Underground nuclear astrophysics and the Sun

Carlo Broggini
(the LUNA Collaboration)
Istituto Nazionale di Fisica Nucleare
Sezione di Padova
I-35131 Padova, ITALY

1 Introduction

Thermonuclear reactions that generate energy and synthesize elements take place inside the stars in a relatively narrow energy window: the Gamow peak. In this region, which is far below the Coulomb energy, the reaction cross-section σ(E) drops almost exponentially with decreasing energy E:

$$\sigma(E) = \frac{S(E)}{E}\, exp(-2\,\pi\,\eta) \tag{1}$$

where $S(E)$ is the astrophysical factor and η is given by $2\,\pi\,\eta = 31.29\, Z_1\, Z_2 (\mu/E)^{1/2}$. Z_1 and Z_2 are the charges of the interacting nuclei in the entrance channel, μ is the reduced mass (in amu), and E is the center of mass energy (in keV).

The extremely low value of the cross-section has always prevented its measurement within the Gamow peak mainly because of the cosmic ray induced background. Instead, the observed energy dependence of the cross-section at high energies is extrapolated to low energy, leading to large uncertainties. In order to explore this new domain of nuclear astrophysics two electrostatic accelerators have been installed underground in the Gran Sasso Laboratory by the LUNA (Laboratory for Underground Nuclear Astrophysics) Collaboration: a 50 kV accelerator [1] and a 400 kV one [2]. The mountain provides a natural shielding equivalent to at least 3800 meters of water which reduces the muon and neutron fluxes by a factor 10^6 and 10^3, respectively. After 18 years LUNA still remains the only underground accelerator facility existing in the world. During this period its activity has been mainly devoted to the study of the key reactions of the proton-proton chain and of the CNO cycle.

2 In search of the resonance

The initial underground activity has been focused on the ^{3}He(^{3}He,2p)^{4}He cross section measurement within the solar Gamow peak (16-28 keV). A resonance at the thermal energy of the Sun was suggested long time ago [3] [4] to explain the observed ^{8}B solar neutrino flux: it would decrease the relative contribution of the alternative reaction ^{3}He(α,γ)^{7}Be, which generates the branch responsible for ^{7}Be and ^{8}B neutrino production in the Sun. A narrow resonance with a peak S-factor 10-100 times the value extrapolated from high energy measurements could not be ruled out with the pre-LUNA data (such an enhancement is required to reduce the ^{7}Be and ^{8}B solar neutrinos by a factor 2-3).

Briefly, the 50 kV accelerator facility consisted of a duoplasmatron ion source, an extraction/acceleration system, a double-focusing 90^{o} analyzing magnet, a windowless gas-target system and a beam calorimeter. The beam energy spread was very small (the source spread was less than 20 eV, acceleration voltage known with an accuracy of better than 10^{-4}), and the beam current was high even at low energy (about 300 μA). Eight thick (1 mm) silicon detectors of 5x5 cm^{2} area were placed around the beam inside the target chamber, where there was a constant ^{3}He gas pressure of 0.5 mbar.

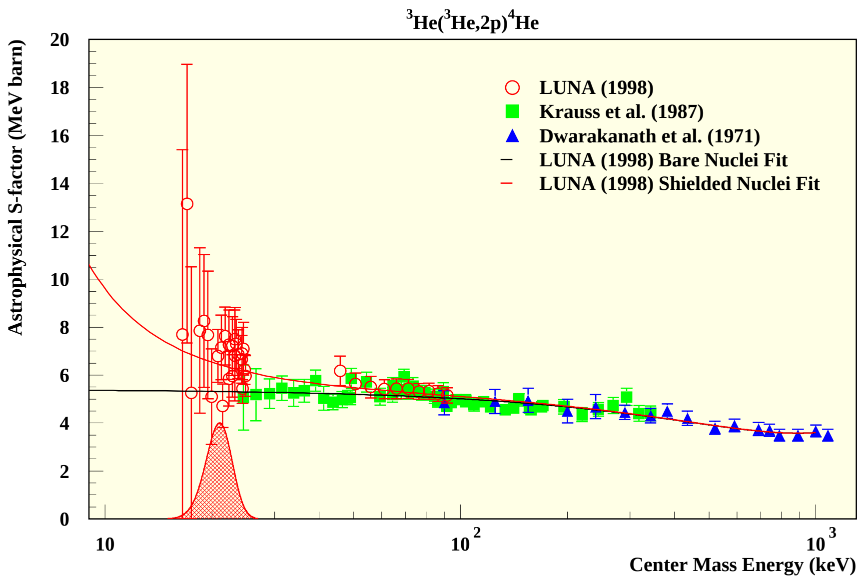

Figure 1: Astrophysical S(E)-factor of ^{3}He(^{3}He,2p)^{4}He.

