Determination of the $^{12}C(p,\gamma)^{13}N$ reaction rates from the $^{12}C(^7Li,^6He)^{13}N$ reaction[†]

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The angular distribution of the $^{12}C(^7Li,^6He)^{13}N$ reaction at $E(^7Li) = 44.0$ MeV was measured at the HI-13 tandem accelerator of Beijing, China. The asymptotic normalization coefficient (ANC) of $^{13}N \rightarrow {}^{12}C + p$ was derived to be (1.64 ± 0.11) fm$^{-1/2}$ through the distorted wave Born approximation (DWBA) analysis. The ANC was then used to deduce the astrophysical $S(E)$ factors and reaction rates for the $^{12}C(p,\gamma)^{13}N$ direct capture reaction at energies of astrophysical relevance.

the $^{12}C(^7Li,^6He)^{13}N$ reaction, DWBA analysis, asymptotic normalization coefficient, astrophysical $S(E)$-factor

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1 Introduction

In stellar evolution, the $^{12}C(p,\gamma)^{13}N$ reaction plays a key role for the following reasons. Firstly, it is the first reaction in the Carbon-Nitrogen-Oxygen (CNO) cycle which dominates the energy production in stars with masses heavier than 1.5 $M_\odot$ [1,2]. Secondly, the $^{12}C(p,\gamma)^{13}N(\beta^+)^{13}C$ reactions can enhance the ^{13}C abundance [3], and thus influence the $^{12}C/^{13}C$ ratio which is thought to be an important measure for stellar evolution and nucleosynthesis [4]. Thirdly, the supply of ^{13}C by the $^{12}C(p,\gamma)^{13}N(\beta^+)^{13}C$ reactions is also important for the $^{13}C(\alpha,n)^{16}O$ neutron source in the asymptotic giant branch (AGB) stars. A recent calculation with parametric one-zone nucleosynthesis showed that more ^{13}C supply is needed at the end of the CNO cycle in solar-metallicity stars [5]. In view of the above-mentioned significance, it is highly desirable to carefully investigate the $^{12}C(p,\gamma)^{13}N$ cross section at energies below 1.0 MeV for the astrophysical interest.

The $^{12}C(p,\gamma)^{13}N$ reaction has been studied over a wide energy range down to about $E_{c.m.} = 70$ keV [6–13] since 1950. However, an obvious discrepancy exists in the experimental data at the lower energies. In the even lower energy range, no experimental data are available so far, and the astrophysical $S(E)$ factors can only be derived by the extrapolation which results in inevitable uncertainty. In the energy range of $E_{c.m.} \leqslant 200$ keV, the $^{12}C(p,\gamma)^{13}N$ reaction is dominated by the tail of the s-wave capture into the broad $1/2^+$ resonance at $E_r = 421$ keV. Although the contribution from the direct capture is believed to be much smaller than that from the resonance tail, the interference between the two processes can lead to a considerable variation of $S(E)$ factors, since both of them proceed via s-wave and then decay by $E1$ transitions. As a result, the $S(E)$ factors either increase by the constructive interference or decrease by the destructive one. Thus the reliable experimental data on the direct capture are needed to derive the $S(E)$ factors, particularly at energies of $E_{c.m.} \leqslant 200$ keV. A practicable scheme to deduce the $S(E)$ factors for the direct capture in $^{12}C(p,\gamma)^{13}N$ is combining the asymptotic normalization coefficient (ANC) of $^{13}N \rightarrow {}^{12}C + p$ and R-matrix approach [14,15]. The ANC can be deduced from the angular distribution of one proton transfer reactions. The $(^7Li,^6He)$ reactions are considered to be a valuable spectroscopic tool because the shapes of their angular distributions can be well reproduced by the distorted wave Born approximation (DWBA) [16]. Thus, the $^{12}C(^7Li, {}^6He)^{13}N$ reaction

can be used to extract the nuclear ANC of $^{13}N \rightarrow {}^{12}C + p$.

