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Proton capture on the excited isomeric state of ^{26}Al strongly influences the abundance of ^{26}Mg ejected in explosive astronomical events and, as such, plays a critical role in determining the initial content of radiogenic ^{26}Al in presolar grains. This reaction also affects the temperature range for thermal equilibrium between the ground and isomeric levels. We present a novel technique, that exploits the isospin symmetry of the nuclear force, to address the long-standing challenge of determining proton-capture rates on excited nuclear levels. Such a technique has in-built tests that strongly support its veracity and, for the first time, we have experimentally constrained the strengths of resonances that dominate the astrophysical ^{26m}Al$(p,\gamma)^{27}$Si reaction. These constraints demonstrate that the rate is at least a factor ∼8 lower than previously expected, indicating an increase in the stellar production of ^{26}Mg and a possible need to reinvestigate sensitivity studies involving the thermal equilibration of ^{26}Al.

PACS numbers:

The radioisotope ^{26}Al provides us with rare insight into the nature of nuclear processes in stars throughout the Milky Way. Its existence in the early Solar System has been inferred from the observation of ^{26}Mg isotopic excesses in meteorites [1], while space-based observations of the characteristic 1.809-MeV γ rays, associated with its β decay, have provided direct confirmation of active nucleosynthesis in our Galaxy [2, 3]. In fact, it has even been suggested that energy released by the in situ decay of ^{26}Al in protoplanetary disks, orbiting young stars, may have caused the melting of icy planetesimals, thereby influencing the conditions required of planetary systems to support life [4]. Consequently, determining the astrophysical origin of ^{26}Al represents one of the key goals of modern nuclear astrophysics.

Recently, large ^{26}Al/^{27}Al ratios have been reported for several presolar grains of possible nova and asymptotic giant branch (AGB) star origins [5–8], indicating that such environments may make a significant contribution to the overall galactic abundance of ^{26}Al. However, observations of ^{26}Al cosmic γ rays, by the COMPTEL and INTEGRAL satellite missions, point towards massive stars and core-collapse supernovae as being the likely dominant astrophysical source [9]. Hence, the exact origin of ^{26}Al remains controversial.

In this regard, stellar nucleosynthesis of ^{26}Al is complicated by the presence of a 0^+ isomer, ^{26m}Al (half life $t_{1/2} = 6.3$ s), located 228.31(3) keV above the 5^+ ground state, ^{26g}Al ($t_{1/2} = 7.2 \times 10^5$ yr). This isomeric level undergoes a superallowed β^+ decay directly to the ^{26}Mg ground state, bypassing emission of the telltale 1.809-MeV γ ray. As such, it does not contribute to the abundance of ^{26}Al inferred by space-based telescopes. However, reactions involving the isomeric state of ^{26}Al directly affect the astrophysical production of ^{26}Mg, which needs to be understood in order to ascribe ^{26}Al signatures to presolar grains. Therefore, it is imperative that uncertainties in the production and destruction of ^{26m}Al in stellar scenarios be reduced. Furthermore, whilst neutron-capture reactions are expected to have the most significant influence on the observed flux of ^{26}Al γ rays from supernovae, the relative proton-capture rates on ^{26g}Al and ^{26m}Al will determine the onset of thermal equilibrium between the two levels − this results in a reduction of the astrophysical half-life of ^{26g}Al and impacts on the amount of ^{26}Al produced at high temperatures [10] of relevance for γ-ray observations.

At stellar temperatures below 0.1 GK, ^{26m}Al and ^{26g}Al are produced in roughly equal quantities via the reaction

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sequence: ^{24}Mg$(p,\gamma)^{25}$Al$(\beta^+\nu_e)^{25}$Mg(p,γ) [11]. However, in higher-temperature scenarios ($T \geq 0.3$ GK), such as Oxygen-Neon (ONe) novae, the ^{25}Al$(p,\gamma)^{26}$Si reaction competes significantly with the β^+ decay of ^{25}Al, and a large fraction of explosive hydrogen-burning events bypass the direct population of the ^{26}Al ground state [12, 13]. As such, nuclear reactions on the isomer are likely to play a more significant role in these environments. Specifically, depending on the energies of excited states above the proton threshold of 7691.3(1) keV in ^{27}Si [14] and the proton occupation of orbitals (quantified here as a spectroscopic factor), isomeric-capture reactions may govern the pathway of nucleosynthesis in certain stellar scenarios.

