National Superconducting Cyclotron Laboratory
Proposal Form—PAC 28

TITLE: Precision study of the diffractive contribution to one-proton knockout on ^{9}C

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

SPOKESPERSON: D. Bazin
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Is this a thesis experiment? ~~Yes~~ No If yes, for whom?____

OTHER EXPERIMENTERS: (please spell out first name)

Name	Organization	Check, if applicable Grad	Sr. Grad
J.A. Tostevin	University of Surrey, Guildford, UK		
A. Gade	NSCL-MSU		
B. Lynch	NSCL-MSU		
B. Tsang	NSCL-MSU		
M. Famiano	NSCL-MSU		
F. Delaunay	NSCL-MSU		
M. Wallace	NSCL-MSU		x
A. Rogers	NSCL-MSU		x
R.T. de Souza	Indiana University, Bloomington, IN		
S. Hudan	Indiana University, Bloomington, IN		

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	^{16}O	150	100	24	46
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: 24 46

TOTAL TIME REQUEST (HOURS): 70

(Calculated as per item 4. of the Notes for PAC 28 in the Call for Proposals)

HOURS APPROVED: ________________ HOURS RESERVED: ______________________

Access to:		SET UP TIME (before start of beam)	TAKE DOWN TIME
	Experimental Vault	____30____ days	_____5____ days
	Electronics Set-up Area	____15____ days	_____0____ days
	Data Acquisition Computer	____15____ days	_____0____ days

WHEN WILL YOUR EXPERIMENT BE READY TO RUN? _____04____ / ___01___ / ___2005__

DATES EXCLUDED: mid-May to mid-June 2005 and August 2005

EXPERIMENTAL LOCATION:

___ Transfer Hall (in the A1900)
___ N2 vault
___ N3 vault (92” chamber removed)
___ N4 vault (Sweeper line)
___ S1 vault (RPMS line)
___ S2 vault

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

EXPERIMENTAL EQUIPMENT:

___ A1900
___ 4pi Array
___ Neutron Walls
___ NaI Array
___ Segmented Ge Array [ ] classic [ ] mini [ ] beta [ ] delta [ ] other
___ S800 Spectrograph [x] with [ ] without scattering chamber
___ Other (give details)

___ Beta Counting System
___ 92" Chamber
___ Modular Neutron Array
___ Neutron Emission Ratio Observer

___ Beta-NMR Apparatus
___ Sweeper Magnet
___ SuperBall
_x_ High Resolution Array
___ APEX NaI Array

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

TARGETS: ^{9}Be 100 mg/cm^{2}

LIST ALL RESOURCES THAT YOU REQUEST THE NSCL TO PROVIDE FOR YOUR EXPERIMENT BEYOND THE STANDARD RESOURCES OUTLINED IN ITEMS 6, 7, AND 11. OF THE NOTES FOR PAC 28 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.)

SUMMARY (no more than 200 words):

Single-nucleon knockout reactions of fast radioactive beams are rapidly becoming a powerful tool for identifying single-particle structure in exotic nuclei and for investigating effects of correlations in the nuclear wave function. It is now becoming clear that the knockout cross sections can be used to infer accurate spectroscopic factors, independent of model expectations. The theory of knockout reactions expresses the (A,A-1) cross section to a given final state as the incoherent sum of two contributions. In the first, referred to as stripping or inelastic breakup, the nucleon reacts with the target and is removed from the beam. The second, referred to as diffractive or elastic dissociation, corresponds to separation of the residue and the nucleon through their two-body interactions with the target, each being at most elastically scattered. The contribution from diffractive process is approximately 50% of the cross section for halo states, and even for deeply bound nucleons it is still about 20%. It is therefore an essential ingredient, which, nevertheless has been studied very little. We propose an experiment aimed at a detailed study of the one-proton diffraction from ^{9}C by measuring the characteristics of the ^{8}B residue and the proton using the S800 spectrograph in coincidence with the HiRA detector array.

