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ASTROPHYSICAL ASPECTS OF THE ^{25}Mg(p, γ)^{26}Al REACTION

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Abstract: The reaction rates of ^{25}Mg(p, γ)^{26}Al have been calculated at stellar temperatures of $T_9 = 0.005$ to 10 using the data presented in recent capture work. At $T_9 > 0.2$, the rates are in good agreement with the results incorporated in a recent compilation. However, near the important temperature range of $T_9 \simeq 0.08$ the rates are higher by a factor of about 400. These calculations are uncertain by a factor of two. In addition, the branching f_0 to the ^{26}Al ground state approaches a value of $f_0 \simeq 0.80$ at $T_9 < 0.1$, while the compilation gives $f_0 \simeq 0.57$. The reasons for these changes are discussed. The results increase significantly the abundance of ^{26}Al in various astrophysical scenarios, which produce ^{26}Al via the MgAl cycle near $T_9 = 0.08$, and thus will be of importance for the explanation of extinct ^{26}Al in meteoritic samples as well as of the 4 solar masses of ^{26}Al found in the interstellar medium via γ-ray astronomy.

1. Introduction

Recent efforts in γ-ray astronomy have led to the discovery of an 1809 keV γ-ray line [1]), which is known to be produced in the β-decay of ^{26}Al ($T_{1/2} = 7.2 \times 10^5$ y). From its intensity it was estimated [2]) that about 4 solar masses of ^{26}Al nuclides are present in the interstellar medium of our galaxy. The presence of ^{26}Al in the interstellar medium had already been concluded in 1977 from the observation of ^{26}Mg isotopic enrichments (extinct ^{26}Al) in carbonaceous meteorites [3,4]). Thus, while the Mg isotopic variations show that ^{26}Al must have been produced not later than some 4.6 billion years ago (the condensation of solar-system material), the observation of the 1809 keV γ-ray line provides evidence that ^{26}Al nucleosynthesis continued at least until "recently", about 1 million years ago (the lifetime of ^{26}Al). Clearly, any astrophysical scenario for ^{26}Al nucleosynthesis must be concordant with both observations [2,5,6]). The most likely mechanism for ^{26}Al nucleosynthesis is in the hydrogen burning MgAl cycle (fig. 1). Laboratory results for the reaction rates of the processes in this cycle have helped to test the various suggested astrophysical models [5-9]), i.e. novae, supernovae, red giants, Wolf-Rayet stars and supermassive stars, which - under special circumstances - could just explain one or the other observation, but not both. At present, no definite decision can be made on the dominant production mechanism for ^{26}Al in our galaxy, but the most popular

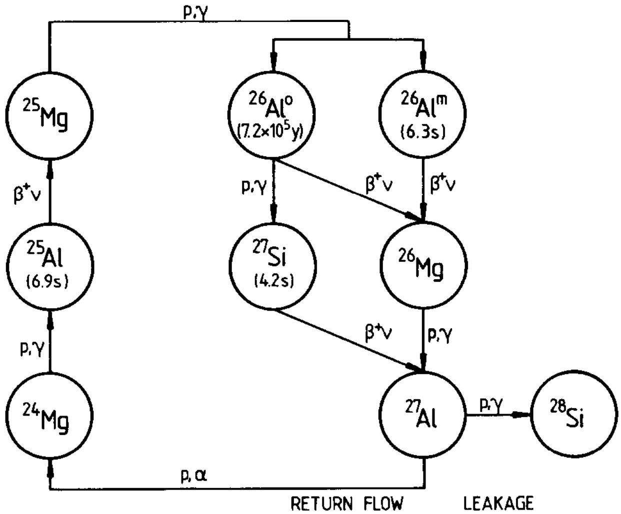

Fig. 1. Sequence of nuclear reactions and β-decays involved in the low-temperature operation of the hydrogen-burning MgAl cycle. The half-lives of all radioactive nuclides are indicated. The symbols $^{26}Al^{o}$ and $^{26}Al^{m}$ refer to ^{26}Al in its ground state and its isomeric state at $E_x = 228$ keV, respectively. The $^{27}Al(p, \gamma)^{28}Si$ reaction leads to a leakage of catalytic material out of the cycle.

scenarios appear to be associated with novae and Wolf-Rayet stars, where ^{26}Al nucleosynthesis occurs near $T_9 = 0.1$ ($T_9 = 10^9$ K).

