STUDYING STARS BY GOING UNDERGROUND: THE LUNA EXPERIMENT AT GRAN SASSO LABORATORY*

Antonio Caciolli

(for the LUNA Collaboration)

Istituto Nazionale di Fisica Nucleare, Sezione di Padova
via Marzolo 8, 35131 Padova, Italy
caciolli@pd.infn.it

(Received November 22, 2013)

One of the main ingredients of nuclear astrophysics is the knowledge of the thermonuclear reactions responsible for powering the stellar engine and for the synthesis of the chemical elements. At astrophysical energies, the cross section of nuclear processes is extremely reduced by the effect of the Coulomb barrier and often extrapolations are needed. The Laboratory for Underground Nuclear Astrophysics (LUNA) is placed under the Gran Sasso mountain. Thanks to the environmental background reduction provided by its position, many reactions involved in hydrogen burning has been measured directly at astrophysical energies. Based on this progress, currently there are efforts in several countries to construct new underground accelerators. The exciting science that can be probed with these new facilities will be highlighted.

DOI:10.5506/APhysPolB.45.137
PACS numbers: 25.40.Ep, 25.40.Lw, 26.20.Cd, 26.65.+t

1. Introduction

Nuclear processes generate the energy that makes stars shine. Moreover, they are responsible for the synthesis of the elements (and isotopes) in stars. As a matter of fact, hydrogen, helium, and all isotopes until lithium and beryllium are synthesized during the Big Bang Nucleosynthesis (BBN). All other nuclei are produced during the different characteristic phases of the star evolution [1].

* Presented at the XXXIII Mazurian Lakes Conference on Physics, Piaski, Poland, September 1–7, 2013.

The understanding of these nuclear processes is the goal of nuclear astrophysics and, in particular, the knowledge of the nuclear cross sections involved in that processes. The astrophysically relevant energy range is given by the folding of two strongly energy dependent functions [1, 2]: the Maxwell–Boltzmann velocity distribution and the cross section of charged particle induced reactions. The folding results in a structure called the Gamow peak, which peaks at the energy E_{G} (called the Gamow energy)

$$E_{\mathrm{G}} \approx 0.1220 \left(Z_1^2 Z_2^2 \mu\right)^{\frac{1}{3}} T_9^{\frac{2}{3}} \,, \tag{1}$$

where $Z_{1,2}$ are the charges of the two reaction partners, $\mu = m_1 m_2/(m_1{+}m_2)$ their reduced mass, and $T_9 = T/10^9$ K is the temperature of the astrophysical scenario under study. The Gamow energy of nuclear reactions taking place in the Sun, with its core temperature of $T_9 \approx 0.016$, is typically 20 keV depending on the precise reaction, leading to cross sections in the range of pbarn and below. As a matter of fact, in this energy range the cross section is highly reduced by the effect of the Coulomb repulsion and the nuclear reactions can occur only via tunnel effect. In particular, the cross section can be written as

$$\sigma(E) = \frac{S(E)}{E} \exp(-2\,\pi\,\eta) \,, \tag{2}$$

where $S(E)$ is the astrophysical factor (which contains the nuclear physics information) and η is the Sommerfeld parameter, given by

$$2\,\pi\,\eta = 31.29\, Z_1\, Z_2 (\mu/E)^{1/2} \,, \tag{3}$$

μ is the reduced mass (in units of a.m.u.), and E is the center-of-mass energy (in units of keV).

Due to these small cross section values, the rate of the reactions, characterized by a typical energy release of a few MeV, is too low, down to a few events per year, in order to stand out from the laboratory background. In many cases, it is not possible even to reach energy values close to the Gamow peak and extrapolations are needed, leading to substantial uncertainties. A way to handle that background problem is to go in an underground environment. As a matter of fact, the natural shielding provided by an underground site will guarantee a reduction of the cosmic flux of orders of magnitude leading to the success of experimental nuclear physics. LUNA (Laboratory for Underground Nuclear Physics) [3, 4] is placed under the Gran Sasso National Laboratories of INFN. Two accelerators were used during years. First, a 50 kV accelerator (hereafter LUNA1) [5] and then a 400 kV accelerator (hereafter LUNA2) [6].

