TRIUMF - EEC SUBMISSION EEC meeting: 200812S *Original Proposal*	TRIUMF	**Exp. No.** S1203 - *Active (Stage 2)* **Date Submitted:** 2008-11-12 07:09:48

Title of Experiment:

Spectroscopy of ^{12}Li

Name of group:

Spokesperson(s) for Group

H. Al Falou, R. Kanungo

Current Members of Group:
(name, institution, status, % of research time devoted to experiment)

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S.P. Fox	University of York	Senior Research	10%
C.Y. Wu	Lawrence Livermore National Laboratory	Research Scientist	10%
S. Williams	TRIUMF	Research Associate	10%
J.N. Orce	TRIUMF	Research Associate	10%
D. Cross	Simon Fraser University	Student (Graduate)	10%
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R. Kshetri	Simon Fraser University	PDF	10%
G. Ball	TRIUMF	Research Scientist	10%
C.J. Pearson	TRIUMF	Research Associate	10%
I. Tanihata	RCNP/Osaka University	Professor	10%
B.R. Fulton	University of York	Professor	10%
A. Shotter	TRIUMF/ Edinburgh University	Research Scientist	10%
C.E. Svensson	University of Guelph	Professor	10%
G. Hackman	TRIUMF	Research Scientist	10%
P.E. Garrett	University of Guelph	Professor	10%
A.M. Laird	University of York	Lecturer	10%
C. Andreoiu	Simon Fraser University	Assistant Professor	10%
C. Ruiz	TRIUMF	Research Scientist	5%
N. Orr	LPC/Caen	Research Scientist	5%
L. Buchmann	TRIUMF	Research Scientist	5%
B. Davids	TRIUMF	Research Scientist	5%
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J. Gibelin	LPC/Caen	Associate Professor	5%
N. L. Achouri	LPC/Caen	Research Scientist	5%

Beam Shift Requests:

20 shifts on: SEBT3A; ISACII

Basic Information:

Date submitted: 2008-11-12 07:09:48

Date experiment ready:

Summary:

The very neutron-rich light nuclei provide a unique testing ground for our understanding of nuclear structure. The resonances in unbound light-nuclei are expected to provide important constraints on our understanding of evolution of nuclear shell structure and nuclear binding.

In this proposal we aim to make a pioneering attempt to search for the low-lying p-wave resonance(s) in the most neutron-rich N=9 isotone 12Li. The experiment will also allow the first search for the d-wave resonance(s) as well.

The specific interest in the low-lying resonance(s) in this nucleus arises from the observation of lowering of the 1s1/2 orbital both for the N=9 isotones as well as for the Z=3 isotopes. Following the trend, it is expected that in 12Li an inversion of the s-orbital and p-orbital might occur. Therefore the lowest resonance in 12Li would be highly probable of being a p-wave resonance.

The low-lying p-wave resonance can be expected to be best populated through the 11Li(d,p)12Li transfer reaction since the ground state of the 11Li has a mixed configuration of s- and p- orbitals. We therefore propose to study this reaction using the 5A MeV beam available at ISACII, TRIUMF. The beam properties of TRIUMF will make it probably the only place at present in the world to study this reaction.

The experiment will be performed at the TIGRESS beamline at ISACII, using a box-shaped silicon detector array, SHARC that is scheduled to be commissioned in Spring 2009.

The feasibility study of the experiment based on detailed Monte Carlo simulations suggest that we will be able to scan resonance energies upto 3 MeV to search for the p- and d- wave resonances. The total beamtime of 10 days is requested based on count rates estimated taking into account realistic detection capability and one step distorted wave Born approximation calculations.

Plain Text Summary:

Summary of Experiment Results:

Primary Beamline: isac2a

Secondary Channel

Base:

Primary/Secondary Beam

Proton Beam

Primary Energy:

Primary Intensity:

Primary Pulse Width:

Secondary Beam

Secondary Particle Type:

Secondary Energy: 5000

Secondary Spot Size: 2mm

Secondary Intensity: 5000

Special Characteristics:

Target:

Production Target

Samples List:

Spectrometers:

TRIUMF Support:

NSERC:

The small annular silicon detector has been funded by NSERC.

NSERC:

The small annular silicon detector has been funded by NSERC.

