EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Letter of Intent to the ISOLDE and Neutron Time-of-Flight Committee

Destruction of the cosmic γ-ray emitter ^{26}Al by neutron induced reactions

P.J. Woods[1] , C. Lederer[2] , F.Käppeler[3], E. Berthoumieux[4] , E. Chiaveri[4] , N. Colonna[5] , T. Davinson[1], C. Guerrero[4] , F. Gunsing[6] , J. Heyse[7] , G. Lotay[1] , C. Massimi[8] , W. Mondelaers[7] , R. Reifarth[9] , P. Schillebeeckx[7] , G. Tagliente[5] , C. Wagemans[10] , A. Wallner[3,11] , C. Weiss[4] , and the n TOF Collaboration

[1] Department of Astronomy and Physics, University of Edinburgh, United Kingdom

[2] University of Vienna -Faculty of Physics, Austria

[3] Karlsruhe Institute of Technology, Campus Nord, Institut für Kernphysik, Karlsruhe, Germany

[4] European Organization for Nuclear Research (CERN), Geneva, Switzerland

[5] Istituto Nazionale di Fisica Nucleare, Bari, Italy

[6] Commissariat ` l'Energie Atomique (CEA) Saclay - Irfu, Gif-sur-Yvette, France

[7] IRMM, Geel, Belgium

[8] INFN-Sezione di Bologna and University of Bologna, Bologna, Italy

[9] Goethe University of Frankfurt, Frankfurt, Germany

[10] University of Gent, Gent, Belgium

[11] Australian National University, Canberra, Australia

Spokespersons: P.J. Woods (pjw@ph.ed.ac.uk), C. Lederer (claudia.lederer@univie.ac.at), F. Käppeler (franz.kaeppeler@kit.edu),

Technical coordinator: E. Berthoumieux (eric.berthoumieux@cern.ch)

Abstract

The first observation of γ-rays from the radioisotope ^{26}Al ($t_{1/2}$ ~ 1 My) showed nucleosynthesis is ongoing in our galaxy. Detailed satellite telescope observations indicate that galactic ^{26}Al is predominantly produced in different burning stages of massive Wolf-Rayet stars. Recent reaction network calculations have shown the rates of the neutron induced destruction reactions ^{26}Al(n,p) and ^{26}Al(n,α) are the major source of uncertainty in predicting the amount of ^{26}Al material ejected into the interstellar medium by Wolf-Rayet stars. The limited experimental data sets on the ^{26}Al(n,p) and ^{26}Al(n,α) reactions exhibit major discrepancies, and do not cover all the relevant stellar burning energy range. Consequntly stellar modellers have identified new measurements on these reactions as the highest priority for predicting ^{26}Al abundances. We propose to measure the ^{26}Al(n,p) and

^{26}Al(n,α) cross-sections at the n_TOF facility from thermal energies up to 1 MeV covering the entire energy range of astrophysical interest. The experiment will use a highly enriched ^{26}Al sample, and the charged particles will be detected using a new double-sided silicon strip detector system.

