PROCEEDINGS OF SCIENCE

The JUNO experiment: status and physics potential

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The Jiangmen Underground Neutrino Observatory (JUNO) is a multi-purpose experiment designed to study fundamental neutrino properties and investigate various neutrino sources. Thanks to its 20 kton active mass and its unprecedented energy resolution of 2.95% at 1 MeV, JUNO is expected to shed light on the neutrino mass ordering (NMO) and measure several of the oscillation parameters with unprecedented precision. Besides its main ambitious goal, JUNO's extensive physics program includes studies of neutrinos from the Sun, the atmosphere, supernovae, and planet Earth, as well as explorations of physics beyond the Standard Model.

As of the date of the proceeding, the detector construction is nearing its end, and the experiment is about to begin filling, preparing for data taking. This proceeding provides an overview of the current status of the JUNO experiment and its role in advancing the field. It describes the design and components of the JUNO detector, and concludes by examining JUNO's physics potential and program, emphasizing its capabilities in studying neutrinos from reactors and other sources.

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1. Introduction

Neutrino physics is a rapidly evolving field with a strong foundation built on decades of research. This foundation is the standard 3ν oscillation framework, described by a total of six parameters, which explains how neutrinos change their flavor as they travel. This paradigm has been in place since 1998 [1] and has stood up to rigorous testing, even against alternative models with more than three neutrino types [2], still under active investigation. Among the six parameters describing the framework, five have been measured and are being continuously refined [3]. These include two mass-squared differences (Δm^2_{21} and $|\Delta m^2_{31}|$), defining the mass differences between the three neutrino types, and three mixing angles (θ_{12}, θ_{13} and θ_{23}), which govern how neutrinos mix to produce the flavors observed in interactions. Despite these advances, several fundamental questions remain unanswered. These include the measurement of the last unknown parameter $\delta_{\rm CP}$ hinting to the presence of CP violation in the leptonic sector, the determination of the neutrino mass ordering (i.e. the sign of Δm^2_{31}), and the octant of the mixing angle θ_{23} (i.e., $\theta_{23} < \pi/4$ or $\theta_{23} < \pi/4$). Although not directly contributing to oscillations, the absolute neutrino mass scale and the nature of the neutrino (whether it is a Dirac or Majorana particle) are also still unknown.

In the coming years, neutrino physics will see the emergence of new-generation experiments [4–6] designed to shed light on these topics. In this context, the Jiangmen Underground Neutrino Observatory (JUNO) is currently under construction in southern China and it is poised to make significant contributions to addressing these open questions. JUNO's primary scientific goal is the determination of the neutrino mass ordering (NMO), providing a definitive answer to this long-standing question within around six years of exposure. Thanks to it's design and performances, JUNO can also significantly improve the present precision of Δm^2_{31}, Δm^2_{21}, and θ_{12} parameters, at the same time investigating many other aspects and sources in neutrino physics.

2. The JUNO detector

To achieve its scientific objectives, JUNO features multiple detector systems (see Fig. 1) working together to reach high efficiency, mitigate backgrounds and attain the desired physics performances [4]. Ancillary detectors are also employed to monitor the radiopurity of its scintillator [7] and to precisely constrain the shape of the unoscillated antineutrino spectrum [8].

2.1 Central Detector

At the heart of JUNO lies the central detector (CD), a 20-kiloton liquid scintillator (LS) detector [10] housed within a 35.4-meter-diameter spherical acrylic vessel. The LS consists of linear alkylbenzene (LAB) as the scintillation solvent, 2,5-diphenyloxazole (PPO) as the primary fluor, and p-bis-(o-methylstyryl)-benzene (bis-MSB) as the wavelength shifter [4, 11, 12]. This composition is specifically formulated to maximize light yield and transparency and was carefully chosen based on dedicated studies conducted with a Daya Bay detector [11]. The scintillation light produced by interactions in the LS is captured by 17,612 20-inch large PMTs (LPMTs) [13, 14] and 25,600 3-inch small PMTs (SPMTs) [15] anchored to a stainless steel (SS) structure, directed towards the centre of the CD, and surrounded by a Earth's magnetic field compensation coils [4]. The use of two sizes of PMTs, creates a dual calorimetry system that offers the capability