The rates of the various reactions of the MgAl cycle are well-known [10]) at the higher temperatures, while substantial uncertainties exist, e.g. for the ^{26}Al production reaction $^{25}Mg(p, \gamma)^{26}Al$, at the important temperature range below $T_9 \simeq 0.2$. Thus, stringent tests of the astrophysical models require improved information on reaction rates at $T_9 < 0.2$, i.e. $E_p < 220$ keV for the $^{25}Mg(p, \gamma)^{26}Al$ reaction, where E_p corresponds to the Gamow peak [10]).

2. Total reaction rates

De Neijs *et al.* [11]) have investigated the $^{25}Mg(p, \gamma)^{26}Al$ reaction in the energy range $E_p(\text{lab}) = 0.3$ to 2.0 MeV, where the lowest-lying resonance at $E_R(\text{lab}) =$ 317 keV corresponds to a stellar temperature of $T_9 = 0.3$. The studies were extended by Elix *et al.* [12]) down to $E_p(\text{lab}) = 80$ keV; they found additional resonances at $E_R(\text{lab}) = 198$, 255 and 304 keV. Upper limits on the strengths $\omega\gamma$ for the expected resonances (fig. 2) at $E_R(\text{c.m.}) = 93$ and 130 keV were also reported [12]). The level structure of ^{26}Al near the proton threshold was investigated subsequently in several papers [13-16]) with the use of various nuclear reactions. These investigations together with the much more accurate results from refs. [17-19]) established the level structure of ^{26}Al as shown in table 1. It should be remarked that the E_x values given in the $^{25}Mg(\tau, d)^{26}Al$ paper by Betts *et al.* [13]) are quite poor. To determine which deuteron

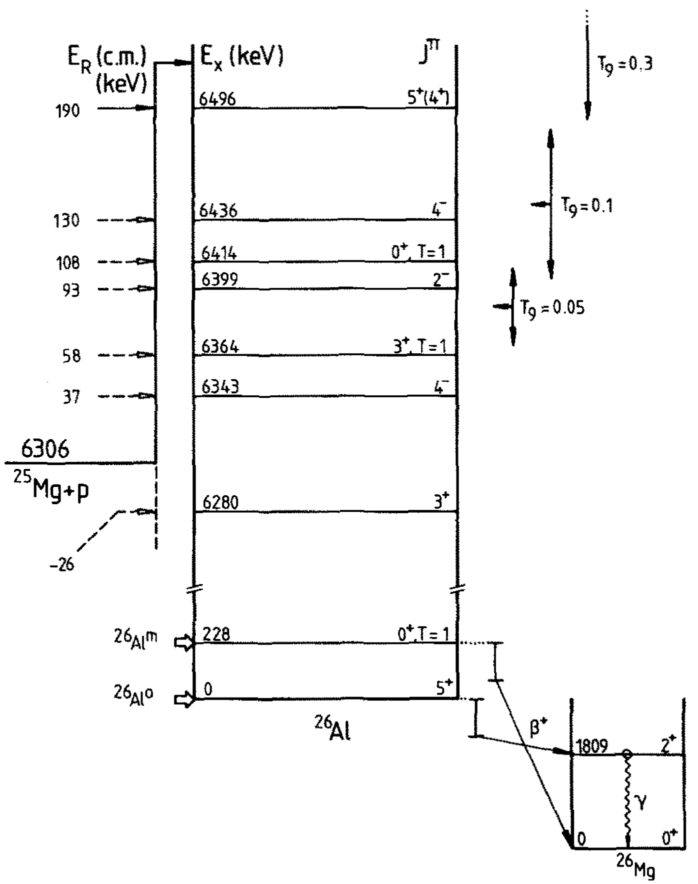

Fig. 2. Level structure of ^{26}Al near the proton threshold. The excitation energies and $J^{\pi}(T)$ assignments are from refs. [18,19]). The E_R(c.m.) = 190 keV resonance is the lowest resonance observed in the direct yield measurements [12]). The energies of the expected low-energy resonances are indicated. The 6280 keV state corresponds to a subthreshold resonance at $E_R = -26$ keV. Also shown are the energy regions (Gamow peak) of astrophysical interest for different stellar temperatures T_9 ($T_9 = 10^9$ K).

peak corresponds to which level deduced from the (p, γ) work, one can best derive energies directly from the deuteron spectrum (their fig. 1) with the help of a calibration curve based on the (p, γ) energies of strongly excited isolated levels.

