TRIUMF - RESEARCH PROPOSAL	Experiment no.	Sheet 1 of 16

Title of proposed experiment

(α,p) reactions in type I X-ray bursts: time-reversed approach at ISAC II

Name of group

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Members of group (name, institution, status)

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Date for start of preparations: late 2006

Date ready: April 2007

Completion date: April 2008

Beam time requested:

12-hr shifts	Beam line/channel	Polarized primary beam?
24	ISAC II	No

SUMMARY	Sheet 2 of 16

Do not exceed one page.

The aim of this proposal is to investigate a series of (α,p) reactions of relevance to type I X-ray bursts via the time-reversed approach.

X-ray bursts are driven by a thermonuclear runaway on the surface of an accreting neutron star. The runaway is triggered by the triple α process and the break-out reactions from the Hot-CNO cycles which cause the feeding of the *rp*-process. The actual break-out is triggered by the reaction sequence ^{18}Ne(α,p)^{21}Na(p,γ)^{22}Mg(α,p)^{25}Al(p,γ)^{26}Si, leading to a sequence of alpha and proton captures (the so-called α*p*-process) up to the Ca-Ti region. Subsequent (α,p) reactions, specifically on ^{22}Mg, ^{26}Si, ^{30}S, and ^{34}Ar, are believed to be critical for type I X-ray bursts as they might provide a waiting-point impedance in the reaction flow, as suggested by Fisker *et al*.. In particular, the effects of experimentally unknown reactions such as ^{30}S(α,p)^{33}Cl and ^{34}Ar(α,p)^{37}K might even be directly visible as a double peak structure, as observed in the light curve of some X-ray bursts.

Here we propose to study both the ^{18}Ne(α,p)^{21}Na reaction and the (α,p) reactions on ^{22}Mg, ^{26}Si, ^{30}S, and ^{34}Ar in view of their importance as a breakout route from the HCNO cycle (the former) and as possible waiting points in the reaction flow (the latter). Because of the difficulties associated with direct studies involving RIBs and ^{4}He gas targets, it is proposed to investigate the time reversed (p,α) processes, whereby information on the relevant direct reaction cross sections can be obtained by means of the detailed balance theorem.

The first of these reactions to be studied is ^{21}Na(p,α)^{18}Ne, as an intense enough beam is already available at TRIUMF. As compared to previous studies of this reaction, the measurement aims to provide an independent data set to shed light on current discrepancies between direct and inverse determinations of the ^{18}Ne(α,p)^{21}Na reaction rate.
The measurement will be undertaken in two phases with the TUDA scattering chamber at ISAC II using a pulsed beam of ^{21}Na and standard CH_2 targets. Phase I will cover the energy range E_{lab} = 103 – 110 MeV, corresponding to E_{cm} = 2.0 – 2.4 MeV for the direct ^{18}Ne(α,p)^{21}Na where current information is ambiguous. At these energies many other channels from reactions with ^{12}C in the target will also be open, requiring the coincident detection of both reaction products in the exit channel so as to appropriately identify the reaction of interest. This will be achieved by using standard silicon strip detector arrays both for the ejectiles and for the heavy recoils. Time-of-flight techniques, in combination with total energy reconstruction will be used to distinguish between alphas and elastically scattered protons, and between heavy recoils and scattered beam ions respectively. While being scientifically relevant on itself, the successful completion of Phase I will also provide useful insight into the proposed approach and will help establishing the sensitivity limits before pushing the measurements to lower energies (Phase II)

The study of the ^{18}Ne(α,p)^{21}Na via the time-reversed approach represents a crucial preliminary step before proceeding to the study of the other, more challenging, (α,p) reactions on ^{22}Mg, ^{26}Si, ^{30}S, and ^{34}Ar as will be briefly outlined in the proposal.

BEAM and SUPPORT REQUIREMENTS	**Sheet** 3 **of** 16

Experimental area

TUDA scattering chamber @ ISAC II

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

Proton 500 MeV
ISAC production target

Secondary channel

ISAC II beamline

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

^{21}Na beam: E_{lab} = 103 – 110 MeV (4.9 – 5.2 MeV/u)
beam current: $5x10^6$ pps

TRIUMF SUPPORT:
Summarize all equipment and technical support to be provided by TRIUMF. If new equipment is required, provide cost estimates.

NOTE: Technical Review Forms must also be provided before allocation of beam time.

