The Origin of Oxygen in the Universe - A new approach to an Old Question

K. E. Rehm
Physics Division, Argonne National Laboratory, 9700 South Cass Av., Argonne, IL, 60439, USA
E-mail: rehm@anl.gov

Abstract. Carbon and oxygen are not only important elements for the existence of life on Earth, but they also play an important role in the evolution of stars towards the end of their life cycle. The formation of $^{12}$C through the so-called triple-$\alpha$ reaction is quite well understood. The next step, the formation of $^{16}$O through the $\alpha$ capture reaction $^{12}$C($\alpha$, $\gamma$)$^{16}$O on the other hand, still has an experimental uncertainty of $\sim 30\%$. Direct measurements of the $^{12}$C($\alpha$, $\gamma$)$^{16}$O reaction by detecting either the outgoing $\gamma$ radiation in a high acceptance Ge-detector array or the residual $^{16}$O nuclei in a mass spectrometer do not allow for order-of-magnitude improvements. In this contribution, the possibility of using superheated bubble detectors for a measurement of the time-inverse $^{16}$O($\gamma$, $\alpha$)$^{12}$C reaction is being discussed. The first results of a 'proof-of-principle' experiment of the $^{19}$F($\gamma$, $\alpha$)$^{15}$N reaction are also being presented.

1. Introduction
The isotopes $^{16}$O and $^{12}$C are, after $^1$H and $^4$He, the third and fourth most abundant nuclei in the visible universe. Most of the carbon and oxygen which we observe today is produced by helium burning in red giant stars. These two elements are not only crucial for all living organisms, but their relative abundances, which are determined by the competition between the triple-$\alpha$ and the $^{12}$C($\alpha$, $\gamma$)$^{16}$O reactions, is also an important parameter for the evolution of a massive star at the end of its lifetime during the carbon-, neon-, and oxygen-burning phases [1, 2, 3]. The cross section for the triple-$\alpha$ process is experimentally quite well determined [4]. Our knowledge of the $^{12}$C($\alpha$, $\gamma$)$^{16}$O reaction under typical helium burning conditions ($T_9 \sim 0.2$ or $E_{c.m.} \sim 300$ keV), however, is still limited by its small cross section and by the crucial role played by two sub-threshold states in $^{16}$O [5].

The history of experiments studying the $^{12}$C($\alpha$, $\gamma$)$^{16}$O reaction goes back more than four decades [6, 7]. The magnitude of this cross section, however, is still a hotly debated issue, both experimentally and theoretically, and many recent publications can be found in the literature [8, 9, 10, 11, 12, 13, 14, 15, 16].

Contrary to the triple $\alpha$ reaction which is dominated by the contribution from a resonant state (the so-called Hoyle state) the $^{12}$C($\alpha$, $\gamma$)$^{16}$O reaction proceeds mainly through two radiative capture modes to the $^{16}$O ground state. One is E1 capture with contributions from the 1$^-$ state at $E_x=9.585$ MeV ($E_r=2.418$ MeV) and the sub-threshold 1$^-$ state at $E_x=7.117$ MeV ($E_r=-45$...
keV). The other is E2 capture which is dominated by the contributions from direct capture and the sub-threshold 2+ state at E_x=6.917 MeV (E_r=-245 keV). At energies corresponding to the Gamow window for red giant stars (E_c.m. ∼300 keV), the cross sections are on the order of 10^{-17} b. For that reason, all direct measurements so far were done at higher energies above E_c.m. = 890 keV [4]. These data are then extrapolated into the energy region of astrophysical interest using R-matrix theory. Since the higher-energy data are not very sensitive to the contributions from sub-threshold resonances, the published S-factors in the past 30 years range from 1 to 288 keVb for S_{E1}(300) and 7 to 120 keVb for S_{E2}(300) [17].

Two different techniques have been used in the past for direct measurements of the \(^{12}\text{C}(\alpha, \gamma)^{16}\text{O}\) reaction:

- A highly enriched \(^{12}\text{C}\) target is bombarded with high intensity \(\alpha\) beams and the outgoing \(\gamma\)'s are detected in large-acceptance Ge-detector arrays. The measurements performed at the lowest c.m.energies (E_{cm}=890 keV) have used this technique. The main drawback of this technique is the low efficiency that can be achieved for the detection of 8 MeV \(\gamma\) rays.

- A higher detection efficiency can be obtained by studying the reaction in inverse kinematics, i.e. bombarding a \(^4\text{He}\) gas target with a \(^{12}\text{C}\) beam and detecting the final \(^{16}\text{O}\) nucleus in a mass spectrometer. The difficulty with this technique comes from a small \(^{16}\text{O}\) beam contamination, which currently restricts the lowest energies to about E_{cm} ∼ 1.8 MeV.