1. Physics justification

Single-nucleon knockout reactions with light targets, usually ^{9}Be, of fast radioactive beams are rapidly becoming a powerful tool for identifying single-particle structure in exotic nuclei and for investigating effects of correlations in the nuclear wave function. The technique is very sensitive, experiments have been carried out with incoming beams of less than one atom/s, and it identifies l values from the shape of the momentum distributions. Most importantly, it is now becoming clear that the knockout cross sections can be used to infer accurate spectroscopic factors, independent of model expectations. It thus extends the reach of the (e,e'p) knockout process, which over the past 20 years has shown that proton states in a representative sample of stable (mainly magic) nuclei have occupancies that are reduced by factors 0.6-0.7 relative to many-body calculations in a restricted quantum mechanical state. The heavy-ion knockout reaction extends the knockout technique to cover both proton and neutron states and, even more important, to span the "isospin dimension" by measuring neutron- and proton-spectroscopic factors in nuclei near the driplines. We refer to the general review[1] and also to some recent results[2], and references therein.

Compared with the traditional transfer reactions, rooted in the Born approximation, the knockout reaction offers important formal and practical advantages. The cross sections are calculated in eikonal theory, where the effects of the interactions of the residue and nucleon with the target enter the formalism through their phase shifts obtained in the assumption of a linear trajectory, a very good approximation for heavy ions at these energies. The partial cross sections are expressed by matrix elements with the structure of a sum rule and hence they are, through completeness, inclusive with respect to all final states. The treatment is non-perturbative and contains the effect of projectile breakup to all orders.

The theory[3] of knockout reactions is based on earlier studies of nuclear halo states. It expresses the (A,A-1) cross section to a given final state as the incoherent sum of two contributions. In the first, and usually most important, referred to as stripping or inelastic breakup, the nucleon reacts with the target and is removed from the beam. The second, referred to as diffractive or elastic dissociation, corresponds to separation of the residue and the nucleon through their two-body interactions with the target, each being at most elastically scattered. The contribution from diffractive process is approximately 50% of the cross section for halo states,

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[1] P.G. Hansen and J.A. Tostevin, Annu. Rev. Nucl. Part. Sci. 53, 219 (2003).

[2] A. Gade et al., Phys. Rev. Lett. 93, 042501 (2004)

[3] J.A. Tostevin, J. Phys. G25, 735 (1999).

and even for deeply bound nucleons it is still about 20%. It is therefore an essential ingredient, which, nevertheless has been studied very little.

The reason for this is that the identification of the diffractive channel requires a separate coincidence with a forward-going nucleon with essentially beam velocity, and also a quite large angular coverage. The problem is illustrated in Fig. 1, which shows the laboratory angular distribution of neutrons from ^{11}Be measured in a GANIL experiment. (We note for completeness that this experiment was not done in coincidence with gamma rays. The presence of a 20% branch to excited states was unknown until the work of Aumann et al.[4].) The shape from diffraction theory is not very different from the black-disk estimate, which would place the first diffraction minimum at θ_{min}=3.83/(kR), where k is the nucleon momentum and R the target radius estimated from the nucleon reaction cross section. This corresponds to a laboratory neutron angle of 53^0 in qualitative agreement with Fig. 1. A recent precise experiment[5] on nuclear breakup of ^{11}Be on a carbon target should in the same way have $\theta_{min}=38^0$, where the experimental coverage went only to 12^0, and the energy cutoff was 8MeV. It is clear that such an experiment cannot give quantitative checks on the diffractive channel; the authors themselves estimate their acceptance to be only 31%, a number that must be very sensitive to the assumed shapes of the, unknown, double-differential distribution from diffractive breakup. (Such distributions have actually been calculated in the so-called CDCC approximation, see[6].) The most accurate measurement of the ^{11}Be dissociation cross section, 26.9(1.4) mb supported by gamma coincidences has been carried

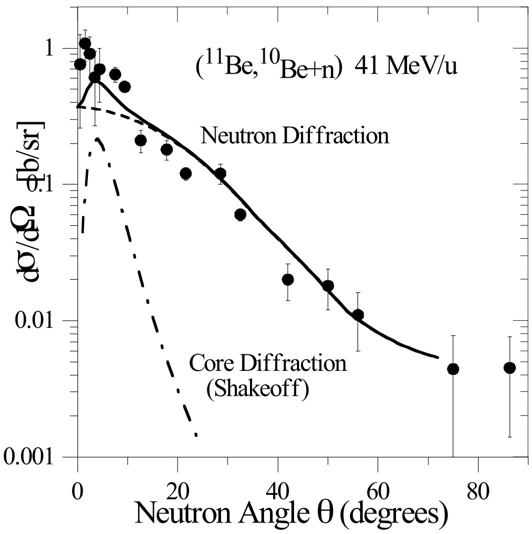

Figure 1: Data from R. Anne et al., NPA 575, 125 (1994). Diffraction distribution calculation by A. Bonaccorso and D. Brink, PRC 57, R22 (1998). The narrow distribution is from elastic (nuclear and Coulomb) scattering of the ^{10}Be followed by shakeoff of the neutron was calculated by F. Barranco and P.G. Hansen, Eur. Phys. J. A 7, 479 (2000). . The same effect can be seen much better in the paper by Palit et. al.[7].

