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Reaction rates for ^{8}Li(p, α) and ^{8}Li(p, n, α) and their effect on primordial nucleosynthesis

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Abstract: Differential-cross-section data are presented for the ^{8}Li(p, α)^{5}He reaction at 1.5 MeV center-of-mass energy, measured with a (radioactive) ^{8}Li beam. The data are used to calculate one of the terms of the thermonuclear reaction rate for destruction of ^{8}Li. In addition, other data are used to estimate the total reaction rate for p+^{8}Li, which is found to be comparable to that used in previous calculations of abundances from primordial nucleosynthesis.

E | NUCLEAR REACTIONS ^{1}H(^{8}Li, α), E(c.m.) = 1.5 MeV; measured $\sigma(E_\alpha)$, $\sigma(\theta)$; deduced ^{8}Li destruction thermonuclear reaction rate, p+^{8}Li total reaction rate. Radioactive beam.

1. Introduction

During the past few years a great deal of attention has been given to inhomogeneous models ^{1}) (IMs) of primordial nucleosynthesis. The largest differences between the predictions of these models and those of the standard model ^{2}) (SM) are in the abundances of the nuclides of mass 7 u or greater. However, even those nuclides, ^{7}Li in particular, have not yet provided definitive tests between the

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SM and the IMs. Late-time processing effects such as neutron back diffusion [3]) and homogenization [4]) can impact those abundances greatly, confusing the comparison between the SM and the IMs. Thus, because of the ambiguities in predictions of the light nuclides, it might ultimately turn out to be more fruitful to examine abundances of heavier nuclides.

Most of the interesting synthesis in the IMs of ^{11}B or heavier nuclides depends on the abundance of ^{8}Li during the time of nucleosynthesis; it is pivotal to the reaction flow to ^{11}B via the ^{8}Li(α, n)^{11}B reaction, and all higher-mass nuclides are funneled through ^{11}B. ^{8}Li is made by reactions such as ^{7}Li(n, γ) and ^{7}Li(d, p), and is destroyed by its β-decay, and by reactions such as ^{8}Li(d, t), ^{8}Li(p, α) and ^{8}Li(p, n, α). To zeroth order ^{8}Li and protons do not coexist in the IMs, but the potential does exist for destruction of ^{8}Li by proton-induced reactions in the interfaces between high- and low-density regions, and at the time at which homogenization occurs. Since both of these features can play a major role in primordial nucleosynthesis, any uncertainty in the p+^{8}Li reaction rate may translate into uncertainties on abundances of mass 11 u or greater nuclides predicted by the IMs.

In this paper we point out some changes in this rate as a result of data not previously considered in its determination. The standard value [5]) for the summed rate has a non-resonant term and a resonance term associated with the level in ^{9}Be at 17.298 MeV excitation energy. Not included in that rate are any effects associated with ^{8}Li(p, n, α) through the ^{9}Be level at 16.975 MeV, which creates a resonance in the ^{8}Li+p system at 0.088 MeV, or that at 17.493 MeV, which, together with that at 17.298 Mev, has been studied in several old experiments [6–8]). New data [9]) allow complete determination of the effects of the 0.088 MeV resonance, while the other experiments allow fairly good estimates for the effects on the rate from the higher-energy resonances. In addition, we present new data from a measurement of the ^{8}Li(p, α)^{5}He cross section, using a (radioactive) ^{8}Li beam, which allows determination of at least off-resonance effects of the (p, α) reaction.

In sect. 2 we describe the experiment by which the ^{8}Li(p, α) cross section was measured, and present the results. Sect. 3 describes the calculations of the thermonuclear reaction rates from those data, and from ^{8}Li(p, n, α) data from other studies, and compares the new rate with that which presently is used in IM calculations. Our conclusions are presented in sect. 4.

