Study of the ^{26}Al$^m(d,p)^{27}$Al reaction and the influence of the ^{26}Al 0^+ isomer on the destruction of ^{26}Al in the Galaxy

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The existence of ^{26}Al ($t_{1/2} = 7.17{\times}10^5$ yr) in the interstellar medium provides a direct confirmation of ongoing nucleosynthesis in the Galaxy. The presence of a low-lying 0^+ isomer (^{26}Al^m), however, severely complicates the astrophysical calculations. We present for the first time a study of the ^{26}Al$^m(d,p)^{27}$Al reaction using an isomeric ^{26}Al beam. The selectivity of this reaction allowed the study of $\ell = 0$ transfers to $T = 1/2$, and $T = 3/2$ states in ^{27}Al. Mirror symmetry arguments were then used to constrain the ^{26}Al$^m(p,\gamma)^{27}$Si reaction rate and provide an experimentally determined upper limit of the rate for the destruction of isomeric ^{26}Al via radiative proton capture reactions, which is expected to dominate the destruction path of ^{26}Al^m in Asymptotic Giant Branch stars, Classical Novae and Core Collapse Supernovae.

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The detection of the characteristic 1.809-MeV γ-ray line from the decay of the long-lived radioisotope ^{26}Al ($t_{1/2} = 7.17{\times}10^5$ yr) in the interstellar medium [1, 2] has demonstrated that nucleosynthesis is an ongoing process in the Galaxy, confirming earlier measurements of excess ^{26}Mg in meteorites [3–5] and presolar dust grains [6, 7]. From the observed γ-ray intensity [2, 8, 9], an equilibrium mass of $\sim$ 2 - 3 solar masses of ^{26}Al in the entire Galaxy [8] has been inferred. It is expected [2, 10, 11] that Galactic ^{26}Al is produced predominately in massive Wolf-Rayet (WR) stars either during the hydrogen-burning or their core collapse supernova (CCSN) phase [8], with additional contributions from asymptotic giant branch (AGB) stars and classical novae (CN) [12, 13]. The existence of a short-lived ($t_{1/2}$ = 6.4 s) isomeric state, located 228 keV above the ground state, however, severely complicates the calculation of its nucleosynthesis [14]. While transitions between the isomeric state (^{26}Al^m, $J^\pi = 0^+$) and the ground state (^{26}Al^g, $J^\pi = 5^+$) are strongly inhibited by the large spin difference ($\Delta J = 5$), they may communicate with each other via thermal excitations involving higher-lying levels in ^{26}Al [15].

In AGB stars, CN and CCSN the destruction of ^{26}Al is governed by radiative proton capture reactions on ^{26}Al^g and ^{26}Al^m [14]. The ^{26}Al$^g(p,\gamma)^{27}$Si reaction has been the subject of several studies (e.g. Refs. [16–24]). A γ-ray study of ^{26}Al$^g + p$ resonances in ^{27}Si identified low-lying resonances which strongly influence the rate of the ^{26}Al$^g(p,\gamma)^{27}$Si reaction [20]. Two recent experiments of the ^{26}Al$^g(d,p)^{27}$Al reaction gave spectroscopic information of key resonances in the mirror nucleus ^{27}Al. From these results the ^{26}Al$^g(p,\gamma)^{27}$Si reaction rate in WR and AGB stars is well constrained [23, 24].

For the isomeric state, however, very scarce experimental information is available on the rate of the ^{26}Al$^m(p,\gamma)^{27}$Si reaction [25, 26]. While the results of Ref. [25] provide excitation energies and proton-decay branching ratios for high-lying states in ^{27}Si ($E_r^m \geq 445$ keV), it is also pointed out that the reaction rate could be dominated by unobserved resonances at lower excitation energies. Ref. [26] provided the exact energies of the critical $\ell = 2$ (E_r^m = 146 keV) and $\ell = 1$ (E_r^m = 378 keV) states that are expected to dominate the rate in a wide range of temperatures. Sensitivity studies have highlighted uncertainties in this reaction as being of critical importance to understand the ^{26}Al production in massive stars and the isotopic abundances of ^{26}Mg synthesized in novae environments [14, 27]. In the most recent of such studies, Iliadis *et al.* [14] adopted the ground state rate for the isomeric rate due to the lack of experimental information.

