Vol 18 No 4, April 2009
1674-1056/2009/18(04)/1421-07
Chinese Physics B
© 2009 Chin. Phys. Soc.
and IOP Publishing Ltd

# Determination of the stellar reaction rate for $^{12}C(\alpha, \gamma)^{16}O$: using a new expression with the reaction mechanism*

Xu Yi(徐 毅)[a)b)], Xu Wang(徐 望)[a)] Ma Yu-Gang(马余刚)[a)],
Cai Xiang-Zhou(蔡翔舟)[a)], Chen Jin-Gen(陈金根)[a)], Fan Gong-Tao(范功涛)[a)b)],
Fan Guang-Wei(樊广伟)[a)b)], Guo Wei(郭 威)[a)], Luo Wen(罗 文)[a)b)],
Pan Qiang-Yan(潘强岩)[a)], Shen Wen-Qing(沈文庆)[a)], and Yang Li-Feng(杨利峰)[a)b)]

[a)] *Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai* 201800, *China*

[b)] *Graduate School of the Chinese Academy of Sciences, Beijing* 100039, *China*

(Received 1 July 2008; revised manuscript received 18 August 2008)

The astrophysical reaction rate of $^{12}C(\alpha, \gamma)^{16}O$ plays a key role in massive star evolution. However, this reaction rate and its uncertainties have not been well determined yet, especially at $T_9$=0.2. The existing results even disagree with each other to a certain extent. In this paper, the E1, E2 and total (E1+E2) $^{12}C(\alpha, \gamma)^{16}O$ reaction rates are calculated in the temperature range from $T_9$=0.3 to 2 according to all the available cross section data. A new analytic expression of the $^{12}C(\alpha, \gamma)^{16}O$ reaction rate is brought forward based on the reaction mechanism. In this expression, each part embodies the underlying physics of the reaction. Unlike previous works, some physical parameters are chosen from experimental results directly, instead of all the parameters obtained from fitting. These parameters in the new expression, with their $3\sigma$ fit errors, are obtained from fit to our calculated reaction rate from $T_9$=0.3 to 2. Using the fit results, the analytic expression of $^{12}C(\alpha, \gamma)^{16}O$ reaction rate is extrapolated down to $T_9$=0.05 based on the underlying physics. The $^{12}C(\alpha, \gamma)^{16}O$ reaction rate at $T_9$=0.2 is $(8.78 \pm 1.52) \times 10^{15}\,\mathrm{cm^3 s^{-1} mol^{-1}}$. Some comparisons and discussions about our new $^{12}C(\alpha, \gamma)^{16}O$ reaction rate are presented, and the contributions of the reaction rate correspond to the different part of reaction mechanism are given. The agreements of the reaction rate below $T_9$=2 between our results and previous works indicate that our results are reliable, and they could be included in the astrophysical reaction rate network. Furthermore, we believe our method to investigate the $^{12}C(\alpha, \gamma)^{16}O$ reaction rate is reasonable, and this method can also be employed to study the reaction rate of other astrophysical reactions. Finally, a new constraint of the supernovae production factor of some isotopes are illustrated according to our $^{12}C(\alpha, \gamma)^{16}O$ reaction rates.

**Keywords:** nucleosynthesis, thermonuclear reaction rate, stellar evolution, supernovae
**PACC:** 2540L, 9530C, 9760B

## 1. Introduction

In the last five decades, nuclear astrophysics has attracted much interest from scientists keen to explore the elements synthesis in the universe.[1,2] It has been shown that most elements are produced in the stellar burning process. The stellar reaction rate is a key input to the star evolution, and many scholars have contributed studies on it.[3−8] At the end of helium burning in a massive star, the main production is $^{12}C$, but $^{12}C$ can capture $\alpha$ particles through the reaction channel $^{12}C(\alpha, \gamma)^{16}O$ and then form $^{16}O$ and emit photons. The $^{12}C(\alpha, \gamma)^{16}O$ is a principal reaction which completes during helium burning in a massive star to determine the yields of $^{12}C$ and $^{16}O$. The abundance ratio of $^{12}C$ and $^{16}O$ is the beginning condition of the continuing nuclear process, which has considerable influence on the nucleosynthesis and star evolution of massive stars. This abundance ratio of $^{12}C$ and $^{16}O$ is determined by the astrophysical $^{12}C(\alpha, \gamma)^{16}O$ reaction rate, which is an essential input of massive stellar evolution.