Under the Gran Sasso Laboratory, the muon flux is reduced by a factor 10^6 and the neutron flux by a factor of 1000 [7]. Further background reduction in the region below 3 MeV in the gamma spectrum can be achieved by implementing a shielding made by copper and lead [8]. A review of the results achieved by the LUNA Collaboration will be presented in this paper combined with a discussion on the future projects for nuclear astrophysics in underground with a MV accelerator.

2. Solar hydrogen burning

Hydrogen burning in the Sun proceeds mainly by the proton–proton chain (*p*–*p* chain, Fig. 1), with a 0.8% contribution from the carbon–nitrogen–oxygen cycle (CNO cycle) [9]. The basic processes are by now well understood, leading to the so-called standard solar model [10] that explains both helioseismological data and neutrino observations. The main uncertainty affecting this model, the solar neutrino puzzle, has been spectacularly solved by large neutrino detectors [11–13, *e.g.*] showing that the missing solar neutrinos have undergone flavour oscillation.

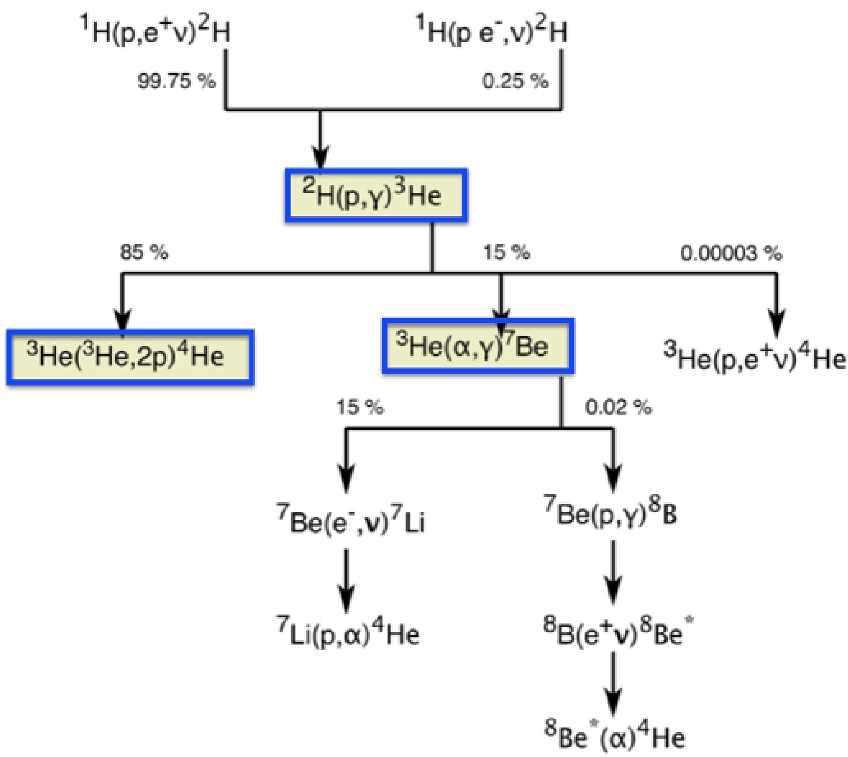

Fig. 1. Reactions scheme of the *p*–*p* chain. The reaction studied by LUNA are highlighted with arrows.

LUNA started its work studying the ^{3}He(^{3}He,2p)^{4}He reaction since there was the discussion on a possible resonance at the Gamow peak energy [14, 15]. This study was done by using the LUNA1 50 kV accelerator. This reaction was studied directly at the energy of the Gamow peak ruling out the resonance existence [16, 17]. The ^{2}H(p,γ)^{3}He reaction, responsible for the production of ^{3}He, was also studied at LUNA1 [18].

