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The ^{26m}Al(p,γ)^{27}Si Reaction Rate in ONe Novae

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Evidence of the ongoing nucleosynthesis of ^{26}Al in our galaxy has been found in presolar grains and in observations of the 1.809-MeV γ ray, which results from the β decay of ^{26g}Al ($t_{1/2} = 7.2x10^5$ yrs) to an excited state in ^{26}Mg. The nucleosynthesis of ^{26}Al is complicated by the existence of the isomeric state, ^{26m}Al, at 228 keV ($t_{1/2} = 6.3$ s), which must be treated independently from ^{26g}Al in certain stellar environments, such as ONe novae, where temperatures are below 0.4 GK. ^{26m}Al β decays directly to ^{26g}Mg, bypassing the emission of the 1.809-MeV γ ray. The ^{26g}Al(p,γ)^{27}Si and ^{26m}Al(p,γ)^{27}Si reactions destroy ^{26}Al in novae and have a direct impact on the net amount of ^{26}Al produced. While the ^{26g}Al(p,γ)^{27}Si reaction rate has been studied extensively, there has been virtually no information published on resonances of the ^{26m}Al(p,γ)^{27}Si reaction and previously published reaction rates [1] have been based on ^{26g}Al + p resonances and Hauser-Feshbach calculations. The ^{27}Al(^{3}He,t)^{27}Si*(p)^{26}Al and ^{28}Si(^{3}He,α)^{27}Si*(p)^{26}Al reactions have been studied at the Wright Nuclear Structure Laboratory at Yale University using ^{3}He beams of 25 and 17.5 MeV, respectively, produced by the Tandem Van de Graaff accelerator. Reaction products were momentum analyzed by the Yale Enge magnetic spectrograph and tritons and alpha particles were detected at the focal plane with a position-sensitive, gas filled ionization detector backed by a plastic scintillator to determine energies of states in ^{27}Si from the two transfer reactions. Proton decays from these excited states in ^{27}Si were detected by the Yale Lamp Shade Array of silicon strip detectors in coincidence with the reaction products of interest detected at the focal plane. Angular correlations were measured to constrain spins and proton branching ratios for ^{26m}Al + p resonances with $E_{cm} > 450$ keV, and a reaction rate has been calculated for ^{26m}Al(p,γ)^{27}Si. The extreme differences in proton decays from excited states in ^{27}Si to ^{26g}Al and ^{26m}Al prove that ^{26m}Al(p,γ)^{27}Si reaction rates found using experimental data for ^{26g}Al + p resonances are not valid, and a direct ^{26m}Al(p,γ)^{27}Si measurement must be made to reliably determine the strengths of low-energy resonances which most likely dominate the reaction rate.

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1. Introduction

The $t_{1/2}$ = 7.2 x 10^5 yr half-life of the ground state of ^{26}Al (hereafter ^{26g}Al), which is short on timescales of galactic chemical evolution ($\sim$Gyr), makes this nucleus a favorable candidate to study ongoing nucleosynthesis in the galaxy. 99.7% of the time ^{26g}Al β^+ decays through an excited state of ^{26}Mg, which then promptly emits a 1.809-MeV γ ray as it decays to its ground state. This 1.809-MeV galactic γ-ray line was first detected by HEAO-3 [2] and, most recently, by the INTEGRAL satellite, which detetected approximately 2.8 $M_\odot$ of galactic steady-state ^{26}Al [3]. Several sites have been suggested to contain environments where ^{26}Al may be produced, including supernovae, asymptotic giant branch (AGB) stars, Wolf Rayet stars, and oxygen neon (ONe) novae. While recent studies suggest the majority of ^{26}Al is synthesized in more massive stellar events [3], such as core-collapse supernovae, an important contribution from ONe novae cannot be ruled out [4, 5]. In addition to the γ-ray observations, ^{26}Mg excesses in the Allende meteorite of up to 40% relative to solar, which suggest the decay of ^{26}Al in situ, gave some of the first evidence of the presence of ^{26}Al in our galaxy at the time of the formation of the solar system [6, 7]. Since that discovery, several presolar grains with isotopic abundances that suggest nova origins have been discovered, including two that have had their ^{26}Al/^{27}Al ratios measured to be quite high ($> 10^{-2}$) relative to solar abundances [8], although the nova origin of these grains has been called into question [9].

The production of ^{26}Al is complicated by the existence of an isomeric state (^{26m}Al) located at 228 keV, with $J^\pi = 0^+$ and $t_{1/2} = 6.3$ s. While the direct M5 electromagnetic transition of the isomer to the $J^\pi = 5^+$ ground state is too slow ($\sim 8x10^5$ years [10]) compared with the isomer's lifetime, it was previously shown by [11] that ^{26g}Al and ^{26m}Al come into thermal equilibrium at temperatures greater than 0.4 GK; however, in stellar environments below this temperature, such as ONe novae, the authors of [11] make the case that the two levels must be treated separately. This issue has been reexamined more recently and is somewhat more subtle as it is not clear when or if ^{26}Al will reach thermal equilibrium [12]. Rather, the authors of [12] have shown that ^{26g}Al and ^{26m}Al do communicate at temperatures below 0.4 GK, and while the two may be entered separately in reaction rate networks, the effective decay rate, which depends on this communication, must be used. Furthermore, the relationship between ^{26g}Al and ^{26m}Al depends on not only the temperature, but also the time scales of the nuclear reactions and equilibration. Therefore, reactions involving the isomeric state of ^{26}Al may also be important at temperatures higher than 0.4 GK, which exist in more massive stellar events that may produce the majority of galactic ^{26}Al. The situation as it pertains to nova nucleosynthesis, where $T \leq 0.4$ GK, is discussed below.

