NATIONAL SUPERCONDUCTING CYCLOTRON LABORATORY
PROPOSAL FOR EXPERIMENT

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

TITLE: Resonance spectroscopy of molecular states in ^{14}Be and ^{12}Be

SPOKESPERSON: R. J. Charity

Address: Department of Chemistry, box 1134
Washington University
St Louis, MO

Phone: (314)935-6578 Fax: (314)935-6184 E-Mail charity@wuchem.wustl.edu

BACKUP SPOKESPERSON: L. G. Sobotka

Institution: Washington University

Phone: (314)935-5360 Fax: (314)935-6184 E-Mail_lgs@wuchem.wustl.edu

Is this a thesis experiment? Yes No Perhaps If yes, for whom? S. Komarov

OTHER EXPERIMENTERS: (please spell out first name)

Name	Organization	Check, if applicable: Grad	Sr. Grad
R.J. Charity	WU		
L.G. Sobotka			
S. Komarov			X
W. Lynch	MSU		
B. Tsang			
G. Verde			
M-J. van Goethem			
M. Wallace			
M. Famiano			
B. Nett.			
M. Thoennessen			
T. Baumann			
A. Wuosmaa	WMU		

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) ^{12}Be	65	1×10^{5}	20%	48	^{18}O	100
b) ^{14}Be	65	2.5×10^{3}	35%	48	^{18}O	100
c) ^{4,6,8}He	45,55,65	10^{6}		8	^{18}O	100
d) A1900 beam change (from 12Be to 14Be).				24 (as we understand the rules)		

TOTAL REQUESTED HOURS: 128 (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	96 hrs
	Electronics Set-up Area	96 hrs)
	Data Acquisition Computer	48 hrs (We will write code before we arrive)

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

Access to:	Experimental Apparatus	24 hrs
	Electronics Set-up Area	24 hrs
	Data Acquisition Computer	48 hrs

WHEN WILL YOUR EXPERIMENT BE READY TO RUN? Summer 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
___________	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: Polypropylene, carbon

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

BEAM TRACKING: Yes ___________ Position only ____X_______ Position and angle

Comments Two PPACS will be required to track the beams into the secondary target chamber

BEAM TIMING: Yes

Comments Needed to select ^{12,14}Be from major contaminants (^{14,15}B) – as determined via LISE++

PARTICLE-BY-PARTICLE MOMENTUM: Yes

Comments need to determined beam energy event-by-event

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

SUMMARY (no more than 200 words)

The high lying molecular-resonance structure of $^{12 \text{ and } 14}$Be will be studied by charged particle-charged particle correlations. The particle-bound secondary beams will be inelastically excited by a (p,p') reaction. The He decay products will be detected in HiRA allowing Be excitation-energy reconstruction. The recoil proton will be tagged giving us another measurement of the excitation energy. We expect to confirm the ^{6}He+^{6}He and ^{4}He+^{8}He levels in ^{12}Be and claimed ^{8}He+^{6}He states in ^{14}Be.

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.

1. PHYSICS JUSTIFICATION

^{14}Be has was first observed in spallation reactions of actinides and then in the $^{14}C(\pi^-,\pi^+)^{14}Be$ reaction. Almost 20 years ago it was produced by the reaction we will use here (fragmentation of ^{18}O.) Over the past decade or so, there have been numerous studies of the ground and low-lying structure of ^{14}Be. Of particular interest has been the related subjects of its size, “neutron halo”, and the momentum representation of the ground state wave function. (The latter determined by measurements of the neutron-$^{14-x}$Be correlations). A quick scan of the TUNL data base yields dozens of papers, both theoretical and experimental, on this subject.