In AGB stars ($T_{peak} \sim 0.14$ GK) and classical novae ($T_{peak} \sim 0.2-0.4$ GK), the destruction of ^{26}Al is governed by the ^{26g}Al$(p,\gamma)^{27}$Si and ^{26m}Al$(p,\gamma)^{27}$Si reactions, respectively. These reactions are dominated by resonant capture into excited states above the proton threshold in ^{27}Si and, over the past three decades, states of relevance for the ^{26g}Al$(p,\gamma)^{27}$Si reaction have been studied extensively [15–24]. In contrast, very little experimental information is available on the rate of the ^{26m}Al$(p,\gamma)^{27}$Si reaction [25–29]. This is due to the immense difficulty in producing beams of pure, isomeric ^{26}Al to uniquely probe low-spin excited states in ^{27}Si. Previous estimates, that have been used in astrophysical nuclear reaction network calculations, are largely based on ^{26g}Al + p resonances and Hauser-Feshbach calculations [30]. As such, these may be inappropriate for temperatures $\leq$0.4 GK, where the strengths of individual resonances are critical. In fact, a post-processing study by Iliadis *et al.* [31] concluded that uncertainties in the ^{26m}Al$(p,\gamma)^{27}$Si reaction may affect the isotopic abundance of ^{26}Mg synthesized in novae environments by more than an order of magnitude.

One of the earliest attempts to experimentally investigate the ^{26m}Al(p,γ) process [26] involved the use of ^{27}Al(^{3}He,t)^{27}Si*$(p)^{26}$Al and ^{28}Si(^{3}He,α)^{27}Si*$(p)^{26}$Al reactions, to observe proton decays from excited states above the ^{26m}Al + p threshold. In that study [26], an excited state at 8136(4) keV, corresponding to a resonance in the ^{26m}Al + p system at $E_r = 445(4)$ keV, was found to dominate the stellar reaction rate. However, 445 keV also represented the energy threshold cutoff of the detection system and as such, it was not possible to observe any resonances with $E_r < 445$ keV. This is of particular significance since the Gamow window for the ^{26m}Al(p,γ) reaction in AGB stars and classical novae covers an energy range of $E_r \sim 100-500$ keV. Consequently, following the pioneering work of Deibel *et al.* [26], a spectroscopy study of ^{27}Si was performed to identify low-energy ^{26m}Al + p resonant states by their γ decays [27, 28]. That work [27, 28], assigned a spin of $J = 1/2$ to the resonance at $E_r = 447.7(6)$ keV, supporting the results of Deibel *et al.* [26], and identified a $J = 5/2$ resonance at $E_r = 146.3(3)$ keV, as well as three $J = 3/2$ resonances at $E_r = 217.8(7)$, 378.3(30) and 492.2(4) keV, respectively. Parities were assigned, based on comparisons with the mirror nucleus, ^{27}Al, and it was proposed that the $5/2^+$, 146 keV resonance dominated the ^{26m}Al(p,γ) reaction for $T < 0.15$ GK, while the $3/2^-$, 378-keV resonance determined the rate for $T \geq 0.2$ GK. Unfortunately, despite these developments, the strengths of the resonances remain almost entirely unknown, leaving considerable uncertainty in the ^{26m}Al(p,γ) stellar reaction rate. Moreover, conflicting information from subsequent studies [29, 32] have obfuscated the parity of the 218-keV resonance, while a measurement of the ^{28}Si(^{3}He,α) reaction now indicates a $3/2^+$ reassignment for the 378-keV state [29].

