PROCEEDINGS OF SCIENCE

Jiangmen Underground Neutrino Observatory (JUNO): on the way to physics data

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The Jiangmen Underground Neutrino Observatory (JUNO) is a 20 kton liquid scintillator experiment under construction in South China, at Kaiping, Jiangmen, Guandong province. Its primary physics goals are the determination of the neutrino mass ordering and the precise determination of the neutrino oscillation parameters by means of the accurate measurement of the oscillated spectrum of antineutrinos emitted by two reactor complexes, Taishan and Yangjiang, located at 53 km distance from the experiment. Given its dimensions and anticipated performance, JUNO has a very rich physics program which includes the study of neutrinos from the Sun, the Earth, the Galaxy, and eventually from Supernovae, and will give important contributions to the study of new physics processes. The JUNO collaboration plans to finish the detector construction by the end of 2023. In this paper I review the detector progress and the updated sensitivities on the main physics channels.

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PoS(NOW2022)022

1. Introduction

The idea of using reactor neutrinos to investigate the neutrino mass ordering (NMO) [1] dates back to about twenty years ago when it was suggested [2, 3] that medium baseline experiments placed at the maximum of the solar oscillation probability could profit from the interference effect between the solar and the atmospheric oscillation frequencies to disentangle the mass ordering information. The method is made possible by the non-vanishing value of the θ_{13} mixing angle [1]. These facts motivated in 2013 the approval of JUNO [4], a huge liquid scintillator experiment located underground (~650 m overburden, 1800 m.w.e.) at 53 km distance from two reactor complexes, Taishan and Yangjiang, which account for a total of 8 nuclear reactors and 26.6 GW of thermal power. Figure 1 shows the oscillated reactor antineutrino spectrum that JUNO will measure after 6 years of data-taking [5], in blue for the case of normal mass ordering and in red for inverted mass ordering. The subtle difference between the two curves contains the NMO information: in order to determine the exact position of the oscillation phase an extremely high performance detector is needed. As the figure shows, at JUNO's location the reactor antineutrino energy spectrum will be distorted by a slow oscillation driven by Δm^2_{21} and modulated by $\sin^2 2\theta_{12}$ – the *solar* oscillation parameters, superimposed to a fast oscillation driven by Δm^2_{31} and modulated by $\sin^2 2\theta_{13}$ – the *atmospheric* oscillation parameters. Therefore, JUNO is intrinsically sensitive to the four oscillation parameters and will be the first detector to observe the two oscillation modes simultaneously.

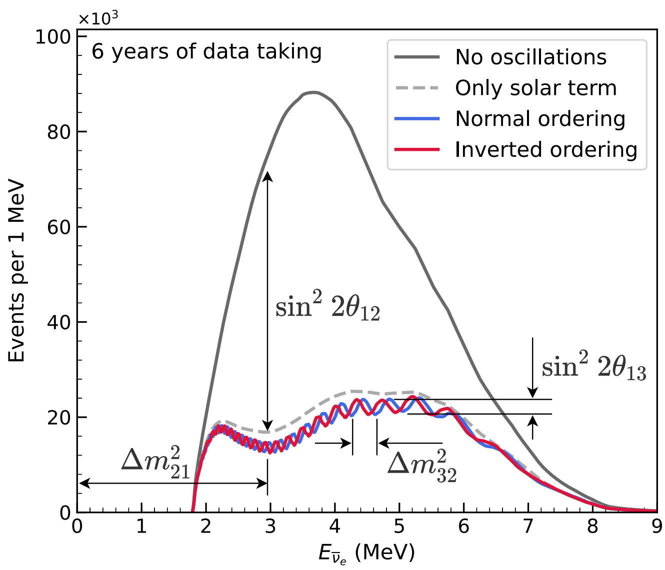

Figure 1: JUNO reactor antineutrino energy spectrum without (black) and with (grey, blue, and red) the effect of neutrino oscillations after 6 years of data-taking. A detector with perfect energy resolution is assumed for illustration purposes.