In ONe novae, ^{26}Al is produced in the MgAl cycle via the reaction sequence ^{24}Mg(p,γ)^{25}Al($\beta^+\nu_e$)^{25}Mg(p,γ)^{26}Al, where the proton capture on ^{25}Mg can lead to either ^{26g}Al or ^{26m}Al. The former leads to the β^+-delayed 1.809-MeV γ ray, while the isomeric state decays directly to the ground state of ^{26}Mg, bypassing this γ-ray emission. Additionally, at ONe nova temperatures ($T_{peak} = 0.1 - 0.4$ GK) the ^{25}Al(p,γ) reaction competes with the β^+ decay of ^{25}Al, and ^{26m}Al is produced via the ^{24}Mg(p,γ)^{25}Al(p,γ)^{26}Si($\beta^+\nu_e$)^{26m}Al reaction sequence, again bypassing the 1.809-MeV γ-ray emission. In each of these scenarios, the main destruction mechanism of ^{26}Al is proton capture on either ^{26g}Al or ^{26m}Al. Previous experimental studies of the destruction of ^{26}Al have focused solely on the ^{26g}Al(p,γ) reaction [5, 13, 14, 15]; although proton capture on the isomer could affect overall ^{26}Al production, there is very little direct experimental information known

about ^{26m}Al(p,γ)[16], and no published information on any ^{26m}Al+p resonances.

Previous calculations of the ^{26m}Al(p,γ)^{27}Si rate were based on experimental information from the ^{26g}Al(p,γ)^{27}Si reaction and Hauser-Feshbach (HF) calculations and were determined [1] using

$$< \sigma v >_m = < \sigma v >_g \frac{[< \sigma v >_m]_{HF}}{[< \sigma v >_g]_{HF}}. \quad (1.1)$$

Clearly, if the structure of the ^{26g}Al + p and ^{26m}Al + p resonances is quite different, a rate based on the scaling in Eq. (1.1) is much less meaningful than one based on actual experimental information. In the sections below we present the first experimentally determined information on the ^{26m}Al(p,γ)^{27}Si reaction.

2. Experiment

The two transfer reactions ^{27}Al(^{3}He,t)^{27}Si* and ^{28}Si(^{3}He,α)^{27}Si* were measured [17] at the Wright Nuclear Structure Laboratory at Yale University using the 20MV ESTU tandem Van de Graaff accelerator. ^{3}He^{2+} beams of 25 MeV (at a current of 30 pnA) incident on a 58 μg/cm^2 ^{27}Al target backed by a 20 μg/cm^2 carbon substrate and of 17.5 MeV (with a typical current of 5 pnA) incident on a 311 μg/cm^2 self-supporting Si target were used for the ^{27}Al(^{3}He,t)^{27}Si* and ^{28}Si(^{3}He,α)^{27}Si* reactions, respectively. The reaction products were momentum analyzed using the Enge split-pole spectrograph placed at 3° and detected by a position-sensitive ionization drift chamber (PIDC) filled with 150 torr of isobutane gas, which was placed at the focal plane and backed up by a plastic scintillator [18]. The PIDC measures position along the focal plane via front and rear wires with delay chip readouts, and energy loss in the drift region, ΔE, via a cathode, while the scintillator determines the residual energy of the particles, E$_{res}$. Protons emitted from excited states of ^{27}Si were detected by the Yale Lamp Shade Array (YLSA), an array of five 16-strip silicon detectors arranged in a lampshade configuration [17]. YLSA was placed at backward angles and the segments, which were tilted forward, covered an angular range of θ_{lab}= 131° to θ_{lab}= 166°.

3. Results

By plotting the cathode (ΔE), scintillator (E$_{res}$), and the focal plane position signals in 2D histograms, the reaction products could be separated from one another, and the particles of interest (tritons or α particles for the ^{27}Al(^{3}He,t)^{27}Si* and ^{28}Si(^{3}He,α)^{27}Si* reactions, respectively) selected to obtain a spectrum of the excited states in ^{27}Si (Fig. 1). The triton and α spectra have resolutions of approximately 35 keV and 70 keV, respectively, in excitation energy and the peaks therein were fit with a Gaussian function, when isolated, or a multi-Gaussian function when several peaks overlapped.