Other Funding:

SHARC silicon detector has been funded by University of York, UK. The electronics have been funded by CFI, Canada.

Muon Justification:

Safety Issues: No major safety hazards

1 Introduction

The very neutron-rich light nuclei provide a unique testing ground for our understanding of nuclear structure. The structure of unbound nuclei are crucial for understanding how limits to nuclear binding originate. Experimentally, this region offers our only practical possibility for detailed spectroscopy of nuclei beyond the neutron dripline. Theoretically, the very light neutron-rich nuclei are capable of being described using ab initio models. In addition, recent advanced shell model approaches, such as, the shell model in the continuum, and the no-core shell model are capable of providing predictions in this region. Therefore, experimental information on them will prove to be useful in forming a complete view of nuclear structure.

In this proposal we wish to explore the resonances in ^{12}Li via ^{11}Li(d,p) one-neutron transfer reaction. The major aim is to study the arrangement and occupancies of the orbitals under extreme neutron-rich conditions. Nucleon stripping transfer reactions in inverse kinematics are an important tool to investigate this through the study of single-particle states in neutron-rich nuclei.

There is a special interest in the $N = 9$ isotonic chain where the $1s_{1/2}$ orbital from the sd-shell is found to intrude into the p-shell. The inversion of the $1s_{1/2}$ and $0d_{5/2}$ orbital in ^{15}C was established through the abnormal spin of $1/2^+$ for this nucleus [1, 2]. The inversion is found to be further pronounced in ^{14}B [3]. This lowering of $1s_{1/2}$ orbital continues for ^{13}Be [4, 5]. The complexity of the spectrum observed from fragmentation of ^{14}Be [5] does not provide any conclusive evidence for the lowest resonance in ^{13}Be. It has been predicted that the ground state of ^{13}Be is $1/2^-$ [6]. This model predicts that the $1s_{1/2}$-orbital is lowered further in ^{13}Be crossing even the $0p_{1/2}$ orbital. The proposed spectroscopy of the most neutron-rich isotone, ^{12}Li, will allow us to determine how these orbitals are arranged.

The ^{12}Li nucleus, located just outside the $Z = 3$ neutron dripline is unbound to neutron emission. Extremely limited information is available on this nucleus. The first attempts to observe ^{12}Li was reported in Ref. [7]. The data showed that ^{12}Li is unbound but the experiment was not suitable for detecting a resonance. The unbound nature of ^{12}Li predicted in the Atomic Mass Evaluation suggests it to be unbound by 1.2(1.0) MeV above the ^{11}Li+n threshold [8]. According to an early shell model calculation, the ground-state spin and parity of ^{12}Li is suggested to be I^π=4^- [9] following the conventional arrangement of neutron orbitals. The lowest excited states, I^π=2^- and I^π=1^-, are expected very close to the ground state at 0.41 and 0.73 MeV, respectively [9].

However, following the observed trend for lowering of the $1s_{1/2}$ orbital in the $N = 9$ isotonic chain it appears to be highly probable that there might be a cross-over of the $1s_{1/2}$ and the $1p_{1/2}$ orbitals in ^{12}Li. Therefore the outermost neutron in ^{12}Li can be expected to occupy the $1p_{1/2}$ orbital giving rise to a low-lying p-wave resonance in this nucleus. There has been no observation or prediction of such a resonance so far. This proposal will therefore make a pioneering attempt to search for the lowest p-wave resonance in ^{12}Li. The proposed measurement will also have the capability of detecting a d-wave resonance for the first time.