The neutrino fluxes emitted by the Sun are strictly correlated with the nuclear processes involved in the hydrogen burning (see Fig. 1 and Fig. 2). The LUNA2 400 kV accelerator program was focused on these processes achieving important results. The ^{3}He(α,γ)^{7}Be reaction was studied by using both the gamma prompt detection [19, 20] and the activation techniques [21, 22] finding a perfect agreement within the two methods. This result was important not only to reduce the systematics, but also to solve the discrepancy previously shown in experiments based on the two different techniques. The ^{3}He(α,γ)^{7}Be reaction reaction controls the ^{7}Be and ^{8}B neutrinos and it is also fundamental for the production of ^{7}Li during the Big Bang Nucleosynthesis (BBN).

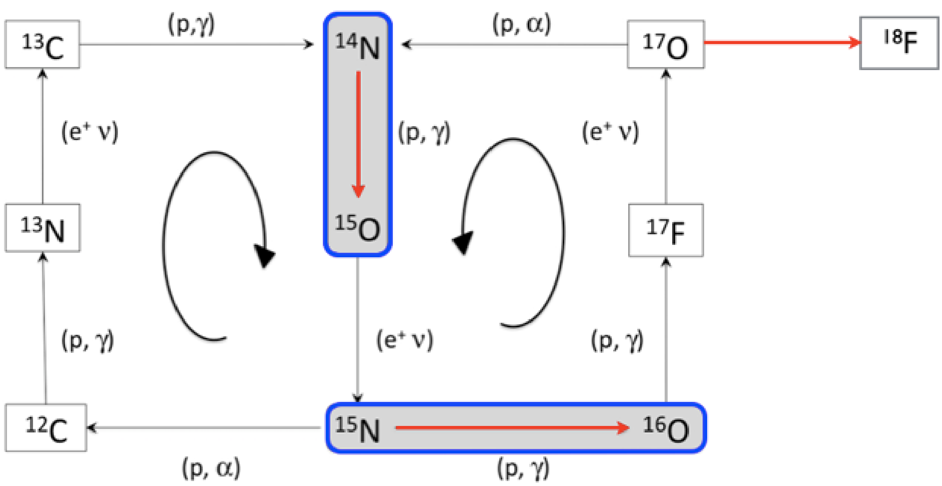

Fig. 2. Reactions scheme of the first and second CNO cycles. Some reactions studied by LUNA are highlighted.

The CN neutrino fluxes are governed by the ^{14}N(p,γ)^{15}O reaction. It is the bottleneck of the first CNO cycle and, therefore, the ^{13}N and ^{15}O neutrinos are controlled by this reaction. The LUNA Collaboration started the study of this reaction by performing two different experiments: one characterised by solid target setup and HPGe detector. This kind of setup allows to study separately all branchings and to perform R-matrix analysis [23, 24]. A second setup, made of a windowless gas target and a 4π-BGO detector, was used to to measure the total cross section in a wide range of energy (down to 70 keV in the center of mass) thanks to the high efficiency provided by the BGO [25, 26]. In those experiments, the cross section was found lower by a factor of 2 with respect to the reported value in NACRE [27] with considerably effects on the neutrino fluxes from the Sun and the age of globular clusters [28].

Recently, a new precise knowledge of the $^{14}\mathrm{N}(p,\gamma)^{15}\mathrm{O}$ cross section has been raised to solve the so-called Solar Composition Problem [9]: the conflict between helioseismology and the new metal abundances (*i.e.* the amount of elements different from hydrogen and helium) that emerged from improved modelling of the photosphere [29]. As a matter of fact, the CNO neutrino flux is decreased by about 30% in going from the high to the low metallicity scenario. This way, it will be possible to test whether the early Sun was chemically homogeneous [30], a key assumption of the standard Solar Model. In order to reduce the nuclear uncertainties in the solar model, a new measurement was performed reaching the final value of $S_{1,14}(0) = 1.57\pm0.13$ keV barn [31, 32].

