TRIUMF — RESEARCH PROPOSAL	Experiment no.	Sheet 1 of 14

Title of proposed experiment:

Precise Determination of the ^{8}Li Valence Neutron ANC: Testing Mirror Symmetry and the ANC Method in Astrophysics

Name of group:

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Members of the group (name, institution, status, per cent of time devoted to experiment)

Name	Institution	Status	Time
L. Buchmann	TRIUMF	Research Scientist	5%
J. A. Caggiano	TRIUMF	Research Scientist	5%
B. Davids	TRIUMF	Research Scientist	40%
D. Howell	Simon Fraser University	M.Sc. Student	50%
R. Kanungo	TRIUMF	Research Associate	20%
J. Pearson	McMaster University	Research Associate	5%
C. Ruiz	TRIUMF and Simon Fraser University	Research Associate	5%
G. Ruprecht	TRIUMF	Research Associate	5%
A. C. Shotter	TRIUMF and University of Alberta	Professor	5%
M. Subramanian	University of British Columbia	M.Sc. Student	10%
N. Timofeyuk	University of Surrey	Research Associate	5%
P. Walden	TRIUMF	Research Scientist	5%

Start of preparations: 4/06

Date ready: 6/06

Completion date: 12/06

Beam time requested:

12-hr shifts	Beam line/channel	Polarized primary beam?
17	ISAC-TUDA	no

Recently, intense interest in asymptotic normalization coefficients (ANC's) has been generated by their connection to radiative capture reactions. In particular, the astrophysical S factor for the important ^{7}Be(p,γ)^{8}B reaction, $S_{17}(0)$ has been derived from measurements of (^{7}Be,^{8}B) transfer reactions. Although much effort has been expended to determine $S_{17}(0)$ both directly by means of radiative capture measurements and indirectly via Coulomb breakup and ANC measurements, the situation is still somewhat confused. The most recent radiative capture measurement is by far the most precise measurement and therefore dominates weighted averages. However, it is curious that the other low energy radiative capture measurements and the indirect measurements agree quite well and imply a lower value for $S_{17}(0)$.

ANC's are usually determined by analysing transfer reaction data in the framework of the distorted wave Born approximation (DWBA). The DWBA transition amplitude for the transfer reaction contains a remnant term which is not proportional to the ANC. All recent DWBA analyses of transfer reactions have implicitly assumed that the ANC can be inferred from the overall constant by which the theoretical DWBA calculation is scaled to match the experimental cross section. In these experiments, particularly those involving heavy ions, the effect of the remnant term on the inferred ANC's is not clear.

We propose to measure the ANC of the valence neutron in ^{8}Li by measuring the elastic transfer reaction ^{7}Li(^{8}Li,^{7}Li)^{8}Li at three beam energies, 8, 11, and 13 MeV. The interference between elastic scattering and neutron transfer produces characteristic oscillations in the differential cross section as a function of the scattering angle. By analysing the amplitudes of the interference minima and maxima, we can determine the ANC for ^{8}Li $\rightarrow ^{7}$Li $+n$. It is essential to ascertain the effect of the remnant term in order to precisely infer the ANC and test previous ANC analyses based on the DWBA. We will accomplish this by carrying out the measurement at three beam energies. In conjunction with previous measurements, this experiment will allow us to test mirror symmetry in the $A = 8$, $T = 1$ system and assess the validity of the ANC method for determining astrophysical S factors. Provided we find no problem with the method, we will use the ANC and charge symmetry to infer the astrophysical S factor for ^{7}Be(p,γ)^{8}B reaction, $S_{17}(0)$.

Experimental area

ISAC experimental hall, TUDA beamline

Primary beam and target (energy, energy spread, intensity, pulse characteristics, emittance)

Secondary channel ISAC HE

Secondary beam (particle type, momentum range, momentum bite, solid angle, spot size, emmittance, intensity, beam purity, target, special characteristics)

$^{8}\mathrm{Li}^{2+}$, 2×10^{7} s^{-1} at 13 MeV, 11 MeV, and 8 MeV

TRIUMF SUPPORT:

A modification of the TUDA chamber will be required. Design and fabrication support will be required.

NON-TRIUMF SUPPORT

Two annular Si detectors and preamps will have to be borrowed or purchased for this measurement. Some funds may be available from TRIUMF for this purpose.