Requested protons: parasitic running

Introduction

^{26}Al was the first cosmic gamma ray emitter to be identified [1]. Its relatively short lifetime (~1 My) compared to galactic timescales provides clear evidence of ongoing nucleosynthesis. Satellite telescope studies of ^{26}Al abundance distributions across the galaxy are providing detailed new information [2] that needs to be complemented by a better knowledge of the production and destruction rates of certain key astrophysical reactions. Observational data suggests that the main sources of ^{26}Al are associated with burning reactions in (massive) Wolf-Rayet stars [2]. There are expected to be three contributions to the ^{26}Al abundance from Wolf-Rayet stars: in the convective hydrogen burning phase of the star where material is emitted over a long period of time by stellar winds; in convective carbon shell burning prior to core collapse followed by ejection into the interstellar medium by the supernova explosion; and in explosive burning neon-carbon burning following the supernova explosion [3]. The key destruction reaction of ^{26}Al in the hydrogen burning phase of Wolf-Rayet stars is ^{26}Al(p,γ)^{27}Si. Significant experimental progress has recently been made in identifying the most important low energy resonances for this reaction [4]. This has resulted in a vast reduction in the uncertainty of the ^{26}Al(p,γ)^{27}Si reaction rate under hydrogen burning conditions found in Wolf-Rayet stars (T~0.05 GK) [4,5]. Recent stellar model calculations of the convective carbon shell and explosive neon carbon shell burning phases of Wolf-Rayet stars show the predicted final ^{26}Al abundance to be most sensitive to uncertainties in the neutron destruction reactions ^{26}Al(n,p)^{26}Mg, and (to a lesser extent) ^{26}Al(n,α)^{23}Na [3]. There are significant uncertainties in applying the Hauser-Feshbach statistical approach to these reactions since although the compound nucleus excitation energy is relatively high (> 13 MeV in ^{27}Al), the ground-state configuration of ^{26}Al is 5^+, therefore the key resonances, corresponding to low orbital angular momentum l_n captures have high spin, and have relatively low level densities. The high spin of the ground-state of ^{26}Al also complicates the use of the principle of detailed balance to derive the reaction rate. For example, the ^{26}Mg(p,n$_0$)^{26}Al reaction [6] is only sensitive the ^{26}Al(n,p$_0$)^{26}Mg ground-state channel whereas the inelastic channel to the first excited 2^+ state at 1.8 MeV, ^{26}Al(n,p$_1$)^{26}Mg, was found to be typically an order of magnitude stronger than the ground-state channel in the energy region of interest [7,8]. This is primarily due to the higher centrifugal barrier for the proton transition to the 0^+ ground-state of ^{26}Mg.

Trautvetter and Käppeler reported the first measurement of the ^{26}Al(n,p$_1$)^{26}Mg reaction [7] which was followed up by a more comprehensive study [8], in which measurements of both the ^{26}Al(n,p$_0$)^{26}Mg and ^{26}Al(n,p$_1$)^{26}Mg reactions were reported. A later study of the ^{26}Al(n,p$_1$)^{26}Mg reaction, and a first study of the ^{26}Al(n,α$_0$)^{23}Na reaction, both performed at the Los Alamos Neutron Science Center (LANSCE), were reported by Koehler et al. [9]. The cross-section data from Ref. [9] are plotted in Figures 1 and 2 for these reactions as a function of neutron energy. The ^{26}Al(n,p$_1$)^{23}Na reaction rate was found to be in disagreement with that of [8] in the one region of burning temperature overlap between the two sets of measurements (see Figure 16 from Ref. [3]).

