Carbon burning in stars – Prospects for underground measurements of the $^{12}$C+$^{12}$C fusion reactions

Frank Strieder
Institut für Experimentalphysik, Ruhr-Universität Bochum, Germany
strieder@ep3.rub.de

Abstract. The $^{12}$C+$^{12}$C fusion reactions are together with the reaction $^{12}$C($\alpha,\gamma$)$^{16}$O the most important nuclear processes in the late stellar evolution. These fusion reactions play a key role in the understanding of various types of astrophysical objects. Thus, a measurement of the $^{12}$C+$^{12}$C cross section at very low energies can serve as flagship experiment for a future underground accelerator laboratory. It is hoped that an appropriate facility for such a study will be created in the near future somewhere in the world. The prospects for the measurement of the carbon fusion reactions will be discussed in the present work.

1. Introduction
The LUNA facility [1] at the Laboratori Nazionali del Gran Sasso, Italy, is yet a unique underground accelerator laboratory for nuclear astrophysics. The availability of high intensity proton and alpha beams and the maximum accelerator voltage of 400 kV makes it an ideal tool for the study of low-energy $(p,\gamma)$ and $(\alpha,\gamma)$ capture reactions. Since there are many reactions to be studied and/or reinvestigated the facility will continue for several more years. However, for an improved measurement of some important reactions induced by charged particles the present LUNA accelerator is not sufficient either because experiments in inverse kinematics are favoured or because only heavy ions are involved. Such key reactions for a future underground accelerator laboratory are the $^{12}$C+$^{12}$C fusion reactions.

2. The carbon fusion reactions
The reactions $^{12}$C($^{12}$C,$\alpha$)$^{20}$Ne ($Q = 4.617$ MeV) and $^{12}$C($^{12}$C,p)$^{23}$Na ($Q = 2.241$ MeV) are referred to as carbon burning in stars [2]. Carbon-burning represents the third stage of stellar evolution for massive stars ($M > 8M_\odot$) and proceeds mainly through the $^{12}$C + $^{12}$C fusion reactions since the Coulomb barrier is lowest among the involved nuclei. Carbon and oxygen are produced as a result of helium burning. The stellar CO core contracts after the central He exhaustion and the core temperature increases. Only massive stars develop temperatures large enough for further burning phases. On the contrary, in low and intermediate mass stars, a high pressure from electron degeneracy and the cooling caused by the production of plasma neutrinos prevent the onset of the carbon burning. The minimum mass of a star for the carbon ignition, called $M_{\text{up}}$, is a fundamental astrophysical parameter that marks the upper limit for CO White dwarf progenitors and the lower limit for core-collapse Supernova progenitors [3]. Stars with an initial mass slightly larger than $M_{\text{up}}$ experience an off-centre carbon ignition under condition of high electron degeneracy. As a result, a relatively large degenerate core with a mass in the range of $1.1 - 1.37 M_\odot$ made of O, Ne and Mg is formed. These stars evolve...
through a super-AGB phase (Asymptotic Giant Branch) and end their lives as massive ONeMg White dwarfs or, eventually, as electron-capture supernovae [4]. Stars more massive than another mass limit M'_{up} – the minimum mass for Ne ignition – ignite central carbon burning and proceed through neon, oxygen, and silicon burning, followed by the iron core collapse [5-7]. On the contrary, stars with M < M'_{up} cannot progress through carbon ignition and conclude their life after the AGB phase as CO White dwarfs. CO White dwarfs accreting mass in close binary systems are the progenitors of the majority of Novae [8] and Type Ia Supernovae [9]. Thus not only the frequencies of Novae and the various types of Supernovae depend on the mass limits M_{up} and M'_{up} but also a large fraction of the stellar nucleosynthesis, i.e. the synthesis of most elements with mass numbers larger than 20.

The determination of M_{up} relies on a precise understanding of the carbon burning reaction rate under stellar conditions. However, at the relevant stellar energies the reaction rate of these $^{12}$C+$^{12}$C fusion reactions is not very well known and provided only by extrapolations of high energy data [10].

