# Coulomb dissociation of $^9$Li and the rate of the $^8$Li$(n, \gamma)^9$Li reaction

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We calculate the Coulomb dissociation of $^9$Li on Pb and U targets at 28.5 MeV/A beam energy within a finite range distorted wave Born approximation formalism of the breakup reactions. Invoking the principle of detailed balance, these cross sections are used to determine the excitation function and subsequently the rate of the radiative capture reaction $^8$Li$(n, \gamma)^9$Li at astrophysical energies. Our method is free from the uncertainties associated with the multipole strength distributions of the $^9$Li nucleus. The rate of this reaction at a temperature of 10 K is found to be about 2900 cm$^3$ mole$^{-1}$ s$^{-1}$.

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## I. INTRODUCTION

The $^8$Li$(n, \gamma)^9$Li reaction plays an important role in determining the amount of matter that can be produced at mass number $A > 8$. Inhomogeneous big bang nucleosynthesis and type II supernova are the proposed sites for such synthesis processes. In the first site, after the production of $^7$Li the path to $A > 12$ nuclei goes through the chain $^7$Li$(n, \gamma)^8$Li$(\alpha, n)^{11}$B, with a weaker branch going through the $^7$Li$(\alpha, \gamma)^{11}$B path (see, e.g., Refs. [1,2]). However, the neutron capture on $^8$Li provides a leak from this primary chain and depending on the rate of this reaction the production of nuclei with $A > 12$ can reduce by 40–50% [3].

In the post-collapse phase of a type II supernova comes the opportunity to produce heavy isotopes via the $r$ process. In the early expanding phase, starting with a He-rich environment the mass-8 gap would be bridged by either $\alpha + \alpha + \alpha \rightarrow {}^{12}$C or $\alpha + \alpha + n \rightarrow {}^9$Be reactions. These reactions would continue until a neutron-rich freeze-out occurs that triggers the $r$ process [4]. At this stage it would also be possible to bridge the $A = 8$ gap through the reaction chain $^4$He$(2n, \gamma)^6$He$(2n, \gamma)^8$He$(\beta^-)^8$Li$(n, \gamma)^9$Li$(\beta^-)^9$Be [5,6]. This chain would provide an alternative path to proceed along the neutron-rich side of the line of stability toward heavier isotopes such as $^{36}$S, $^{40}$Ar, $^{46}$Ca, and $^{48}$Ca. The origin of these neutron-rich isotopes is under debate. It is of critical importance to know to what extent this chain competes with the $^8$Li$(\beta^-)^8$Be$(2\alpha)$ process. An important clue to the answer depends on knowing as accurately as possible the rate of the $^8$Li$(n, \gamma)^9$Li reaction and the neutron density. Reaction chains similar to ones that are supposed to occur in type II supernova can be found in the material ejected from neutron star mergers [7] and thus the importance of the accurate knowledge of this reaction is emphasized again.

The rate ($R$) of a nuclear reaction where two nuclei $b$ and $c$ interact to form the reaction products of the final channel is given by [8]

$$R = N_b N_c \langle \sigma(v_{bc}) v_{bc} \rangle (1 + \delta_{bc})^{-1}, \tag{1}$$

where $N_b$ and $N_c$ represent the total number of nuclei $b$ and $c$ taking part in the reaction and $\delta_{bc}$ is the Kronecker $\delta$ that is unity if $b$ and $c$ are identical and zero otherwise. $\sigma(v_{bc})$ is the cross section for a single target nucleus at the relative velocity of $v_{bc}$. The number densities $N_i$ are related to the matter density $\rho$ and mole fraction $Y_i$ by $N_i = \rho N_A Y_i$, where $N_A$ is the Avogadro number. In Eq. (1) the product $\sigma(v_{bc})v_{bc}$ is averaged over the Maxwell-Boltzmann velocity distribution and is interpreted as the reaction rate per particle pair. This is given by

$$\langle \sigma(v_{bc}) v_{bc} \rangle = \left( \frac{8}{(k_B T)^3 \pi \mu} \right)^{1/2} \times \int_0^\infty \sigma(E_{bc}) E_{bc} e^{-E_{bc}/(k_B T)} dE_{bc}, \tag{2}$$

where $\mu$ is the reduced mass of the interacting nuclei, $k_B$ is the Boltzmann constant, and $T$ is the relevant stellar temperature. $E_{bc}$ represents the energy corresponding to the relative velocity $v_{bc}$.