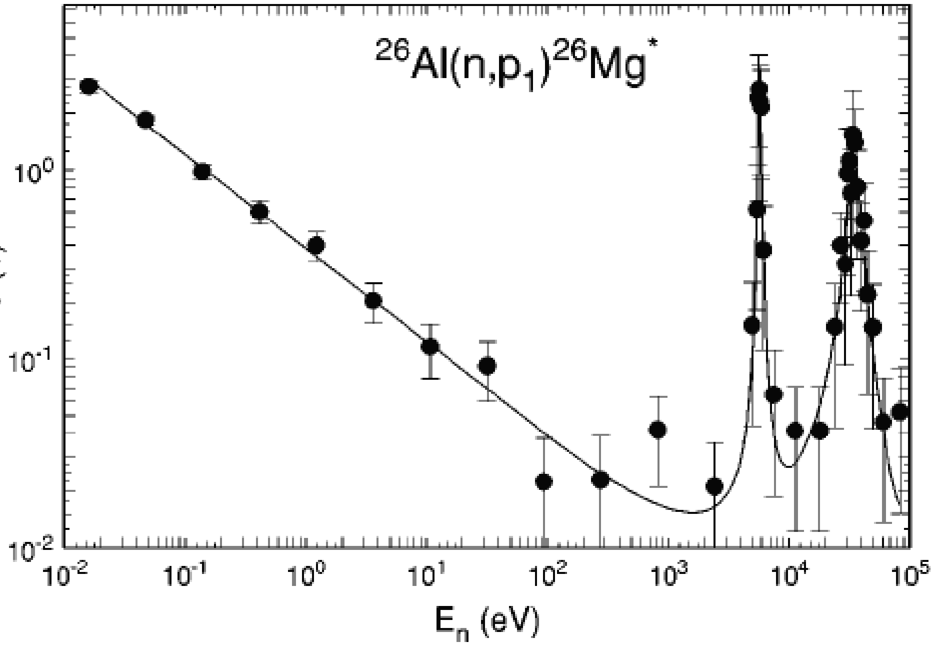

Figure 1. Cross-section data for the ^{26}Al(p,n$_1$)^{26}Mg reaction [9].

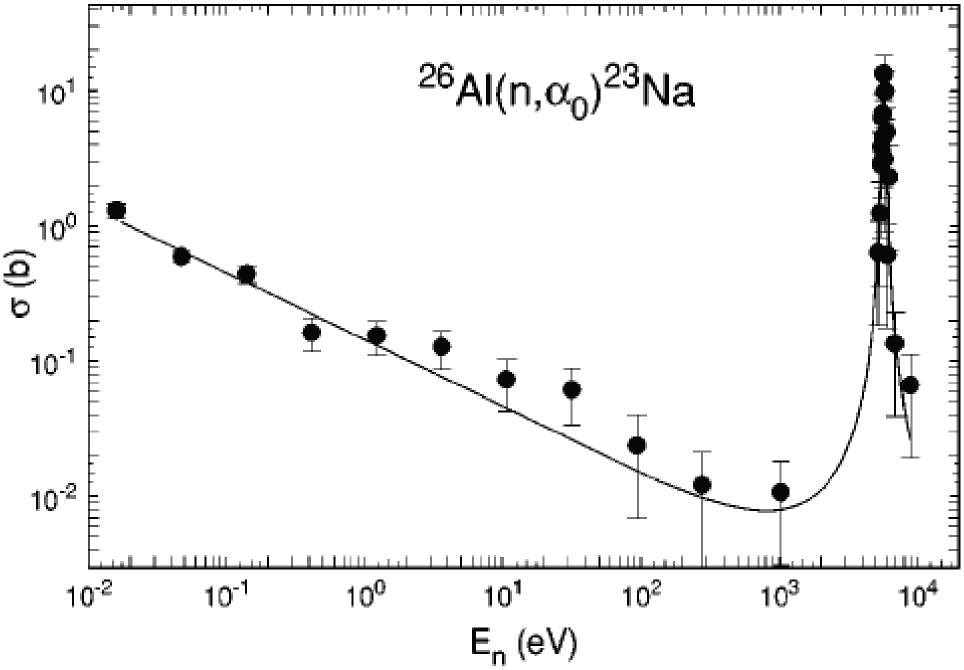

Figure 2. Cross-section data for the ^{26}Al(n,α)^{23}Na reaction [9].