Most important for nucleosynthesis are the J^{π} assignments to the two levels immediately above the proton threshold ($E_{\text{thr}} = 6306$ keV), i.e. those at $E_x = 6343$ and 6364 keV. The $J^{\pi} = 3^+$ assignment to the latter level is obtained from the (p, γ) work [18,19]) alone, and is based on the γ-decay to ten lower levels and on the feeding from 21 higher-energy resonances. It agrees with $l(\tau, \text{d}) = 0+2$ and is in conflict with $l(\tau, \alpha) = 1$. The (p, γ) work also shows that the 6343 keV level does not have s-wave character ($J \neq 2$ or 3) and thus is much less important than the 6364 keV level. Seven γ-branches are observed in the 6343 keV decay and the level is excited

TABLE 1

Excitation energies and J^π; T values of ^{26}Al states near the proton threshold

E_x [a] (keV)	l		$J^\pi; T$			Remarks
	(τ, d) [b]	(τ, α) [c]	γ-decay [a]	γ-feeding [a]	resulting	
6280.33 (9)	0+2		(2, 3); 0	$\neq 2^+$	3^+; 0	
6343.46 (8)		1+3	(3, 4); 0	$\neq 3$	4^-; 0	
6363.99 (8)	1	0+2	(2^+-4^+)	$T=1$, $\neq(2^+, 3^-, 4^+)$	3^+; 1	[d]
6398.64 (21)		1+3	(0^+-4^+)	$T=0$, $\neq(0^+, 1, 3, 4^+)$	2^-; 0	
6414.46 (10)		0+2	$(0-3^+)$	$T=1$, $\neq 3^+$	0^+; 1	[e,f]
6436.44 (11)		1+3	$(3-5^+)$; 0	$\neq(3, 4^+)$	4^-; 0	
6495.94 (7)		0+2	(3^+-5^+); 0	$\neq 3^+$	$(4, 5)^+$; 0	[f]
6550.68 (7)	2		$(4, 5)^+$		$(4, 5)^+$; 0	[g]
6598.32 (16)			(3^+-5^+); 0	$\neq 3^+$	$(4, 5)^+$; 0	
6610.40 (6)	1		3^-		3^-; 0	[h]

[a]) From the ^{25}Mg(p, γ)^{26}Al reaction [18]); the levels above $E_x = 6.45$ MeV have been seen as resonances [12,18]), those below this energy are only excited in the decay of higher-energy resonances.

[b]) Ref. [13]).

[c]) Ref. [16]).

[d]) The $l(\tau, d) = 1$ value must be erroneous.

[e]) This is the only level which can be the analogue of the ^{26}Mg state at $E_x = 6256$ keV with $J^\pi = 0^+$.

[f]) The $l(\tau, \alpha) = 0$ value (with extremely small corresponding spectroscopic factor) must be erroneous.

[g]) The $T = 0$ assignment is based on the argument that for $T = 1$ there is no possible parent level in ^{26}Mg.

[h]) With $T = 0$ determined from γ-ray strength statistics [25]).

at six resonances. A former calculation [10]) of stellar reaction rates was based on erroneous J^π assignments [14,15]) for the two levels mentioned above. Based to a large extent on the results of refs. [17–19]) and including also new data, the reported J^π values [14,15]) have been revised recently [20]).

The stellar reaction rates $N_A\langle\sigma v\rangle$ of ^{25}Mg(p, γ)^{26}Al can have contributions from the narrow resonances, the high-energy wing of the $E_R = -25.7$ keV subthreshold resonance and the direct capture (DC) process into the ^{26}Al bound states. These contributions are discussed in more detail below. It should be noted that the latter two contributions have not been taken into account in previous analyses [14,15,20]).

2.1. NARROW RESONANCES

The reaction rates (in units of reactions $\cdot$ s^{-1} $\cdot$ mole^{-1} $\cdot$ cm^3) for isolated narrow resonances in ^{25}Mg(p, γ)^{26}Al are given by the expression [21])

$$N_A\langle\sigma v\rangle = 1.62 \times 10^{11}\, T_9^{-3/2} \sum_i (\omega\gamma)_i \exp(-11.605\, E_i / T_9) \quad (1)$$

where the strengths $(\omega\gamma)_i$ and the c.m. energies E_i of the various resonances are in units of MeV. For the observed resonances at $E_i > 190$ keV the E_i values were deduced from ref. [18]), and the resonance strengths $(\omega\gamma)_i$ from ref. [12]) ($E_i = 190$ to 293 keV) and ref. [17]) ($E_i = 305$ to 1762 keV). For the low-energy resonances at

$E_i = 37.5$ to 130.4 keV, the resonance energies E_i were taken from ref. [18]) (table 2). Since for these resonances we have $\Gamma_p \ll \Gamma_\gamma \simeq \Gamma$, the strengths are determined by $\omega\gamma \simeq \omega\Gamma_p$ with

$$\Gamma_p(E_i) = 2\gamma_{Wl}^2 C^2 S(l_i) P(l_i, E_i) . \quad (2)$$

Here, the quantity $\gamma_{Wl}^2 = \hbar^2/\mu R^2 = 1.53$ MeV is the Wigner limit (μ = reduced mass in amu, R = interaction radius = 5.33 fm), $C^2 = \frac{1}{2}$ the isospin Clebsch-Gordan coefficient (for both $T=0$ and $T=1$ states), $S(l_i)$ the spectroscopic factor of the resonance state and $P(l_i, E_i)$ the penetrability at the resonance energy E_i for the orbital angular momentum l_i of the resonance.