It is thus clear from Eqs. (1) and (2) that knowledge of the reaction cross section $\sigma(E_{bc})$ as a function of the relative velocity (or energy) in the astrophysically relevant energy region is the prime requirement for calculating the rate of a particular reaction.

Since big bang nucleosynthesis starts when the temperature has fallen to about 100 keV, the rate of the $^8$Li$(n, \gamma)^9$Li reaction is of astrophysical importance for neutron energies in a similar range. This reaction can proceed by both direct capture as well as via resonant capture through the $5/2^-$ state of $^9$Li at the excitation energy of 4.296 MeV. For the inverse reaction $(\gamma, n)$, the resonant capture via this state would

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imply the dominance of the $E2$ transition multipolarity in its excitation from the $3/2^-$ ground state of $^9$Li. The ratio of $E2$ to $E1$ excitation has been estimated in Ref. [9] for a $^9$Li projectile on a $^{208}$Pb target at the beam energy of 28.5 MeV/nucleon. The maximum value of this ratio even at the resonance peak (corresponding to $E_\gamma = 0.26$ MeV) is only 0.018. Within the energy range $E_\gamma = 0$–1 MeV, this ratio is about 0.0023. Therefore, for the reaction $^8$Li$(n,\gamma)^9$Li only the direct capture mechanism through $E1$ transition applies in this energy regime.

Several theoretical predictions of the rate of the $^8$Li$(n,\gamma)^9$Li reaction have been reported. Some of them perform the nuclear structure calculations of $^9$Li and calculate the capture cross sections from the corresponding wave functions [10,11]. Others estimate the rate of this reaction from the systematics that are based on information existing for other nuclei [12,13]. These rates vary from each other by more than an order of magnitude. Hence, efforts have also been made to determine the rate of this reaction by experimental methods [14,15].

Since $^8$Li has a very small half-life ($\approx$838 ms), a direct measurement of the cross section ($\sigma_{n\gamma}^{^9\mathrm{Li}}$) of the reaction $^8$Li$(n,\gamma)^9$Li is nearly impossible. However, with a beam of $^9$Li, it is possible to measure the cross section ($\sigma_{\gamma n}^{^9\mathrm{Li}}$) of the reverse reaction $^9\mathrm{Li}+\gamma \rightarrow {}^8\mathrm{Li}+n$ (photodisintegration process) and use the principle of detailed balance to deduce the cross section $\sigma_{n\gamma}^{^9\mathrm{Li}}$ as

$$\sigma_{n\gamma}^{^9\mathrm{Li}} = 0.8\frac{k_\gamma^2}{k^2}\sigma_{\gamma n}^{^9\mathrm{Li}}. \tag{3}$$

In Eq. (3), the photon wave number is given by $k_\gamma = \frac{E_\gamma}{\hbar c} = \frac{(E_{n-^8\mathrm{Li}}+Q)}{\hbar c}$, in terms of the $Q$ value of the capture reaction with $E_{n-^8\mathrm{Li}}$ being the center of mass (c.m.) energy of the $n-{}^8$Li system. $k$ is the wave vector corresponding to $E_{n-^8\mathrm{Li}}$.

A very promising way of studying the photodisintegration process is provided by the virtual photons acting on a fast charged nuclear projectile when passing through the Coulomb field of a heavy target nucleus [16–18]. The advantage of this Coulomb dissociation (CD) method is that here measurements can be performed at higher beam energies, which enhances the cross sections considerably as compared with those of the direct method. At higher energies the fragments in the final channel emerge with larger velocities, which facilitates their more accurate detection. Furthermore, the choice of the adequate kinematical condition of the coincidence measurements allows the study of low relative energies of the final state fragments and ensures that the target nucleus remains in the ground state during the reaction. However, the success of this method depends on nuclear breakup effects being negligible or at least their magnitude being known as accurately as possible.

