The ^{25}Al(p,γ)^{26}Si Reaction Rate in Novae

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The production of ^{26}Al in novae is uncertain, in part, because of the uncertain rate of the ^{25}Al(p,γ)^{26}Si reaction at novae temperatures. This reaction is thought to be dominated by a long-sought 3^+ level in ^{26}Si, and the calculated reaction rate varies by orders of magnitude depending on the energy of this resonance. We present evidence concerning the spin of a level at 5.914 MeV in ^{26}Si from the ^{28}Si(p,t)^{26}Si reaction studied at the Holifield Radioactive Beam Facility at ORNL. We find that the angular distribution for this level implies either a 2^+ or 3^+ assignment, with only a 3^+ being consistent with the mirror nucleus, ^{26}Mg. Additionally, we have used the updated ^{25}Al(p,γ)^{26}Si reaction rate in a nova nucleosynthesis calculation and have addressed the effects of the remaining uncertainties in the rate on ^{26}Al production.

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1. Introduction

The origin of Galactic ^{26}Al has been a key question in nuclear astrophysics since its observation via detection of 1.809-MeV γ rays [1-3]. Novae may be an important source of ^{26}Al, but it is difficult to estimate the novae contribution because of uncertainties in the nova nucleosynthesis of ^{26}Al. Recent studies have found that an important uncertainty comes from the unknown rate of the ^{25}Al(p,γ)^{26}Si reaction at nova temperatures [4,5]. This reaction bypasses ^{26g}Al production via the sequence ^{25}Al(p,γ)^{26}Si($\beta^+\nu$)^{26m}Al($\beta^+\nu$)^{26g}Mg, which produces no 1.809-MeV γ rays. Recent studies [6-8] have concluded that the ^{25}Al(p,γ)^{26}Si reaction rate is dominated by direct capture and by resonant capture through low-energy 1^+ and 3^+ resonances, with the 3^+ resonance providing the largest contribution in the peak novae temperature range 0.15 – 0.40 GK. This estimated 3^+ contribution is rather uncertain, however, as its resonance energy has not been conclusively determined, and the thermonuclear reaction rate depends exponentially upon its value. Parpottas *et al*. [8] studied the ^{24}Mg(^{3}He,n)^{26}Si reaction and, from a comparison of the observed cross sections to Hauser-Feshbach calculations, concluded a ^{26}Si level at 5914 keV has a spin consistent with a 3^+ assignment. This would seem to be in contradiction to the results obtained in Ref. [9], however, where the angular distribution of tritons populating the 5914-keV state in the ^{28}Si(p,t)^{26}Si reaction was found to be consistent with a 0^+ assignment. Parpottas *et al*. argued that the angular distribution measured in Ref. [9] was not conclusive because it was not measured at the most forward angles where the angular distribution for a 0^+ would be the most distinctive (i.e., peaking at forward angles). The goal of the present work was to measure the triton angular distribution populating the 5914-keV level in the ^{28}Si(p,t)^{26}Si reaction at more forward angles to examine these previous spin assignments and the possibility that the level has $J^\pi = 3^+$.

2. Experiment

The ^{28}Si(p,t)^{26}Si reaction was studied at the ORNL Holifield Radioactive Ion Beam Facility (HRIBF). A 40-MeV proton beam of average intensity ~2 nA was used to bombard a 50-μg/cm^2 natural Si target. Tritons were detected and identified using the Silicon Detector Array (SIDAR) [10] configured with 300-μm-thick detectors backed by 500-μm-thick detectors and covering 11-21 degrees in the laboratory. Tritons were distinguished from other charged particles using standard energy loss techniques. Since the array is segmented, the yields of tritons were measured at all angles in this study simultaneously. The angular distribution of tritons populating the 5914-keV ^{26}Si level is plotted in Fig. 1 along with the data obtained in Ref. [9]. We also show in Fig. 1 distorted-wave Born approximation (DWBA) calculations using the finite range code DWUCK5 [11] for populating 0^+ and 2^+ levels at this energy using the same parameters as described in Ref. [9]. We find, as suggested in Parpottas *et al.* [8], that the angular distribution at forward angles does not agree with a 0^+ assignment and, in fact, that the calculated 0^+ cross section is larger than the data by a factor of 4-5 at the lowest angles measured. We find instead that the angular distribution for the 5914-keV level is fit well by the DWBA calculation describing transfer to a 2^+ state. We had not considered this possibility in