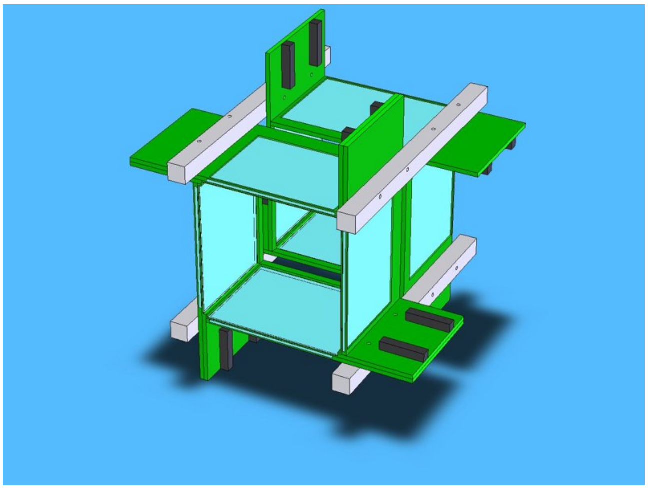
The recent effort [10] towards the observation of ^{12}Li resonance was through proton and neutron removal from ^{14}Be at relativistic energies. The observed ^{11}Li+n invariant mass spectrum has been interpreted to be only an s-wave virtual state with scattering length of $-13.7(1.6)$ fm. This finding contradicts shell-model predictions [9]. An s-wave state must correspond to I^π=2^- or I^π=1^- since the core nucleus ^{11}Li has I^π=$3/2^-$. No indication of a bound state was found, thereby confirming again the unbound nature of the nucleus. No other resonances, specially p-wave or d-wave , were observed.

The p-wave and d-wave resonances were not observed in Ref. [10] probably because, the ground state of ^{14}Be is dominated by $\nu 1s^2_{1/2}$ configuration [11]. The proton removal reaction might therefore populate only the s-wave state in ^{12}Li.

In contrast, since the ground state of ^{11}Li has a configuration mixing of s and p waves, the neutron transfer to ^{11}Li should have a high sensitivity to populate the p-wave resonance(s) in ^{12}Li. In addition, d-wave resonance(s) might be populated as well. The proposed experiment therefore might be expected to provide a first signature on the p-wave and d-wave resonances in the the two-body unbound system ^{11}Li+n. The observation of the resonances in ^{12}Li would be a significant achievement and provide further constraints on our understanding of structure in the $N = 9$ isotonic chain.

2 Experiment

We propose to study the structure of the unbound nucleus ^{12}Li using the one-neutron transfer reaction ^{11}Li(d,p)^{12}Li ($Q(E_r = 0)$ = -2.225 MeV) in inverse kinematics. The experiment will be performed at the TIGRESS beamline (SEBT3A) in the ISAC-II facility using the beam of ^{11}Li, at an energy of 5 A MeV. A thin $(CD_2)_n$ foil (200 μg/cm^2) will serve as the deuteron target. The scattered protons will be detected using the SHARC silicon box detector [12]. A schematic layout of the experimental setup and the reaction are shown in Figure 1.



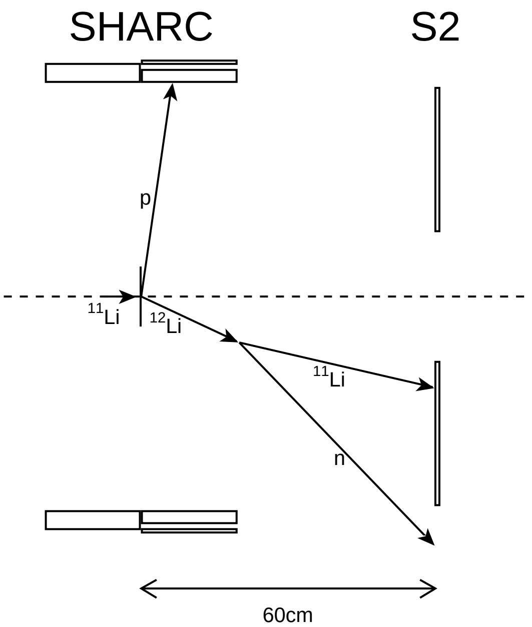


Figure 1: Schematic layout of SHARC (left) and the reaction (right).

This detector has two parts, upstream (E) and downstream (ΔE-E) with respect to the target, which is placed between them. The upstream part is a box with only one layer E detector which is 1.5 mm thick. It is a double-sided strip detector. The downstream has two layers ΔE-E. The ΔE detector is a double-sided strip detector 140 μm thick. The downstream E-detector is 1 mm thick un-segmented detector.

The energy resolution is around 1 % (fwhm) at 5 MeV. The polar angular resolution is on an average 1.6 °, the azimuthal resolution is 3.5 °. The SHARC covers the laboratory angle range of 44 ° − 82° for the forward angles, and 98 ° − 136 ° for the backward angles.