Illiadis et al. [3] highlighted this as the key issue that needs to be resolved for calculating abundances of ^{26}Al produced in the convective carbon shell and explosive neon carbon shell burning phases of Wolf-Rayet stars. Koehler et al. suggested discrepancies between the measurements could be due to angular distribution effects, since the experiments covered different angular ranges, or more likely differences in normalization procedure [9]. Ref [8] used the ^{197}Au(n,γ)^{198}Au reaction for normalization, which Koehler et al. comment is sensitive to any small excess in thermal neutrons in the beam [9], whereas Koehler et al. used the ^{26}Al(n,p$_1$)^{26}Mg cross-section at thermal neutron energies, and the ^{10}B(n,α)^{7}Li reaction, for normalization purposes [9]. Most recently, De Smet et al. reported measurements of the ^{26}Al(n,α_{0+1})^{23}Na reactions using the GELINA neutron time-of-flight facility at the Institute for Reference Materials (IRMM), Geel [10], with the ^{10}B(n,α)^{7}Li reaction used for the neutron flux determination. The GELINA measurements overlapped the lower neutron regime covered by the LANSCE experimental study (maximum energy 10 keV [9]) and also obtained data at higher energies, identifying a number of new resonances for the ^{26}Al(n,α)^{23}Na reaction. A resonance at 6 keV was identified in both studies (the only one identified in [9]) but there was disagreement in the total width Γ. of the resonance. De Smet suggested this may be due to the relatively small solid angle covered by the silicon detection system used in the LANCSE measurements, rendering the measurements sensitive to anisotropy effects - the 6 keV resonance was assigned to a p-wave [10]. The GELINA measurements had better statistical precision mainly due to the use of a sample of a larger number of ^{26}Al atoms [11]. Iliadis et al. noted the experimental discrepancies between these low energy measurements of the ^{26}Al(n,α)^{23}Na reaction rate (see Figure 15 from [3]), and the absence of measurements of the ^{26}Al(n,α)^{23}Na reaction rate in the higher energy astrophysical burning regime above T~0.3-3 GK , and called for new measurements [3]. This regime covers the burning temperatures for convective shell C/Ne burning, and explosive Ne/C burning in Wolf-Rayet stars, and requires measurements up to 1 MeV in neutron energy. In particular, there may be hitherto unobserved strong resonances at high energies that can significantly influence the Maxwellian Averaged Cross-Section (MACS) in the high temperature burning regime.

We propose to make new measurements of the ^{26}Al(n,p)^{26}Mg and ^{26}Al(n,α)^{23}Na reactions at the n_TOF facility CERN [12] using a new high resolution, large solid angle, double-sided silicon strip detector (DSSD) system (see [13] for a description of the instrumentation system) in combination with the high abundance ^{26}Al sample used for the measurements at GELINA [11]. The n_TOF facility combines excellent energy resolution due to a flight path of 185 m, full coverage of the energy range of interest, and a high instantaneous neutron flux. The proposed experimental method is described below.

^{26}Al sample and Measurement

The sample to be used for this measurement was made by IRMM in collaboration with LANSCE [11]. ^{26}Al has been produced by spallation reactions of a proton beam in a potassium chloride target and brought onto a 7.5μm thick Ni backing by electro-deposition. The final quantity of ^{26}Al atoms was determined by γ-ray spectroscopy and yielded (2.67 ± 0.2) x 10^{17} atoms. The active area of the sample is 50x60 mm^2 with an areal density of 0.37 μg.cm^{-2}. The dimensions of the brass target frame are 97 x 82 mm^2. The sample will be tilted at an angle ~40° with respect to the beam axis with the ^{26}Al surface facing downstream, and placed in the existing Silicon monitor chamber on the n_TOF experimental area beam-line. At this position the neutron beam diameter is ~3cm so the beam will intersect the active area of the ^{26}Al sample, but not the brass target frame. This is important since it means the experiment can be run without affecting other experiments downstream in the n_TOF experimental area. The calculated transmission of neutrons through the target backing with an effective thickness of 10 µm (taking into account the tilt of the sample) is shown in Figure 3.