In this Letter, we present a novel method for investigating ^{26m}Al + p resonances using the ^{26}Si(d,p) transfer reaction. In particular, we capitalise on the elegant concept of isospin symmetry, which allows us to describe the structures of nuclear states with the same isospin with the exact same wave function. Here, the nucleus ^{26}Si forms part of a 0^+ isobaric triplet, ^{26}Si$-^{26m}$Al$-^{26}$Mg, and, as such, neutron transfer on ^{26}Si acts as a surrogate for the astrophysical ^{26m}Al$(p,\gamma)^{27}$Si reaction. This provides several distinct advantages over previous studies. Specifically, the reaction mechanism directly populates low-spin excited states of interest in ^{27}Si, while also eliminating any background associated with the ^{26}Al ground state. Furthermore, spectroscopic factors, C^2S, extracted for levels in ^{27}Si, from neutron transfer on ^{26}Si, are inherently twice as large as those for proton capture on ^{26m}Al, owing to the associated Clebsch-Gordon coefficients. This feature is not only useful to improve the accuracy of C^2S but also allows for greater sensitivity in the assignment of upper limits for unobserved excited states. Here, states in ^{27}Si were identified by their characteristic γ decays [27, 28] and angle-integrated cross sections were derived from observed γ-ray intensities, as well as known branching ratios of analog states in the mirror nucleus, ^{27}Al [33]. This methodology has previously been successfully employed in studies of the ^{26}Al(d,n) [23] and ^{30}P(d,n) [34] reactions.

A beam of radioactive ^{26}Si ions at 30 MeV/u was produced by projectile fragmentation of a 150 MeV/u primary beam of ^{36}Ar ions at the National Superconducting Cyclotron Laboratory. This beam was then used to bombard a 9.1(7)-mg/cm^2-thick deuterated polyethylene target $(CD_2)_n$, with a typical intensity of $\sim$1 $\times$ 10^5 pps. Two time-of-flight measurements between a series of fast plastic scintillators (two upstream of the target and one downstream) allowed for the identification of incoming ^{26}Si particles, event-by-event. The ^{26}Si beam purity was determined to be 60(5)% and ^{25}Al was found to represent the main contaminant species. Prompt γ rays were observed with the GRETINA tracking array [35], which, in this instance, comprised of 10 modules positioned at laboratory angles of 58° and 90°, respectively, while projectile-like reaction products were transmitted to the focal plane of the S800 spectrograph [36]. Extracted cross sections for low-lying excited states in ^{27}Si, populated via transfer, may be overestimated due to the