Estimates of the ^{26}Al$^m(p,\gamma)^{27}$Si rate are presently based on Hauser-Feshbach calculations by scaling the ground state (p,γ) rate [28–30]. This approximation is inadequate since very different states and configurations are populated by the ^{26}Al$^g + p$ and ^{26}Al$^m + p$ proton resonances in ^{27}Si as shown in Ref. [25].

Several attempts have been made to produce an isomeric ^{26}Al^m beam with sufficient intensity and a high isomer-to-ground-state ratio in order to study nuclear reactions induced by the 0^+ isomer in ^{26}Al [31–34]. This letter reports on the measurement of the ^{26}Al$^m(d,p)^{27}$Al reaction using a ^{26}Al beam with 70% isomeric content.

Spectroscopic information of states in ^{27}Al populated by single-neutron transfers on the 0^+, $T = 1$ isomer was extracted. Symmetry considerations between members of the $A = 27$ mirror system (^{27}Al, ^{27}Si) were then used to constrain the ^{26}Al$^m(p,\gamma)^{27}$Si reaction rate in relevant astrophysical scenarios.

The experiment was performed at the ATLAS accelerator facility at Argonne National Laboratory. A 4.6 MeV/u ^{26}Al^m beam was produced in-flight [35] via the ^{26}Mg$(p,n)^{26}$Al reaction in inverse kinematics. Details will be given in a separate paper [36].

The purity of the ^{26}Al beam was better than 98% as shown in Fig. 1(a) in a spectrum measured with a silicon detector at 0°. The main contaminant of the ^{26}Al^{13+} beam came from the primary ^{26}Mg^{11+} production beam. An implantation experiment was performed to measure the purity and isomer content of the beam using a rotating stopper setup. After an implantation time of 15 sec the stopper foil was rotated by 180° in between two NaI detectors. Fig. 1(b) shows the annihilation radiation measured with two NaI detectors. The insert confirms the presence of ^{26}Al^m through its known 6.35 s half-life. From this run it was established that 70±10% of the radioactive ^{26}Al beam was in the isomeric 0^+ state.

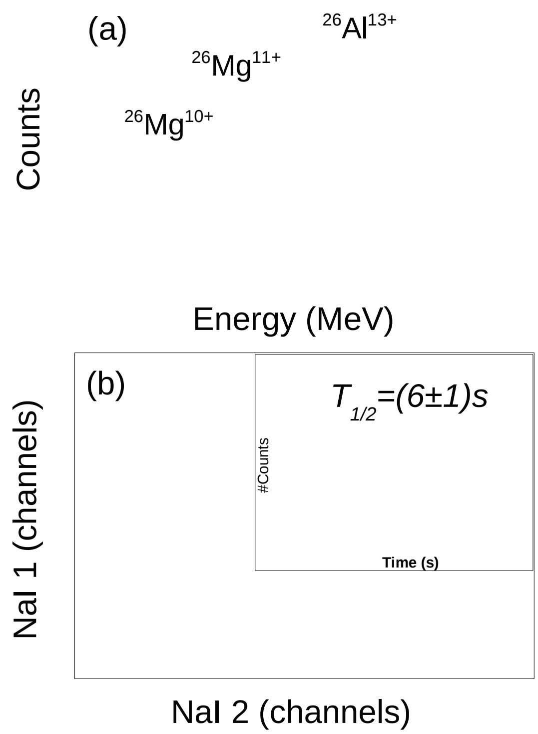

FIG. 1. (color online). (a) Spectrum of the ^{26}Al beam measured at 0° in a silicon detector. The main contaminant is a 11^+ charge state of the ^{26}Mg production beam. (b) Coincidence spectrum measured with the NaI detectors. The insert shows the half-life of the beam determined by the 511-keV coincidences confirming the presence of the isomer.

The ^{26}Al$(d,p)^{27}$Al reaction was measured using a 450 μg/cm^2 thick CD_2 target which was bombarded by a 120 MeV ^{26}Al beam with a typical intensity of $2.5{\times}10^5$ pps. The energy of the beam was very close to the energy used in the measurement of Ref. [23] with a ^{26}Al^g beam. Two Micron-S1 silicon detectors [37] were placed at 45 mm and 90 mm upstream of the target covering an angular range in the laboratory frame of 133° - 151° and 152° - 165°, respectively. Due to the close geometry and the target thickness, the energy resolution achieved in this experiment was limited to 120 keV (FWHM). A silicon detector was used to measure the purity of the ^{26}Al beam. The ^{26}Al^m/^{26}Al^g ratio of the beam was determined from the yield of the 511-keV γ-rays from the β^+ decay of ^{26}Al^m particles stopped in a Au catcher and measured with a NaI detector. During the experiment the isomer-to-ground-state ratio remained constant to within 10%.