Good agreement of the measured cross sections is observed in the energy region studied by both techniques. In addition to these direct techniques, several indirect methods have been investigated in order to improve the reliability of the extrapolations into the astrophysically important energy region. These techniques include data from elastic \(\alpha\) scattering on \(^{12}\text{C}\) [18, 19], \(\alpha\)-transfer reactions to \(^{16}\text{O}\) [20], and \(\beta\)-delayed \(\alpha\) decay of \(^{16}\text{N}\) [22, 23, 21, 11, 24].

In order to discuss the limits and possible improvements for future direct measurements of the \(^{12}\text{C}(\alpha, \gamma)^{16}\text{O}\) reaction, we introduce the concept of a 'modified' luminosity \(L' = I \cdot N \cdot \epsilon\), where \(I\) is the beam intensity (particles/sec), \(N\) the areal target density (target nuclei/cm\(^2\)) and \(\epsilon\) the detection efficiency. When multiplied by the cross section \(\sigma\), the product \(L' \cdot \sigma\) gives the count rate expected in an actual experiment. Sometimes only an order-of-magnitude estimate of the luminosity can be extracted from the information provided in the various publications. The 'modified' luminosities for some of the experiments performed during the last 20 years are shown in Fig. 1. They are typically of the order of \(10^{31}\) sec\(^{-1}\)cm\(^{-2}\) which, when multiplied by a cross section of 1 pb, translate into an expected count rate of 1 count/day. Improvements by factors of 2-5 are possible by choosing higher beam currents or better Ge detector arrays (perhaps located deep underground). The choice of higher efficiency BaF\(_2\) detectors has also been investigated. However, based on the small cross sections and the relatively small luminosities improvements by orders of magnitude do not seem possible with these techniques in the foreseeable future.

2. Studies of time-inverse Reaction \(^{16}\text{O}(\gamma, \alpha)^{12}\text{C}\) Reaction

For experiments studying astrophysically important proton-capture (p,\(\gamma\)) reactions it has been pointed out [25] that measurements of the time-inverse (\(\gamma, p\)) reactions can yield higher count rates when compared to standard (p,\(\gamma\)) experiments. This is caused by two effects: (a) the possibility to use thicker targets and (b) by a more advantageous phase space factor. This has made Coulomb dissociation studies a competitor to direct (p,\(\gamma\)) experiments. Similar advantages also exist for measurements of \((\alpha, \gamma)\) and \((\gamma, \alpha)\) reactions as was pointed out in Ref. [26, 27]. Using the principle of detailed balance, the cross sections for \((\alpha, \gamma)\) and \((\gamma, \alpha)\) reactions are (for
Figure 1. 'Modified’ luminosities obtained in some of the direct measurements of the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ reaction performed during the last 20 years.

The system $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ related by the equation

$$\frac{\sigma(\gamma, \alpha)}{\sigma(\alpha, \gamma)} = \frac{2\mu^2 E_{\text{cm}}(\alpha, \gamma)}{2E_\gamma^2}$$

(1)

where \(\mu\) and \(E_{\text{cm}}\) are the reduced mass and the c.m. energy in the $^{12}\text{C} + \alpha$ system, and \(E_\gamma\) is the corresponding \(\gamma\) energy in the $^{16}\text{O} + \gamma$ system (typically 8 MeV for \(E_{\text{cm}} \sim 1\) MeV). For the lowest energies studied so far the enhancement factor \(\frac{\sigma(\gamma, \alpha)}{\sigma(\alpha, \gamma)}\) is about 50.

Another advantage for studying the time inverse $^{16}\text{O}(\gamma, \alpha)$ reaction originates from the large range of an 8 MeV \(\gamma\) which has a mean absorption length of about 40 cm in water. Thus, in $(\gamma, \alpha)$ experiments, target thicknesses of tens of g/cm$^2$ can be used, which results in yields that are higher by about 6 orders of magnitude when compared to direct $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ experiments where target thicknesses of typically 10 \(\mu\)g/cm$^2$ are used.

The implementation for measuring the time-inverse $^{16}\text{O}(\gamma, \alpha)^{12}\text{C}$ reaction requires a tunable \(\gamma\) beam with the highest possible intensities and a detector system that can identify the occurrence of a breakup of $^{16}\text{O}$ into $^{12}\text{C}$ and \(\alpha\) while being insensitive to \(\gamma\)'s at the level of at least $10^{-11}$. In Ref. [26] an optical TPC has been discussed. While it can identify the occurrence of a $^{16}\text{O}(\gamma, \alpha)^{12}\text{C}$ reaction it operates with gases at pressures of \(~100\) mbar and thus does not make full use of the large range of 8 MeV \(\gamma\)'s. In the following we will discuss the advantageous of using a bubble chamber filled with superheated liquids.

