Title of proposed experiment

Measurement of the $^{25}Al(p,\gamma)^{26}Si$ reaction rate

Name of group
Yale Nuclear Astrophysics

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Members of group (name, institution, status)
(For each member, include percentage of research time to be devoted to this experiment over the time frame of the experiment)

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Date for start of preparations: September 1, 2005

Date ready: March 1, 2006

Completion date: August 31, 2006

Beam time requested:

12-hr shifts	Beam line/channel	Polarized primary beam?
42(^{26}Al)	ICS	no

SUMMARY	

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The detection of the 1.809-MeV γ-ray from ^{26}Mg, after ^{26}Al β-decay, is proof of the ongoing nucleosynthesis of ^{26}Al in our galaxy. However, the site of ^{26}Al production is widely disputed. In novae, the reaction sequence that leads to the production of ^{26}Al, and consequently the 1.809-MeV γ-ray, is $^{24}Mg(p,\gamma)\ ^{25}Al(\beta^+\ \nu_e)\ ^{25}Mg(p,\gamma)\ ^{26}Al^{\ g.s.}$. If the $^{25}Al(p,\gamma)\ ^{26}Si$ reaction is faster than the β–decay rate of ^{25}Al, which has a half-life of 7.183(12) s, this β-decay can be bypassed by the $^{25}Al(p,\gamma)\ ^{26}Si(\beta^+\ \nu_e)\ ^{26}Al^m(\beta^+\ \nu_e)\ ^{26}Mg^{\ g.s.}$ sequence with no 1.809-MeV γ-ray, where $^{26}Al^m$ is an isomer of ^{26}Al. Therefore, an accurate reaction rate for $^{25}Al(p,\gamma)\ ^{26}Si$ is crucial in determining the amount of ^{26}Al produced by novae in the galaxy.

The $^{25}Al(p,\gamma)\ ^{26}Si$ reaction has yet to be studied directly, due to a lack of radioactive ^{25}Al beams. However, it has been shown that the largest source of uncertainty in the reaction rate is a result of uncertainties in the properties of the resonances of ^{26}Si that lie <1 MeV above the proton threshold (S_p = 5.512 MeV). The J^π values and proton branching ratios, Γ_p, of these states also need to be determined to calculate the correct reaction rate of $^{25}Al(p,\gamma)\ ^{26}Si$.

To determine these values a measurement of the $^{26}Al(^3He,t)\ ^{26}Si$ reaction and the resulting proton decay of ^{26}Si has been proposed. This experiment will take place at the Wright Nuclear Structure Lab at Yale University. However, in order to carry out this experiment an ^{26}Al target containing at least ~10^{17} atoms/cm^2 is needed. Therefore, three weeks of ^{26}Al beam time is requested in order to fabricate this target at the HRMS at TRIUMF-ISAC by implanting ^{26}Al into a 40μg/cm^2 carbon foil. This beam time is requested on the condition that implantation of ^{27}Al in a carbon foil can be successfully demonstrated at the GP3 beam line at TRIUMF-ISAC.

BEAM and SUPPORT REQUIREMENTS	

Experimental area

A) ^{27}Al implantation: OLIS, end of general purpose 3 (GP3) beam line in ISAC-1
B) ^{26}Al implantation: exit of HRMS downstairs in ISAC-1
C and D) ^{26}Al(^{3}He,t) ^{26}Si(p) ^{25}Al: WNSL at Yale University

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

A) ~51 keV ^{27}Al beam on C foil
B) 51 keV ^{26}Al beam on C foil, 1.56 x 10^{10} ^{26}Al/sec, beam delivery point at ISAC collection station

Secondary channel

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

none

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.

The ISAC collection station will be used.

There are no DAQ requirements.

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.

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.

Radiation safety

Due to the relatively long half-life of ^{26}Al (7.2 X 10^5 yr) no special radiation safety measures are necessary. ^{27}Al is stable and therefore also requires no safety measures.

Chemical safety

The aluminum will be implanted into the carbon foil under a vacuum. Thus, no special chemical procedures for the handling of aluminum metal are necessary.

