Radiative Capture on Nuclear Isomers: Direct Measurement of the $^{26m}\mathrm{Al}(p,\gamma)^{27}\mathrm{Si}$ Reaction

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We present the first direct measurement of an astrophysical reaction using a radioactive beam of isomeric nuclei. In particular, we have measured the strength of the key 447-keV resonance in the $^{26m}\mathrm{Al}(p,\gamma)^{27}\mathrm{Si}$ reaction to be 432^{+146}_{-226} meV and find that this resonance dominates the thermally averaged reaction rate for temperatures between 0.3 and 2.5 GK. This work represents a critical development in resolving one of the longest standing issues in nuclear astrophysics research, relating to the measurement of proton capture reactions on excited quantum levels, and offers unique insight into the destruction of isomeric $^{26}\mathrm{Al}$ in astrophysical plasmas.

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In explosive astrophysical environments, such as novae, supernovae, and neutron star mergers, a significant fraction of atomic nuclei are expected to exist in excited quantum states. These elevated levels participate in nucleosynthesis much in the same way as nuclear ground states and, as such, play an essential role in determining the abundance of chemical elements in our Galaxy [1,2]. Unfortunately, due to the immense difficulty in measuring the rates of particle captures on excited nuclear states, experimentally, stellar rates are obtained from ground state (laboratory) rates, using theoretically estimated stellar enhancement factors [3]. This approach may represent a considerable oversimplification for instances where nuclear isomers exist. Isomeric states have relatively long half-lives ($t_{1/2} > 1$ ns), in comparison to typical γ-decaying levels, and, as such, it is possible for their stellar destruction rates to be fast in relation to their depopulation via electromagnetic transitions [2]. Specifically, below a limiting temperature, ground and isomeric states are not in thermal equilibrium, and they are entered into nuclear reaction networks as entirely independent species. In this case, it is important to determine the rate at which proton capture occurs on both the ground and isomeric levels. Similarly, at temperatures higher than the critical value for which thermal equilibrium is achieved, it is equally important to constrain the isomeric capture rate, as this may disturb the equilibrium. A particularly notable example of this in nuclear astrophysics is the special case of $^{26}\mathrm{Al}$ [3–7].

The presence of radioactive $^{26g}\mathrm{Al}$ ($t_{1/2} = 7.2 \times 10^5$ yr) in the modern universe and early solar system has been inferred from: (i) the detection of characteristic 1.809-MeV γ rays throughout the interstellar medium [8,9], (ii) observations of $^{26}\mathrm{Mg}$ excesses in meteorites [10], and (iii) the extraction of large isotopic $^{26}\mathrm{Mg}$ anomalies from presolar grains [11–14]—microscopic pieces of matter found in meteorites that carry important information about the nucleosynthetic pathway followed in the parent star around which they were formed. These discoveries provided direct evidence for ongoing nucleosynthesis in our Galaxy and offered up a possible explanation for the differentiation and water sublimation of icy planetesimals, that influence the formation of habitable planetary systems such as our own [15]. However, stellar nucleosynthesis of $^{26}\mathrm{Al}$ is complicated by the presence of a 0^+ isomer, $^{26m}\mathrm{Al}$ ($t_{1/2} = 6.3$ s), located 228.305(13) keV [16] above the 5^+, $^{26g}\mathrm{Al}$ ground state. This isomeric level exhibits a superallowed β^+ decay directly to the $^{26}\mathrm{Mg}$ ground state, bypassing emission of the characteristic 1.809-MeV γ ray, and, as such, does not contribute to the abundance of $^{26}\mathrm{Al}$ inferred from satellite observations [9,17]. Nevertheless, subsequent proton capture reactions on $^{26m}\mathrm{Al}$ impact all three observational signatures of $^{26}\mathrm{Al}$ in our universe, either directly or indirectly [4,18], and, as such, it is essential that uncertainties in both the $^{26g}\mathrm{Al}(p,\gamma)^{27}\mathrm{Si}$ and $^{26m}\mathrm{Al}(p,\gamma)^{27}\mathrm{Si}$ reactions be reduced.

