CNO neutrinos and metallicity of stars

Stefano Davini[1]

[1]Gran Sasso Science Institute, L'Aquila AQ 67100, Italy

DOI: http://dx.doi.org/10.3204/DESY-PROC-2016-05/25

The detection of neutrinos resulting from the CNO cycle would be the first direct evidence of the nuclear process that is believed to fuel massive stars. A precise measurement of the CNO solar neutrino fluxes would also help resolving the solar metallicity problem, as the predicted fluxes strongly depend on the inputs of the solar modelling. This articles, part of the Magellan 16 proceedings, reviews the connections between CNO neutrinos and solar metallicity, and the experimental attempts to detect them.

1 Introduction

CNO neutrinos are the neutrinos emitted in the CN and NO bi-cycle, one of the two set of fusion reactions in the Sun. The reactions in the CNO bi-cycle which involves the emission of neutrinos are the following:

$$
\begin{aligned}
{}^{13}\mathrm{N} &\rightarrow {}^{13}\mathrm{C} + e^+ + \nu_e \qquad (1.19\,\mathrm{MeV}), & (1)\\
{}^{15}\mathrm{O} &\rightarrow {}^{15}\mathrm{N} + e^+ + \nu_e \qquad (1.73\,\mathrm{MeV}), & (2)\\
{}^{17}\mathrm{F} &\rightarrow {}^{17}\mathrm{O} + e^+ + \nu_e \qquad (1.74\,\mathrm{MeV}), & (3)
\end{aligned}
$$

where the energy in parenthesis is the kinetic energy available to the final states of the reactions. The relevance of the CNO bi-cycle to the total luminosity of the Sun is estimated to be of the order of $\sim 1\%$: the contribution to the energy budget of the CNO reactions is marginal in Sun-like stars and therefore the flux of the CNO neutrinos is low, in the ballpark of one hundredth of the *pp* solar neutrino flux, and hard to determine experimentally.

Nevertheless, a precision measurement of the CNO neutrino flux would be of paramount importance in astrophysics: the accuracy of the physical description of the Sun provided by Solar Standard Models (SSMs) has been challenged by developments in stellar spectroscopic techniques over the last decade. An experimental determination of CNO neutrino fluxes is likely the only probe to settle the challenge.

The accuracy of the description of the physics of the Sun is critical because of the fundamental role that Solar Standard Models play in our understanding of the Universe. The Solar Standard Model is the calibration input for stellar evolution and plays a fundamental role in cosmology. Examples of the role of the SSM as source of calibration in astrophysics and cosmology are the following: convection models in stars are calibrated forcing solar models to reproduce present day solar radius and temperature, the evolution of metals and helium in the Universe needs input from both Big Bang Nucleosynthesis and initial SSM composition, the SSM is used as a benchmark against additional physics processes in stars.

2 The Solar abundance problem

The agreement between solar models and helioseismology has been altered after new spectroscopic determinations of the photosphere composition [1]. The new determinations were obtained with an advanced three-dimensional hydrodynamic model instead of a one-dimensional model, better atomic and molecular data, and non local thermodynamic equilibrium (NLTE) calculations. Using the new input, the abundances of C, N, O in the Sun are lowered by 20-30%. The new abundances are challenging for the SSM, because the previous agreement with helioseismic data is lost.

Does this disagreement question the validity of the Solar Standard Models or stellar models in general? The answer is not easy. "It seems clear that the low metallicity solar abundances are here to stay", says Serenelli [2]. A good consequence of the Solar abundance problem is that it motivated further work on solar models, such as nuclear reaction rates, radiative opacities, and state equations.

Solar opacities and CNO neutrinos play a major role in the Solar abundance problem. A suitable change of solar opacity profile produces same effects on helioseismic observable and neutrino fluxes of a change of solar composition, *except for CNO neutrinos*. CNO neutrinos can thus break the degeneracy between solar abundances and radiative opacities.

3 Solar neutrinos and solar abundancies

This section is an informal review of the experimental determination of the solar neutrino fluxes and what the determinations can tell us about the Sun. Both the experimental determination and SSM predictions are subject to rapid changes over time, so the values reported here are truncated at the first significant digit or given as order of magnitude. Any reader interested in more digits can find them in the references.

The solar neutrino detectors which are operative at present day are Borexino [3], 300 ton (fiducial) liquid scintillator detector at Laboratori Nazionali del Gran Sasso (LNGS) in Italy, and Super-Kamiokande [4], 22.5 kton (fiducial) water Cherenkov detector at the Kamioka mine in Japan. Borexino is engaged in the spectroscopy of solar neutrinos, which is possible due to the low threshold (as low to detect *pp* neutrino recoils on electrons) and the ultra-pure detector conditions. Super-Kamiokande is exploiting its big mass and directionality capabilities to perform a precision measurement the flux solar neutrinos which recoils on electrons with kinetic energy above 3.5 MeV, which are essentially ^{8}B neutrinos (the flux of *hep* neutrinos is to low to allow for a detection at present time).