High intensity ^{21}Na beam
Operational support

NON-TRIUMF SUPPORT:

Summarize the expected sources of funding for the experiment.
Identify major capital items and their costs that will be provided from these funds.

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

SAFETY

Summarize possible hazards associated with the experimental apparatus, precautions to be taken, and other matters that should be brought to the notice of the Safety Officer. Details must be provided separately in a safety report to be prepared by the spokesperson under the guidance of the Safety Report Guide available from the Science Division Office.

No unusual safety hazards are associated with this experiment. Standard alpha particle sources will be used for calibration purposes.

1 Astrophysical motivation

Type I X-ray bursts are observed as sudden, intense emissions of X-rays with typical intensities of 10^{36}-10^{38} ergs/s, i.e. at least forty times larger than the ambient X-ray flux observed between bursts. Their luminosity curves are characterized by a fast (1-10 s) rise to a sharp peak, followed by an exponential-like decline over typical timescales of 10-100 s. In some cases, X-ray bursts showing a double-peak structure in the luminosity curve have been observed. The origin of the double peak is still controversial, but some authors claim that this might be due to waiting points in the nuclear reaction network (see later).

Type I X-ray bursts are believed to be caused by a thermonuclear runaway on the surface of a neutron star which is accreting material from a companion star in a semi-detached binary system. The bursts are driven by the rapid proton capture process (*rp* process) fusing H and He into heavier elements up to Te [1]. It is currently accepted that the runaway is triggered by the triple-α process and the break-out reactions from the Hot-CNO cycles which cause the feeding of the *rp*-process. The actual break-out is likely to be triggered by the reaction sequence ^{18}Ne(α,p)^{21}Na(p,γ)^{22}Mg(α,p)^{25}Al(p,γ)^{26}Si, which also initiates the so-called α*p*-process, involving alpha and proton captures up to the Ca-Ti region [2] (and references therein). At $T_9 \cong 1$, typical for X-ray bursts [3], the Gamow windows for these (α,p) reactions lie in the range $E_0 \sim 1.3 – 2.0$ MeV with typical widths $\Delta E_0 \sim 0.4 – 0.8$ MeV.

Recently, some authors [3] have claimed that (α,p) reactions on ^{22}Mg, ^{26}Si, ^{30}S, and ^{34}Ar may provide a waiting-point impedance in the reaction flow and the effects of reaction rates such as ^{30}S(α,p)^{33}Cl and ^{34}Ar(α,p)^{37}K might even be directly visible as a double peak structure (Figure 1), as observed in some X-ray bursts.

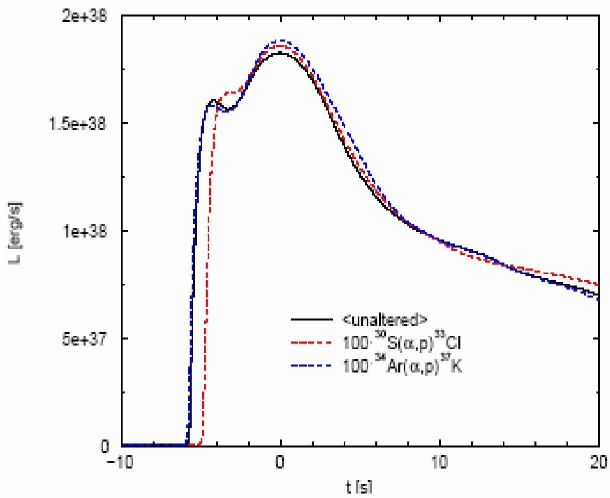

Figure 1: Luminosity curve simulation. The effect of altering the reaction rates (here by a factor 100) for some (α,p) reactions results in more or less pronounces dips in the light-curve, thus appearing as a double peak structure (details in Fisker et al. [3])

Such conclusions, however, are based on purely theoretical grounds, i.e. Hauser-Feshbach calculations, since no experimental data are available at present. In general, the use of Hauser-Feshbach approach is appropriate provided the level density in the contributing energy window is sufficiently high to justify a statistical treatment, the critical level density being usually estimated between 5 and 10 MeV^{-1} [4]. However, the level density may fall below critical value in certain nuclei lighter than Fe, at shell closures, and for very neutron-rich or proton-rich isotopes near the drip lines. In these cases, single resonances or direct capture contributions will become significant [4] and theoretical estimates may become unreliable.