Introduction and Scientific Justification

One of the important ongoing questions in nuclear astrophysics is the site of ^{26}Al production. After the ground state of ^{26}Al β–decays to ^{26}Mg, a 1.809-MeV γ-ray is emitted 99.7% of the time. This γ-ray was first detected in the extraterrestrial environment by HEAO-3 [1,2]. The presence of this extraterrestrial ^{26}Al, which has a half-life of 7.2 X 10^5 yr, is clear evidence of ongoing nucleosynthesis in the galaxy. This first measurement was followed by several others [3 and references therein] including that of COMPTEL [4,5], which produced a detailed map of the 1.809-MeV γ-ray distribution throughout the galactic plane. New measurements being carried out by INTEGRAL will provide a higher resolution map of the 1.809-MeV γ-ray line; preliminary results have already been reported [6]. The source of the large amounts, ~1-3 M_{υ}, of ^{26}Al in the galaxy is the subject of intense debate.

Proposed sites for the production of ^{26}Al are supernovae, novae (especially ONe novae), Wolf-Rayet stars and Asymptotic Giant Branch (AGB) stars. Although the overall contribution to galactic ^{26}Al from novae is thought to be no more than 0.4 M_{υ} [7], it cannot be disregarded altogether. In addition, determining the production rate of ^{26}Al will further constrain nova models. This rate is not known in large part due to the uncertainties in the key reaction ^{25}Al(p,γ)^{26}Si[8,9]. ^{26}Al is ejected from novae as a result of the reaction sequence ^{24}Mg(p,γ)^{25}Al($\beta^+ \nu_e$)^{25}Mg(p,γ)^{26}Al$^{g.s.}$. It is this ^{26}Al$^{g.s.}$, which β–decays into ^{26}Mg*, which in turn emits the 1.809-MeV γ-ray that is detected. However, the ^{25}Al beta decay, which has a half-life of 7.183(12) s, can be bypassed by the ^{25}Al(p,γ)^{26}Si($\beta^+ \nu_e$)^{26}Al^m($\beta^+ \nu_e$)^{26}Mg$^{g.s.}$ sequence, if the ^{25}Al(p,γ)^{26}Si reaction is faster than the ^{25}Al β–decay rate. ^{26}Al^m is an isomer of ^{26}Al, which decays only to the ground state of ^{26}Mg, bypassing the 1.809-MeV γ-ray (figure 1). This sequence bypasses the emissions of the 1.809-MeV γ-ray. The beta decay half-lives of ^{26}Si and ^{26}Al^m in this reaction sequence are 2.234(13) s and 6.3452(19) s, respectively.

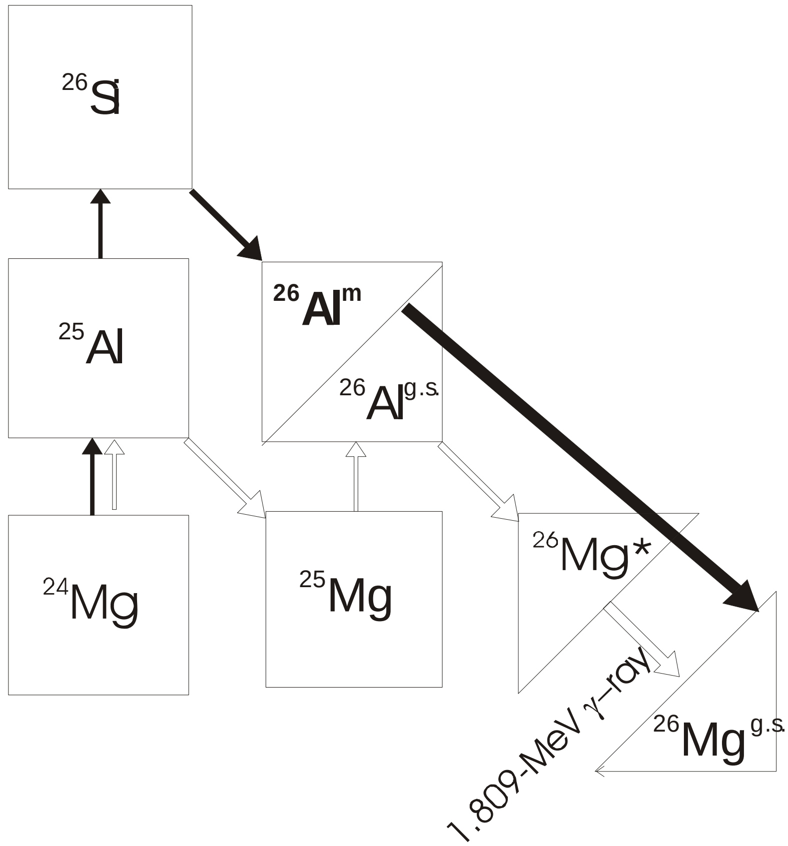

Figure 1. Competing reaction sequences. The filled arrows represent the reaction chain that does not produce a 1.809-MeV gamma ray.