The neutrinos emitted in the *pp* and *pep* reactions are the ones whose fluxes are predicted with the highest accuracy by the SSM, because of the luminosity constraint. The uncertainty of the *pp* flux prediction in the SSMs is below the per-mille level, while the uncertainty of the *pep* flux is at the percent level. The neutrino fluxes from these reactions are not directly sensitive to the Solar abundances, but to the radiative opacities. The flux of *pp* and *pep* reactions is indeed mostly driven by the core temperature, therefore to the radiative gradient determined by the opacity. Neutrinos from *pp* and *pep* reactions are not good probes for the Solar abundances, but they may be excellent probes of the core temperature if their flux is measured with enough precision, and they provide a test of the solar luminosity.

The experimental accuracy is about 10% for *pp* neutrinos (Borexino, [5]) and about 25% for *pep* neutrinos (Borexino, [6]). The determination of the *pp* neutrino interaction rate in Borexino is challenging because of the backgrounds due to of ^{14}C. The determination of the *pep* neutrino interaction rate in Borexino is challenging because of the low statistics (few events per day in the region of interest and the fiducial volume) and the backgrounds due to the cosmogenic ^{11}C and the radiogenic ^{210}Bi.

^{7}Be and ^{8}B solar neutrinos are emitted in the proton-proton chain, therefore their fluxes are subject to the same degeneracy between the core temperature (then radiative opacity) and the Solar abundances described above. The experimental determination of the ^{7}Be and ^{8}B solar neutrino flux is more precise than their theoretical counterpart in the SSMs. The best measurement of the ^{7}Be solar neutrino flux is from Borexino [7], with an accuracy of about 5%. The uncertainty in the SSM is about 7%. The best measurement of the ^{8}B solar neutrino flux is from Super-Kamiokande [8], with an accuracy of about 3%. The uncertainty in the SSM is about 14%.

^{8}B solar neutrinos deserve a few more sentences of merit, even if a bit off-topic. The measurement of the ^{8}B solar neutrino interaction rate in the SNO experiment, exploiting both neutral current (sensitive to all neutrino flavors) and charged current reactions (sensitive to electron neutrino only) in in D_2O, firmly established the flavor conversion of solar neutrinos. Art Mc. Donald, spokesperson of SNO, was awarded half of the Nobel prize in 2015, and the other half was awarded to Takashi Kajita of Super-Kamiokande for the discovery of the atmospheric neutrino oscillation in Super-Kamiokande.

Closing this off-topic paragraph on neutrino oscillation and history of physics, we return to CNO neutrinos. The temperature profile in the solar core is established by the proton-proton chain (and not by the CNO bi-cycle), therefore the experimental measurement of CNO neutrino flux may be used to probe the Solar abundances, being the flux linear in the abundance of carbon and nitrogen. The only experimental limit on the CNO neutrino flux is from Borexino [6]. The limit is about 40% higher than the high metallicity SSM predictions, therefore the Solar abundances of metals are basically unconstrained.

4 The challenges of CNO neutrino detection

It should be clear from the previous sections that CNO neutrinos are the perfect probe to determine the solar abundances. The goal should be clear: measure the CNO neutrino fluxes to get the abundances. Why this has not been done? Because an experimental determination of the CNO neutrino flux is extremely, extremely, challenging.

The reason why CNO neutrinos are the best probe is also one of the reason why they are so hard to detect. The solar luminosity and the temperature in the core are driven by the proton-proton reactions, with the CNO bi-cycle reactions being a marginal source of energy in the Sun. This means that the CNO neutrino flux can discriminate between the high metallicity and low metallicity SSM models, breaking the degeneracy with the radiative opacity. But this also means that the CNO neutrino fluxes from the Sun are low, $3\text{–}5 \cdot 10^{8}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, at the level of 1% of the *pp* neutrino flux. The low flux alone would be not so much of a problem: ^{8}B neutrinos are even lower in flux (a factor hundred less), but many of their recoils have high enough energy to be detectable even with water Cherenkov detectors, at energy above backgrounds from radiogenic and cosmogenic radioactivity. The Nature is not so kind with CNO neutrinos: the CNO energy spectrum falls below 2 MeV, and this means being overwhelmed by natural radioactivity backgrounds.