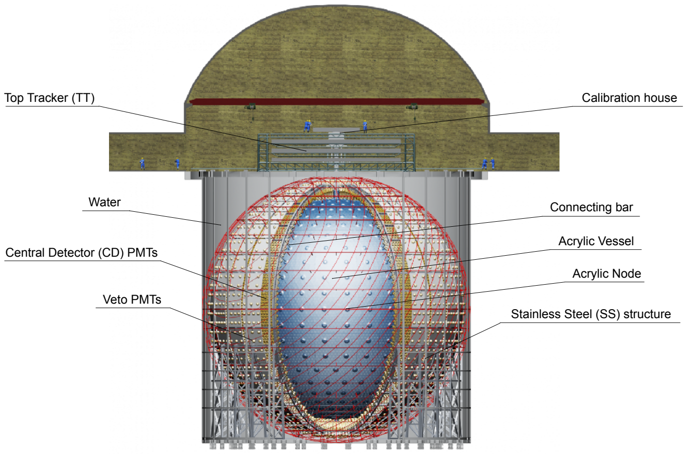

Figure 1: scheme of the JUNO detector components from [9].

to (i) accommodate a wide signal dynamic range, (ii) reach a higher photocoverage [4] and (iii) calibrate out instrumental non-linearities inherent in the PMTs and readout electronics [16, 17]. This configuration is projected to ensure the desired energy resolution of 2.95% at 1 MeV [18]. The PMTs and their readout have been tested [13–15, 19, 20], characterized and their installation is nearing completion.

2.2 Water Pool

Encapsulating the CD is the water pool (WP), filled with approximately 35 kilotons of ultrapure water and instrumented with 2,400 inward-facing 20-inch PMTs [4]. The WP serves a dual purpose, acting both as an active veto for cosmic muons and a passive shield against external radioactivity and neutrons emanating from cosmic rays. Additionally, the WP functions as a water Cherenkov detector, capable of detecting muons not tagged by the other subdetectors.

2.3 Top Tracker

Positioned above the WP and CD is the top tracker (TT) [4, 21], a system originally used in the OPERA experiment. The TT is composed of 496 plastic scintillator strip modules, each 6.86 meters long, arranged into two perpendicular layers to provide two-dimensional tracking information. Each strip is read out on both sides by wavelength-shifting fibers coupled to PMTs. The TT's primary function is to reconstruct and extrapolate the tracks of atmospheric muons, which helps to evaluate the contribution of cosmogenic backgrounds to the neutrino signal, ultimately enhancing the effectiveness of the muon veto strategy performance.

2.4 Calibration System

To achieve its ambitious physics goals, JUNO requires a precise understanding of its energy response [4, 22]. For JUNO to determine the neutrino mass ordering, an unprecedented energy resolution of less than 3% at 1 MeV is needed [18, 23] and a comprehension of the energy scale non-linearities below 1% is required [4]. This is achieved by a multi-faceted calibration system that employs a variety of radioactive sources, including gamma and neutron sources, cosmogenic ^{12}B, and a pulsed UV laser. A key aspect of the calibration strategy involves the deployment of sources at multiple positions within the CD, enabling the characterization and correction of non-uniformities in the detector response. This is accomplished using a vertical spooling system, a guide tube system attached to the acrylic sphere, cable loops, and eventually a remotely operated vehicle (ROV).

2.5 Purification Power Plant

Achieving an exceptional radiopurity of the LS is essential for JUNO's success, particularly for measurements involving low-energy neutrinos from the Sun and supernovae. The LS undergoes a multi-stage purification process, encompassing alumina column chromatography, distillation, water extraction, and steam stripping [24], with the online scintillator internal radioactivity investigation system (OSIRIS) serving as the final quality control checkpoint before filling. OSIRIS [7] is a dedicated pre-detector designed to validate the radiopurity of 15% of the LS flux before it is filled into the CD. OSIRIS boasts a large detection volume of approximately 20 tons and employs an array of 87 PMTs to achieve exceptional sensitivity to uranium (U) and thorium (Th) contamination, reaching levels as low as 10^{-16} g/g. The liquid scintillation purification plant has been fully completed and commissioned. The OSIRIS radiopurity monitoring pre-detector has been commissioned and is now acquiring data [25–27].