Recent observations by the Beppo SAX, RXTE and CHANDRA satellites have provided a wealth of new data on X-ray bursters. In order to compare model predictions with observations, the models should include accurate reaction rates that need to be determined by laboratory experiments. At present many rates in the *rp*-process are uncertain by several orders of magnitude. In order to reduce uncertainties in the rates, experimental information is needed.

This proposal addresses the experimental investigation of (α,p) reactions:
- on ^{18}Ne, in view of its importance as a breakout route from the HCNO cycle, and
- on ^{22}Mg, ^{26}Si, ^{30}S, and ^{34}Ar nuclei, as possible waiting points in the reaction flow leading to X-ray bursts.

Owing to the intrinsic difficulties in direct studies involving RIBs and ^{4}He gas targets, it is proposed to investigate the time reversed (p,α) processes, whereby information on the relevant direct reaction cross sections can be obtained by means of the detailed balance theorem (Section 3).

2 Current status of knowledge

2.1 The ^{18}Ne(α,p)^{21}Na reaction

The first direct measurements of the ^{18}Ne(α,p)^{21}Na reaction were undertaken by the LEDA collaboration at Louvain-la-Neuve, Belgium. The measurements were performed in inverse kinematics using a ^{18}Ne beam on a helium-filled target chamber which contained silicon detector telescopes to detect reaction protons, determine their track and hence the CM energy of the interaction. Measurements were performed at E_{cm} = 2.0-3.0 MeV [5] and at E_{cm} = 1.7-3.0 MeV [6]. The latter measurement improved the rejection of background proton events (which limited the former measurement to the higher CM energies) and reported the identification of a greater number of states in the compound system ^{22}Mg. It is for this reason that the direct reaction cross section curves (Figure 2) corresponding to [5] and [6] differ. Protons from the decay of ^{22}Mg states (excitation energies E_x ~10-11 MeV) were identified and resonance strengths obtained.

More recently, a collaboration at the Argonne National Laboratory has studied the ^{18}Ne(α,p)^{21}Na reaction by using the time-inverse reaction ^{21}Na(p,α)^{18}Ne and the principle of detailed balance [7]. The experiment was performed at the ATLAS facility with a ^{21}Na beam produced in-flight by the reaction ^{2}H(^{20}Ne,^{21}Na)n and refocused onto a $(CH_2)_n$ target. The ^{21}Na beam intensity was ~5000 pps. Alpha particles from the ^{21}Na(p,α)^{18}Ne reaction were detected in coincidence with ^{18}Ne recoils, by using a combination of silicon strip detector (for the alpha particles) and a gas ionization chamber for the heavy recoils. The total cross section for the ^{18}Ne(α,p) reaction at E_{cm}=2.5 MeV was determined to be a factor of ~50 smaller than that reported by Groombridge et al. [6] (see Figure 2). From the direct measurements, the corresponding state in ^{22}Mg was reported to decay mainly to the ground state of ^{21}Na and although the cross section for the time-inverse reaction ^{21}Na(p,α)^{18}Ne is expected to be lower than the direct reaction ^{18}Ne(α,p) (in the latter case inelastic channels can also contribute), the discrepancy of a factor of ~50 appears to be too large to be accounted for by this means alone.

More recently, new results have been reported by the Argonne group [7,], which are displayed in Figure 3 (beam current ~5x10^5 pps [8]). The result of the Hauser-Feshbach calculation assuming only transitions to the ground state has been superimposed on the original figure, showing good agreement with the inverse data points.

At the time of writing the LEDA Collaboration is performing a direct measurement at Louvain-la-Neuve (Belgium) [9], with the aim to try and reconcile current discrepancies between the two sets of data (direct and inverse). In addition a proposal (E870) to further investigate the ^{18}Ne(α,p) reaction has already been accepted at TRIUMF and is awaiting the development of an adequately intense ^{18}Ne beam. However, it is unlikely that either measurement will reach the required sensitivity to investigate the energy region of astrophysical interest for which beam intensities in excess of 10^8 pps would be required.

It is therefore highly desirable to perform an independent measurement of the time-reverse reaction with an aim to provide data points in the region E_{cm} = 1.7 – 2.5 MeV, where only partial information is available at present (in particular, a discrepancy seems to be present between HF curve given in Figure 3 and the upper limits around E_{cm} ~ 2 MeV in Figure 2). From this measurement we expect to learn about the viability of the proposed approach and the sensitivity limits before pushing the measurements to lower energies (Phase II, see later). The proposed approach is outlined in Section 3.2.

