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Physics potential for detecting solar neutrinos with the JUNO experiment

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The Jiangmen Underground Neutrino Observatory (JUNO) is a next-generation neutrino experiment located in China. Although the main goals of JUNO are to determine the neutrino mass ordering (NMO) and to perform sub-percent precision measurements of oscillation parameters with reactor antineutrinos, its physics program is broader and includes studies on solar neutrinos. The JUNO central detector is an acrylic sphere 35.4 meters in diameter filled with 20 kt of liquid scintillator (LS). It is equipped with photomultiplier tubes (PMTs) of two types: 17,612 20-inch PMTs and 25,600 3-inch PMTs. The central detector is designed to provide an unprecedented energy resolution of 3% at 1 MeV. Although the target level of radiopurity of LS for performing the NMO analysis is set at 10^{-15} g/g of ^{238}U and ^{232}Th, the solar neutrino analysis targets a level below 10^{-16}-10^{-17} g/g.
The exceptional radiopurity of JUNO will enable the detection of neutrinos produced in the Sun in the pp chain — ^{8}B, ^{7}Be, pep neutrinos — as well as neutrinos from the CNO cycle. Depending on the exact achieved background level, JUNO will set stringent limits on the fluxes of ^{7}Be, pep and CNO neutrinos, potentially exceeding the limits of Borexino in a few years of data-taking.

The primary detection channel for solar neutrinos in JUNO is the neutrino-electron elastic scattering process. However, JUNO's large target mass of ^{13}C nuclei makes possible the first model-independent measurement of ^{8}B solar neutrinos via charged-current and neutral-current interactions on ^{13}C, complementing the elastic scattering channel.

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1. Introduction

Solar neutrinos play a dual role: while being messengers of the Sun, they can be used to investigate the nature of the Sun itself and vice versa, the Sun through solar neutrinos serves as a laboratory to study properties of the neutrinos and neutrino interactions with matter. Historically, the study of solar neutrinos significantly shaped the development of neutrino physics and astrophysics. As an example, the resolution of the "solar neutrino deficit" problem [1, 2] came through the discovery that neutrinos can transform between different flavors during their travel from Sun to Earth — a phenomenon called neutrino oscillations. This discovery proved that neutrinos have masses and was recognized by the 2015 Nobel Prize in physics. The Standard Solar Model (SSM) predicts that solar neutrinos are produced in the two primary nuclear fusion processes occurring in the Sun that convert hydrogen into helium: the proton-proton (pp)-chain and the CNO (carbon-nitrogen-oxygen) cycle. Solar neutrinos have different energy signatures and represent a natural source of neutrinos with energies up to $O(10)$ MeV as shown in Figure 1.