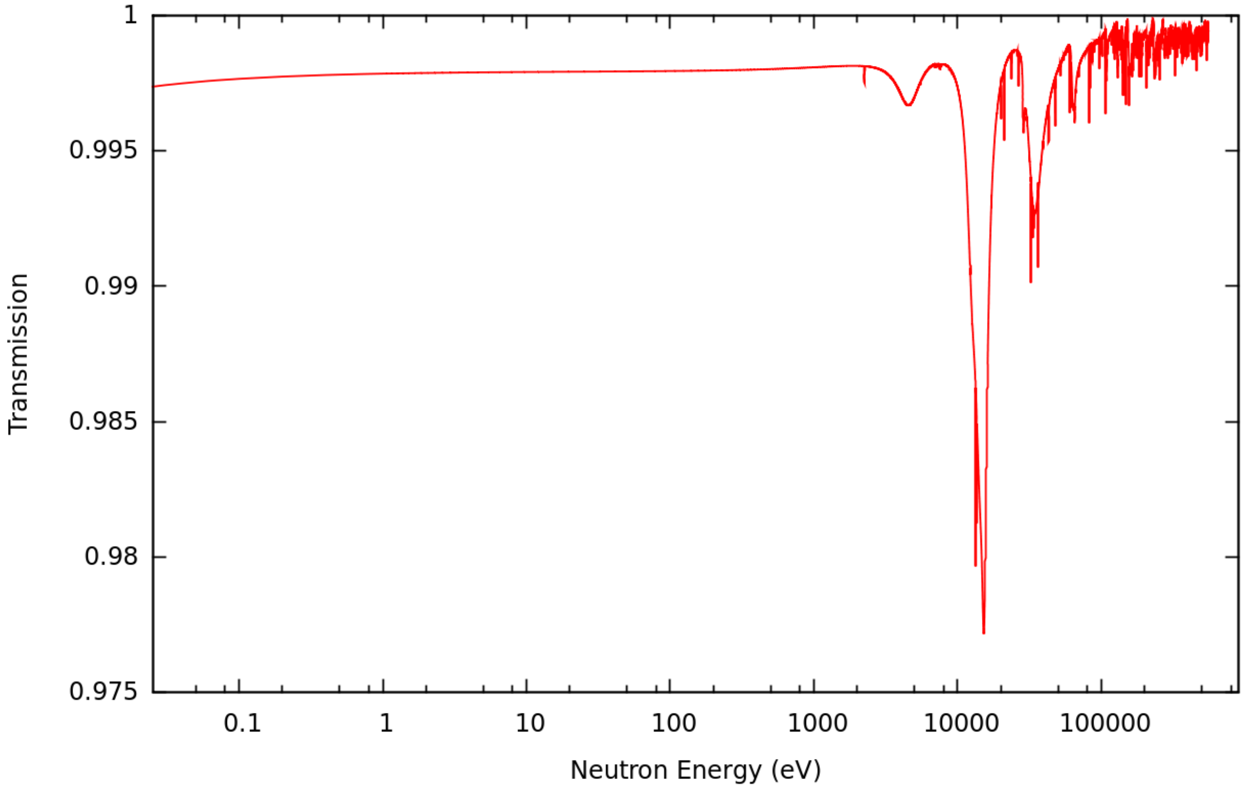

Figure 3. Calculated transmission of neutrons through 10 µm of natural Nickel using the resonance data of the JENDL-4.0 library. Apart from two resonance awhere the transmission decreases by 2 % and 1%, respectively, the effect is less than 0.5%.

In October our collaboration successfully performed a test study of the n + ^{7}Li → α + t reaction using a single 5*5cm^{2} DSSD instrumented with the Edinburgh Nuclear Physics Group electronics system [13]. Figure 4 shows an energy spectrum taken from this test. The energy resolution is limited by energy straggling in the thick ^{6}Li target, the peak represents the triton channel and the broad plateau at lower energies, the α-particles. The low energy component is not produced promptly with the beam and most probably corresponds to β–particles from activity produced in the target by the neutron beam. Importantly, there is very little background. We were able to move the DSSD at least within 5 cm of the beam axis. There were also no problems associated with recovery from the proton pulse up to neutron energies of 1 MeV required for the ^{26}Al experiment. In the ^{26}Al experiment we will mount two 5*5cm^{2} ΔE-E DSSD (strips with 5mm pitch) telescope systems ~5cm from the beam axis, placed adjacent to another and parallel to the beam axis. This covers a laboratory polar angular range ~ 30-110° with respect to the centre of the sample, and corresponds to a solid angle of approximately 2 steradians. The proposed set-up is shown in Figure 5, and could in principle be augmented by the use of additional DSSD detectors and/or the detectors here could be moved closer to the sample and beam axis.

