PROCEEDINGS OF SCIENCE

Effects of triple-alpha reaction rates on the nucleosynthesis in massive stars

Yukihiro Kikuchi*, **Masa-aki Hashimoto, Masaomi Ono**
Department of Physics, Kyushu University, Fukuoka 812-8581, Japan
E-mail: kikuchi@phys.kyushu-u.ac.jp

Shin-ichiro Fujimoto
Kumamoto National College of Technology, Kumamoto 861-1102, Japan

Ogata, Kan, and Kamimura (2009) evaluated directly nonresonant triple-alpha reaction rate by solving the Schrödinger equation of the three-body system. The scattering wave function is obtained by the continuum-discretized coupled-channels method (CDCC). The CDCC results drastically differ from previous rates at low temperature. We investigated the effect of this triple-alpha reaction rate (OKK rate) on the *s*-process in a massive star during the helium and carbon burnings in Kikuchi et al. (2012). In the present paper, we investigate the effects of triple-alpha and ^{12}C(α,γ)^{16}O reaction rates on the massive star evolution and the nucleosynthesis. We calculate the massive star evolution of a 25 $M_\odot$ star from helium core burning phase to the phase just before the core-collapse. We also perform a spherically symmetric hydrodynamic simulation of the supernova explosion and the nucleosynthesis to estimate the ejected elements. Though the production of *s*-elements depends on the combinations of the reaction rates, we roughly confirm the weak *s*-process that is the production of *s*-elements up to $A = 90$. We find that most *s*-elements produced during the stellar evolution survived even after the supernova explosion. We show that the production of *p*-elements depends on peak temperatures during the supernova shock propagation and *p*-process layers, which is affected eventually by the stellar evolution path, triple-α and ^{12}C(α,γ)^{16}O reaction rates.

XIII Nuclei in the Cosmos,
7-11 July, 2014
Debrecen, Hungary

*Speaker.

1. Introduction

Triple-α reaction is an important nuclear reaction during helium burning in stellar evolution. Nomoto (1982a) [1] (and also [2]) described the rate including the nonresonant process approximately. However, the nonresonant contribution was included applying resonant formulae. After the study by Nomoto's method, Fynbo et al. (2005) [3] improved the rate with recent experimental data. The authors treated the nonresonant process using the same method of Nomoto, and therefore they obtained similar rates. On the other hand, Ogata et al. (2009) [4] calculated the rate of the triple-α reaction (hereafter OKK) evaluating the nonresonant triple-α process by directly solving the Schödinger equation of the triple-α system. The triple-α scattering wave function was obtained by using the continuum-discretized coupled-channels (CDCC) method. In the left panel of Fig. 1, the reaction rates mentioned above are plotted. At low temperature ($T = 10^8$ K), the OKK rate is more than 6 orders of magnitude larger than the Nomoto's rate. To investigate the impact and the validity of the OKK rate, several applications to astrophysical phenomena have been reported [5, 6, 7, 8, 9, 10, 11].

The $^{12}C(\alpha,\gamma)^{16}O$ reaction is an important helium burning reaction as well as the triple-α reaction. Caughlan, Fowler, Harris, and Zimmermann (1985) (hereafter CF85) [12] reported a reaction

