

Overview of Solar Neutrino Experiments

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Abstract. Solar neutrinos have played a major historic role in the development of neutrino physics and understanding of the fusion processes in the Sun. Neutrino experiments worldwide continue to measure neutrinos originating in the core of the Sun in the search for new insights. Recent years have marked the discovery of the carbon-nitrogen-oxygen fusion cycle, tackling the Sun metallicity problem, and the search for physics beyond the Standard Model.

1. Introduction

The Sun is powered by the two groups of thermonuclear reactions known as the pp chain and the carbon-nitrogen-oxygen (CNO) cycle. The result of both is the conversion of four protons into a ${}^4\text{He}$ nucleus releasing around 26 MeV. This energy is released in the form of photons or kinetic energy of produced particles. Neutrinos produced in different cycles can be distinguished by their energy spectra.

The biggest achievement of solar neutrinos is that they are actually *the* proof that fusion powers the stars. Neutrinos promptly escape the core of the Sun, and in mere 8 minutes they are observable at Earth, while even photons take 100 000 years to get from the core to the surface of the Sun. Solar neutrino experiments can provide information on fusion rates, stability of the Sun, and its metallicity (the abundance of the elements heavier than helium). Metallicity in turn predicts the opacity of solar plasma, the key factor in the size, temperature, and lifespan of a star. Solar neutrino fluxes depend on Sun's chemical composition and opacity, hence different Standard Solar models (SSM) predict different fluxes for various neutrino species. Currently, the metallicity of the Sun is not unequivocally determined, and low and high metallicity (LM and HM, respectively) classes of SSMs are available for the reference [1]. As history already showed, solar neutrinos are suitable to study not only the processes in the core of the Sun, but also the fundamental properties of neutrinos themselves. The neutrino flavour transition is the most intriguing one. Vacuum oscillations are predominant for low energy solar neutrinos, while neutrino flavour transition through a resonance known as the Mikheyev-Smirnov-Wolfenstein (MSW) effect dominates high energy neutrinos. The transition region between the two is of special interest for searches of possible deviations from MSW effect with large mixing angle, as well as exploring some exotic phenomena such as anomalous magnetic moment, or non-standard neutrino interactions.

The first experiment to detect neutrinos from the Sun was the Chlorine experiment of Ray Davis et al. at the Homestake mine in South Dakota [2]. These observations were supported by later measurements from gallium-based experiments: GALLEX [3]; SAGE [4]; and GNO [5]. These radio-chemical experiments can achieve very low energy thresholds, but perform



an integral measurement of all neutrinos above threshold, producing a single integrated flux measurement. Water Cherenkov experiments such as Super-Kamiokande (Super-K) and the Sudbury Neutrino Observatory (SNO) have higher thresholds, but performed real-time detection thus allowing extraction of both directional and spectral information, albeit accessing only 0.01% of the solar flux. This capability allowed Kamiokande-II to first demonstrate that the observed neutrinos were in fact coming from the Sun. Scintillator experiments, such as Borexino, demonstrated thresholds much lower than Cherenkov detectors and can also perform real-time detection.

2. Contemporary detectors with sensitivity to solar neutrinos

Borexino was a 270-tonne liquid-scintillator experiment that detects solar neutrinos by means of their weak elastic scattering off electrons. Borexino was located deep underground in the Laboratori Nazionali del Gran Sasso in Italy, under 3,800 m water equivalent of rock that suppresses the flux of cosmic radiation by a factor of 10^6 . This low level of background together with an unprecedented scintillator radiopurity has enabled real-time detection of solar neutrinos, including the first-time measurements of pp, pep, ^7Be , and CNO neutrinos. Borexino gathered data from 2007 to 2021.

Super-Kamiokande, a 50000-tonne water-Cherenkov neutrino detector, has been taking data since 1996. Kamioka site provides 2700 m.w.e. overburden for the experiment. Super-K has measured ^8B neutrinos using neutrino-electron scattering in the same manner as its predecessor, Kamiokande. In 2022, the Super-Kamiokande collaboration has finalized loading the water with Gadolinium, and will continue data taking with a neutron tagging ability.

The *SNO+* experiment is located at a 5890 m.w.e. depth in the SNOLAB underground laboratory in Canada. SNO+ re-uses the SNO detector structure, replacing heavy water with 780 tonnes of liquid scintillator. The first phase of SNO+ utilized 905 tonnes of ultra-pure water and provided both tests on the detector performance and physics results. Since 2021, SNO+ is completely filled with liquid scintillator and is taking relevant solar neutrinos data, in the following phase it will be loaded with ^{130}Te for neutrinoless double beta decay measurements.