SAFETY

No special requirements exist for this measurement.

1 Scientific Justification

Recently, the nuclear physics community has shown intense interest in asymptotic normalization coefficients (ANC's). Many measurements of ANC's in transfer reactions with light and heavy ions have been performed, including quite a number with radioactive beams. Most of these measurements are motivated by the goal of determining astrophysical reaction rates indirectly. For many non-resonant (p,γ) and even some (n,γ) reactions important in stars, the radiative capture occurs well outside the nuclear interior. The rates of these reactions are therefore determined by the probability of finding the valence nucleon at large distances. This probability is given by the ANC, which is the normalization of the tail of the overlap integral between the wave functions of the target and recoil nuclei. The ANC uniquely determines the astrophysical S factor of charged-particle induced radiative capture reactions at zero energy [1]. By exploiting this relation, the astrophysical S factor for the important ^{7}Be(p,γ)^{8}B reaction, S$_{17}$(0) has been derived from measurements of (^{7}Be,^{8}B) transfer reactions [2]. Although much effort has been expended in recent years to determine S$_{17}$(0) both directly by means of radiative capture measurements and indirectly via Coulomb breakup and ANC measurements, the situation is still somewhat confused. The most recent radiative capture measurement [3] is by far the most precise measurement and therefore dominates weighted averages. However, it is curious that the other low energy radiative capture measurements and the indirect measurements agree quite well and imply a lower value for S$_{17}$(0) [4].

ANC's are usually determined by analysing transfer reaction data in the framework of the distorted wave Born approximation (DWBA). For these analyses to be valid, two conditions must hold true. First, the reaction must be peripheral, so that poorly known contributions from the nuclear interior do not affect the ANC derived from the measured cross section. Second, the interaction mediating the reaction must be weak enough that multi-step corrections to the DWBA analysis are small. In addition to these two conditions, there is a third requirement that has received less attention. The DWBA transition amplitude for the transfer reaction contains a remnant term which is not proportional to the ANC. In the prior form, the DWBA transition amplitude takes the form

$$T_{fi} = \int\int \chi^{(-)}(\mathbf{k_b},\mathbf{r_b})^* \langle \Psi_{^8Li}\Psi_{^7Li}|(V_{n^7Li}+V_{^7Li^7Li}-U_{^7Li^8Li})|\Psi_{^7Li}\Psi_{^8Li}\rangle \chi^{(+)}(\mathbf{k_a},\mathbf{r_a})d\mathbf{r_a}d\mathbf{r_b}, \tag{1}$$

where $\chi^{(-)}(\mathbf{k_b},\mathbf{r_b})$ and $\chi^{(+)}(\mathbf{k_a},\mathbf{r_a})$ are the distorted waves in the exit and entrance channels. The difference between the core-core interaction and the ^{7}Li-^{8}Li optical potential, $V_{^7Li^7Li} - U_{^7Li^8Li}$, is known as the remnant term. If it is not negligibly small, this term destroys the proportionality between the DWBA cross section and the ANC. All recent DWBA analyses of transfer reactions have implicitly assumed that the remnant term can be factored in this way and that the ANC can be inferred from the overall constant by which the theoretical DWBA calculation is scaled to match the experimental cross section. In such experiments, particularly those involving heavy ions, the effect of the remnant term on the inferred ANC's is not clear.

Recent theoretical work shows that the charge symmetry of the strong interaction implies a relation between the ANC's of the one-nucleon overlap integrals in light, mirror nuclei [5]. This relation has been used to deduce the ANC for ^{8}B→^{7}Be+p from the ^{8}Li →^{7}Li +n ANC [6]. The results of this ANC determination from a neutron transfer reaction were in good agreement with the results of prior proton transfer reactions in the isospin mirror system [2]. Both of these ANC determinations imply values of $S_{17}(0)$ that are considerably smaller than the recent, high precision direct measurement of the low energy radiative capture cross section [3]. It is important to ascertain if the low values of $S_{17}(0)$ implied by the ANC determination can be confirmed by an independent ANC measurement in the isospin mirror system.