2.1. Second, third CNO cycles, and the Mg–Al

In recent years, the LUNA Collaboration focused its attention on several reactions involved in hydrogen burning Nova explosion. The first reaction studied in this program was the $^{15}\mathrm{N}(p,\gamma)^{16}\mathrm{O}$. This is the link from the first to the second CNO cycle and it was studied intensively at the LUNA accelerator. Data acquired with a gas target setup and natural nitrogen (which contains a 0.37% of $^{15}\mathrm{N}$) to study the $^{14}\mathrm{N}(p,\gamma)^{15}\mathrm{O}$ reaction were analysed to determine the $^{14}\mathrm{N}(p,\gamma)^{15}\mathrm{O}$ cross section in the energy range from 230 keV down to 90 keV in the center of mass [33]. After that, two new experiments were performed by using $^{15}\mathrm{N}$ enriched solid targets ([34] and reference therein). The LUNA measurements cover totally the Gamow peak in Nova explosion, where the $^{15}\mathrm{N}(p,\gamma)^{16}\mathrm{O}$ is mainly important and the cross section was found to be lower than a factor of 2 with respect what reported in the NACRE database [27]. This leads to a reduction of $^{16}\mathrm{O}$ produced by Novae of a 40%.

Another important reaction for Nova scenarios is the $^{17}\mathrm{O}(p,\gamma)^{18}\mathrm{F}$ which is the link from the second and third CNO cycle.

The $^{17}\mathrm{O}(p,\gamma)^{18}\mathrm{F}$ reaction was investigated from 2011 to 2013. In particular, the ratio between the reaction rates of $^{17}\mathrm{O}(p,\alpha)^{14}\mathrm{N}$ ($Q = 1.2$ MeV) and $^{17}\mathrm{O}(p,\gamma)^{18}\mathrm{F}$ ($Q = 5.6$ MeV) channels is one of the most important parameters for the galactic synthesis of $^{17}\mathrm{O}$, the stellar production of radioactive $^{18}\mathrm{F}$, and for predicted O isotopic ratios in premolar grains [35, 36].

Since the ^{18}F is a radionuclides with a half life of $\approx$ 110 min, the cross section has been derived both by detecting the prompt gamma rays and by counting the 511 keV γs emitted by the ^{18}F decay. The results are perfectly in agreement reducing considerably the systematic uncertainties [37]. The LUNA results affect not only the direct capture evaluation, but the 183.3 keV resonance strength was also measured with a value of $\omega\gamma = (1.67 \pm 0.12)\mu$eV. As a matter of fact, the LUNA measurements cover the whole Gamow peak referred to Nova scenarios reducing by a factor of 4 the uncertainty on this reaction in stellar models and, in particular, on the oxygen and fluorine isotopes produced in Nova explosions [37]. The very low uncertainty obtained in this experiment was possible thank to an intensive study of the target, realised and tested directly by the LUNA group with IBA and SIMS technique [38].

Now, the LUNA Collaboration is preparing a new effort to study the (p, α) channel on ^{17}O at astrophysical energies. To reach this goal, a new chamber has been constructed which allows to place 8 silicons detectors in backward directions (the setup scheme is reported in Fig. 3). The setup improves the efficiency which is a crucial parameter in measuring nuclear reaction at such low energies. The goal of this project is to measure by the end of this year the 65 keV resonance strength of the $^{17}\mathrm{O}(p, \alpha)^{14}\mathrm{N}$ reaction.