3. Selected recent results

-The measurements of the fluxes

Borexino has performed the only measurements of low-energy neutrinos originating from pp-chain: pp, pep, and ^7Be neutrinos, and has improved the precision of these measurements over the last decade. Moreover, in 2020, the Borexino collaboration published the first measurement of neutrino from CNO-fusion cycle. Table 1 summarizes the latest rates (measured in counts per day per 100t) and fluxes values without any threshold; the first error is statistical, the second systematic. The rate-to-flux conversion assumes neutrino flavor conversion [6] with the neutrino oscillation parameters from [7]. In addition, Borexino has performed the ^8B neutrino flux measurement with the lowest threshold and put an upper limit on hep-neutrinos [8]. SNO holds the best upper limit on the challenging hep-neutrinos flux measurement. These neutrinos are the highest energy of the solar neutrino branches, and are produced furthest from the core. A measurement of this flux could offer insights into the solar density in the outer core.

The most precise published ^8B neutrino measurement fluxes are $2.53^{+0.31}_{-0.28}(\text{stat})^{+0.31}_{-0.10}(\text{syst}) \times 10^6 \text{ cm}^{-2}\text{s}^{-1}$ (SNO+) [10] and $(2.345 \pm 0.039) \times 10^6 \text{ cm}^{-2}\text{s}^{-1}$ (Super-K) [11], both with 5-MeV threshold and assuming no oscillations. Including the effects of oscillations the flux becomes $5.95^{+0.75}_{-0.71}(\text{stat})^{+0.28}_{-0.30}(\text{syst}) \times 10^6 \text{ cm}^{-2}\text{s}^{-1}$. SNO+ recent achievements in reducing backgrounds show promising results in obtaining cleaner more precise ^8B data sample with the same and lowered energy thresholds.

- Solar luminosity and stability

A precise measurement of pp neutrinos offers insight into solar luminosity, and the ability to

Table 1. The latest most-precise rates and fluxes of low-energy neutrinos. The shown result of ${}^7\text{Be}$ neutrinos contains the ground and excited state lines. The shown pep neutrinos result was obtained with high metallicity constraint on CNO neutrino flux.

	Rate[cpd/100t]	Flux[cm^2s^{-1}]	Reference
pp	$134 \pm 10_{-10}^{+6}$	$6.1 \pm 0.5_{-0.5}^{+0.3} \times 10^{10}$	Borexino (2018) [8]
${}^7\text{Be}$	$48.3 \pm 1.1_{-0.7}^{+0.4}$	$4.99 \pm 0.11_{-0.08}^{+0.06} \times 10^9$	Borexino (2018) [8]
pep	$2.43 \pm 0.36_{-0.22}^{+0.15}$	$1.27 \pm 0.19_{-0.13}^{+0.08} \times 10^8$	Borexino (2018) [8]
CNO	$6.7_{-0.8}^{+2.0}$	$6.6_{-0.9}^{+2.0} \times 10^8$	Borexino (2022) [9]

probe the luminosity constraint. Using the neutrino flux measurements, Borexino has obtained the Sun luminosity value of $(3.89_{-0.42}^{+0.35}) \times 10^{33} \text{ erg s}^{-1}$, that is consistent with the photon luminosity of $(3.846 \pm 0.015) \times 10^{33} \text{ erg s}^{-1}$. Considering that it takes around 10^5 years for radiation to flow from the energy-producing region to the surface of the Sun, this comparison proves also that the Sun has been in thermodynamic equilibrium over this timescale.

- Sun metallicity

Metallicity is a key input of the SSMs and is determined experimentally by the spectral analysis of the photosphere, sometimes complemented by studies of meteorites: while measurements and some from the past two decades [12] have been suggesting a lower content of heavy elements with respect to the earlier ones, the most recent results [13] point to a higher value. Noticeably, SSMs implementing the class of “low-metallicity” compositions fail to reproduce helioseismological measurements, while “high-metallicity” ones are in better agreement with them. Metallicity impacts the SSM predictions of ${}^8\text{B}$, ${}^7\text{Be}$, and CNO fluxes significantly, but in an indirect way. The metal content affects the solar opacity, which in turn impacts the Sun’s temperature profile, which ultimately controls the rate of nuclear reactions and thus neutrino emission. Thus deriving information on metallicity from the measurements of solar neutrinos presents a certain degree of ambiguity. However, in this respect, the CN cycle which is catalyzed by the C and N, is special: its flux has an additional, almost linear dependence on the abundances of these metals in the solar core, providing a unique handle for their non-ambiguous determination. Borexino has recently evaluated the C and N abundances in the Sun with respect to the H abundance for the first time with solar neutrinos. The result of $N_{CN} = 5.78_{1.00}^{+1.86} \times 10^4$ displays a 2σ tension with the LZ spectroscopic photospheric measurements. On the other hand, the CNO measurement used together with the ${}^7\text{Be}$ and ${}^8\text{B}$ solar neutrino fluxes, also measured by Borexino, permits to disfavour at 3.1σ C.L. the LZ, as an alternative to the HZ.