The $^{12}C(^7Li, {}^6He)^{13}N$ angular distribution was measured at $E(^7Li) = 44.0$ MeV. The spectroscopic factor and ANC were derived based on DWBA analysis, and then used to calculate the astrophysical $S(E)$ factors and rates of the $^{12}C(p, \gamma)^{13}N$ direct capture reaction at energies of astrophysical interest with the R-matrix approach. We have also computed the contribution from the resonant capture and the interference effect between resonant and direct captures.

2 Measurement of the $^{12}C(^7Li, {}^6He)^{13}N$ angular distribution

The experiment was performed at the HI-13 tandem accelerator of Beijing, China. A carbon target in thickness of 39.0 μg/cm² was bombarded with the 44.0 MeV ^7Li beam in intensity of about 100 pnA. The ^6He ions from the $^{12}C(^7Li, {}^6He)^{13}N$ reaction were analyzed with the Q3D magnetic spectrograph. In order to attain a good angular resolution, the solid angle for the reaction products was set to be 0.23 msr. A two dimensional position sensitive silicon detector (PSSD) was placed at the focal plane of the spectrograph, which assured the full detection of ^6He ions emitted within the solid angle. During the measurement, a Faraday cup placed at 0° in the reaction chamber was utilized to record the beam current which served as the normalization standard in determining the absolute cross section, while two independent silicon detectors (SSDs) at ± 30° were used for both monitoring the beam balance and relatively normalizing the measured cross sections. The normalization was checked at several angles from 23° to 40° with the elastic scattering data of 36.0 MeV ^7Li on ^{12}C [17].

The $^{12}C(^7Li, {}^6He)^{13}N$ differential cross sections were measured in the angular range of $7° \leqslant \theta_{lab} \leqslant 23°$, corresponding to $11° \leqslant \theta_{c.m.} \leqslant 37°$. The measured angular distribution is shown in Figure 1. The experimental errors are from the uncertainties of statistics, target thickness (5%) and solid angle (6%).
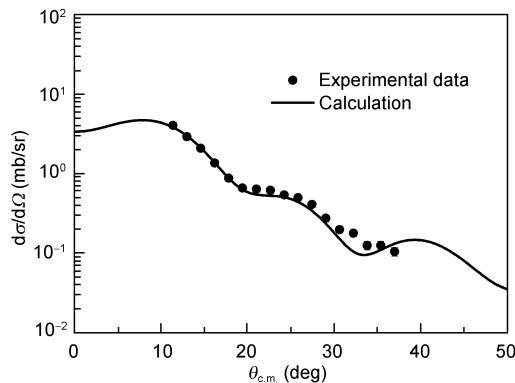
Figure 1 Angular distribution of the $^{12}C(^7Li, {}^6He)^{13}N$ reaction at $E(^7Li)$ = 44.0 MeV.

3 Determination of the ^{13}N nuclear ANC

The spins and parities of ^{12}C and ^{13}N ground states are 0^+ and $1/2^-$, respectively. The $^{12}C(^7Li, {}^6He)^{13}N$ cross section is dominated by the $(0^+,0) \rightarrow (1/2^-,1/2)$ transition, thus only $1p_{1/2}$ orbit in ^{13}N can be populated. If the reaction is peripheral, the differential cross section can be expressed as

$$\left(\frac{d\sigma}{d\Omega}\right)_{exp} = \left(\frac{C_{^7Li}}{b_{^7Li}}\right)^2 \left(\frac{C_{1,1/2}^{^{13}N}}{b_{1,1/2}^{^{13}N}}\right)^2 \left(\frac{d\sigma}{d\Omega}\right)_{DWBA}, \quad (1)$$

where $(\frac{d\sigma}{d\Omega})_{exp}$ and $(\frac{d\sigma}{d\Omega})_{DWBA}$ denote the measured and calculated differential cross sections respectively. $C_{1,1/2}^{^{13}N}$ and $C_{^7Li}$ are the nuclear ANCs of $^{13}N \rightarrow {}^{12}C + p$ and $^7Li \rightarrow {}^6He + p$, $b_{1,1/2}^{^{13}N}$ and $b_{^7Li}$ are the single particle ANCs of the bound state protons in ^{13}N and ^7Li, which can be calculated with the bound state single particle wave function and Whittaker function at a larger radius. The ratio of C/b is the so called spectroscopic factor. The proton spectroscopic factor of ^7Li was derived to be 0.41 ± 0.05 in our previous work [18]. The nuclear ANC of ^{13}N ground state can then be extracted by normalizing the theoretical differential cross sections to the experimental data via eq. (1).

