TRIUMF — RESEARCH PROPOSAL	Experiment no. 923	Sheet 1 of 17

Title of proposed experiment:

Measurement of ^{25}Al + p Resonances through Elastic Scattering

Name of group: TUDA

Spokesperson for group: A.A. Chen / L. Buchmann

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

Name	Institution	Status	Time
A.A. Chen	Simon Fraser University	Research Associate	100%
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J.M. D'Auria	Simon Fraser University	Professor	80%
T. Davinson	University of Edinburgh	Research Scientist	30%
B. Fulton	University of York	Professor	20%
D. Groombridge	University of York	Research Fellow	20%
A. Murphy	University of Edinburgh	Professor	20%
P.D. Parker	Yale University	Professor	30%
J. Pearson	University of York	Graduate Student	20%
I. Roberts	University of Edinburgh	Graduate Student	30%
A. Robinson	University of Edinburgh	Graduate Student	30%
C. Ruiz	University of Edinburgh	Graduate Student	30%
F. Sarazin	TRIUMF	Research Fellow	30%
A. Shotter	TRIUMF	Professor	10%
P. Walden	TRIUMF	Senior Research Scientist	20%
P. Woods	University of Edinburgh	Professor	20%

Start of preparations: 2001

Date ready: January 2002

Completion date: 2003

Beam time requested:

12-hr shifts	Beam line/channel	Polarized primary beam?
32 (^{25}Al)	2A / ISAC	No
6 (stable)	na / ISAC	na

Within the context of explosive nucleosynthesis, the ^{25}Al(p,γ)^{26}Si reaction bypasses the production of the important radionuclide ^{26}Al. The present rate of the ^{25}Al(p,γ)^{26}Si reaction suffers from significant uncertainties due to the lack of relevant structure information in the compound nucleus ^{26}Si. We propose to measure the ^{25}Al + p elastic scattering reaction in inverse kinematics with the intent of exploring the level structure of ^{26}Si in more detail, and as a preliminary study to the potential measurement of the ^{25}Al(p,γ)^{26}Si at the DRAGON facility. Using the TUDA facility and ^{25}Al beams from ISAC, the ^{25}Al(p,p)^{25}Al reaction will be measured in inverse kinematics by taking energy scans in the CM energy range of about 400 - 1450 keV, with solid targets of polyethylene. This energy range covers the ^{25}Al + p resonances in ^{26}Si considered to be important in stellar explosions.

Experimental area

TUDA facility in the ISAC experimental hall.

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

500 MeV proton beam from the TRIUMF cyclotron.

Secondary channel ISAC - HE

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

The secondary beam required is ^{25}Al with an intensity of 10^7 particles per second and with laboratory energies from 400 to 1500 keV/u. In addition, ^{25}Mg stable beams of comparable intensity and energies will be used to calibrate the TUDA facility.

TRIUMF SUPPORT:

Continued infrastructure support from TRIUMF for TUDA at ISAC, including assigned personnel.

NON-TRIUMF SUPPORT

The TUDA scattering facility, electronics, targets and detector systems will be provided by the University of Edinburgh group.

Standard TUDA operation with short-lived radioactive isotopes (^{25}Al, $T_{1/2}$=7.2 sec). Low voltage detectors and electronics.

1 Scientific Motivation

1.1 Introduction: The ^{25}Al(p,γ)^{26}Si Reaction

Recent studies of ^{26}Al gamma-emission in the galaxy [1] and of ^{26}Al/^{27}Al isotopic anomalies in meteorites [2] have advanced our understanding of galactic and stellar evolution, as well as the origin of the solar system. While the observations of galactic gamma-ray emission point to massive stars as possible major contributors to the ^{26}Al distribution [3], at present the origin of the ^{26}Al remains an open question, requiring further understanding on how ^{26}Al is produced in various stellar settings. Within the present framework of nucleosynthesis in high temperature stellar environments such as novae, the production of ^{26}Al can be bypassed if the ^{25}Al(p,γ)^{26}Si reaction becomes faster than the β^+ decay of ^{25}Al [4]. The strengths and locations ^{25}Al+p resonances in ^{26}Si have been estimated using shell-model calculations and nuclear structure information from analog assignments [5], but the stellar reaction rate remains uncertain by about a factor of 1000, and no direct measurements have yet been attempted.

The present author, along with the DRAGON collaboration, has submitted a proposal to the TRIUMF EEC for a direct measurement of the ^{25}Al(p,γ)^{26}Si reaction. The reader is referred to that proposal for a more detailed description of the nuclear astrophysics motivation than that given above. For the present proposal, we focus on the fact that the level structure of ^{26}Si is presently uncertain and warrants further study, as described in the ^{25}Al(p,γ)^{26}Si proposal. The direct measurement of the ^{25}Al(p,γ)^{26}Si reaction will be greatly aided by a more thorough knowledge of the structure of ^{26}Si at energies up to 1 MeV in the CM frame, especially with regard to s-wave resonances. Furthermore, measurements above E_{cm} = 1 MeV may provide constraints on mirror assignments for the levels below. The aim of the present experiment is to provide further information on the structure of ^{26}Si over this range of energies.