Charge symmetry also implies a relation between the widths of narrow proton resonances and the ANC's of mirror neutron bound states [5]. In the case of the 1^+ first excited state in the A = 8, T = 1 system this prediction can be tested. In units where $\hbar = 1$, calculations give $1.70 \pm 0.03 \times 10^{-3}$ for $\Gamma_p/|C_n|^2$. Using the very precise value of Γ_p determined in Ref. [3] and $|C_n|^2$ from Ref. [6], the experimental value is $2.2 \pm 0.2 \times 10^{-3}$, and there is a 2.5σ discrepancy between theory and experiment. As the neutron ANC completely dominates the error budget for the experimental value, an independent, precise measurement of the ANC for the 1^+ state of ^{8}Li would be highly desirable.

We propose to measure the ANC of the valence neutron in ^{8}Li by measuring the elastic transfer reaction ^{7}Li(^{8}Li,^{7}Li)^{8}Li at three beam energies, 8, 11, and 13 MeV. By measuring a transfer reaction with identical initial and final states, we take advantage of several important facts. First, the vertex of interest appears twice in the reaction, so we can improve the statistical precision of the ANC determination relative to a reaction that involves two distinct vertices. Second, we need only consider a single target-projectile interaction, limiting the uncertainties due to optical potentials. Finally, by measuring elastic scattering simultaneously, we can determine the optical model parameters that are the single largest reported source of uncertainty in ANC determinations from transfer reactions. At these energies near the Coulomb barrier, we expect the reaction to be peripheral [7], and that multi-step effects are small [8]. In any event, we will measure inelastic excitations of both the target and projectile and use these to evaluate the importance of multi-step processes using coupled channels calculations. By measuring the inelastic excitations of ^{8}Li to its first 1^+ excited state we will also measure its ANC and test charge symmetry for this state.

The interference between elastic scattering and neutron transfer produces characteristic oscillations in the differential cross section as a function of the scattering angle. By analysing the amplitudes of the interference minima and maxima, we can determine the ANC for $^8\text{Li} \rightarrow {}^7\text{Li} + n$. It is essential to ascertain the effect of the remnant term in order to precisely infer the ANC and test previous ANC analyses based on the DWBA. We will accomplish this by carrying out the measurement at three beam energies. Since the first part of the remnant term, $V_{^7Li^7Li}$, is independent of energy, measurements at several energies will allow us to determine the optical potential, the remnant term, and the ANC unambiguously and with high precision. Moreover, measuring at three energies will give us redundant information in case one of the energies coincides with a resonance in the compound nucleus, ^{15}C. In conjunction with previous measurements, this experiment will allow us to test mirror symmetry in the A = 8, T = 1 system and assess the validity of the ANC method for determining astrophysical S factors. Provided we find no problem with the method, we will use the ANC and charge symmetry to infer the astrophysical S factor for ^{7}Be(p,γ)^{8}B reaction, $S_{17}(0)$.

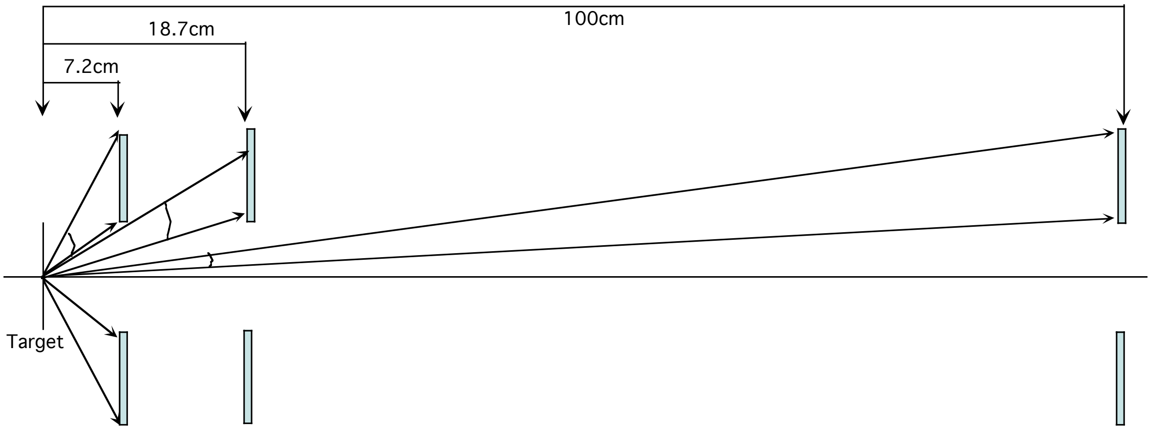

Fig. 1 Schematic experimental setup, showing the target and three LEDA detectors.