The angular distribution of the $^{12}C(^7Li, {}^6He)^{13}N$ reaction was calculated with the DWBA code FRESCO [19]. The bound state wave function was obtained by solving the Schrödinger equation using a Woods-Saxon potential with standard geometrical parameters ($r_0 = 1.25$ fm and $a = 0.65$ fm), the potential depth was adjusted to reproduce the observed binding energy of the valence proton. The optical potential parameters for both the entrance and exit channels were extracted by fitting the angular distributions of elastic scattering with the code SFRESCO [19]. The $^7Li + {}^{12}C$ elastic scattering was measured in the present work. Since there is no experimental data for ^6He elastic scattering on ^{13}N, the angular distribution of $^6Li + {}^{13}C$ elastic scattering at $E(^6Li)$ = 28.0 MeV [20] was used to extract the potential parameters of the exit channel. The extracted potentials are listed in Table 1.

Generally, the spectroscopic factor or nuclear ANC is determined by fitting the theoretical calculations to the experimental data at the first peak in the angular distribution for the forward angles [21], since the experimental differential cross sections for the backward angles are very sensitive to the inelastic coupling effects and other high-order ones, which can not be well described theoretically. In the DWBA calculation, the differential cross sections at three forward angles were

Table 1 Optical potential parameters used in the DWBA calculations, where U, W are in MeV, r and a in fm

Channel	U_V	r_R	a_R	W_V	r_I	a_I	r_c
$^7Li + {}^{12}C$	194.55	0.50	0.82	7.66	1.31	0.75	1.30
$^6He + {}^{13}N$	170.50	0.79	0.67	10.70	1.31	0.75	1.30

used to extract the ANC. The normalized angular distribution is also presented in Figure 1. The nuclear ANC and the spectroscopic factor for $^{13}N \rightarrow {}^{12}C + p$ are deduced to be (1.64 ± 0.11) fm$^{-1/2}$ and 0.64 ± 0.09, respectively. The spectroscopic factors extracted by different experiments and the theoretical values are listed in Table 2 [22–38]. The spectroscopic factor obtained in our work agrees with the theoretical ones reported in refs. [22,23] and the experimental results given in refs. [26,28,29,37]. The Nuclear ANC of $^{13}N \rightarrow {}^{12}C + p$ from this work is in good agreement with the value of (1.65 ± 0.20) fm$^{-1/2}$ extracted from the $^{12}C(^{10}B,^{9}Be)^{13}N$ reaction [39].

4 The $^{12}C(p,\gamma)^{13}N$ astrophysical $S(E)$ factors

Following the approach used in our previous work [15], the astrophysical $S(E)$ factors of the $^{12}C(p,\gamma)^{13}N$ reaction were calculated by the R-matrix method. For the radiative capture reaction $B+b \rightarrow A+\gamma$, the cross section to the state of nucleus A with the spin J_f can be written as [14,15]

$$\sigma_{J_f} = \sum_{J_i} \sigma_{J_i J_f}, \tag{2}$$

$$\sigma_{J_i J_f} = \frac{\pi}{k^2} \frac{2J_i + 1}{(2J_b + 1)(2J_B + 1)} \sum_{Il_i} |U_{Il_i J_f J_i}|^2, \tag{3}$$

where J_i denotes the total angular momentum of the colliding nuclei B and b in the initial state, J_b and J_B are the spins of nuclei b and B, and I, k and l_i are their channel spin, wave number and orbital angular momentum in the initial state,

Table 2 The theoretical and experimental proton spectroscopic factors in the ^{13}N ground state