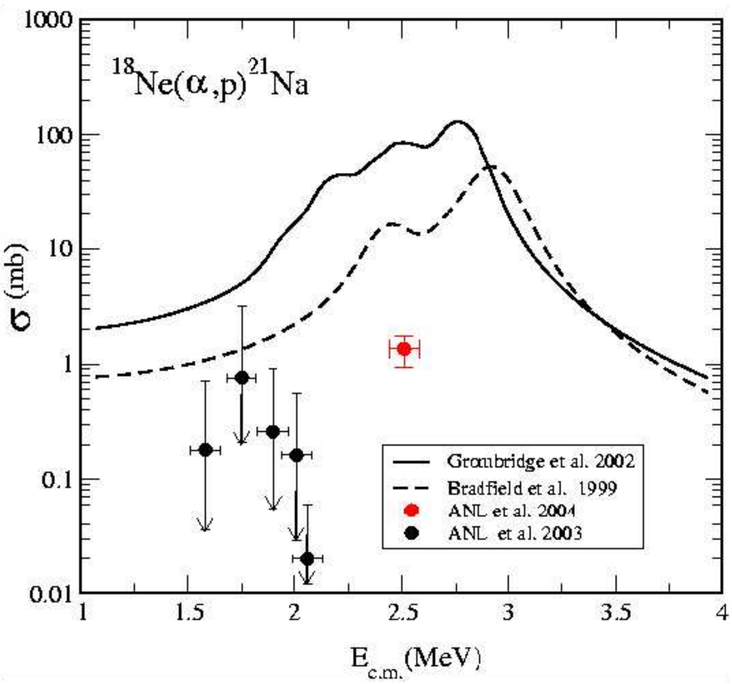

Figure 2: Comparison of ^{18}Ne(α,p)^{21}Na cross-sections. Solid and dashed lines represent cross section trends as derived from direct measurements [5,6]. Black and red dots represent the results of detailed balance from the time-reversed (i.e. inverse) measurements. Figure from Argonne Annual Report, 2004 [7]

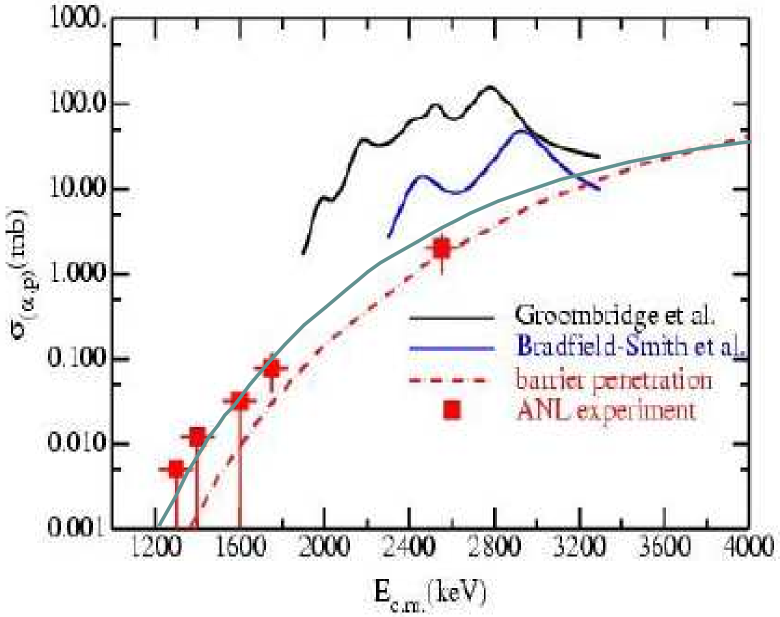

Figure 3: Same as Figure 2, with red squares representing results from time-reversal measurements. The dashed line is the result of a barrier penetration calculation, normalised to the point at the highest energy. The green solid curve is the Hauser-Feshbach calculation [4] for the $^{18}Ne(\alpha,p)$ reaction assuming ground state to ground state transitions only. Figure adapted from Argonne Annual Report, 2005 [7]

2.2 (α,p) reactions on ^{22}Mg, ^{26}Si, ^{30}S, and ^{34}Ar

At present there are no experimental data available for (α,p) reactions on ^{22}Mg, ^{26}Si, ^{30}S, and ^{34}Ar and the astrophysical implications of these reactions are based on theoretical rates derived from Hauser-Feshbach calculations [4]. It should be noted though that all the (α,p) reactions in this proposal involve spin-less particles in their entrance channels, so that only natural parity states (i.e. $J^{\pi}= 0^+, 1^-, 2^+, 3^-,\ldots$) can be populated in the compound nucleus. As a consequence, the reaction cross section may be entirely dominated by single resonances within the Gamow window (here typically $E_0 \sim$ 1-2 MeV, $\Delta E_0 \sim$ 0.8-1.0 MeV) and current theoretical predictions might turn out to be unreliable in such cases. Clearly any experimental information would represent a major improvement in the current situation. It is hoped that, with the upgrades of existing experimental facilities such as ISAC II, more and more reactions will become accessible to experimentalists.