2.6 Taishan Antineutrino Observatory

Finally, the JUNO experiment comprises the Taishan Antineutrino Observatory (TAO), a satellite detector located approximately 40 meters from one of the Taishan nuclear power plant reactor cores [8]. TAO's primary objective is to precisely measure the unoscillated reactor antineutrino spectrum, serving as a data-driven input to constrain the spectra of other reactor cores and improve the precision of neutrino oscillation measurements in JUNO. This near-detector measurement with TAO will help mitigate uncertainties associated with reactor antineutrino flux predictions, thereby enhancing JUNO's sensitivity to the neutrino mass ordering [23].

3. The JUNO physics potential

JUNO's wide physics program is enabled by its unique design and strategic location. The peculiar combination of size, energy resolution and multiple interaction channels makes it an effective multi-purpose experiment. Due to composition of the liquid scintillator (mainly carbon and hydrogen), several detection channels exists [4]. The golden channel is represented by inverse beta decay (IBD) on free protons (i.e. hydrogen). This reaction produces a distinct signal characterized by a prompt signal from the positron's kinetic energy deposition and annihilation, and a delayed signal from neutron capture, allowing for effective background suppression [28]. In addition, neutrinos and antineutrinos in JUNO can interact through elastic scattering on electrons and protons, as well as through neutral and charged current interactions mainly with carbon atoms (both ^{12}C and ^{13}C). The experiment is expected to perform leading measurements in various areas of neutrino physics.

3.1 Reactor antineutrinos

JUNO's placement at a baseline of 52.5 kilometers from the nuclear power plants of Taishan and Yangjiang, with a total thermal power of 26.6 GW_{th}, provides an ideal setting for studying

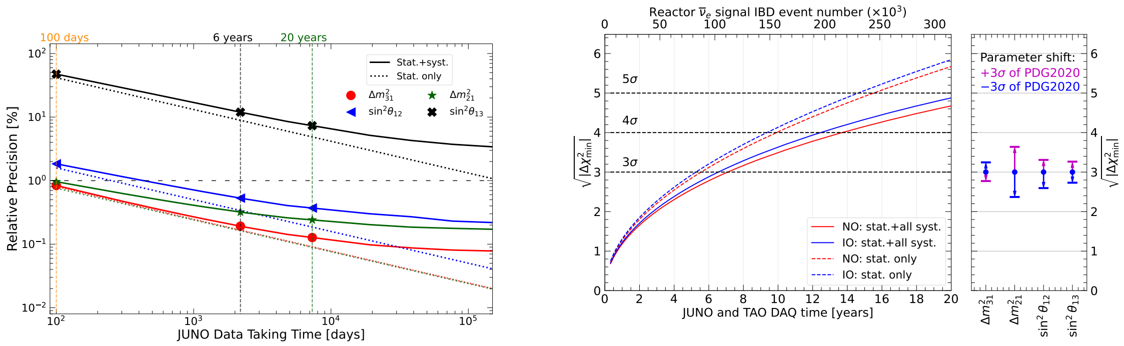

Figure 2: relative precision of the oscillation parameters (left) from [29] and JUNO sensitivity to NMO (right) as a function of JUNO data taking time for the normal and inverted orderings from [23].

reactor antineutrinos. The experiment is designed to measure the oscillation parameters θ_{12}, Δm^2_{21}, and Δm^2_{31} with an unprecedented precision better than 0.6% in less than 6 years of data taking [29] (see Fig. 2). At the same time, JUNO will determine the NMO by observing the fine interference pattern in the energy spectrum of reactor antineutrinos. This measurement is projected to achieve a 3σ significance within 6.5 years of data [23] (see Fig. 2). The unprecedented precision of JUNO's measurement in three of the oscillation parameters will also enable various synergies in other areas of neutrino physics [30, 31] and strengthen the determination of the NMO using its complementarity with other experiments [32, 33].

3.2 Atmospheric neutrinos

JUNO is also capable of detecting atmospheric neutrinos. These measurements are crucial for understanding the production mechanisms and propagation of atmospheric neutrinos, as well as for constraining models of neutrino interactions at low energies. The JUNO experiment leverages atmospheric neutrinos and an accurate flavor separation and track reconstruction for distinguishing between electron neutrinos and muon neutrinos. This enables JUNO to achieve sensitivity to the NMO, complementing its primary method using reactor antineutrinos. Depending on the performances achieved, atmospheric neutrinos could enhance JUNO sensitivity to NMO up to one σ unit in 6 years [4].