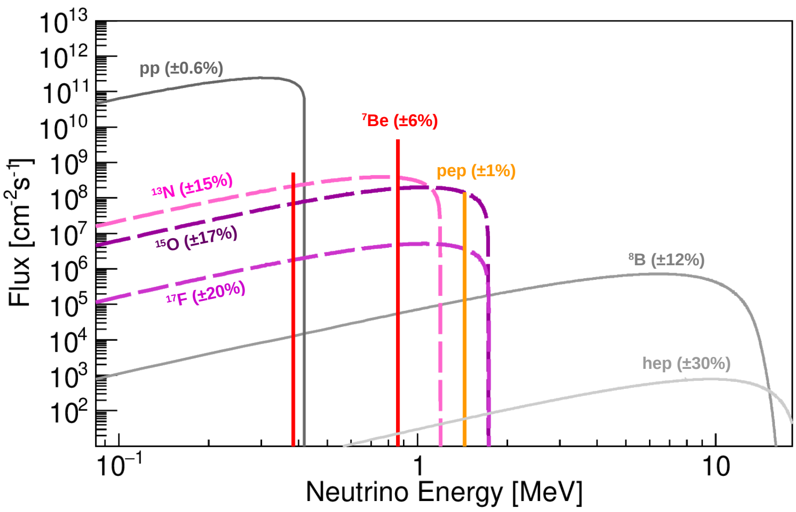

Figure 1: Energy spectra of solar neutrinos from the pp-chain (solid lines) and CNO cycle (dashed lines). The spectral shapes are taken from http://www.sns.ias.edu/~jnb/ and flux normalization from the HZ-SSM predictions given in [3]. The flux (vertical scale) is given in units of $cm^{-2}s^{-1}MeV^{-1}$ for continuum sources and in $cm^{-2}s^{-1}$ for monoenergetic sources. The values in parentheses show the corresponding relative uncertainties of the SSM predictions. Figure is taken from [4].

The dominant pp-chain accounts for nearly all solar energy production (99%) and generates pp, pep, hep, ^{7}Be, and ^{8}B neutrinos. The subdominant CNO cycle (1% of solar energy output), catalyzed by carbon, nitrogen, and oxygen nuclei, produces ^{13}N, ^{15}O, and ^{17}F neutrinos and serves as a direct probe of the Sun's heavy element composition — a key parameter that remains controversial in solar modeling and is directly related to the "solar metallicity problem". Note that all solar neutrinos, at the moment of their production, are electron neutrinos and change their flavor due to the neutrino oscillations. Figure 2 shows the pp-chain (left) and the CNO cycle (right) in detail.

Substantial experimental progress has been made by Borexino [6, 7] and Super-Kamiokande [8] via high-precision real-time spectroscopy of solar neutrinos based on elastic scattering off electrons.

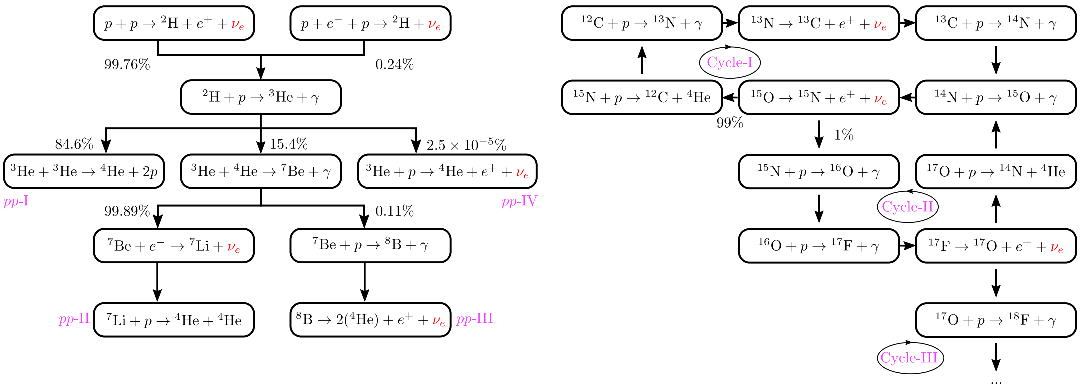

Figure 2: Nuclear reaction chains in the Sun: the dominant pp chain (left) and the CNO cycle (right) showing the production of different neutrino species. Figure is taken from [5].

The energy dependence of the electron neutrino survival probability P_{ee} measured for pp, ^{7}Be, pep, and ^{8}B neutrinos at Borexino [6] is compatible with the transition from the so-called vacuum to the matter-dominated region predicted by the Mikheyev-Smirnov-Wolfenstein (MSW) matter effect. Additionally, Borexino, thanks to its extraordinary radiopurity, observed solar neutrinos from the CNO cycle for the first time [7].

However, several open questions remain in solar neutrino physics. In neutrino oscillation physics, the transition region of P_{ee} is not fully explored since it is difficult to reach an analysis threshold for elastic scattering electrons to less than 3 (3.5) MeV in Borexino (Super-Kamiokande). The exact shape of the transition region is not only sensitive to Δm^2_{21} value, but can also be used to test new physics, such as non-standard interactions or the existence of sterile neutrinos. Additionally, solar physics, and especially the question of solar metallicity, will profit from more precise flux measurements of all neutrino components.