$S_{^{13}N}$	Experiments or theory	Year	Reference
0.61	theory	1967	[22]
0.56	theory	1969	[23]
0.78 – 1.35	$^{12}C(d,n)$	1970	[24]
0.74	$^{12}C(d,n)$	1971	[25]
0.53 ± 0.12	$^{12}C(d,n)$	1972	[26]
0.70 – 1.48	$^{12}C(^{3}He,d)$	1969	[27]
0.56 – 0.78	$^{12}C(^{3}He,d)$	1976	[28]
0.68 ± 0.12	$^{12}C(^{3}He,d)$	1976	[29]
0.81 ± 0.12	$^{12}C(^{3}He,d)$	1979	[30]
0.48 ± 0.12	$^{12}C(^{3}He,d)$	1980	[31]
1.34	$^{12}C(a,t)$	1969	[32]
0.91	$^{12}C(a,t)$	1972	[33]
0.72	$^{12}C(^{7}Li,^{6}He)$	1979	[34]
0.38 ± 0.05	$^{12}C(^{7}Li,^{6}He)$	1986	[35]
0.64 ± 0.09	$^{12}C(^{7}Li,^{6}He)$	2008	present work
0.25, 0.40	$^{12}C(^{10}B,^{9}Be)$	1974	[36]
0.62	$^{12}C(^{14}N,^{13}C)$	1975	[37]
0.29, 0.40	$^{12}C(^{16}O,^{15}N)$	1979	[38]

respectively. $U_{Il_i J_f J_i}$ is the transition amplitude from the initial continuum state (J_i, I, l_i) to the final bound state (J_f, I). In the single-level, single-channel approximation, the resonant amplitude for the capture into the resonance with energy E_{R_n} and spin J_i, and subsequent decay into the bound state with the spin J_f can be expressed as

$$U_{Il_i J_f J_i}^{R} = -ie^{i(\omega_{l_i} - \phi_{l_i})} \frac{[\Gamma_{bIl_i}^{J_i}(E)\Gamma_{\gamma J_f}^{J_i}(E)]^{1/2}}{E - E_{R_n} + i\Gamma_{J_i}/2}. \tag{4}$$

Here it is assumed that the boundary parameter is equal to the shift function at resonance energy, and ϕ_{l_i} is the hard-sphere phase shift in the l_ith partial wave,

$$\phi_{l_i} = \arctan\left[\frac{F_{l_i}(k, r_c)}{G_{l_i}(k, r_c)}\right], \tag{5}$$

where $F_{l_i}^2$ and $G_{l_i}^2$ are the regular and irregular Coulomb functions, and r_c is the channel radius. The Coulomb phase factor ω_{l_i} is given by

$$\omega_{l_i} = \sum_{n=1}^{l_i} \arctan\left(\frac{\eta_i}{n}\right), \tag{6}$$

where η_i is the Sommerfeld parameter. $\Gamma_{bIl_i}^{J_i}(E)$ is the observable partial width of the resonance in the channel $B + b$, $\Gamma_{\gamma J_f}^{J_i}(E)$ is the observable radiative width for the decay of the given resonance into the bound state with the spin J_f, and $\Gamma_{J_i} \approx \sum_{I} \Gamma_{bIl_i}^{J_i}$ is the observable total width of the resonance level. The energy dependence of the partial widths is determined by

$$\Gamma_{bIl_i}^{J_i}(E) = \frac{P_{l_i}(E)}{P_{l_i}(E_{R_n})} \Gamma_{bIl_i}^{J_i}(E_{R_n}) \tag{7}$$

and

$$\Gamma_{\gamma J_f}^{J_i}(E) = \left(\frac{E + \varepsilon_f}{E_{R_n} + \varepsilon_f}\right)^{2L+1} \Gamma_{\gamma J_f}^{J_i}(E_{R_n}), \tag{8}$$

where $\Gamma_{bIl_i}^{J_i}(E_{R_n})$ and $\Gamma_{\gamma J_f}^{J_i}(E_{R_n})$ are the experimental partial and radiative widths, ε_f is the proton binding energy of the bound state in nucleus A, and L is the multipolarity of the gamma transition. The penetrability $P_{l_i}(E)$ is expressed as

