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β decay of ^{26}P to determine the ^{25}Al(p,γ)^{26}Si reaction rate in novae

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Classical novae may make a non-negligible contribution to the observed Galactic inventory of the long lived radionuclide ^{26}Al. The largest remaining nuclear-physics uncertainty associated with the production of ^{26}Al in nova models is the thermonuclear rate of the ^{25}Al(p,γ)^{26}Si reaction. This rate is expected to be dominated by resonant capture through a 3^+ level in ^{26}Si. Numerous studies over the past decade have contributed evidence that this 3^+ level lies at an excitation energy of roughly 5926 keV, which is 412 keV above the proton-emission threshold. However, the strength of this resonance has never been measured directly because a ^{25}Al beam of sufficient intensity is not available. We are preparing to measure the beta decay of ^{26}P, which is known to populate the 3^+ ^{26}Si level of interest strongly. A fast ^{26}P beam will be produced by the fragmentation of a ^{36}Ar primary beam on a ^{9}Be target, isolated using a fragment separator, and directed towards a double sided germanium strip detector that will be used to correlate implanted fragments with their subsequent beta decays. Beta-delayed gamma rays will be detected using the surrounding Segmented Germanium Array (SeGA) to determine the gamma-ray branching ratio of the 3^+ level. In combination with the known proton partial width and the known spin, this branching ratio would provide the first value for the 3^+ resonance strength that is independent of estimates based on mirror arguments or the shell model. Our experiment is scheduled to run at the National Superconducting Cyclotron Laboratory from August 27th to 30th, 2012.

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1. Introduction

A classical nova is the result of thermonuclear runaway on the surface of a white dwarf star that is accreting hydrogen-rich material from a companion star. Novae are well suited for studies of explosive stellar nucleosynthesis because the observational, theoretical, and nuclear-experimental aspects of their study are each fairly advanced. It is possible that novae make a significant contribution of up to 20 % [1] to the steady-state Galactic ^{26}Al abundance that is now routinely detected using γ-ray telescopes [2]. This is important for studies of Galactic chemical evolution including the modeling of massive stars and their supernovae because the Galactic ^{26}Al/^{60}Fe abundance ratio is used as a benchmark for nucleosynthesis in these models [3].

In recent years, the thermonuclear rates of the ^{25}Al$(p,\gamma)^{26}$Si reaction have contributed the largest remaining nuclear-physics uncertainties to the expected production of ^{26}Al in novae [4]. These uncertainties were as large as an order of magnitude in 2006 and resulted in a factor of 3.4 variation in the amount of ^{26}Al expected to be produced by a nova on a 1.35 solar mass ONeMg white dwarf. The large uncertainty in the reaction rate was due to the uncertainty in the ^{25}Al$(p,\gamma)^{26}$Si resonance energy and strength of an expected 3^+ level in ^{26}Si, motivating many recent experimental studies of ^{26}Si structure above the proton threshold that have contributed to determining the energy and strength of this resonance but without absolutely conclusive results [4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 17, 18]. A 2009 evaluation [15] of available experimental data pointed out the utility of ^{26}P β decay for the study of this level resulting in the conclusion that it resides at a relatively precise c.m. resonance energy of 412(2) keV (or $E_x = 5926$ keV, using the Q value of 5513.7 keV from Ref. [12]) based on its β-delayed proton emission [16], reducing the uncertainty in the ^{25}Al$(p,\gamma)^{26}$Si rate by large factors. More evidence in support of this resonance energy based on the ^{28}Si$(p,t)^{26}$Si*(p) reaction was recently published [17]. Unfortunately, no γ decays of this state have been observed yet due to the relatively large proton branching ratio. In the evaluation of Ref. [15] the accepted lifetime of the ^{26}Mg mirror level was employed in the estimation of the 3^+ resonance strength and it has been argued [5, 19] that the lifetime measurement [20] of the ^{26}Mg mirror level is erroneous. The shell model has been used [5] instead to calculate a gamma-ray partial width for the ^{26}Si level that is higher than the estimate based on the mirror-level lifetime by a factor of three. The thermonuclear ^{25}Al$(p,\gamma)^{26}$Si reaction rates are proportional to the γ-ray partial width of this level at nova temperatures and, therefore, the uncertainty in the width translates directly into an uncertainty in the rate.