The temperature when the reaction $^{12}C(\alpha, \gamma)^{16}O$ occurs in the star is about $0.2\times10^9$ K ($T_9$=0.2), corre-

*Project supported partially by the Innovation Program of Science and Technology of the Chinese Academy of Sciences (Grant Nos KJCX2.SW.N13 and KJCX3.SYW.N2), the National Natural Science Foundation of China (Grant Nos 10775167, 10675156 and 10610285), the Major State Basic Research Development Program (Grant No 2007CB815004), the Hundred Talent Project of the Chinese Academy of Sciences (Grant No 26010701), the Shanghai Development Foundation for Science and Technology (Grant No 06JC14082).

spondingly, the $E_{\rm c.m.}$ of the reaction is about 0.3 MeV according to Gamow theory. The cross section of $^{12}$C($\alpha$, $\gamma$)$^{16}$O is about $10^{-17}$ barn at $E_{\rm c.m.}$=0.3 MeV, so it is too small to be measured. So far, there are more than 30 experiments to study $^{12}$C($\alpha$, $\gamma$)$^{16}$O cross section at the low $E_{\rm c.m.}$, but no experimental data available below $E_{\rm c.m.}$=0.9 MeV around.[9] Recently, we proposed performing the photodisintegration reaction $^{16}$O($\gamma$, $\alpha$)$^{12}$C experiment, which is promising to obtain the cross section at the $E_{\rm c.m.}$=0.8 MeV.[10] Another experiment of $\alpha(^{12}{\rm C},^{16}{\rm O})\gamma$ reaction is in progress, and the cross section at $E_{\rm c.m.}$=0.7 MeV can be measured.[11,12] On the other hand, the theoretical approach has become the unique way to understand the $^{12}$C($\alpha$, $\gamma$)$^{16}$O reaction at lower energies. In general, the cross sections are obtained by R-matrix[13] fitting to experimental data and extrapolating down to lower $E_{\rm c.m.}$, and the astrophysical reaction rate is usually calculated based on the theoretical cross section. So far, there are four reports on the $^{12}$C($\alpha$, $\gamma$)$^{16}$O reaction rate. References [14] and [15] obtained the reaction rate from their own experimental and fitting data, while references [16] and [17] are the compilation of astrophysical reaction rate. Up to now, many experimental and theoretical works have been done to contribute to the $^{12}$C($\alpha$, $\gamma$)$^{16}$O reaction rate, so an updated reaction rate is necessary.

Often an analytic expression with an appropriate parametrization is requested for the stellar evolution models. An analytic expression of the $^{12}$C($\alpha$, $\gamma$)$^{16}$O reaction rate is introduced by Ref.[14] for computational purposes, but the underlying physics of the reaction is not embodied in this expression. However, we believe an analytic expression of the reaction rate with the underlying physics can be extrapolated to the temperature range where the reaction mechanism is physical, and it could be requested for the calculation of the star evolution. Therefore, based on the $^{12}$C($\alpha$, $\gamma$)$^{16}$O reaction mechanism, we attempt to give a new analytic expression of the reaction rate.

This article is organized as follows. In Section 2, we calculate the astrophysical $^{12}$C($\alpha$, $\gamma$)$^{16}$O reaction rate. Then, a new theoretical expression of $^{12}$C($\alpha$, $\gamma$)$^{16}$O reaction rate, based on the reaction mechanism, is presented in Section 3. The fit and extrapolation results of this new $^{12}$C($\alpha$, $\gamma$)$^{16}$O reaction rate expression are obtained in Section 4, which are compared with other works and discussed in Section 5. After a simple astrophysical implication of this new $^{12}$C($\alpha$, $\gamma$)$^{16}$O reaction rate is illustrated in Section 6, and the conclusions are given finally.

## 2. Direct calculation of the $^{12}$C($\alpha$, $\gamma$)$^{16}$O reaction rate

In stellar energies, the reaction rate of two-nuclei reaction in the star at temperature $T$, is[18]

$$N_A\langle\sigma\upsilon\rangle = N_{\rm A}\frac{(8/\pi)^{1/2}}{\mu^{1/2}(k_{\rm B}T)^{3/2}} \times \int \sigma(E)E\exp(-E/k_{\rm B}T){\rm d}E, \quad (1)$$

where we assume that the star can be considered as a perfect gas following the Maxwell–Boltzmann distribution. In Eq.(1), $N_{\rm A}$ is Avogadro's number, $\mu$ is the dimensionless reduced mass, and $k_{\rm B}$ is Boltzmann's constant, $\sigma(E)$ is the cross section related to the reaction energies $E$. For each temperature $T$, the reaction rate can be calculated according to Eq.(1) and the cross section data. In general, the integral range of Eq.(1) is chosen as $[0,\ E_0 + 3\Delta E_0]$. Here

$$E_0 = \left[\pi\frac{e^2}{c\hbar}Z_1Z_2k_{\rm B}T\left(\frac{\mu m_N c^2}{2}\right)^{1/2}\right]^{2/3} \quad (2)$$

and

$$\Delta E_0 = 4(E_0k_{\rm B}T/3)^{1/2} \quad (3)$$

are deduced based on Gamow theory, where $T_9$ is the temperature expressed in $10^9$ K.