A separate measurement of the (d,p) reaction with the main beam contaminant ^{26}Mg^{11+} was also performed. Since protons from the 86 MeV ^{26}Mg$(d,p)^{27}$Mg reaction arrived later at the two Si detectors they could be eliminated by using their different time-of-flight. A run with a pure carbon target was performed which yielded a smooth background that was scaled to a region containing no peaks from the ^{26}Al$(d,p)^{27}$Al reaction and subtracted from the CD_2 target data.

The energy spectrum of states populated in the present ^{26}Al$(d,p)^{27}$Al experiment with a 70% ^{26}Al^m and 30% ^{26}Al^g beam measured in the angular range $\theta_{c.m.} \sim 6°$ - 12° is shown in Fig. 2(a) in comparison with the results of Ref. [23] using a pure ^{26}Al^g beam (Fig. 2(b)). The data of Ref. [23] were folded with a Gaussian of width 120 keV, normalized to the strength of the 3.004 MeV $9/2^+$ state, which is predominantly populated with the ^{26}Al^g beam and then subtracted from the energy spectrum measured in this experiment. The resulting spectrum representing states populated by the isomeric ^{26}Al$^m(0^+)$ beam, is shown in Fig. 2(c). The shape of the peak at $\sim$ 10 MeV is due to a background of low-energy β^+ decay events in the silicon detectors. These events merge with the $E_{ex} \sim 10$ MeV peak at the most forward angles due to the kinematic compression but are well separated at other angles. The states in Fig. 2 are shown as a function of the ^{27}Al apparent excitation energy which is calculated using the Q-value for the ground state. Therefore, the states populated by the isomer component of the beam appear shifted down in energy.

The most remarkable feature of the energy spectrum measured with the ^{26}Al^m beam shown in the bottom panel of Fig. 2 is the high selectivity of the (d,p) reaction. The spectrum is dominated by the $1/2^+$ states at $E_{ex} = 0.84$, 6.8 and 10.2 MeV in ^{27}Al [38]. Transfers to other states (e.g. the $5/2^+$ ground state in ^{27}Al) are weaker by about one order of magnitude.