2. Experiment

We have designed an experiment to search for ^{26}P β-delayed γ rays de-exciting the 5926-keV ^{26}Si level at Michigan State University's National Superconducting Cyclotron Laboratory. In particular, we will search for an expected transition of 1739 keV, which would provide more evidence that the 5926-keV ^{26}Si level corresponds to the key 3^+ resonance in the ^{25}Al$(p,\gamma)^{26}$Si reaction. We wish to determine the absolute intensity for the 1739-keV line (and other weaker transitions) in the β decay of ^{26}P through the 5926-keV level and, hence, to determine Γ_γ/Γ of the 5926-keV level, thereby determining the key ^{25}Al$(p,\gamma)^{26}$Si 3^+ resonance strength $\omega\gamma$ in combination with $\Gamma_p = 2.9(10)$ eV from Ref. [5] (note that $\omega\gamma \propto \frac{\Gamma_\gamma \Gamma_p}{\Gamma}$ and $\Gamma = \Gamma_\gamma + \Gamma_p$). To our knowledge, accomplishing these goals will complete the determinations of the nuclear reaction rates relevant to ^{26}Al production in nova models to a level of precision that should be sufficient for the foreseeable future. On the other hand, non-observation of the 1739-keV γ ray above the minimum expected intensity could reintroduce large uncertainties to the fraction of Galactic ^{26}Al produced in novae because the energy of the important 3^+ level would be in question once again.

The 5926-keV ^{26}Si level is populated very strongly (18 %) by the β decay of ^{26}P [16]. We plan to measure the de-excitation of the 5926-keV ^{26}Si level, populated through the β decay of ^{26}P, to search for an expected 1739-keV gamma ray that would be the strongest γ-ray signature of the 3^+ level [15]. Recent estimates [15] suggest that 71 % of the γ-ray branching from the 3^+ level should be via the 1739-keV γ-ray transition to the known 3^+ level at $E_x = 4187$ keV. We will also search for weaker γ-ray branches from the 5926-keV level whose detection would supplement the information from the strongest branch. Since the absolute β-delayed proton intensity through the 5926-keV level has been measured to be 18.0(9) % [16], we only need to measure the corresponding absolute $\beta\gamma$ intensity to determine Γ_γ/Γ. We expect the absolute ^{26}P($\beta\gamma$) branching through this level to be between 0.1 % and 2.2 %, depending on whether we use the mirror level in ^{26}Mg or the shell model to estimate Γ_γ and incorporating the intrinsic uncertainties in these methods (factors of 2 and 3, respectively [5, 15]). Measurements of these γ-ray transitions will also provide independent measurements of the 3^+ excitation energy that may be used to confirm the resonance energy in combination with the well-known ^{25}Al$(p,\gamma)^{26}$Si Q value [11, 12, 13].

We will produce a ^{26}P beam of up to 200 pps using projectile fragmentation of a 150 MeV/u ^{36}Ar beam on a 1 g/cm^2 Be target. After separation using the A1900 fragment separator and a radio-frequency fragment separator, the ^{26}P fragments will be implanted into a segmented, planar Ge detector. Particle identification will be accomplished through standard time-of-flight and energy-loss measurements. Energy loss will be measured using two 60-μm Si PIN detectors upstream of the experiment station and the time-of-flight will be measured between a scintillator at the extended focal plane of the A1900 the PIN detector. The planar Ge detector will be used to detect both the high-energy implanted ions and the low-energy beta decays. The timing correlation between an identified implanted ion and the subsequent β decay will significantly reduce room backgrounds and allow beam impurities to be differentiated from ^{26}P ions. The implant-decay correlations will be particularly important to veto events from ^{24}Al, an expected beam contaminant whose decay will produce many high-energy γ ray lines producing substantial Compton background in the region of interest and a second-escape peak at 1732 keV.