A proper set of cross section data is essential for the $^{12}$C($\alpha$, $\gamma$)$^{16}$O reaction rate calculation. Considering the independence of each work contributing to $^{12}$C($\alpha$, $\gamma$)$^{16}$O, we argue that the mean values of all published $^{12}$C($\alpha$, $\gamma$)$^{16}$O cross section can be considered as a reliable data set for reaction rate calculation. Therefore, we evaluate the mean values of E1, E2 and total cross sections of $^{12}$C($\alpha$, $\gamma$)$^{16}$O based on these published literatures.[19−32] The reason why we choose these cross section data for calculation is that these theoretical results are deduced from various experimental data, which are obtained by different experimental approach. To our best knowledge, almost all published $^{12}$C($\alpha$, $\gamma$)$^{16}$O cross section data are all included. The contribution to the reaction rate resulting from cascade cross section of $^{12}$C($\alpha$, $\gamma$)$^{16}$O is negligible in the calculation.

As with the integral range for Eq.(1), the E1, E2 and total (E1+E2) reaction rates of $^{12}$C($\alpha$, $\gamma$)$^{16}$O are calculated according to the mean values of these E1, E2 and total cross sections and these results are shown

in Fig.1. In our calculation, the minimum of temperature range is limited to $T_9 = 0.3$. Because below $E_{c.m.}$=0.4 MeV (corresponding to $T_9 = 0.3$ based on Gamow theory), these cross sections used for reaction rate calculation are very diverse, there would be larger uncertainty of reaction rate if these cross sections are involved in the calculation of reaction rate. A detailed and quantitative study about this chosen temperature range is given by Ref.[33]. Meanwhile, the reaction rate below $T_9 = 0.3$ will be explored by our new approach presented later in this article. On the other hand, the maximum temperature range is limited to $T_9 = 2$ following Ref.[14].

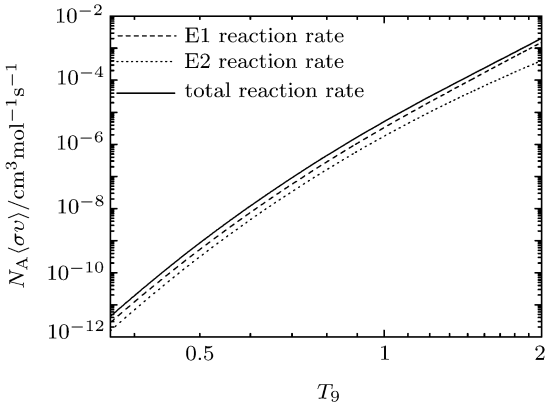



**Fig.1.** The results of E1, E2 and total (E1+E2) reaction rate of $^{12}C(\alpha, \gamma)^{16}O$, which are evaluated according to the mean values of the E1, E2 and total cross section of all available cross section data. See the text for the literature on the cross section data used for calculation.

## 3. A new theoretical expression of the $^{12}C(\alpha, \gamma)^{16}O$ reaction rate

For the low energy astrophysics reaction, there are two types of reaction mechanism, i.e., the direct and resonance capture process. The reaction rate of direct capture process can be parametrized as

$$N_A\langle\sigma v\rangle_{DC} = \frac{p_0}{T_9^{2/3}}\exp\left(-\frac{C}{T_9^{1/3}}\right)\left(\sum_{i=1}^{N} p_i T_9^i + 1\right). \quad (4)$$

Here $p_i$ ($i$=1, 2...) are fitted to the reaction rate calculated and

$$C = 3\left(\frac{\mu\pi^2}{2k_B}\right)^{1/3}\left(\frac{e^2 Z_1 Z_2}{\hbar}\right)^{2/3}. \quad (5)$$

While, the reaction rate of resonance capture process can be deduced by a modified Breit–Wigner approximation and written as

$$N_A\langle\sigma v\rangle_{res} = \frac{p_0}{T_9^{2/3}}\exp\left(-\frac{C}{T_9^{1/3}} - \left(\frac{T_9}{T_f}\right)^2\right) \times \frac{1}{(E_0 - E_r)^2 + \Gamma^2/4}\left(\sum_{i=1}^{N} p_i T_9^i + 1\right). \quad (6)$$

Here, the definitions of $p_i$ ($i$=1, 2...) and $C$ are the same as Eq.(4). $E_r$ and $\Gamma_r$ are the position and reduced width of the resonance state in the reaction centre of mass system, respectively. The definition of $E_0$ is the same as Eq.(2), and $T_f$ is the cut-off temperature, which means that the reaction rate is only contributed below $T_f$.

For $^{12}C(\alpha, \gamma)^{16}O$, the E1 and E2 transition are dominative below $T_9$=2. Thus, the total reaction rate can be written as

$$N_A\langle\sigma v\rangle_{Etotal} = N_A\langle\sigma v\rangle_{E1} + N_A\langle\sigma v\rangle_{E2}. \quad (7)$$

