Thermonuclear ^{6}Li(n,γ)^{7}Li reaction rate: A revisit

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Introduction

The radiative ^{6}Li(n,γ)^{7}Li capture reaction has been studied at energies of astrophysical interest. This thermonuclear reaction rate has remained independent of temperature so far. Its temperature dependence has been explored within the statistical model. Apart from the compound nuclear contribution, the pre-equilibrium as well as the direct effects have been taken into account. The corresponding Maxwellian-averaged thermonuclear reaction rate of relevance in astrophysical plasmas in the temperature range from 10^6 K to 10^{10} K has been calculated. Analytical expression as a function of T_9 (unit of 10^9 K) has been provided by fitting the calculated reaction rate.

Theoretical formalism

The radiative neutron capture cross section varies inversely as velocity in the range of thermal energies. At these energies, the feature of $\sigma(E) \propto E^{-1/2}$ leads to approximate constancy of thermonuclear reaction rates with respect to plasma temperature. However, above thermal energies, especially in the domain of astrophysics, the neutron induced reaction cross section deviates from the $1/v$ law. Thus it is expected that $\langle\sigma v\rangle$ has to have a temperature dependence. All the thermonuclear reaction rates do have temperature dependence except few radiative neutron capture reactions such as ^{6}Li(n,γ)^{7}Li reaction. This rate has remained independent of temperature so far [1, 2]. Hence, its temperature dependence has been explored.

The computer code TALYS [3] allows a comprehensive astrophysical reaction rate calculations apart from other nuclear physics calculations. To a good approximation, in the interior of stars the assumption of a thermodynamic equilibrium holds and nuclei exist both in the ground and excited states. This assumption along with cross sections calculated from compound nucleus model for various excited states facilitates Maxwellian-averaged reaction rates. The Hauser-Feshbach statistical model calculations has been extended by adding some new and important features. Apart from coherent inclusion of fission channel it also includes reaction mechanism that occurs before equilibrium is reached, multi-particle emission, competition among all open channels, width fluctuation corrections in detail, coupled channel description in case of deformed nuclei and level densities that are parity-dependent. Nuclear models are also normalized for available experimental data using separate approaches such as on photo-absorption data, the E1 resonance strength or on s-wave spacings, the level densities.

The astrophysical nuclear reaction rate can be calculated by folding the Maxwell-Boltzmann energy distribution for energies E at the given temperature T with the cross section $\sigma^\mu_{\alpha\alpha'}(E)$. The relative populations of various energy states of nuclei with excitation energies E^μ_x and spins I^μ in thermodynamic equilibrium follows the Maxwell-Boltzmann distribution. In order to distinguish between different excited states the superscript μ is used along with the incident α channel in the formulas that follow. Taking due account of various target nuclei excited state contributions, the effective nuclear reaction rate in the entrance channel $\alpha \to \alpha'$ can be expressed as

$$N_A\langle\sigma v\rangle^*_{\alpha\alpha'} = \left(\frac{8}{\pi m}\right)^{1/2} \frac{N_A}{(kT)^{3/2}G(T)} \quad (1)$$

$$\times \int_0^\infty \sum_\mu \frac{(2I^\mu+1)}{(2I^0+1)} \sigma^\mu_{\alpha\alpha'}(E) E \exp\left(-\frac{E+E^\mu_x}{kT}\right) dE$$

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where N_A is the Avogadro number, k and m are the Boltzmann constant and the reduced mass in the α channel, respectively, and

$$G(T) = \sum_{\mu}(2I^{\mu}+1)/(2I^{0}+1)\exp(-E_x^{\mu}/kT)$$

is the temperature dependent normalized partition function.

Calculations and Results

The reaction rate for the reaction ^{6}Li(n,γ)^{7}Li has been calculated theoretically using the TALYS [3] code. Although, in this reaction the nuclei involved are light, the results of the calculations are expected to be reasonable, particularly as the reaction being induced by low energy neutrons and not by charged particles implying dominant contributions from compound nuclear reaction. Moreover, apart from the compound nuclear contribution, it accounts for the pre-equilibrium and the direct effects as well. However, the pre-equilibrium effects do not play any role at energies below the ^{7}Li neutron separation energy of 7.25 MeV. The results of calculations for reaction rate in units of cm^{3}s^{-1}mol^{-1} as a function of T_9 generated from TALYS code have been presented in Table-1.

TABLE I: ^{6}Li(n,γ)^{7}Li reaction rate (cm^3/s/mol).

T_9	Reaction Rate	T_9	Reaction Rate	T_9	Reaction Rate
0.0001	408.43	0.3	436.44	2.5	824.89
0.0005	440.24	0.4	466.02	3.0	883.00
0.001	423.09	0.5	492.41	3.5	936.22
0.005	414.78	0.6	516.58	4.0	985.55
0.01	392.78	0.7	539.18	5.0	1074.75
0.05	369.81	0.8	560.55	6.0	1153.17
0.1	375.42	0.9	580.88	7.0	1222.50
0.15	388.01	1.0	600.31	8.0	1284.74
0.2	403.71	1.5	686.76	9.0	1342.36
0.25	420.29	2.0	760.28	10.0	1397.99

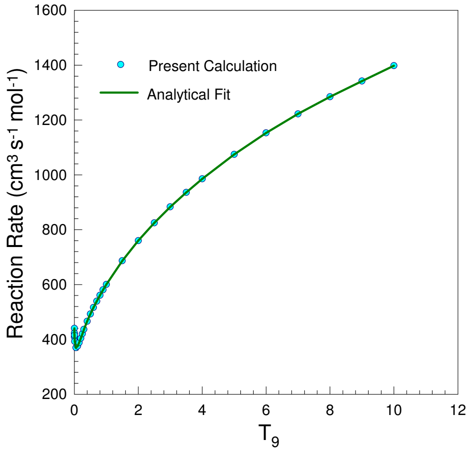

FIG. 1: Plot of ^{6}Li(n,γ)^{7}Li reaction rate as function of temperature T_9.

The results of the calculations as a function of temperature T_9 generated from TALYS code have been fitted quite accurately as a function of T_9. The plot of reaction rate as a function of temperature T_9 has been shown in Fig.-1. The dots represent results of the present calculations (Table-1) while the continuous line corresponds to the mean value of its fitting by the function of T_9 given by

$$N_A < \sigma v >= (387.75 \pm 0.95) + (219.45 \pm 1.91)T_9 \\ -(20.45 \pm 0.59)T_9^2 + (0.867 \pm 0.045)T_9^3 \quad (2)$$

Summary and Conclusion

New analytical expression for the thermonuclear reaction rate of ^{6}Li(n,γ)^{7}Li neutron capture reaction has been developed as a function of T_9. This has been achieved by fitting the results of the reaction rate generated from nuclear reaction theory calculations. Apart from the compound nuclear contribution, the pre-equilibrium and the direct effects have been accounted for. As expected, the thermonuclear reaction rate has been found to be temperature dependent which increases monotonically beyond thermal neutron energies up to $10T_9$ that corresponds to $\sim$ 0.86 MeV. This new reaction rate may find its usefulness in the domains of nuclear astrophysics such as stellar burning and nucleosynthesis.

References

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