1.2 Spectroscopy of ^{26}Si

The ^{25}Al(p,γ)^{26}Si reaction rate has been estimated by Iliadis et al. [5]. The Q-value is 5518 keV. While resonances within 1 MeV of the proton threshold of ^{26}Si can contribute for temperatures less than 1.5 GK, they find that the rate at lower temperatures is dominated by an s-wave ($J^\pi = 3^+$) resonance whose mirror is a known state in ^{26}Mg at E_x = 6.125 MeV. Iliadis et al. use Coulomb displacement energies to assign an energy of E_x = 5.970 MeV (E_r = 452 keV), with an associated uncertainty of ±100 keV. The widths and resonances strength have not been measured, and were also calculated using information available on the respective mirror state. Unfortunately, no 3^+ resonance in ^{26}Si has been observed in this energy region to date. Overall, using the presently available nuclear structure information, the ^{25}Al(p,γ)^{26}Si rate at nova temperatures is uncertain by a factor of 100 - 1000. This uncertainty would be reduced with better spectroscopy of ^{26}Si although even then a direct measurement would still be necessary.

The structure of ^{26}Si has been determined from measurements of the ^{28}Si(p,t)^{26}Si [6] and ^{24}Mg(^{3}He,n)^{26}Si [7] [8] reactions, and more recently through a measurement of the ^{29}Si(^{3}He,^{6}He)^{26}Si reaction [9]. Note that the (^{3}He,^{6}He) measurement should be sensitive to

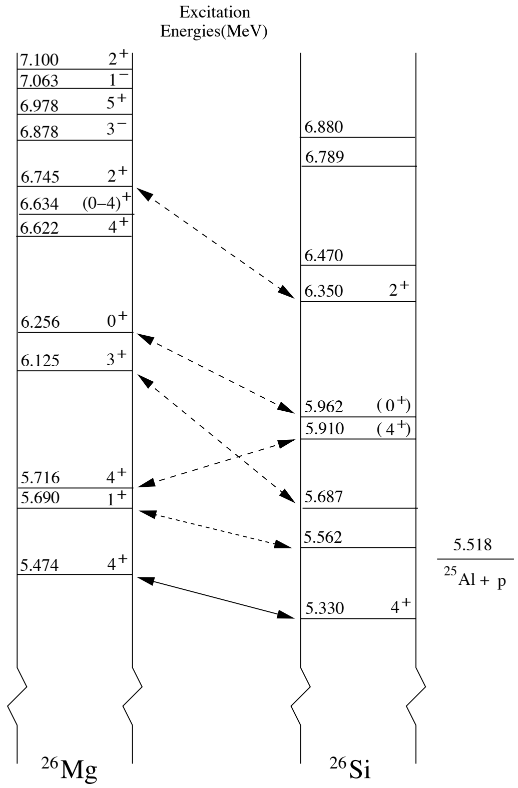

Fig. 1 Level structure of ^{26}Si close to the ^{25}Al+p threshold and the analog state region in ^{26}Mg. The solid arrow shows a firm mirror assignment, while dashed arrows show tentative assignments used in the present proposal.

unnatural parity states, while the two-nucleon transfer reactions are expected to populate them only weakly at best. Lastly, the ORNL/University of North Carolina group has recently remeasured the ^{28}Si(p,t)^{26}Si reaction [10], which should provide confirmation of the (p,t) results from Ref. [6] with better energy resolution (uncertainties $< \pm 10$ keV), and determination of spins and parities for many of the observed states. The data analysis is still in progress.

The energy levels of ^{26}Si and ^{26}Mg in the region of interest are shown in Figure 1, along with tentative analog assignments. Among the shortcomings in our present knowledge are the fact that many of the energies are not known to sufficient precision, ranging from ±15 keV for the best cases and ±30 for the worst. Furthermore, as already mentioned, the location of the key 3^+ resonance is presently unknown. Another deficiency is that the mirror assignments from which information on partial widths are extracted are only tentative. One should also note that another s-wave resonance corresponding to a T=1 level in ^{26}Al at $E_x = 6.85$ MeV has yet to be observed in either ^{26}Si or ^{26}Mg.

The discussion above points to the need for further study of the structure of ^{26}Si. Our expectation is that the situation will be further elucidated with results from ongoing and planned experiments. For example, the ORNL/UNC (p,t) experiment data analysis is almost complete. Also, a measurement of the p(^{27}Si,d)^{26}Si is planned at the Michigan State University coupled-cyclotron facility next year [11], which should provide further information.