Over the past several decades, extensive experimental and theoretical efforts have constrained the rate of the $^{26g}\mathrm{Al}(p,\gamma)^{27}\mathrm{Si}$ reaction in explosive astrophysical environments [19–29]. However, in contrast, significant uncertainties remain in the $^{26m}\mathrm{Al}(p,\gamma)$ reaction, due to an absence of direct measurements. Previous studies of this reaction [30–35] indicate that the rate is dominated by resonant capture to excited states above the $^{26m}\mathrm{Al}+p$ threshold in ^{27}Si at 7691.6(1) keV [36]. In particular, several key, low-spin levels identified at $E_x = 7909.1(7)$ and 8139.0(6) keV [33], corresponding to resonances at $E_r = 217.5(7)$ and 447.4(6) keV, respectively, are expected to have the most influential effect on the rate over the temperature range of classical novae and supernovae [30,32]. Most recently, Hallam *et al.* [35] used an innovative experimental technique to reduce uncertainties in the strengths of resonances in the $^{26m}\mathrm{Al}(p,\gamma)$ reaction. Specifically, the concept of isospin symmetry was utilized to mimic proton capture on the isomeric state of ^{26}Al via $^{26}\mathrm{Si}(d,p)^{27}\mathrm{Si}$ transfer. In that study [35], no strong single-particle states were observed and stringent upper limits were placed on the spectroscopic factors of all resonant levels with $E_r < 500$ keV. Intriguingly, however, by adopting a relatively small spectroscopic factor ($C^2S = 0.01$), from shell-model calculations, based on a $1/2^+$ assignment for the 447-keV resonance, a relatively large value of 385 meV was estimated for its strength [35]. Given the fact that the next proton-decaying resonant state in the $^{26m}\mathrm{Al}+p$ system is not known to appear until $E_r = 627$ keV [32], it may be reasonably concluded that the 447-keV resonance is likely to dominate the entire $^{26m}\mathrm{Al}(p,\gamma)$ rate for $T > 0.3$ GK (the contribution of the 447-keV resonance is now expected to be more than an order of magnitude more than the 627-keV state at $T = 1$ GK, and more than a factor of ~ 2 at $T = 2$ GK, even if a strength of 500 meV is assumed for the resonant level at 627 keV). Thus, the unmeasured strength of the 447-keV resonance represents the key remaining uncertainty in constraining the rate of the $^{26m}\mathrm{Al}(p,\gamma)$ reaction in classical novae and supernovae environments.

Recently, remarkable advancements in radioactive beam technology have provided the means to produce intense beams of isomeric nuclei for use in direct reaction studies [31]. These developments, together with the relatively large predicted strength of the 447-keV resonance [35], now offer, for the first time, the unique experimental opportunity of studying the rate of proton capture on excited quantum states, directly. In this Letter, we present a direct experimental investigation of the $^{26m}\mathrm{Al}(p,\gamma)$ reaction, in which an intense beam of isomeric ^{26}Al was used to measure the strength of the key 447-keV resonance in the $^{26m}\mathrm{Al}+p$ system, that is expected to dominate the rate over the temperature range of classical novae and supernovae. The results obtained are of critical importance for our understanding of astrophysical processes involving excited quantum states, as direct measurements most closely reproduce the actual reaction occurrence within the star, out of all presently available techniques.

Here, the Detector of Recoils and Gammas of Nuclear Reactions (DRAGON) [37] was used to perform a direct measurement of the $^{26m}\mathrm{Al}(p,\gamma)$ reaction at the ISAC-I radioactive beam facility at TRIUMF. Unstable ^{26}Al was produced by bombarding a thick SiC production target with up to 70 μA of 500 MeV protons from TRIUMF's sector focussing cyclotron and initially accelerated to energies of 150 A keV using a radio-frequency quadrupole accelerator (RFQ). This beam was then stripped to a higher charge state using a thin carbon foil, further accelerated with a continuously variable energy drift-tube linear accelerator (DTL) [38] to energies of 390- and 469-A keV, and delivered to the DRAGON windowless gas target, filled with H_2 gas at 6.66(13) mbar. A highly efficient array of 30 bismuth germanate (BGO) detectors [37] surrounding the gas target was used to detect γ rays resulting from (p,γ) reactions, while $^{27}\mathrm{Si}^{7+}$ recoils were transmitted to the focal plane of DRAGON. These recoils were identified using a local time-of-flight (TOF) system based on two microchannel plates (MCPs) and an isobutane-filled ionization chamber. Stopping powers were determined with gas in and gas out of the target system, and charge state distributions at recoil energies were measured using a stable beam of ^{28}Si.