3 The experiment

3.1 Objectives

The objective of this proposal is to investigate a series of (α,p) reactions which are believed to be crucial in type I X-ray bursts. In particular, it is suggested to study:

a) the $^{18}Ne(\alpha,p)^{21}Na$ reaction as the main breakout route from the HCNO cycle; and

b) (α,p) reactions on ^{22}Mg, ^{26}Si, ^{30}S, and ^{34}Ar isotopes.

The experimental investigation is aimed at determining the cross sections of these important (α,p) reactions by using the time-reversed approach through the principle of detailed balance, as outlined in the following section.

3.2 Methodology

Direct studies of (α,p) reactions with radioactive ion beams are extremely difficult because they suffer from limitations both in beam intensities and target densities. In addition, none of the required beams are presently available at TRIUMF, with the possible exception of ^{18}Ne. An alternative approach would be to study the reactions of interest, here generically indicated as X(α,p)Y, by their time-reversed Y(p,α)X processes, using a radioactive ion beam Y and a solid CH_2 target.
The time-reversed approach is justified by the fact that the cross-section $\sigma_{\alpha X}$ for reaction α + X → p + Y is related to the cross-section σ_{pY} for the inverse process p + Y → α + X by detailed balance according to the reciprocity theorem:

$$\frac{\sigma_{\alpha X}}{\sigma_{pY}} = \frac{m_p m_Y}{m_\alpha m_X} \frac{E_{pY}}{E_{\alpha X}} \frac{(2J_p + 1)(2J_Y + 1)}{(2J_\alpha + 1)(2J_X + 1)} \qquad (1)$$

where E_{ij} refers to the centre-of-mass energy for the direct and inverse reactions involved (here, $E_{pY} = E_{\alpha X} + Q$), m_i are the masses of the respective particles and J_i the nuclear spin of the interacting particles. Clearly the main limitation of this approach arises from the fact that excited states in the p+Y system (otherwise populated in the direct approach) cannot be accessed here. By implication, only lower limits to the cross section for the relevant direct reactions can be established. It is worth stressing, however, that even partial information would represent a major improvement in the current situation as no experimental data exist for any of the mentioned reactions, apart from the ^{18}Ne(α,p) case.
Finally, it should be pointed out that, while only natural parity states in the compound system can be accessed by route α+X (here spin-less particles) such restriction does not apply when forming the compound system via route p+Y. However, by kinematically selecting events which leave both particles α and X in their ground states, one can make sure that only natural parity states have been populated through the p+X channel. This in turn enables a meaningful extraction of cross section $\sigma_{\alpha X}$ from a measurement of σ_{pY} as given by equation (1).
The requirement on the kinematic selection can be fulfilled provided that the first excited states for nuclei in the exit channel are sufficiently high in energy (~1 MeV) to allow for experimental discrimination (location of first excited state is at: 1.89 (^{18}Ne), 1.24 (^{22}Mg), 1.28 (^{26}Si), 2.21 (^{30}S) and 2.09 (^{34}Ar) MeV respectively, while for ^{4}He it is at 20.210 MeV). Incidentally, Hauser-Feshbach calculations for all (p,a) reactions considered here have shown that contributions to excited states in the exit channel are negligible with respect to ground state transitions only [4]. Hence all these reactions represent excellent cases for the application of the time-reverse approach.

A level scheme for the ^{18}Ne(α,p)^{21}Na case is shown in Figure 3, where the grey shaded area represents the energy region to be covered during Phase I of this proposal (see following Sections).