While very interesting, these works are not particularly relevant to this proposal and thus will not be discussed. We wish to study the high-lying strength that is “molecular” in nature. Molecular-resonance states consisting of two alpha cores surrounded by “valance” neutrons have been predicted [1,2,3]. These states are analogs to atomic molecules, for example, H_2 consisting of two proton cores surrounded by valence electrons. The existence of molecular resonance states in ^{12}Be had been inferred by the observation of resonances associated with the ^{6}He-^{6}He and ^{4}He-^{8}He decay channels of ^{12}Be* excited by inelastic scattering on protons and C targets [4]. Figure 1 shows the resonances observed in the ^{4}He-^{8}He decay channel. Molecular states have also been predicted for ^{14}Be[5]. Recently, the resonance spectroscopy of multiple charged-particle channels of $^{12\text{ and }14}$Be were studied at RIKEN. While our searches for full papers on this work turned up empty, published abstracts [6] of this work suggest that two resonances in He + He channels were found in both ^{12}Be and ^{14}Be. Specifically, for inelastically excited $^{14}Be \rightarrow ^{14}Be^* \rightarrow ^{8}He + ^{6}He$, the final fragments exhibited peaks in the relative energy spectra at 1.4 and 2.2 MeV. Such states would be at $E^*(^{14}Be) = 9.9$ and 10.7 MeV. The questions of whether these states actually exist and, if so, whether they have transparent structures, motivate this work.

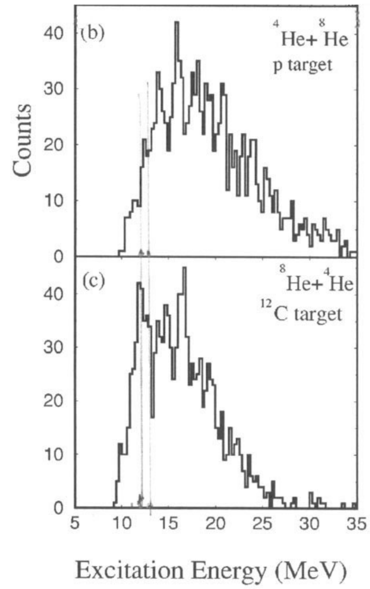

Fig. 1: Spectrum of the ^{8}He + ^{6}He exit channel taken from [4] for c) a pure carbon target and b) a CH_2 target for which a C subtraction has been applied. (Part a of this figure was the total CH_2 spectrum. It was removed as the authors made a scale error when plotting this panel and thus the published figure is very misleading.)

A second motivation for this work is that it will also allow us to study the ^{14}Be* → ^{10}Be + ^{4}n channel (threshold at 5 MeV). A valiant attempt to identify the exit channel as containing a bound ^{4}n has been published [7]. However, only 6 candidate events were identified and the evidence is not convincing. Additional work on characterizing this exit channel is clearly required. The apparatus proposed here will allow some characterization and elimination of some potential backgrounds, but if candidate events are found, the neutron detection will have to be done by a device which can determine the kinematics of the n-p scattering. The relevant thresholds for breakup of ^{12,14}Be are shown in Fig. 2. The claimed molecular resonances in the ^{8}He + ^{6}He channel are shown.

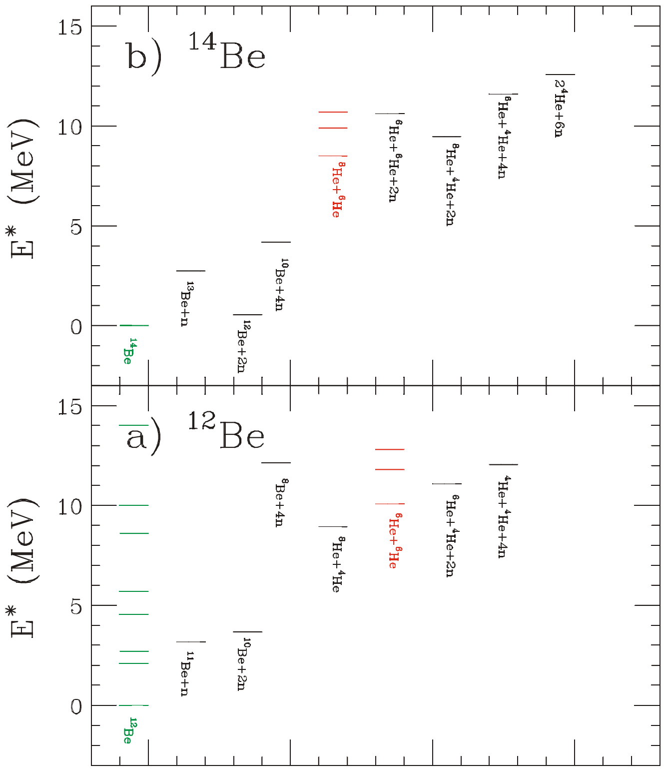

Figure 2: Threshold energies of various decay channels for ^{12}Be and ^{14}Be. The two reported resonances are shown above the ^{8}He+^{6}He ground state.