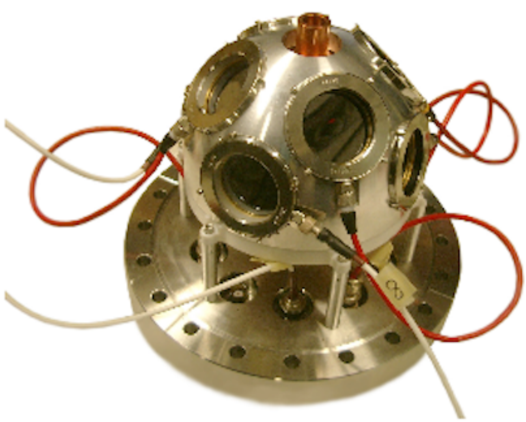

Fig. 3. Picture of the scattering chamber. The beam enters the chamber from the top which is connected with the cold trap.

The study of the CNO cycles is the natural precursor for the hydrogen burning in Mg–Al cycles. The problem of the ^{26}Al production is one of the most interesting cases [39]. LUNA measured precisely several resonances for $^{24,25}\mathrm{Mg}(p, \gamma)^{26,27}\mathrm{Al}$ in order to reduce the uncertainties on those reactions as requested in the astrophysical models [40, 41]. The impact of the LUNA results is discussed in details in a recent work [42].

3. Big Bang Nucleosynthesis

The ^{3}He(α,γ)^{7}Be reaction has an important role in solving the problem of the Spite plateau [43]. LUNA measured this reaction in the Gamow peak for Big Bang Nucleosynthesis reducing the uncertainties to 3% overall. Another problem concerning lithium isotopes has been raised recently: the ^{6}Li has been measured to be 3 orders of magnitude higher than what expected in BBN [44, 45]. While it is generally believed that ^{6}Li is produced by cosmic-ray spallation over the lifespan of the universe, the ^{6}Li observations in halo stars seem to suggest a primordial origin instead. For ^{6}Li production in the Big Bang, the main nuclear physics unknown is the ^{2}H(α,γ)^{6}Li reaction rate. The setup used to study this reaction is already described in details [46]. The scattering chamber was filled with high purity deuterium gas. The accelerated deuterium particles, after Rutherford scattering with the α-beam, interact with the gas itself producing the two reactions: ^{2}H$(d,n)^3$He and ^{2}H$(d,p)^3$H. In particular, the neutrons emitted by the ^{2}H$(d,n)^3$He were responsible for a high beam induced background in the γ-spectrum. A long and detailed study of this background was required in order to perform the analysis of the data [46, 47]. The precise knowledge of the background was achieved by the comparison of experimental measurement and Monte Carlo simulations able to reproduce the experimental data.

4. Science case for a future higher-energy accelerator underground

Recent advances in astronomy and astrophysics require nuclear data at energies that are higher than the high-energy limit of LUNA2.

Most notably, the ^{12}C(α,γ)^{16}O reaction still eludes experimental and theoretical efforts to pin down its precise rate [48]. This reaction, together with the triple-α reaction [49], determines the ratio of carbon to oxygen at the end of helium burning, a value that has wide-ranging impacts on the nucleosynthesis of heavier elements.

Whereas a direct ^{12}C(α,γ)^{16}O study at the relevant energy of 300 keV is impossible due to the forbiddingly-low absolute yield, a study in a low-background environment such as LUNA at higher energies can help improve necessary extrapolations by providing constraints at energies where there are currently no data. The study of this reaction is based on a precise knowledge of the targets, since the background induced by the parasitic (α,γ) reaction on ^{13}C can overwhelm the signal of the ^{12}C(α,γ)^{16}O reaction if the isotopic ratio ^{12}C/^{13}C is less than 10^5 (at least three order of magnitude higher than in natural carbon). The LUNA Collaboration has started a deep investigation on ^{12}C enriched targets and their stability, by performing analysis tests on different backings and cleaning techniques and to understand the behaviour of the produced targets against irradiated charge. Those tests are performed at the Laboratori Nazionali di Legnaro and they will continue also in 2014 in order to have a complete understanding of the targets and in order to keep better under control the production techniques used in their creation. This work is essential for the success of the ^{12}C(α,γ)^{16}O cross section measurements.