The s-wave spectroscopic factor for the 6364 keV state of $S(l=0, 6364\text{ keV}) \simeq 0.24$ were estimated from fig. 2 of ref. [20]), relative to that of the 6280 keV state, where for the latter state a value of $S(l=0, 6280\text{ keV}) = 0.043$ was obtained from table 1 of ref. [13]). The error in the $S(l=0, 6364\text{ keV})$ spectroscopic factor for the 6364 keV state (astrophysically the most important state, as shown below) might be of the order of a factor 2. The p-wave spectroscopic factor for the 6343 keV state of $S(l=1, 6443\text{ keV}) \simeq 0.22$ was estimated from fig. 4 of ref. [13]) relative to that of the 5396 keV state ($S(l=1, 5396\text{ keV}) = 0.080$). Similarly, the values of $S(l=1, 6399\text{ keV}) \simeq 0.026$ and $S(l=1, 6436\text{ keV}) \simeq 0.014$ were estimated from fig. 2 of ref. [20]) relative to that of the peak for the $E_x = 6598 + 6610$ keV unresolved states, where the spectroscopic factors for the latter states were found in the following way: (i) for the 6598 keV state, the $\omega\gamma$ value from ref. [12]) and the condition $\Gamma_p \ll \Gamma_\gamma$ from ref. [18]) led to $S(l=2, 6598\text{ keV}) \simeq 0.9 \times 10^{-3}$; (ii) similarly, one finds $S(l=1, 6610\text{ keV}) \simeq 0.17$. Thus, the unresolved peak for the 6598 + 6610 keV states should be dominated by the contribution from the 6610 keV state. Using fig. 4 of ref. [13])

TABLE 2

Parameters of low-energy resonances

E_x (keV)	J^π	E_R(c.m.) [a]) (keV)	l_R	$S(l_R)$ [b])	Γ_p (eV)	$\omega\gamma$ (eV)
6280.33	3^+	−25.7 [c])	0	0.043 [d])		
6343.46	4^-	37.5	1	≃0.22	2.6E − 18	1.9E − 18
6363.99	3^+	58.0	0	≃0.24	2.1E − 12	1.2E − 12
6398.64	2^-	92.6	1	≃0.026	1.0E − 09	4.3E − 10 [e])
6414.46	0^+	108.5	2	<0.067	<2.3E − 09	<1.9E − 10 [f])
6436.44	4^-	130.4	1	≃0.014	2.3E − 07	1.7E − 07 [g])

[a]) Calculated from column 1 using $Q = 6306.0 \pm 0.5$ keV [ref. [22])].

[b]) As estimated from fig. 4 of ref. [13]) and fig. 2 of ref. [20]) (see text).

[c]) Subthreshold resonance.

[d]) From table 1 of ref. [13]).

[e]) An experimental upper limit of 4×10^{-8} eV is reported [12]).

[f]) An upper limit of 4×10^{-8} eV is estimated from fig. 2 of ref. [12]).

[g]) Since the experimental upper limit of 4×10^{-8} eV [ref. [12])] is smaller than the estimated value, the upper limit was assumed as the actual value.

and $S(l=1, 5396\,\text{keV}) = 0.080$ this led to $S(l=1, 6610\,\text{keV}) \simeq 0.19$, in good agreement with the above value. Finally, an upper limit of $S(l=2, 6414\,\text{keV}) < 0.067$ for the d-wave state at 6414 keV was deduced from fig. 2 of ref. [20]) relative to the 6091 keV state ($(2J_f+1)S(l=2, 6091\,\text{keV}) = 3.4$, table 1 of ref. [13])).

The values for $\Gamma_p(E_i)$ and $(\omega\gamma)_i$ calculated from the spectroscopic factors are given in table 2. The resulting reaction rates due to all the known narrow resonances are summarized in column 2 of table 3 as a function of stellar temperature. It turned out that the inclusion or omission of the $E_R = 108.5$ and 130.4 keV resonances ($E_x = 6414$ and 6436 keV) had an influence on the total reaction rates by a factor 1.03 and 1.93, respectively, near $T_9 = 0.1$. The resonance energies E_i are known to a precision of ±0.5 keV (table 2), which introduces an error in the reaction rates, e.g. for the $E_R = 58.0$ keV resonance at $T_9 = 0.08$ of ±7%, a negligible error compared to the uncertainty in the associated spectroscopic factor.