It should be noted that it is not possible to separate the ^{26g}Al and ^{26m}Al components of an accelerated beam, even with the highest resolution mass separators. As such, all direct reaction studies of ^{26}Al necessarily involve both nuclear species. In the present case, the isomeric ^{26}Al beam intensity was determined from measurements of the superallowed β^+ decay of ^{26m}Al to the ground state of ^{26}Mg. Specifically, during the experiment, a mass-dispersed radioactive beam was deposited onto a mass slit, located downstream of the first electric dipole of the DRAGON recoil separator [39]. The resulting positrons were then guided up a "horn," surrounded by two NaI detectors placed at 180° with respect to one another, at the top of the mass slit box. By comparing the number of coincident 511-keV annihilation γ rays with GEANT4 simulations of the NaI detector response, an average ^{26m}Al beam intensity of $\sim 4.0 \times 10^5$ pps was determined. In contrast, Faraday cup measurements established the average ground state ^{26}Al component as $\sim 3.6 \times 10^9$ pps and the isobaric contaminant ^{26}Na rate as $\sim 2.0 \times 10^8$ pps (established via ion chamber data during regular attenuated beam runs). The ^{26}Na contaminant does not influence the determination of the ^{26m}Al beam intensity, as ^{26}Na decays solely via β^- decay, and does not affect any of the detected (p,γ) events, as similar captures in ^{27}Mg would populate excited levels ~ 9 MeV above the neutron-emission threshold energy (i.e., any ^{27}Mg excited state would decay via neutron emission before reaching the focal plane of DRAGON).