The resonant component of the reaction rate is given by [10],

$$< \sigma \upsilon > = \left(\frac{2\pi}{\mu kT} \right)^{3/2} \hbar^2 \sum_i (\omega\gamma)_i \exp\left(\frac{-E_{r,i}}{kT} \right), \tag{1}$$

where T is the temperature and $(\omega\gamma)_i$ is the resonance strength given by

$$(\omega\gamma)_i = \frac{2J_i + 1}{(2J_1 + 1)(2J_2 + 1)} \left(\frac{\Gamma_p \Gamma_\gamma}{\Gamma} \right)_i . \tag{2}$$

Therefore, the reaction rate depends exponentially on the resonance energies, $E_{r,i}$, and even small uncertainties in those energies can cause significant errors in the calculated reaction rate. Additionally, the spin of the resonant state, J_i, and its gamma and proton partial widths, Γ_γ and Γ_p respectively, are needed to calculate the resonance strength and the reaction rate.

Due to the current lack of radioactive ^{25}Al beams, the ^{25}Al(p,γ) ^{26}Si reaction has not yet been studied directly. However, there have been a number of indirect studies of ^{26}Si through the ^{28}Si(p,t)^{26}Si [11,12,13], ^{24}Mg(^{3}He,n) ^{26}Si [14,15,16] and ^{29}Si(^{3}He,^{6}He) ^{26}Si [17] reactions. It has been shown [18] that the largest uncertainties in the ^{25}Al(p,γ) ^{26}Si reaction rate are the results of the uncertainties in the resonances of ^{26}Si that lie <1 MeV above the proton threshold (S_p = 5.518 MeV). More specifically, two missing states (a 1^+ and a 3^+ resonance) are predicted to make the dominant contribution to this reaction rate [18]. Those two states, which were not yet observed when ref. [18] was written, were predicted to lie at excitation energies of 6.542 MeV and 5.970 MeV, respectively, based on their mirror levels in ^{26}Mg. There have been several recent measurements of the astrophysically important region of 5.9-6.0 MeV [13,16,17]. However, there are several discrepancies in the states observed and the J^π values assigned (table I).

Endt [19]		Bardyan *et al.* [13]		Parpottas *et al.* [16]		Caggiano *et al.* [17]	
E_x	J^π	E_x	J^π	E_x	J^π	E_x	J^π
		5.515(5)	4+	5.515(4)	4+	5.526(8)	4+
5.562(28)							
				5.670(4)	1+	5.678(8)	1+
		5.916(2)	0+	5.912(4)	3+		
5.940(25)	0+			5.946(4)	0+	5.945(8)	3+
6.350(25)	2+	6.300(4)		6.312(4)	2+		
		6.380(4)		6.388(4)	2+		
6.470(30)	0+			6.471(4)	0+		

Table I. Previously determined excitation energies and J^π values for ^{26}Si located 1 MeV above the proton threshold.

It is important to note, that while much of the experimental work done to determine the ^{25}Al(p,γ) ^{26}Si reaction rate has focused on the level energies of ^{26}Si, there are other values that contribute to the uncertainty of this rate, such as the gamma and proton partial widths, Γ_γ and Γ_p respectively. To date, there has been no direct experimental determination of these partial widths. Previous works have used values based on the ^{26}Mg mirror states from [18] to determine the gamma widths and relied on the model prescriptions of [10] to calculate the proton widths [12,15,16].

The J^π and level excitation energy discrepancies found in the three most recent measurements of ^{26}Si [13,16,17], clearly need to be resolved in order for the reaction rate of ^{25}Al(p,γ) ^{26}Si to be accurately determined. Measurements are also needed to resolve the doublets found in the relevant energy region and lower the uncertainties of the excitation energies. Finally, other parameters that are used in the reaction rate calculation such as the gamma and proton partial widths need to be directly determined experimentally in order to lower the uncertainties in this reaction rate and to more accurately calculate the amount of ^{26}Al in the galaxy due to novae.