In the recent past, attempts have been made to measure the CD of $^9$Li on U and Pb targets at the beam energy ($E_{\mathrm{beam}}$) of 28.5 MeV/A [14] and on a Pb target at $E_{\mathrm{beam}}$ of 39.7 MeV/A [15]. The corresponding cross sections were used to get the photoabsorption cross sections $\sigma_{\gamma n}^{^9\mathrm{Li}}$ by following the method of virtual photon number [16],

$$\sigma_{\gamma n}^{^9\mathrm{Li}} = \frac{E_\gamma}{n_{E\lambda}}\frac{d\sigma}{dE_\gamma}, \tag{4}$$

where $n_{E\lambda}$ is the virtual photon number [19] of electric multipole order $\lambda$ and $\frac{d\sigma}{dE_\gamma}$ is the measured CD cross section. $\sigma_{n\gamma}^{^9\mathrm{Li}}$ can be obtained from $\sigma_{\gamma n}^{^9\mathrm{Li}}$ by using Eq. (3), which can be used to get the rate of the reaction $^8$Li$(n,\gamma)^9$Li. In Ref. [14]$R$ was estimated to be $<$7200 cm$^3$ s$^{-1}$ mole$^{-1}$, while it was reported to be $<$790 cm$^3$ s$^{-1}$ mole$^{-1}$ in Ref. [15].

## II. METHOD OF CALCULATION

In the theoretical determination of $\sigma_{n\gamma}^{^9\mathrm{Li}}$ within the CD approach, one calculates the Coulomb dissociation cross sections of $^9$Li by using a theory of the CD process. In Ref. [9], first order Coulomb excitation theory has been used for this purpose. A crucial quantity that enters in calculations within this theory is the reduced transition probability $B(E\lambda)$ of a particular transition. This quantity depends on the wave function of the relative motion of $n$ and $^8$Li in the ground as well as excited states of $^9$Li. Since the CD method involves excitation of the projectile to its continuum, the evaluation of $B(E\lambda)$ depends sensitively on information about the continuum structure of the projectile. In Ref. [9] the continuum states were calculated by treating them as scattering states with the same $n-{}^8$Li potential that was obtained by fitting the binding energy of the $^9$Li ground state. The calculated CD cross section is used to get $\sigma_{n\gamma}^{^9\mathrm{Li}}$ with the help of Eq. (3). From the comparison with the experimental capture cross sections $\sigma_{n\gamma}^{^9\mathrm{Li}}$ of Ref. [14], a value of $<$2200 cm$^3$ s$^{-1}$ mole$^{-1}$ has been obtained for the rate of the $^8$Li$(n,\gamma)^9$Li reaction. We note that this value differs from that reported in Ref. [14] by a factor of about 4.

In this article we use a fully quantum mechanical theory of Coulomb breakup reactions to calculate the Coulomb dissociation of $^9$Li that is then used to extract the rate of the capture reaction $^8$Li$(n,\gamma)^9$Li. The theory of CD reactions used by us is formulated within the post-form finite range distorted wave Born approximation (FRDWBA) [20] where the electromagnetic interaction between the fragments and the target nucleus is included to all orders and the breakup contributions from the entire nonresonant continuum corresponding to all the multipoles and the relative orbital angular momenta between the fragments are taken into account [21]. Full ground state wave function of the projectile, of any orbital angular momentum configuration, enters as an input into this theory. Unlike the theoretical models used in Ref. [9], this model does not require the knowledge of the positions and widths of the continuum states. Thus our method is free from the uncertainties associated with the multipole strength distributions occurring in other formalisms as we need only the ground state wave function of the projectile as input.

Let us consider the reaction $a+t \rightarrow b+c+t$, where the projectile $a$ breaks up into fragments $b$ (charged) and $c$ (uncharged) in the Coulomb field of a target $t$. The relative

energy spectra for the reaction is given by

$$\frac{d\sigma}{dE_{bc}} = \int_{\Omega_{bc},\Omega_{at}} d\Omega_{bc} d\Omega_{at} \left\{ \sum_{lm} \frac{1}{(2l+1)} |\beta_{lm}|^2 \right\} \times \frac{2\pi}{\hbar v_{at}} \frac{\mu_{bc}\mu_{at} p_{bc} p_{at}}{h^6}, \quad (5)$$

where $v_{at}$ is the $a$–$t$ relative velocity in the entrance channel, $\Omega_{bc}$ and $\Omega_{at}$ are solid angles, $\mu_{bc}$ and $\mu_{at}$ are reduced masses, and $p_{bc}$ and $p_{at}$ are appropriate linear momenta corresponding to the $b$–$c$ and $a$–$t$ systems, respectively.