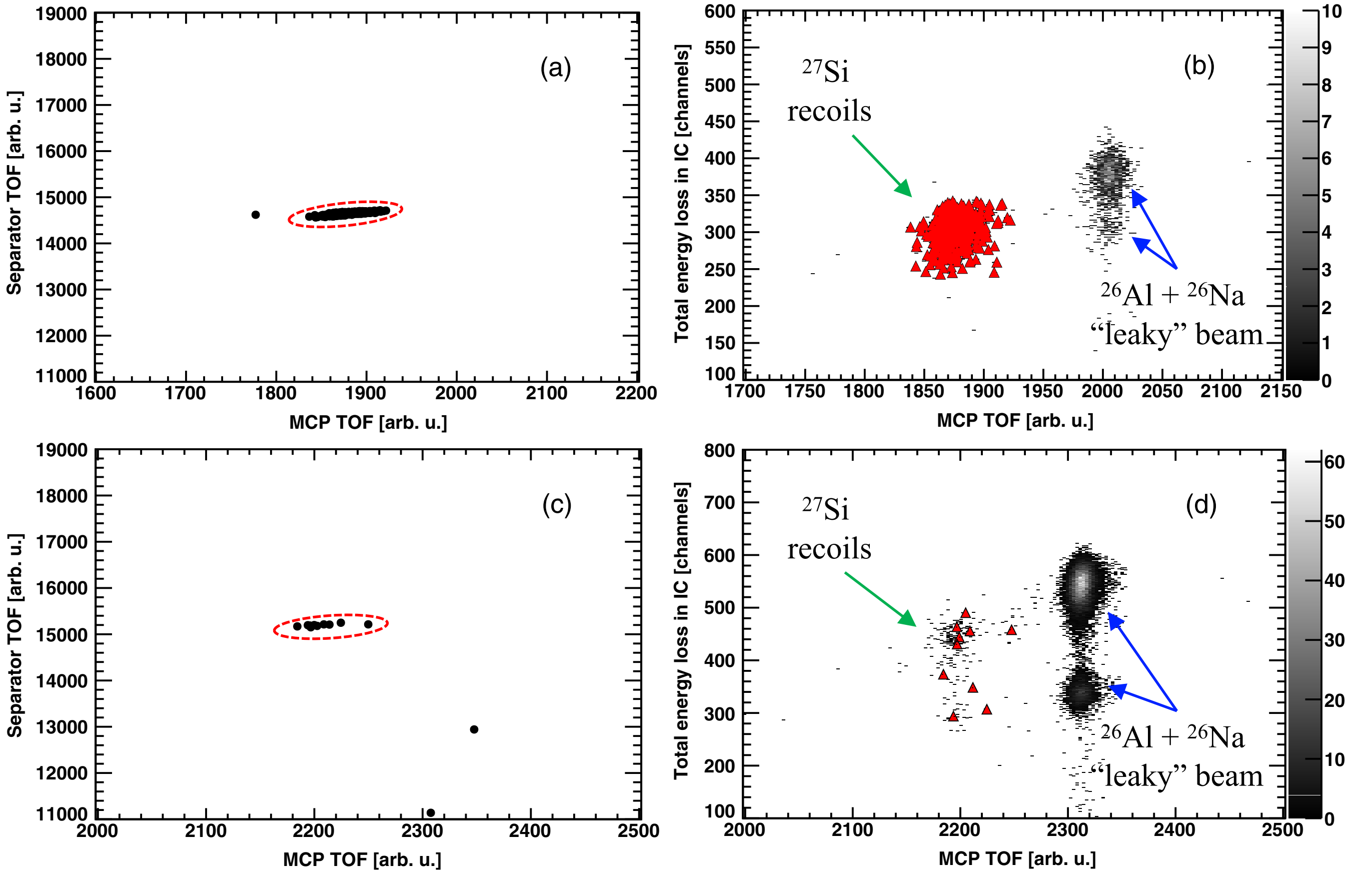

FIG. 1. (a) Separator time of flight (TOF), defined as the time between detecting a prompt γ ray and a heavy ion, vs MCP TOF spectrum at $E_{\text{beam}} = 390$ A keV. (b) Total energy loss in the ionization chamber (sum of energy loss in all IC anode segments) vs MCP TOF spectrum at $E_{\text{beam}} = 390$ A keV. Here, positively identified $^{26g}\text{Al} + p$ resonant events, corresponding to those that appear in the separator TOF vs MCP TOF cluster observed in (a) with a BGO energy > 1.5 MeV, which also fall inside the expected energy region of the ionization chamber, are highlighted by red triangles. (c) Separator TOF vs MCP TOF spectrum at $E_{\text{beam}} = 469$ A keV. (d) Total energy loss in the ionization chamber vs MCP TOF spectrum at $E_{\text{beam}} = 469$ A keV. Here, positively identified $^{26m}\text{Al} + p$ resonant events, corresponding to those that appear in the separator TOF vs MCP TOF cluster observed in (c) with a BGO energy > 1.5 MeV, which are also in coincidence with signals in the expected energy region of the ionization chamber, are highlighted by red triangles.

To validate the experimental technique, an initial beam energy of 390 A keV was chosen to place a known, $\ell = 0$ $^{26g}\text{Al} + p$ resonance at $E_r = 369$ keV [19,20] at the center of DRAGON's windowless gas target. This resonance is known to exhibit strong γ-decay branches to the $7/2_1^+$, $9/2_1^+$, $11/2_1^+$, and $7/2_3^+$ excited states in ^{27}Si [19,20,25,33]. Based on the previously established γ-decay scheme, we determine a BGO array detection efficiency of 0.83(8), and, by gating on γ rays with energies > 1.5 MeV, we observe a cluster of 339(18) events in the separator TOF vs MCP TOF spectrum [Fig. 1(a)], that also have the expected energy loss in the ionization chamber for ^{27}Si recoils, as illustrated by the red triangles in Fig. 1(b). Using values of of 0.99(1), 0.77(1), 0.80(1), 0.64(6), and 0.40(2) for the MCP detection, MCP transmission, ionization chamber, BGO, and charge state fraction efficiencies, respectively, we establish a resonance strength of $\omega\gamma = 61(8)$ meV. This is in good agreement with previously reported values of 65(18) meV [19] and 64(10) meV [20], and hence, verifies the experimental methodology. A full list of parameters used for the determination of resonance strengths is provided in Table I.

For a measurement of the $^{26m}\text{Al}(p,\gamma)$ reaction, the beam energy was increased to 469 A keV. At this setting, center-of-mass energies covered within the target were restricted to $E_r = 456$–439 keV and, based on previous work [32,33], the key 447-keV resonance is the only state known to exist in this region in the $^{26m}\text{Al} + p$ system. Considering Fig. 1(c), we see that there is a clear clustering of recoil events free from background in the γ-gated separator TOF vs MCP TOF spectrum, indicating the presence of an $A = 27$ radiative capture resonance. By also requiring a coincident ^{27}Si event to be observed in the ionization chamber, we obtain a total of ten definitive, recoil-γ coincidences, as shown in Fig. 1(d). Measurements were also taken off-resonance at a beam energy of 484 A keV. No coincident

TABLE I. Summary of parameters used for the determination of resonance strengths. The values N_{inc} and N_{det} represent the number of incident particles and number of detected events, respectively, while the parameters η_{BGO}, η_{MCP}, η_{trans}, η_{IC}, and η_{CSF} correspond to the BGO array, MCP, transmission, ionization chamber, and charge state fraction efficiencies.

