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Rate of the ^{8}Li(n,γ)^{9}Li reaction from the Coulomb dissociation of ^{9}Li

PoS(NIC X)236

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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,γ)^{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^{9}K is found to be about 2900 cm^{3} mole^{-1} s^{-1}.

10th Symposium on Nuclei in the Cosmos
July 27 - August 1, 2008
Mackinac Island, Michigan, USA

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The ^{8}Li(n,γ)^{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.*, Ref. [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 be reduced by 40-50% [3].

Several theoretical predictions of the rate of ^{8}Li$(n,\gamma)^9$Li have been reported. Some of them perform nuclear structure calculations of ^{9}Li and calculate the capture cross sections from the corresponding wave functions [4, 5]. Others estimate the rate of this reaction from the systematics that are based on information existing for other nuclei [6, 7]. 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 [8, 9].

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

In this work we use a fully quantum mechanical theory of Coulomb breakup reactions to calculate the Coulomb dissociation (CD) of ^{9}Li which is then used to extract the rate of the capture reaction ^{8}Li(n,γ)^{9}Li. The theory of CD reactions used by us is formulated within the post form finite range distorted wave Born approximation (FRDWBA) [10] where the electromagnetic interaction between the fragments and the target nucleus is included to all orders and the breakup contributions from the entire non-resonant continuum corresponding to all the multipoles and the relative orbital angular momenta between the fragments are taken into account. Full ground state wave function of the projectile, of any orbital angular momentum configuration, enters as an input into this theory. Unlike the theoretical model used in Ref. [11], this model does not require the knowledge of the positions and widths of the continuum states. Thus our method is free from 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

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

where v_{at} is the a–t relative velocity in the entrance channel, Ω_{bc} and Ω_{at} are solid angles, μ_{bc} and μ_{at} are reduced masses, and p_{bc} and p_{at} are appropriate linear momenta corresponding to the b–c and a–t systems, respectively. β_{lm} is the reduced amplitude in the FRDWBA.

One can then relate the cross section in Eq. (1) to the photodissociation cross section, $\sigma_{\gamma n}^{a}$, for the reaction $a+\gamma \rightarrow b+c$ and then calculate the the radiative capture cross section, $\sigma_{n\gamma}^{a}$, for the reaction, $b+c \rightarrow a+\gamma$, by the principle of detailed balance. For more details of the theory one is referred to Ref. [12].

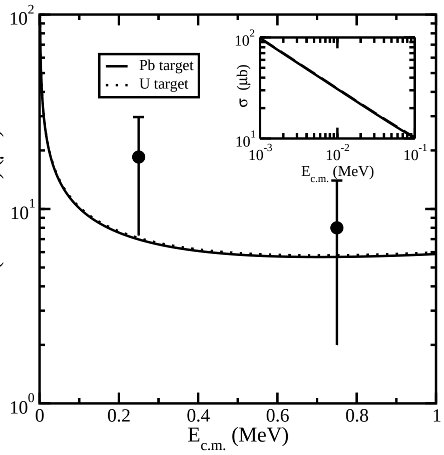

Figure 1: Direct capture (DC) cross sections to the ground state (GS) of ^{9}Li. The solid and dotted curves (which almost coincide with each other) are calculated using the Coulomb dissociation of ^{9}Li on Pb and U targets at 28.5 MeV/A beam energy. The inset shows the values of the capture cross sections upto $E_{\mathrm{c.m.}} \leq$ 100 keV. The experimental data are from Ref. [8].

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 $E_{\mathrm{c.m.}} \leq$ 100 keV) by presenting cross sections as a function of $E_{\mathrm{c.m.}}$ 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 ± 0.14 for the ground state of ^{9}Li which has been extracted recently from a transfer reaction measurement [13], a shell model value of 0.94 was used in Ref. [11]. 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. [8] have uncertainty of approximately a factor of 2. Furthermore, the second Coulomb dissociation measurement of ^{9}Li as reported in Ref. [9] indicates that the extracted capture cross section could even be substantially lower than those reported in Ref. [8]. 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.

The reaction rates [14] 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 10^9K). 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.

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,γ)^{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

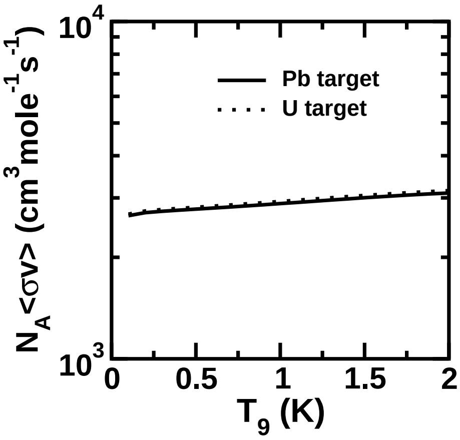

Figure 2: Capture rates for the ^{8}Li(n,γ)^{9}Li reaction as a function of temperature in units of 10^{9}K. Solid and dotted lines are reaction rates derived from the Coulomb dissociation of ^{9}Li on Pb and U targets, respectively.

Table 1: The comparison of reaction rates of the ^{8}Li(n,γ)^{9}Li reported as reported by various authors

Reference	Reaction rate $(cm^{3}mol^{-1}s^{-1})$
Malaney and Fowler [7]	43000
Mao and Champagne [4]	25000
Descouvemont [5]	5300
Rauscher *et al.* [6]	4500
Zecher *et al.* [8]	< 7200
Kobayashi *et al.* [9]	< 790
Bertulani [11]	2200
Present work	2900

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 1, we present a comparison of the rates of the reaction ^{8}Li(n,γ)^{9}Li reported by various workers. It is interesting to note that the rate of the ^{8}Li(n,γ)^{9}Li reaction extracted by us is within 30% in agreement with that computed in Ref. [11] where a completely different theoretical model of CD process was used. On the other hand, our rate is about 45-35% smaller than those reported in Refs. [5, 6] where they have been obtained from structure model calculations of ^{9}Li. Our value is in sharp disagreement with the result of Ref.[4] where calculations were performed within the spd-shell model and with those of Ref.[7] which have been obtained from the systematics of similar nuclei. The rate of Ref. [4] is larger by a factor of 7.2 whereas that of Ref. [7] 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}Li $\rightarrow^{8}$Li + n partition was taken into consideration.

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

In summary, we have calculated the rate of the ^{8}Li(n,γ)^{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}Li $\rightarrow$ ^{8}Li $+n$ partition [13], has been incorporated in our theory.

The rate of this reaction at a temperature of 10^9K 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,γ)^{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,γ)^{9}Li capture cross section at this low relative energy to get a more accurate picture of the reaction rate.

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