The Experiment

Once this implantation method is proven possible, using an ^{27}Al beam on C foil, this work will involve three parts: (i) fabrication of a ^{26}Al target, (ii) measurement of the excitation energies and J^π values of states in ^{26}Si in the region $0 < E_r < 1$ MeV above proton threshold through the ^{26}Al(^{3}He,t) ^{26}Si* reaction and (iii) measurement of the proton partial widths for these states via the proton branching ratio Γ_p/Γ for the proton decays of ^{26}Si.

A. ^{27}Al target test

Targets have been fabricated previously at TRIUMF using the implantation method (see ref. 30 and below). Therefore, ^{26}Al implantation in C foil should be possible. However, to be certain that it is, an ^{27}Al target should be fabricated via implantation to show that implantation with Al is indeed feasible.

B. ^{26}Al target fabrication

Previous experiments have used ^{26}Al targets that were fabricated via evaporation and molecular plating [20, 21]. However, creating ^{26}Al targets using these methods has several drawbacks. These targets typically contain large amounts of ^{27}Al, with ^{27}Al/^{26}Al ratios of 10-16. Other problems include the low efficiency (~10%) of evaporation, the precipitation of other species during molecular plating [22] and inhomogeneity of the samples using both methods. Targets have also been fabricated via the ^{26}Mg(p,n) ^{26}Al reaction [23]. In all of these methods the number of ^{26}Al atoms deposited onto the targets has only been on the order of 10^{15}- 10^{16} atoms/cm^2, which is considerably less than the 10^{17} atoms/cm^2 needed to create a usable target for coincidence ^{26}Al(^{3}He,t) ^{26}Si(p)^{25}Al measurements of these proton decays. Using the method of implantation will solve most, if not all, of these problems, while also providing a more robust target.

We propose to fabricate this ^{26}Al target at ISAC. TRIUMF is unique, in that it is the only facility in the world that can produce a significant amount of ^{26}Al beam. This is because the production target is able to withstand 85 μA of proton current [24]. ^{26}Al is one of the few radioactive beams that have been made by TRIUMF with enough intensity to perform experiments, which are astrophysically significant (the others are ^{21}Na and ^{22}Na). Therefore, this experiment takes advantage of one of the capabilities that make TRIUMF distinctive.

Implantation is not a simple process; however, development of the process is not necessary. The experiment for which this target is produced does not rely on highly specific target parameters such as the depth and location of the ^{26}Al in the target or the target profile. Thus, the main challenge is simply being able to embed enough ^{26}Al in the carbon foil to create a usable target.

A beam of ^{26}Al will be created to embed ^{26}Al in a carbon target, which is approximately 40 μg/cm^2 thick. Our group has fabricated similar targets of ^{20}Ne at WNSL, by varying the beam energy and location to distribute 7.3±1.0 μg/cm^2 of ^{20}Ne in a 40 μg/cm^2 carbon foil [25]. In this procedure, the foil was first bombarded with the highest energy of ^{20}Ne available (40 keV) at low current, which deposited ^{20}Ne near the target's center. Then the current was increased while decreasing the beam energy, thereby implanting ^{20}Ne throughout the foil, from the middle of the target to the front. The target was reversed and the process repeated (figure 2). This method produced a durable target that avoided saturation and was free from thermal damage.

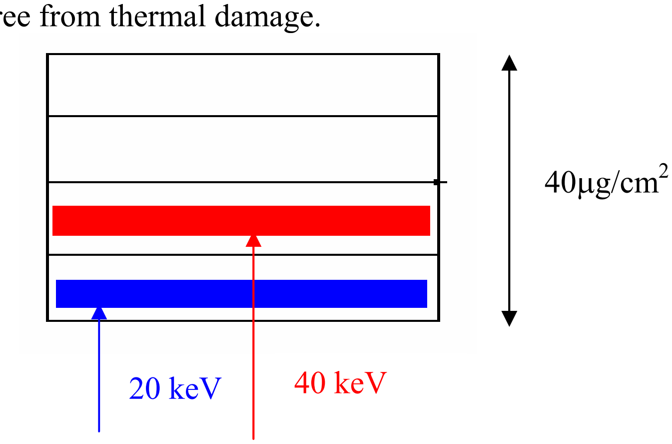

Figure 2. Schematic of ^{20}Ne target midway through production. Colored arrows indicate implantation beam energy.