2 Description of the Experiment

We intend to use three LEDA detectors [9] to detect ^{7}Li and ^{8}Li nuclei produced in transfer and elastic scattering reactions induced by ^{8}Li beams at 8, 11, and 13 MeV. The three annular, segmented Si detectors will be positioned 7.2, 18.7, and 100 cm downstream of the target. The near detector will cover laboratory angles from 35 - 61°. The middle detector will cover lab angles from 15-35°, although the angles from 29 - 35° will be obscured by the near detector. Small laboratory angles from 2.9 - 7.4° will be covered by the far detector. The geometry is depicted in Fig. 1.

The optimal beam spot size is a function of the transverse emittance of the beam and the detector distances. As we will employ three detectors at different distances, we have chosen a beam spot size optimal for the middle detector. This optimum is ±1 mm (2 mm diameter). When combined with the transverse emittance of ISAC, this spot size implies an angular divergence of the beam of ± 4.3 mrad for the 8 MeV beam, which is the worst case, as the emittance is inversely proportional to the beam velocity. These figures represent 2σ envelopes, implying that 95% of the beam will be within 1 mm of the target centre, and will make an angle of less than 4.3 mrad with respect to the nominal beam axis. The target will be 25 μg cm^{-2} of ^{7}LiF on a thin, 15 μg cm^{-2} C backing. Multiple scattering will also naturally be worst for the 8 MeV beam. The 2σ envelope in this case is 4.0 mrad, which is smaller than the intrinsic angular spread of the beam. Summing the two contributions in quadrature gives a 2σ angular divergence of 5.9 mrad. The third contribution to the angular resolution comes from the finite size of the beam spot and of each annular strip in the silicon detectors. This contribution is dominant for the two nearest LEDA detectors, but is smaller than the other two for the far detector. Evaluated at the innermost annulus where it is the worst, its 2σ contribution amounts to 31 mrad for the near detector 17 mrad for the middle LEDA, and 3.5 mrad for the far detector. This implies that the total 2σ angular resolution will be no worse than 32 mrad for the near detector, 18 mrad for the middle, and 6.9 mrad for the far detector.

We have carried out Monte Carlo simulations of the experiment taking into account the finite energy and timing resolution of the LEDA detectors, the beam emittance, and the effects of multiple scattering and energy loss straggling in the target. Conservative

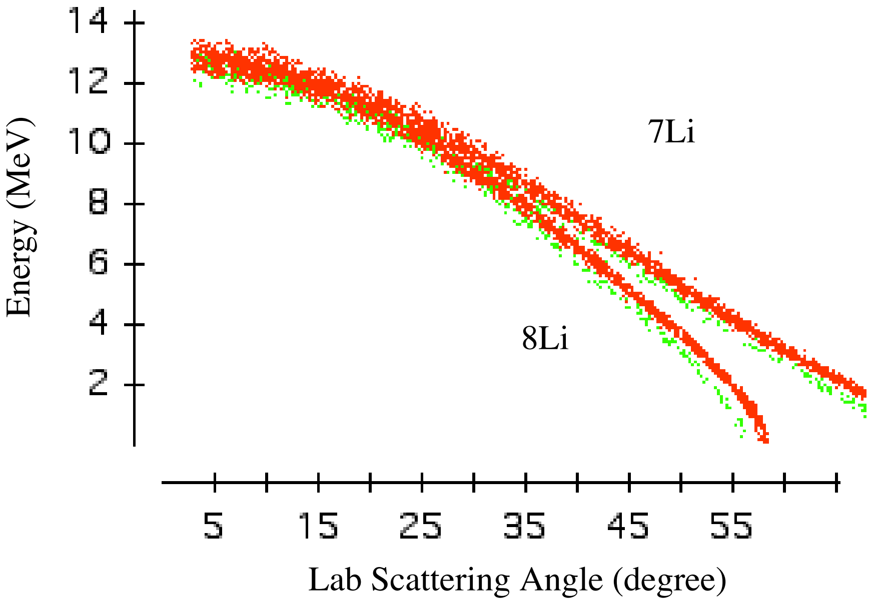

Fig. 2 Simulated energy versus laboratory scattering angle spectrum for elastic transfer (red) and inelastic excitation of the 478 keV state in ^{7}Li (green).