The $9/2^+$ state at 3.004 MeV in ^{27}Al was used for

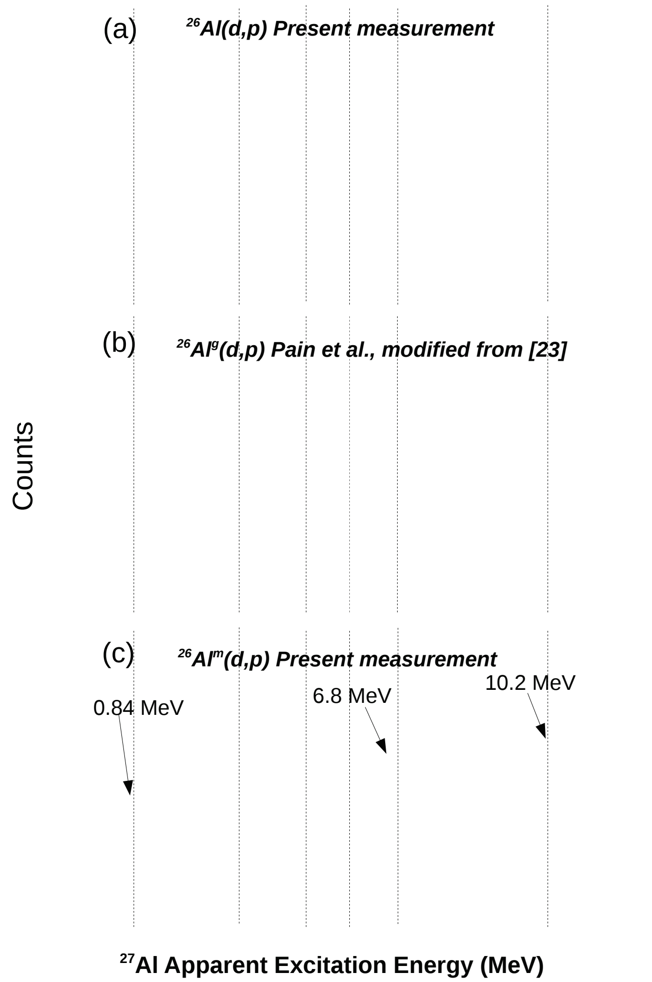

FIG. 2. (color online). (a) Apparent excitation energy spectrum of ^{27}Al obtained from the ^{26}Al(d,p) reaction at $\theta_{cm} \sim 6^\circ$ - 12°. A smooth carbon background has been subtracted. The ^{27}Al excitation energy was calculated using the Q-value for the ground state. Therefore, states populated by the isomer component of the beam appear shifted down in energy. (b) Data from the ^{26}Al$^g(d,p)$ reaction in a similar angular range [23] folded with a 120 keV Gaussian, normalized to the state at 3.004 MeV are shown for comparison. (c) Apparent excitation energy spectrum of ^{27}Al from the ^{26}Al$^m(d,p)$ reaction. The spectrum was obtained by subtracting contributions from the ^{26}Al^g beam measured in Ref. [23].

beam normalization. This state is dominantly populated via $\ell = 0$ transfer from the ground state (5^+) component of the beam as shown in Fig. 3(a). The angular distribution was fitted with the adiabatic distorted-wave approximation (ADWA) using the TWOFNR code [39] and the finite-range distorted-wave Born approximation (DWBA) using the PTOLEMY code [40]. The deuteron bound-state wave function was described using the Argonne ν_{18} potential [41], which in the case of ADWA was done using the Johnson-Tandy adiabatic model [42]. The target bound-state form factors were generated using a Woods-Saxon potential with a spin-orbit derivative term, defined by $r_0 = 1.25$ fm, $a = 0.65$ fm, $V_{\rm so} = 6$ MeV, $r_{\rm so0} = 1.1$ fm, and $a_{\rm so} = 0.65$ fm. For the DWBA calculations, two sets of global optical-model potentials were explored for the deuterons [43, 44] and similarly for the protons [45, 46]. The same proton potentials were used for the nucleus-nucleon optical potentials in the ADWA calculations. Variations in the resulting spectroscopic factors of less than 10% were seen between the calculated cross sections using the two models and the different combinations of optical-model parameters. The fit to the 3.004 MeV state was normalized so that the spectroscopic factor of 0.49(2) of Ref. [24] was reproduced. From this procedure the total intensity of the ^{26}Al^g beam could be determined. The total intensity of the ^{26}Al^m beam was then obtained using the measured 0.7/0.3 ratio.

Angular distributions for the three transitions to $1/2^+$ states at E$_{ex}$ = 0.84, 6.8 and 10.2 MeV in ^{27}Al are shown by the solid points in Fig. 3(b-d). The uncertainties are dominated by the beam normalization and background subtraction. For that a 15% systematic uncertainty was added linearly to the statistical uncertainties. The distributions are all forward peaked confirming that the 0^+ isomeric beam preferentially populates $2s_{1/2}$ states in ^{27}Al via $\ell = 0$ neutron transfers. The solid lines in Fig. 3(b-d) are DWBA calculations assuming an $\ell = 0$ transfer, populating $2s_{1/2}$ states in ^{27}Al at the corresponding excitation energies with their determined spectroscopic factors shown in the insert. The dashed and dotted lines in Fig. 3(b) are examples of angular distributions for $\ell = 1$ - 4 transfers populating a 0.84 MeV state in ^{27}Al with the same spectroscopic factors used for $\ell = 0$ showing that $\ell = 0$ transfer dominates the forward-peaked angular distributions.

The $T = 3/2$, $2s_{1/2}$ states in our measurement are pure $\ell = 0$ transfers from the ^{26}Al^m (0^+, $T = 1$) isomeric beam since $T = 3/2$ states cannot be reached from the ^{26}Al^g(5^+, $T = 0$) state. The $T = 3/2$, $2s_{1/2}$ states at E$_{ex}$ = 6.81 MeV and E$_{ex}$ = 10.24 MeV are the strongest peaks in our spectrum. These states are the isobaric analog states of the ground and 3.47 MeV states in ^{27}Mg [47, 48] with spectroscopic factors of $C^2S = 0.11\pm0.03$ and $C^2S = 0.16\pm0.04$, respectively. In addition, the $T = 1/2$, $1/2^+$ state at 0.84 MeV is also strongly populated in our measurement with an $\ell = 0$ transfer and a spectroscopic factor of $C^2S = 0.08\pm0.02$.