The kinematic loci for the protons emitted from ^{11}Li(d,p)^{12}Li reaction are shown in Figure 2 for the laboratory frame. The different curves, as labeled in the figure show the condition for different values of ^{12}Li resonance energies (E_r). The numbers represent the corresponding center of mass scattering angles. The large coverage of SHARC allows us to probe the resonances of ^{12}Li in a broad range of excitation energies. It is seen that for smaller resonance energies the forward center of mass angle scattering will emit the protons in the backward direction in the laboratory. While the larger center of mass angle scattering emits protons in the forward direction in the laboratory.

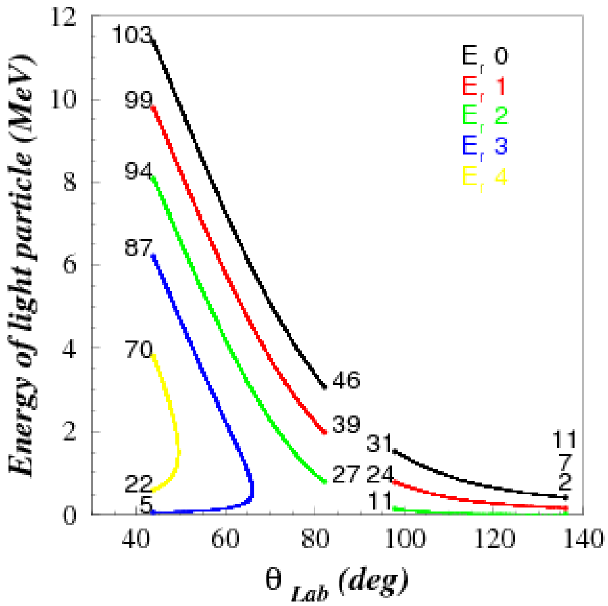


Figure 2: Kinematic loci for p produced in ^{11}Li(d,p)^{12}Li reaction for different value of ^{12}Li resonance energy E_r (in MeV). The angular acceptance of SHARC is taken into account in this figure. The labeled numbers show the equivalent centre of mass angle.

The SHARC detector will be used for detecting the light ejectiles (i.e. p, d, t) from elastic, inelastic and transfer reactions induced by ^{11}Li with the deuteron target. We do not require particle identification in the upstream detector because due to the kinematical constraints of the two-body reactions, only protons would be emitted in the backward angles. However the capability of eliminating the background from other reactions such as fusion evaporation and/or breakup will be required. This will be accomplished through detection of the protons and the heavy residue in coincidence. At forward angles one needs to separate the different reaction channels. This will be done using a ΔE-E identification of p,d,t.

An annular silicon array (S2) placed 60 cm downstream of the target is primarily intended to aid in reducing background, especially for the backward laboratory angles, by detecting the heavy residues. The laboratory angular coverage of the annular detector will be $1° - 3.3$ °. In addition, the S2 detector also covers the backward center of mass angles from elastic scattering with deuterons ($165° - 175°$). The forward center of mass angles for ^{11}Li+d elastic scattering will be covered by the downstream half of SHARC ($52° - 92°$). The elastic scattering data will be used to determine the optical potentials.

To study the feasibility of detecting the resonances in ^{12}Li we have performed detailed Monte Carlo simulations that include the resolution of the detectors and the target effects. We used a Breit-

Wigner shape to parametrize the resonance states (E_r is the resonance energy and Γ_0 is the width). The resonances in the two-body unbound system ^{11}Li+n have been assumed to have single-particle resonance widths. This assumption is a rather conservative estimate on possible resonance widths. The p-wave resonances at E_r=1 MeV and 2 MeV have been assumed to have widths Γ_0 of 0.65 MeV and 1 MeV respectively. The d-wave resonance at E_r=3 MeV is assumed to have a width Γ_0 of 1.65 MeV. These estimates present the limit of our detection capability for resonances placed 1 MeV apart.

