Detection of MeV scale neutrinos and the solar energy paradigm

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Abstract. The fundamental solar energy paradigm establishes that the energy in the Sun is due to a series of nuclear reactions which turn hydrogen into helium. In particular, for the Sun the fundamental reaction corresponds to \( p + p \rightarrow d + e^+ + \nu_e + 0.42 \text{ MeV} \). This is a very slow process which drives the evolution of the Sun over a timescale of \( 10^9 \) years. Electron neutrinos produced in the core interact only weakly and travel almost undisturbed from the core to the surface. They are a unique probe to explore the interior of stars. Observations of solar neutrinos are discussed in the paper. The solar energy paradigm proposed in 1938 by H. Bethe has been measured in realtime by Borexino at 10% level in 2014. This observation allows to probe the solar stability over a \( 10^3 \) years timescale. At present, solar neutrinos offer the opportunity to understand the new Solar Abundance Problem, that is our lack of knowledge of the chemical composition of the Sun. Therefore, improving solar neutrino measurements is of great interest for astrophysics. At the same time, a better determination of some astrophysical factors will reduce uncertainties on predictions to better identify a possible inadequate assumption in the solar model.

1. Introduction

The source of energy in our Sun and in H-burning stars makes electron neutrinos through the following process:

\[
4p \rightarrow ^4\text{He} + 2e^+ + 2\nu_e
\]  

Eq. (1) produces about 26.73 MeV of energy, including positrons annihilation. Neutrinos from Eq. (1) are known as solar neutrinos. These neutrinos have an average energy of 0.53 MeV and carry about 2% of the solar energy. The total energy per unit of time (luminosity) released by the Sun is \((2.40 \pm 0.01) \times 10^{39} \text{ MeV}/\text{s}\) [1]. Hydrogen burning works by means of two processes known as pp-chain and CNO-cycle. These processes consist of a number of interactions which turn hydrogen into helium as from Eq. (1) [2]. This solar energy paradigm was proposed in 1938 by H. Bethe in a comprehensive and systematic work [3]. However, the first proto idea behind this solar paradigm goes back to 1868 when Joseph N. Lockyer discovered helium on the solar surface. Another fundamental information in this puzzle came in 1956 when by means of radiometric methods applied on meteorites the age of the Earth was determined to be \((4.55 \pm 0.07) \times 10^9\) years. This observation can only be supported with a Sun driven by nuclear fusion as proposed by H. Bethe. Experimental evidence of this theory came in 1968 with the first measurement of solar neutrinos [4]. As a matter of fact, solar neutrinos can stream from the center to the surface of the Sun with an extremely low probability of interaction and carry information on the
nuclear processes taking place in the core of our star. Therefore, solar neutrinos are a unique probe to understand how stars work. In figure 1 we show the burning rate in stars as a function of the central temperature. The black dot shows the position of our Sun. In this case the size of the star is such that the dominant energy contribution comes from the pp-chain.

Figure 1. Burning rate in stars from the pp-chain and the CNO-cycle. For our Sun (black dot) the dominant contribution comes from the pp-chain.