The simultaneous detection of 2 protons has been the signature which unambiguously identified a ^{3}He(^{3}He,2p)^{4}He fusion reaction (detection efficiency: 5.3± 0.2, Q-value of the reaction: 12.86 MeV). No event fulfilling the selection criteria was detected during a 23 day background run with a ^{4}He beam on a ^{4}He target. Figure 1 shows the obtained results together with two existing measurements [5][6] of the astrophysical factor $S(E)$. The cross section varies by more than two orders of magnitude in the measured energy range. At the lowest energy of 16.5 keV it has the value of 0.02 pb, which corresponds to a rate of about 2 events/month, rather low even for the "silent" experiments of underground physics. The obtained result [7] showed that the ^{3}He(^{3}He,2p)^{4}He cross section does not have any narrow resonance within the Gamow peak of the Sun. Consequently, the astrophysical solution of the ^{8}B and ^{7}Be solar neutrino problem based on its existence has been ruled out. With ^{3}He(^{3}He,2p)^{4}He LUNA provided the first cross section measurement of a key reaction of the proton-proton chain at the thermal energy of the Sun. In this way it also showed that, by going underground and by using the typical techniques of low background physics, it is possible to measure nuclear cross sections down to the energy of the nucleosynthesis inside stars.

3 The ^{7}Be and ^{8}B solar neutrino flux

^{3}He$(\alpha,\gamma)^7$Be (Q-value=1.586 MeV) is the key reaction for the production of ^{7}Be and ^{8}B neutrinos in the Sun since their flux depends almost linearly on the ^{3}He$(\alpha,\gamma)^7$Be cross section. The error on $S_{3,4}$, 9.4% [8] is the main nuclear limitation to the extraction of physics from the ^{8}B and ^{7}Be neutrino flux measurements [9] [10]. The capture reaction is dominated, at low energies, by the non-resonant direct capture mechanism to the ground state and to the 429 keV first excited state of ^{7}Be. The cross section can be determined either from the detection of the prompt γ ray or from the counting of the produced ^{7}Be nuclei. The latter requires the detection of the 478 keV γ due to the excited ^{7}Li populated in the EC decay of ^{7}Be (branching ratio of $10.44 \pm 0.04\,\%$, $T_{1/2} = 53.22 \pm 0.06$ days). Both methods have been used in the past to determine the absolute cross section in the energy range $E_{c.m.} \geqslant 107$ keV (see [11] [12] and references therein) but the $S_{3,4}$ extracted from the measurements of the induced ^{7}Be activity are 13% higher [8] than the values obtained from the detection of the prompt γ-rays.

The underground experiment has been performed with the ^{4}He$^+$ beam from the 400 kV accelerator in conjunction with a windowless gas target made of oxygen free high conductivity copper, chosen because of its radioactive cleanness, and filled with ^{3}He at 0.7 mbar. The beam enters the target chamber through a 7 mm diameter collimator and it is stopped on a power calorimeter placed 35 cm downstream. The ^{7}Be nucleus produced by the ^{3}He$(\alpha,\gamma)^7$Be reaction inside the ^{3}He gas target are implanted into the calorimeter cap (thanks to the forward kinematics and low lateral straggling). After the irradiation, this cap (7 cm diameter) is removed and placed in front of a germanium detector for the measurement of the ^{7}Be activity.

In the first phase of the experiment we obtained the ^{3}He$(\alpha,\gamma)^7$Be cross section from the activation data [13] [14] alone, i.e. by counting the ^{7}Be nuclei collected on the calorimeter cap. Their uncertainty of 4 % (systematic and statistical combined in quadrature) is comparable to or lower than previous activation studies at high energy and lower than prompt-γ studies at comparable energy. However, the claimed discrepancy between the results obtained with the two different methods can not be solved by activation (or prompt γ) data only, even if very precise.