In addition to the reaction of interest, the main background reaction channels involve elastic and inelastic scattering of ^{11}Li from deuterons and the two-neutron transfer reactions. The simulation considers the ^{11}Li* unbound excited state at an excitation energy of 1.3 MeV and with a width Γ_0 of 0.4 MeV. This state decay to ^{9}Li+n+n. Two states are taken into account in the case of the unbound nucleus ^{10}Li : a p-state at 0.51 MeV with a width Γ_0 of 0.54 MeV and a s-virtual state with scattering length -30 fm. These states decay to ^{9}Li+n. Fig 3 shows the Monte Carlo simulation results considering all these reaction channels. The curves shown in Figure 3(a) represent the regions where we will be able detect and identify the protons in the upstream and the downstream detectors of SHARC. The energy plotted in the figure is corrected for the energy loss in the target assuming that the reaction occurred in the middle of the target and contains the detector resolution as well. The threshold for detection has been considered to be 300 keV.

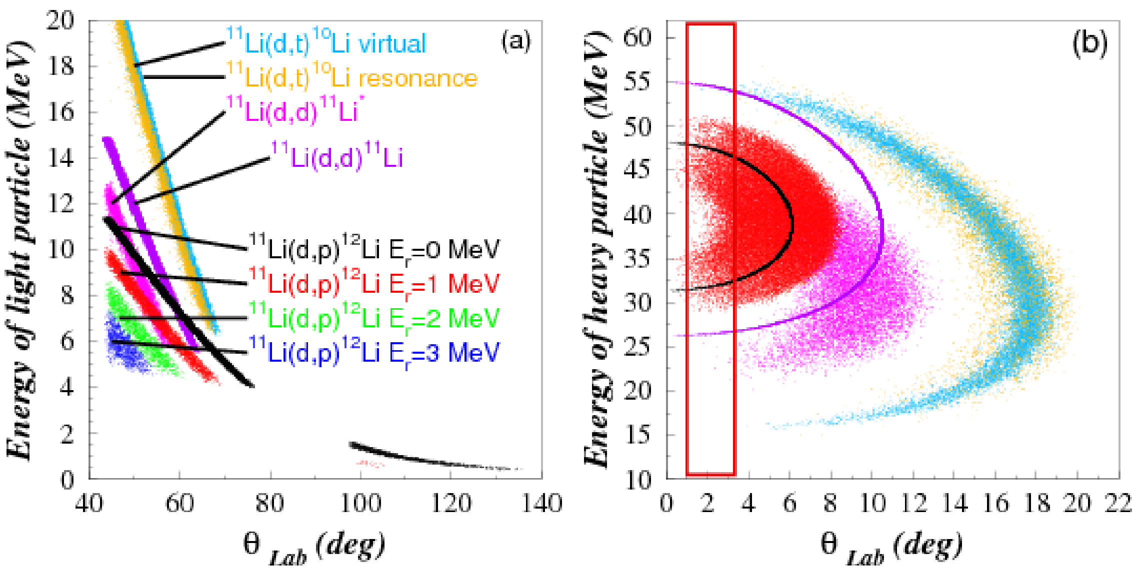


Figure 3: Monte Carlo simulations for ^{11}Li+d induced reactions. (a) for light ejectiles as expected to be detected using SHARC. (b) for the heavy residue (S2 covers the rectangular region). The different reactions are labeled in (a) and the same colour coding is used in (b). Effects of E_r = 2 and E_r = 3 are not included in the panel (b).

The regions $\sim 90^\circ \pm 8^\circ$ are outside the coverage of SHARC. Protons in the region less than 4 MeV in the downstream part will stop in the ΔE-detector. Therefore we consider that the identification of the reaction channel for this region will be difficult though not necessarily impossible. For the estimates discussed below we have omitted this region from our detection capability. The Figure 3b shows the loci of the heavy residues after decay of the resonances in $^{10-12}$Li. The region enclosed by a rectangle shows the coverage of the S2 detector.

Figure 4 shows the Monte-Carlo simulation for identifying the protons with ΔE-E correlation in the downstream half of the SHARC detector. E is the energy observed in the E- downstream-detector. ΔE is the energy loss corrected using the observed effective thickness of silicon traversed by the light particle in the downstream ΔE detector. The simulations include the expected detector resolution. It is seen that this allows us to separate between the protons, deuterons and tritons, thereby separating the effects of the ^{11}Li(d,d) and ^{11}Li(d,t) reaction channel in part of the downstream detector. The laboratory angles for ^{11}Li(d,p)^{12}Li covered by the ΔE-E identification is $\theta_{lab} = 44\ ° - 76°$.