The reduced amplitude $\beta_{lm}$ in the post-form finite range distorted wave Born approximation is given by

$$\beta_{lm} = \langle \exp(\gamma \vec{k}_c - \alpha \vec{K}) | V_{bc} | \Phi_a^{lm} \rangle \times \langle \chi^{(-)}(\vec{k}_b) \chi^{(-)}(\delta \vec{k}_c) | \chi^{(+)}(\vec{k}_a) \rangle, \quad (6)$$

where $\vec{k}_b, \vec{k}_c$ are Jacobi wave vectors of fragments $b$ and $c$, respectively, in the final channel of the reaction, $\vec{k}_a$ is the wave vector of projectile $a$ in the initial channel, and $V_{bc}$ is the interaction between $b$ and $c$. $\Phi_a^{lm}$ is the ground state wave function of the projectile with relative orbital angular momentum state $l$ and projection $m$. In the above, $\vec{K}$ is an effective local momentum associated with the core-target relative system, whose direction has been taken to be the same as the direction of the asymptotic momentum $\vec{k}_b$ [20,22]. $\alpha, \delta$, and $\gamma$ in Eq. (5) are mass factors relevant to the Jacobi coordinates of the three body system (see Fig. 1 of Ref. [20]). The $\chi^{(-)}$s are the distorted waves for relative motions of $b$ and $c$ with respect to $t$ and the c.m. of the $b$–$t$ system, respectively, with ingoing wave boundary condition, and $\chi^{(+)}(\vec{k}_a)$ is the distorted wave for the scattering of the c.m. of projectile $a$ with respect to the target with outgoing wave boundary condition.

It should be mentioned that in Eq. (6), the interactions between the fragments $b$ and $c$ and the target nucleus are included to all orders, but the $b$-$c$ interaction is treated to first order only. Since for relative energies of our interest there are no resonances in the $n + {}^8$Li continuum, we expect this approximation to be valid. It is clearly a good approximation for the deuteron and the neutron halo systems [17]. For those cases where higher order effects of the fragment-fragment interaction are known to be nonnegligible, our model will have a limited applicability. It should be noted that in calculating the relative energy spectra within this theory explicit information about the continuum strength distribution of the projectile is not required; the entire continuum is automatically included in our post-form theory.

Physically, the first term in Eq. (6) contains the structure information about the projectile through the ground state wave function $\Phi_a^{lm}$ and is known as the vertex function, while the second term is associated only with the dynamics of the reaction. The charged projectile $a$ and the fragment $b$ interacts with the target by a point Coulomb interaction and hence $\chi_b^{(-)}(\vec{k}_b)$ and $\chi^{(+)}(\vec{k}_a)$ are substituted with the appropriate Coulomb distorted waves. For pure Coulomb breakup, of course, the interaction between the target and the uncharged fragment $c$ is zero and hence $\chi^{(-)}(\delta \vec{k}_c)$ is replaced by a plane wave. This will allow the second term of Eq. (6) to be evaluated analytically in terms of the bremsstrahlung integral [23]. A more detailed description of how the reduced amplitude $\beta_{lm}$ is simplified and an analytical expression for the bremsstrahlung integral, as used in our case, can be found in Refs. [20] and [21].

One can then relate the cross section in Eq. (5) to the photodissociation cross section, $\sigma_{\gamma n}^a$, for the reaction $a + \gamma \to b + c$, by

$$\frac{d\sigma}{dE_{bc}} = \frac{1}{E_\gamma} \sum_\lambda n_{\pi\lambda} \sigma_{\gamma n}^a, \quad (7)$$

where $n_{\pi\lambda}$ is the equivalent photon number of type $\pi$ (electric or magnetic) and multipolarity $\lambda$ [16] and photon energy $E_\gamma = E_{bc} + S_n$, with $S_n$ being the one neutron separation energy of the projectile $a$. The relative energy between the fragments in the final state is denoted by $E_{bc}$. As discussed earlier, for the case of our interest, transition of $E1$ multipolarity dominates. The virtual photon number for this case has been calculated by following the same method as that used in Ref. [9].