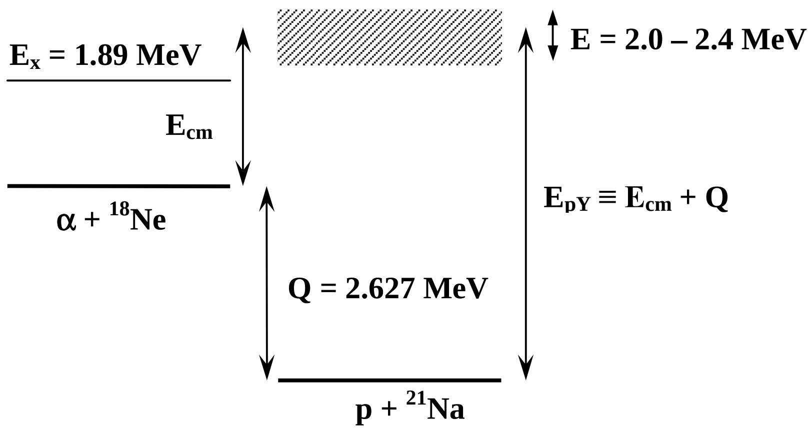

Figure 3: Schematic level diagram relating direct and inverse approaches for the ^{18}Ne(α,p)^{21}Na case.

3.3 Experimental Setup

The time reverse approach outlined here requires beam energies in the range E_{lab} ~ 4 – 6 MeV/u. In this energy regime, significant background is expected from reactions on ^{12}C in the target and thus the coincident measurement of both reaction products (here protons and ^{18}Ne ions) is required for a unique identification of the reaction of interest. Because of the inverse kinematics, both reaction products are strongly forward focussed, with the recoils and the ejectiles being emitted within a cone of at most ~ 4^o and 20^o respectively. An overview of kinematics loci for all five (α,p) reactions of interest is shown in Figure 4.

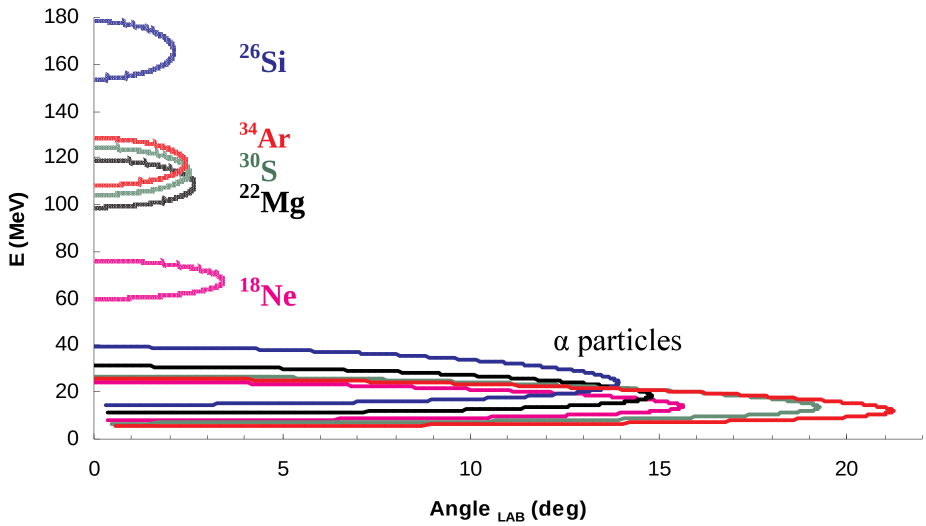

Figure 4: Kinematics curves of all (p,α) reactions of interest calculated at their relevant astrophysical energies

Kinematic coincidence of recoils and ejectiles will be achieved by using double-sided annular strip detector arrays. A sketch of the experimental setup is shown in Figure 5 and consists of a LEDA array (1mm thick, covering θ ~ 34^o – 60^o), mainly for elastically scattered protons, and two Double Sided Silicon Strip Detector arrays for alphas (DSSSD_near, 500 µm thick, covering θ ~ 6.5^o – 20^o) and heavy ions (DSSSD_far, 500 µm thick, covering θ ~ 1.5^o – 4.7^o) respectively.