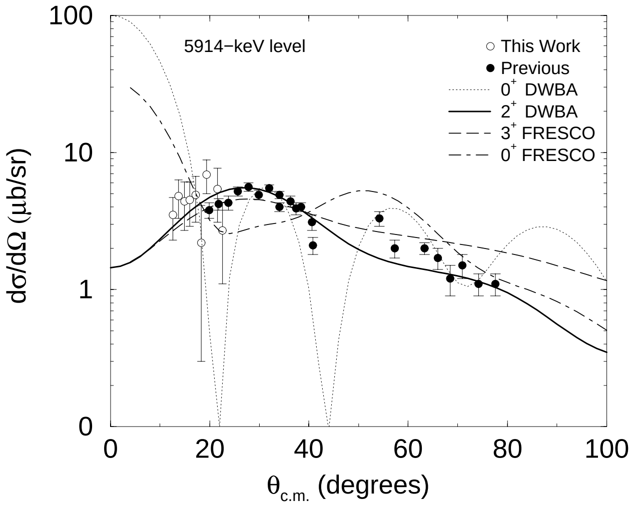

Figure 1: The angular distribution for the 5914-keV level is plotted with open circles from this work and closed circles from Ref. [9]. DWBA calculations for the direct population of 0^+ and 2^+ levels are shown along with FRESCO calculations of a multi-step process populating 3^+ and 0^+ levels.

Ref. [9] because of the strong evidence from Bohne *et al*. [12] that a 0^+ level had to be present in this energy region and the reasonable fit we obtained for a 0^+ angular distribution to our previous data set. It now appears that the measurement of Bohne *et al.* could not resolve the 5914-keV level from a level at 5946 keV, which appears to be a 0^+ [8].

We additionally show in Fig. 1 the results of a FRESCO [13] coupled-channel calculation describing the multi-step process $^{28}Si(p,d)^{27}Si(1/2^+)(d,t)^{26}Si(3^+)$. Such a mutli-step process would be required to populate an unnatural parity level in the $^{28}Si(p,t)^{26}Si$ reaction and has been found to be important in other (p,t) studies [14]. Optical model parameters were taken from Ref. [14] and good agreement was observed for the first step [$^{28}Si(p,d)^{27}Si$] between the FRESCO calculation and the data of Kozub [15] using the spectroscopic factor of 0.64 from Ref. [15]. The best fit to our data is shown in Fig. 1 and results in a spectroscopic factor of 3.1 for the second step $^{27}Si(1/2^+)(d,t)^{26}Si(3^+)$, which seems reasonable considering the maximum spectroscopic factor for neutron pickup from the $1d_{5/2}$ orbital from the first excited state of ^{27}Si is 4 if one assumes the ^{16}O core to be closed. Other possibilities were considered such as a multi-step population of 0^+ (shown in Fig. 1) and 1^+ levels or direct transfer to 1^-, 3^-, and 4^+ levels, but none produced results consistent with the data.

3. Astrophysical Reaction Rate

While both a direct population of a 2^+ level and a multi-step population of a 3^+ are reasonable interpretations of our angular distribution, the lack of a known 2^+ level in the mirror ^{26}Mg makes the 3^+ scenario more likely. We, therefore, calculate the $^{25}Al(p,\gamma)^{26}Si$ reaction rate based on the assumption that the 5914-keV level has $J^\pi = 3^+$, but consider the alternative in the reaction rate uncertainty calculations. Full details are given in Ref. [16], but briefly we take the

Table 1: Resonance parameters for ^{26}Si levels used in the calculation of the ^{25}Al(p,γ)^{26}Si reaction rate.