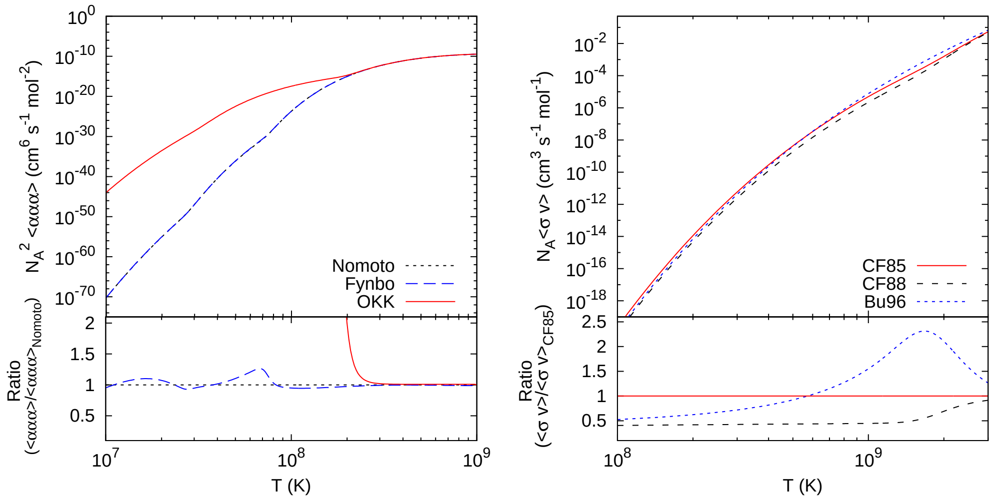

Figure 1: The main reaction rates during the helium burning. The left panel shows triple-α reaction rates as a function of the temperature. 'Nomoto', 'Fynbo', and 'OKK' are taken from Nomoto et al. (1982a) [1], Fynbo et al. (2005) [3], and Ogata et al. (2009) [4], respectively. The upper panel shows thermonuclear reaction rates and the lower panel shows the ratios of the reaction rates relative to that of 'Nomoto'. $\langle\alpha\alpha\alpha\rangle$ means the reaction rate per three α particles. The right panel shows $^{12}C(\alpha,\gamma)^{16}O$ reaction rates as a function of the temperature. 'CF85', 'CF88', and 'Bu96' are taken from Caughlan et al. (1985) [12], Caughlan and Fowler (1988) [13], and Buchmann et al. (1996a) [14], respectively. Upper panel shows thermonuclear reaction rates per particle and lower panel shows the ratio of the rates relative to that of 'CF85'.

rate compilation for astrophysics which includes a ^{12}C$(\alpha,\gamma)^{16}$O reaction rate. This reaction rate is based on experimental data at a higher energy and extrapolated to a lower energy. However, Caughlan and Fowler (1988) [13] updated the rate (hereafter CF88). The reaction rate was derived based on the experimental data by Plaga et al. (1987) [15] and Redder et al. (1987) [16]. On the other hand, a reaction rate was reported by Buchmann et al. (1996) [14, 17] (hereafter Bu96). This rate is enhanced around 10^9 K compared with CF85 and CF88 rates and two times smaller than that of CF85 at 300 keV. In this reaction rate, E_1 radiation capture rate was estimated by the β-delayed α-decay of ^{16}N and elastic scattering.

To check the validity of the OKK rate, we investigate the effects of uncertainties of the triple-α and ^{12}C$(\alpha,\gamma)^{16}$O reaction rates on the evolution of massive stars. They could affect the production of nuclei including the *s*- and *p*-process elements.

2. Method

To investigate the uncertainties of triple-α and ^{12}C$(\alpha,\gamma)^{16}$O reaction rates, we selected combinations from available nuclear data for the two reactions, that is, Fynbo-CF85, Fynbo-Bu96, OKK-CF85, and OKK-Bu96, which expected to cover the possible uncertainties inherent to the experiments and/or theories. The stellar evolutionary code was almost the same as Refs. [18, 19] but for the revised reaction rates. We performed stellar evolution calculation of 8 $M_\odot$ helium core, which corresponds to a 25 $M_\odot$ star at the zero age main sequence. To estimate the amount of the ejecta from the supernova explosion into the interstellar medium, we performed an one-dimensional hydrodynamic simulation using the hydrodynamic code described in preceding studies [20]. The equations of the hydrodynamics were the same as in Ref. [21]. The explosion was initiated by a thermal bomb: We injected a thermal energy around the silicon and iron interface to obtain the explosion energy of 1.0×10^{51} erg [22].