Even if a large fraction of the CNO neutrino spectrum is above the Cherenkov emission threshold in water, CNO neutrinos are well below the experimental threshold of the water Cherenkov detector Super-Kamiokande (about 3.5 MeV). The only detector type available today for detecting CNO neutrinos are ultra-pure organic liquid scintillators. Borexino at LNGS *is the most radio-pure detector* between 200 keV and 2 MeV, among the detectors operated at present time and in the past. Even Borexino could only provide limits to the CNO neutrino flux, because of the residual radioactive backgrounds and the correlation with *pep* neutrinos in determining the fluxes with fit to the energy spectrum.

The main radioactive backgrounds in Borexino, which any future organic liquid scintillator detector for CNO neutrinos will have to fight, are the radiogenic ^{210}Bi and the cosmogenic ^{11}C.

^{210}Bi is a β^- emitter with end point 1.16 MeV and five days half-life. The real problem is that the spectral shapes of ^{210}Bi and electron recoils from CNO neutrinos are *very similar* and do not show distinct features like peaks. ^{210}Bi is part of the ^{238}U chain, its predecessor is ^{210}Pb and its daughter is ^{210}Po. ^{210}Bi and ^{210}Po are found not to be in secular equilibrium, therefore constraining the activity of ^{210}Bi from the rate of ^{210}Po (which is easier to measure) is not trivial (but not impossible *in principle*, as shown in [9]). It is particularly challenging to remove ^{210}Bi by purification methods [10]; it is indeed the only radiogenic β^- emitter in the phase-II of Borexino whose activity is above 10 decays per day per 100 tons (^{14}C is excluded in this evaluation).

^{11}C is a cosmogenic radioactive isotope, generated in the inelastic scattering of muons on ^{12}C, $\mu + ^{11}\mathrm{C} \rightarrow \mu + ^{12}\mathrm{C} + \mathrm{n}$. ^{11}C is a β^+ emitter with end point 1.98 MeV (including the energy from the annihilation of the electron-positron pair) and 20 minutes half-life. The background due to cosmogenic isotopes can be of course reduced by increasing the detector overburden. Another way to reduce the background is to track the muon and locate the neutron capture, then apply space-time cuts to exclude regions of the detector where it is more likely that ^{11}C was produced (and decays), like it was done in Borexino [11]. This method however sacrifices substantial fractions of the total exposure. Also, it is possible to constrain ^{11}C by exploiting the slightly different scintillation pulse shape for β^- and β^+ decay in liquid scintillators, mainly due to ortho-positronium formation [12].

5 The ideal CNO hunter

It should be clear to the reader that hunting CNO neutrinos is not an easy task. I will review here the features that a CNO neutrino *must* have in order to have some chances to perform a measurement.

The detector must be large. The ideal scale is kiloton. The CNO neutrino fluxes and cross sections are low, therefore the detector should be large enough to collect a relevant number of CNO interactions. Large detectors also allow for better fiducialization, which is important because the low energy tails of the external background (due mainly to ^{208}Tl and ^{214}Bi γ-rays) must be negligible around the CNO neutrino endpoint.

High energy resolution. It is of paramount importance to discriminate the CNO neutrino electron recoils from the radioactive background and the residual solar neutrinos. In particular, the energy spectrum of ^{210}Bi decay and CNO neutrino electron recoils are very similar, and the risk is not being able to resolve the two components if the resolution is not high enough. Also in absence of any radioactive background (a dream detector), the spectrum due to CNO neutrinos must be identified below the spectrum of ^{7}Be and *pep* neutrinos.

Ultra-pure detector. In particular, the levels of ^{222}Rn, ^{210}Pb, ^{210}Bi, and ^{210}Po must be ultra-low. ^{210}Bi should be below the CNO interaction rate, which in Borexino is predicted to be 5 (3) decays per day per 100 tons in the high (low) metallicity SSM. Consider that it is *sufficient* to remove the contamination of ^{210}Bi to place *limits* on the CNO neutrino flux, but it is *necessary* to estimate the residual ^{210}Bi activity in the detector to *convincingly measure* the CNO neutrino flux.

Deep detector. Cosmogenic backgrounds must not be an issue. It is true that most of cosmogenic decays can be removed by space-time cuts, but these cuts usually remove a substantial fraction of the detector exposure.

Stable detector. In order to measure CNO neutrinos, the residual radioactive backgrounds in the detector must be known. The radioactive backgrounds should be stable in space in order to be measured with enough accuracy. In particular, there must be no convection moving radioactive contaminants around the detector and changing their concentration over time. Experiments should consider thermal insulation to prevent or decrease convective motions due to temperature changes in the experimental halls.