These highly selective (d,p) data allow us to search for states in ^{27}Al which are mirrors to the states above the proton threshold in ^{27}Si (S$_p$ = 7.463 MeV) that are expected to dominate the ^{26}Al$^m(p,\gamma)^{27}$Si astrophysical reaction rate. Taking into account an average value for the $A = 27$ mirror energy differences of ~ 200 keV [21, 49] and a 228 keV difference between the ground state and the isomeric state, the states in ^{27}Al which are mirrors to the astrophysically relevant states in ^{27}Si are expected

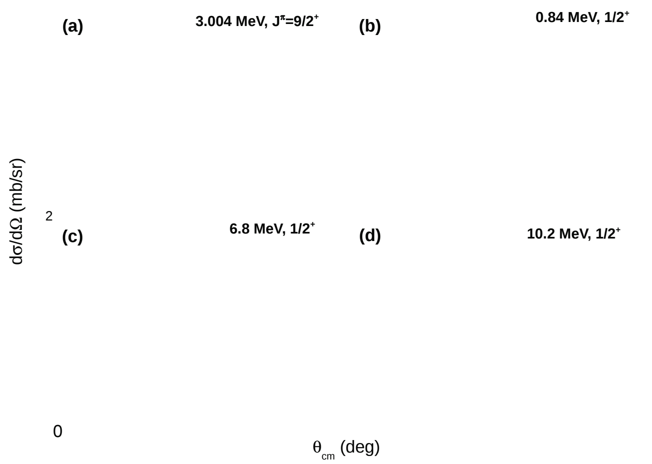

FIG. 3. (color online). (a) Angular distribution and DWBA and ADWA fits for the $9/2^+$ state in ^{27}Al at E_{ex} = 3.004 MeV. The data agree with the $\ell = 0$ transfer from the 5^+ ground state component observed in [24]. A spectroscopic factor, $C^2S = 0.49$ [24] was used to obtain the absolute beam normalization of the cross section. Angular distributions and DWBA calculations for the states in ^{27}Al at (b) E_{ex} = 0.84 MeV, (c) E_{ex} = 6.8 MeV, and (d) E_{ex} = 10.2 MeV. These three states are strongly populated by $\ell = 0$ neutron transfers on the isomeric component of the ^{26}Al beam.

at $E_{ex} \sim$ 7.9 - 8.5 MeV.

In this energy region the structure of the spectrum measured with the mixed ^{26}Al beam (Fig. 2(a)) is very similar to the one obtained with a pure ^{26}Al^g (see Fig. 2(b)). After subtracting the contribution from the ground state beam, two very small structures remain in our spectra in the astrophysically relevant energy region at E_{ex} = 7.9(3) MeV and E_{ex} = 8.5(3) MeV. The yield at E_{ex} = 7.9 MeV agrees with the $5/2^+$ state reported by Lotay *et al.* [21] at E_{ex} = 8.063 MeV, where this state was assigned to be the mirror of the level at E_{ex} = 7.838 MeV in ^{27}Si (E_r^m = 146 keV). The yield at E_{ex} = 8.5 MeV could be the mirror of the $3/2^-$ level at E_{ex} = 8.070 MeV in ^{27}Si (E_r^m = 378 keV). With the statistics obtained in the present experiment, no states with spectroscopic factors > 0.025 can be attributed to transfers from the ^{26}Al^m beam in this energy region. The 146-keV and 378-keV resonances are expected to dominate the ^{26}Al$^m(p,\gamma)^{27}$Si reaction rate [26]. For the spectroscopic factors of the mirror states in ^{27}Si the same limits have been adopted. Spectroscopic factors of mirror analog states are expected to agree within 20% [24, 50, 51]. For the strength of the 146-keV and 378-keV resonances upper limits of 0.03 μeV and 165 meV, respectively, have been extracted. This allows us to calculate limits of the astrophysical rate of the ^{26}Al$^m(p,\gamma)^{27}$Si reaction which are solely based on experimental data. This rate is shown in Fig. 4(a) in comparison with the recommended NACRE rate of Angulo [29, 30], and the ground state rate extracted from Refs. [20, 23, 24].