2.2. THE $E_R = -25.7$ keV SUBTHRESHOLD RESONANCE

The high-energy wing of the $E_R = -25.7$ keV subthreshold resonance was calculated [21]) from the Breit–Wigner expression for the cross section $\sigma(E)$ and converted into the astrophysical S-factor

$$S(E) = \sigma(E) E \exp(2\pi\eta) \tag{3}$$

yielding

$$S(E) = \pi\lambda\!\!\!^{-2}\omega\Gamma_p(E)\Gamma_\gamma(E)[(E_R - E)^2 + (\tfrac{1}{2}\Gamma(E))^2]^{-1} E \exp(2\pi\eta)\,. \tag{4}$$

The energy dependence of the proton width $\Gamma_p(E)$ was calculated using eq. (2) and $C^2S(l=0, 6280\,\text{keV}) = 0.022$ (table 2): e.g. at $E = 10$ keV one finds $\Gamma_p(E) = 7.5 \times 10^{-44}$ eV. For the high-energy wing at these low energies one has again $\Gamma_p(E) \ll \Gamma_\gamma(E) \simeq \Gamma(E)$, where $\Gamma_\gamma(E)$ is essentially independent of incident energy. The upper limit of 35 fs for the lifetime of the 6280 keV state [17]) corresponds to $\Gamma_\gamma > 19$ meV. Transition strength arguments and all-state M1 average strengths [25]) applied to the observed $6.28 \to 4.19$ and $6.28 \to 4.60$ MeV γ-ray transitions resulted in an average value of $\Gamma_\gamma \simeq 9$ meV, leading to $\Gamma_\gamma \simeq 14$ meV as the best estimate at the present time (±factor 2). With these values the $S(E)$ factor calculated at $E = 10$ to 100 keV was parametrized using the polynomial

$$\begin{aligned} S(E) &= S(0) + S'(0)E + S''(0)E^2/2 \\ &= 2.22 - 0.052E + 0.00033E^2\ (\text{keV}\cdot\text{b})\,, \end{aligned}$$

where E is in units of keV. The reaction rate $N_A\langle\sigma v\rangle$ of this "non-resonant" wing was calculated using the relations [21])

$$N_A\langle\sigma v\rangle = 4.34 \times 10^5 \tau^2 (\mu Z)^{-1} \exp(-\tau) S_{\text{eff}}(E_0) \tag{5}$$

TABLE 3

Reaction rates $N_A\langle\sigma v\rangle$ [a]) and branching ratio $f_0(^{26}Al)$

T_9 (10^9 K)	Resonances		Direct capture		$E_R = -26$ keV		Total	
	$N_A\langle\sigma v\rangle$	f_0	$N_A\langle\sigma v\rangle$	f_0	$N_A\langle\sigma v\rangle$	f_0	$N_A\langle\sigma v\rangle$	f_0
0.005	1.38E−47	0.79	5.54E−46	0.71	9.95E−48	0.90	5.69E−46	0.73
0.006	2.09E−41	0.79	9.73E−43	0.71	1.63E−44	0.90	2.19E−41	0.79
0.007	5.25E−37	0.79	3.78E−40	0.71	5.88E−42	0.90	5.25E−37	0.79
0.008	1.02E−33	0.79	5.18E−38	0.71	7.53E−40	0.90	1.02E−33	0.79
0.009	3.60E−31	0.79					3.60E−31	0.79
0.01	3.87E−29	0.79					3.87E−29	0.79
0.02	2.04E−19	0.81					2.04E−19	0.81
0.03	6.74E−15	0.81					6.74E−15	0.81
0.04	1.21E−12	0.81					1.21E−12	0.81
0.05	2.81E−11	0.81					2.81E−11	0.81
0.06	2.75E−10	0.82					2.75E−10	0.82
0.07	1.80E−09	0.82					1.80E−09	0.82
0.08	9.02E−09	0.82					9.02E−09	0.82
0.09	3.61E−08	0.81					3.61E−08	0.81
0.1	1.20E−07	0.79					1.20E−07	0.79
0.2	1.50E−03	0.85					1.50E−03	0.85
0.3	3.22E−01	0.84					3.22E−01	0.84
0.4	4.84E+00	0.83					4.84E+00	0.83
0.5	2.53E+01	0.82					2.53E+01	0.82
0.6	7.84E+01	0.80					7.84E+01	0.80
0.7	1.79E+02	0.79					1.79E+02	0.79
0.8	3.38E+02	0.78					3.38E+02	0.78
0.9	5.57E+02	0.77					5.57E+02	0.77
1	8.38E+02	0.76					8.38E+02	0.76
2	5.95E+03	0.70					5.95E+03	0.70
3	1.27E+04	0.69					1.27E+04	0.69
4	1.90E+04	0.69					1.90E+04	0.69
5	2.38E+04	0.69					2.38E+04	0.69
6	2.70E+04	0.69					2.70E+04	0.69
7	2.89E+04	0.69					2.89E+04	0.69
8	2.99E+04	0.70					2.99E+04	0.70
9	3.01E+04	0.70					3.01E+04	0.70
10	2.99E+04	0.70					2.99E+04	0.70