The stellar temperature range corresponds to a Gamow peak energy for $^{12}$C+$^{12}$C fusion reactions of about $E_G = 1.5 \pm 0.3$ MeV and thus the cross section of these key processes must be known with high accuracy down to this energy region. Previous experiments [11–16] using charged-particle or $\gamma$-ray spectroscopy obtained useful data over a wide range of energies down to the centre-of-mass energy $E = 2.0$ MeV. However, below $E = 3.0$ MeV the reported cross sections are partly rather uncertain, because at these energies the presence of $^1$H and $^3$H contamination inside or on the surface of the C targets hampered in most cases the measurement of the $^{12}$C+$^{12}$C processes. For example, in $\gamma$-ray spectroscopy the transitions from the first excited state in $^{\text{20}}$Ne ($E_{\gamma} = 1634$ keV) and $^{\text{22}}$Na ($E_{\gamma} = 440$ keV) were normally the prominent lines in the $\gamma$-spectra but at low energies their observation suffered from an intense background from the $E_{\gamma} \approx 2.36$ MeV line of $\text{^1H}^{(12}\text{C},\text{p})^{13}\text{N}$ and the $E_{\gamma} = 3.09$ MeV line of $\text{^2H}^{(12}\text{C},\text{p})^{13}\text{C}$. In one of the studies [16] C targets with a low hydrogen contamination were produced allowing for reasonable precise measurements by $\gamma$-ray spectroscopy of the $\alpha$- and $p$- channels down to $E = 2.0$ MeV.

### 3. Future studies of the $^{12}$C+$^{12}$C fusion reactions

As a key condition improved studies of the $^{12}$C+$^{12}$C fusion reactions require C targets with an ultra-low hydrogen contamination. Moreover, a reduction of $\gamma$-ray background from natural radioactivity and cosmic-rays is also an essential step for a measurement towards a lower energy limit than presently available. The reduction of the $\gamma$-ray background from natural radioactivity can be achieved by conventional passive shielding such as lead placed around the $\gamma$-ray detectors and active shielding to reduce the influence of cosmic-rays. However, the passive shielding is limited to a certain thickness. One cannot add further shielding material since cosmic-ray muons interact with the material and create energetic neutrons which, in turn, create $\gamma$-rays in the lead. Clearly, all background components are dramatically reduced with the significantly suppressed muon flux in an underground laboratory. The best solution is to install an accelerator facility in a laboratory deep underground. In summary, only these two key requirements, i.e. ultra-low H contamination and a low-background environment, combined with a high intensity $^{12}$C ion beam, e.g. a particle current of 300 $\mu$A, will allow for a $\gamma$-ray spectroscopy measurement of the $^{12}$C+$^{12}$C fusion reactions down into the region of the Gamow peak.