The high-resolution mass separator at TRIUMF will allow us to create a target that is free of ^{27}Al as well as any other contaminants of A ≠ 26. The only target contaminant will be ^{26}Mg, which is acceptable as discussed below.

C. $^{26}Al(^{3}He,t)^{26}Si$

Once the ^{26}Al target is made, it will be brought to the Wright Nuclear Structure Lab (WNSL) at Yale University to be used to measure excited states in ^{26}Si via the $^{26}Al(^{3}He,t)^{26}Si$ reaction. The ^{26}Al target will be bombarded by ^{3}He nuclei, and the resulting tritons produced by the $^{26}Al(^{3}He,t)^{26}Si$ reaction will exit the target chamber and enter our Enge Split-Pole magnetic spectrograph, which separates the reaction products based on their magnetic rigidity (i.e. their charge and momentum) and focuses them onto a focal plane [27]. Their energy can then be determined with uncertainties as small as 1 keV [11]. The simulation of the focal plane clearly shows that peaks due to the usual ^{12}C and ^{16}O contaminants do not interfere with the ^{26}Si excitation energy range of interest, $E_x \leq 1$ MeV above the proton threshold, as shown in the red box in figure 3.

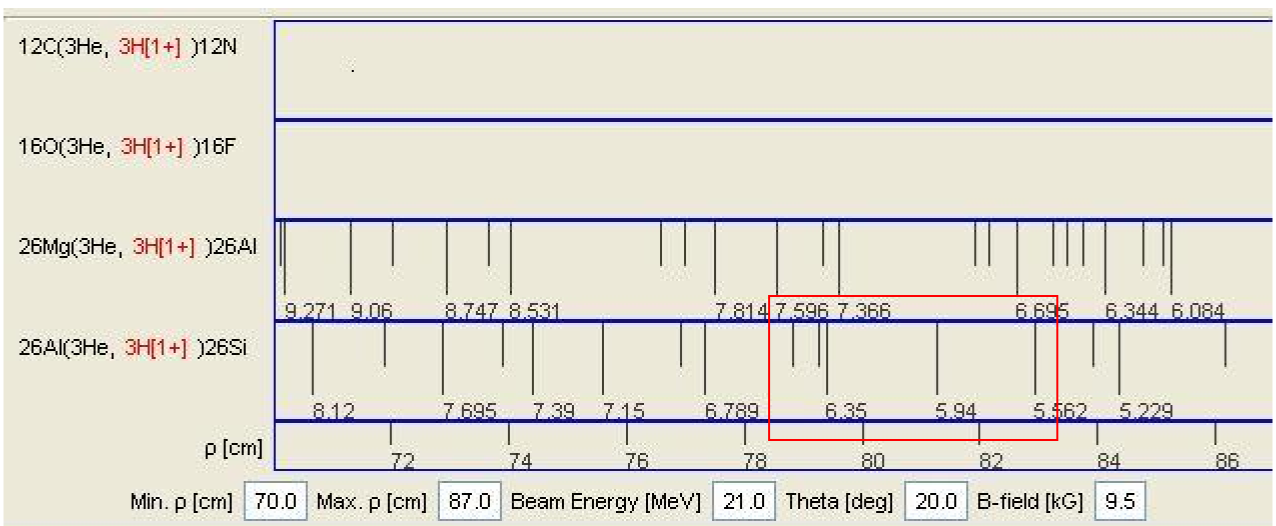

Figure 3. Simulation of Focal Plane for $^{26}Al(^{3}He,t)^{26}Si$ reaction.

However, there will be ^{26}Mg and ^{26}Na (which beta decays to ^{26}Mg with a half-life of 1.077(5) s) contaminating the target. There are several contaminant peaks from $^{26}Mg(^{3}He,t)^{26}Al$ in the region of interest. In order to distinguish these contaminant peaks from the peaks produced by ^{26}Al, a (^{3}He,t) measurement will be done using a ^{26}Mg target. Additionally, simulations show that the lines from the proton decays of ^{26}Si and ^{26}Al, resulting from the $^{26}Mg(^{3}He,t)^{26}Al$ reaction, can be easily separated in the coincidence measurements (figure 4).

