton knockout reaction generate double hits in the HiRA array. The numbers don't add up to 100% because the M_p=0 data contains the S800 singles which were down-scaled by a factor of 5 to avoid losses from the dead time of the data acquisition. Assuming that a 10% branch of the two-proton knockout of ^{9}C goes to two-proton diffraction, the detection efficiency for the triple coincidence proton-proton-^{7}Be residue is about 15%, in qualitative agreement with the estimation made for ^{28}Mg in this proposal.

Reaction	M_p=0	M_p=1	M_p=2
$^{9}C \rightarrow {}^{8}B$	20.1%	14.1%	0.1%
$^{9}C \rightarrow {}^{7}Be$	13.0%	13.3%	1.5%

Table 2: proton multiplicity observed in two runs of experiment 05038 corresponding to one- and two-proton knockout from ^{9}C. The numbers don't add up to 100% because of singles down-scaling.

The ^{28}Mg secondary beam will be produced from the fragmentation of a 140 MeV/u ^{40}Ar primary beam. The rate measured during our previous experiment is about 8.4×10^{3} atoms/s/pnA, for a total momentum acceptance of 1%. The energy of the ^{28}Mg at the exit of the A1900 fragment separator is 91 MeV/u. As in our previous experiment with the S800+SeGA setup, all reaction residues can be identified on an event-by-event basis in the S800 spectrograph.

The high energy of the diffracted protons entails the use of a thick reaction target without much broadening of their energy. In fact, the thickness limitation stems from the energy-loss broadening of the heavy residue momentum, due to its lowered atomic number by 2 units. For a

94 mg/cm^2 thick ^{9}Be target, this broadening amounts to a width of 20 MeV, or 0.4% in momentum, still a relatively small value compared to the observed width of the momentum distribution. The 91 MeV protons on the other hand only lose 0.6 MeV. Protons emitted from the target breakup in the stripping channel will be easily sorted from diffracted protons due to their damped energy.

The S800 spectrograph will be set in focussed mode in order to keep a relatively small beam spot on target, necessary because of the close geometry used for the HiRA detector array. Our previous experiment showed that the momentum width of the ^{26}Ne residues is wider than the 5% acceptance of the S800 spectrograph [Baz03], therefore three settings of the magnetic rigidity will be necessary to cover the full parallel momentum distribution of the residues. Taking into account the detection efficiency of HiRA, we predict a rate of approximately 80 counts per hour in the double diffraction channel for a 50 pnA primary beam intensity and a 94 mg/cm^2 thick reaction target. To get reasonable statistics (2000 counts) on this weakest channel, assuming the 86 μb cross section estimated above, about 24 hours of accumulation are necessary for each magnetic rigidity setting of the spectrograph, yielding a total of 72 hours. The statistics on the diffraction/stripping and double stripping channels will be about 20 and 100 times greater, respectively. Because of the expected high rate of the secondary beam (> 500,000 particles per second), the time-of-flight will be measured using a diamond film detector. This type of detector has already been successfully used at the object location of the S800 beam line for several experiments performed during the first half of 2006, and combines the advantages of radiation hardiness and excellent time resolution. Such a detector will eventually become part of the standard S800 setup.

In order to perform the energy calibration of the HiRA array - in particular the CsI detectors - a proton beam of 85 MeV is required as a calibration beam. The A1900 fragment separator can easily provide such a calibration beam, for which 4 hours of beam on target are necessary using elastic scattering from a ^{12}C target.

IV. References

[Baz03] D. Bazin et al., Phys. Rev. Lett. **91**, 012501 (2003)

[Fri05] J. Fridmann et al., Nature **435**, 922 (2005)

[Tos04] J. A. Tostevin et al., Phys. Rev. C **70**, 064602 (2004)

[Tos06] J. A. Tostevin, in preparation

[Yon06] K. Yoneda et al., submitted to Phys. Rev. C (2006)

[Goe04] M.-J. van Goethem et al., Nucl. Instr. and Meth. In Phys. Res. A **526**, 455 (2004)

Status of Previous Experiments

Experiment 01013 measured the two-proton knockout from ^{28}Mg, ^{30}Mg and ^{34}Si, using the S800+SeGA setup. The results have been published [Baz03], and have motivated the development of the reaction theory for the stripping component [Tos04].

Experiment 05038, the precision study of the diffractive contribution to one-proton knockout on ^{9}C, has been successfully completed in January of 2006, and is presently under analysis. Some preliminary results are used in the Physics justification to demonstrate the feasibility of this proposal. In particular, some two-proton knockout data was obtained at the higher magnetic rigidity setting of the S800 spectrograph, which show a clear signal for triple proton-proton-residue coincidences.

Educational Impact of Proposed Experiment

This proposal will be part of the Ph. D. of a future graduate student.

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 and you will need to designate a Safety Representative for your experiment.

SAFETY CONTACT FOR THIS PROPOSAL: D. Bazin

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.

Spectrograph Worksheet for S800 Spectrograph and Sweeper Magnet

The NSCL web site contains detailed technical information and service level descriptions about the S800 Spectrograph (Service Level Description) and the Sweeper Magnet (Service Level Description).

1. Timing detectors

Is a plastic timing scintillator required (at the object of the S800 or in front of the sweeper magnet)?

[x] No: A diamond film detector will be used instead (see text).