2. The ^{8}Li(p, α)^{5}He experiment

The experiment was performed at the radioactive nuclear beam (RNB) facility installed at the University of Notre Dame FN-model HVEC Van de Graaff accelerator facility. The RNB facility utilizes a large bore 3.5 T superconducting solenoid ion lens, supplied by the University of Michigan group [10]), to separate and focus secondary, unstable beams such as ^{6}He, ^{7}Be and ^{8}Li at E/A values of a few

MeV/u or less [11-13]). The ^{8}Li beam is produced via the reaction ^{9}Be(^{7}Li, ^{8}Li)^{8}Be at $E(^{7}\mathrm{Li}) \approx 17$ MeV. The ^{8}Li beam, with $E(^{8}\mathrm{Li}) \approx 14.6$ MeV, $\Delta E \leq 0.6$ MeV FWHM, and intensity of $10^{7}\ \mathrm{s}^{-1}$ was focused into a spot of 5 mm by 5 mm with angular divergence of ±4°. The beam is typically comprised of more than 70% $^{8}\mathrm{Li}^{3+}$ ions with the major contaminants being <10% of $^{4}\mathrm{He}^{2+}$ ($E \approx 14$ MeV), low energy $^{7}\mathrm{Li}^{2+}$ (2–5%), and other low energy ions (<5% each), depending somewhat on the secondary beam collimation.

The ^{8}Li(p, α)^{5}He data were obtained as part of other measurements [12]) which utilized secondary targets of $^{13}\mathrm{C}^{1}\mathrm{H}_2$ (areal density $= 0.54 \pm 0.02\ \mathrm{mg \cdot cm^{-2}}$) and melamine, $\mathrm{C_3N_6}^{1}\mathrm{H_6}$ (areal density $= 0.9 \pm 0.1\ \mathrm{mg \cdot cm^{-2}}$). The reaction was studied in a reverse-kinematics mode, i.e., the ^{8}Li beam was incident on protons in the target material. The resulting center-of-mass energy at the center of the target is thus low, *viz.*, $E_{\mathrm{c.m.}} = 1.5$ MeV, and therefore close to energies appropriate for determination of reaction rates relevant to nucleosynthesis. The advantages of using reverse kinematics have been demonstrated previously in related measurements of the ^{7}Li(p, α)^{4}He reaction [14]).

The secondary reaction products were detected in a ΔE–E counter telescope [12]) consisting of a large area (300 mm^{2}), thin (17–28 μm) silicon surface-barrier detector backed by a 25 mm by 25 mm resistive-anode, two-dimensional, position-sensitive silicon detector (PSD) of nominally 200 μm depth [15]). The latter permits us both to correct for the kinematic energy shifts of the reaction products and to divide the detector into finite elements to permit detailed measurements of angular distributions [12]). Some α-particle spectra observed for the $^{13}\mathrm{C}^{1}\mathrm{H}_2$ and melamine targets are displayed in fig. 1. At forward angles the PSD E-detector was not quite thick enough to stop the full-energy α-particles from ^{1}H(^{8}Li, α)$^{5}\mathrm{He_{g.s.}}$ as the Q-value is large (+14.4 MeV). However, it was close enough that the $^{5}\mathrm{He_{g.s.}}$ group could be readily identified in the ΔE–E spectra. At lab angles larger than about 20°, the $^{5}\mathrm{He_{g.s.}}$ group was stopped. Although it would have been difficult to separate the $^{5}\mathrm{He}_1^*$ contribution from that of the $^{5}\mathrm{He_{g.s.}}$ at forward angles, the spectra for angles greater than 20° suggest that contribution is small. In any event, the $^{5}\mathrm{He}_1^*$ contribution should be included in our reaction-rate determination, as ^{8}Li(p, α)$^{5}\mathrm{He}_1^*$ will also destroy ^{8}Li in astrophysical environments.

As seen in fig. 1, an α-particle group identified as that from ^{1}H(^{8}Li, ^{4}He)$^{5}\mathrm{He_{g.s.}}$ is observed. At $E_\alpha \leq 14$ MeV, which is well below the region of interest, a large α-particle elastic-scattering group and inelastic spectrum are observed which are due to the small α-particle contamination in the ^{8}Li RNB. The ^{8}Li elastic scattering from ^{13}C, ^{12}C and ^{14}N in the targets was used for normalization of the cross section, based on previous measurements of $^{8}\mathrm{Li} + {}^{12}\mathrm{C}$ scattering [16]).

The full-energy α-particle group, in addition to having the correct Q-value, exhibits the variation of energy with angle expected for the (p, α) reaction. The $^{5}\mathrm{He_{g.s.}}(\frac{3}{2}^-)$, although neutron unstable, has a sufficiently narrow decay width [17]) ($\Gamma = 0.6$ MeV) to produce a well-defined α-particle group from ^{1}H(^{8}Li, α)$^{5}\mathrm{He_{g.s.}}$.