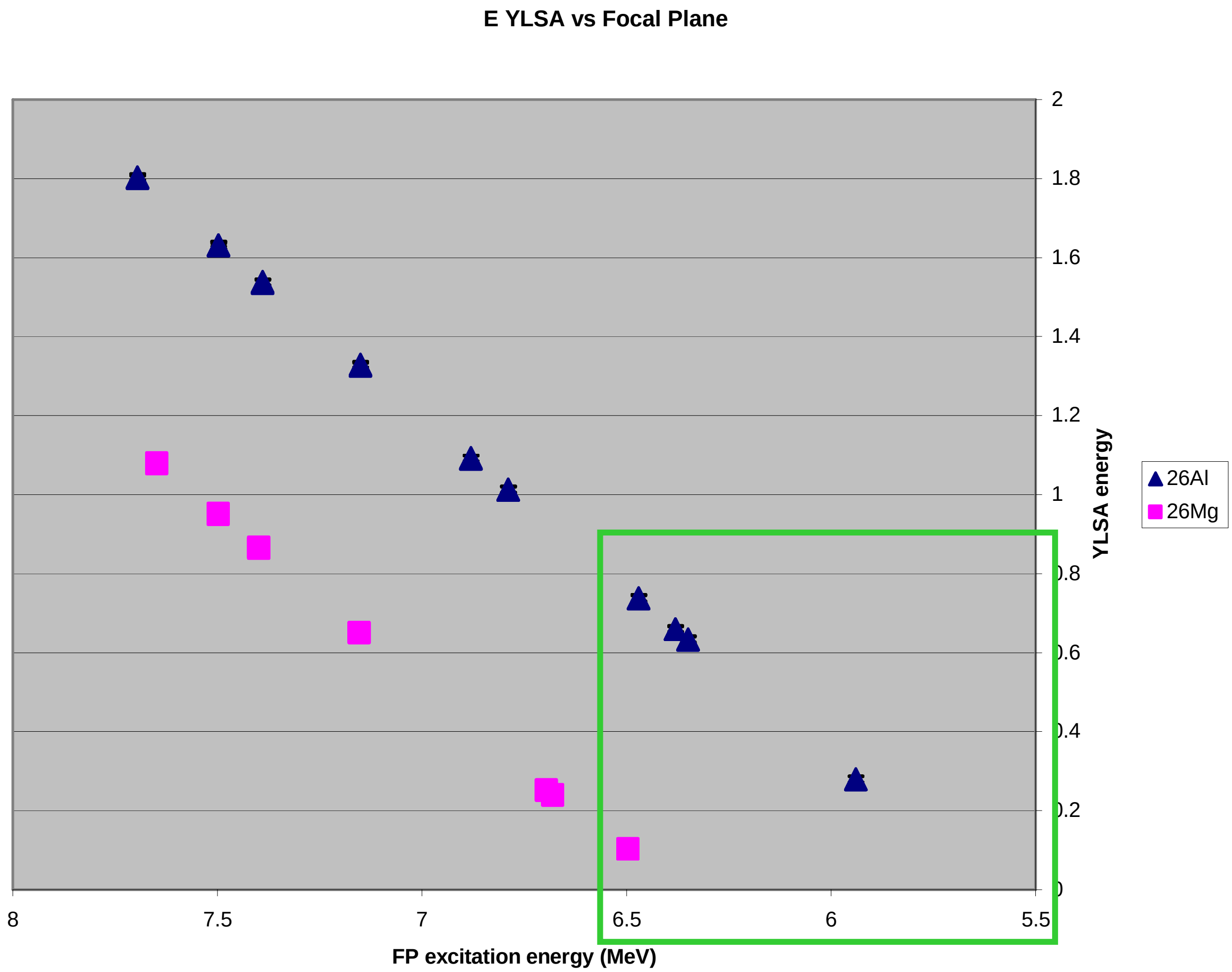

Figure 4. Plot of the energy deposited in YLSA vs. Focal Plane position (excitation energy of parent nucleus) for simulations of the proton decays from ^{26}Si and ^{26}Al.

The J^{π} values for these levels can be measured by changing the angle of the Enge Split-Pole Spectrograph and measuring the cross-section of the reaction at several different angles. Using the code DWUCK4, DWBA calculations can be used to fit these measured angular distribution and in turn determine the angular momentum transfer, l, and the total angular momentum transfer, J, for the excited states of interest in the reaction. Simulations of different J and l transfers show that different l transfers are distinct (figure 5). Thus, this experiment would determine the angular moment transfer and narrow the possible total angular momentum, J, to two values.