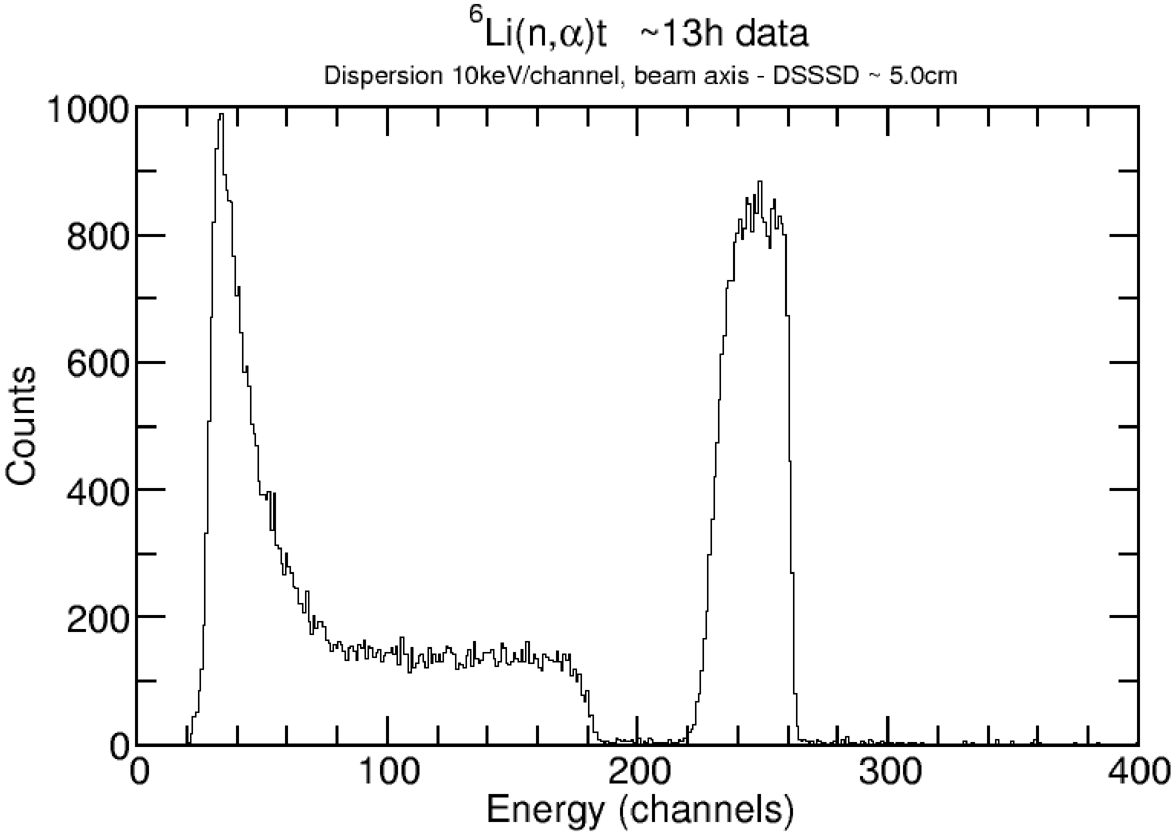

Figure 4. Energy spectrum taken for the test experiment study of the ^{6}Li + n → α + t reaction performed in October 2011 at the n_TOF facility. The broadened peak represents tritons of energy ~2.9 MeV. Note in the main experiment there will be negligible straggling in the thin ^{26}Al sample.