According to Eq.(4), Eq.(6) and the $^{12}C(\alpha, \gamma)^{16}O$ reaction mechanism, the expressions of E1 and E2 reaction rates are given respectively as

$$N_A\langle\sigma v\rangle_{E1} = \frac{p_0}{T_9^{2/3}((E_0 - E_{11})^2 + \Gamma_{11}^2/4)} \times \exp\left(-\frac{C}{T_9^{1/3}} - \left(\frac{T_9}{T_{f1}}\right)^2\right) \times (1 + p_1 T_9 + p_2 T_9^2) + \frac{p_3}{T_9^{2/3}((E_0 - E_{12})^2 + \Gamma_{12}^2/4)} \times \exp\left(-\frac{C}{T_9^{1/3}}\right) \times (1 + p_4 T_9 + p_5 T_9^2) \quad (8)$$

and

$$N_A\langle\sigma v\rangle_{E2} = \frac{p_6}{T_9^{2/3}((E_0 - E_{21})^2 + \Gamma_{21}^2/4)} \times \exp\left(-\frac{C}{T_9^{1/3}} - \left(\frac{T_9}{T_{f2}}\right)^2\right) \times (1 + p_7 T_9 + p_8 T_9^2) + \frac{p_9}{T_9^{2/3}}\exp\left(-\frac{C}{T_9^{1/3}}\right) \times (1 + p_{10} T_9 + p_{11} T_9^2). \quad (9)$$

The first part of the right-hand side of Eq.(8) presents the contribution of E1 subthreshold resonance reaction rate ($^{16}$O:1$^-$(7.117 MeV)$\rightarrow$ 0$^+$(g.s.)) to the total $^{12}C(\alpha, \gamma)^{16}O$ reaction rate. The second part of the right-hand side of Eq.(8) presents contribution of E1 broad resonance reaction rate ($^{16}$O:1$^-$(9.582 MeV)$\rightarrow$ 0$^+$(g.s.)) to the total reaction

rate. $E_{11}$ and $\Gamma_{11}$ are the position energy and the reduced width of the subthreshold resonance state, and $E_{12}$ and $\Gamma_{12}$ are the position energy and the reduced width of the broad resonance state, respectively. The first part of the right-hand side of Eq.(9) presents the contribution of E2 subthreshold resonance reaction rate ($^{16}$O:$2^+$(6.917 MeV)$\rightarrow 0^+$(g.s.)) to the total reaction rate. The second part of the right-hand side of Eq.(9) presents the contribution of E2 direct capture reaction rate to the total reaction rate. $E_{21}$ and $\Gamma_{21}$ are the position energy and the reduced width of the subthreshold resonance state respectively. In Eqs.(8) and (9), $T_{\rm f1}$ and $T_{\rm f2}$ are the temperature limits, and $p_0 - p_{11}$ are the parameters which need to be fitted. The improvements of this analytic expression are that each part of Eqs.(8) and (9) embodied the underlying physics and some parameters are physically determinant. Furthermore, these physical parameters could be adjusted if more accurate $^{12}$C($\alpha$, $\gamma$)$^{16}$O resonant properties (position energy and reduced width) are determined from experiments.

## 4. The fit and extrapolation of the $^{12}$C($\alpha$, $\gamma$)$^{16}$O reaction rate

In Eqs.(8) and (9), the parameters $p_0 - p_{11}$, as well as the $3\sigma$ fitting errors of these parameters, are obtained from fitting to the calculated reaction rate shown in Fig.1. In the fitting procedure, $T_{\rm f1}$=$T_{\rm f2}$=2 are chosen. For the coincidence between the calculation and the fit of reaction rate, the mean values of the resonance position energy and width of $^{12}$C($\alpha$, $\gamma$)$^{16}$O are evaluated based on the same published literatures which are used for the reaction rate calculation in Section 2. All parameter results are listed in Table 1. In Fig.2, the relative deviation of the $^{12}$C($\alpha$, $\gamma$)$^{16}$O reaction rate between the calculated result according to numerical integration shown in Fig.1 and the calculated result from the new analytic expression of Eqs.(8) and (9) is shown. One can find the maximum deviation of them is less than 1% in the temperature range of $T_9$ = 0.3 to 2. Therefore, this new analytic expression reproduced the $^{12}$C($\alpha$, $\gamma$)$^{16}$O reaction rate precisely.

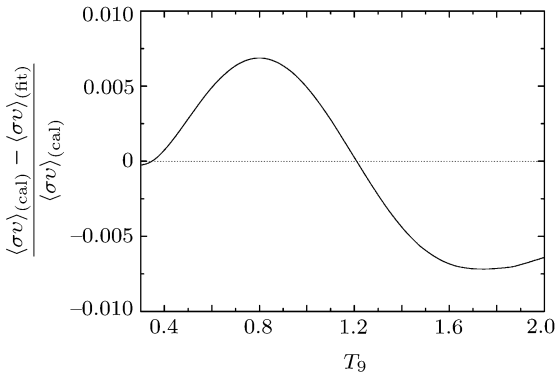



**Fig.2.** The relative deviation of the $^{12}$C($\alpha$, $\gamma$)$^{16}$O reaction rate between the calculated result according to numerical integration shown in Fig.1 and calculated result from the new analytic expression of Eqs.(8) and (9). The label of (fit) means the total $^{12}$C($\alpha$, $\gamma$)$^{16}$O reaction rate calculated from the analytical expression of Eqs.(8) and (9), and the label of (cal) means the total $^{12}$C($\alpha$, $\gamma$)$^{16}$O reaction rate calculated according to numerical integration shown in Fig.1.