The reaction identification in the upstream half of SHARC will be done through coincidence condition with the heavy residue detector. Therefore, the angular coverage of the S2 detector has been chosen accordingly.

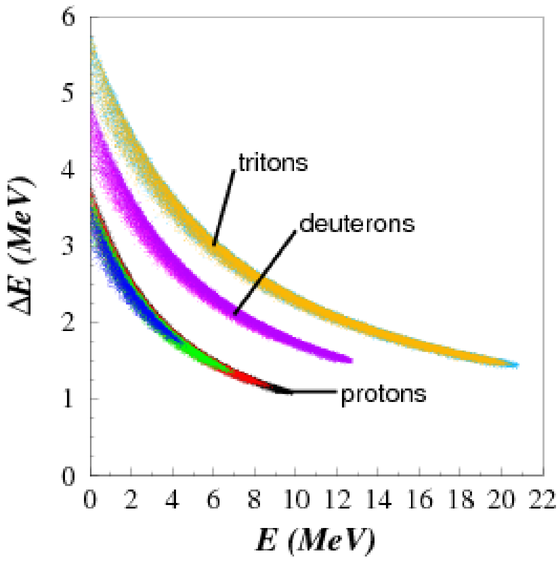


Figure 4: Simulation for identification of the light ejectiles using ΔE-E correlation. The different reactions are labeled in Figure 3(a) and the same colour coding is used in this Figure.

The center of mass angles for ^{11}Li(d,p)^{12}Li covered by the SHARC detector varies with the resonance energy (E_r) of ^{12}Li (Fig. 2). For example, the ranges for $E_r = 0$ MeV are from $\theta_{cm} = 11\ ° - 31°$ and $46\ ° - 103°$. The ΔE-E identification covers $\theta_{cm} = 54\ ° - 103°$. The S2 detector covers $\theta_{cm} = 11\ ° - 37°$. Using the Monte-Carlo simulation, the excitation energy resolution is estimated to be less than 200 keV (FWHM) for the forward laboratory angles and around 400 keV (FWHM) for the backward angles. This includes effect of energy-loss in the target as well as detector resolution.

In summary, the proposed experiment will allow us to undertake the first search for the existence of the p-wave and d-wave resonance(s) in ^{12}Li up to ∼3 MeV with sufficient resolution to detect the resonance peak. The shape of the angular distribution will help us to identify the nature of the resonance(s).

3 Count rate estimate and beamtime

The count rate is estimated based on calculated cross sections. The cross section for the ^{11}Li(d,p)^{12}Li reaction was estimated by finite range DWBA calculations with global optical model parameters for entrance and exit channels [13, 14]. The calculated angular distributions for the s-wave, p-wave and d-wave valence neutron in ^{12}Li are shown in Figure 5.

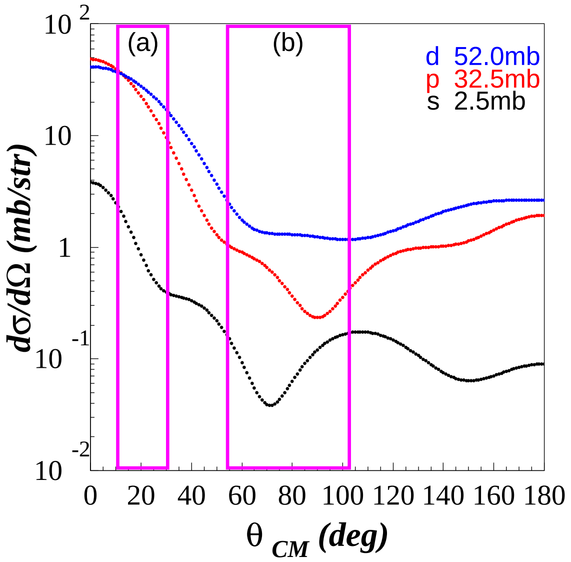


Figure 5: The curves represent DWBA calculations for ^{11}Li(d,p)^{12}Li (ex. $E_r = 0$). The rectangular regions show the coverage for $E_r = 0$ (see Figure 2 for different energies). (a) is identified by the upstream E SHARC detector in coincidence with the heavy residue in S2. (b) is identified by the downstream ΔE-E SHARC detector.