assumptions were made for these parameters: LEDA energy resolution = 2% FWHM, timing resolution and beam pulse width = 500 ps (1σ), beam energy spread = 0.5% (1σ), beam angular divergence = 2.5 mrad (1σ), and beam spot size = 1 mm (1σ). Fig. 2 illustrates the separation between the two nuclei in their ground states and when ^{7}Li is excited to its first excited state at 478 keV. The simulations reveal that complete separation of ^{7}Li and ^{8}Li and their excited states on the basis of total energy measurements will be possible only at laboratory angles greater or equal to 45°. However, this does not mean we cannot cover smaller laboratory angles. By positioning the far detector at 100 cm, we can separate the ^{7}Li and ^{8}Li on the basis of total energy and time of flight. This is illustrated in Fig. 3. We cannot use time of flight for separation in the middle and near detectors because the flight path is too short. Instead, for angles smaller than 45° in those detectors, we will utilize the angle and energy correlation derived from coincident detection of both nuclei to achieve the necessary particle identification. ^{7}Li nuclei detected in the middle LEDA will be accompanied by ^{8}Li detection in the near detector. Detection of ^{7}Li in the near detector at lab angles from 35 - 52° will be done in coincidence with ^{8}Li in the same detector. Beam normalization will be obtained via direct charge collection in a Faraday cup downstream of the detectors, as well as through detection of elastic ^{8}Li at small lab angles in the far LEDA detector. At these angles, the cross section will not differ substantially from the Rutherford value. Beam alignment will be continuously monitored by checking for asymmetries in the elastic scattering, as all azimuthal angles will be covered.

Various background reactions can present two difficulties, particle identification and count rates. As we are measuring elastic scattering, the only reactions that will have competitive rates are elastic scattering on target nuclei heavier than Li. In particular, the F component of the target will elastically scatter more ^{8}Li than the Li component.

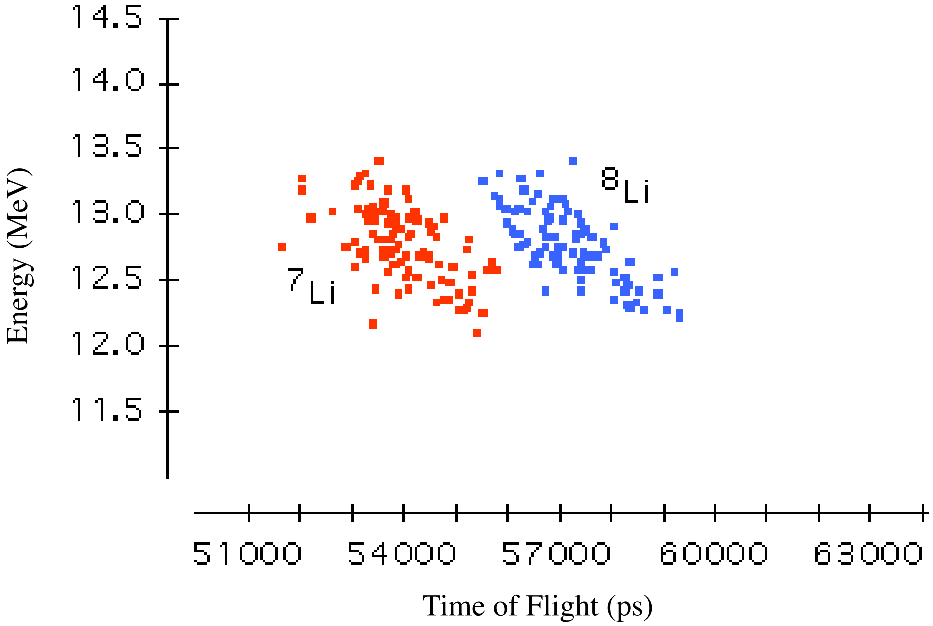

Fig. 3 Simulated total energy versus time of flight spectrum for the far LEDA detector.