Of course, the procedure of relating the CD cross sections calculated by Eq. (5) to $\sigma_{\gamma n}^a$ by Eq. (7) is valid only when transitions of a single multipolarity and type give the dominant contribution to the breakup cross section and nuclear breakup effects are negligible. Both of these conditions are supposed to be fulfilled in the case of our interest. Furthermore, the post-form amplitudes [Eq. (5)] include fragment-target interaction to all orders while the right-hand side of Eq. (7) has been written within first order perturbation theory. Therefore, relating the post-form CD cross section to the photodissociation cross sections via Eq. (7) is valid only when higher order effects make negligible contribution to the CD cross sections at the relevant beam energy. Indeed, it has been shown in Ref. [21] that for the Coulomb breakup reaction involving projectiles of similar mass range, the higher order effects are almost negligible for $E_{bc}$ of our interest ($<$100 keV) for beam energies around 30 MeV/nucleon. Therefore, necessary conditions for the validity of Eq. (7) are fulfilled for the present case. Nevertheless, we emphasize that, in general, the validity of Eq. (7) in each case must be checked before using this to extract the photodissociation cross section from the post-form Coulomb dissociation cross section.

The radiative capture cross section, $\sigma_{n\gamma}^a$, for the reaction $b + c \to a + \gamma$ is then related to the photo dissociation cross section, $\sigma_{\gamma n}^a$, by the principle of detailed balance [16] (Eq. (3) for the reaction of our interest).

## III. RESULTS AND DISCUSSIONS

As shown above, the ground state wave function of the projectile enters into the calculations of the CD cross sections within our theory. For $^9$Li, we obtain this wave function by assuming the neutron-$^8$Li core interaction to be of Woods-Saxon type whose depth is searched, for a given configuration, to reproduce the corresponding binding energy.

Within this model, the valence neutron in $^9$Li (spin-parity $3/2^-$) is assumed to move relative to an inert $^8$Li core (with intrinsic spin-parity $2^+$) in a Woods-Saxon plus spin-orbit

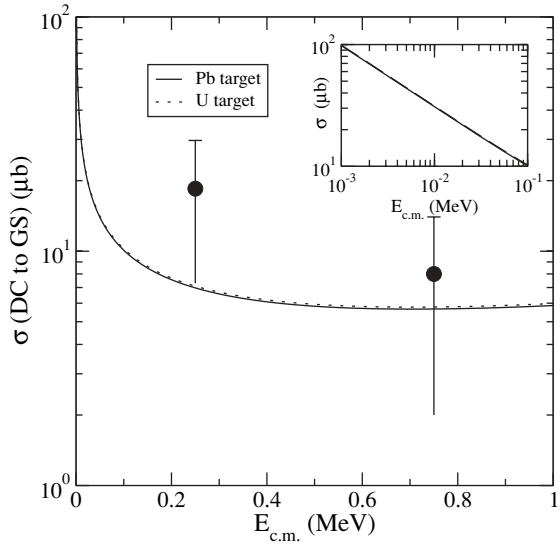


FIG. 1. Direct capture (DC) cross sections to the ground state (GS) of $^9$Li. The solid and dotted curves (which almost coincide with each other) are calculated using the Coulomb dissociation of $^9$Li on Pb and U targets at 28.5 MeV/A beam energy. The inset shows the values of the capture cross sections up to $E_{\text{c.m.}} \leqslant 100$ keV. The experimental data are from Ref. [14].

potential, with an adjustable depth $V_0$ for the initial channel:

$$V(r) = V_0 \left(1 - F_{\text{s.o.}}(\vec{l}.\vec{s})\frac{r_0}{r}\frac{d}{dr}\right) f(r), \tag{8}$$

where

$$f(r) = (1 + \exp((r - R)/a))^{-1}. \tag{9}$$

Using $a = 0.52$ fm, $r_0 = 1.25$ fm, $^8$Li core radius $R = 2.49$ fm, and the spin-orbit strength $F_{\text{s.o.}} = 0.351$ fm, the depth of the Woods-Saxon potential was searched to reproduce the one-neutron separation energy of $^9$Li (4.05 MeV). This yielded $V_0 = -45.21$ MeV. With this potential, the rms distance of the core-neutron relative motion and the rms size of $^9$Li came out to be 3.10 and 2.55 fm, respectively.