The next-generation Jiangmen Underground Neutrino Observatory (JUNO) [9], located in China, is uniquely positioned to answer open questions in solar and neutrino physics. With its exceptional combination of a massive liquid scintillator (LS) target of 20 kton, unprecedented energy resolution for this detector class ($3\%/\sqrt{E(\mathrm{MeV})}$), and exceptional radiopurity, JUNO will simultaneously provide precision spectroscopy of low-energy solar neutrinos and model-independent studies of high-energy components through multiple detection channels.

2. The JUNO detector

Although JUNO is primarily designed for the determination of the neutrino mass ordering [10] and the sub-percent precision measurement of the following three oscillation parameters: Δm^2_{21}, Δm^2_{31}, and $\sin^2\theta_{12}$ [11], its overall physics potential and program are richer [9]. It includes the study of neutrinos from many other sources, including the Sun [4, 12, 13].

The JUNO detector consists of several components with the main one being the Central Detector (CD). The CD is a large spherical volume, submerged in water, that sits in a laboratory 650 meters deep underground. JUNO's CD is composed of a 20 kton LS target housed within a spherical acrylic vessel 35.4 m in diameter. The CD is equipped with a sophisticated photodetection system that includes 43,212 photomultiplier tubes (PMTs) of two types: 17,612 20-inch PMTs and 25,600 3-inch PMTs, which are mounted on the surrounding stainless steel structure. This configuration provides an extensive total photo-coverage of ~78%, yielding high photoelectron (PE) statistics of ~1600 PEs per 1 MeV at the detector's center, leading to an unprecedented energy resolution for a liquid scintillator detector of approximately $3\%/\sqrt{E(\mathrm{MeV})}$. As of mid-2025, the experiment has successfully completed its construction phase and is finalizing the LS filling phase. Data-taking with the fully LS-filled detector is expected to begin within 2025.

The LS mixture is mainly composed of linear alkylbenzene (LAB) and contains 2.5 g/L of 2,5-diphenyloxazole (PPO) as a scintillation fluor and 3 mg/L of p-bis-(o-methylstyryl)-benzene (bis-MSB) as a wavelength shifter. The light attenuation length is planned to be greater than 20 m at 430 nm to accommodate the huge CD dimensions.

The solar neutrino program's success critically depends on achieving ultra-low levels of radioactive backgrounds. The LS of JUNO undergoes a complex multi-stage purification process to satisfy the purification requirements [9, 14]. Moreover, special attention is given to screening and purification of all detector-related constructions before the LS filling phase.

3. Solar neutrino detection channels in JUNO

JUNO can detect solar neutrinos through the following three channels [9]: Elastic Scattering (ES) off electrons, Charged-Current (CC), Neutral-Current (NC).

ES channel. This channel is the primary detection channel for solar neutrinos in JUNO: $\nu_x + e^- \rightarrow \nu_x + e^-$. The ES channel is sensitive to all active flavors, but with different cross sections: electron neutrinos have about 6 times larger cross section than muon and tau neutrinos. The background for ES events consists of intrinsic natural radioactivity in the LS, gamma rays from external detector materials, and unstable isotopes produced by cosmic ray muons. The analysis threshold for this channel depends on the rates of cosmogenic and radiogenic decays (e.g., ^{11}C, ^{14}C).

CC and NC channels on ^{13}C. A unique feature of JUNO is the presence of a large mass of ^{13}C nuclei (approximately 200 tons) due to the natural abundance of ^{13}C (1.1%) in the 20 kton of carbon-rich LS. This makes it possible to detect solar neutrinos via interactions on ^{13}C nuclei, similar to the approach used by SNO with heavy water.