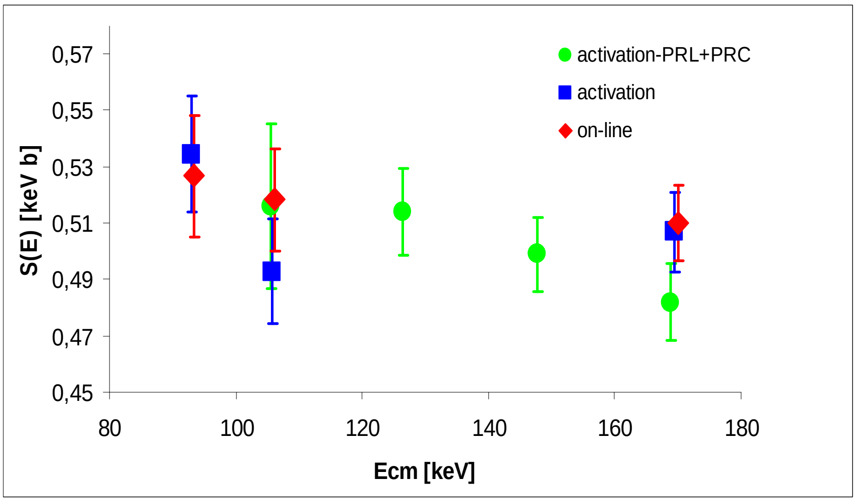

Figure 2: Astrophysical S-factor for ^{3}He$(\alpha,\gamma)^7$Be obtained with the activation method only (circles) and with activation (squares) and prompt γ (diamonds) simultaneously

As a matter of fact, in the second phase of the experiment we performed a new high accuracy measurement using simultaneously prompt and activation methods. The prompt capture γ-ray is detected by a 135 % relative efficiency ultra-low background HPGe detector placed in close geometry with the target. The germanium detector is surrounded by a 5 cm copper + 25 cm lead shielding and everything is closed inside an anti-radon box. At energies higher than 0.5 MeV we measured a background rate of 4.1 count/h/kg, one order of magnitude only worse than the best ultra-low background germanium set-up running in Gran Sasso (in spite of the presence of the beam-pipe entering our shielding and of the calorimeter inside the target chamber). Data have been collected at $E_{c.m.}$ = 170, 106, 93 keV. In this interval the cross section varies from 10.25 nbarn to 0.23 nbarn, with a total error of about 4%. Beam induced background has been measured with a 400 keV α beam on a ^{4}He gas target: no counts have been observed in addition to laboratory background. Figure 2 shows the astrophysical factor obtained with both methods simultaneously [15] and with activation only, during the first phase of the experiment. As we can see, the two methods give the same result within the quoted experimental error. Recently, similar conclusions have been reached in a new simultaneous activation and prompt experiment [16] which covers the $E_{c.m.}$ energy range from 330 keV to 1230 keV.