The count rates based on the DWBA calculations have been estimated for a ^{11}Li beam intensity $\sim 5\times10^3$/sec and a 200 μg/cm^2 $(CD_2)_n$ target. The rates assume resonances with spin J=2 and spectroscopic factors of unity. The rates are determined for the regions where we expect a clean identification of the reaction channel. All the estimations are for a period of 9 days.

Since nothing is known about the resonance energy of the p-wave and d-wave, the counting rate is estimated for different resonance energies E_r of ^{12}Li. The total count rates for the p-wave and d-wave resonances are summarized in Table 1. This shows that the peak position of the resonance(s) can be determined with sufficient statistical accuracy.

Although a very broad s-wave resonance might be hard to isolate, the estimation for the population of this orbital is a total of 69 counts with 40 counts for the region of θ_{cm}=11 ° − 37° assuming E_r=0 due to the low energy enhancement suggested in the invariant mass spectrum in [10].

Figure 6 shows the count rate estimation for different regions with a center of mass angle bin of 6 °. This shows the detection capability of the resonance nature from the angular distribution.

As the beam intensity is fairly low ($\sim 5\times10^3$/sec) there is no potential problem of high count rate (even from forward angle Rutherford scattering) in any of the silicon detector arrays.

Based on the above-mentioned estimates of count rate the total beamtime requested is 10 days. This includes one day for setup of the experiment with beam and 9 days of data collection time.

E_r	p	d
0	1086	1617
1	817	1227
2	118	215
3	63	114

Table 1: Total counts for the p-wave and d-wave populations in the regions of identification as shown in Figure 3(b).

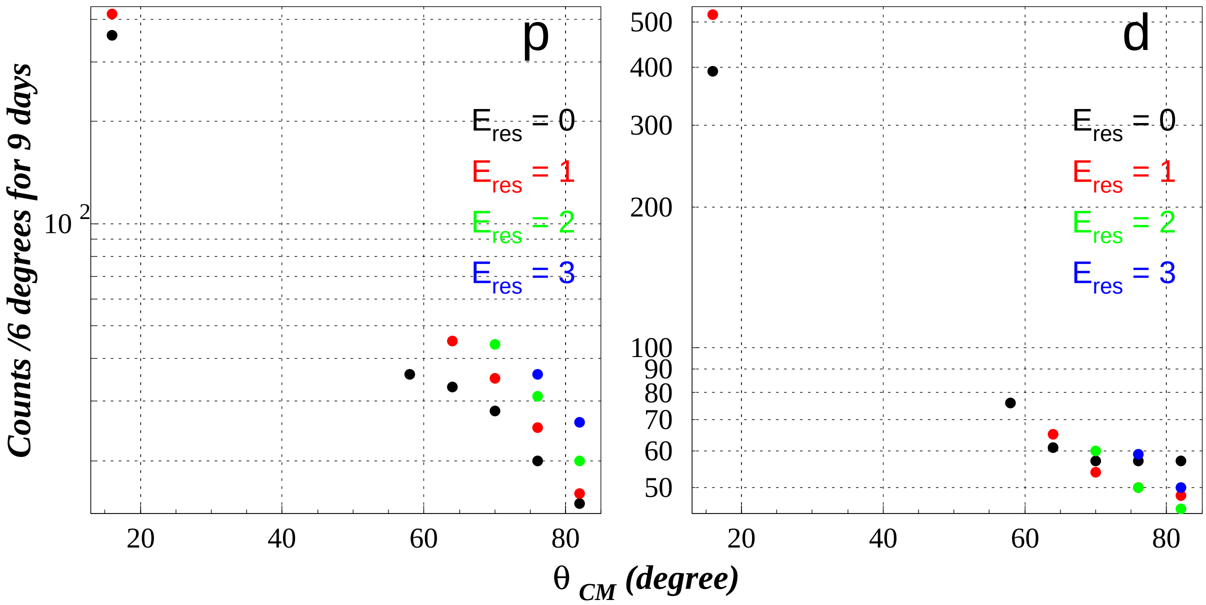


Figure 6: Count rate estimate for the p and d waves.

The beam conditions of ISAC II makes TRIUMF the ideally suited place for performing this pioneering search for p-wave and d-wave resonances in ^{12}Li that will be best done using the proposed ^{11}Li(d,p)^{12}Li reaction.

