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Reaction rates of the $\alpha + d \to {}^6$Li + γ direct capture process and primordial abundance of the ^{6}Li element within few-body models

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Abstract. The rates of the $\alpha + d \to {}^6$Li + γ astrophysical direct capture reaction and the primordial abundance of the ^{6}Li element are calculated within the cluster models. It is shown that the combined E2(two-body)+E1(three-body) model describes the direct data of the LUNA collaboration quite well. For the primordial abundance ratio ^{6}Li/H the calculated value of $(0.72 \pm 0.01) \times 10^{-14}$ is close to the LUNA data $(0.80 \pm 0.18) \times 10^{-14}$. The calculated abundance ratio ^{6}Li/^{7}Li of $(1.40 \pm 0.12) \times 10^{-5}$ is within the range of the Standard Model prediction.

Key words. Capture reaction, astrophysical S factor, reaction rate, ^{6}Li abundance

1. Introduction

The second lithium problem in nuclear astrophysics is related to the ratio of primordial abundances ^{6}Li/ ^{7}Li. For this ratio the astrophysical data (Asplund et al. 2006) yield a value which overestimates the prediction of the big bang nucleosynthesis (BBN) model (Serpico et al. 2004) by three orders of magnitude. The rate of the direct capture reaction

$$\alpha + d \to {}^6\mathrm{Li} + \gamma \qquad (1)$$

within the energy interval $30 \leq E_{\mathrm{cm}} \leq 400$ keV (Serpico et al. 2004) is one of the most important input variables of the BBN model for the abundance ratio. For the estimation of the reaction rates one needs values of the theoretical astrophysical S factor. Until recently the above process was studied separately in the two-body (Tursunov et al. 2015) and three-body models (Tursunov et al. 2016; Baye et al. 2018; Tursunov et al. 2018).

Recent comparative analysis have demonstrated (Tursunov et al. 2019) that the best theoretical description of the data is achieved within the combined E1(three-body)+E2(two-body) model.

The E2 S factor is strongly dependent on the asymptotic normalization constant of the $\alpha + d$ configuration, which can be well described in the two-body model. However, the isospin forbidden E1 astrophysical S factor can not be adequately estimated within the two-body model due to luck of the isospin mixing in the initial and final states. A small isotriplet part of about 0.5% of the final ^{6}Li ground state wave function is able to reproduce the forbidden E1 S factor.

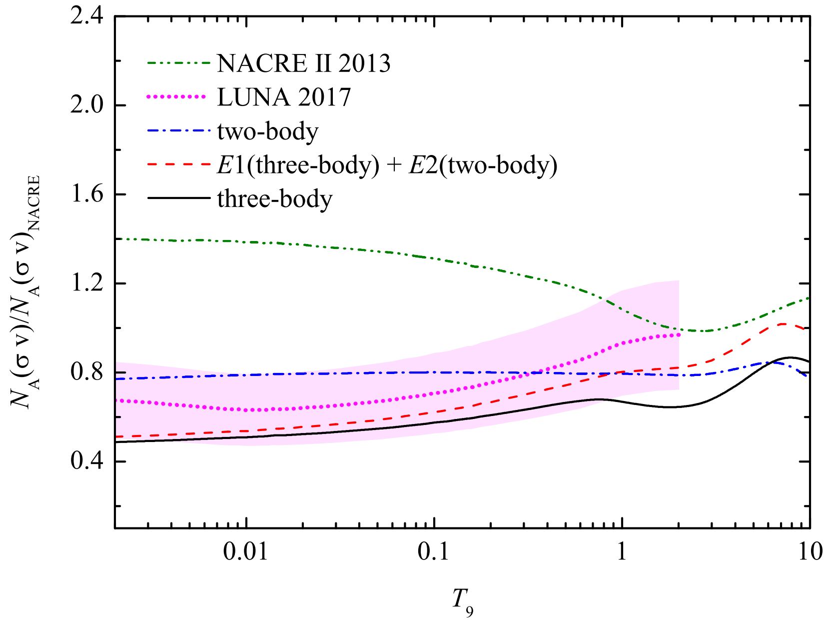

Fig. 1. Comparison of calculated reaction rates of the $\alpha + d \rightarrow {}^6\mathrm{Li}+\gamma$ process with available experimental data (first published in Tursunov et al. 2019)

2. Reaction rates and primordial abundance of ^{6}Li

Details of the reaction rate calculations are given in Ref. (Tursunov et al. 2018). The reaction rate $N_A(\sigma v)$ is estimated according to Refs. (Fowler et al. 1975; Angulo et al. 1999).