**Table 1.** All parameter results of the analytic expression (equation (8) and equation (9)) of $^{12}$C($\alpha$, $\gamma$)$^{16}$O reaction rate. The $3\sigma$ fit errors of $p_0 - p_{11}$ are also given.

| E1 part | | E2 part | |
|---|---|---|---|
| parameter | value | parameter | value |
| $T_{\rm f1}$ | 2 | $T_{\rm f2}$ | 2 |
| C | 32.1 | C | 32.1 |
| $E_{11}$ | –0.045 | $E_{21}$ | –0.245 |
| $\Gamma_{11}$ | 0.292 | $\Gamma_{21}$ | 0.265 |
| $E_{12}$ | 2.42 | | |
| $\Gamma_{12}$ | 0.551 | | |
| $p_0$ | $(2.25 \pm 0.348) \times 10^8$ | $p_6$ | $(2.13 \pm 0.312) \times 10^8$ |
| $p_1$ | $-0.126 \pm 0.0429$ | $p_7$ | $-0.556 \pm 0.114$ |
| $p_2$ | $0.0457 \pm 0.0153$ | $p_8$ | $0.598 \pm 0.0504$ |
| $p_3$ | $(1.60 \pm 0.0675) \times 10^8$ | $p_9$ | $(1.08 \pm 0.0423) \times 10^8$ |
| $p_4$ | $0.932 \pm 0.0145$ | $p_{10}$ | $-0.710 \pm 0.00936$ |
| $p_5$ | $-0.371 \pm 0.00543$ | $p_{11}$ | $0.219 \pm 0.00564$ |

This new analytic expression of $^{12}C(\alpha, \gamma)^{16}O$ reaction rate, Eqs.(8) and (9), can be extrapolated below $T_9$=0.3 because of the underlying physics. Below $T_9$=2, the $^{12}C(\alpha, \gamma)^{16}O$ reaction rate calculated based on this new expression and the parameter results in Table 1 could be included in the astrophysical reaction rate networks and used for the study of stellar evolution.

Under astrophysical environment, the $^{12}C(\alpha, \gamma)^{16}O$ occurs at the end of helium burning, when the temperature is $T_9$=0.2. So the reaction rate under this temperature is crucial. Extrapolating Eqs.(8) and (9), we can evaluate the recommended value, as well as the up and low limits of the $^{12}C(\alpha, \gamma)^{16}O$ astrophysical reaction rate at $T_9$=0.2 according to the parameters listed in Table 1. Notice that the up and low limits of the reaction rate are calculated according to the $3\sigma$ fitting errors of the parameters $p_0 - p_{11}$. These values are compared with the results of Refs.[14–17] and listed in Table 2. One can find that our constraint of the reaction rate at $T_9$=0.2, are covered by the results suggested by previous works.[14,15,17] Thus, we believe that our extrapolated results are reliable. Meanwhile, we give a relative smaller uncertainty of $^{12}C(\alpha, \gamma)^{16}O$ reaction rate at $T_9$=0.2.

**Table 2.** Comparison of the astrophysical $^{12}C(\alpha, \gamma)^{16}O$ reaction rate at $T_9$=0.2. The unit for the reaction rate is $cm^3mol^{-1}s^{-1}$.

| works | recommended | low limit | up limit |
|---|---|---|---|
| Ref.[14] | $7.04 \times 10^{15}$ | $3.04 \times 10^{15}$ | $13.4 \times 10^{15}$ |
| Ref.[15] | $7.58 \times 10^{15}$ | $5.25 \times 10^{15}$ | $10.2 \times 10^{15}$ |
| Ref.[16] | $4.73 \times 10^{15}$ | | |
| Ref.[17] | $9.11 \times 10^{15}$ | $5.44 \times 10^{15}$ | $12.8 \times 10^{15}$ |
| present | $8.78 \times 10^{15}$ | $7.27 \times 10^{15}$ | $10.3 \times 10^{15}$ |

## 5. Comparison and discussion

In the temperature range of $T_9$=0.05 to 2, the $^{12}C(\alpha, \gamma)^{16}O$ reaction rates, i.e., the recommended value and the constraint (the up and low limits), are calculated based on Eqs.(8) and (9) and the parameters in Table 1. Notice that the constraint is evaluated according to the $3\sigma$ fitting errors of the parameters $p_0 - p_{11}$ (see Table 1). These results are compared with previous works and shown in Fig.3, where the ratios of the $^{12}C(\alpha, \gamma)^{16}O$ reaction rate given by Refs.[14–17] to our recommend reaction rate are illustrated. The grey band shows the uncertainty of our recommend reaction rate, i.e., the edges of the grey band are the reaction rate ratios of our up and low limits to our recommended result. We can see that in the whole temperature region displayed, our results present an average trend of three recent works.[14,15,17] Especially, the latest reaction rate result determined from the experiment described in Ref.[15] is well covered by our reaction rate constraint. The agreement proves that the $^{12}C(\alpha, \gamma)^{16}O$ reaction rate is well described by our new expression with its underlying physics. So we believe that the reaction rate results are reliable below $T_9$=2, and this fitting and extrapolation method is reasonable. Notice that the reaction rate compiled by Ref.[16] is lower than the rest results by a factor of 2 approximately, possibly the reason is that there are no adequate experimental and theoretical $^{12}C(\alpha, \gamma)^{16}O$ cross sections can be employed for reaction rate calculation at that time.