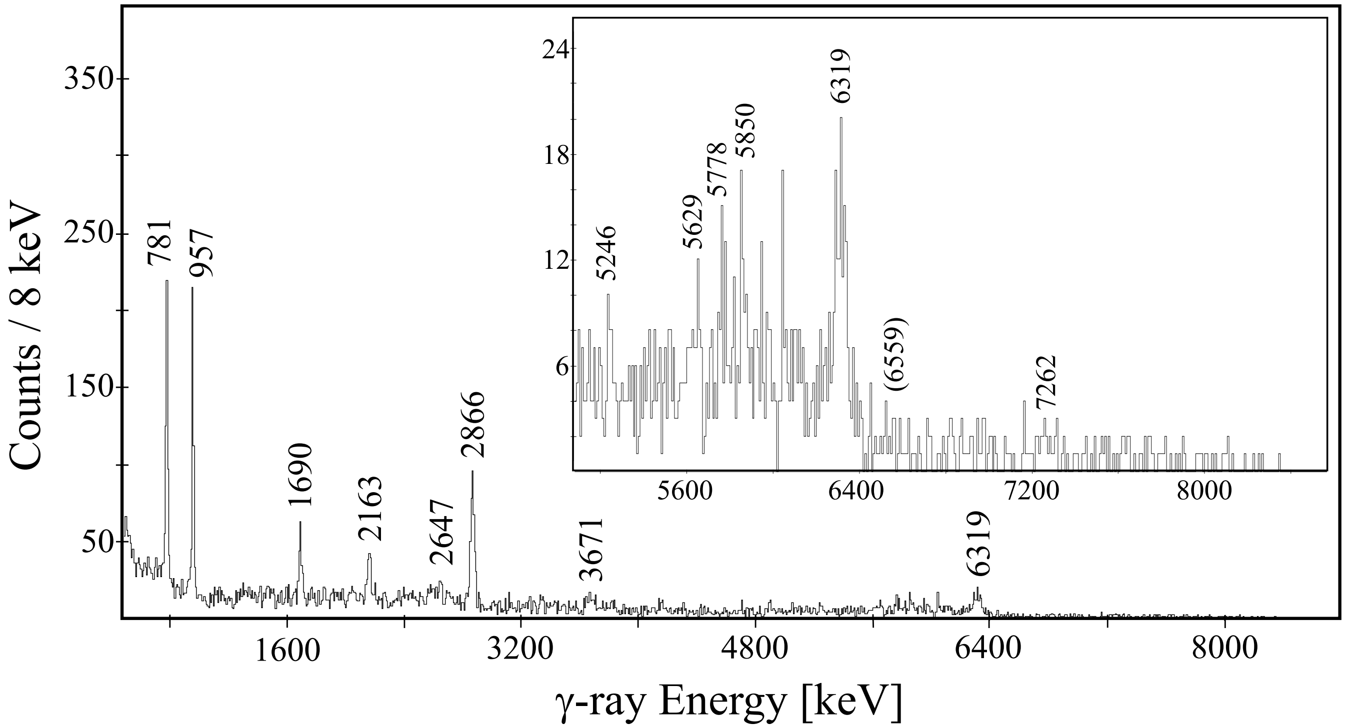

FIG. 1: Doppler-reconstructed γ-ray spectrum in coincidence with ^{27}Si recoils detected in the S800 spectrograph. (Inset) Expanded energy region of interest for nuclear astrophysics. A low-intensity transition is observed at 7262 keV. Fitting the peak based on the width of the 6319-keV γ ray yields a total of 13 counts, supporting its existence at the $\sim 2\sigma$ confidence level, assuming a flat background.

indirect feeding of states, by discrete γ-ray transitions, from higher-lying levels. As such, a γ-γ coincidence matrix was produced in order to quantify the relative feeding of levels in ^{27}Si and remove such counts from the calculations of cross sections. The S800 spectrometer was run in focused mode and provided clean separation of ^{27}Si ions from other recoil species, as well as a 95(1)% acceptance. The GRETINA efficiency was obtained from a GEANT4 simulation and validated by source measurements covering energies up to 3.5 MeV, as well as high-energy γ-ray yields up to 6 MeV, produced in-beam by nucleon-removal reactions on ^{18}O. Finally, the possibility of background generated by ^{26}Si(^{12}C,^{11}C) reactions was investigated using a 13(1)-mg/cm^2-thick polyethylene target $(CH_2)_n$. However, the level of background was found to be negligible.

Figure 1 shows the Doppler-corrected γ-ray spectrum measured with GRETINA when gating on ^{27}Si ions at the focal plane of the S800 spectrograph. The selective population of low-spin excited states in ^{27}Si via the ^{26}Si(d,p) reaction is clearly highlighted. However, no γ decays were observed from any proton-unbound excited levels and, as such, it is expected that no strong single-particle states exist within the resonance energy region, $E_r = 100-500$ keV, in the ^{26m}Al + p system. Nevertheless, the absence of significant background makes it possible to assign stringent upper limits for the strengths of these resonances based on the present data. Spectroscopic factors were extracted by comparing measured cross sections to theoretical values obtained from calculations in the adiabatic distorted wave approximation (ADWA) using the code `TWOFNR` [37]. Here, the Koning-Delaroche global optical model parameterization [38] was used to calculate the $d-^{26}$Si distorting potentials [39]. Table I presents a summary of extracted spectroscopic factors for observed levels in ^{27}Si, together with a comparison to analog states in ^{27}Al and shell-model calculations. Shell-model calculations are based on the USDB Hamiltonian within the sd-shell model space [44] for even-parity states, and on the WBP Hamiltonian, which includes a $sd-pf$ Hamiltonian, for odd-parity states [45].