Our nuclear reaction network includes the nuclei from neutron and proton to ^{241}U linked by particle reactions and weak interactions. The numbers of the nuclei were 1714 and 1852 for the stellar evolution and the supernova explosion, respectively. The reaction rates were taken from JINA REACLIB compilation ver. 1.0 [23], which includes charged particle reactions and (n,γ) reactions updated from those in Bao et al. [24]. The β-decay and electron capture rates at finite temperature and density are taken from Takahashi and Yokoi for nuclei above ^{59}Fe [25]. The initial compositions except CNO elements are set to be the solar system abundances [26]; we assumed that CNO elements were converted to ^{14}N and the mass fraction X(^{14}N) was set to be 0.0137. Other elements heavier than oxygen were distributed in proportion to the solar values.

3. Results

First, we show the results of normalized overproduction factors of elements lighter than $A=33$ in Fig. 2. The two horizontal dotted lines indicate the values of the overproduction of ^{16}O (dashed line) multiplied or divided by a factor of 2, respectively. If a value is within the dotted lines, it is consistent with the solar abundances. Fynbo-CF85 model reproduces the overproduction factors of $20\leq A\leq 32$ nuclei except for ^{21}Ne. In OKK-CF85 model, ^{20}Ne and ^{23}Na are enhanced by a factor of two compared to that of ^{16}O (these nuclei are synthesized from ^{12}C+^{12}C reactions). ^{22}Ne which is produced from ^{14}N, and nuclei in the range of $28 \leq A \leq 31$ are well reproduced. In Fynbo-Bu96 model, isotopes of $20 \leq A \leq 28$ are well reproduced except for ^{23}Na. In OKK-Bu96 model, those of $20 \leq A \leq 27$ are over produced.

Second, in Fig. 3, we show the overproduction factors of weak *s*-elements up to $A = 90$. Although there are some differences among the models, we roughly confirm the occurrence of the weak *s*-process, i.e., the production of *s*-elements up to $A = 90$. Some *s*-elements are destroyed by photodisintegrations during the supernova explosion but most other *s*-elements survived. Therefore, the results are nearly the same as those in the presupernova stage. The overproduction factors for OKK-CF85 model are the least enhanced among the four models, and those of OKK-Bu96 model are the most enhanced in particular around $A = 90$. These differences are related to the helium and carbon burnings, which are important for the weak *s*-process.

Finally, the overproduction factors of *p*-elements are shown in Fig. 4. The overall overproduction levels of *p*-elements are in the order of Fynbo-CF85 model, OKK-Bu96 model, OKK-CF85 model, and Fynbo-Bu96 model. The layers where the *p*-elements can be produced are called *p*-process layers (hereafter PPLs), which are related to the peak temperatures [27]. The PPLs for the Fynbo-CF85 model exist in regions with the peak temperatures of $\sim 2 - 3.5 \times 10^9$ K and the corresponding mass of the PPLs is equal to 0.65 $M_\odot$, which is the largest among the four models. Before the core-collapse, Fynbo-CF85 model forms high temperature and density regions due to continuous gravitational contraction. The sizes of PPLs in other models are 0.27 $M_\odot$ (OKK-Bu96 model), 0.24 $M_\odot$ (OKK-CF85 model), and 0.19 $M_\odot$ (Fynbo-Bu96 model), respectively. We can recognize that the overproduction levels reflect the sizes of PPLs, i.e., the larger the size of PPLs

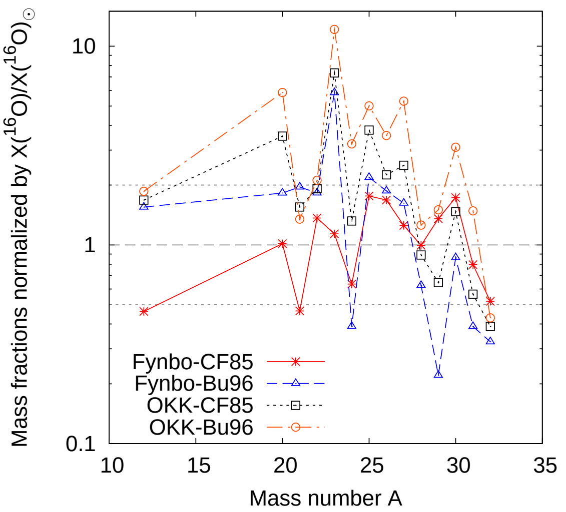

Figure 2: The overproduction factors of the nuclei lighter than $A = 33$, which are normalized by that of ^{16}O. The asterisks, triangles, squares, and circles are the results from the models of Fynbo-CF85, Fynbo-Bu96, OKK-CF85, and OKK-Bu96, respectively.