[ ] Yes

i. What is the desired thickness? [ ] 125 μm [ ] 1 mm [ ] other _____

ii. What maximum rate is expected on this scintillator? _______ Hz

2. Tracking detectors

Tracking detectors for incoming beam are available for Z>10. Performance limitations are to be expected at rates exceeding 200 kHz.

Are tracking detectors needed?

[x] No

[ ] Yes

3. Focal-plane rates

a) What detectors are planned to be used? All

b) What is the maximum rate expected in the focal-plane detection system? 1000 Hz

4. For S800 experiments only: Optics mode and rigidities:

a) Which optics mode is needed?

[ ] Dispersion matched [x] focused [ ] Other _________________________

b) What are the maximum and minimum rigidities planned to be used for the analysis beam line?

3.0 Tm minimum, 3.5 Tm maximum

c) What are the maximum and minimum rigidity planned to be used for the spectrograph?

3.0 Tm minimum, 3.8 Tm maximum

d) The maximum particle rate in the focal plane is 6 kHz when the CRDC detectors are being used. What is the maximum total particle rate expected in the S800 focal plane?

1000 Hz

Beam Request Worksheet Instructions

Please use a separate worksheet for each distinct beam-on-target requested for the experiment. Do not forget to include any beams needed for calibration or testing. This form does not apply for experiments based in the A1900. Note the following:

(a) **Beam Preparation Time** is the time required by the NSCL for beam development and beam delivery. This time is calculated as per item 4. of the Notes for PAC 30 in the Call for Proposals. This time is not part of the time available for performing the experiment.

(b) **Beam-On-Target Time** is the time that the beam is needed by experimenters for the purpose of performing the experiment, including such activities as experimental device tuning (for both supported and non-supported devices), debugging the experimental setup, calibrations, and test runs.

(c) The experimental device tuning time (XDT) for a supported device is calculated as per item 5. of the Notes for PAC 30 in the Call for Proposals. For a non-supported device, the contact person for the device can help in making the estimate. In general, XDT is needed only once per experiment but there are exceptions, e.g. a change of optics for the S800 will require a new XDT. When in doubt, please consult the appropriate contact person.

(d) A **primary beam** can be delivered as an on-target beam for the experiment either at the full beam energy or at a reduced energy by passing it through a degrader of appropriate thickness. The process of reducing the beam energy using a degrader necessarily reduces the quality of the beam. Please use a separate worksheet for each energy request from a single primary beam.

(e) Report the Beam-On-Target **rate** in units of particles per second per particle-nanoampere (pps/pnA) for secondary beams or in units of particle-nanoampere (pnA) for primary or degraded primary beams.

(f) More information about **momentum correction** and **timing start signal** rate limits are given in the A1900 service level description.

(g) For rare-isotope beam experiments, please remember to send an electronic copy of the LISE++ files used to obtain intensity estimates.

Beam Request Worksheet

Please use a separate sheet for each distinct beam-on-target requested

			Beam Preparation Time	Beam-On-Target Time
Primary Beam (from beam list)				
Isotope	^{40}Ar			
Energy	140	MeV/nucleon		
Minimum intensity	50	particle-nanoampere		
Tuning time (16 hrs; 0 hrs if the beam is already listed in an earlier worksheet):			16 hrs	
Beam-On-Target				
Isotope	^{28}Mg			
Energy	91	MeV/nucleon		
Rate at A1900 focal plane	8400	pps/pnA (secondary beam) or pnA (primary beam)		
Total A1900 momentum acceptance	1	% (e.g. 1%, not ±0.5%)		
Minimum Acceptable purity	70	%		
Additional requirements	[ ]	Event-by-event momentum correction from position in A1900 Image 2 measured with [ ] PPAC [ ] Scintillator		
	[x]	Timing start signal from A1900 extended focal plane		
Delivery time per table (or 0 hrs for primary/degraded primary beam):			6 hrs	
Tuning time to vault:			4 hrs	
Total beam preparation time for this beam:			**10 hrs**	
Experimental device tuning time [see note (c) above]: S800 [x] SeGA [ ] Sweeper [ ] Other [ ]				4 hrs
On-target time excluding device tuning:				72 hrs
Total on-target time for this beam:				**76 hrs**

Beam Request Worksheet

Please use a separate sheet for each distinct beam-on-target requested

			Beam Preparation Time	Beam-On-Target Time
Primary Beam (from beam list)				
Isotope	^{40}Ar			
Energy	140	MeV/nucleon		
Minimum intensity	50	particle-nanoampere		
Tuning time (16 hrs; 0 hrs if the beam is already listed in an earlier worksheet):			0 hrs	
Beam-On-Target				
Isotope	^{1}H			
Energy	85	MeV/nucleon		
Rate at A1900 focal plane	10000	pps/pnA (secondary beam) or pnA (primary beam)		
Total A1900 momentum acceptance	0.1	% (e.g. 1%, not ±0.5%)		
Minimum Acceptable purity	80	%		
Additional requirements	[ ]	Event-by-event momentum correction from position in A1900 Image 2 measured with [ ] PPAC [ ] Scintillator		
	[ ]	Timing start signal from A1900 extended focal plane		
Delivery time per table (or 0 hrs for primary/degraded primary beam):			4 hrs	
Tuning time to vault:			4 hrs	
Total beam preparation time for this beam:			**8 hrs**	
Experimental device tuning time [see note (c) above]: S800 [x] SeGA [ ] Sweeper [ ] Other [ ]				4 hrs
On-target time excluding device tuning:				4 hrs
Total on-target time for this beam:				**8 hrs**