The implantation detector is a 256-fold segmented, 1-cm thick planar Ge detector. The segmented detector will allow a higher rate of implant-decay correlations than an un-segmented detector because each segment will effectively act as an independent detector. We expect that roughly 50 of these segments will actually be active by virtue of being hit by the ^{26}P beam, leading to an implantation rate of a few ^{26}P ions per second per segment. Assuming an implantation rate of 100 s^{-1} into 50 illuminated pixels results in an average of approximately 500 ms between consecutively implanted ^{26}P ions, which is sufficiently long to identify most ^{26}P decays [$t_{1/2} = 43.7(6)$ ms] while vetoing a large fraction of ^{24}Al decays. Ultimately, we may limit the total implantation rate based on the fraction of the steady-state ^{24}Al ions detected in the beam in order to optimize the veto efficiency.

The implantation detector will be surrounded by the Segmented Germanium Array (SeGA) to

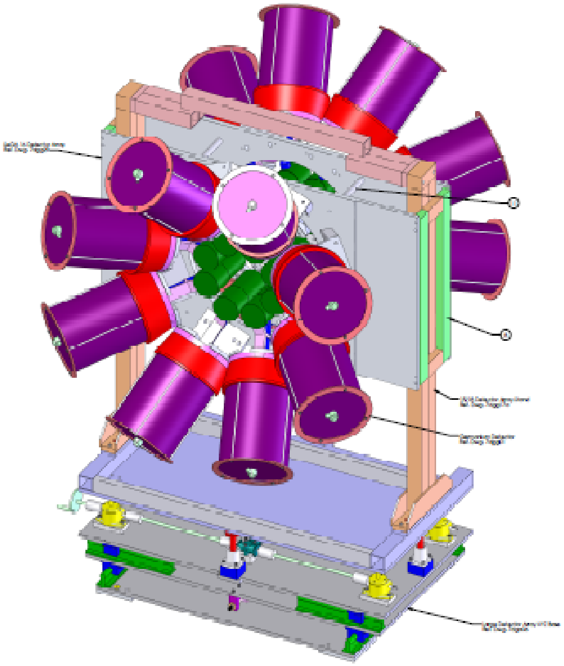

Figure 1: Technical drawing showing the Segmented Germanium Array surrounding our planar germanium detector.

detect β-delayed γ rays (Fig. 1). We have simulated the performance of the SeGA using a Geant4 Monte-Carlo simulation and find its full-energy-peak add-back efficiency to be 3 % at 1739 keV. Fortunately, the other daughters produced in the ^{26}P decay chain (^{24}Mg and ^{25}Al) do not produce high-energy gamma rays that introduce substantial additional backgrounds at 1739 keV, with the exception of the line at 1790 keV from ^{26}P(βp)^{25}Al*, whose absolute intensity is well known [16].

Conveniently, stronger ^{26}P($\beta\gamma$) branches have already been measured [16] and we can use them for in-situ calibrations of efficiency and energy. In particular, the strong 1796-keV line nearby has an absolute ^{26}P($\beta\gamma$) branching that is known to be 55(11) %, with a precision well within that of the proton width that will ultimately limit the uncertainty on the resonance strength derived. This line will form a doublet with the 1790-keV line from ^{26}P(βp)^{25}Al*, but their absolute intensities are both well known [16]. We note that minor portions of the β-delayed γ-decay scheme in Ref. [16] were likely misinterpreted due to the incompleteness of the ^{26}Si level scheme in 2004, but it is possible to reconstruct the correct decay scheme quantitatively using the detailed ^{26}Si γ-decay scheme from Ref. [6]. Our new data will also certainly help with the construction of the decay scheme. Offline calibrations using standard γ-ray sources will be used to independently verify the gamma-ray efficiency obtained using the online data.

3. Outlook

Experiment 10034 is scheduled to run at NSCL later this month from August 27th to 30th, 2012.

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