In general, good agreement is observed between the spectroscopic factors, C^2S, of excited states in ^{27}Si and those of analog states in ^{27}Al, determined via mirror ^{26}Mg(d,n) and ^{26}Mg(^{3}He,d) reactions. Moreover, the present results are reasonably well reproduced by shell-model calculations. For completeness, we note that excited levels in ^{27}Si at 5850 and 6559 keV were previously assigned as $3/2^+$ states [46]. However, the presently reported cross sections would result in unfeasibly large C^2S for transfers to the $1d_{3/2}$ orbital. Consequently, assignments of $(3/2^-,7/2^+)$ and $3/2^-$ are now indicated for the 5850- and 6559-keV states, respectively. Furthermore,

TABLE I: Properties of states in ^{27}Si populated in the ^{26}Si(d,p) reaction. Excitation energies and J^π assignments are adopted from Ref. [27] unless noted otherwise, and spectroscopic factors, C^2S, for analog states in ^{27}Al have been taken from ^{26}Mg(d,n) [40] and ^{26}Mg(^{3}He,d) [41–43] reaction studies. The values C^2S_{SM} relate to shell-model calculations for the ^{26}Si(d,p) reaction.

E_x [keV]	E_γ [keV]	$B.R.$ %	J^π_n	σ [μb]	nlj ADWA	$C^2S_{(d,p)}$	$C^2S_{(d,n)}$ [40]	$C^2S_{(^3He,d)}$ [41–43]	C^2S_{SM}	Analog State in ^{27}Al [keV]
781	781	100	$1/2^+_1$	780(170)	$2s_{1/2}$	0.43(9)	0.41	0.50	0.41	844
957	957	94	$3/2^+_1$	610(140)	$1d_{3/2}$	0.11(3)	0.08	0.07	0.05	1014
2163	2163	100	$7/2^+_1$	440(110)			^{a}			2212
2647	1690	77	$5/2^+_2$	300(90)	$1d_{5/2}$	0.05(2)	0.03	0.04	0.007	2735
	2647	20								
2866	2866	96	$3/2^+_2$	1790(390)	$1d_{3/2}$	0.38(8)	0.47	0.63	0.32	2982
4285	3328	41	$5/2^+_3$	380(140)	$1d_{5/2}$	0.06(2)	0.03	0.04	0.04	4410
	4285	52								
5850	4893	26	$(3/2^-_2)$	491(130)	$2p_{3/2}$	0.06(2)	^{a}		0.001	(6080)
	5850	74								
5850	4893	26	$(7/2^+_4)$				^{a}			(5961)
	5850	74								
6027	5246	80	$3/2^-_3$	170(80)	$2p_{3/2}$	0.02(1)	0.02	0.04	0.09	6159
6319	3671	15	$7/2^-_2$	2850(650)	$1f_{7/2}$	0.14(3)	0.22	0.20	0.23	6477
	4156	9								
	6319	76								
6559	5778	50	$3/2^{-\,b}_4$	550(200)	$2p_{3/2}$	0.07(3)	0.07		0.12	6604
	(6559)	17								
6586	5629	100	$5/2^+_8$	200(60)	$1d_{5/2}$	0.04(1)	^{a}		0.002	(6767)
7262^c	7262	100	$(7/2^-_3)$	160(60)	$1f_{7/2}$	0.008(3)	^{a}		0.002	(7477)

^{a}Seen in Ref. [40] but no C^2S reported
^{b}Parity assignment based on extracted cross section
^{c}State reported in Ref. [29]

we report the observation of a high-energy excited state at 7262 keV that, based on its measured cross section and comparison to shell-model calculations, most likely corresponds to the tentative $7/2^-$ state observed in the earlier work of Parikh *et al.* [29]. Intriguingly, it should be pointed out that the expected C^2S of $\sim$0.2, based on shell-model calculations, for the first $1/2^+$ excited state in the ^{27}Si-^{27}Al system, populated via single-proton or single-neutron transfer on ^{26m}Al, is in disagreement with the recently reported value of 0.08(2) from a study of the ^{26m}Al(d,p) reaction [25]. This discrepancy is possibly due to complications associated with the subtraction of background arising from the ^{26}Al ground state [25] and further highlights the benefit of using an analog reaction to directly populate the same states in ^{27}Si, that are populated in the astrophysical ^{26m}Al(p,γ) reaction.