- The main CC channel is: $\nu_e + {}^{13}\mathrm{C} \rightarrow e^- + {}^{13}\mathrm{N(ground\ state)}$. The ground state ^{13}N undergoes a delayed β^+ decay with Q = 2.2 MeV and a lifetime of 863 s. This provides a distinct coincidence signature between the prompt electron and the delayed positron.
- The main NC channel is: $\nu_x + {}^{13}\mathrm{C} \rightarrow \nu_x + {}^{13}\mathrm{C}^*(\frac{3}{2}^-, 3.685\,\mathrm{MeV})$. This channel is sensitive to all active neutrino flavors with identical cross sections and produces a characteristic 3.685 MeV gamma ray.

4. ^{8}B solar neutrino studies

Model-independent measurement. By combining the CC, NC, and ES channels, JUNO can perform a model-independent measurement of the ^{8}B solar neutrino flux and oscillation parameters [12, 13]. This would be the first such measurement since SNO [15] and adds a unique contribution to the global solar neutrino program. The left panel of Figure 3 shows the expected visible energy spectra of all single event sources for 10 years of data taking. Table 1 shows the expected event numbers for the three channels in 10 years of data taking. The CC channel provides sensitivity to the ν_e component, the NC channel is sensitive to all active flavors with identical cross sections, and the ES channel is sensitive to all flavors but with different cross sections. With 10 years of data, JUNO can reach 1σ precision levels of 5% for the ^{8}B neutrino flux and this expected precision is significantly better than that of 11.6% uncertainty from the latest prediction of the SSM [3]. When combined with SNO data, a world-best precision of 3% is expected for the ^{8}B neutrino flux measurement. This measurement represents the only model-independent approach planned after SNO, providing crucial cross-validation of solar neutrino flux measurements. The combination of three detection channels allows JUNO to disentangle solar physics from neutrino oscillation effects, contributing uniquely to both solar physics and fundamental neutrino research.

Channel	Threshold [MeV]	Signature	Events (10 years)
CC on ^{13}C	2.2	e^-+^{13}N decay	3,929
NC on ^{13}C	3.685	γ	3,032
ES on electrons	0	e^-	3.0×10^5

Table 1: Main detection channels for ^{8}B solar neutrinos in JUNO and expected event numbers.

Spectral analysis capabilities. With sufficient radiopurity, the analysis threshold can be reduced to 2 MeV for ^{8}B neutrinos, which is significantly lower than current experiments, though it cannot be reduced further due to numerous cosmogenic ^{11}C decays. This low threshold enables detailed examination of the spectral distortion dominated by neutrino flavor transformation in dense solar matter, providing sensitivity to the MSW transition region. The upturn feature in the electron neutrino survival probability P_{ee} at lower energies becomes clearly visible in the recoil electron spectrum, allowing JUNO to probe the transition from vacuum-dominated oscillations to matter-dominated oscillations.

Day-night asymmetry. JUNO's location at 22°N latitude enhances the day-night asymmetry compared to higher-latitude experiments. The MSW effect during neutrino propagation through Earth causes ν_e regeneration at night, leading to measurable signal rate variations. If $\Delta m^2_{21} = 4.8 \times 10^{-5}$ eV^2, JUNO can observe day-night asymmetry at approximately 3σ significance with 10 years of data-taking, providing additional constraints on oscillation parameters and testing the MSW mechanism in terrestrial matter.

Sensitivity to the solar oscillation parameters. Thanks to the day-night asymmetry and the spectral distortion in the MSW transition region, with 10 years of data, JUNO can reach 1σ precision levels of 8% for $\sin^2\theta_{12}$, and 20% for Δm^2_{21} (see the right panel of Figure 3). These precision levels are comparable to the current global solar neutrino data constraints [16]. These oscillation parameters will also be measured independently through reactor antineutrinos with sub-percent precision. A direct comparison between solar and reactor measurements from the same detector would provide a unique test of the charge, parity and time symmetry and probe potential discrepancies that could indicate new physics beyond the Standard Model.