$$P_{l_i}(E) = \frac{kr_c}{F_{l_i}^2(k, r_c) + G_{l_i}^2(k, r_c)}. \tag{9}$$

The nonresonant amplitude can be calculated by

$$\begin{aligned} U_{Il_i J_f J_i}^{NR} = &-(2)^{3/2} i^{l_i + L - l_f + 1} e^{i(\omega_{l_i} - \phi_{l_i})} \frac{\mu_{Bb}^{L+1/2}}{\hbar k} \\ &\times \left[\frac{Z_b e}{m_b^L} + (-1)^L \frac{Z_B e}{m_B^L}\right](k_\gamma r_c)^{L+1/2} \\ &\times \sqrt{\frac{(L+1)(2L+1)}{L}} \frac{1}{(2L+1)!!} \\ &\times C_{J_f Il_f} F_{l_i}(k, r_c) G_{l_i}(k, r_c) \\ &\times W_{l_f}(2\kappa r_c) \sqrt{P_{l_i}}(l_i 0 L 0 | l_f 0) \\ &\times U(L l_f J_i I; l_i J_f) J_L'(l_i l_f), \end{aligned} \tag{10}$$

where $k_\gamma = (E + \varepsilon_f)/\hbar c$ is the wave number of the emitted photon. $C_{J_f Il_f}$ denotes the nuclear ANC of $^{13}N \rightarrow {}^{12}C +$

p, and l_f is relative orbital angular momentum of the bound state. $W_l(2\kappa r)$ is the Whittaker hypergeometric function with $\kappa = \sqrt{2\mu_{Bb}\varepsilon_f}$. $(l_i0L0|l_f0)$ and $U(Ll_fJ_iI; l_iJ_f)$ are the Clebsch-Gordan and Racha coefficients, respectively. $J'_L(l_il_f)$ is the integral expression defined as

$$J'_L(l_il_f) = \frac{1}{r_c^{L+1}} \int_{r_c}^{\infty} \mathrm{d}r\, r^L \frac{W_{l_f}(2\kappa r)}{W_{l_f}(2\kappa r_c)}$$
$$\times \left[\frac{F_{l_i}(k,r)}{F_{l_i}(k,r_c)} - \frac{G_{l_i}(k,r)}{G_{l_i}(k,r_c)} \right]. \qquad (11)$$
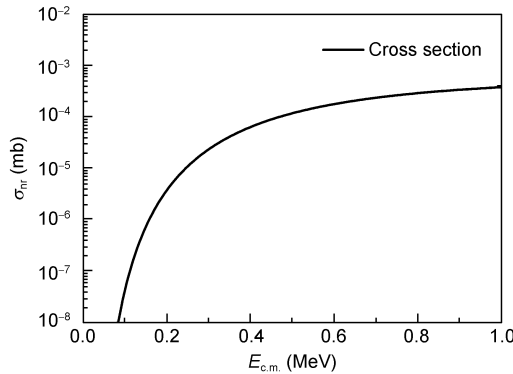
The non-resonant amplitude contains the radial integral ranging only from the channel radius r_c to infinity since the internal contribution is contained within the resonant part. Furthermore, the R-matrix boundary condition at the channel radius r_c implies that the scattering of particles in the initial state is given by the hard sphere phase. Hence, the problems related to the interior contribution and the choice of incident channel optical parameters do not occur. Therefore, the direct capture cross section only depends on the ANC and the channel radius r_c. Using the experimental ANC ((1.64± 0.11) fm$^{-1/2}$) from the present work, the non-resonant ^{12}C$(p,\gamma)^{13}$N cross sections vs. $E_{c.m.}$ were calculated, as shown in Figure 2. In the calculation, r_c was taken to be 5.0 fm following the previous works in refs. [15,40].