The excitation and characterization of such high-lying states is difficult. However, the apparatus we will eventually have at the NSCL will allow us to undertake such studies with greater detail than previously possible. In short a (p,p') reaction will be used to inelastically excite the particle-stable beam to above the threshold for the molecular decay channel. The excitation energy can be tagged with the scattered proton. This tagging can be done by an annular Si-CsI telescope positioned near the target. The decay fragments will be steered into the HiRA array using the SWEEPER magnet. MoNA neutron array will detect free neutrons at zero degrees. The relative energy of the fragments plus the threshold decay energy must coincide with the (p,p') Q-value determined from the initial ^{14}Be momentum, $E_{p'}$ and $\theta_{p'}$. Agreement, within experimental resolution factors (see below) of the reaction confirms the reconstructed excitation energy. This along with the single proton detection at large angles (see p,p' kinematics below) and charge 4 in HiRA, eliminates background reactions. Apart from ^{6}He-^{8}He decays channels, with MoNa one can also look at other decays channels with neutrons, for example ^{6}He-^{6}He-2n channels (see Fig. 2)

Our reasons for desiring to use the (p,p') reaction are also motivated by the published spectra in [4] which is shown in Fig. 1 for excitation by proton and C targets. The excitation spectrum for the proton recoil was generated in this work via a subtraction scheme. It clearly shows the most detail. The direct (p,p`) detected by tagging should be better still.

In the case of ^{4}n studies, we can detect the recoil proton again in the annular counter and a ^{10}Be fragment in HiRA. If the remaining four neutrons are bound into one particle, then from the detection of the proton and ^{10}Be fragment, the full kinematics of the reaction are determined and the scattering angle and velocity of the ^{4}n will be inferred. A strong velocity-angular correlation between the inferred values and those of neutron-like events detected in MoNa would be suggestive of ^{4}n emission. A wider correlation would be indicative of the emission of four individual neutrons.

All of these experimental goals can be achieved by the experimental apparatus shown in Fig. 3.

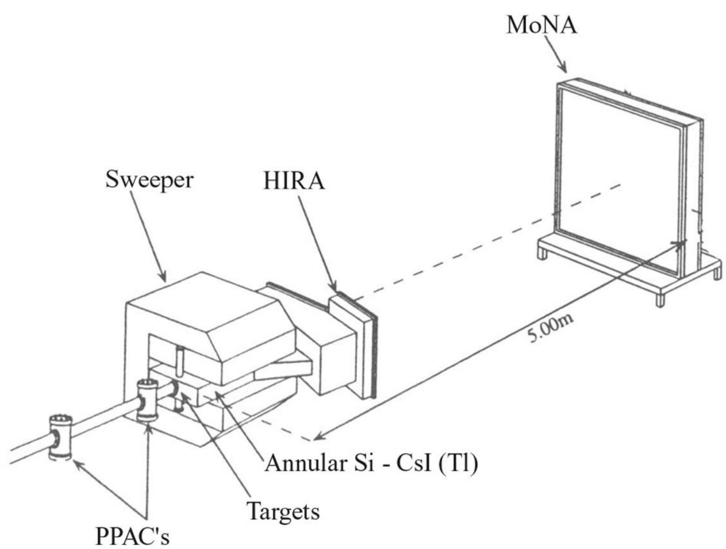

Figure 3: Schematic of the ultimate experimental apparatus. This set-up is similar to that used for the NSCL study of the Dissociation of ^{8}He [10] and this figure is a modified version of a figure from this work. **For the proposed test HiRA will be centered at 0^{o} and MoNA will not be used.**

2. GOALS OF THE PRESENT EXPERIMENT

This proposal represents a first step towards the goals stated above. At this time, NONE of the three major pieces of equipment needed for this project is on hand, in particular the Sweeper magnet will not be read for use before April 2003 at the earliest. Therefore, we propose to start with a simpler setup consisting of the annular detector for recoil-proton detection and the HiRA array (centered at zero degrees) for the detection of breakup products. We propose to start with a ^{12}Be beam for setup and confirm the existence and location of the ^{6}He + ^{6}He and ^{4}He + ^{8}He resonances [4]. Subsequently, we propose to continue with a ^{14}Be beam and look for ^{6}He + ^{8}He decay. As stated above, we will deduce the excitation energy from both the He-He relative energy and from the energy and angle of the recoil proton to look for consistency.