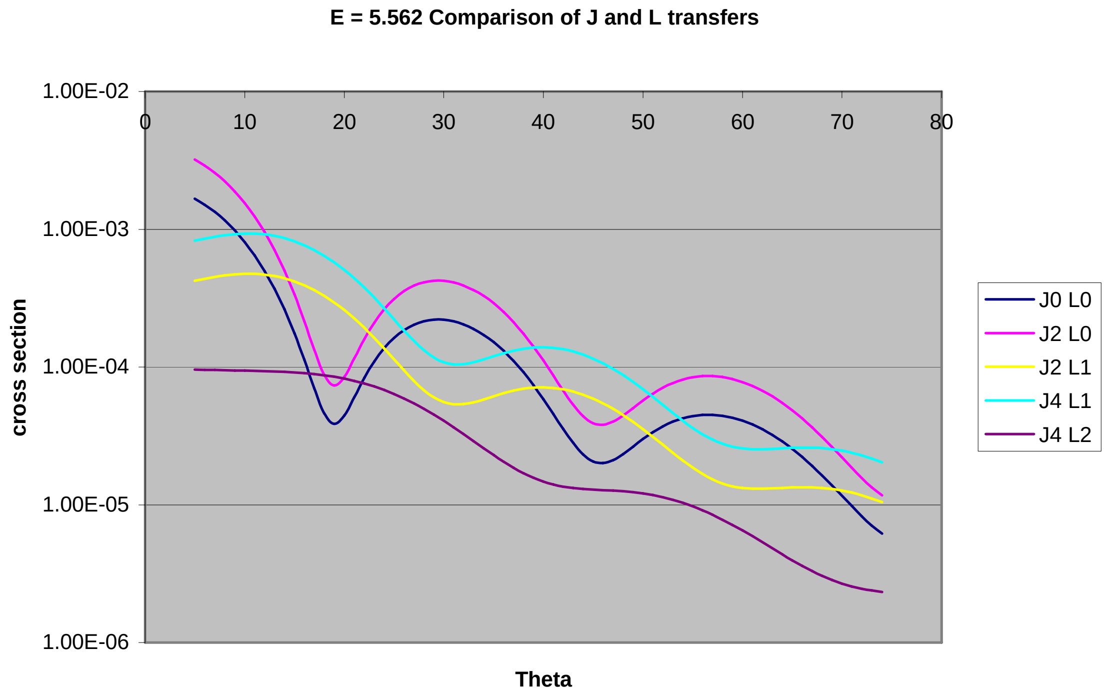

Figure 5. DWBA calculations of the ^{26}Al(^{3}He,t) ^{26}Si reaction for different J and l transfers, using the code DWUCK4.

D. Measurement of the proton branching ratio

The proton decay branching ratio, Γ_p/Γ, for each of these resonances will be measured by detecting the protons, which decay from the ^{26}Si states in coincidence with the tritons detected in the spectrometer focal plane. These protons will be detected using the Yale Lamp Shade Array (YLSA). YLSA is an array of five position-sensitive silicon-strip detectors mounted in the target chamber, which extend from θ_{lab}=131° to θ_{lab}=166°, subtending 14% of the lab solid angle [28]. By fitting the calculated $d\sigma/d\Omega$ to the angular distribution measured by YLSA and integrating over θ, the branching ratio can be directly extracted [28, 29]. Monte Carlo calculations for YLSA give an efficiency of about 11% for an s-wave proton decay ($3^+ \rightarrow 1/2^+ \otimes 5/2^+$). For a p-wave proton decay the efficiency is 24%.

Even if it is not possible to determine the J^π values using angular distributions as explained above, by using YLSA it will be possible to resolve the 0^+ / 3^+ discrepancy of the 5.916/5.912 MeV state illustrated in Table I. This is because the 3^+ state has an $l = 0$ transfer, whereas the 0^+ state has an $l = 4$ transfer. Therefore, the 3^+ state will have a much stronger proton branching ratio, and by gating on that strong state in the YLSA spectrum it is possible to see where the state is located on the focal plane.