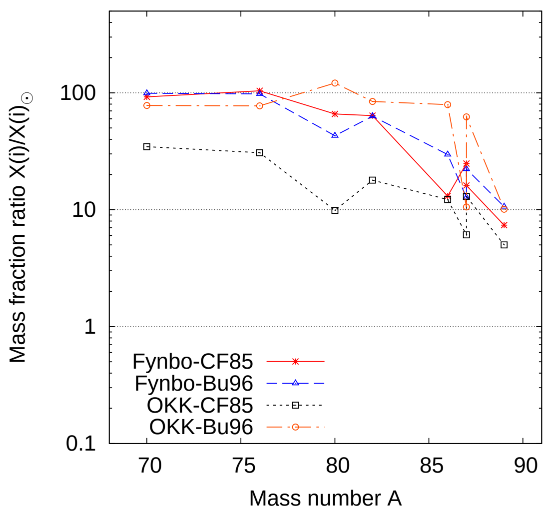

Figure 3: The overproduction factors of the pure *s*-nuclei. The symbols are same as the left panel.

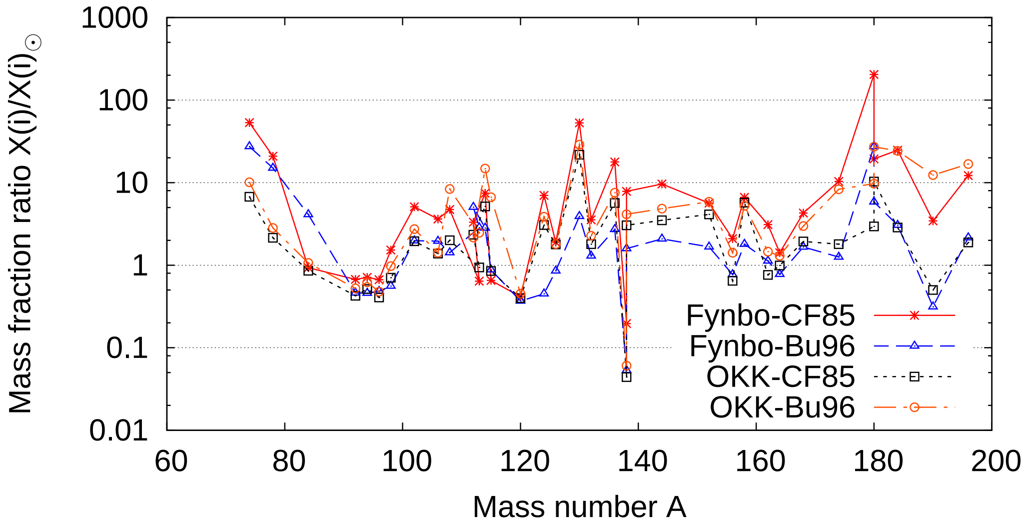

Figure 4: The overproduction factors of the *p*-nuclei. The symbols are same as Fig. 2.

is, the higher the overproduction level results. We find that the peak temperatures are determined by the temperature distribution at the presupernova stage. Therefore the amount of *p*-elements are affected by the stellar evolution path which is affected by both triple-α and $^{12}C(\alpha,\gamma)^{16}O$ reaction rates.

4. Summary

We investigated the effects of the uncertainties of triple-α and $^{12}C(\alpha,\gamma)^{16}O$ reaction rates on the elements ejected by the core-collapse supernova explosion. We adopted OKK and Fynbo rates for the triple-α reaction and CF85 and Bu96 rates for the $^{12}C(\alpha,\gamma)^{16}O$ reaction. In order to estimate the yields of elements ejected by the supernova explosions, we calculated the stellar evolution, the supernova explosion, and the related nucleosynthesis. Furthermore, we compared the results with the solar system abundances to investigate the effects of the reaction rates. Fynbo-CF85 model reproduced the elements of $20 \leq A \leq 32$ well and Fynbo-Bu96 gave the same level except for ^{23}Na which is coming from ^{12}C. Both OKK-CF85 and OKK-Bu96 models overproduce the elements produced from the enriched ^{12}C. The *s*-elements in the four models kept the yields even after the supernova explosion. Therefore, we confirmed that the yields of weak *s*-elements are mainly determined by the helium and carbon burnings during the stellar evolution. We found that the production of *p*-elements depends on the size of the *p*-process layers, which are affected by the stellar evolution path.