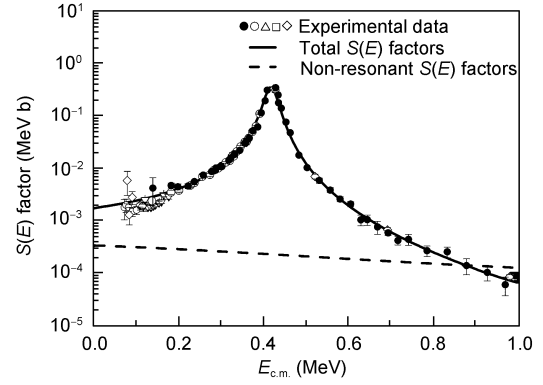The astrophysical $S(E)$ factors are related to the cross sections $\sigma(E)$ by

$$S(E) = E\sigma(E) \exp(E_G/E)^{1/2}, \qquad (12)$$

where the Gamow energy $E_G = 0.978Z_1^2Z_2^2\mu$ MeV, μ is the reduced mass of the system. Using the resonance parameters (E_R=421 keV, $\Gamma_{tot}(E_R) = 36.5$ keV, and $\Gamma_\gamma(E_R) = 0.67$ eV) from ref. [41], the $S(E)$-factors for direct and resonant captures can be then derived.

Since the incoming angular momentum (s-wave) and the multipolarity ($E1$) for the direct and resonant capture γ-radiation are identical, there is an interference between the direct and the two capture processes. Following ref. [9], the total S-factor is calculated by

Figure 3 Astrophysical $S(E)$ factors as a function of $E_{c.m.}$ for the ^{12}C$(p,\gamma)^{13}$N reaction. The dashed line and the solid line are the contributions from the direct proton capture total $S(E)$ factors. The experimental data are taken from refs. [6–9,12]

$$S_{tot}(E) = S_{dc}(E) + S_{res}(E)$$
$$\pm 2[S_{dc}(E)S_{res}(E)]^{1/2}\cos(\delta_r), \qquad (13)$$

where δ_r is the resonance phase shift, given by

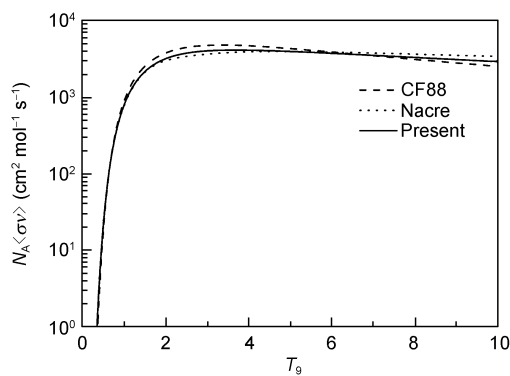$$\delta_r = \arctan\left[\frac{\Gamma_p(E)}{2(E-E_r)}\right]. \qquad (14)$$

The experimental results from the direct measurement of ^{12}C$(p,\gamma)^{13}$N reaction [9] show that the interference between the resonant and direct captures is constructive below the resonance energy, and destructive above it. Based on this interference pattern, we derived the total $S(E)$ factors of the ^{12}C$(p,\gamma)^{13}$N reaction, as shown in Figure 3. One can see that the present S(E) factors are in good agreement with the experimental data from ref. [42] and the references therein. Very recently, Burtebaev et al. [12] measured the cross sections of the ^{12}C$(p,\gamma)^{13}$N reaction at beam energies E_p = 354, 390, 460, 463, 565, 750, and 1061 keV. They obtained ANC(^{13}N) = 1.72 fm$^{-1/2}$, Γ_1^γ = (0.65 ± 0.07) eV and Γ_1^p = (35.0 ± 1.0) keV by fitting their experimental data with R-matrix approach. Their ANC value is also in accord with ours.