The $\gamma$-ray spectroscopy has the disadvantage that the transitions $\alpha_0$ and $p_0$ directly into the ground state of $^{\text{20}}$Ne and $^{\text{22}}$Na, respectively, cannot be observed. Direct particle identification would allow for measuring the total cross section for each channel. Such a measurement could be performed with standard silicon surface barrier detectors in close geometry to the target and under backward angles with respect to the beam direction. Furthermore, a compact $\Delta E$-E Silicon detector telescope or a Bragg detector would allow for particle identification, e.g. $\alpha$ and $p$. In this geometry background problems arise mainly from elastically scattered $^{12}$C nuclei and the reaction $^{12}$C(d,p)$^{14}$C. In addition, a close distance to the target leads to a heating of the detectors due to the heat radiation of the target under a high intensity $^{12}$C beam. This effect influences drastically the performance of the particle detector. On the other hand an ion beam intensity of about 300 particle $\mu$A $^{12}$C – a factor 20 to 50 more than in previous experiments, e.g. [13] – would allow to mount the detectors in a far geometry without a
significant loss of count rate compared to previous experiments but avoiding the problems of detector heating. However, such a particle spectroscopy measurement might also benefit from an underground laboratory in particular in case of Si detectors if the two detectors of the ΔE-E telescope are very close to each other and the detectors have a large surface area. This technique was successfully exploited in the measurement of the reaction $^3\text{He}(\text{He},2p)^4\text{He}$ at the LUNA I facility [17] and a clear advantage of the underground environment for the ΔE-E Si detector setup was observed [18]. An important issue in the particle spectroscopy is the background discrimination in particular for low reaction yield: a distinguished background detection for heavy ion reactions is difficult if not impossible. In case of background reactions emitting ejectiles of the same species – may be even with a comparable energy – as the expected experimental signal, the background cannot be identified with any detection technique. In turn, this is an advantage of the γ-ray spectroscopy which provides a clear and unique signal if the signal-to-noise ratio allows for a precise observation of the signal. Therefore, the $^{12}\text{C}+^{12}\text{C}$ fusion reactions are an excellent case for experimental studies using a future underground facility with a larger accelerator than presently available and an ion source able to provide high intensity heavy ion beams. 

The possible improvement for a γ-ray spectroscopy measurement of the $^{12}\text{C}+^{12}\text{C}$ fusion reactions in an underground laboratory can be estimated from the recent $^3\text{He}(\alpha,\gamma)^7\text{Be}$ experiment at LUNA [19, 20]. The detection setup of this experiment, in particular the arrangement of the passive shielding, was adapted to meet the special requirements for a measurement of γ-ray energies below $E_\gamma = 2.5$ MeV. The achievements in terms of background reduction can be considered as a kind of standard for future nuclear cross section measurements. Hence, the natural γ-ray background near the relevant 1634 keV γ-ray line of the $^{12}\text{C}(^{12}\text{C},\alpha)^{20}\text{Ne}$ reaction can be used to calculate the sensitivity limit. The background for the HPGe detector in the well-shielded setup of the LUNA experiment is reduced by a factor 800 compared to the shielded setup in a recent experiment at earth’s surface [16].

A similar or improved γ-ray background can probably be expected for all future underground accelerator laboratories at depths comparable to Gran Sasso. Unfortunately, the environmental (unshielded) γ-ray background in this γ-ray energy region in an underground laboratory located in sedimentary rocks is relatively high if compared to the reduction of cosmic-ray background. An advantage for measurements in this particular γ-ray energy region could come from the potential of salt mines where typically the unshielded γ-ray background provided by the salt environment is significantly reduced with respect to sedimentary rocks, including the $^{40}\text{K}$ γ-ray line. This reduction approximately amounts to one order of magnitude, e.g. between the Boulby UK Dark Matter underground laboratory located in the Boulby Salt and Potash Mine, U.K., – where the laboratory is placed in a salt layer – and Gran Sasso (sedimentary rock). The reduction could be even larger for sites located in salt layers with a very low $^{40}\text{K}$ content. Unfortunately, most of such sites are at depths less than 300 m, e.g. in Romania [21], and thus with an insufficient shielding against cosmic-ray background.

The $^{12}\text{C}+^{12}\text{C}$ experiment could be performed in a similar way as previously with a single detector in close geometry. In a recent theoretical work [22] a hypothetical resonance at $E = 1.5$ MeV has been proposed based on the carbon ignition temperature in superburst models. The proposed experiment with a high intensity $^{12}\text{C}$ ion beam, reasonable experimental parameters, and the above background assumption would have a resonance strength detection limit of at least 1 μeV for a resonance at $E = 1.5$ MeV. Thus, the hypothetical resonance of [22] would be within reach in such a measurement. Unfortunately, a proper passive shielding similar to the LUNA $^3\text{He}(\alpha,\gamma)^7\text{Be}$ experiment for an improved detection system such as a Ge crystal ball would lead to handling problems and large experimental difficulties. This approach could take advantage of the potential of salt mines due to the lower unshielded γ-ray background and the shielding requirements may be reduced. However, even in a well-shielded detector setup the actual environmental and cosmic-ray induced backgrounds are only some of the components determining the final background in the detector. Other important components are the purity of the shielding material, and in particular beam-induced background. Very
often the final detection limit can only be estimated through the measurement in the underground laboratory itself. While for most cases in low-energy cross section measurements the natural background is dominating the γ-ray spectra or at least the beam induced background can be reduced to the level of the other background sources that might be different in an underground measurement. In particular new beam induced background components might appear which at low-energies give rise to the same yield than expected from the actual measurement, but normally in earth’s surface experiments covered by the natural background (see for example the case of the reaction $^{25}\text{Mg}(p,\gamma)^{26}\text{Al}$ as shown in [1]).