Reaction	E_r (keV)	N_{inc}	N_{det}	η_{BGO}	η_{MCP}	η_{trans}	η_{IC}	η_{CSF}	$\omega\gamma$ (meV)
$^{26g}\mathrm{Al} + p$	369	$1.090(9) \times 10^{13}$	339(18)	0.83(8)	0.99(1)	0.77(1)	0.80(1)	0.40(2)	61 ± 8 (stat) ± 6 (sys)
$^{26m}\mathrm{Al} + p$	447	$6.93(20) \times 10^{10}$	10(3)	0.64(6)	0.99(1)	0.77(1)	0.80(1)	0.37(2)	432 ± 137 (stat) ± 51 (sys)

events were observed in those data runs, confirming zero background counts in the region of interest. This implies a resonance strength of 432 ± 137 (stat) ± 51 (sys) meV for the 447-keV state, which is remarkably similar to the recent estimate of Ref. [35]. However, we note that some potential background may arise from the presence of a possible degenerate $J^\pi = 3/2^-$ level located at 446.1 (7) keV in the ground state, $^{26g}\mathrm{Al} + p$ system [30,33,35]. This level, which would correspond to either the $3/2^-_5$ or $3/2^-_6$ excited state in $^{27}\mathrm{Si}$, was not previously observed in direct measurement studies of the $^{26g}\mathrm{Al}(p,\gamma)$ reaction using radioactive targets [19,20] and the only plausible $3/2^-$ analog state in the relevant energy region of the mirror nucleus, $^{27}\mathrm{Al}$, at 8182 keV [40] was not observed in the high statistics $^{26g}\mathrm{Al}(d,p)$ study of Ref. [26]. Shell-model calculations predict proton spectroscopic factors for the $3/2^-_5$ and $3/2^-_6$ excited states in $^{27}\mathrm{Si}$ of 0.000 07 and 0.0066, respectively, which, in turn, indicate resonance strengths of ~0.0002 meV and ~0.01 meV—shell-model calculations were performed using the same procedure as described in Refs. [28,35]. Based on the observed differences between experimentally determined spectroscopic factors and theoretical predictions in the $T = 1/2$, $A = 27$ system [29], we assign a reasonably conservative upper limit of 0.02 meV for the strength of the potential $E_r = 446$ keV resonance in the $^{26g}\mathrm{Al}(p,\gamma)$ reaction (we note that the possible 446-keV, $^{26g}\mathrm{Al}(p,\gamma)$ resonance could equally correspond to a much weaker $3/2^+$ state as indicated by a recent β-decay study of $^{27}\mathrm{P}$ [41]). This implies a maximum contribution of four background counts from ground state reactions to the observed recoil-γ coincidences, shown in Fig. 1(d), and a definitive strength for the $^{26m}\mathrm{Al} + p$ resonance at 447 keV of $\omega\gamma = 432^{+146}_{-226}$ meV.

In order to assess the astrophysical implications of the present work, we consider contributions to the $^{26m}\mathrm{Al}(p,\gamma)$ stellar reaction rate from known resonances at $E_r = 218$, 447, 626, 683, and 754 keV [32,35] (it is important to note that the earlier study of Ref. [35] has already ruled out a number of resonances with $E_r < 500$ keV as having a significant influence on the rate). For the strength of the 218-keV state, we adopt the upper limit reported in Ref. [35] for a $3/2^-$ assignment, while for the strength of the 447-keV resonance, we use the presently measured value. In contrast, estimates for the remaining resonance strengths are made using shell-model calculations and by assuming that the 626-, 683-, and 754-keV levels correspond to the $3/2^+_{12}$ ($C^2S = 0.0017$, $\Gamma_\gamma = 0.51$ eV), $5/2^+_{15}$ ($C^2S = 0.0003$, $\Gamma_\gamma = 1.6$ eV), and $1/2^+_8$ ($C^2S = 0.0025$, $\Gamma_\gamma = 0.79$ eV) excited states in $^{27}\mathrm{Si}$, respectively. These assignments are consistent with earlier γ-ray spectroscopy work [33] and the results of $^{27}\mathrm{P}$ β-decay studies [41,42], and we obtain $\omega\gamma = 45$, 23, and 741 meV for the resonant states at $E_r = 626$, 683, and 754 keV, respectively. As can be seen in Fig. 2, the 447-keV resonance governs the entire $^{26m}\mathrm{Al}(p,\gamma)$ stellar reaction rate over the peak temperature