The DSSD detectors and electronics system and modified flange for the silicon monitor chamber will be provided by the Edinburgh Group. The Edinburgh Group has already purchased silicon detectors for the ΔE-E telescope systems which are 20 and 500μm thick, respectively. The Q-value for the ^{26}Al(n,α_0) reaction is 2.96 MeV (and 2.52 MeV for the (n,α_1) reaction) which corresponds to an α-particle range ~14 μm in Silicon, hence all α's from the ground and inelastic channels will stop in the ΔE detector. We would expect to operate this detector at a low energy threshold ~ 200 keV and obtain an energy resolution ~30 keV FWHM (straggling effects will be negligible in the thin ^{26}Al sample). The Q-value for the ^{26}Al(n,p_0)^{26}Mg reaction is 4.78 MeV, corresponding to a maximum proton range ~200μm in silicon. The lowest energy deposited by protons in the ΔE detector (corresponding to normal incidence to the silicon surface from the ground-state channel) will be ~ 300 keV so all proton channels will give ΔE-E coincidence signals allowing clean particle identification. The most intense reaction channel, ^{26}Al(n,p_1)^{26}Mg, has a Q-value of 2.97 MeV. Normalisation will be perfomed using the well known ^{10}B(n,α) reaction as used in the studies of Koehler [9]] and de Smet [10].

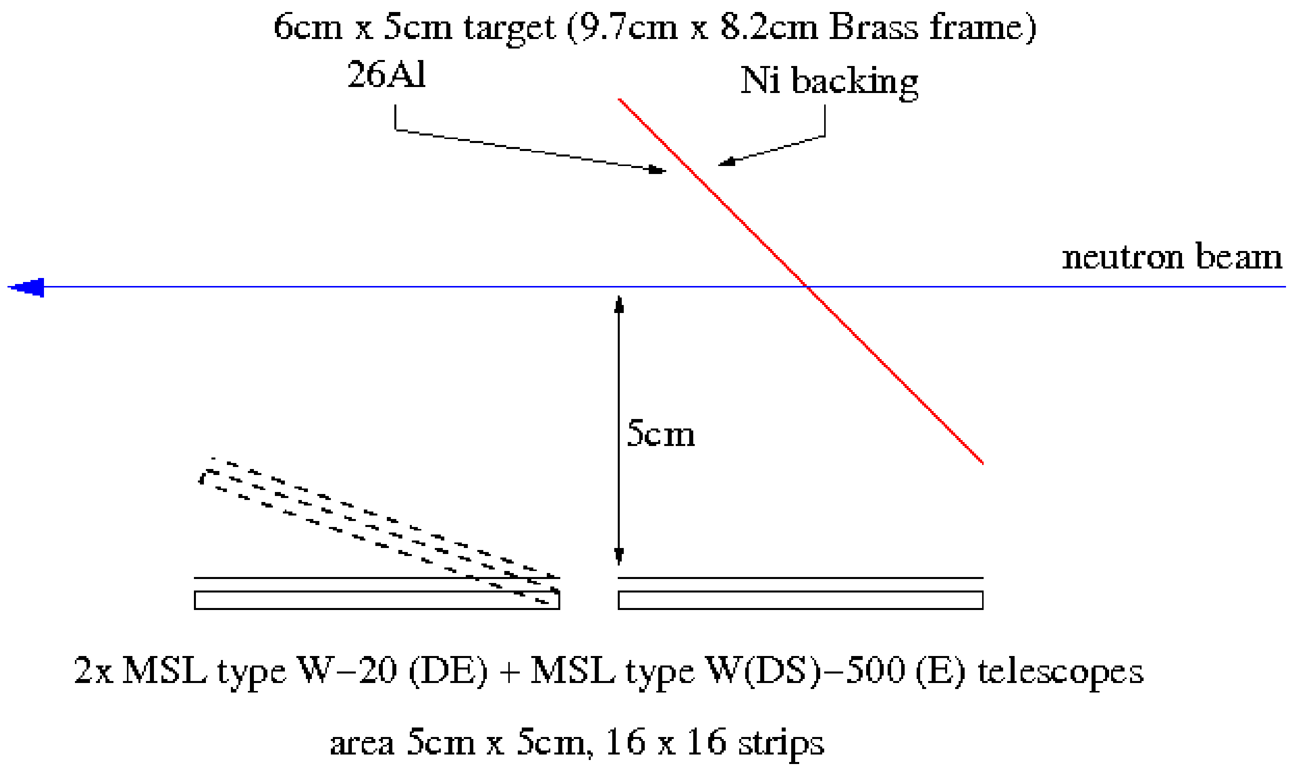

Figure 5: The proposed experimental set-up. The detector geometry is not fixed and in principle detectors could be moved to a closer geometry to increase the solid angle and angular range and could be augmented by additional DSSDs. Rate calculations assume the geometry as shown above.