Experimental equipment required

A) ^{27}Al target test

In order to show that target implantation with Al is possible, ^{27}Al will bombard a 40 μg/cm^2 carbon foil. That foil will be mounted on a flange at the end of the GP3 beam line, located in ISAC1. No additional equipment is needed for this test.

B) ^{26}Al target production

The target implantation portion of this experiment can be done using existing beamlines at ISAC. The carbon foils will be mounted in a chamber that has already been built for the production of a ^{22}Na target [30]. The chamber consists of a target ladder and a LN_2-cooled coil to remove vacuum contaminants. Fortunately, due to the long half-life of ^{26}Al no additional equipment will be needed for safety reasons.

C) ^{26}Al(^{3}He,t) ^{26}Si and D) proton branching ratio

The rest of the experiment will be preformed at WNSL using the Split-Pole Enge Spectrograph, focal plane detector and silicon strip detector, YLSA. No additional equipment or modifications to existing equipment will be needed to carry out the last two phases of the experiment.

Experimental beam requirements

A) ^{27}Al target test

The ^{27}Al test target will be fabricated using OLIS on the ground level in ISAC-1. Since no radioactive beam is needed to produce this target, it can be fabricated while the proton beam from the cyclotron is being used for other experiments. The fabrication should only take a day to complete. This test is planned for 12/17/2005, after the E989 run at DRAGON, when OLIS is not being used. Thus, the method of implantation with Al would be proven possible before ^{26}Al beam time is assigned for spring 2006.

B) ^{26}Al target production

The target implantation will take place immediately downstream of the high-resolution mass separator, which is one floor below ground level in the ISAC-1 experimental hall. An advantage to this location is that stable beam can be run to DRAGON while the target is being made. Therefore, other experiments and the target fabrication can be preformed concurrently. Due to the low intensity of the ^{26}Al beam that is available, most likely only one target can be produced in the time allotted.

Currently, there are efforts to enhance the ^{26}Al beam intensity at TRIUMF. A "high-power" production target, which in the future is capable of handling 85 μA of the primary proton beam (due to collimator limitations), fitted with special cooling fins has been installed. By achieving 85 μA of proton current the ^{26}Al beam intensity will increase by 120%. This gain is due to the present proton beam intensity of 70μA and the increase of 40% in ^{26}Al intensity for every 5μA of proton beam current. Thus far, ISAC has been able to produce a beam of 2.5×10^{10} ^{26}Al/sec, which is calculated from the current on FC14, immediately downstream from the HRMS. Assuming that 50% of this beam reaches the collection station, which was the case during the ^{22}Na target implantation, a beam of 1.25×10^{10} ^{26}Al/sec will bombard the C foil at the collection station. In order to create a usable target, 10^{17} atoms/cm^2 of ^{26}Al must be embedded in the carbon. By focusing a beam of 1.56×10^{10} ^{26}Al/sec onto a 3 x 3 mm^2 spot, the time needed to embed 10^{17} atoms of ^{26}Al, assuming 67% efficiency due to rastering, would be 10 days [26]. Provided that the ^{27}Al test target is fabricated successfully, three weeks of beam time is asked for due to the amount of time we expect ^{26}Al beam to be unavailable during the run. This estimate is based on the time that ^{26}Al beam was unavailable during E989.

C and D) ^{26}Al(^{3}He,t) ^{26}Si and proton branching ratio

As discussed above the last two phases of the experiment will take place at Yale. The 20 MV ESTU tandem accelerator will accelerate ^{3}He nuclei, created by a He negative ion source (NEC Negative RF charge exchange source), to an energy of 21 MeV, which will bombard the ^{26}Al target. The reaction products will then be analyzed to determine energy levels of ^{26}Si and the proton branching ratios, to better determine the reaction rate of ^{25}Al(p,γ) ^{26}Si.

In addition to reducing uncertainties in the ^{25}Al(p,γ) ^{26}Si reaction rate, an ^{26}Al can be used to study other reactions involved in the production of ^{26}Al in the galaxy, such as ^{26}Al(p,γ) ^{27}Si. Mass measurements can also be made using this target. For example, to date there is only one mass measurement of ^{24}Al used in the accepted mass tables. An ^{26}Al target could be used to find a more precise mass of ^{24}Al via the ^{26}Al(p,t) ^{24}Al reaction at WNSL. There are multiple important uses for an ^{26}Al target, which would lead to a more reliable production rate of ^{26}Al is the galaxy.

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