Table 1 Level parameters adopted for low-lying ^{25}Al + p resonances.

E_x (keV)	E_r (keV)	$E_{^{25}Al}$(MeV)	J$^{\pi\ a)}$	ℓ	Γ (keV) $^{b)}$
5687(15)	169(15)	4.358	(3$^+$)	s, d, g	$8.1\times10^{-5\ c)}$
5910(30)	392(30)	10.110	(4$^+$)	d, g	4.4×10^{-5}
5962(15)	444(15)	11.451	(0$^+$)	d	2.2×10^{-5}
6350(25)	832(25)	21.457	2$^+$	s, d, g	7.9×10^{-2}

$^{a)}$ Assignments in parentheses are tentative.
$^{b)}$ Derived from estimates in Ref. [5].
$^{c)}$ Width scaled from estimate for 3$^+$ state at E$_x$= 5970(100) keV in Ref. [5].

Another useful approach is the measurement of elastic scattering. This method has already been used successfully to measure ^{21}Na+p resonances in ^{22}Mg [12], providing level structure information and guidance for the subsequent direct measurements of the radiative capture reaction with the DRAGON facility. At ISAC, with ^{25}Al beams, we propose to probe the resonance structure of ^{26}Si using elastic scattering, which generally can provide information on energies, total widths and spins. However, since the ^{25}Al+p system has two entrance channel spins (s = 2 or 3), the final spin of the state needs to be derived through other means, such as nuclear structure arguments or analog assignments. The spin may also be extracted from the angular distribution of the scattered protons. If present estimates are correct, however, the widths of the lowest resonances (listed in Table 1) are likely to be too narrow for measurement with elastic scattering. Nevertheless, the widths of the higher energy resonances are likely to be sufficiently broad ($\Gamma > 1$ keV). Note from Figure 1 that the spins of these higher resonances are presently unknown.

One should mention in passing that while elastic scattering will be sensitive primarily to resonances at higher energies, these measurements can be complemented with a measurement of the ^{24}Al(^{3}He,p)^{26}Si transfer reaction in inverse kinematics. Near-threshold states in ^{26}Si are determined by detecting the proton groups. This reaction has the advantage of a large Q-value of 14.732 MeV, which allows for many excited states in ^{26}Si to be populated. Also, only relatively low beam intensities ($\sim10^5$ particles/second) are required. We plan to propose a measurement of this reaction with the TUDA facility and a ^{3}He gas cell once the technique has been developed in the context of another proposal by the TUDA collaboration to the TRIUMF EEC to measure the ^{17}Ne(^{3}He,p)^{19}Na [13].

2 Experimental Description

2.1 Experimental Technique

The experiment will be carried out in inverse kinematics with beams of ^{25}Al ($T_{1/2}$ = 7.2 seconds) from the TRIUMF-ISAC facility and polyethylene (CH_2) targets in the TUDA scattering chamber. TUDA has been specifically designed for studying charged particle reactions in inverse kinematics using the well-known LEDA silicon detector arrays, developed by the University of Edinburgh group, and allows for flexible set-up of detector configuration to suit a given experiment. To date, the TUDA facility has already been commissioned, and first elastic scattering experiments have been successfully performed