For temperatures of T_9 (GK) ≤ 0.15, typical of AGB stars, the 146-keV resonance dominates the rate. At these temperatures, no significant contribution of the isomeric state to the abundance of ^{26}Al is expected. For temperatures between $0.2 \leq T_9 \leq 1.0$, typical of oxygen-neon novae and CCSN, the reaction rate is dominated by the 378-keV resonance. For temperatures in this range ($T_9 \geq 0.3$), the ^{25}Al$(p,\gamma)^{26}$Si reaction competes significantly with the β-decay of ^{25}Al, leading to a significant abundance of ^{26}Al in its isomeric state [52]. Moreover, at these temperatures communication between the ground state and the isomeric state is expected through thermal excitations. The ratio between isomeric and g.s. rates is shown in Fig. 4(b). The solid curve gives the ratio based on experimental data presented in this paper and that of Refs. [20, 23, 24] while the dashed curve is based on the recommended NACRE/STARLIB calculations [29, 30, 53]. At temperatures $T_9 \geq 0.3$ the destruction rates via proton capture in the isomer and ground state are comparable and would need to be properly included in network calculations to account for the observed abundance of ^{26}Al synthesized in such environments. At temperatures $T_9 \leq 0.3$ no significant contribution of the isomeric state to the abundance of ^{26}Al is expected. This behavior is different from the one expected from the NACRE/STARLIB calculations shown by the dashed curve in Fig. 4(b) where the NACRE calculations overestimates the ^{26}Al$^m(p,\gamma)^{27}$Si rate in the temperature rate $T_9 \leq 0.5$.

In summary, we developed a high-quality ^{26}Al isomeric beam and used it to study the ^{26}Al$^m(d,p)^{27}$Al reaction. This highly-selective reaction preferentially populates ℓ = 0, $T = 3/2$ and $T = 1/2$ states in ^{27}Al providing a powerful spectroscopic tool. Mirror symmetry arguments between ^{27}Al and ^{27}Si were used to search for astrophysically relevant states to constrain the ^{26}Al$^m(p,\gamma)^{27}$Si reaction rate. This provides, for the first time, with data from previous experimental studies, an upper limit for the reaction rate relevant for the destruction of Galactic ^{26}Al in AGB stars, CN and CCSN as well as for the accurate determination of isotopic abundances of ^{26}Mg in such environments.

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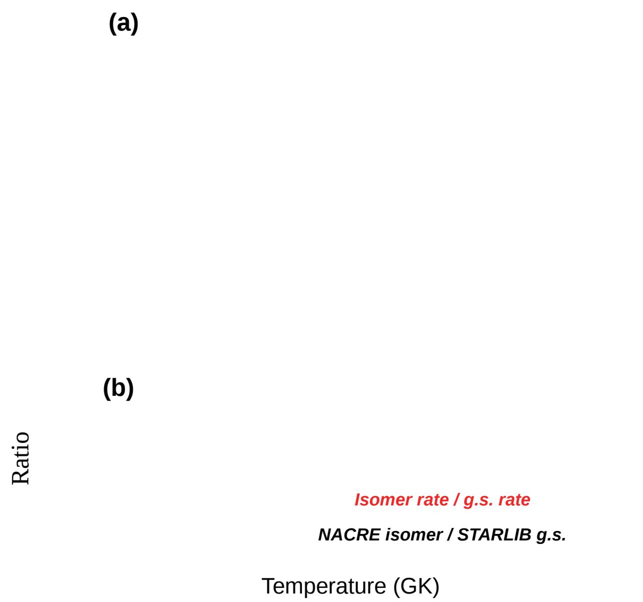

FIG. 4. (color online). (a) Upper limits for the rate of the $^{26}\mathrm{Al}^m(p,\gamma)^{27}\mathrm{Si}$ reaction in stellar environments as a function of the temperature. The isomer (m) rate (this work) is shown compared to the ground state (g) and the recommended NACRE rate [29, 30]. The (g) rate was calculated with parameters from Refs. [20, 23, 24]. (b) Ratios between the experimental isomeric (m, this work) and ground state (g, [20, 23, 24]) rates (solid line) and the isomeric/ground state rates recommended by the NACRE/STARLIB calculations (dahsed line) [29, 30, 53].

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