We have calculated the capture cross sections of the $^8$Li$(n, \gamma)^9$Li reaction as a function of the c.m. relative energy ($E_{\text{c.m.}}$) between neutron and $^8$Li in the range of 0–1 MeV, using the Coulomb breakup cross section obtained with our method. Because our aim in this article is to narrow down the theory dependent uncertainty in the extracted rate of this reaction, we compare our results with experimental capture cross sections the same as those in Ref. [9]. In Fig. 1, we show the direct capture cross sections to the ground state of $^9$Li obtained from the Coulomb dissociation of $^9$Li on Pb (solid line) and U targets (dotted line) at 28.5 MeV/A beam energy. In the inset of this figure we have highlighted the values of the cross sections in the astrophysically interesting region (for $E_{\text{c.m.}} \leqslant 100$ keV) by presenting cross sections as a function of $E_{\text{c.m.}}$ on a log-log plot. As expected, the capture cross section is independent of the target used during the Coulomb dissociation. It should be noted that while we have used a spectroscopic factor ($S$) of $0.68 \pm 0.14$ for the ground state of $^9$Li that was extracted recently from a transfer reaction

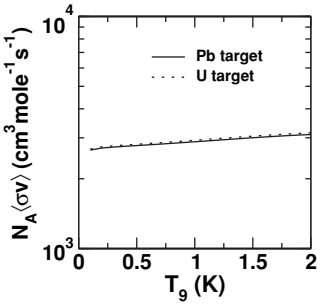


FIG. 2. Capture rates for the $^8$Li$(n, \gamma)^9$Li reaction as a function of temperature in units of $10^9$ K. Solid and dotted lines are reaction rates derived from the Coulomb dissociation of $^9$Li on Pb and U targets, respectively.

measurement [24], a shell model value of 0.94 was used for it in Ref. [9]. It is worth mentioning that transfer reaction cross sections are very sensitive to the angular momentum state of the projectile and hence have been widely used to extract nuclear spectroscopic factors. Had we used the shell model value of $S$, our results would have been proportionately higher.

Nevertheless, it should be noted that the experimental data of Ref. [14] have uncertainty of approximately a factor of 2. Furthermore, the second Coulomb dissociation measurement of $^9$Li as reported in Ref. [15] indicates that the extracted capture cross section could even be substantially lower than those reported in Ref. [14]. Therefore, to firm up the theoretical capture cross sections as extracted from the Coulomb dissociation method, the uncertainty in the experimental data should be minimized as much as possible.

Reaction rate ($R$) calculated from the capture cross sections are plotted in Fig. 2 as a function of $T_9$ (the temperature equivalent of relative energy in units of $10^9$ K). Solid and dotted lines show reaction rates derived from the Coulomb dissociation of $^9$Li on Pb and U targets, respectively. The rate changes in the range 2800–3100 cm$^3$ mole$^{-1}$ s$^{-1}$ for $T_9$ between 0.5 and 2 and the value at $T_9 = 1$ is approximately 2900 cm$^3$ mole$^{-1}$ s$^{-1}$, when averaged over the two targets.

As is evident from the integrand in Eq. (2), for a fixed stellar temperature, the maximum contribution to the reaction rate is highly dependent on the reaction cross section and in turn on the relative energy. At $T_9 = 1$, the maximum contribution to the $^8$Li$(n, \gamma)^9$Li reaction rate comes from a low relative energy of 45 keV. At this low energy it is extremely difficult to measure reaction cross sections by direct methods. This is where the power of the CD method becomes more evident as an indirect method in nuclear astrophysics. With recent advances in experimental techniques it is possible to measure relative energy spectra at quite low relative energies.