3. The use of a bubble chamber for nuclear astrophysics experiments

Bubble chambers were one of the principle detectors for tracking energetic particles in high energy physics experiments. Invented more than 50 years ago, their operational principles are well understood [28]. These type of detectors have recently seen a renaissance in Dark Matter searches and three groups are utilizing superheated liquids in a search of nuclear recoils induced by possible WIMP interactions [29, 30, 31]. The liquids used in these experiments are fluorocarbon compounds which are superheated close to room temperatures. However, water, (the
most convenient oxygen-containing liquid), requires temperatures of $\sim 250$ C and pressures in excess of 75 atm.

Contrary to bubble chambers used in high energy physics which are superheated only for a short period of time, Dark Matter searches require detectors that are superheated for longer periods (e.g. days). This can be achieved by choosing a glass vessel as a container for the superheated liquid. When located deep-underground, background rates of $\sim$counts/day have been achieved. In order to avoid the high-pressure/temperature conditions required for a water-filled bubble chamber we have therefore, for a first 'proof-of-principle' experiment, studied the time-inverse of the reaction $^{15}$N($\alpha$, $\gamma$)$^{19}$F by bombarding fluoro-carbon liquids with $\gamma$ beams from the HI$\gamma$S facility at Duke University.

Fig. 2 shows a schematic of the experimental setup. A $\gamma$ beam from the HI$\gamma$S facility collimated to a diameter of 1 cm hits a cylindrical glass vessel (diameter $\sim 3$ cm) filled with C$_4$F$_{10}$. This fluoro-carbon compound is superheated at T$\sim$30 C and p$\sim$3 atm. If an incident $\gamma$ causes a $^{19}$F($\gamma$, $\alpha$)$^{15}$N reaction the outgoing $\alpha$-$^{15}$N pair is stopped in the liquid and acts as a nucleation center producing a bubble. The glass vessel is continuously monitored by two CCD cameras taking pictures every 10 ms. If a bubble is detected, the pressure in the vessel is immediately increased which brings the liquid out of the superheated state, thus leading to a quenching of the bubble. After a time delay of typically 1 s, the pressure is again reduced bringing the detector back to the superheated state for the detection of another event. Fig. 3 shows a sequence of photographs taken 10 ms apart showing the growth and the quenching of a bubble produced via the $^{19}$F($\gamma$, $\alpha$)$^{15}$N reaction in a superheated C$_4$F$_{10}$ liquid. The energy of the $\gamma$ beam was 5.3 MeV.

The normalization of the incident $\gamma$ flux is achieved by using a high efficiency Ge detector located after the bubble chamber. With this setup, an excitation function of the $^{15}$N($\alpha$, $\gamma$)$^{19}$F reaction has been measured in the energy range $E_\gamma$=5-6 MeV. The uncertainty of the incident
Figure 3. Sequence of photographs taken with one of the CCD cameras at time intervals of 10 ms. When the occurrence of a bubble is detected, the pressure in the vessel is increased, leading to the quenching of the bubble. This pressure increase takes typically 50 msec.

Figure 4. Preliminary cross sections obtained in a 'proof-of-principle' experiment for the $^{15}\text{N}(\alpha, \gamma)^{19}\text{F}$ reaction. The arrows indicate the location of known resonances in $^{19}\text{F}$. See text for details.

$\gamma$-beam is determined by the energy spread of the electron beam in the storage ring and by the amount of collimation and was about 1% for this experiment. A preliminary excitation function for the $^{15}\text{N}(\alpha, \gamma)^{19}\text{F}$ reactions is shown in Fig. 4. The cross section scale covers almost four orders of magnitude ranging from 1 nb to 10 $\mu$b. The cross sections in Fig. 4 have not been unfolded with the experimental resolution. In order to measure the yield at the maximum of the excitation function, the intensity of the incident $\gamma$ beam had to be reduced to $5\times10^3 \gamma$’s/sec. For a 20 cm long vessel filled with water and assuming a beam intensity of $5\times10^7 \gamma$’s/sec, the calculated count rate for the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ reaction at a cross section of 1 pb is about $\sim 100$ events/day. This estimate includes the increase in cross section for the $^{16}\text{O}(\gamma, \alpha)^{12}\text{C}$ reaction discussed in Section 2. This rate is about a factor of 100 larger than what can be obtained with
standard techniques.