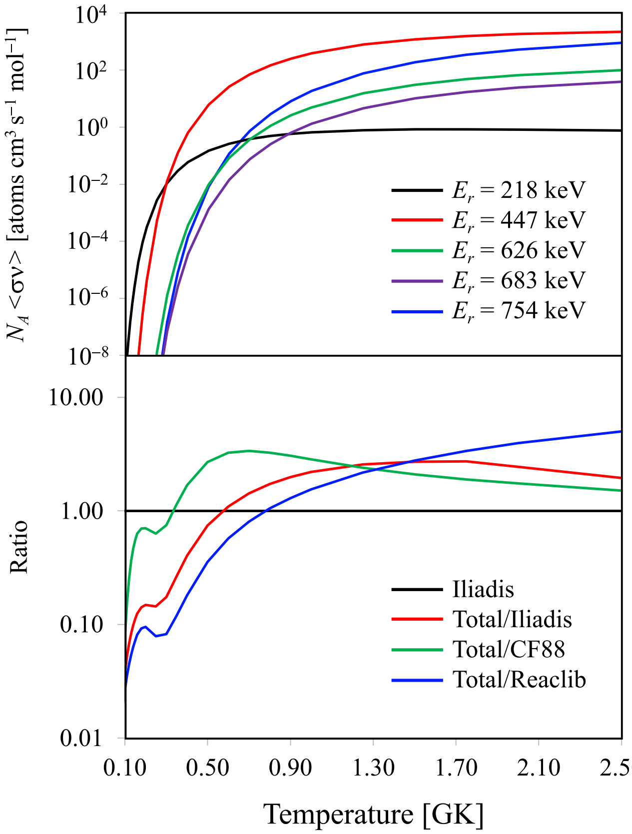

FIG. 2. Top: contribution of individual resonances to the $^{26m}\mathrm{Al}(p,\gamma)$ stellar reaction rate. Bottom: comparison of the $^{26m}\mathrm{Al}(p,\gamma)$ rate from this Letter with the previously reported estimates of Caughlan and Fowler (CF88) [44] and the REACLIB database [43], as well as the experimentally constrained $^{26g}\mathrm{Al}(p,\gamma)$ reaction, which has been recommended as an approximation for the $^{26m}\mathrm{Al}(p,\gamma)$ reaction by Iliadis *et al.* [4].

range of classical novae and supernovae, in agreement with Ref. [35]. In fact, even if the present lower limit for the resonance strength is used, and assuming a factor of 10 uncertainty in the shell-model spectroscopic factor of the 626-keV resonance, the 447-keV state still provides the dominant contribution to the rate for temperatures $T = 0.3$–1.5 GK. Intriguingly, at temperatures $\sim$2.5 GK, for which it is likely that more resonances contribute to the rate than are currently being considered, we now expect at least a factor $\sim$5 increase in the rate in comparison to that of the previously reported REACLIB estimate [43]. Whereas, it would appear that the experimentally constrained $^{26g}\mathrm{Al}(p,\gamma)$ reaction does indeed provide a reasonable approximation for the astrophysical $^{26m}\mathrm{Al}(p,\gamma)$ rate at high temperatures. As such, although significant discrepancies exist at lower temperatures, the present Letter offers evidence in support of theoretical studies that adopted the ground state rate for the $^{26m}\mathrm{Al}(p,\gamma)$ reaction in investigating ^{26}Al nucleosynthesis in massive stars and core collapse supernovae (e.g., Ref. [4]). That being said, the strength of resonances in the $^{26m}\mathrm{Al} + p$ with $E_r > 447$ keV remains uncertain and it is possible that these could still increase the overall $^{26m}\mathrm{Al}(p,\gamma)$ rate considerably at high temperatures.

In summary, we have performed the first direct measurement of an astrophysical reaction using a radioactive beam of isomeric nuclei. In particular, the key 447-keV resonance in the $^{26m}\mathrm{Al}(p,\gamma)$ reaction was measured to have a resonance strength of 432^{+146}_{-226} meV and was found to dominate the entire stellar reaction rate over the temperature range 0.3–2.5 GK. Further constraints on the rate of the $^{26m}\mathrm{Al}(p,\gamma)$ reaction at temperatures relevant for classical novae would now require an indirect determination of the $E_r = 218$ keV resonance strength, while additional direct measurements of higher-energy resonances, such as the 626-, 683-, and 754-keV states, would allow for the reaction to be fully defined for $T > 1$ GK.

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