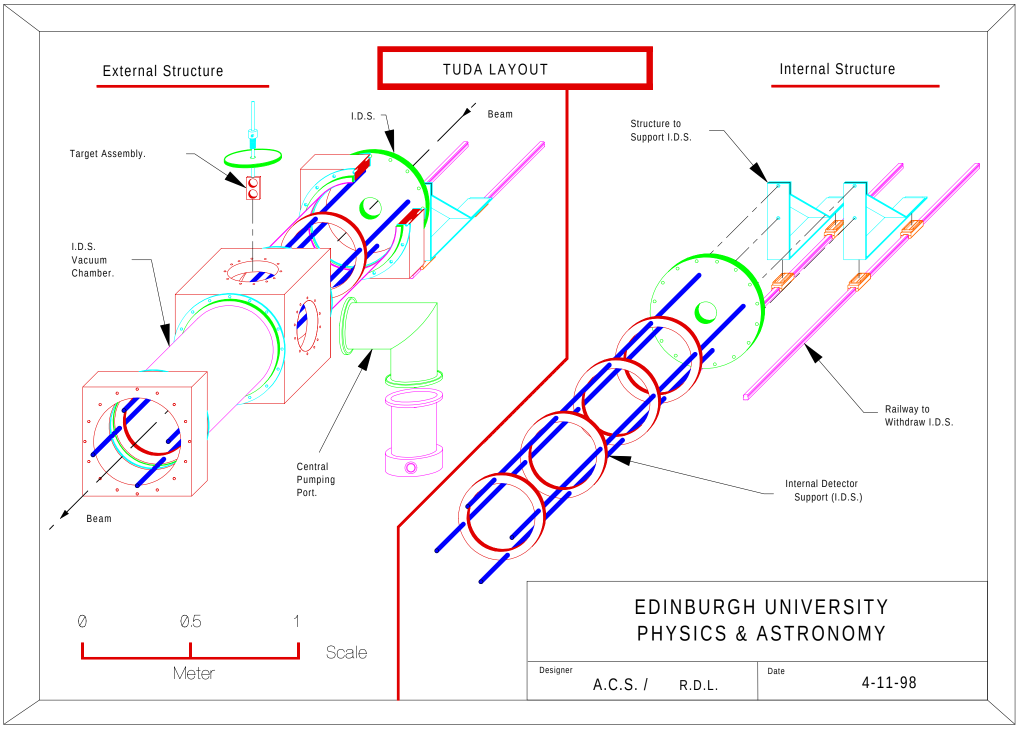

Fig. 2 TUDA schematic

and analyzed.

Each LEDA detector consist of 8 sectors. Each sector is further comprised of 16 silicon strips which provide information on the scattering angle. Each strip is 4 mm wide, resulting in an angular resolution of about 1° at a distance of 20 cm away from the target location. The performance of these detectors has been well established in previous measurements, with an energy resolution of 25 keV for 5.5 MeV alpha-particles and a timing resolution of 1-2 nsec. At present, TUDA has the capability of 256 channels, although an upgrade to 512 channels is anticipated for 2002.

The measurement will consist of a systematic search for states in ^{26}Si within E_{cm} = 1.45 MeV above the proton threshold. This will require ISAC beams in the laboratory energy range of 400-1500 keV/u. A survey of the excitation function will be measured with thick target scans over the full energy range. $(CH_2)_n$ targets of 250 μg/cm^2, corresponding to an energy scan of 240 keV/u, will be used for this purpose. Thin $(CH_2)_n$ targets of 50 μg/cm^2 will be used to study specific resonances in more detail.

The recoil protons from the target will be detected with a configuration of two LEDA arrays in the forward hemisphere to maximize solid angle coverage. The lower limit for the laboratory angle is determined by the maximum scattering angle of 2.3° for the ^{25}Al. The two detectors will be set up to give a coverage in lab solid angle from 4° to 33°. The main sources of scattered background come from recoil scattering of ^{12}C from the target, and scattering of ^{25}Al from the ^{12}C with a maximum opening angle of 30° for low beam energies. The detectors will be covered with mylar foils of sufficient thickness to suppress this scattered background. One detector will be left unprotected in order to normalize to the scattering of ^{25}Al off the ^{12}C, and to monitor the hydrogen depletion in the polyethylene target. Further suppression of background (including the beta-decay positrons) will be achieved using the RF time structure of the beam. Gain-matching will be performed with an alpha source. For each energy, short runs with a C/Au foil will be taken for beam normalization, assuming that the ^{25}Al scattering on gold has a pure Rutherford cross-section.

In order to estimate a typical count rate in one strip, we assume a Rutherford cross-section of 35 mb/sr at θ(lab) = 30°, a 1° coverage corresponding to a strip width of 4 mm located about 20 cm upstream from the target, and a thin target thickness of about 4×10^{18} hydrogen atoms/cm^2. For an ^{25}Al beam intensity of 10^7 particles/second, the resulting count rate per strip is about 1 event/minute. At these rates, we expect to obtain high statistical accuracy quickly by integrating over the large angular range of the TUDA array.

Prior to the p(^{25}Al,p)^{25}Al measurement, known resonances in the ^{25}Mg(p,p)^{25}Mg reaction will be used to calibrate the TUDA facility. Several broad resonances have been seen in other ^{25}Mg(p,p)^{25}Mg studies [14], which can be used for this purpose. Beam currents comparable or slightly higher to that used for the radioactive ^{25}Al beam measurements will be requested.

3 Beam Time Required

The estimates below assume a beam intensity of 10^7 particles/second for both stable and radioactive beams.

For stable beam calibration using ^{25}Mg(p,p)^{25}Mg, 2 calibration points with high statistics will be measured at known resonances, requiring a total of 6 shifts.

For the p(^{25}Al,p)^{25}Al measurement, thick target scans will be performed over the energy range of 400-1500 keV/u. The average energy range covered in a single scan is about 210 keV/u. As a consistency check, each scan will overlap the previous one by 100 keV/u, therefore requiring 10 scans to cover the full energy range. Assuming 2 shifts for each scan, the beam time requirements for the thick target scans are 20 shifts of ^{25}Al beam. For thin target scans over selected resonances, we assume measurements for 4 resonances with 3 shifts/resonance, resulting in a total of 12 shifts.

In summary:

- Stable ^{25}Mg beam shifts: 6
- Total radioactive ^{25}Al beam shifts: 32
- Total shifts: 38

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