Another important open issue of nuclear astrophysics is the neutron source reactions. In particular, the ^{13}C(α, n)^{16}O and ^{22}Ne(α, n)^{25}Mg reactions. They are responsible for the production on neutrons involved in the slow neutron capture process, called the astrophysical s-process. Whereas those reactions are the subject of intensive experimental study [50, *e.g.*], so far the reactions actually producing the neutrons have not yet been measured in the relevant energy range since they should be addressed by an underground accelerator.

A third topic is to complement some of the proton- and α-capture reactions studied at the LUNA2 accelerator at higher energy. Such a continuation is particularly important for the Big Bang reactions ^{3}He(α,γ)^{7}Be and ^{2}H(α,γ)^{6}Li, where the present LUNA2 400 kV machine can only cover the lower part of the relevant energy region.

5. Future underground accelerator facilities

Based on the successes of the LUNA Collaboration, around the world several efforts are underway to install high-current, stable-beam accelerators in underground sites. LUNA-MV project was started in order to install a 3 MV machine in the underground laboratories of Gran Sasso. The new accelerator has already been financed by the Italian government and it should be installed in the next year at the Gran Sasso Laboratory. The synergy between the existing LUNA2 and the new LUNA-MV accelerator will allow to perform reaction studies in a wide range of energies with complete understanding of the setups involved. The planned DIANA facility at the Deep Underground Science Laboratory DUSEL in the Unites States also includes a megavolt and a lower-energy machine. Another project is under discussion at the Canfranc underground laboratory in the Pyrenees, Spain. As part of a staged approach, even an accelerator laboratory in a shallow-underground facility such as Felsenkeller (Dresden, Germany) is under consideration.

At present, the existing 400 kV LUNA2 machine continues its scientific program outlined here. The next few years will show where this highly successful approach will eventually be complemented by one or more higher-energy accelerators underground. The technique is sufficiently mature to address not only the data needs of the astrophysics community, but it has the potential to benefit also the astroparticle and other communities.

The work at LUNA is carried out in the framework of the LUNA Collaboration; see *e.g.* Ref. [46] for an author list. Financial support by OTKA K101328, NN83261, DFG (BE 4100/2-1), and NAVI is also gratefully acknowledged.

REFERENCES

[1] C. Iliadis, *Nuclear Physics of Stars*, Wiley-VCH, 2007.

[2] C. Rolfs, W. Rodney, *Cauldrons in the Cosmos*, University of Chicago Press, Chicago 1988.

[3] H. Costantini *et al.*, *Rep. Prog. Phys.* **72**, 086301 (2009).

[4] C. Broggini, D. Bemmerer, A. Guglielmetti, R. Menegazzo, *Annu. Rev. Nucl. Part. Sci.* **60**, 53 (2010).

[5] U. Greife *et al.*, *Nucl. Instrum. Methods* **A350**, 327 (1994).

[6] A. Formicola *et al.*, *Nucl. Instrum. Methods* **A507**, 609 (2003).

[7] D. Bemmerer *et al.*, *Eur. Phys. J.* **A24**, 313 (2005).

[8] A. Caciolli *et al.*, *Eur. Phys. J.* **A39**, 179 (2009).

[9] A.M. Serenelli, S. Basu, J.W. Ferguson, M. Asplund, *Astrophys. J. Lett.* **705**, L123 (2009) [`arXiv:0909.2668 [astro-ph.SR]`].

[10] J.N. Bahcall, M.H. Pinsonneault, *Phys. Rev. Lett.* **92**, 121301 (2004).

[11] J. Hosaka *et al.*, *Phys. Rev.* **D73**, 112001 (2006).