If resonance structures are observed, then the spin of each state can be inferred from angular correlation measurements. Specifically we look at the scattering angle of the ^{14}Be* (inferred from either the ^{6}He - ^{8}He pair or independently from the recoil proton) and the center-of –mass emission angle of the ^{6}He - ^{8}He pair. Correlation plots of these two angles, for a single state, show parallel-ridge structures, the frequency of which is related to the spin of the state [8,9]. This technique was used to infer the spins of some the ^{12}Be $\rightarrow$ ^{6}He + ^{6}He molecular resonance states [4].

In addition to the physics just listed, this experiment should provide us better understanding of the reactions, their cross sections, and the detection apparatus, thus allowing us to better plan for the inclusion of the MoNA array in a future proposal.

3. EXPERIMENTAL DETAILS

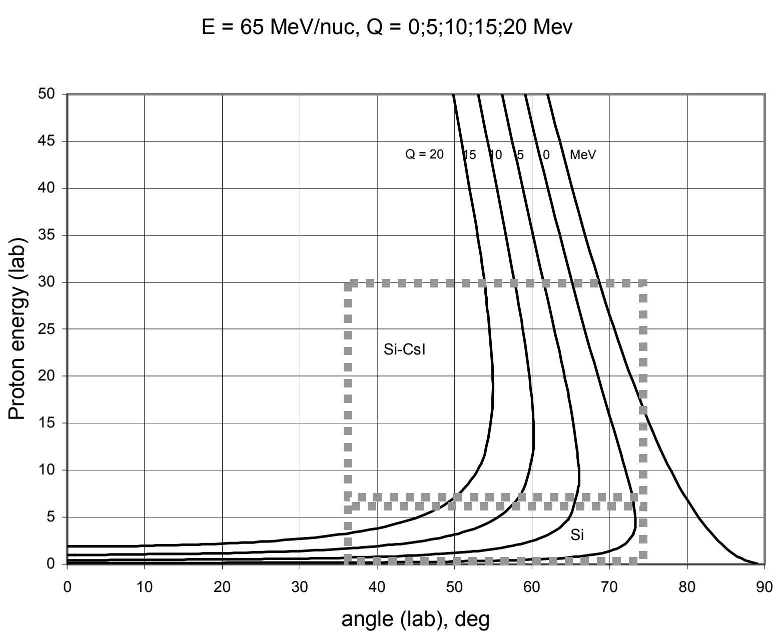

Figure 4: Kinematics – E_P(lab) in MeV vs θ_p(lab) - for (p,p'). The curves are for Q-values (excitation energy) in 5 MeV increments and the boxes represent the acceptance of the ring counter. Note that to a significant degree, the scattering angle determines the Q-value. (The ring counter divides its opening angle into 48 bins.)

The HiRA Si-CsI telescopes will be arranged in a 4x5 array at 60 cm from the target, allowing coverage out to 16^o with an angular resolution of 0.2^o. (This comparable to that obtained from the beam tracking.) These detectors are expected to have good isotope resolution for He fragments and the energy resolution from the CsI(Tl) detectors is expected to 0.5%. Overall the Be excitation energy is expected to be reconstructed form the relative energy of the He-He pairs to a few 100 keV.

The recoil protons will be detected in an annular detector covering angles from 20^o to 70^o. The (p,p') kinematics is shown in Fig. 4. The branch at very low E_p, extending to small angles corresponds to a very small solid angle in the CM system and thus small cross section. The boxes represent the coverage by the annular detector used for p' detection. We have achieved 40 keV and 1 ns resolution for alpha particles with the annular Si we plan to use. The energy (time) resolution will be somewhat better (worse) for protons. The Si detector will be followed by a ring of CsI(Tl) detectors, allowing tagging up to E_p = 40 MeV, albeit with somewhat poorer resolution. This limits us to 300 keV excitation-energy resolution, however larger sources of uncertainty come from the spread in beam energy and the spread in the proton energy loss in the target. We will restrict the momentum cut on the beam to 1.5% which unfortunately this still leads to a excitation energy resolution of about an 1 MeV. We will explore in the experiment smaller momentum cuts if the counting rates permit and the use beam particle-by-particle momentum tracking to reduce this resolution.