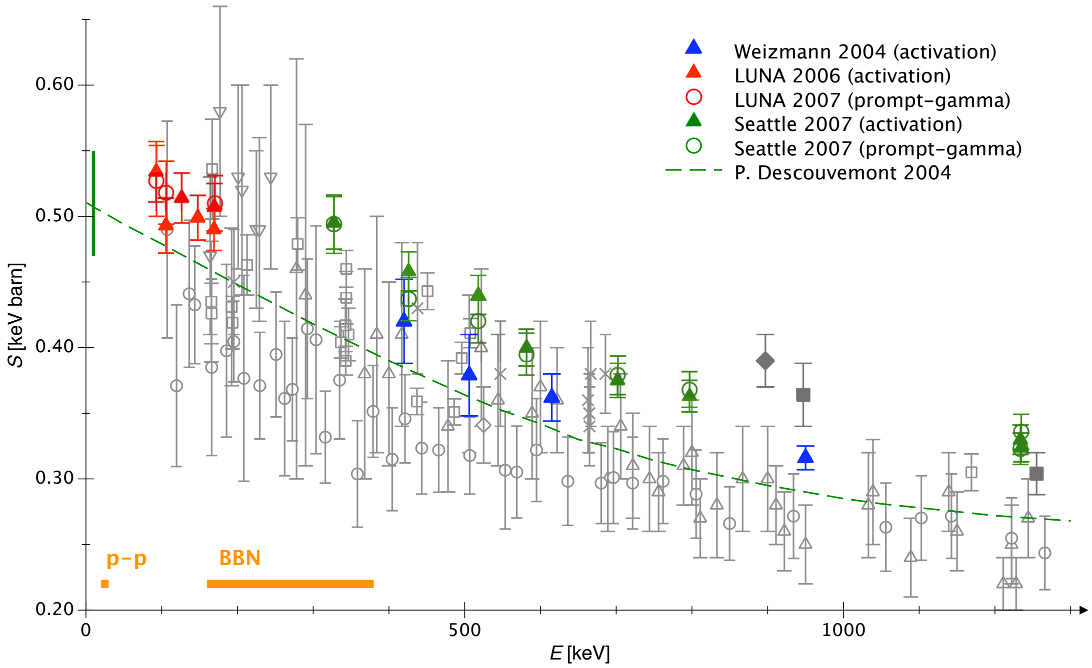

Figure 3: Astrophysical S-factor for $^3He(\alpha,\gamma)^7Be$. The results from the modern, high precision experiments are highlighted. Horizontal bars show the Gamow peak of the Sun and of the Big Bang Nucleosynthesis.

The energy dependence of the $^3He(\alpha,\gamma)^7Be$ cross section seems to be theoretically well determined [8]. The only free parameter is the normalization. If we rescale the fit of [17] in Figure 3 to our data we obtain $S_{3,4}(0)$=0.560±0.017 keV barn, to be compared to the value of 0.53±0.05 used in the Standard Solar Model. Thanks to our small error, the total uncertainty on the ^8B solar neutrino flux goes from 12 to 10%, whereas the one on the ^7Be flux goes from 9.4 to 5.5% [18]. This is particularly important for the Borexino experiments which is now running to achieve a precise measurement of the ^7Be neutrino flux from the Sun.

4 The CNO cycle and the metallicity of the Sun

In our Sun the CNO cycle accounts for just a small fraction of the nuclear energy production, whereas the main part is supplied by the proton-proton chain. $^{14}N(p,\gamma)^{15}O$ (Q-value of the reaction: 7.3 MeV) is the slowest reaction of the cycle and it rules its energy production rate. In particular, it is the key reaction to know the ^{13}N and ^{15}O solar neutrino flux, which depends almost linearly on this cross section. The energy region studied so far in nuclear physics laboratories is well above the region of interest for the CNO burning in astrophysical conditions (in particular, the solar Gamow peak is between 20 and 33 keV).

In the first phase of the LUNA study, data have been obtained down to 119 keV energy [19] [20] with solid targets of TiN (typical thickness of 80 keV). A 126% HpGe, placed at 55^o from the beam direction and at distances between 1.5 and 20.5 cm from the target, detected the γ rays. A detector with excellent energy resolution is necessary in order to unambiguously separate the different contribution to the cross section. As a matter of fact, five different radiative capture transitions contribute to the ^{14}N(p,γ)^{15}O cross section at low energy: ground state, 6.79, 6.17, 5.24 and 5.18 MeV. Since they differently depend on the energy, each of them has to be measured and extrapolated to the low energy region. Finally, the total cross section is given by the sum of the different contributions.

The total cross section can be measured at very low energies by using a γ ray detector with very high efficiency (to compensate for the rapidly decreasing cross section) as well as a very pure, thin and stable ^{14}N target. All this has been achieved in the second phase of the LUNA study with a large 4π BGO summing detector (about 70% efficiency and 8% resolution in the energy region between 6 and 8 MeV) and with a windowless gas target [21] (the chamber is designed to fit inside the central hole of the BGO crystal detector). Figure 4 shows our results [22], corrected for the electron screening effect [23] (10% and 3% effect at 70 and 150 keV, respectively). At the lowest energy of 70 keV we measured a cross section of 0.24 pb, with an event rate of 11 counts/day from the reaction. In Figure 4 we see that our data starts at a much lower energy than the previous direct experiments [24][25][26], while overlapping over a wide energy range. We remark the excellent agreement with the R-matrix fit from the LUNA study with the germanium detector set-up [20].

The results we obtained first with the germanium detector data [19][20] and then with the BGO set-up [22] are about a factor two lower than the existing extrapolation at very low energy [8][27]. As a consequence the CNO neutrino yield in the Sun is decreased by about a factor two [28, 10], with respect to the estimates. The lower cross section is affecting also stars which are more evolved than our Sun. In particular, the age of the Globular Clusters is increased by 0.7-1 Gyr [28, 29] and the dredge-up of carbon to the surface of AGB stars is much more efficient [8].