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[4] T. Aumann, Phys. Rev. Lett. 84, 35 (2000).

[5] N. Fukuda et al., Phys. Rev. C 70, 054606 (2004)

[6] J.A. Tostevin et al., Phys. Rev. C 66, 024607 (2002).

out by the GSI group[7]. The result must include a 5 mb contribution from Coulomb breakup, so it is somewhat below their theoretical value of 29.8 mb.

The neutron experiments are in general difficult and all the interesting cases have considerable branches to excited states that will require an additional gamma coincidence requirement. The idea behind the present proposal is instead to study the diffractive distribution of protons from ^{9}C to ^{8}B, which has no bound excited states and to use the charged-particle detector array HiRA, which can offer a much larger angular coverage of the diffracted protons than can the neutron detection facilities currently used at the NSCL. The experiment will measure the precise cross sections for stripping and diffraction dissociation. It is interesting that an approximate value for the ratio has been provided by Enders, who found an ingenious technique for separating the dissociation events in a telescope experiment[8], which for ^{9}C gave the stripping to diffraction ratio of 2.8(9), theory 2.2. Most important, subtraction of the normalized proton-coincident events from the inclusive ^{8}B parallel-momentum spectrum will provide individual shapes for the two components that can be compared with the appropriate calculations in eikonal and CDCC theories. This is something that has not been done before. The subtraction necessary to obtain the stripping part should be very reliable, since the correction from the diffraction part is known[8] to be only about 25%.

2. Goals of the experiment

The goal of this experiment is to measure the diffracted protons in coincidence with the heavy residue in the one-proton knockout of ^{9}C at 100 MeV/u on a ^{9}Be target. The diffraction minimum θ_{min}, calculated from the black-disk estimate, is equal to 38.5° for protons at 100 MeV, which gives a lower limit for the angular coverage of the proton detector. The HiRA detector array will identify the high-energy protons, and measure their angular distribution as well as their kinetic energy. The characteristics of the forward focused ^{8}B residues will be measured using the S800 spectrograph, which provides particle identification, as well as the full momentum vector reconstruction.

An inclusive cross section of 54(4) mb was measured at 78.3 MeV/u in [8]), with an approximate contribution from diffraction of 14(4) mb. The theoretical cross sections for stripping and diffraction are calculated in the eikonal model, and include the usual A/(A-1)

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[7] R. Palit et al., Phys. Rev. C. 68, 034318 (2003).
[8] J. Enders et al., Phys. Rev. C 67, 064301 (2003).

center-of-mass correction[9] valid for the p-shell, as well as the radial mismatch factor**Error! Bookmark not defined.** M, a small correction arising from the imperfect overlap of the least bound nucleon's single-particle state in the residue with its original configuration in the projectile. In the case of the one-proton knockout from ^{9}C, the binding energies of the valence protons in the projectile and the residue differ by almost a factor of 10, with $S_p(^8B)=0.137$ MeV. However, because of the Coulomb barrier and the l=1 centrifugal barrier, the initial and final proton single-particle wave functions remain very similar, and the mismatch factor stays close to unity, at M=0.976. The calculated Coulomb dissociation cross section is very small for a ^{9}Be target, 1.1 mb as calculated in [8]).

3. Experimental details

The diffractive dissociation channel will be singled out using the S800 spectrograph to characterize the ^{8}B residue, in coincidence with the HiRA detector array to characterize the diffracted proton. The HiRA array is composed of 20 individual telescope units, each made of two Silicon strip detectors (65 μm and 1.5 mm) followed by a 4 cm thick CsI scintillator crystal[10]. In standard configuration, the array is arranged in four towers of five telescopes each, placed on each side of the target. The punch-through energy for protons is around 110 MeV, therefore the CsI thickness should cover the full range of the diffracted protons at our energy of 100 MeV/u . Because of the large angular coverage needed, and the fact that the particle identification in HiRA will be performed via energy-loss measurement rather than time-of-flight at these energies, the array will be placed in a close geometry, around 17 cm from the target. At this distance, each telescope covers approximately 20° in the laboratory frame with an average angular resolution of about 0.3°. The angular range covered with this geometry will therefore span from 5° to 45°, enough to cover the diffraction distribution past the first minimum from our estimate. Monte-Carlo simulations indicate an average geometric efficiency around 40% for the covered angular range.