The Solar Standard Model (SSM) is a general framework to study the characteristics of stars [2]. In particular, observation of solar neutrinos offer an opportunity to test the SSM and the use of some fundamental assumptions. The SSM is a reference model to understand how stars work. In the SSM it is assumed energy generation through hydrogen burning; hydrostatic equilibrium between the gravitational inward force and the one due to the pressure from the heat produced by nuclear fusion; the primordial core metal abundance equal to the today’s surface metal abundance (zero-age homogeneous Sun). In the SSM boundary conditions include the value of the present metal abundance on the surface, \((Z/X)_{surf}\), and the solar luminosity, \(L_\odot\) (\(X\) is the abundance of hydrogen and \(Z\) that of elements heavier than helium). The age, \((4.57 \pm 0.02) \times 10^9\) years, and the mass, \((1.9886 \pm 0.0003) \times 10^{30}\) kg, are fixed. The model which, after iterative evolution, matches the boundary conditions produces as output the present value for: the solar neutrino fluxes, the depth of the convective zone, the surface helium abundance, \(Y_{surf}\), the density and sound speed profiles. In figure 2 we show the solar neutrino fluxes at Earth and predicted uncertainties obtained by the SSM. It turns out that the pp-chain and CNO-cycle make neutrinos from a number of reactions. The most abundant neutrinos (91%) are named pp-neutrinos and are sub-MeV particles. The CNO neutrinos from \(\beta\) decays of \(^{13}\text{N}\), \(^{15}\text{O}\) and \(^{17}\text{F}\) account for only 0.8% of the total flux. The \(^8\text{B}\) neutrinos measured by Homestake...
in 1968 accounts for only 0.009%. In the SSM neutrino fluxes are given as a power function of fundamental parameters. As an example, the \( \nu_e \) and \( \nu_{\mu} \) fluxes are given as a power function of the luminosity constraint. The luminosity constraint corresponds to the assumption that \( L_\odot = L_\nu \), with \( L_\nu \) being the solar neutrino luminosity. In table 2 the pp flux is given with and without the luminosity constraint.

\[
\phi_{\text{pp}} \propto S_{11}^{+0.14} \cdot S_{33}^{+0.03} \cdot S_{34}^{-0.06} \cdot S_{1,14}^{-0.02} \cdot L_\odot^{+0.73} \cdot \tau_\odot^{-0.07} \cdot Op_\odot^{-0.14} \cdot (Z/X)^{-0.08} \\
\phi_{7\text{Be}} \propto S_{11}^{-0.97} \cdot S_{33}^{-0.44} \cdot S_{34}^{+0.88} \cdot L_\odot^{+3.56} \cdot \tau_\odot^{+0.69} \cdot Op_\odot^{-1.49} \cdot (Z/X)^{+0.59}
\]

where \( L_\odot \), \( \tau_\odot \) and \( Op_\odot \) are the solar luminosity, age and opacity, \( S_{ij} \) astrophysical factors for reactions taking place in the core of the Sun [2]. \( S_{33} \) for \( ^3\text{He} + ^3\text{He} \rightarrow ^4\text{He} + 2p \). \( S_{34} \) for \( ^3\text{He} + ^4\text{He} \rightarrow ^7\text{Be} + \gamma \). \( S_{11} \) for \( p + p \rightarrow ^2\text{H} + e^+ + \nu_e \). \( S_{1,14} \) for \( p + ^{14}\text{N} \rightarrow ^{15}\text{O} + \gamma \). The astrophysical factors are known at the level of 5 - 7% and give an important contribution to the predicted uncertainty of neutrino fluxes [1, 2]. For \( ^{7}\text{Be} \) the 5.2% (5.4%) experimental uncertainty on \( S_{33}(S_{34}) \) accounts for 2.2% (4.6%) in the uncertainty of the predicted value for the flux. Therefore, improving the error on astrophysical factors, it is important considering that \( ^{7}\text{Be} \) and \( ^{8}\text{B} \) fluxes are measured at 5% and 3% level, respectively.

Helioseismology, the study of propagation of acoustic waves in the solar interior, is another important method to probe the SSM in addition to solar neutrinos. In fact from helioseismology we could determine the depth of the convective zone and \( \gamma \text{surf} \). Before 2005 the SSM used as input for chemical abundances the so-called GS98 composition [5]. We point out that the CNO elements abundances can only be inferred from the solar photosphere. In 2005 a new model for the solar photosphere was proposed [6] and later revised in 2009 [7]. The SSM which makes use of this latter composition is referred to as SSM-AGSS09. The new model has led to a downward revision of the heavy elements abundances up to 30-40% with respect to SSM-GS98. The SSM developed with GS98 is in agreement with helioseismology measurements. On the contrary, the SSM developed with AGSS09 shows large disagreement. This is shown in figure 3. The AGSS09 is thought to be based on a much more robust understanding of the solar photosphere. This conflict between SSM predictions and helioseismology is known as the Solar Abundance Problem. At present this disagreement means that we do not know exactly the solar chemical composition. The zero-age homogeneous Sun assumption could be wrong.