However, the kinematics of this reaction are so different that the ^{8}Li will be distinguishable from ^{8}Li and ^{7}Li produced in the reaction of interest on the basis of total energy in singles at all angles. The situation for elastic scattering off the C component of the target is not as favourable, at least at large lab angles. Here we will need to use the energy-angle correlation obtained from coincidence measurements to distinguish the two varieties of elastic scattering. The same goes for inelastic excitations of the first excited state in ^{7}Li, while inelastically excited ^{8}Li will be separable at all angles in singles alone. Elastic scattering into the far detector will limit the beam intensity to 2×10^7 s^{-1} in order to maintain an overall count rate less than 3 kHz, which can be managed with dead times not exceeding a few percent.

The relation between laboratory and centre-of-mass angles is particularly simple for the case of ^{7}Li in this reaction: the cm angle is twice the laboratory angle. The range of ^{7}Li angles in the cm system covered in the experiment is shown in Fig. 4. Transparent boxes indicate the cm angular range in which only ^{7}Li or ^{8}Li can be detected (and distinguished from the other), while the coloured boxes indicate the range of ^{7}Li cm angles in which both the ^{7}Li and ^{8}Li will be detected. Also shown in the figure are DWBA calculations performed using two different optical model potentials. The potentials are global fits for ^{7}Li + ^{7}Li and ^{6}Li + ^{6}Li scattering from 5-40 MeV and are taken from Ref. [10]. While not precisely appropriate for the ^{8}Li + ^{7}Li scattering considered here, they are close enough to give an indication of what we can expect. We have used the first optical potential to perform 3 calculations in which the spectroscopic factor (ANC) of the valence neutron in ^{8}Li has been set equal to 0.8, 1.0, and 1.2 times a theoretical value from microscopic three-cluster model calculations [11]. This allows us to see the difference in the predicted cross section produced by a variation of the ANC which we intend to determine. As Fig. 4 makes plain, a sufficient range of angles will be covered to determine both the optical

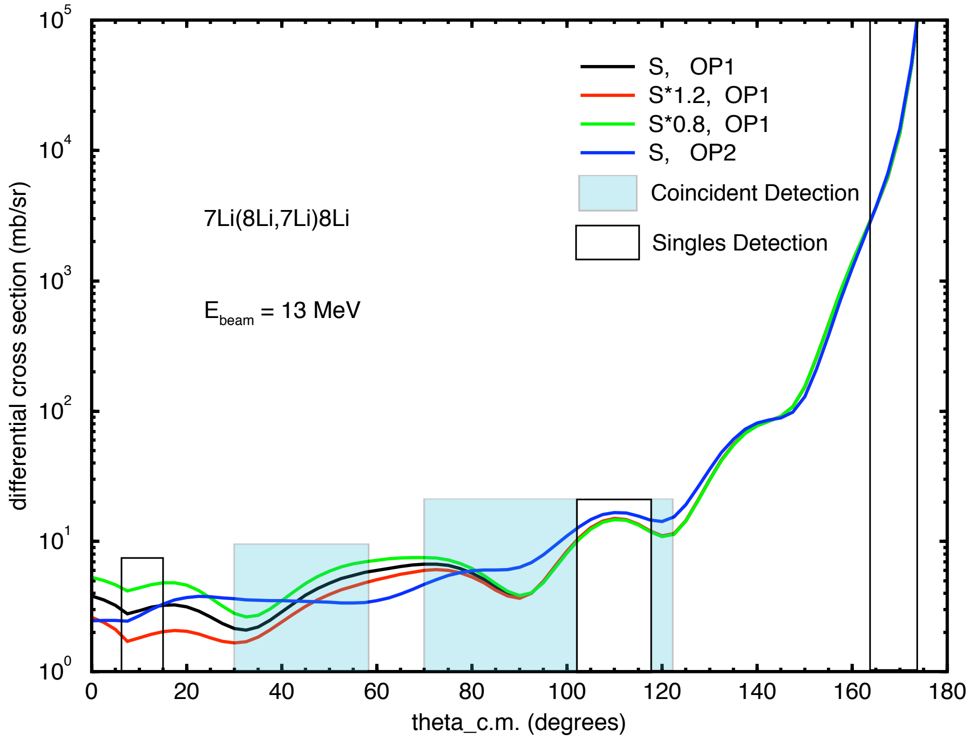

Fig. 4 Calculated differential cross section for ^{7}Li(^{8}Li,^{7}Li)^{8}Li as a function of the ^{7}Li centre of mass angle. Results with two different optical potentials (OP) are shown. Three different valence neutron spectroscopic factors (S) were used to generate the three curves with the first optical potential. The angular ranges covered by the three LEDA detectors are shown. Transparent boxes indicate regions where only ^{7}Li or ^{8}Li can be detected, while the coloured boxes show the angular range in which the ^{7}Li will be detected in coincidence with the ^{8}Li recoil.

model potential parameters and the ANC with good precision.