For an evaluation of the ^{26m}Al(p,γ) reaction rate, we consider only the contributions of the 146-, 218-, 378-, 448- and 492-keV resonances. The γ-decay properties of these states have already been reported elsewhere [27, 46] and we assume, here, that they correspond to $\sim$100% branches (any significant low-energy branches would have been observed in Refs. [27, 46]). Using the known γ-ray energies of Refs. [27, 46], we have determined an upper limit for the angle-integrated cross section of each resonance. This was achieved by fixing the peak widths of transitions, based on the 6319- and 7262-keV γ rays, and assessing the total number of counts present over the relevant energy regions of unobserved decays. Whilst some background is expected in the regions investigated, we chose to base our upper limits on the total number of counts in order to obtain a far more conservative estimate. These cross sections enable the extraction of spectroscopic factors, C^2S, for key resonant states in the ^{26m}Al(p,γ) reaction and thus, provide stringent experimental constraints on the rate [47]. We estimate an overall uncertainty of $\sim$36% in the determination of spectroscopic factors (based on earlier experimental work [23, 34] and incorporating a $\sim$20% uncertainty in the extraction of cross sections, due to possible unobserved γ-decay branches). In addition, we estimate a $\sim$35% uncertainty in shell-model calculations of γ-ray partial widths and a factor $\sim$1.7 uncertainty in the derived proton-partial widths of resonant states [47]. In the case of the ^{26m}Al + p resonant states at 218 and 448 keV, for which the parity remains ambiguous, we have determined C^2S for both possibilities. Unfortunately, due to the high excitation energy of ^{26m}Al + p resonant states, it is generally not possible to uniquely identify resonances with shell-model states. That being said, should the 448-keV resonance correspond to a $1/2^+$ state, it may be unambiguously identified as the $1/2^+_7$ level, owing to the low level-density of $1/2^+$ states in ^{27}Si. As such, in estimating the $1/2^+$, 448-keV resonance strength, we have adopted a value of $C^2S = 0.01$, from shell-model calculations. A summary of the properties of ^{26m}Al(p,γ) resonances is presented

TABLE II: Properties of resonant states in the ^{26m}Al$(p,\gamma)^{27}$Si reaction. Upper limits for proton partial widths have been estimated using present cross sections, while γ-ray widths have been determined using a lifetime lower limit of 1 fs, for γ-decaying states, unless otherwise noted. In the case of the 218- and 448-keV resonances, we present strength estimates for both even- and odd-parity assignments.

E_x [keV]	E_γ [27] [keV]	E_r [27] [keV]	J^π	σ [μb]	$C^2S_{^{26}Si(d,p)}$ [a]	$C^2S_{^{26m}Al(p,\gamma)}$ [a]	Γ_p [meV]	Γ_γ [meV]	$\omega\gamma$ [meV]
7838	6879.6(2)	146.3(3)	$5/2^+$	≤ 168	≤ 0.03	≤ 0.015	$\leq 4.9 \times 10^{-6}$	≤ 658	$\leq 1.5 \times 10^{-5}$
7909	7127.1(7)	217.8(7)	$3/2^-$	≤ 43	≤ 0.01	≤ 0.005	$\leq 2.7 \times 10^{-2}$	≤ 658	≤ 0.054
			$3/2^+$		≤ 0.01	≤ 0.005	$\leq 7.1 \times 10^{-4}$	≤ 658	$\leq 1.4 \times 10^{-3}$
8070	7111.5(30)	378.3(30)	$3/2^+$	≤ 14	≤ 0.003	≤ 0.0015	≤ 0.16	≤ 658	≤ 0.33
8140	7180.9(6)	447.7(6)	$1/2^+$	≤ 58	≤ 0.09	≤ 0.045	683^b	890^c	385
			$1/2^-$		≤ 0.02	≤ 0.01	≤ 190	≤ 658	≤ 147
8184	7401.7(4)	492.2(4)	$3/2^-$	≤ 15	≤ 0.002	≤ 0.001	≤ 45	165 [27]	≤ 70

$^a C^2_{(d,p)} = 2/3$ and $C^2_{(p,\gamma)} = 1/3$
$^b C^2S = 0.01$ − see text for details
^{c}Adopted from shell-model calculations for the $1/2^+_7$ state