[a]) In units of reactions · s^{-1} · $mole^{-1}$ · cm^3.

with $Z = 12$ and

$$\tau = 4.25(Z^2\mu/T_9)^{1/3}, \qquad (6)$$

$$S_{\text{eff}}(E_0) = S(0)[1 + (\tfrac{5}{12}\tau^{-1})] + S'(0)[E_0 + (\tfrac{35}{36})kT] + S''(0)[E_0^2 + (\tfrac{89}{36})E_0 kT]/2, \qquad (7)$$

$$E_0 = 122(Z^2\mu T_9^2)^{1/3}\ (\text{keV}). \qquad (8)$$

The $N_A\langle\sigma v\rangle$ results are summarized in column 6 of table 3.

2.3. THE DIRECT CAPTURE PROCESS

Finally, the direct capture process into all bound states of ^{26}Al was calculated [23]) using the spectroscopic factors $S(l_f, E_f)$ of ref. [13]). The summation of the astrophysical $S(E)$ factors for all states was found to be nearly energy-independent with $S(0) = 73$ keV · b. Using the above expressions for "non-resonant" reaction mechanisms (eqs. (5)–(8)), the resulting reaction rates are given in column 4 of table 3.

2.4. SUMMARY AND COMPARISON WITH RECENT COMPILATION

The total reaction rates including all three contributions discussed above are given in column 7 of table 3. One sees that the narrow resonances dominate the reaction rates at all temperatures except for $T_9 < 0.006$, where the DC process and the high-energy wing of the $E_R = -25.7$ keV subthreshold resonance come into play. The total rates from the present work, $N_A\langle\sigma v\rangle$(present), are compared in fig. 3 with those incorporated in the recent compilation of Caughlan *et al.* [10]), $N_A\langle\sigma v\rangle$ (CFHZ1985), where the latter rates were based at $T_9 > 0.2$ on the work of refs. [11,12]) and at $T_9 < 0.2$ on the work of refs. [14,15]). At $T_9 > 0.2$ good agreement is noted within 30%, although the present accuracy based on the data of refs. [17–19]) is significantly higher. However, at $T_9 \simeq 0.03$ to 0.2 the present rates are higher by a factor up to $\simeq 410$, and at $T_9 < 0.03$ they are lower by a factor up to $\simeq 480$. These differences are due predominantly to the erroneous assignment of $J^\pi = 3^+$ to the 6343 keV state ($E_R = 37.5$ keV, $l = 0$), which is now known to have $J^\pi = 4^-$ (table 1). Furthermore, we showed that an s-wave resonance exists at $E_R = 58.0$ keV ($E_x = 6364$ keV). This

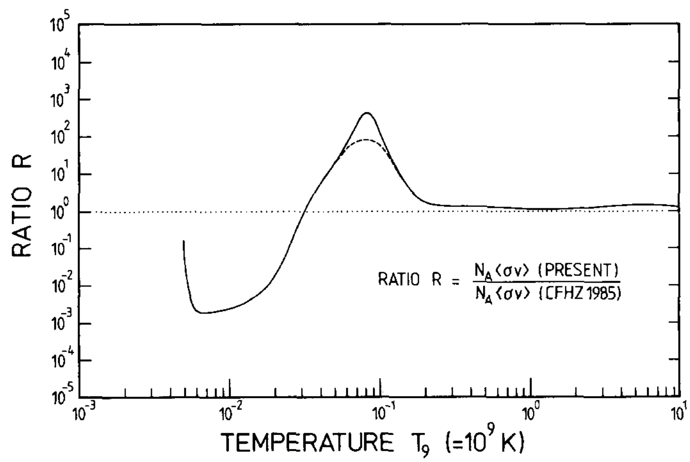

Fig. 3. The temperature dependence of the stellar reaction rates of ^{25}Mg(p, γ)^{26}Al calculated by Caughlan *et al.* [10]) is compared with the present results where for a better comparison only the ratio of the rates is plotted. The solid and dashed curves reflect the uncertainties in the input data of ref. [10]).

shift in the location of the s-wave resonance leads predominantly to the features shown in fig. 3 at $T_9 < 0.2$.