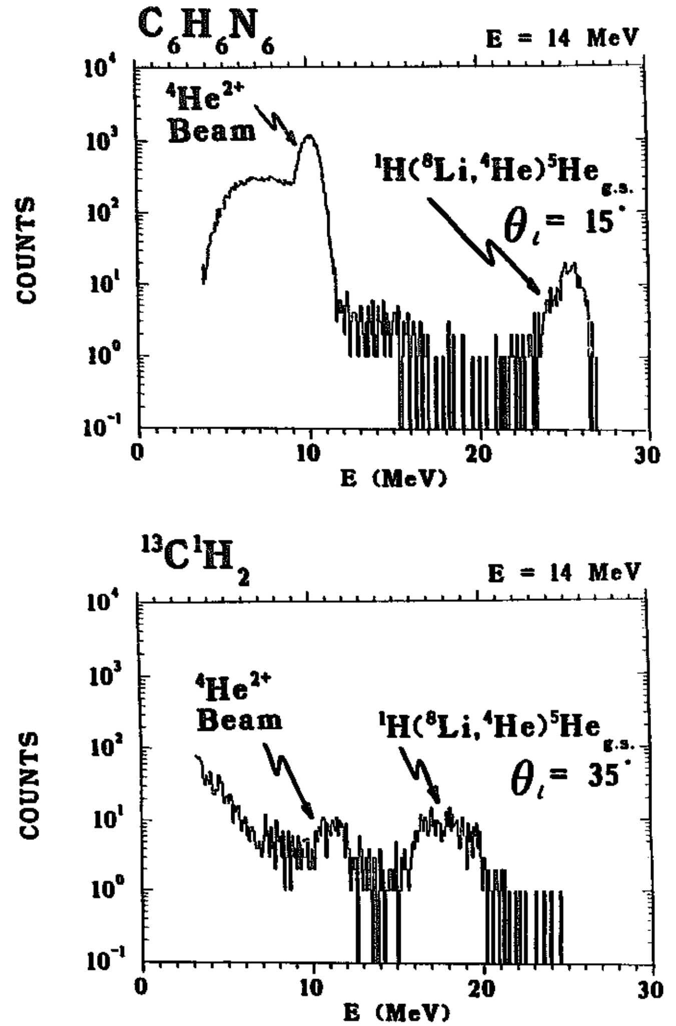

Fig. 1. alpha-particle spectra from the ^{1}H(^{8}Li, α)^{5}He reaction at scattering angles of 15° and 35°. Note the different targets, indicated at the upper left of each spectrum.

In contrast, the ^{5}He excited level ($J^\pi = \frac{1}{2}^-$, $E_x = 4$ MeV) is rather broad ($\Gamma \sim 4$ MeV) and could thus contribute to the α-particle continuum observed below the full-energy α-particle group (see fig. 1). We estimate that the total average yield of the ^{5}He* group for the angles at which measurements were made is no more than 10% of that of the ground-state group. Likewise, α-particles from ^{8}Li(p, n)^{8}Be$\rightarrow 2\alpha$ would not yield distinct α-particle groups. [This reaction has been studied separately in collaboration with a group from Florida State University, using coincident α-particle detection, and will be reported elsewhere [18].] Alpha-particle spectra from targets which do not contain ^{1}H, e.g., $^{12}C^2H_2$, do not exhibit the distinct group seen using $^{13}C^1H_2$ and melamine. In addition, the ^{8}Li(p, α)^{5}He$_{g.s.}$ cross sections deduced from chemically different targets are in agreement despite the different target compositions.

The ^{1}H(^{8}Li, α) angular distribution measured at $E_{c.m.} = 1.5$ MeV is shown in fig. 2. The shape is suggestive of a compound-nuclear (CN) reaction as it lacks the strong forward-peaking characteristic of direct reactions at this energy [12]), and,