The 100 MeV/u ^{9}C secondary beam will be produced from the fragmentation of a 150 MeV/u ^{16}O. The rate calculated with LISE++ is 2,100 atoms/s/pnA for a total momentum acceptance of 1%. The main contaminant is ^{8}B with a similar rate of 1,900 atoms/s/pnA, and traces of ^{7}Be and ^{6}Li at 60 and 50 atoms/s/pnA, yielding a purity of 51%. The incoming beam rate in Ender's experiment was limited by the unreacted particles collected in the detector setup.

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[9] A.E.L. Dieperink and T. de Forest, Jr., Phys. Rev. C 10, 533 (1974)

In this proposal, no such limitation occurs because the unreacted beam is filtered out by the S800 spectrograph. In addition, the reactions produced by the contaminants are easily distinguished from those coming from ^{9}C using time-of-flight.

The high energy of the diffracted protons entails the use of a relatively thick reaction target without much broadening of the proton energy distribution. The thickness limitation stems in fact from the energy-loss broadening of the residue momentum distribution because of its lowered atomic number. For a 100 mg/cm^{2} thick ^{9}Be target, the energy-loss broadening amounts to 4.2 MeV, or 0.54%. In comparison, the 100 MeV proton energy loss in the same thickness is only 0.6 MeV. Protons emitted from the target breakup in the stripping channel will be easily distinguished from diffracted protons in the HiRA array due to their damped energy.

The S800 spectrograph will be run in focused mode, in which the secondary beam is focused on the reaction target surrounded by HiRA to keep a good angular resolution. The emittance of the secondary beam will be tracked event by event using the S800 tracking PPACs, as now routinely done in most experiments. The momentum resolution achieved is about 0.1%. The secondary beam flux will be monitored using two thin plastic scintillators: one located at the focal plane of the A1900 fragment separator, and the other located at the object of the S800. Several normalization runs will be necessary to ensure a good absolute measurement of the cross sections.

The count rate estimate is based on the measured 14(4) mb diffraction cross section[8], and a 100 mg/cm^{2} thick ^{9}Be reaction target. We obtain a rate of 0.2 ^{9}C diffractions per second per pnA of primary beam. Taking into account transmission losses, maximum primary beam intensity, the HiRA detector array efficiency, about 4 detected coincidences per second are expected for the one-proton diffractive dissociation of ^{9}C. As this proposal aims at a precise comparison between the calculated and measured shapes of the momentum distributions, good statistics in the tails of the distributions is required. We estimate about 12 hours of accumulation for each magnetic rigidity setting should suffice. Three settings will be necessary to cover the full extent of the residue's longitudinal momentum distribution. Including the necessary incoming beam normalization, a total of 42 hours of beam time is requested for this experiment.

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[10] Nucl. Instr. and Meth. In Phys. Res. A 526, 455 (2004)

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:

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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.
^{241}Am alpha source for HiRA calibrations

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 28 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 28 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	Bea On-T Ti

Primary Beam (from beam list)

Isotope ^{16}O

Energy 150 MeV/nucleon

Minimum intensity 100 particle-nanoampere

Tuning time (18 hrs; 0 hrs if the beam is already listed in an earlier worksheet): 18 hrs

Beam-On-Target

Isotope ^{9}C

Energy 100 MeV/nucleon

Rate 2000 pps/pnA (secondary beam) or pnA (primary beam)

Total A1900 momentum acceptance 1 % (e.g. 1%, not ±0.5%)

Minimum Acceptable purity 50 %

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): 12 hrs

Tuning time to vault: 4 hrs

Total beam preparation time for this beam: **24** **hrs**

Experimental device tuning time [see note (c) above]: 4
S800 [x] SeGA [ ] Sweeper [ ] Other [ ]
On-target time excluding device tuning: 42

Total on-target time for this beam: **46**