3. Branching to the ground state of ^{26}Al

In the temperature range of $T_9 < 0.4$, the half-lifes of all the radioactive nuclides involved in the MgAl cycle (fig. 1) are short compared to the nuclear burning times with the exception of the ground state of ^{26}Al(^{26}Al$^{\circ}$). The 0^+ isomeric state (^{26}Al^{m}) at $E_x = 228$ keV has a β-decay half-life of 6.3 s, which is many orders of magnitude shorter than that of the 5^+ ground state. It was shown by Ward and Fowler [24]) that thermal equilibrium between these two levels of ^{26}Al is not achieved at $T_9 < 0.4$ and consequently the ground state and isomeric state of ^{26}Al have to be treated as separate nuclear species in astrophysical environments at these temperatures (fig. 1). Since at these temperatures the population of ^{26}Al^{m} via ^{25}Mg(p, γ)^{26}Al is of no relevance to the astrophysical quest (sect. 1), the branching f_0 of the capture yield in ^{25}Mg(p, γ)^{26}Al responsible for $\gamma\gamma$ cascades to the ground state must be known.

The observed branchings f_0 for all bound and unbound states up to $E_x = 8067$ keV are summarized in table 4. Is should be noted that the branchings deduced from the data of refs. [17-19]) are significantly more accurate due to the many more γ-ray branches observed. For the $E_R = -26$ keV subthreshold resonance ($E_x = 6280$ keV) one finds $f_0 = 0.90$ (tables 3 and 4). For the direct capture process into all bound states of ^{26}Al, the individual astrophysical $S(E)$ factors were multiplied by their branchings f_0 for each final state (table 4) and then summed: $S(0) = 52$ keV · b. This result together with $S_{tot}(0) = 73$ keV · b (sect. 2.3) led to f_0(DC) = 0.71 (table 3). Finally, the resonance strengths $(\omega\gamma)_i$ in eq. (1) were also multiplied by their associated f_0 values (table 4). The resulting fractional reaction rates were then divided by the total rates at each temperature (column 2 of table 3) leading to the f_0 values given in column 3 of table 3. The weighted f_0 values from all three contributions are given in column 9 of table 3 and are illustrated in fig. 4.

Shown in fig. 4 are also the f_0 values deduced from the recent compilation [10]). The two results agree fairly well at the higher temperatures. The deviations at low temperatures are due to different input data: (i) for the 6343 keV state Champagne *et al.* [14,15]) reported $f_0 = 0.57 \pm 0.05$, whereas $f_0 = 0.79 \pm 0.03$ is found from ref. [17]), (ii) as discussed earlier, the dominant s-wave resonance at low energies is not the 6343 keV state [14,15]) but the 6364 keV state with $f_0 = 0.81 \pm 0.02$ (table 4). The present work supports the previous hypothesis of Ward and Fowler [24]) that the value of $f_0 \simeq 0.84$ is a fairly accurate measure of the relative production ratios of ^{26}Al$^{\circ}$ and ^{26}Al^{m} by the ^{25}Mg(p, γ)^{26}Al reaction at temperatures of $T_9 < 0.4$.

4. Conclusions

The significantly higher reaction rates $N_A\langle\sigma v\rangle$ together with the higher branching ratio f_0(^{26}Al) in the important temperature range $T_9 = 0.03$ to 0.2 (figs. 3 and 4)

TABLE 4

Branching ratio of ^{26}Al levels to the ground state ($=f_0$) [a])