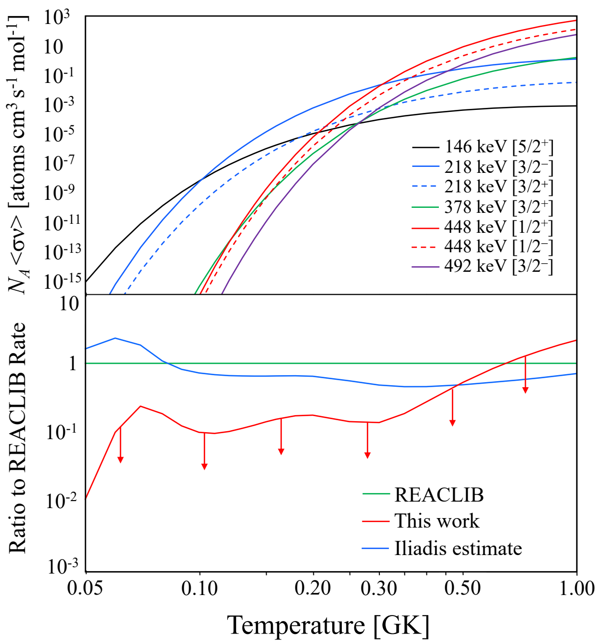

FIG. 2: (Color online) (top) Upper-limit contributions of individual resonances to the ^{26m}Al(p,γ) stellar reaction rate. The direct capture component for the ^{26m}Al(p,γ) reaction is negligible for temperatures > 0.02 GK [17]. (bottom) Comparison of the ^{26m}Al(p,γ) rate from this work, accounting for systematic uncertainties stated in the text, with the previously reported REACLIB estimate [48], and the experimentally constrained ^{26g}Al(p,γ) reaction, which has been recommended as an approximation for ^{26m}Al(p,γ) [49].

in Table II.

Figure 2 illustrates the contribution of individual resonances to the ^{26m}Al(p,γ) stellar reaction rate, together with a comparison of the current upper limit, accounting for uncertainties, to the earlier REACLIB estimate [48], which, for temperatures $\leq$0.4 GK, is based on the NACRE evaluation [30]. The new upper limit obtained in this work indicates that the ^{26m}Al(p,γ) reaction rate is at least a factor ∼8 smaller than previously expected up to temperatures of 0.35 GK. We therefore conclude that there will be an increase in the expected abundance of ^{26}Mg synthesized in AGB stars and classical nova explosions. In particular, the nova sensitivity study of Iliadis *et al.* [31], predicts that our new rate will lead to a 30−60 % increase in the ejected abundance of ^{26}Mg in nova events. Consequently, the information obtained here is critical for accurately classifying the initial ^{26}Al/^{27}Al ratio in presolar grains and hence, the contribution of AGB stars and classical novae to the observed galactic abundance of ^{26}Al. Furthermore, it is also fascinating to note that the current ^{26m}Al(p,γ) rate is considerably slower than the corresponding ^{26g}Al(p,γ) reaction, which has recently been suggested as a more reliable approximation for the ^{26m}Al(p,γ) rate [49]. Given the significant discrepancy between the current rate and theoretical calculations [48], we would encourage that sensitivity studies of the destruction of ^{26}Al in massive stars and CCSN be repeated − although it is currently anticipated that the equilibration of ^{26}Al levels has only a minor effect on the ^{26}Al yields in massive star sites [49].

In summary, we have, for the first time, been able to mimic isomeric-state proton capture in astrophysical environments, utilizing isospin symmetry. In particular, the non-observation of electromagnetic transitions from excited states in ^{27}Si, known to predominantly γ decay [27], demonstrates that there are no strong, single-particle states in the energy region $E_r = 100 - 500$ keV of the ^{26m}Al(p,γ) reaction. As such, the stellar reaction rate is significantly lower than previously expected [30, 48, 49], over the temperature range ∼0.05 − 0.35 GK. We now expect a considerable increase in the ejected abundance of ^{26}Mg from AGB stars and classical novae, and highlight a possible need to revisit sensitivity studies of the thermal equilibration of ^{26}Al. Furthemore, with its proven versatility, the present, pioneering technique may be extended to investigations of other astrophysically important processes involving isomeric states, such as the ^{34g,m}Cl(p,γ) and ^{38g,m}K(p,γ) reactions.

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