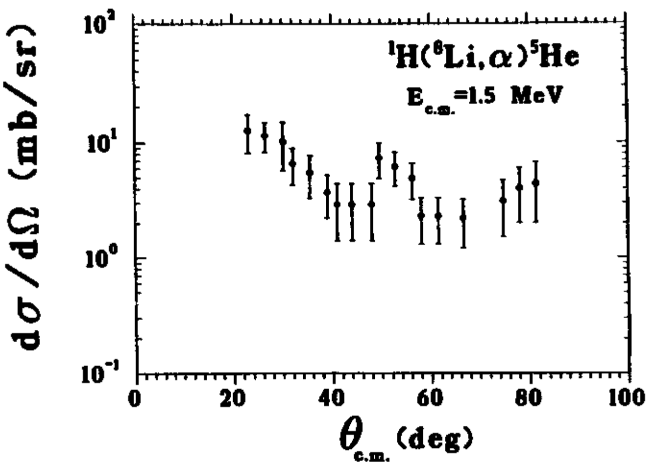

Fig. 2. Angular distribution measured for $^1H(^8Li, \alpha)^5He_{g.s.}$ at $E_{c.m.} = 1.5$ MeV.

indeed, is found to be represented fairly well by a $1/\sin\theta$ angular distribution. In addition, at some angles an α-particle group which appeared to be the sequential decay product of $^5He_{g.s.}$ was identified. The yield of this group, which is the recoil from large-angle $^1H(^8Li, \alpha)$ scattering, is again consistent with a CN-type angular distribution ($1/\sin\theta$). Thus the differential cross section was assumed to be symmetric about $\Theta_{c.m.} = 90°$, and a polynomial was fitted to the data. When integrated, it gave a total cross section of 60 ± 15 mb at $E_{c.m.} = 1.5$ MeV. Our differential and integrated cross sections are several times larger than the corresponding $^7Li(p, \alpha)^4He_{g.s.}$ and $^8Li(p, n)^8Be(g.s.) \rightarrow 2\alpha$ cross sections [14,18]) at comparable $E_{c.m.}$, but appear comparable in magnitude to the cross sections observed [8]) for $^7Li(d, \alpha)^5He_{g.s.}$ at a similar $E_{c.m.}$. Note, however, that the $^8Li(p, n)^8Be$ experiment [18]) was sensitive only to decays of the ^8Be ground state; two α-particle production through ^8Be excited states could be important. Also, at slightly higher energy, $E_{c.m.} \approx 1.7$ MeV, a broad resonance ($\Gamma \sim 1$ MeV) is observed [17,20]) in both $^7Li(d, \alpha)^5He_{g.s.}$ and $^6Li(t, \alpha)^5He_{g.s.}$ corresponding to $E_x(^9Be) \approx 18.6$ MeV. Our data thus include the low-energy tail of this resonance, as well as the non-resonant (p, α) yield. Obviously more $^8Li(p, \alpha)$ data would better define this component of the $^8Li + p$ reaction rate, though the present data do set a useful upper limit on it. In any event, as shown below, known narrow resonances with large neutron-decay widths (in particular, the resonance at 17.298 MeV in ^9Be) dominate the $^8Li + p$ reaction rate at lower energies, so a more accurate measurement of the $^8Li(p, \alpha)$ rate would probably not improve substantially the determination of the $^8Li + p$ rate in the region of greatest interest for primordial nucleosynthesis.

3. Calculation of thermonuclear reaction rates

The cross section for $^8Li(p, \alpha)$ would not be expected to exhibit obvious resonances below the broad resonance which occurs at an excitation energy of 18.6 MeV in the compound nucleus, since no such structures were observed in that same excitation region in the (same) compound nucleus in the ^{7}Li(d, p) and ^{7}Li(d, n) studies [6,7]. Nevertheless, at that high an excitation energy, the cross section is likely to have both a direct contribution and significant contributions from tails of nearby resonances. However, in the absence of information about specific resonances or of obvious narrow resonances contributing to the excitation function, that cross section was taken to be non-resonant. Thus it can be described by a non-resonant formalism, for which the astrophysical S-factor can be determined from [19])

$$S(E) = E\sigma(E)\exp(2\pi Z_1 Z_2 e^2/\hbar v), \quad (1)$$

where the Z_j represent the charge numbers of the (charged) nuclei which interact, and v is their relative velocity. Since the ^{8}Li(p, α) total cross section is 60 mb, the S-factor is 880 keV · b at 1.5 MeV center-of-mass energy. The resulting reaction rate can be calculated from standard formulae [19]),

$$\langle\sigma v\rangle = \left(\frac{2}{\mu}\right)^{1/2} \frac{\Delta}{(kT)^{3/2}} S(E_0)\exp(-3E_0/kT), \quad (2)$$