E_x (keV)	f_0	E_x (keV)	f_0	E_x (keV)	f_0	E_x (keV)	f_0
417	1.00	5132	0.51	6610	0.87 (0.88) [e])	7455	0.29
1058	0.00	5142	0.94	6680	0.67	7464	0.67
1759	0.98	5195	0.05	6724	0.96	7495	0.68
1851	0.01	5245	0.75	6784	0.56	7497	0.58
2069	1.00	5396	0.92	6789	0.90	7529	0.94
2070	0.22	5431	0.10	6801	0.63	7540	0.38
2072	0.11	5457	0.73	6802	0.53	7548	0.88
2365	0.46	5462	0.41	6816	0.97	7557	0.56
2545	0.45	5488	0.46	6818	0.56	7561	0.36
2661	0.68	5495	0.26	6852	0.61	7592	0.81
2740	0.01	5513	0.91	6874	0.24	7596	0.69
2913	0.46	5545	0.61	6876	0.60	7605	0.37
3074	0.20	5569	0.97	6892	0.93	7623	0.38
3160	0.79	5585	0.06	6936	0.49	7628	0.88
3403	1.00	5598 [b])	0.73	6964	0.87	7648	0.48
3508	1.00	5671	0.36	7001	0.44	7762	0.74
3596	0.24	5676	0.96	7015	0.68	7772	0.76
3675	0.94	5692	0.93	7051	0.69	7773	0.67
3681	0.23	5726	0.90	7086	0.19	7814	0.22
3724	0.00	5849	0.60	7093	0.43	7825	0.87
3751	0.36	5883	0.56	7109	0.82	7832	0.86
3754	0.01	5916	0.67	7142	0.71	7865	0.62
3922	1.00	5924	0.58	7153	0.74	7874	0.46
3963	0.29	5950	0.39	7161	0.58	7880	0.28
3978	0.01	6028	0.10	7167	0.71	7891	0.75
4192	0.93	6084	0.97	7198	0.07	7921	0.93
4206	0.91	6086 [b])	0.40	7222	0.98	7939	0.87
4349	0.24	6120	0.00	7238	0.67	7953	0.92
4431	0.50	6198 [b])	0.40	7254	0.71	7982	0.63
4480	0.05	6238	0.23	7286	0.05	8001	0.18
4548	0.45	6270 [b])	0.34	7291	0.87	8008	0.57
4599	0.88	6280	0.90	7308	0.54	8011	0.94
4622	0.30	6343	0.79 (0.57) [c])	7348	0.82	8036	0.23
4705	0.77	6364	0.81 (0.75) [c])	7366	0.59	8047	0.67
4773	0.77	6399 [b])	0.85 (0.80) [c])	7397	0.65	8064	0.73
4940	0.04	6414 [b])	0.71	7399	0.81	8066	[d])
4941	0.76	6436	0.73	7410	0.88	8067	0.96
4952	0.63	6496	0.74 (0.66) [e])	7425	0.67		
5007	0.24	6551	0.80 (0.76) [e])	7440	0.04		
5010	0.00	6598	(0.71) (0.84) [c])	7444	0.38		

[a]) From ref. [18]). The errors for f_0 are of the order 0.01 for the resonances and for strongly excited bound states.

[b]) Part of the γ-decay is missing.

[c]) Refs. [14,15,20]).

[d]) Not determined.

[e]) Ref. [12]).

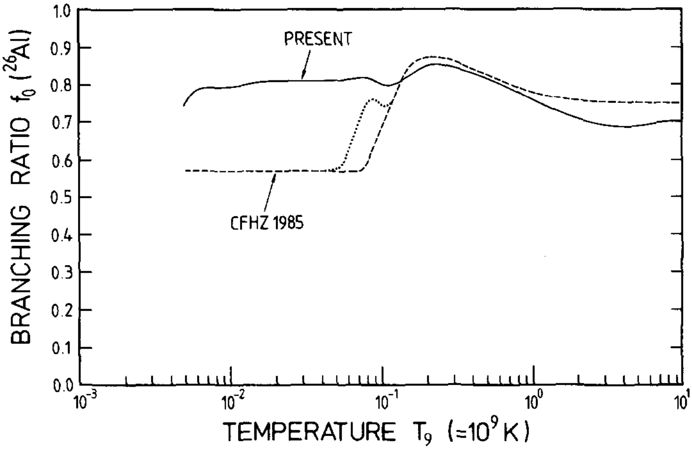

Fig. 4. Temperature dependence of the branching ratio $f_0(^{26}\text{Al})$ for forming the ground state of ^{26}Al from the source reaction $^{25}\text{Mg}(\text{p}, \gamma)^{26}\text{Al}$. The solid curve is the result from the present work, while the dashed and dotted curves are obtained from the recent compilation [10]).

increase substantially the abundance of ^{26}Al in the MgAl cycle. Thus, these results might help to test stringently the various astrophysical models for ^{26}Al nucleosynthesis (sect. 1). However, quantitative consequences have to await the results of complete calculations on the suggested astrophysical scenarios [5-9]).

The rates at the above temperature range are influenced predominantly by the s-wave resonance at $E_R = 58.0$ keV. Using the estimated strength of this resonance (table 2) and assuming a 1 mA proton beam incident on a thick and pure ^{25}Mg target, the resonance would produce about three capture γ-ray transitions per day. Clearly, a direct yield measurement of this resonance represents a challenge to the experimentalist.

The present way of obtaining the main astrophysical information of the difficult-to-measure resonances near the particle threshold, namely via feeding them through many higher-energy resonances, has not or very little been applied for other nuclei. There are many other cases where this technique could be useful.

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