In Table I, we present a comparison of the rates of the reaction $^8$Li$(n, \gamma)^9$Li reported by various workers. It is interesting to note that the rate of the $^8$Li$(n, \gamma)^9$Li reaction extracted by us is within 30% in agreement with that computed from the capture cross sections of Ref. [9] where a completely different theoretical model of the CD process was used. On the other hand, our rate is about 45–35% smaller than those reported in Refs. [11] and [12] where they have been obtained

TABLE I. Comparison of reaction rates of the $^8$Li$(n,\gamma)^9$Li reaction as reported by various authors.

| Reference | Reaction rate (cm$^3$ mole$^{-1}$ s$^{-1}$) |
|---|---|
| Malaney and Fowler [13] | 43000 |
| Mao and Champagne [10] | 25000 |
| Descouvemont [11] | 5300 |
| Rauscher *et al*. [12] | 4500 |
| Zecher *et al*. [14] | <7200 |
| Kobayashi *et al*. [15] | <790 |
| Bertulani [9] | 2200 |
| Present work | 2900 |

from structure model calculations of $^9$Li. Our values are in sharp disagreement with the results of Ref. [10] where calculations were performed within the *spd*-shell model and with those of Ref. [13] which have been obtained from the systematics of similar nuclei. The rate of Ref. [10] is larger by a factor of 7.2 whereas that of Ref. [13] is even larger (by a factor of almost 15). It may be worthwhile to see what these calculations would predict if the latest experimental information on the spectroscopic factor for the $^9\text{Li} \rightarrow {}^8\text{Li} + n$ partition was taken into consideration.

Thus, our calculations do not support the large rate for the $^8$Li$(n,\gamma)^9$Li reaction. This would suggest that a significant portion of $^8$Li would remain available for $\alpha$ capture to $^{11}$B and would not be destroyed by the $^8$Li$(n,\gamma)^9$Li reaction. Therefore, the $^8$Li$(n,\gamma)^9$Li reaction does not hamper the formation of $A > 12$ elements through the $^8$Li$(\alpha,n)^{11}$B$(n,\gamma)$ $^{12}$Be$(\beta^-)^{12}$C$(n,\gamma)\cdots$ reaction chain.

## IV. SUMMARY AND CONCLUSIONS

In summary, we have calculated the rate of the $^8$Li$(n,\gamma)^9$Li reaction by studying the inverse photodissociation reaction in terms of the Coulomb dissociation of $^9$Li on heavy targets at 28.5 MeV/A using a theory formulated within the finite range post-form distorted wave Born approximation. This capture reaction provides, in an inhomogeneous early universe, a leak from the primary chain of nucleosynthesis, thereby reducing the production of heavy elements. The advantage of our theoretical method is that it is free from the uncertainties associated with the multipole strength distributions of the projectile. The newly extracted experimental ground state spectroscopic factor for the $^9\text{Li} \rightarrow {}^8\text{Li} + n$ partition [24] has been incorporated in our theory.

The rate of this reaction at a temperature of $10^9$ K has been found to be about 2900 cm$^3$ mole$^{-1}$ s$^{-1}$. This value is in agreement (within 30%) with the earlier Coulomb dissociation analysis of this data using a different theoretical model. Thus theoretical uncertainty in the rate of $^8$Li$(n,\gamma)^9$Li reaction as determined from the Coulomb dissociation of $^9$Li is much lower than the experimental uncertainties in this data. Therefore, it would be worthwhile to make more precise measurements of the Coulomb dissociation reaction. The maximum contribution to the reaction rate at this stellar temperature came from a low relative energy of 45 keV. Thus in future experiments an attempt should be made to measure the $^8$Li$(n,\gamma)^9$Li capture cross section at this low relative energy to get a more accurate picture of the reaction rate.

Our calculations also suggest that this reaction rate is not high enough to destroy enough of $^8$Li so as to significantly reduce the formation of $A > 12$ elements through the $^8$Li$(\alpha,n)^{11}$B$(n,\gamma)^{12}$Be$(\beta^-)^{12}$C$(n,\gamma)\cdots$ reaction chain.

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