The main conclusion from the LUNA data has been confirmed by an independent study at higher energy [26]. However, there is a 15% difference between the total S-factor extrapolated by the two experiments at the Gamow peak of the Sun. In particular, this difference arises from the extrapolation of the capture to the ground state in ^{15}O, a transition strongly affected by interference effects between several resonances and the direct capture mechanism. In order to provide precise data for

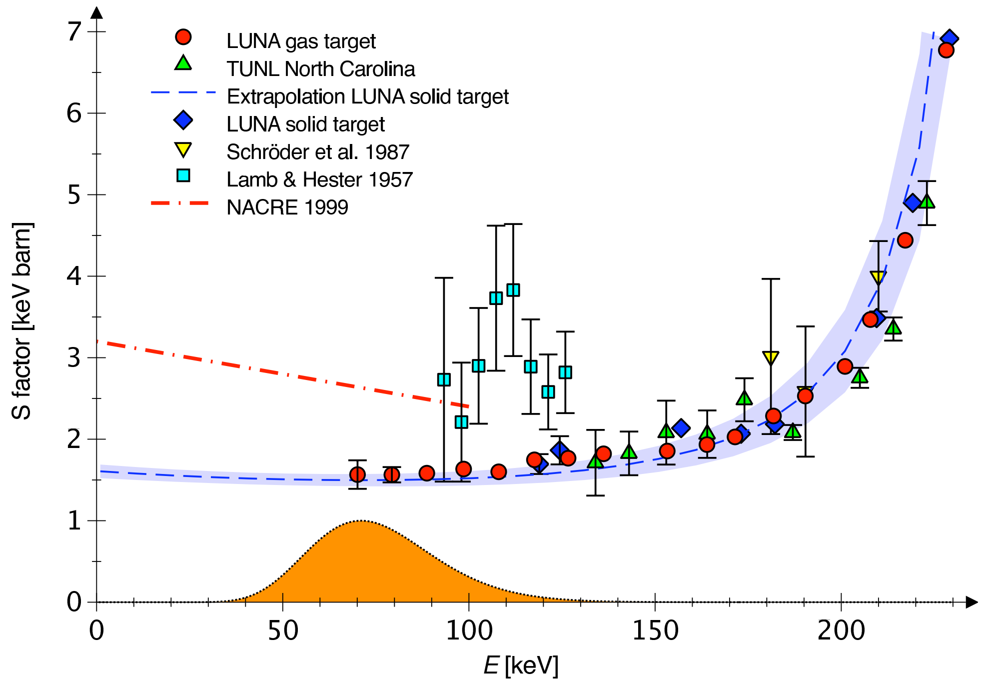

Figure 4: Astrophysical S(E)-factor of $^{14}N(p,\gamma)^{15}O$ as function of the center of mass energy E. The errors are statistical only. The Gamow peak for T_6=60 is also shown.

the ground state capture we performed a third phase of the $^{14}N(p,\gamma)^{15}O$ study.

Low energy measurements of the radiative capture to the ground state in ^{15}O are hampered by the systematic uncertainty due to the correction for the summing effect: primary and secondary gamma rays from the strong cascade transitions which are detected in coincidence and have the same signature as a true ground state capture gamma ray. In the new experiment we used a segmented Clover germanium detector [31] to reduce the summing correction and, in order to obtain sufficient statistics, we concentrate on the beam energy region immediately above the 259 keV resonance, where precise data effectively constrain the R-matrix fit for the ground state transition. Thanks to these improvements we could finally reduce to 8% the total error on the S-factor: $S_{1,14}(0)=1.57\pm0.13$ keV barn [32]. Thanks to this relatively small error it will soon be possible to measure the metallicity of the central region of the Sun by comparing the detected CNO neutrino flux with the predicted one [33]. As a matter of fact, the CNO neutrino flux is decreased by about 35% in going from the high to the low metallicity scenario [34] .