The estimated numerical values of the $\alpha(d,\gamma)^6$Li reaction rates in the temperature interval 10^6 K $\leq T \leq 10^{10}$ K ($0.001 \leq T_9 \leq 10$) are given in Table 1.

In Fig. 1 we compare the estimated theoretical reaction rates of the $\alpha(d,\gamma)^6$Li process in two-body and three-body models with the results of the LUNA 2017 collaboration (Trezzi et al. 2017) and with the data of the NACRE II collaboration (Xu et al. 2013) divided by the NACRE 1999 data (Angulo et al. 1999). The results of the three-body model are consistent with the LUNA data. Also, this model reproduces the temperature dependence of the LUNA data. The line of the two-body model is inside the experimental error bar, but its behavior is different from that of the LUNA data. In other words, it does not reproduce the temperature dependence. On the other hand, the combined E2(two-body)+E1(three-body) model yields a precise description of the direct LUNA data.

The analytical approximation of the reaction rates is required for the calculation of the primordial abundance. For the ^{6}Li nucleus we have:

$$N_{24}(\sigma v) = p_0 T_9^{-2/3} \exp(-7.423 T_9^{-1/3}) \times \\ \times(1 + p_1 T_9^{1/3} + p_2 T_9^{2/3} + p_3 T_9 + \\ + p_4 T_9^{4/3} + p_5 T_9^{5/3} + p_6 T_9^2 + p_7 T_9^{7/3}) + \\ + p_8 T_9^{-3/2} \exp(-7.889 T_9^{-1}). \quad (2)$$

In Table 2 we give the coefficients of the approximation of the reaction rates for the $d(\alpha,\gamma)^6$Li capture process within the range

Table 1. Numerical values of the calculated reaction rates for the direct d$(\alpha,\gamma)^6$Li capture process within the temperature range 10^6 K $\leq T \leq 10^{10}$ K ($0.001 \leq T_9 \leq 10$).

T_9	$N_A(\sigma v)$, cm^3(mol s)$^{-1}$		T_9	$N_A(\sigma v)$, cm^3(mol s)$^{-1}$	
	Three-body model (Tursunov et al. 2018)	Combined model		Three-body model (Tursunov et al. 2018)	Combined model
0.001	3.474×10^{-30}	3.620×10^{-30}	0.12	1.828×10^{-5}	1.982×10^{-5}
0.002	1.042×10^{-23}	1.088×10^{-23}	0.13	2.682×10^{-5}	2.913×10^{-5}
0.003	1.419×10^{-20}	1.482×10^{-20}	0.14	3.794×10^{-5}	4.126×10^{-5}
0.004	1.333×10^{-18}	1.395×10^{-18}	0.15	5.205×10^{-5}	5.669×10^{-5}
0.005	3.361×10^{-17}	3.518×10^{-17}	0.16	6.959×10^{-5}	7.589×10^{-5}
0.006	3.928×10^{-16}	4.116×10^{-16}	0.18	1.167×10^{-4}	1.275×10^{-4}
0.007	2.794×10^{-15}	2.929×10^{-15}	0.2	1.826×10^{-4}	2.000×10^{-4}
0.008	1.408×10^{-14}	1.477×10^{-14}	0.25	4.530×10^{-4}	4.985×10^{-4}
0.009	5.517×10^{-14}	5.794×10^{-14}	0.3	9.166×10^{-4}	1.013×10^{-3}
0.010	1.788×10^{-13}	1.879×10^{-13}	0.35	1.624×10^{-3}	1.801×10^{-3}
0.011	4.997×10^{-13}	5.255×10^{-13}	0.4	2.624×10^{-3}	2.918×10^{-3}
0.012	1.240×10^{-12}	1.305×10^{-12}	0.5	5.681×10^{-3}	6.352×10^{-3}
0.013	2.796×10^{-12}	2.944×10^{-12}	0.6	1.056×10^{-2}	1.191×10^{-2}
0.014	5.819×10^{-12}	6.130×10^{-12}	0.7	1.792×10^{-2}	2.044×10^{-2}
0.015	1.132×10^{-11}	1.194×10^{-11}	0.8	2.876×10^{-2}	3.334×10^{-2}
0.016	2.081×10^{-11}	2.195×10^{-11}	0.9	4.428×10^{-2}	5.226×10^{-2}
0.018	6.110×10^{-11}	6.451×10^{-11}	1	6.556×10^{-2}	7.874×10^{-2}
0.02	1.545×10^{-10}	1.632×10^{-10}	1.5	2.715×10^{-1}	3.434×10^{-1}
0.025	9.899×10^{-10}	1.049×10^{-9}	2	6.036×10^{-1}	7.722×10^{-1}
0.03	4.084×10^{-9}	4.335×10^{-9}	2.5	9.884×10^{-1}	1.260×10^{0}
0.04	3.229×10^{-8}	3.439×10^{-8}	3	1.393×10^{0}	1.758×10^{0}
0.05	1.409×10^{-7}	1.506×10^{-7}	4	2.261×10^{0}	2.784×10^{0}
0.06	4.349×10^{-7}	4.660×10^{-7}	5	3.242×10^{0}	3.911×10^{0}
0.07	1.072×10^{-6}	1.152×10^{-6}	6	4.345×10^{0}	5.165×10^{0}
0.08	2.264×10^{-6}	2.437×10^{-6}	7	5.538×10^{0}	6.521×10^{0}
0.09	4.266×10^{-6}	4.602×10^{-6}	8	6.783×10^{0}	7.932×10^{0}
0.10	7.377×10^{-6}	7.973×10^{-6}	9	8.049×10^{0}	9.360×10^{0}
0.11	1.193×10^{-5}	1.291×10^{-5}	10	9.314×10^{0}	1.077×10^{1}