An initial calibration of the focal plane for the ^{27}Al(^{3}He,t)^{27}Si reaction was performed using known energy levels [19] from the ^{32}S(^{3}He,t)^{32}Cl and ^{13}C(^{3}He,α)^{12}C reactions. The ^{12}C(^{3}He,α)^{11}C reaction [19] was used for an initial calibration for the ^{28}Si(^{3}He,α)^{27}Si reaction study. For each spectrum, once well-known [19], well-separated states in ^{27}Si were identified, they were used for an internal calibration to reduce systematic errors associated with using a different calibration reaction. Excitation energies determined using this internal calibration were in agreement with the

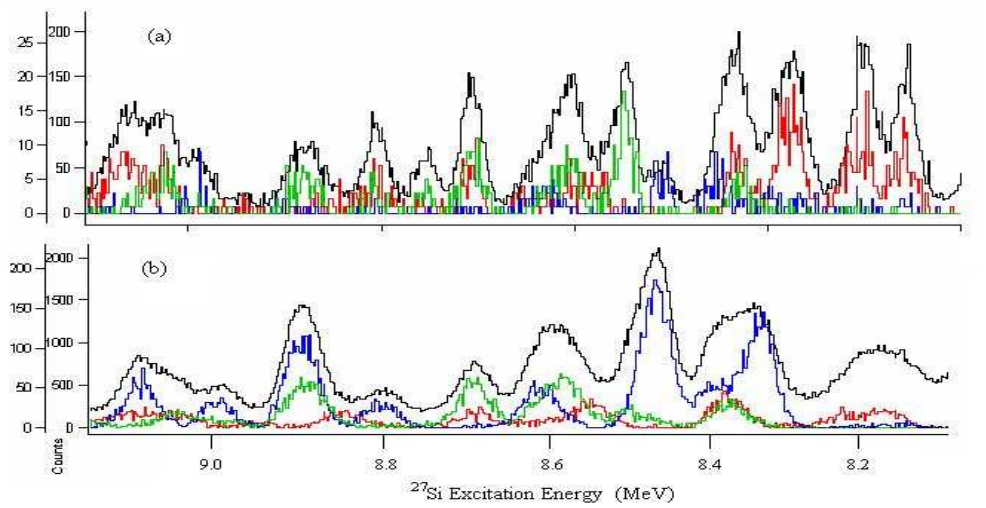

Figure 1: Focal plane position spectra of (a) the tritons from the ^{27}Al(^{3}He,t)^{27}Si reaction and (b) the alpha particles from the ^{28}Si(^{3}He,α)^{27}Si reaction in coincidence with proton decays to the ground state (red), isomeric state (blue), and second excited state (green) in ^{26}Al. The rightmost vertical scales refer to the spectra of all detected (a) tritons and (b) alpha particles, which are shown in black.

those found using the initial focal plane calibration reactions. The ^{27}Si energy levels determined from the two transfer reactions were also in agreement and the final excitation energies were found by taking a weighted average of the two sets of measurements determined using the internal calibration.

Protons that decayed from the excited states in ^{27}Si to the ground, isomeric, and second excited states in ^{26}Al were detected by YLSA in coincidence with the reaction products of interest that were detected at the focal plane. Proton decays to specific ^{26}Al states were selected to produce focal plane spectra corresponding to each particular decay channel (Fig. 1).

The angular correlations of the decay protons to the reaction products were measured and fit with a sum of Legendre polynomials,

$$W(\theta) = \sum_{k=0,2,\ldots}^{n} A_k P_k(cos\theta) \tag{3.1}$$

where the number of terms needed to fit the angular distribution is related to the angular momentum transfer of the proton decay by $k = 2l$. Thus, the minimum number of terms needed to fit the distribution determined the minimum angular momentum transfer, l_{min}, which was used to constrain the spins of the resonances in ^{27}Si. By integrating $W(\theta)$ over $\theta = 0$ to π, proton branching ratios, Γ_p/Γ, were determined [20].

4. Conclusions

Using the excitation energies measured in this work, resonance energies were determined via the relation $E_r = E_x - Q_{p\gamma}$ [20]. These resonance energies, the proton branching ratios determined above, the spins of the resonances determined from l_{min}, and assumed γ partial particle widths

(Γ_γ) of 1 eV, were used to calculate a reaction rate for the ^{26m}Al(p,γ)^{27}Si reaction over the temperature range $0.1 < T_9 < 0.4$ [20]. The rate is dominated by the lowest measured resonance, $E_r = 447$ keV. While this rate was found to be $2-10$ orders of magnitude less than the previously reported rate [1], this is most likely partially due to the inability to detect resonances below 447 keV as a result of the proton energy detection threshold of YLSA, which was slightly lower than 450 keV. Furthermore, as can be seen clearly in Fig. 1, there are stark differences in the proton decays to the ^{26g}Al and ^{26m}Al states from levels in ^{27}Si. Thus, any ^{26m}Al+p calculation based on ^{26g}Al+p resonance strengths is not viable and a reaction rate calculation based on experimentally determined information for the ^{26m}Al(p,γ)^{27}Si reaction is currently needed to give meaningful information on its contribution to the production of galactic ^{26}Al. In order to determine the effect of the ^{26m}Al(p,γ)^{27}Si reaction rate on the overall production of ^{26}Al in ONe novae, resonances below 450 keV must be directly measured. This work provides motivation for undertaking such a measurement and gives information on where specific resonances are located.

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