[12] I. Ahmad *et al.*, *Phys. Rev.* **C74**, 065803 (2006).

[13] C. Arpesella *et al.*, *Phys. Rev. Lett.* **101**, 091302 (2008).

[14] W.A. Fowler, *Nature* **238**, 24 (1972).

[15] V.N. Fetysov, Y.S. Kopysov, *Phys. Lett.* **B40**, 602 (1972).

[16] M. Junker *et al.*, *Phys. Rev.* **C57**, 2700 (1998).

[17] R. Bonetti *et al.*, *Phys. Rev. Lett.* **82**, 5205 (1999).

[18] C. Casella *et al.*, *Nucl. Phys.* **A706**, 203 (2002).

[19] D. Bemmerer *et al.*, *Phys. Rev. Lett.* **97**, 122502 (2006).

[20] G. Gyürky *et al.*, *Phys. Rev.* **C75**, 035805 (2007).

[21] F. Confortola *et al.*, *Phys. Rev.* **C75**, 065803 (2007).

[22] H. Costantini *et al.*, *Nucl. Phys.* **A814**, 144 (2008).

[23] A. Formicola *et al.*, *Phys. Lett.* **B591**, 61 (2004).

[24] G. Imbriani *et al.*, *Eur. Phys. J.* **A25**, 455 (2005).

[25] A. Lemut *et al.*, *Phys. Lett.* **B634**, 483 (2006).

[26] D. Bemmerer *et al.*, *Nucl. Phys.* **A779**, 297 (2006).

[27] C. Angulo *et al.* [NACRE Coll.], *Nucl. Phys.* **A656**, 3 (1999).

[28] G. Imbriani *et al.*, *Astron. Astrophys.* **420**, 625 (2004).

[29] C. Pena-Garay, A.M. Serenelli, `arXiv:0811.2424 [astro-ph]`.

[30] W.C. Haxton, A.M. Serenelli, arXiv:0902.0036 [astro-ph.SR].

[31] M. Marta *et al.*, *Phys. Rev.* **C78**, 022802(R) (2008).

[32] M. Marta *et al.*, *Phys. Rev.* **C83**, 045804 (2011).

[33] D. Bemmerer *et al.*, *J. Phys. G* **36**, 045202 (2009).

[34] A. Caciolli *et al.*, *Astron. Astrophys.* **533**, A66 (2011).

[35] C. Fox *et al.*, *Phys. Rev.* **C71**, 055801 (2005).

[36] J.R. Newton *et al.*, *Phys. Rev.* **C81**, 045801 (2010).

[37] D.A. Scott *et al.*, *Phys. Rev. Lett.* **109**, 208001 (2011).

[38] A. Caciolli *et al.*, *Eur. Phys. J.* **A48**, 144 (2012).

[39] C. Iliadis *et al.*, *Astrophys. J. Suppl. Series* **193**, 16 (2011).

[40] B. Limata *et al.*, *Phys. Rev.* **C82**, 015801 (2010).

[41] F. Strieder *et al.*, *Phys. Lett.* **B707**, 60 (2012).

[42] F. Strieder *et al.*, *Astrophys. J.* **763**, 100 (2012).

[43] M. Spite, F. Spite, *Nature* **297**, 483 (1982).

[44] V. Smith, D. Lambert, P. Nissen, *Astrophys. J.* **408**, 262 (1993).

[45] M. Asplund *et al.*, *Astrophys. J.* **644**, 229 (2006).

[46] M. Anders *et al.*, *Eur. Phys. J.* **A49**, 28 (2013).

[47] M. Anders *et al.*, in preparation.

[48] L. Buchmann, C. Barnes, *Nucl. Phys.* **A777**, 254 (2006).

[49] H. Fynbo *et al.*, *Nature* **433**, 136 (2005).

[50] M. Heil *et al.*, *Phys. Rev.* **C77**, 015808 (2008).