where

$$\Delta = \frac{4}{3^{1/2}}(E_0 kT)^{1/2}, \quad (3)$$

$$E_0 = [(2\mu)^{1/2}\pi e^2 Z_1 Z_2 kT/2\hbar]^{2/3}, \quad (4)$$

where μ is the reduced mass. Using these expressions, the (assumed non-resonant) contribution of the ^{8}Li(p, α) reaction to the proton-induced destruction rate of ^{8}Li is

$$N_A\langle\sigma v(\text{non-resonant})\rangle = 1.031\times10^{10} T_9^{-2/3}\exp(-8.492 T_9^{-1/3})\ \text{cm}^3\,\text{s}^{-1}\,\text{mol}^{-1}, \quad (5)$$

where N_A is Avogadro's number and T_9 is the temperature in 10^9 K. This rate is about 20% larger than the (theoretical) non-resonant component of Wagoner's reaction rate [5]). Since the preliminary results of an independent experiment [18]) have shown that the cross section for ^{8}Li(p, n)^{8}Be$_{g.s.} \to \alpha\alpha$ is much smaller than that which we measure for ^{8}Li(p, α)^{5}He, this term should constitute most of the non-resonant component in the rate for ^{8}Li destruction. In any event, neutron decays of ^{9}Be compound states to ^{8}Be would be included in the neutron width used below in the determination of resonance contributions to the total reaction rate.

The rate of destruction of ^{8}Li by protons via the resonance corresponding to the state in the p + ^{8}Li system at 0.088 MeV can be calculated from the narrow resonance expression [19])

$$\langle\sigma v\rangle = \left(\frac{2\pi}{\mu kT}\right)^{3/2} \hbar^2 \frac{2J_R+1}{(2J_1+1)(2J_2+1)} \frac{\Gamma_p(\Gamma_n+\Gamma_\alpha)}{\Gamma}\exp(-E_R/kT), \quad (6)$$

where J_R, J_1 and J_2 are the spins of the resonance, incident nucleus and target nucleus, E_R is the center-of-mass energy of the resonance, Γ is the total width of the resonance, and Γ_p, Γ_n and Γ_α are the proton, neutron and α-particle partial widths. Γ was found [9] to be 490 eV, while $\Gamma_n+\Gamma_\alpha$ is 380 eV and Γ_p is 12 eV. The value of J_R is given [9] as $\frac{1}{2}$ or $\frac{3}{2}$; we have assumed the latter value. With these parameters, eq. (5) gives a contribution to the reaction rate of

$$N_A\langle\sigma v(E_R=0.088\text{ MeV})\rangle=6.79\times10^5T_9^{-3/2}\exp(-1.02/T_9)\text{ cm}^3\text{ s}^{-1}\text{ mol}^{-1}\,. \quad (7)$$

Two higher-lying resonances are seen in the ^{7}Li(d, p), ^{7}Li(d, n) and ^{7}Li(d, α) reactions which would appear in the p + ^{8}Li system at 0.411 and 0.606 MeV (center-of-mass energies). The contribution to the ^{8}Li destruction rate from the higher-energy resonance can be determined using eq. (6), as it is a narrow resonance. The total width Γ is [16] 47 keV. The zero-degree cross section [7] from ^{7}Li(d, n) is about 40 mb/sr at the peak of the resonance; assuming the angular distribution to be isotropic gives a total cross section from that reaction at that energy of about 500 mb. We estimated the total resonant cross section [6] for ^{7}Li(d, p), assuming a non-interfering non-resonant component, to be about 50 mb and that [8] for ^{7}Li(d, α) to be about 80 mb. Since the resonant peak cross sections and widths for ^{7}Li(d, n), ^{7}Li(d, p) and ^{7}Li(d, α) should be related by $(\sigma_n+\sigma_\alpha)/\sigma_p=(\Gamma_n+\Gamma_\alpha)/\Gamma_p$, and, because of the way in which the measurement was made, σ_n would include σ_α, this information thus gives the values for the widths needed to calculate the reaction rate for destruction of ^{8}Li via this resonance. Thus $\Gamma_{n+\alpha}=42.7$ keV and $\Gamma_p=4.3$ keV. Using the proposed [8] value of $J_R=\frac{3}{2}$ for this resonance, the reaction rate is

$$N_A\langle\sigma v(E_R=0.606\text{ MeV})\rangle=2.88\times10^8T_9^{-3/2}\exp(-7.024/T_9)\text{ cm}^3\text{ s}^{-1}\text{ mol}^{-1}\,. \quad (8)$$