5 Astrophysical ^{12}C$(p,\gamma)^{13}$N reaction rates

The astrophysical ^{12}C$(p,\gamma)^{13}$N reaction rate is calculated with

$$N_A\langle\sigma v\rangle = N_A\left(\frac{8}{\pi\mu}\right)^{1/2} \frac{1}{(k_BT)^{3/2}} \int_0^{\infty} S(E)$$
$$\times \exp\left[-\left(\frac{E_G}{E}\right)^{1/2} - \frac{E}{k_BT}\right] \mathrm{d}E, \qquad (15)$$

where $v = \sqrt{2E/\mu}$. N_A and k_B are Avogadro and Boltzmann constants respectively. The updated reaction rates are shown in Figure 4, together with the previous ones from NACRE and CF88 compilations. The present reaction rates are larger than those of NACRE and CF88 by about 20% in the low

Figure 2 The non-resonant cross sections of the ^{12}C$(p,\gamma)^{13}$N reaction computed with the ANC derived from the present experiment.

Figure 4 The $^{12}\text{C}(p,\gamma)^{13}\text{N}$ reaction rates from the present work as well as those from NACRE and CF88 compilations.

temperature range of $T_9 < 0.5$, and very close to their average value in the temperature range of $0.5 \leqslant T_9 \leqslant 10.0$.

The total reaction rates as a function of temperature obtained in our work are parameterized with an expression used in the astrophysical reaction rate library REACLIB [43],

$$
\begin{aligned}
N_A\langle\sigma v\rangle = {} & \exp(a_0 + a_1 T_9^{-1} + a_2 T_9^{-1/3} + a_3 T_9^{1/3} + a_4 T_9 \\
& + a_5 T_9^{5/3} + a_6 \ln T_9) + \exp(b_0 + b_1 T_9^{-1} + b_2 T_9^{-1/3} \\
& + b_3 T_9^{1/3} + b_4 T_9 + b_5 T_9^{5/3} + b_6 \ln T_9).
\end{aligned} \tag{16}
$$

The values of fit parameters a_{0-6} and b_{0-6} are listed in Table 3, and the fitting errors are less than 1% in the temperature range of $0.01 \leqslant T_9 \leqslant 10$.

6 Conclusion and discussion

The $^{12}\text{C}(p,\gamma)^{13}\text{N}$ reaction is of considerably astrophysical interest. The cross sections in the energy range of astrophysical relevance are very small and difficult to be measured directly. In the energy range of $E_{\text{c.m.}} \leqslant 200$ keV, the $^{12}\text{C}(p,\gamma)^{13}\text{N}$ cross sections depend on the tail of the s-wave capture into the broad $1/2^+$ resonance at $E_r = 421$ keV, the direct capture to the ground state and their interference. The determination of the resonant parameters for the $1/2^+$ state and the ANC of ^{13}N ground state is helpful in extrapolating the experimental data at high energies down to the energies of astrophysical interest (around 25 keV).

Table 3 The fitting parameters of the $^{12}\text{C}(p,\gamma)^{13}\text{N}$ reaction rates

Parameters	Value	Parameters	Value
a_0	1.1397×10^1	b_0	4.0200×10^1
a_1	-2.9913×10^{-2}	b_1	2.1886
a_2	-1.1507×10^1	b_2	-1.5188×10^2
a_3	7.6988	b_3	1.1973×10^2
a_4	-3.4841	b_4	-3.7889
a_5	3.8122×10^{-1}	b_5	1.2086×10^{-1}
a_6	4.5641×10^{-2}	b_6	-8.1517×10^1

We measured the angular distribution of the $^{12}\text{C}(^7\text{Li}, ^6\text{He})^{13}\text{N}$ reaction at $E_{^7\text{Li}} = 44.0$ MeV, and deduced the nuclear ANC and spectroscopic factor for the ^{13}N ground state. The astrophysical $S(E)$ factors and reaction rates of the $^{12}\text{C}(p,\gamma)^{13}\text{N}$ reaction are then extracted with the R-matrix approach. The $S(E)$ factor at 25.0 keV is found to be (1.87 ± 0.13) keV b. The result is consistent with that of (1.75 ± 0.22) keV b obtained by Burtebaev et al. [12], and slightly higher than the earlier values of (1.45 ± 0.20) keV b, (1.54 ± 0.08) keV b and (1.33 ± 0.15) keV b reported in refs. [9–11]. The clarification of this deviation requires further studies of the resonant parameters for the $1/2^+$ state is needed.

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