E_x (keV)	$E_{c.m.}$ (keV)	J^{π}	Γ_p (eV)	Γ_{γ} (eV)
5673(4)	155	1^+	$1.3*10^{-9}$	0.11
5914(2)	396	3^+	2.3	0.033
5946(4)	428	0^+	0.019	$8.8*10^{-3}$

direct capture rate from Ref. [6] and add to it contributions from resonances listed in Table 1. Higher energy resonances were considered but found to make negligible contributions to the reaction rate at nova temperatures. The resulting reaction rate is plotted in Fig. 2 where the uncertainty band includes contributions from the uncertain spin of the 5914-keV level, the uncertain energy of the 3^+, and uncertainties in partial widths.

We have used the calculated ^{25}Al(p,γ)^{26}Si reaction rate in a nova nucleosynthesis model looking at the effect of the uncertainties on the produced amount of ^{26}Al. We have used the tool set available at the Computational Infrastructure for Nuclear Astrophysics [17] to perform the calculations. We find the uncertainties in the ^{25}Al(p,γ)^{26}Si reaction rate result in a factor of 3.4 variation in the amount of ^{26}Al ejected in a calculation for nucleosynthesis for nova outbursts on a 1.35 solar mass ONeMg white dwarf [18,19]. Further reduction of this uncertainty would come from a definitive confirmation of the 3^+ resonance energy.

In conclusion, we have studied the energy and angular distributions of tritons from the ^{28}Si(p,t)^{26}Si reaction. We find the angular distribution of tritons populating the 5914-keV ^{26}Si level to be consistent with either a direct population of a 2^+ level or a multi-step population of a 3^+, with the latter being more likely. We have updated ^{25}Al(p,γ)^{26}Si reaction rate calculations and find the remaining uncertainties in the rate produce about a factor of 3 uncertainty in the

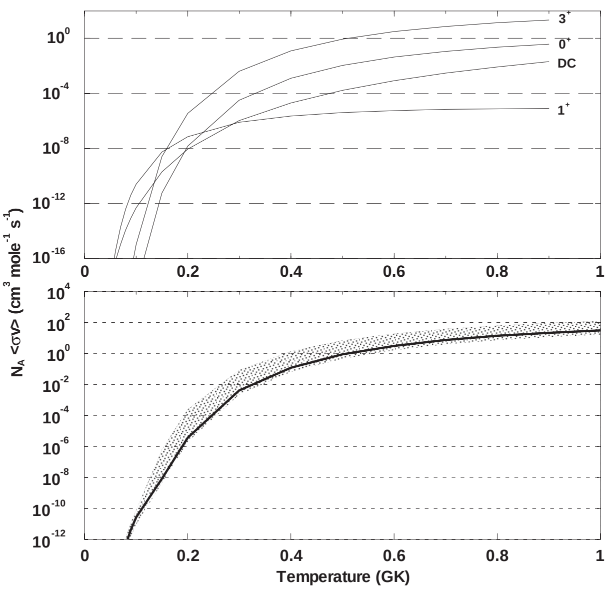

Figure 2: The top figure shows contributions of resonances and direct capture to the ^{25}Al(p,γ)^{26}Si reaction rate. The bottom plot shows the total rate along with the estimated uncertainty.

amount of ^{26}Al ejected from 1.35 solar mass ONeMg novae. Further studies of ^{26}Si are needed to reduce these uncertainties. Oak Ridge National Laboratory is managed by UT-Battelle, LLC, for the U.S. Department of Energy under contract DE-AC05-00OR22725. This work was also supported by U.S. DOE contracts DE-FG02-96ER40955, DE-FG03-93ER40789, DE-FG02-97ER41041, and DE-FG02-88ER40387.

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