The cross section for ^{12}Be(p,p')^{6}He+^{6}He reaction at E/A=30 MeV was estimated to be 0.4 mb [3]. We will use this number for count rate estimates for ^{6}He+^{8}He pairs as well. From the fragmentation of E/A=100 MeV ^{18}O beam on a Be target, the LISE++ code predicts approximately $2.5x10^3$ and $1x10^5$ particles per second of ^{14}Be and ^{12}Be, respectively. With a suitably close pack arrangement of the HiRA modules we could get around 30% efficiency for detecting He pairs (this will depend on the decay energy of course). With a 2 mg/cm^2 polypropylene target, this gives us .012 and 0.75 detected He-He pairs per second, respectively.

We request 2 days with the ^{12}Be beam for setup. During this time we will optimize the beam-impurity rejection, determine the beam-momentum resolution, and take data with the polypropylene target. ^{14,15}B contamination is expected to be most problematic as this can also lead to He-He pair production. However this problem can be suppressed using time-of-flight and position information from the tracking detectors. We will also run with a C target to determinant the contribution from the C content in the polypropylene target. In principle our recoil proton tagging will eliminate this contribution, but we will check this by using untagged polypropylene data and subtracting the C contribution.

In two days of running with the ^{14}Be beam, we could expect a few thousand counts in the most prominent resonance peaks which should be adequate for angular-correlation studies. If the count rates are significantly lower, we will increase the target thickness to compensate, but of course will sacrifice the energy resolution of the detected proton recoil. Finally we request one shift of mixed ^{4,6,8}He beam for energy calibrate of the light output from the CsI(Tl) detectors.

[1] N. Itagaki and S. Okabe, Phys. Rev C **61**, 044306 (2000).

[2] Y. Kanada-En'yo, H. Horiuchi and A. Dote, Phys. Rev C **60**, 064304 (1999)

[3] M. Ito, K. Kato, Y. Sakuragi, E. Hiyama, and M. Kamimura, RIKEN Review **39**, 123 (2001).

[4] Freer *et al*., Phys. Rev. Lett. **82**, 1383 (1999), Phys. Rev. C **63**, 034301 (2001).

[5] Y. Kanada-En'yo, Los Alamos preprint server, arXiv:nucl-th/0204040 v1

[6] A. Saito*, et al*., //www.aps.org/aps/meet/HAW01/baps/S160.html#SDE.009 and DE.010.

[7] F. Marque's, *et al*., Phys. Rev. C **65**, 044006-8 (2002).

[8] W. Rae and R. Bhowmik, Nucl. Phys **A420**, 320 (1984)

[9] M. Freer, Nucl. Instrum. Methods Phys. Res., Sect. A **383**, 463 (1996)

[10]Y. Iwata *et al*., Phys. Rev. C **62** 064311 (2000).

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

This experiment requires:

1) **An annular Si+CsI telescope** for excitation energy tagging. This array has been constructed at WU and is ready. (It will be used in our level density experiment that we hope to run in early 2003).

2) **HiRA** for the charged particle detection. HiRA is presently being constructed and will be available early in 2003 for experiments (line this one) which to not require the full array. We anticipate the full array to be completed and running with the final electronics by the end of the summer of 2003.

This experiment would be run in the N4 vault. A schematic of the experimental equipment is shown in Fig. 2.

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: L. G. Sobotka

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

249Cf	Radioactive sources required for checks or calibrations.
NO	Transport or send radioactive materials to or from the NSCL.
NO	Transport or send— to or from the NSCL—chemicals or materials that may be considered hazardous or toxic.
_NO_______	Generate or dispose of chemicals or materials that may be considered hazardous or toxic.
_NO______	Mixed Waste (RCRA) will be generated and/or will need disposal.
_NO_______	Flammable compressed gases needed.
_YES______	High-Voltage equipment (Non-standard equipment with > 30 Volts).
_NO______	User-supplied pressure or vacuum vessels, gas detectors.
_NO______	Non-ionizing radiation sources (microwave, class III or IV lasers, etc.).
_NO______	Biohazardous materials.

PLEASE PROVIDE BRIEF DETAIL ABOUT EACH CHECKED ITEM.

ALPHA SOURCE FOR SET-UP
HV FOR NEUTRON DETECTORS