$0.001 \leq T_9 \leq 10$. They reproduce the calculated reaction rates within 1.89% and 1.88% for three-body and combined models, respectively.

Using the calculated rates of the reaction on the base of the PArthENoPE (Pisanti et al. 2008) public code we are able to estimate the ^{6}Li primordial abundance. For the baryon density parameter we use the Planck 2015 best fit $\Omega_b h^2 = 0.02229^{+0.00029}_{-0.00027}$ (Ade et al. 2016) and for the neutron life time $\tau_n = 880.3 \pm 1.1$ s (Olive et al. 2014). Then for the ^{6}Li/H abundance ratio we have an estimate $(0.66-0.68) \times 10^{-14}$ and $(0.71-0.73) \times 10^{-14}$ within the three-body and combined E2(two-body)+E1(three-body) models, respectively. These numbers agree well with the new LUNA data ^{6}Li/H=$(0.80\pm0.18)\times10^{-14}$ (Trezzi et al. 2017).

If we adopt for the ^{7}Li/H abundance ratio a value of $(5.2\pm0.4)\times10^{-10}$ (Kontos et al. 2013) then within the combined model we obtain an estimation $(1.40\pm0.12)\times10^{-5}$ for the ^{6}Li/^{7}Li abundance ratio. The theoretical estimation is

Table 2. Coefficients of analytical approximation for the reaction rates of the d$(\alpha,\gamma)^6$Li direct capture process.

Model	p_0	p_1	p_2	p_3	p_4	p_5	p_6	p_7	p_8
Three-body model	6.004	-2.558	34.730	-115.482	205.801	-169.456	71.428	-11.614	42.354
Combined model	6.741	-3.731	41.646	-137.035	242.156	-201.509	85.095	-13.814	61.752

consistent with the Standard Model prediction (Serpico et al. 2004).

3. Conclusions

The reaction rates of the $\alpha(d,\gamma)^6$Li astrophysics process and the primordial abundance of the ^{6}Li element are calculated and compared in different cluster models. It is shown that the temperature dependence of the LUNA data for the reaction rates is not reproduced in the two-body model. The three-body model describes well the direct LUNA data. It reproduces both the absolute values and temperature dependence of the experimental reaction rate.

The best description of the LUNA data is achieved within the combined E2(two-body)+E1(three-body) model. For the ^{6}Li/H primordial abundance ratio it yields an estimate $(0.72\pm0.01)\times10^{-14}$, in a good agreement with the LUNA values $(0.80 \pm 0.18) \times 10^{-14}$. In addition, for the ^{6}Li/^{7}Li abundance ratio we have obtained a value $(1.40 \pm 0.12) \times 10^{-5}$, consistent with the prediction of the Standard Model.

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