The next step involves a similar test using a water-filled bubble chamber. A setup that allows measurements at 250° C and p=75 atm is presently being assembled at Argonne. Contrary to the $^{19}\text{F}(\gamma, \alpha)$ reaction which used the mono-isotopic $^{19}\text{F}$, reactions on the target contaminants $^{17,18}\text{O}$ can contribute to the $^{16}\text{O}(\gamma, \alpha)$ reaction. For this reason water, which is highly enriched in $^{16}\text{O}$, has been purchased. Similar to the study of the $^{19}\text{F}(\gamma, \alpha)$ reaction we will start the measurement of the $^{16}\text{O}(\gamma, \alpha)$ reaction in the vicinity of the known $1^-$ resonance at $E_{\gamma} = 9.585$ MeV, where several cross sections measurements using other techniques have been performed in the past and will extend the $(\gamma, \alpha)$ measurements to the lowest energies possible. Reactions induced by cosmic ray neutrons can be eliminated by using an acoustical readout system as done e.g. in Ref. [32].

Acknowledgments
The bubble chamber experiment is a collaboration between Argonne National Laboratory, Fermi National Accelerator Laboratory, University of Illinois, Duke University and the University of North Carolina. I want to thank my collaborators B. Digiovine, C. Ugalde, Roy Holt, D. Henderson(ANL), A. Robinson, A. Sonnenschein (FNAL), N. Sturcchio (UoI), A. Raut, G. Rusev, A. Tochenv (Duke) and A. Champagne (UNC) for their contributions to this experiment. This work was supported by the US Department of Energy, Office of Nuclear Physics under contract No. DE-AC02-06CH11357 and by the NSF JINA Grant. No. PHY0822648.

[1] T. A. Weaver and S. E. Woosley, Phys. Rep. 227, 65 (1993).
[2] S. E. Woosley and T. A. Weaver, Astrophys. Journal, Suppl., 101, 181 (1995).
[3] G. Wallerstein et al. Rev. Mod. Phys. 69, 995 (1997).
[4] L. R. Buchmann and C. A. Barnes, Nucl. Phys. 777, 254 (2006).
[5] (www.tnln.duke.edu/nucldata).
[6] H. M. Loebenstein, D. W. Mingay, H. Winkler, and C. S. Zaidins, Nucl. Phys. A91, 481 (1967).
[7] R. J. Jaszcak, J. H. Gibbons, and R. L Macklin, Phys. Rev. C2, 63 (1970).
[8] J. W. Hammer et al., Nucl. Phys. A 752, 514c (2005).
[9] M. Assuncao et al., Phys. Rev. C 73, 055801 (2006).
[10] A. Belhout et al., Nucl. Phys. A793, 178 (2007).
[11] R. H. France III, E. L. Wills, J. E. McDonald, and M. Gai, Phys. Rev. C 75, 065802 (2007).
[12] P. Descouvemont, J. Phys. G35, 014006 (2008).
[13] C. Matei, C. R. Brune, and T. N. Massey, Phys. Rev. C78, 065801 (2008).
[14] F. Strieder, J. Phys. G35, 014009 (2008).
[15] P. Tischhauser et al., Phys. Rev. C 79, 055803 (2009).
[16] H. Makii et al., Phys. Rev. C 80, 065802 (2009).
[17] R. Kunz et al., Astrophys. J. 567, 643 (2002).
[18] H. Makii et al., Phys. Rev. C 80, 065802 (2009).
[19] R. Plaga et al., Nucl. Phys. A465, 291 (1987).
[20] P. Tischhauser et al., Phys. Rev. Lett. 88, 072501 (2002).
[21] C. R. Brune et al., Phys. Rev. Lett. 83, 4025 (1999).
[22] R. Azuma et al., Phys. Rev. C 50, 1194 (1994).
[23] L. R. Buchmann et al., Phys. Rev. Lett. 70, 726 (1993).
[24] Z. Zhao et al., Phys. Rev. Lett. 70, 2066 (1993).
[25] X. D. Tang et al., Phys. Rev. C 81, 045809 (2010).
[26] G. Baur and H. Rebel, J. Phys.(London) G20, 1 (1994).
[27] M. Gai, 21st Winter Workshop on Nuclear Dynamics, arXiv:nucl-ex/0504003v1.
[28] Y. Xu et al., Nucl. Instr. Meth. A 581, 866 (2007).
[29] F. Seitz, Phys. Fluids 1.2 (1958).
[30] S. Archambault et al., Phys. Lett. B682, 185 (2009).
[31] E. Behnke et al., Phys. Rev. Lett. 106, 021303 (2011).
[32] M. Felizardo et al., Phys. Rev. Lett. 105, 211301 (2010).
[33] S. Archambault et al., New J. Phys. 13, 043006 (2011).