Calculation of the component of the rate via the 0.411 MeV resonance is not as simple as that for the other resonances, as it is broad ($\Gamma=200$ keV) and thus requires specification of the penetrability of the Coulomb barrier (included implicitly in the Γ's) as a function of energy over the resonance. Thus the Breit–Wigner form of the cross section σ_{BW} must be included explicitly in the integral which defines the reaction rate as [19]

$$\langle\sigma v\rangle=\left(\frac{8}{\pi\mu}\right)^{1/2}\left(\frac{1}{kT}\right)^{3/2}\int_0^\infty\sigma_{BW}(E)E\exp(-E/kT)\,dE\,. \quad (9)$$

Again the ^{7}Li(d, p) and ^{7}Li(d, n) studies [6,7] were used to estimate the value for Γ to be 200 keV, and the ratio of Γ_n to Γ_p to be 420 to 110 mb at the peak of the resonance. Studies [20] of the ^{7}Li(d, α) reaction through this resonance suggest that the resonant yield is appreciably smaller than that for ^{7}Li(d, n), so Γ_α has been neglected in comparison to Γ_n. In any event, that partial width would be included in Γ_n. Numerical integration of the above expression, assuming an s-wave neutron emission and $J_R=\frac{5}{2}$ [the tentative assignment for this state [17]], gives a numerical reaction rate. It was then fitted, allowing the resonance energy, exponent of T_9, and leading coefficient to vary [21]), to give

$$N_0\langle \sigma v(E_R = 0.411 \text{ MeV})\rangle = 1.13 \times 10^9 T_9^{-0.433} \exp(-3.982/T_9) \text{ cm}^3 \text{ s}^{-1} \text{ mol}^{-1}. \quad (10)$$

Note that all of the above results clearly depend on the fact that the ^{7}Li(d, p) proton decays from the resonances go to the ground state of ^{8}Li, since in p + ^{8}Li interactions that is the entrance channel. This has been verified [22]) to be predominantly the case for the 0.411 MeV resonance, but is not known to be the case for the 0.606 MeV resonance. However, since the former resonance dominates the reaction rate throughout the region of interest to primordial nucleosynthesis, this is not a critical assumption for use of this rate in models thereof.