Count Rate Estimates

The expected number of resonance counts are estimated for the (n,α) and (n,p) channels using the cross-section data published in Ref. [9] assuming 1.6e19 protons on target and the set-up of Fig 5.

Resonance energy (keV)	(n,α)	(n,p)
6	~ 50 counts	~15 counts
33	Not detectable	~ 40 counts

The table above lists the expected number of counts for both channels in the two strongest, known resonances. A detection efficiency of 20% and a tilt of 40 degrees of the target were assumed, increasing the effective target thickness by a factor of 1.3. Statistical uncertainties that can be reached are ~16% (α channel at 5.57 keV and proton channel at 33.7 keV) and 26% (proton channel at 5.57 keV), respectively. It should be noted that while these statistical uncertainties are higher than other measurements typically performed at n_TOF, the discrepancies between the resonance yields reported in the few previous studies of the ^{26}Al(n,p) and ^{26}Al(n,α) reactions are large. These discrepancies are typically a factor of 2-3 (see for example Figure 9, in ref. [10]), and cannot be accounted for by statistical uncertainties [3,9,10]. New measurements are therefore essential.

Summary

In this Letter of Intent we propose a new study of the ^{26}Al(n,p) and ^{26}Al(n,α) reactions to address systematic uncertainties in previous measurements of these reactions. The reactions for the first time would be studied across the full range of neutron energies relevant for convective C/Ne shell burning, and explosive Ne/C shell burning in Wolf-Rayet stars, thought to be the dominant source of cosmic ^{26}Al.

References

[1] W.A. Mahoney et al., Astrophys. J. 262, 742 (1982).

[2] R. Diehl et al., Nature (London), 298, 445 (2006).

[3] C. Iliadis, A. Champagne, A. Chieffi and M. Limongi, Ast. Phys. J. Supp. 193, 16 (2011).

[4] G. Lotay., P.J. Woods, D. Seweryniak, M.P. Carpenter, R.V.F. Janssens, and S. Zhu,

Phys. Rev. Lett. 102, 162502 (2009).

[5] G. Lotay, P.J. Woods, D. Seweryniak, M.P. Carpenter, H.M. David, R.V.F. Janssens, and S. Zhu, Phys. Rev. C84, 035802 (2011).

[6] R.T. Skelton, R.W. Kavanagh and D.G. Sargood, Ap. J. 271, 404 (1983).

[7] H.P. Trautvetter and F Kaeppeler, Z. Phys. A318, 121 (1984).

[8] H.P. Trautvetter, H.W. Becker, U. Heinemann, L. Buchmann, C. Rolfs, F. Kaeppeler, M. Baumann, H. Freiseleben, H.-J. Lutke-Stezkamp, P. Geltenbort and F. Gonnenwein, Z. Phys. A323, 1 (1996).

[9] P.E. Koehler, R.W. Kavanagh, R.B. Vogelaar, Yu. M. Gledenov and Yu. P. Popov,

Phys. Rev. C56, 1138 (1997).

[10] L. de Smet, C. Wagemanns, J. Wagemanns, J.Heyse, J. van Gils, Phys. Rev. C76, 045804 (2007).

[11] C. Ingelbrecht et al., Nucl. Inst. Meth. A480, 114 (2002).

[12] U. Abbondanno et al., (n_TOF collaboration) Technical Report CERN-SL-2002-053 ECT, CERN, Geneva, 2003.

[13] P.J. Sellin, P.J. Woods, D. Branford, T. Davinson, N.J. Davis, D.G. Ireland, K. Livingston, R.D. Page, A.C. Shotter, S. Hofmann, R.A. Hunt, A.N. James, M.A.C. Hotchkis, M.D. Freer, and S.L. Thomas, Nucl. Inst. Meth. A311, 217 (1992).