5. Acknowledgments

This work has been supported in part by a Grant-in-Aid for Scientific Research (24540278) of the Ministry of Education, Culture, Sports, Science and Technology of Japan.

References

[1] K. Nomoto, Astrophysical Journal **253**, 798 (1982).

[2] K. Nomoto, F.-K. Thielemann, and S. Miyaji, Astronomy & Astrophysics **149**, 239 (1985).

[3] H. O. U. Fynbo *et al.*, Nature **433**, 136 (2005).

[4] K. Ogata, M. Kan, and M. Kamimura, Progress of Theoretical Physics **122**, 1055 (2009), 0905.0007.

[5] A. Dotter and B. Paxton, Astronomy and Astrophysics **507**, 1617 (2009), 0905.2397.

[6] M. Saruwatari and M. Hashimoto, Progress of Theoretical Physics **124**, 925 (2010), 1004.0983.

[7] F. Peng and C. D. Ott, Astrophysical Journal **725**, 309 (2010), 1008.3411.

[8] Y. Matsuo *et al.*, Progress of Theoretical Physics **126**, 1177 (2011), 1105.5484.

[9] P. Morel, J. Provost, B. Pichon, Y. Lebreton, and F. Thévenin, Astronomy and Astrophysics **520**, A41 (2010).

[10] T. Suda, R. Hirschi, and M. Y. Fujimoto, Astrophysical Journal **741**, 61 (2011), 1107.4984.

[11] Y. Kikuchi, M. Ono, Y. Matsuo, M. Hashimoto, and S. Fujimoto, Progress of Theoretical Physics **127**, 171 (2012), 1110.0206.

[12] G. R. Caughlan, W. A. Fowler, M. J. Harris, and B. A. Zimmerman, Atomic Data and Nuclear Data Tables **32**, 197 (1985).

[13] G. R. Caughlan and W. A. Fowler, Atomic Data and Nuclear Data Tables **40**, 283 (1988).

[14] L. Buchmann, R. E. Azuma, C. A. Barnes, J. Humblet, and K. Langanke, Phydical Review C **54**, 393 (1996).

[15] R. Plaga *et al.*, Nuclear Physics A **465**, 291 (1987).

[16] A. Redder *et al.*, Nuclear Physics A **462**, 385 (1987).

[17] L. Buchmann, Astrophysical Journal Letters **468**, L127 (1996).

[18] K. Nomoto and M. Hashimoto, Physics Reports **163**, 13 (1988).

[19] M. Hashimoto, Progress of Theoretical Physics **94**, 663 (1995).

[20] M. Hashimoto, K. Nomoto, and T. Shigeyama, Astronomy & Astrophysics **210**, L5 (1989).

[21] M. D. Johnston and A. Yahil, Astrophysical Journal **285**, 587 (1984).

[22] T. Shigeyama, K. Nomoto, and M. Hashimoto, Astronomy & Astrophysics **196**, 141 (1988).

[23] R. H. Cyburt *et al.*, Astrophysical Journal Supplement Series **189**, 240 (2010).

[24] Z. Y. Bao *et al.*, Atomic Data and Nuclear Data Tables **76**, 70 (2000).

[25] K. Takahashi and K. Yokoi, Atomic Data and Nuclear Data Tables **36**, 375 (1987).

[26] E. Anders and N. Grevesse, Geochimica et Cosmochimica Acta **53**, 197 (1989).

[27] M. Rayet, M. Arnould, and N. Prantzos, Astronomy & Astrophysics **227**, 271 (1990).