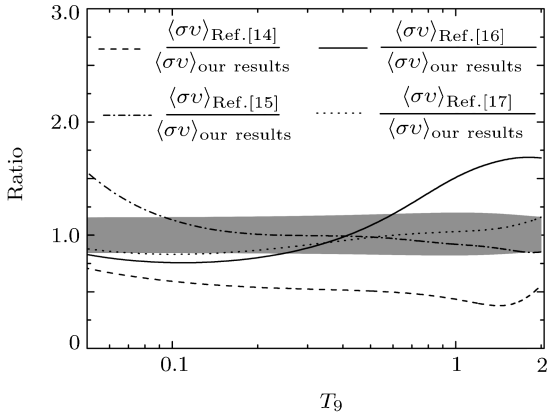



**Fig.3.** The ratios of the $^{12}C(\alpha, \gamma)^{16}O$ reaction rate given by Refs.[14–17] to our recommend reaction rate. The grey band shows the uncertainty of our recommend reaction rate. See the text for more details.

The contributions of the $^{12}C(\alpha, \gamma)^{16}O$ reaction rate correspond to different part of reaction mechanism are also calculated based on our theoretical expression, and the results are illustrated in Fig.4. The figure shows that the contributions of the E1 and E2 subthreshold resonance reaction rate are dominative below $T_9 = 1$, while the contribution of the reaction rate corresponding to the E1 broad resonance at 9 MeV of $^{16}O$ is dominative above $T_9 = 1.5$. The proportion of the reaction rate corresponding to the direct capture of E2 transition is small and almost a constant. These trends are accordant to the results of Ref.[15], which are directly obtained from the cross section fitted to experimental data. Consequently, the underlying physics in our theoretical expression is embodied and it is effective below $T_9 = 2$.

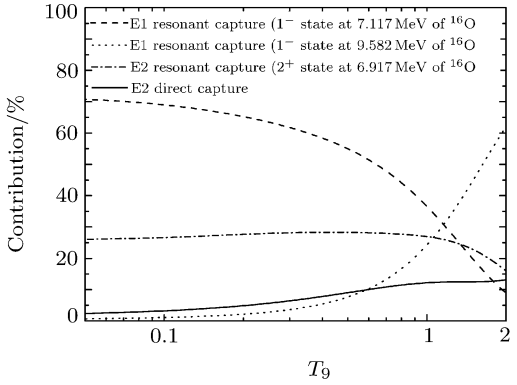



**Fig.4.** The contributions of reaction rate with different part of reaction mechanism to the total reaction rate of $^{12}$C($\alpha$, $\gamma$)$^{16}$O.

## 6. An astrophysical implication

So far, many works devote to study the nucleosynthesis and evolution of massive star after helium burning, which can help us to understand the explosion of type-II supernovae and the production mechanism of neutron star and black hole.[34] As well known, the $^{12}$C($\alpha$, $\gamma$)$^{16}$O reaction rate plays a key role on nucleosynthesis in massive star evolution. The relationships between the astrophysical $^{12}$C($\alpha$, $\gamma$)$^{16}$O reaction rate and the properties of massive star evolution have been studied by Refs.[35, 36] and so on. However, reference [36] points out that a more precise $^{12}$C($\alpha$, $\gamma$)$^{16}$O reaction rate, with the smaller uncertainty, is needed to match the reaction rate deduced from astronomical observation. The similar conclusion is also given by Ref.[37].

Our $^{12}$C($\alpha$, $\gamma$)$^{16}$O reaction rate results can be employed for the study of massive star evolution, which could improve on this situation. Here, we attempt to re-investigate the results of massive star evolution obtained by Ref.[36] and give a simple astrophysical implication of our new reaction rate. The supernovae production factors of selected isotopes, calculated by Ref.[36], are plotted against to various $^{12}$C($\alpha$, $\gamma$)$^{16}$O reaction rates in Fig.5. The supernovae production factor is defined as the ratio of the abundance of isotopes produced in supernovae to their solar abundance. In Fig.5, one can find that the supernovae production factors of these isotopes are indeed sensitive to the $^{12}$C($\alpha$, $\gamma$)$^{16}$O reaction rate. The supernovae production factor determined by our recommended value and constraint of the $^{12}$C($\alpha$, $\gamma$)$^{16}$O reaction rate are illustrated with solid line and grey band in Fig.5, where the results given by Ref.[38] are also shown. We can see that the constraint of the supernovae production factors of these isotopes determined by our reaction rate results is included in the constraint of Ref.[38], and the recommended results of both works agree well with each other.