3.3 Solar neutrinos

The exceptional radiopurity of JUNO's LS enables the detection of various solar neutrino species. These measurements will provide valuable insights into the Sun's energy production mechanisms and contribute to the global effort of understanding solar neutrino oscillations. Depending on the radiopurity that it will achieve, JUNO will measure with competitive precision fluxes coming from ^{7}Be, pep, and CNO neutrinos, exceeding Borexino measurements in few years of data taking [34] (see Fig. 3). JUNO will also be able to set competitive limits of 5% on ^{8}B in 10 years of data-taking, measuring at the same time Δm^2_{21} and θ_{12} in a channel complementary to that of reactor antineutrinos [35].

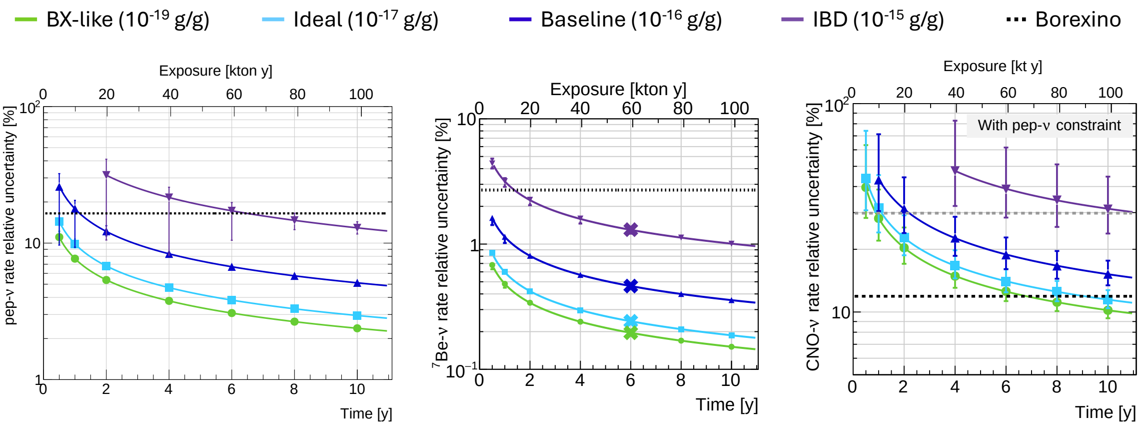

Figure 3: Relative uncertainties of pep, ^{7}Be and CNO neutrino rates as a function of JUNO exposure for different radiopurity scenarios from [34].

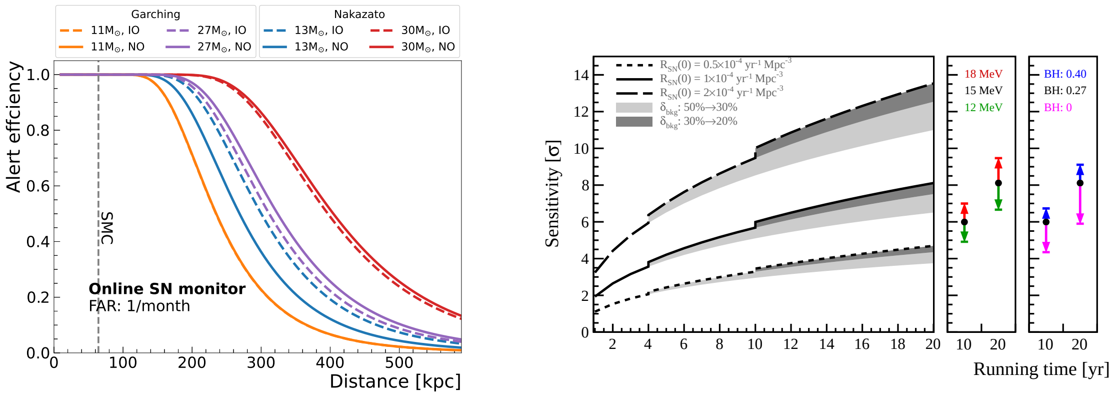

Figure 4: alert efficiency of the online CCSN monitor (left) at different distances for different models from [36] and DSNB discovery potential at JUNO (right) as a function of the running time from [37].