The Solar Abundance Problem replaces the previous Solar Neutrino Problem. This latter has been known since 1968 following the first observation of solar neutrinos. The measured flux of solar neutrinos was only 1/3 of the predicted flux by the SSM. This deficit was later confirmed by other experiments using gallium [8, 9, 10], water [11, 12] and liquid scintillator [13]. This anomaly was understood in terms of neutrino oscillations [14]. In 2002 the SNO experiment proved that neutrino oscillations can solve the observed deficit [15]. The flux of \( ^{8}\text{B} \) was measured to be consistent with the SSM. Figure 4 shows the Solar Neutrino Problem with respect to GS98 predictions by the SSM.

2. Solar neutrinos observations and the solar energy paradigm

In this Section we review solar neutrino observations and discuss implications for the solar energy paradigm. In table 1 a summary of the solar neutrino experiments is provided [16]. At present two experiments, Super-Kamiokande and Borexino, are taking data in realtime on solar neutrinos. The aim of new measurements is to improve the understanding of the MSW [14] effect in the framework of solar neutrino oscillations and solve the Solar Abundance Problem. This latter target can only be solved by detecting CNO neutrinos. This might be possible in Borexino [16]. In table 2 solar neutrino measurements are reported together with SSM predictions. We notice that \( ^{8}\text{B} \) and \( ^{7}\text{Be} \) fluxes are measured with an uncertainty smaller than the one for predictions. The luminosity constraint corresponds to the assumption that \( L_\odot = L_\nu \), with \( L_\nu \) being the solar neutrino luminosity. In table 2 the pp flux is given with and without the luminosity constraint.
Figure 3. Comparison between the SSM predictions and helioseismology observations. Filled ellipse show 1 and 3σ contours for helioseismology measurements. The upper dashed ellipses correspond to the high-metallicity SSM with GS98. The lower dashed ellipses correspond to the low-metallicity SSM with AGSS09.

Figure 4. The Solar Neutrino Problem. The dashed horizontal line corresponds to the SSM predictions with GS98 abundances. Measurements from solar neutrino experiments are shown.

Detection of pp solar neutrinos from $p+p \rightarrow d+e^++\nu_e+0.42$ MeV provides the opportunity to probe the slowest process which drives the evolution of our Sun on a $10^9$ years timescale and compare the neutrino luminosity with the solar luminosity. Moreover, due to the fact that photons produced in the core take some $10^5$ years to stream to the surface, this observation explores the solar variability over this time window. pp solar neutrinos have been detected in realtime by Borexino [17]. Because of the low energy carried by these neutrinos, the major challenges faced for this measurement are the content of $^{14}$C contamination in the liquid scintillator and the rate of pile-up events due to $^{14}$C. The $^{14}$C $\beta$ decay has an endpoint at 0.156 MeV, thus a low detection energy threshold is fundamental for such a measurement. The extreme radio purity of Borexino allows to perform this measurement with a threshold at 0.05 MeV. The flux measured in Borexino is equal to $\phi_{pp} = (6.6 \pm 0.7) \times 10^{10}$ cm$^{-2}$s$^{-1}$. From this measurement we could determine the neutrino luminosity: $L_\nu(pp - \text{chain})/L_\odot = 1.04 \pm 0.07$ and $L_{CNO}/L_{pp} < 0.08(2\sigma)$. SSM predicts that $L_{CNO}/L_{pp} \sim 0.7\%$. A direct measurement of the $L_\nu/L_\odot$ ratio is important to disregard any exotic energy production in the Sun. The pp solar neutrino measurement performed in Borexino in 2014 is a direct observation of the solar energy
paradigm proposed in 1938.