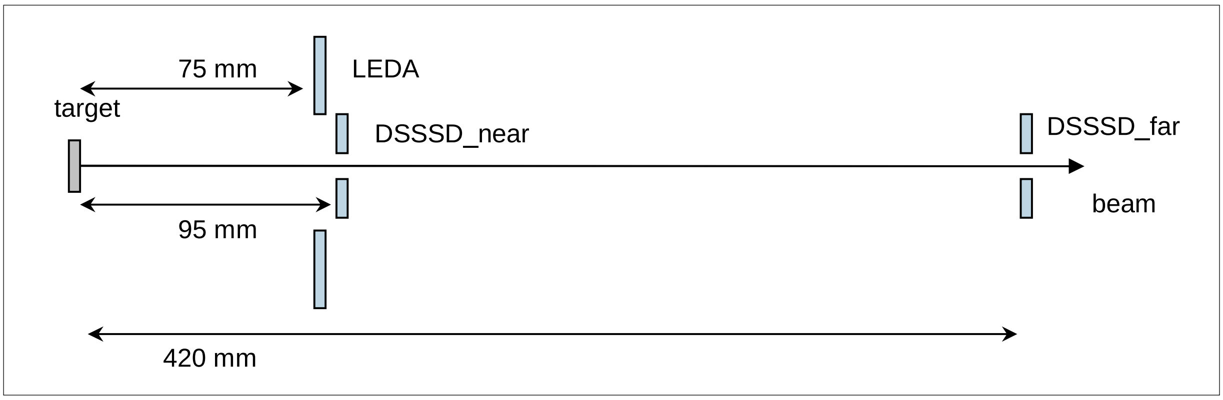

Figure 5: Experimental setup

Clearly a main issue for the correct identification of the reaction of interest is the correct discrimination between elastically scattered ^{21}Na-beam ions and the ^{18}Ne from the reaction of interest. This will be achieved by a combination of ToF/fast coincidence, total energy reconstruction and identification of reaction plane. In addition, the detection of elastically scattered protons in the LEDA detector will help to optimize identification of ^{21}Na in the DSSSD_far detector. Finally, protons from the decay of well-known states in ^{22}Mg will be used for calibration purposes.

For this setup, the total (coincident) detection efficiency is about 85%, as determined by a Monte Carlo simulation (see Figure 6) assuming isotropic distribution of reaction products in the centre-of-mass system [10]. Multi-scattering effects are estimated to be negligible for the planned setup and energies.

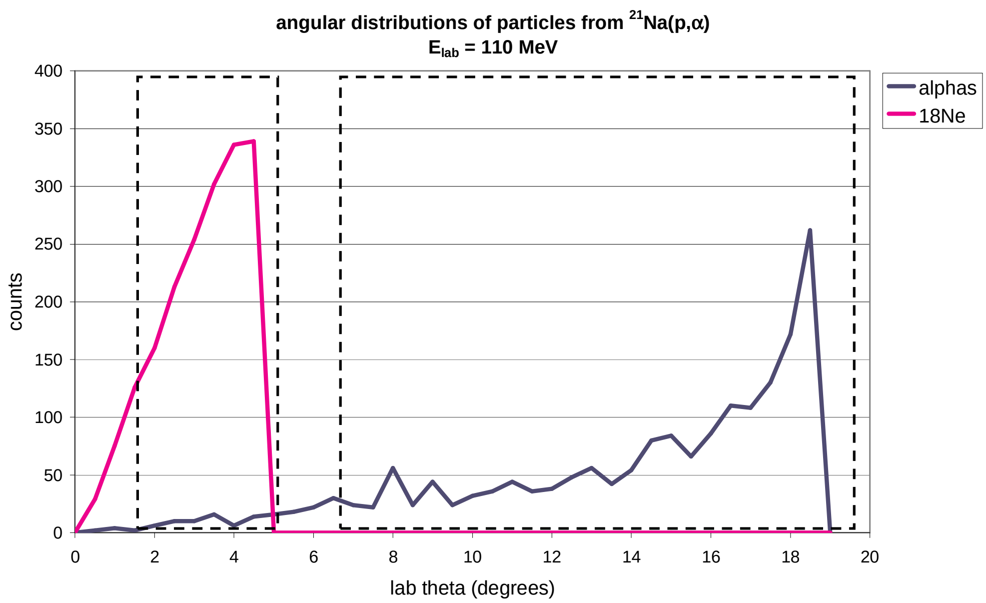

Figure 6: Monte Carlo simulation of angular distribution of particles in the exit channel for a beam energy E = 110 MeV. The dashed boxes represent the range of angular coverage in the laboratory system [10].

4 Beam request

The following details the beam time request for the case of the $^{21}Na(p,\alpha)^{18}Ne$ reaction only. While the full experiment will aim to cover the energy range corresponding to E_{cm} = 1.6 – 2.4 MeV (for the direct reaction), the measurements will be carried out in two separate stages and a formal request is made here for Phase I only (E_{cm} = 2.0 – 2.4 MeV in ΔE_{cm} = 200 keV steps). Depending on the successful completion of Phase I a further beam time request will be made for Phase II at a later stage.
For Phase I, we request a total of **20 shifts** for data taking. In addition, **2 shifts** are required for runs on a ^{12}C target in order to assess background contributions, and further **2 shifts** are required for beam energy changes, calibration purposes and contingency.