Background control and event selection. Achieving these sensitivities requires exceptional background control. For the CC channel, the coincidence signature of prompt electron and delayed positron (from ^{13}N β^+ decay with 863 s lifetime) provides excellent background rejection. After optimized selection cuts including energy, fiducial volume, vertex correlation, and muon veto strategies, the CC channel is expected to have about 647 signal events with 275 background events in 10 years. The NC channel exploits the characteristic 3.685 MeV gamma ray, clearly distinguishable above the continuous background spectrum. The ES channel benefits from the large target mass and low-energy threshold capability. Moreover, machine learning approaches have shown promising results for reactor antineutrino selection in large LS-based detectors such as JUNO [17], and could potentially offer additional improvements for the solar neutrino-related event selection, though the distinct coincidence signatures may limit such benefits.

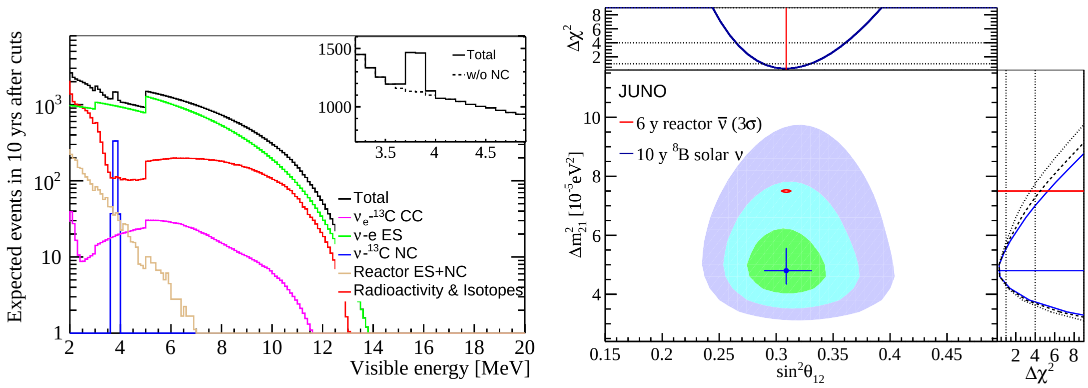

Figure 3: Left: Expected visible energy spectra of all single event sources. Notice the distinct 3.685 MeV gamma peak from NC interactions on ^{13}C above the continuous ES background. Right: 68.3%, 95.5%, and 99.7% confidence level allowed regions in the $\sin^2\theta_{12}$ and Δm^2_{21} plane using ^{8}B solar neutrinos with 10 years of data taking at JUNO and the comparison with the 6 years-based results with reactor antineutrinos. The left figure is taken from [12] and the right figure from [13].

5. Sensitivity to ^{7}Be, pep, and CNO solar neutrinos

JUNO's large target mass and excellent energy resolution make it competitive for detecting intermediate-energy solar neutrinos [4]. The analysis is performed in the energy range 0.45-1.6 MeV to avoid the ^{14}C background dominant at lower energies. For the ^{7}Be, pep, CNO analysis, four radiopurity scenarios are considered (as an example, the contamination levels of only ^{232}Th and ^{238}U are listed, more details about other sources of background can be found in Ref. [4]): 1) *Borexino-like*: the most complicated to achieve, matching Borexino's levels of $\sim 10^{-19}$ gg^{-1}; 2) *Ideal*: optimistic scenario with 10^{-17} gg^{-1}; 3) *Baseline*: baseline scenario with 10^{-16} gg^{-1}; 4) *IBD*: minimum requirements for the main reactor antineutrino physics program with 10^{-15} gg^{-1}.

pep neutrinos. The pep neutrino flux is approximately 50 times smaller than ^{7}Be, making the measurement more challenging. The main backgrounds are ^{210}Bi and cosmogenic ^{11}C. JUNO can reach statistical uncertainties of 2.4-13% after 10 years depending on radiopurity, significantly improving upon Borexino's 17% precision (see Figure 4, left panel).

^{7}Be neutrinos. The high rate (approximately 500 cpd/kton) and distinct spectral shape with a Compton-like edge at 665 keV make ^{7}Be neutrinos a relatively straightforward target. JUNO will be competitive with Borexino's 2.7% precision after 1 year of data taking and can reach unprecedented

statistical precision of 0.15–1.0% after 10 years, depending on the radiopurity scenario achieved (see Figure 4, middle panel).