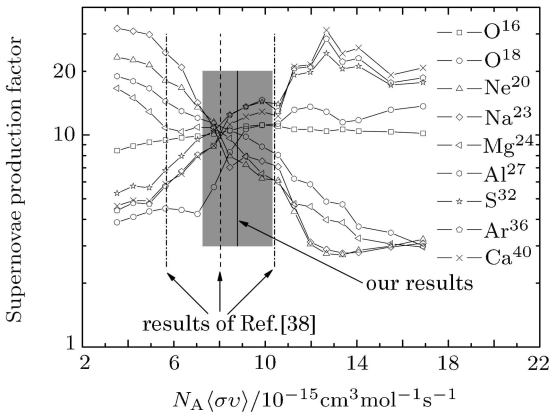



**Fig.5.** The supernovae production factors for selected isotopes calculated by Ref.[36] as a function of the various $^{12}$C($\alpha$, $\gamma$)$^{16}$O reaction rate. The grey band and the solid line illustrate the supernovae production factor results determined by our constraint and recommended value of the $^{12}$C($\alpha$, $\gamma$)$^{16}$O reaction rate, respectively. The dash line and the dash-dot lines illustrate the recommended and limits results determined by Ref.[38].

## 7. Conclusions

The $^{12}$C($\alpha$, $\gamma$)$^{16}$O reaction rates are studied in this paper. We calculate the E1, E2 and total $^{12}$C($\alpha$, $\gamma$)$^{16}$O reaction rates in the temperature range from $T_9$=0.3 to 2 according to all the available cross section data up to now. Then the $^{12}$C($\alpha$, $\gamma$)$^{16}$O reaction rates with their uncertainties are explored in the temperature range of $T_9$=0.05 to 2 by using an analytic expression with the underlying physics. The procedure is presented as follows. Firstly, we give the analytic expression of the reaction rate based on the reaction mechanism. Secondly, in the expression, some parameters are physical and chosen from experimental results; the rest parameters, with the fitting errors, are obtained by fitting to the calculated reaction rate. Then, the reaction rate, with its uncertainty, is evaluated based on the parameters and its fitting errors in the expression. Finally, the analytic expression is extrapolated to the even lower temperature range where the reaction mechanism is reasonable.

At the temperature of helium burning in star, i.e. $T_9$=0.2, the reaction rate with its uncertainties is $(8.78 \pm 1.52) \times 10^{15}\,\mathrm{cm^3 s^{-1} mol^{-1}}$, which is close to recent experimental and theoretical determination.[14,15,17] This agreement confirms that the extrapolated $^{12}$C($\alpha$, $\gamma$)$^{16}$O reaction rate and its

uncertainty are reliable at $T_9$=0.2. After comparing with previous works of $^{12}C(\alpha, \gamma)^{16}O$ reaction rate at $T_9$=0.05 to 2, we find the agreement between our result and the result of Refs.[14, 15, 17] is good. However, the reaction rate of Ref.[16] is lower than our result by a factor of 2 approximately, which could be revised by using the updated cross sections. Finally, we give an astrophysical implication, namely the new constraint of the supernovae production factors of some isotopes, based on our $^{12}C(\alpha, \gamma)^{16}O$ reaction rate. It is shown that this new reaction rate results could remedy the massive star evolution possibly.

Through the calculations and discussions, we conclude that our new results of the $^{12}C(\alpha, \gamma)^{16}O$ reaction rate are reliable below $T_9$=2, and we hope that our results can be included in the astrophysical reaction rate networks. Moreover, the method presented to investigate the $^{12}C(\alpha, \gamma)^{16}O$ reaction rate could also be employed to study other astrophysical reaction rate, which might be useful for the study of star evolution.

## References


[1] Burbidge E M, Burbidge G R, Fowler W A and Hoyle F 1957 *Rev. Mod. Phys.* **29** 547

[2] Wallerstein G, Iben I Jr, Parker P, Boesgaard A M, Hale G M, Champagne A E, Barnes C A, Kappeler F, Smith V V, Hoffman R D, Timmes F X, Sneden C, Boyd R N, Meyer B S and Lambert D L 1997 *Rev. Mod. Phys.* **69** 995

[3] Shu N C, Bardayan D W, Blackmon J C, Chen Y S, Kuzob R L, Parker P D and Simth M S 2003 *Chin. Phys. Lett.* **20** 1470

[4] Liu Z H and Zhou H Y 2005 *Chin. Phys* **14** 1544

[5] Su J, Li Z H, Guo B, Liu W P, Bai X X, Zeng S, Lian G, Yan S Q, Wang B X and Wang Y B 2006 *Chin. Phys. Lett.* **23** 55

[6] Liu H L, Liu M Q, Lai X J and Luo Z Q 2007 *Chin. Phys.* **16** 1637

[7] Liu H L, Liu M Q, Liu J J and Luo Z Q 2007 *Chin. Phys.* **16** 3300

[8] Liu H L, Luo Z Q, Lai X J and Liu J J 2008 *Chin. Phys.* B **17** 2317

[9] Buchmann L R and Barnes C A 2006 *Nucl. Phys.* A **777** 254

[10] Xu Y, Xu W, Ma Y G, Guo W, Chen J G, Cai X Z, Wang H W, Wang C B, Lu G C and Shen W Q 2007 *Nucl. Instr. Meth.* A **581** 866