### Table 1. Solar neutrino experiments.

| Detector       | Active mass | Threshold [MeV] | Data taking |
|----------------|-------------|-----------------|-------------|
| Homestake      | 615 tons $C_2Cl_4$ | 0.814           | 1968-1994   |
| Kamiokande II/III | 3 kton $H_2O$         | 9/7.5/7.0      | 1986-1995   |
| SAGE           | 50 tons molten metal Ga | 0.233       | 1990-present|
| GALLEX         | 30.3 tons $GaCl_3 - HCl$ | 0.233       | 1991-1997   |
| GNO            | $GaCl_3 - HCl$         | 0.233       | 1998-2003   |
| Super-Kamiokande | 50 ktons $H_2O$         | 5            | 1996-2001   |
|                | $H_2O$            | 7            | 2003-2005   |
|                |                   | 4.5          | 2006-2008   |
|                |                   | 3.5          | 2008-present|
| SNO            | 1 kton $D_2O$        | 3.5          | 1999-2006   |
| Borexino       | 300 tons $C_9H_{12}$  | 0.2          | 2007-present|

### Table 2. Solar neutrino fluxes: best-fit results against predictions. Best-fit for pp are determined with and without the luminosity constraint.

| Source          | SSM-GS98 (high-Z) | SSM-AGSS09 (low-Z) | data                                      |
|-----------------|-------------------|--------------------|-------------------------------------------|
| $pp \times 10^{10} \text{ cm}^{-2}\text{s}^{-1}$ | 5.98 (1 ± 0.006)  | 6.03 (1 ± 0.006)  | 6.03 (1$^{+0.05}_{-0.01}$)                          |
|                |                   |                    | 6.3 (1 ± 0.06)                              |
| $pep \times 10^8 \text{ cm}^{-2}\text{s}^{-1}$ | 1.44 (1 ± 0.012)  | 1.47 (1 ± 0.012) | 1.63 (1 ± 0.21)                              |
| $^7\text{Be} \times 10^9 \text{ cm}^{-2}\text{s}^{-1}$ | 5.00 (1 ± 0.07) | 4.56 (1 ± 0.07) | 4.99 (1 ± 0.05)                              |
| $^8\text{B} \times 10^6 \text{ cm}^{-2}\text{s}^{-1}$ | 5.58 (1 ± 0.13) | 4.59 (1 ± 0.13) | 5.33 (1 ± 0.03)                              |
| CN-cycle $\times 10^6 \text{ cm}^{-2}\text{s}^{-1}$ | 5.25 (1 ± 0.14) | 3.76 (1 ± 0.14) | $< 6.3$ (95%)                                 |
| p-value         | 0.88              | 0.58              |                                           |

3. Conclusions
More than 40 years of solar neutrino observations has led to determine the most of the neutrino fluxes, some at a better accuracy than predictions (see table 2). The energy production of the Sun has been proved at 10% level and solar variability studied over a timescale of $10^5$ years. A fundamental challenge to face in the coming years is the detection of CNO neutrinos. This measurement could help solving the Solar Abundance Problem providing important information on the chemical composition of the Sun which is yet not well known. Solving this controversy could prove a basic assumption of the SSM is inadequate. At the same time, a better
experimental determination of astrophysical factors improves the opportunity to probe the SSM. In fact, $S_{34}$, $S_{17}$ and $S_{1,14}$ are known at 5.4%, 7.7% and 7.5%, respectively [1]. These uncertainties give a dominant contribution to the overall uncertainty in the predictions of $^7\text{Be}$, $^8\text{B}$ and CNO solar neutrino fluxes at the level of 5-8%. In conclusion, being the Sun a laboratory to understand how stars work, improve our understanding of the Sun is of great interest. This challenge needs an effort from experiments on solar neutrinos and from experiments which can make a better measurement of some astrophysical factors.

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