The solar phase of LUNA has almost reached the end and a new and rich program of nuclear astrophysics mainly devoted to study the Mg-Al and Ne-Na cycles has already started about 2 years ago. There is only one reaction, which we are studying now, still significant for solar neutrinos: ^{15}N(p,γ)^{16}O, which is the leak reaction from the first CNO cycle to the second one, where ^{17}F neutrinos are produced (their flux from the Sun is expected to be about 2 orders of magnitude lower than the ^{13}N and ^{15}O ones).

5 Conclusions

Underground nuclear astrophysics started almost 18 years ago with the goal of exploring the fascinating domain of nuclear astrophysics at very low energy. During these years LUNA has proved that, by going underground and by using the typical techniques of low background physics, it is possible to measure nuclear cross sections down to the energy of the nucleosynthesis inside stars. In particular, the measurements of ^{3}He(^{3}He,2p)^{4}He within the Gamow peak of the Sun has shown that nuclear physics was not the origin of the solar neutrino puzzle.

The cross section of ^{3}He$(\alpha,\gamma)^7$Be has been measured with two different experimental approaches and with a 4% total error. Thanks to this small error, the total uncertainty on the ^{7}Be solar neutrino flux has been reduced to 5.5%. Many years after the pioneering measurement of the ^{3}He$(\alpha,\gamma)^7$Be cross section performed in 1959 [35], nuclear physics does not give anymore a dominant contribution to the uncertainties of the solar neutrino flux.

Finally, the study of ^{14}N(p,γ)^{15}O has shown that the expected CNO solar neutrino flux has to be decreased by about a factor two, with an error small enough to pave the way for a measurement of the central metallicity of the Sun.

References

[1] U. Greife et al., Nucl. Instr. Meth. A **350**, 327 (1994).

[2] A. Formicola et al., Nucl. Instr. Meth. A **507**, 609 (2003).

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

[4] V.N. Fetysov and Y.S. Kopysov, Phys. Lett. B **40**, 602 (1972).

[5] A. Krauss et al., Nucl. Phys. A **467**, 273 (1987).

[6] M.R Dwarakanath and H. Winkler, Phys. Rev. C **4**, 1532 (1971).

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

[8] E.G. Adelberger et al., Rev. Mod. Phys. **70**, 1265 (1998).

[9] G. Fiorentini et al., astro-ph/0310753.

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

[11] M.Hilgemeier et al., Z. Phys. A **329**, 243 (1988).

[12] B.S. Nara Singh et al., Phys. Rev. Lett. **93**, 262503 (2004).

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

[14] G. Gyurky et al., Phys. Rev. C **75**, 035805 (2007).

[15] F. Confortola et al., Phys. Rev. C **75**, 065803 (2007).

[16] T.A.D. Brown et al., Phys. Rev. C **76**, 055801 (2007).

[17] P. Descouvement et al., Data Nucl. Data Tables **88**, 203 (2004).

[18] C. Pena Garay, private communication,(2006).

[19] A. Formicola et al., Phys. Lett. B **591**, 61 (2004).

[20] G. Imbriani et al., Eur. Phys. J.A **25**, 455 (2005).

[21] C. Casella et al., Nucl. Instr. Meth. A **489**, 160 (2002).

[22] A. Lemut et al., Phys. Lett. B **634**, 483 (2006).

[23] H. Assenbaum et al., Z. Phys. A **327**, 461 (1987).

[24] W. Lamb and R. Hester, Phys. Rev. **108**, 1304 (1957).

[25] U. Schroeder et al., Nucl. Phys. A **467** 240 (1987).

[26] R.C. Runkle et al., Phys. Rev. Lett. **94** 082503 (2005).

[27] C. Angulo et al., Nucl. Phys. A **656**, 3 (1999).

[28] S. Degl'Innocenti et al., Phys. Lett. B **591**, 61 (2004).

[29] G. Imbriani et al., Astronomy and Astrophysics **420**, 625 (2004).

[30] F. Herwig and S.M. Austin, Astrophysical Journal **613**, L73 (2004).

[31] Z. Elekes et al., Nucl. Instr. Meth. A **503**, 580 (2003).

[32] M. Marta et al., Phys. Rev. C **78**, 022802 (2008).

[33] W.C. Haxton and A.M. Serenelli., arXiv: 0805.2013, (2008).

[34] J.N. Bahcall et al., Astrophysical Journal **621**, L85 (2005).

[35] H.D. Holmgren and R.L. Johnston, Phys. Rev. **113**, 1556 (1959).