[11] Sagara K, Nakashima T, Nakamura M, Okuda H, Yagita T, Tsuruta K, Ikeda N and Morinobu S 2002 *Nucl. Instr. Meth.* A **484** 88

[12] Sagara K, Nakashima T, Nakamura M, Okuda H, Yagita T, Tsuruta K and Ikeda N 2006 in *Nuclear Physics Trends: 6th China–Japan Joint Nuclear Physics Symposium* (AIP Conference Proceeding CP865) edited by Ma Y G and Ozawa A **225**

[13] Lane A M and Thomas R G 1958 *Rev. Mod. Phys.* **30** 257

[14] Buchmann L R 1996 *Astrophys. J.* **468** L127

[15] Kunz R, Fey M, Jaeger M, Mayer A, Hammer J W, Staudt G, Harissopulos S and Paradellis T 2002 *Astrophys. J.* **567** 643

[16] Caughlan G R and Fowler W A 1988 *At. Data Nucl. Data Tables* **40** 283

[17] Angulo C, Arnould M, Rayet M, Descouvemont P, Baye D, Willain C L, Coc A, Barhoumi S, Aguer P, Rolfs C, Kunz R, Hammer J W, Mayer A, Paradellis T, Kossionides S, Chronidou C, Spyrou K, Innocenti S D, Fiorentini G, Ricci B, Zavatarelli S, Providencia C, Wolters H, Soares J, Grama C, Tahighi J, Shotter A and Rachti M L 1999 *Nucl. Phys.* A **656** 3

[18] Fowler W A, Caughlan G R and Zimmerman B A 1967 *Ann. Rev. Astron. Astrophys.* **5** 525

[19] Dyer P and Barnes C A 1974 *Nucl. Phys.* A **233** 495

[20] Kettner K U, Becker H W, Buchmann L, Gorres J, Krawinkel H, Rolfs C, Schmalbrock P, Trautvetter H P and Vlieks A 1982 *Z. Phys.* A **308** 73

[21] Redder A, Becker H W, Rolfs C, Trautvetter H P, Donoghue T R, Rinckel T C, Hammer J W and Langanke K 1987 *Nucl. Phys.* A **462** 385

[22] Kremer R M, Barnes C A, Chang K H, Evans H C, Filippone B W, Hahn K H and Mitchell L W 1988 *Phys. Rev. Lett.* **60** 1475

[23] Filippone B W, Humblet J and Langanke K 1989 *Phys. Rev.* C **40** 515

[24] Barker F C and Kajino T 1991 *Aust. J. Phys* **44** 369

[25] Buchmann L, Azuma R E, Barnes C A, D'Auria J M, Dombsky M, Giesen U, Jackson K P, King J D, Korteling R G, McNeely P, Powell J, Goy G, Vincent J, Wang T R, Wong S M and Wrean P R 1993 *Phys. Rev. Lett.* **70** 726

[26] Azuma R E, Buchmann L, Backer F C, Barnes C A, D'Auria J M, Dombsky M, Giesen U, Jackson K P, King J D, Korteling R G, McNeely P, Powell J, Goy G, Vincent J, Wang T R, Wong S M and Wrean P R 1994 *Phys. Rev.* C **50** 1194

[27] Ouellet J M L, Butler M N, Evans H C, Lee H W, Leslie J R, MacArthur J D, McLatchie W, Mak H B, Skensved P, Whitton J L and Zhao X 1996 *Phys. Rev.* C **54** 1982

[28] Trautvetter H P, Roters G, Rolfs C, Schmidt S and Descouvemont P 1997 *Nucl. Phys.* A **621** 161c

[29] Brune C R, Geist W H, Kavanagh R W and Veal K D 1999 *Phys. Rev. Lett.* **83** 4025

[30] Angulo C and Descouvemont P 2000 *Phys. Rev.* C **61** 064611

[31] Kunz R, Jaeger M, Mayer A, Hammer J W, Staudt G, Harissopulos S and Paradellis T 2001 *Phys. Rev. Lett.* **86** 3244

[32] Braizinha B, Eiró A M and Santos F D 2001 *Nucl. Phys.* A **689** 369c

[33] Xu Y, Xu W, Ma Y G, Guo W, Chen J G, Cai X Z, Wang H W, Wang C B, Lu G C and Shen W Q 2006 *High Energy Phys. Nucl. Phys.* **30** 252

[34] Woosley S E and Heger A 2002 *Rev. Mod. Phys.* **74** 1015

[35] Imbriani G, Limongi M, Gialanella L, Terrasi F, Straniero O and Chieffi A 2001 *Astrophys. J.* **558** 903

[36] Tur C, Heger A and Austin S M 2007 arXiv: astro-ph/0705.4404v5, *Astrophys. J.* in press

[37] Metcalfe T S, Salaris M and Winget D E 2002 *Astrophys. J.* **573** 803

[38] Weaver T A and Woosley S E 1993 *Phys. Rep.* **227** 65