CNO neutrinos. The CNO measurement is the most challenging due to low signal rates and spectral degeneracy with pep neutrinos and ^{210}Bi background. With a constraint on the pep neutrino rate at 1.4% precision level, JUNO can measure CNO neutrinos with 10–15% precision in favorable radiopurity scenarios after 6 years, enabling a direct measurement of solar metallicity (Figure 4, right panel).

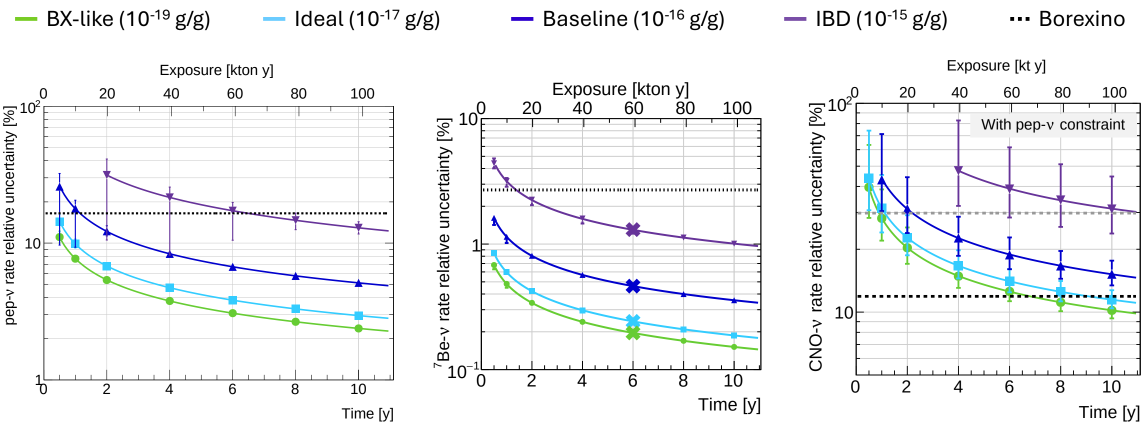

Figure 4: Relative uncertainties of pep, ^{7}Be and CNO neutrino rates as a function of JUNO exposure for different radiopurity scenarios: Borexino-like, Ideal, Baseline, IBD. The black dashed lines show the best Borexino result. Figures are adapted from [4].

6. Summary

JUNO will try to perform five important solar neutrino measurements. For *^{8}B flux*, 5% precision (10 years) using CC (3,929 events), NC (3,032 events), and ES (3.0×10^5 events), with 3% precision when combined with SNO data, representing the first model-independent measurement since SNO. *Oscillation parameters* $\sin^2\theta_{12}$ and Δm^2_{21} will be measured to 8% and 20% precision respectively, comparable to current global analysis constraints, enabling direct and complementary comparison with reactor antineutrino-based results. For *intermediate-energy neutrinos*, precision levels of 2.4–13% (pep), 0.15–1.0% (^{7}Be), and 10–30% (CNO) can be achieved, depending on radiopurity (10^{-19}–10^{-15} g/g), improving over Borexino results: ^{7}Be 2.7% → 0.15%, pep 17% → 2.4% in the best case scenario. The *CNO measurement* at 10–15% precision will constrain solar metallicity, requiring more than 6 years of data collection. *Day-night asymmetry* enables 3σ observation of terrestrial MSW effects in the case of $\Delta m^2_{21} = 4.8 \times 10^{-5}$ eV^2 at 22°N latitude.

Thus, the JUNO solar neutrino program represents a promising step forward in precision neutrino astronomy. By combining the advantages of liquid scintillator-based detector technologies with large target mass and unprecedented energy resolution, JUNO will provide insights into both solar physics and fundamental neutrino properties, complementing and advancing the results of experiments of the previous generation.

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