Particle identification. Discriminating α backgrounds from β backgrounds allows to tag ^{210}Po, ^{212}Bi-Po, and ^{214}Bi-Po, making it possible to evaluate the activity of branches in the ^{238}U and ^{232}Th chains, and investigate if the secular equilibrium condition is met. Discrimination of β radioactivity from γ radioactivity may be helpful to reduce external background and β^+ decays.

Directionality. Measuring the direction of recoil electrons, which is correlated to the incoming direction of neutrinos, would be tremendously helpful and nihil the relevance of mostly all internal radiogenic backgrounds. Unfortunately, today there is no demonstrated directional detection technology for neutrino recoils at 1 MeV, scalable to kiloton masses.

6 Future CNO hunters

Among experiments under construction, or ready to be approved, or proposed, there are few that may be good CNO hunters. This list is not exhaustive by purpose (and the space in this proceeding has a upper bound), therefore nobody should feel offended if their favorite experiment is not in the list.

SNO+ at SNOLab is a organic liquid scintillator detector with the advantages of being large (1 kton) and deep (the ^{11}C production rate should be reduced of a factor hundred respect to Borexino at LNGS). SNO+ may start a solar neutrino campaign after the neutrino-less double beta decay (in ^{130}Te) phase.

The JINPING Neutrino Experiment is a proposed organic liquid scintillator detector with the advantages of being even larger (20 kton) and even deeper (China JinPing Laboratory-II, already under construction, is going to be the deepest underground laboratory) [13]. In the letter of intent, one can read "We predict a capacity to discover solar neutrinos from the carbon-nitrogen-oxygen (CNO) cycle with more than 5 sigma of statistical significance".

ARGO at LNGS is a 200 ton fiducial two-phase liquid argon time projection chamber (LAr TPC) for direct dark matter WIMP searches [14]. LAr TPCs have the advantages of having higher Z and better scintillation light yield and resolution of organic liquid scintillators. Simulations in [14] show that "such a detector could measure the CNO neutrino rate with $\sim$15% precision".

Solar neutrinos are going to be a background for the next (or the next to next) generation of direct dark matter WIMP experiment. The reader should not be surprised of a possible growing interest in solar neutrino detection over the next decade(s).

7 Conclusion and outlook

There *is* a solar abundance problem. And it is likely that the new solar abundances are here to stay. The experimental measurement of the flux of neutrinos from the CNO bi-cycle can settle the problem. However, the experimental detection of CNO neutrinos is challenging. Some future projects may be able to detect CNO solar neutrinos.

Aknowledgments

I gratefully acknowledge the Organizers of Magellan 16 for the invitation.

Appendix A: Multidisciplinar workshop

Multidisciplinar workshops, like Magellan, are indeed very useful to strengthen the bonds between astrophysicist and particle physicists. Recalling a famous quotation from Feynman, even if we (or academia) split the topics in different subjects, the Nature does not.

A problem with multidisciplinary is that sometimes the lack of a common background is huge. Question time is very useful construct bridges over this gap. In the question time, I was asked if it is possible to detect neutrinos from other stars besides the Sun. The answer is no, except SuperNovae neutrinos. To convince yourself, you can try to compute the number of neutrino interactions detected in one year in a Borexino-like detector (Borexino detects about 200 neutrinos per day per 100 tons) from a Sun-like star one light year from us.

References

[1] M. Asplund *et al.*, Annual Review of Astronomy & Astrophysics, **47** 481 (2009).

[2] A. Serenelli, Eur. Phys. J. **A 52** 78 (2016).

[3] G. Alimonti *et al.*, Nucl. Instr. Meth. A **A600** 568-593 (2009).

[4] Y. Fukuda *et al.*, Nucl. Instr. Meth. A **A501** 418-462 (2003).

[5] G. Bellini *et al.*, Nature **512** 7515, 383-386 (2014).

[6] G. Bellini *et al.*, Phys. Rev. Lett **108** 051302 (2012) .

[7] G. Bellini *et al.*, Phys. Rev. Lett **107** 141302 (2011).

[8] K. Abe*et al.*, arXiv:hep-ex/1606.07538 (2016).

[9] F.L. Villante *et al.*, Phys. Lett. **B701** 336 (2011).

[10] G. Alimonti *et al.*, Nucl. Instr. Meth. A **A609** 58-78 (2009).

[11] G. Bellini *et al.*, Phys. Rev. **D89** 112007 (2014).

[12] D. Franco *et al.*, Phys.Rev. **C83** 0105504 (2011).

[13] J.F. Beacom *et al.*, arXiv:physics,ins-det/1602.01733 (2016).

[14] D. Franco *et al.*, arXiv:physics,ins-det/:1510.04196 (2015).