- Mikheyev-Smirnov-Wolfenstein (MSW) effect

The Super-Kamiokande (Super-K) experiment made a high statistics measurement of the flux of ${}^8\text{B}$ neutrinos via elastic scattering (ES), which is sensitive primarily to ν_e , but with some admixture of other flavors. This result was combined with the charged current (CC) measurement from SNO, an interaction that is sensitive only to ν_e at relevant energies, allowing a measurement of the pure ν_e flux [14]. Disagreement between the two at the 3σ level was evidence for some non-electron component in the solar neutrino flux. The follow-up SNO neutral current (NC) measurement, an interaction that is equally sensitive to all three flavors, confirmed at 5σ that the ν_e produced in the Sun’s core were changing flavor prior to detection on Earth [15]. Finally, the KamLAND liquid scintillator (LS) detector that confirmed that this flavor change was in fact due to oscillations, by observing the characteristic oscillation pattern in the spectrum of reactor neutrinos. Borexino measured the neutrino-electron survival probability, for the first time, in the vacuum regime with the pp and at its border with ${}^7\text{Be}$. Therefore with

SuperK and Borexino, the MSW model is confirmed both in vacuum and in matter regimes.

Although data exists in the transition region between vacuum- and matter-dominated oscillation, the precision is not yet sufficient to either confirm the MSW oscillation scenario, or to offer sensitivity to possible non-standard interaction (NSI) models. The latest relevant publications are [16] [17]. Additional data in this sensitive region, dominated by spectral measurements of ^8B neutrinos, would offer strong constraints on non-standard models, and further insights into the interaction of neutrinos with matter. Constraints in the transition region are currently dominated by spectral measurements of ^8B neutrinos.

- Day/night asymmetry

SNO and Super-K have sought evidence of the predicted regeneration of ν_e as neutrinos pass through the earth at night, due to matter effects [18] [17]. In the latest published dataset, Super-K have measured a $(-3.6 \pm 1.6(\text{stat}) \pm 0.6(\text{syst}))\%$ day/night rate asymmetry, and combining other datasets have observed a 2.9σ indication of this effect [11]. Borexino have also searched for day/night asymmetry, and placed strong constraints. Greater statistics are required to confirm the precise magnitude and nature of this effect.

- Directionality

The Borexino Collaboration demonstrated statistical direction reconstruction using early-time PMT hits [19]. SNO+ has indications of event-level directional sensitivity in LS data, enhanced by the current low fraction of PPO, which results in a slower scintillation time profile, enhancing the clarity of the prompt Cherenkov component.

4. Prospects for future measurements

The most recent upgrade to Super-K is the addition of gadolinium, a project known as SK-Gd, which will enhance neutron capture efficiency [20][21]. This can improve the separation of solar neutrinos from radioactive background from cosmic ray induced spallation, improving Super-K's sensitivity to the day/night effect and the ^8B spectral shape. Furthermore, upcoming Hyper-K with 250 ktonne total mass and 40% photocoverage is going to significantly contribute to statistics-limited high energy solar neutrino measurements. JUNO liquid scintillator experiment, currently under construction, has the potential to measure ^8B with the threshold of 2MeV, much lower than purely Cherenkov detectors. Finally, significant work is ongoing to develop Theia experiment that would be a truly "hybrid" detector – designed to leverage both Cherenkov and scintillation light together and improve the precision of solar neutrinos measurements among other physics goals.

5. Conclusion

Solar neutrinos continue to be an active field of research, with recent groundbreaking results and physics goals in both solar studies and fundamental neutrino interactions. Moreover, a diverse set of techniques have been used to observe solar neutrinos to date, and the latest developments and proof of concept pave further advancements in neutrino detection for solar neutrinos and beyond.

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