3 Experimental Equipment

The experiment will require 3 LEDA detectors and the associated electronics. In addition, the TUDA vacuum chamber and its Faraday cup will be used.

4 Readiness

Design and fabrication work on the TUDA vacuum chamber will be required. This is required in order to accommodate the 100 cm distance from the target to the far detector. The simplest way to approach the problem would be to move the target ladder from the centre of the chamber to the front. We anticipate that this will require approximately 1 month after the initial design consultation. Funds will be requested from TRIUMF and NSERC to purchase LEDA detectors and preamps.

5 Beam Time required

The beam time required will be dictated by the statistics required to make a measurement of the cross section at the smallest angles with 10% statistical precision. This will allow a determination of the ANC to the same or better precision. The transfer cross section is smallest there, so better precision will be obtained at larger angles. According to our DWBA estimate, the cm cross section in this region is ≈ 2 mb sr^{-1} for a beam energy of 13 MeV. As the far detector will subtend 0.18 sr in the cm system, this implies a cross section of 0.36 mb. The rate is given by $R = I\sigma n_t = 2{\times}10^7 s^{-1} {\times} 0.36{\times}10^{-27} cm^2 {\times} 5.8{\times}10^{17} cm^{-2} =$ 0.004 s^{-1}. At this rate, we will require a bit more than 4.5 shifts to accumulate the 800 counts needed for a 10% relative measurement in each of 8 angular bins covered by the far detector. As the cross section is not anticipated to be smaller at the lower beam energies, we request 5 shifts of beam on target at each energy plus 2 shifts for set up and calibrations, for a total of 17 shifts.

6 Data Analysis

Data analysis will be carried out using existing computer facilities at TRIUMF. Calculations will be performed here and at the University of Surrey.

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PUBLICATION LIST OF SPOKESPERSON(S)

Include publications in refereed journals over at least the previous 5 years.

Please see attachment.

Selected Publications of Barry Davids

"^{16}O Coulomb dissociation: towards a new means to determine the ^{12}C + α fusion rate in stars"; F. Fleurot, A.M. van den Berg, **B. Davids**, M.N. Harakeh, V.L. Kravchuk, H.W. Wilschut, J. Guillot, H. Laurent, A. Willis, M. Assunção, J. Kiener, A. Lefebvre, N. de Séréville, V. Tatischeff; Physics Letters B **615**, 167 (2005).

"EMMA: a recoil mass spectrometer for ISAC-II at TRIUMF"; **Barry Davids** and Cary N. Davids; Nuclear Instruments and Methods in Physics Research A **544**. 565 (2005).

"Nuclear matrix elements for the ^{48}Ca two-neutrino double-β decay from high-resolution charge-exchange reactions"; S. Rakers, C. Bäumer, A. M. van den Berg, **B. Davids**, D. Frekers, D. De Frenne, Y. Fujita, E.-W. Grewe, P. Haefner, M. N. Harakeh, M. Hunyadi, E. Jacobs, H. Johansson, B. C. Junk, A. Korff, A. Negret, L. Popescu, H. Simon, and H. J. Wörtche; Physical Review C **70**, 054302 (2004).

"Deuteron elastic and inelastic scattering at intermediate energies from nuclei in the mass range $6 \leq A \leq 116$"; A. Korff, P. Haefner, C. Bäumer, A. M. van den Berg, N. Blasi, **B. Davids**, D. De Frenne, R. de Leo, D. Frekers, E.-W. Grewe, M. N. Harakeh, F. Hofmann, M. Hunyadi, E. Jacobs, B. C. Junk, A. Negret, P. von Neumann-Cosel, L. Popescu, S. Rakers, A. Richter, and H. J. Wörtche; Physical Review C **70**, 067601 (2004).

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