3.4 Supernovae neutrinos

JUNO is expected to exhibit excellent sensitivity to neutrinos from core-collapse supernovae (CCSN), with an anticipated detection of 5000 events from inverse beta decay (IBD), 300 events from elastic neutrino-electron scattering, and 2000 events from elastic neutrino-proton scattering for a typical galactic supernova at 10 kpc [4, 36]. The experiment's real-time monitoring system (see Fig. 4) will play a critical role in providing early alerts for follow-up multi-messenger observations of CCSN. In addition to the large number of events expected from a galactic supernova, JUNO is sensitive to pre-supernova neutrinos from nearby stars, up to a distance of approximately 1.6 kpc for a 30-solar-mass progenitor star [36]. Thanks to its size and its background rejection capabilities JUNO is also expected to detect neutrinos from the diffuse supernovae neutrino background (DSNB) [37]. This DSNB carries valuable information about the cosmic star-formation rate, average SN neutrino energy spectrum, and the proportion of black hole formation in CCSN. The DSNB detection in JUNO, expected at a rate of 2-4 events per year, is primarily achieved through the IBD reaction, potentially reaching a discovery sensitivity up to >5σ in 10 years (see Fig. 4).

3.5 Geoneutrinos

JUNO is also sensitive to the antineutrinos emitted in the radioactive decays powering the inner processes of our planet, namely the geoneutrinos. With an expected IBD detection rate of ~400 geoneutrinos per year, JUNO will contribute to our understanding of the Earth's composition and internal heat production [4, 38]. By studying the flux and energy spectrum of U and Th geoneutrinos, JUNO can provide constraints on the abundance of radioactive elements in the Earth's mantle and crust, shedding light on the Earth's formation and evolution. Within its first year of operation, JUNO is projected to collect more geoneutrino events than all previous experiments combined, achieving unparalleled statistics and a flux measurement precision of 13%, when assuming a fixed Th/U mass ratio of 3.9. This dataset will also allow JUNO to separately determine the contributions of U and Th with high statistical significance reaching a precision of 40% and 80% on U and Th respectively after one year. Additionally, JUNO's sensitivity to geoneutrinos from the Earth's crust in combination with an accurate geochemical/geophysical modeling of the close and far lithosphere, offers an opportunity to refine geological models and potentially disentangle the mantle signal.

3.6 Nucleon decays

Thanks to its large target mass, excellent energy resolution, and efficient background rejection capabilities, JUNO's sensitivity extends to searches for rare processes such as nucleon decay, particularly the proton decay channel $p \to \bar{\nu} K^+$ [39] and the neutron invisible decays $n \to invisible$ and $nn \to invisible$ [40]. JUNO's strategy for the proton decay process foresees the tagging of a time-correlated three-fold coincidence signal: a prompt signal from the K^+ kinetic energy, a short-delayed signal from its decay daughters, and a long-delayed signal from the final Michel electron. This triple coincidence allows for effective identification of the decay and suppression of background, improving current Super-Kamiokande proton lifetime upper limit in about 6 years of data and reaching a limit exceeding $> 1.1 \times 10^{34} y$ at 90% confidence level in 10 years [39]. In the second detection channel, neutrons decay into invisible particles, such as neutrinos, that are challenging to detect directly. However, they can leave behind detectable signatures in the LS detector: invisible decays of s-shell neutrons in ^{12}C can produce a highly excited residual nucleus. De-excitation modes of this nucleus can lead to the emission of secondary particles, resulting in a time- and space-correlated triple coincidence signal, that will permit to JUNO to improve the current lifetime upper limits by one order of magnitude in less than 2 years, reaching $> 5.0 \times 10^{31} y$ and $> 1.4 \times 10^{32} y$ at 90% confidence level in 10 years for $n \to invisible$ and $nn \to invisible$, respectively [40].

4. Conclusion

JUNO is a cutting-edge neutrino experiment with a comprehensive physics program. JUNO is poised to make groundbreaking discoveries in neutrino physics, ranging from the definitive determination of the neutrino mass ordering to precision measurements of oscillation parameters. Its sensitivity to neutrinos from diverse sources, including reactors, the atmosphere, the Sun, supernovae, and the Earth, as well as its potential to search for nucleon decays, positions JUNO at the forefront of neutrino research.

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