4 Readiness

The ^{11}Li beam has been developed and accelerated to ISAC II at 5 A MeV for previous experiments. The TIGRESS beamline that exists will be used for the experiment setup. The scattering chambers necessary for the experiment exist. The SHARC silicon detector developed by the University of York, UK is expected to be commissioned in spring of 2009 as will be the associated digital electronics for these detectors. All other necessary detectors and electronics are existing. The TIGRESS data acquisition system will be used. The offline data analysis will be done using personal computers. Since no new major development is required for this experiment, we therefore request for a Stage 2 approval for this experiment.

5 References

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List of Publications of H. Al Falou

"Etude expérimentale des noyaux légers non liés riches en neutrons".
H. Al Falou.
CNRIUT 2008, France.

"Etude de la Structure des Noyaux Non Liés ^{7,9}He et ^{10}Li".
H. Al Falou, N.L. Achouri, B. Bastin, B. Laurent, J.-L. Lecouey, F. M. Marqués, N. A. Orr.
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nucl-ex/0504009 (April 2005).

"Search for a low-lying excited state in ^{7}He".
H. Al Falou et al.
In preparation.

"Structure of the $N = 7$ isotones ^{9}He and ^{10}Li".
H. Al Falou et al.
In preparation.

List of Publications of R. Kanungo

1. Persistence of the N=50 shell closure in the neutron-rich isotope ^{80}Ge
H. Iwasaki , S. Michimasa, M. Niikura, M. Tamaki, N. Aoi, H. Sakurai, S. Shimoura, S. Takeuchi, S. Ota, M. Honma, T.K. Onishi, E. Takeshita, H.J. Ong, H. Baba, Z. Elekes, T. Fukuchi, Y. Ichikawa, M. Ishihara, N. Iwasa, S. Kanno, R. Kanungo, S. Kawai, T. Kubo, K. Kurita, T. Motobayashi, A. Saito, Y. Satou, H. Suzuki, M.K. Suzuki, Y. Togano, Y. Yanagisawa
Phys. Rev. C 78 (2008) 021304R

2. High precision branching ratio measurement for the superallowed β^+ emitter ^{62}Ga.
P.Finlay, G.C.Ball, J.R.Leslie, C.E.Svensson, I.S. Towner, R.A.E.Austin, D.Bandyopadhyay, A.Chaffey, R.S.Chakrawarthy, P.E.Garrett, G.F.Grinyer, G.Hackman, B.Hyland, R.Kanungo, K.G.Leach, C.M.Mattoon, A.C.Morton, C.J.Pearson, A.A.Phillips, J.J.Ressler, F.Sarazin, H.Savajols, M.A.Schumaker, J.Wong
Phys. Rev. C 78 (2008) 0225502

3. High precision half-life determination for the superallowed β^+ emitter ^{62}Ga.
G.F.Grinyer, P.Finlay, C.E.Svensson, G.C.Ball, J.R.Leslie, R.A.E.Austin, D.Bandyopadhyay, A.Chaffey, R.S.Chakrawarthy, P.E.Garrett, G.Hackman, B.Hyland, R.Kanungo, K.G.Leach, C.M.Mattoon, A.C.Morton, C.J.Pearson, A.A.Phillips, J.J.Ressler, F.Sarazin, H.Savajols, M.A.Schumaker, J.Wong
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Phys. Rev. Lett, 100 (2008) 192502

5. Spectroscopic factors for the ^{9}Li ground state and N=6 shell closure
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6. Lifetime of states in ^{19}Ne above the ^{15}O+α threshold
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Phys. Rev. C 77 (2008) 035803

7. High-precision half-life determination of the superallowed β^+ emitter ^{62}Ga
G.F.Grinyer, P.Finlay, C.Svensson, G.C.Ball, J.R.Leslie, R.A.Austin, D.Bandyopadhyay, A.Chaffey, R.S.Chakrawarthy, P.E.Garrett, G.Hackman, B.Hyland, R.Kanungo, K.G.Leach, C.M.Mattoon, A.C.Morton, C.J.Pearson, A.A.Phillips, J.J.Ressler, F.Sarazin, H.Savajols, M.A.Schumaker, J.Wong
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8. Shell closures in the N ad Z=40-60 region for neuron and proton-rich nuclei.
R. Kanungo,
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