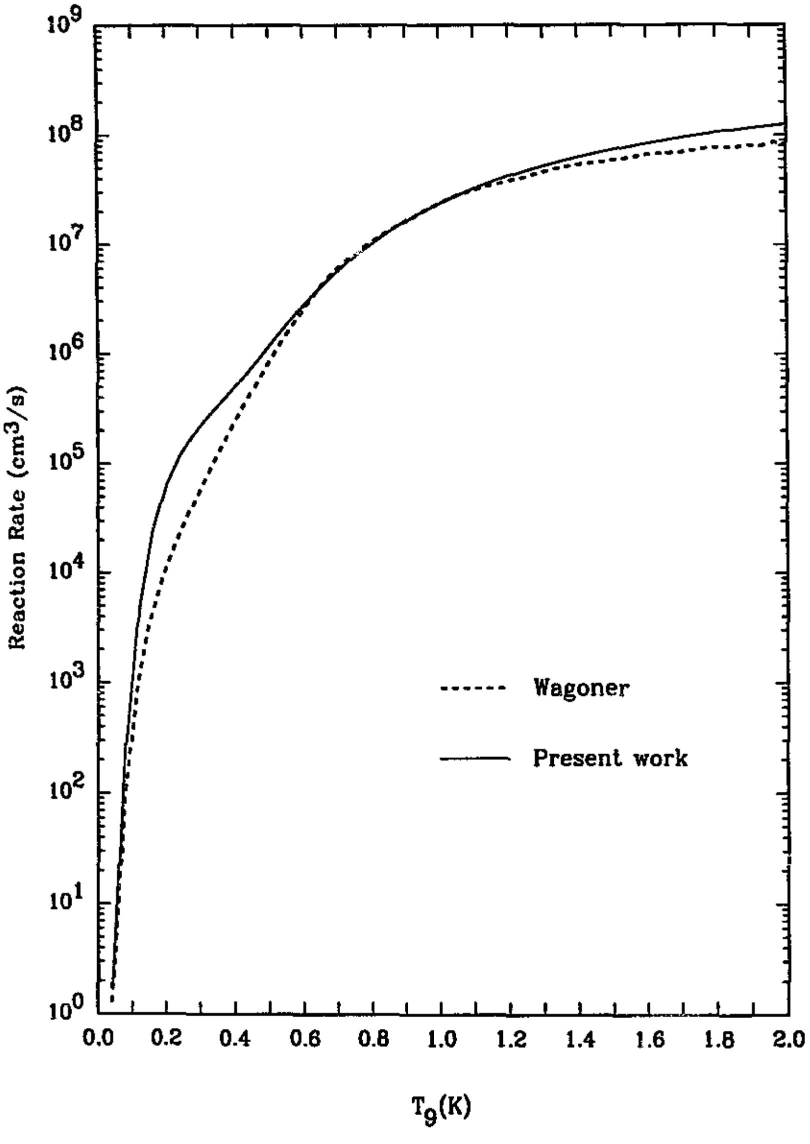

Fig. 3. Comparison of thermonuclear reaction rate for destruction of ^{8}Li due to photon-induced reactions of Wagoner [5]) to that from the present work.

Note also that the result given in eq. (9) could be affected by assuming the emitted particles were other than s-wave. This would be a second-order effect, however, as the widths at the middle of the 0.411 MeV resonance peak were determined directly, instead of being calculated from spectroscopic factors. Because of the direct width determination, this assumption does not affect the other (narrow resonance) components calculated for the reaction rate.

For all resonances except that at 0.411 MeV we assumed $J_R = \frac{3}{2}$. Since the plausible range for the spin varies from $\frac{1}{2}$ to $\frac{7}{2}$, assuming only s-, and p-wave proton captures on the $J^\pi = 2^+$ ^8Li ground state, this assumption guarantees that each component of our reaction rate will be in error by no more than a factor of 2 due to uncertainty in J_R. However, since J_R appears to be $\frac{5}{2}$ for the 0.411 MeV resonance, and it dominates the reaction rate over most of the region of interest to primordial nucleosynthesis, the uncertainty in the total rate, as it affects primordial nucleosynthesis, is probably less than a factor of two.

Using these various components for the reaction rate, we get a summed rate of

$$N_A\langle\sigma v\rangle_{tot} = 1.031\times 10^{10} T_9^{-2/3} \exp(-8.429 T_9^{-1/3}) + 6.79\times 10^5 T_9^{-3/2} \exp(-1.02 T_9^{-1}) + 2.88\times 10^8 T_9^{-3/2} \exp(-7.024 T_9^{-1}) + 1.13\times 10^9 T_9^{-0.433} \exp(-3.982 T_9^{-1})\ \mathrm{cm^3\, s^{-1}\, mol^{-1}}. \quad (11)$$

The comparison of this new rate with that of Wagoner [5]) is shown in fig. 3.

4. Conclusions

Because the 0.411 MeV resonance was treated as a broad resonance, it yields a larger (smaller) rate for lower (higher) T_9 than does the corresponding term in Wagoner's [5]) rate. The non-resonant term in the present rate is comparable to, but slightly larger than, that of Wagoner [5]). The terms associated with the 0.088 and 0.606 MeV resonances do not have corresponding terms in the Wagoner rate. As can be seen from fig. 3, the new total rate is very similar to that [5]) previously used in the primordial nucleosynthesis codes, at least over the portion of the temperature range in which such nucleosynthesis occurs. This results from compensating changes in the non-resonant rate and that associated with the 0.411 MeV resonance in the temperature range for T_9 of about 0.5–1.0 K. Above that temperature range, the increase in the non-resonant term from that of Wagoner [5]) increases the rate. Below that range, the increase in the rate from that of Wagoner due to the broad-resonance treatment of the 0.411 MeV resonance, together with the newly added term corresponding to the resonance at 0.088 MeV, produces a fairly large increase in the rate from that of Wagoner.

Because of the similarity of the old and new rates for destruction of ^8Li due to proton-induced reactions over the temperature range in which primordial nucleosynthesis occurs, little change would be expected in predicted abundances from primordial nucleosynthesis from use of the new rate.

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