This request is based on the calculation of the expected yield $Y=N_pN_T\sigma\eta$ with the following assumptions:

1) $N_p = 5x10^6$ pps (i.e. beam current ~ 0.8epA)
2) $N_T \sim 3x10^{19}$ protons cm^{-2} (i.e. target thickness dx = 350 $\mu g/cm^2$)
3) integrated cross-sections σ as given by the HF formalism for the time-reversed reaction (ground state to ground state transitions only)
4) isotropic distribution for the reaction products in centre-of-mass system
5) total detection efficiency η = 85%

	E_{lab} [MeV]	**E_{cm} [MeV]**	**E_{cm} (direct reaction) [MeV]**	**σ [mb]**	**Yield [counts/hr]**	**Shifts [12 hrs]**	**Total Counts**
Phase I	110	5.0	2.4	0.41	180	4	8600
	106	4.8	2.2	0.18	80	6	5800
	103	4.7	2.0	7.1×10^{-2}	33	10	4000
Phase II	98	4.4	1.8	2.4×10^{-2}	11	10	1300
	93	4.2	1.6	4.6×10^{-3}	2	10	240

It is expected that there will be a period of several months between Phase I and II to allow for data analysis and for any necessary improvements to be implemented.

5 Readiness

It is expected that the TUDA scattering chamber facility will be capable of running the proposed experiment as soon as a ^{21}Na beam of the required intensity becomes available at ISAC II.

The TUDA scattering facility is essentially ready should beam time be granted. The required silicon detectors for light particles are also available.

6 Data Analysis

The TUDA acquisition system is VME based and capable of acquiring data from up to 512 electronic channels, which is more than enough for our proposed set up (at most 256 channels). The VME DAQ is also capable of handling up to 10 kHz event rate and again this is sufficient for our purposes (maximum expected rate from elastic scattering on ^{12}C is ~ 10 kHz). The data will be acquired online event-by-event allowing cuts and coincidence requirements to be applied offline as necessary. The data being acquired will be monitored online using a Sun workstation to verify beam and target status and detector/electronics stability.

7 Future directions

The ^{21}Na(p,α)^{18}Ne reactions can be studied as soon as ISAC II becomes operational, since an intense enough beam of ^{21}Na is already available. However, depending on the sensitivity of the proposed approach, the extension of this measurement to the lowest energy regions (Phase II) might require a different setup, for which additional planning will be needed. This would represent the immediate future directions upon successful completion of Phase I.

After assessing the viability of the proposed approach, further studies of the (p,α) reactions listed in this proposal can be carried out as soon as their respective beams become available. The first likely candidate is the ^{25}Al(p,α)^{22}Mg reaction, as the ^{25}Al beam development is currently underway. All other reactions will have to await the development of the appropriate beam which is hereby advocated.

7 References

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1. *Level structure of ^{21}Mg: Nuclear and astrophysical implications*
A.St.J. Murphy, **M. Aliotta**, T. Davinson, A. Robinson, P. Woods, C. Ruiz, J. D'Auria, R. Azuma, L. Buchmann, A. Chen, D. Hutcheon, A. Laird, P. Walden, B.R. Fulton, B.A. Brown
Physical Review C 73 (2006) 034320

2. *Low-lying states in the unbound ^{11}N nucleus*
E. Casarejos, C. Angulo, P.J. Woods, F.C. Barker, P. Descouvemont, **M. Aliotta**, T. Davinson, P. Demaret, M. Gaelens, P. Leleux, Z. Liu, M. Loiselet, A.S. Murphy, A. Ninane, I.A. Roberts, G. Ryckewaert, J.S. Schweitzer, F. Vanderbist
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3. *Electron screening in ^{7}Li(p,α)^{4}He and ^{6}Li(p,α)^{3}He for different environments*
J. Cruz, Z. Fülöp, G. Gyürky, F. Raiola, A. Di Leva, B. Limata, M. Fonseca, **M. Aliotta**, H.W. Becker, A. D'Onofrio, L. Gialanella, G. Imbriani, A.P. Jesus, K.U. Kettner, J.P. Ribeiro, V. Roca, C. Rolfs, M. Romano, E. Samorjai, F. Strieder, F. Terrasi
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