In summary, our knowledge of the reaction rate of the $^{12}\text{C}+^{12}\text{C}$ fusion reactions will certainly be improved very much by a measurement in an appropriate future underground accelerator laboratory. The final sensitivity limit depends not only on the reduction of the natural background but also on the purity of the C target, i.e. hydrogen contamination must be reduced to a minimum. Nevertheless, with an optimized experimental setup and an accelerator such as a 3 MV high-current, single-stage machine with an ECR ion source a measurement over the energy range of the Gamow peak for massive stars at $E = 1.5$ MeV appears feasible. Finally, both experimental approaches, i.e. particle and γ-ray spectroscopy, to measure the $^{12}\text{C}+^{12}\text{C}$ cross section would benefit from the underground environment.

Acknowledgments
The present work has been supported by the Deutsche Forschungsgemeinschaft (DFG, Ro 429/44). In addition, the author would like to thank O. Straniero for fruitful discussions.

References
[1] Costantini H, Formicola A, Imbriani G, Junker M, Rolfs C and Strieder F 2009 Rep. Prog. Phys. 72 086301-25
[2] Rolfs C E and Rodney W S 1988 Cauldrons in the Cosmos (University of Chicago Press)
[3] Becker S A and Iben I 1979 Bulletin of the American Astronomical Society 12 417
[4] Siess L 2007 Astron. Astrophys. 476 893-909
[5] Chieffi A, Limongi M and Straniero O 1998 Astrophys. J. 502 737-762
[6] Woosley S E, Heger A and Weaver T A 2002 Rev. Mod. Phys. 74, 1015-1071
[7] El Eid M F, Meyer B S and The L S 2004 Astrophys. J. 611, 452-465
[8] Kraft R P 1964 Astrophys. J. 139 457-475
[9] Hillebrandt W and Niemeyer J 2000 Annu. Rev. Astron. Astrophys. 38 191-230
[10] Caughlan GR and Fowler W A 1988 Atomic Nucl.Data Tables 40 283-334
[11] Kettner K U, Lorenz-Wirzba H and Rolfs C E 1977 Phys. Rev. Lett. 38 337-340
[12] High M D and Cujec B 1977 Nucl. Phys. A 282 181-188
[13] Becker H W, Kettner K U, Rolfs C E and Trautvetter H P Z. Phys. A 303 305-312
[14] Aquilera E F et al 2006 Phys. Rev. C 73 064601-12
[15] Barron-Palos L et al 2006 Nucl. Phys. A 779 318-332
[16] Spillane T et al 2007 Phys. Rev. Lett. 98 122501-4
[17] Junker M et al 1998 Phys. Rev. C 57 2700-10
[18] Junker M 1996 Ph. D. thesis (Ruhr-Universität Bochum, Germany)
[19] Confortola F et al 2007 Phys. Rev. C 75 065803-4
[20] Caciolli A et al 2009 Eur. Phys. J. A 39 179-186
[21] Bordeau C, Rolfs C, Margineanu R, Negoita F and Simion C 2008 J. Phys. G 35 014011-6
[22] Cooper R L, Steiner A W and Brown E F 2009 Astroph. J 702 660-671