2. The JUNO detector

The highly demanding performance requested to JUNO to disentangle the NMO in terms of large statistical significance, excellent energy resolution (< 3% at 1 MeV), good understanding of the energy response (better than 1%), and low radioactive background have driven the dimensions and design of the experimental setup [4, 6]. JUNO consists of a Central Detector (CD), a Water Cherenkov Detector (WCD) and a muon tracker (the Top Tracker, TT), as shown in figure 2. The CD consists of a spherical acrylic vessel of 35.4 m of diameter and 12 cm thickness (for a total mass of about 580 t) supported by a stainless steel (SS) structure with inner diameter of 40.1 m, sitting on 30 pairs of SS legs. Both the vessel and the structure are submerged in a cylindrical water pool of 43.5 m of diameter and 44 m of height. The acrylic vessel contains 20 kton of liquid scintillator (LS), used to convert energy depositions into visible light. Then, the scintillation light is read by a synergetic system of 17,612 20-inch photomultiplier tubes (LPMTs) and 25,600 3-inch photomultiplier tubes (SPMTs) installed on the inner side of the SS structure and reaching about 78% of coverage efficiency. Additional 2,400 LPMTs are mounted in the water pool – containing 35 kton of ultra-pure water – to act as a WCD to veto cosmic muons. Moreover, a TT is installed on top covering about 50% of the water pool, to precisely measure the muon directions and support the veto strategies. Finally, JUNO has a carefully studied calibration system, to keep at minimum the energy scale non-linearity, with multiple sources and multidimensional scan systems (details in [7]).

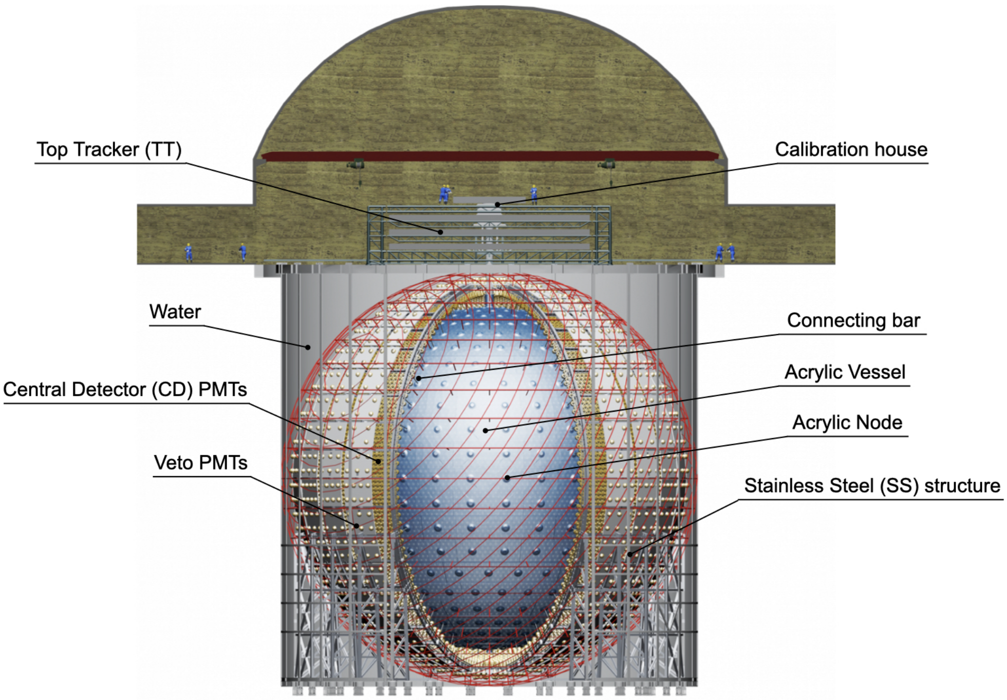

Figure 2: Schematic drawing of the JUNO detector.

Thanks to its dimensions and anticipated performance, JUNO will in fact be a neutrino observatory. Besides measuring ~60 reactor antineutrinos per day, it will detect several atmospheric neutrinos per day, plentiful solar neutrinos per day, ~400 geoneutrinos per year, and hopefully it will discover the signal from the diffuse Supernova neutrino background (DSNB) with few expected events per year. In the lucky case of a Supernova explosion within 10 kpc, JUNO will measure thousands events in a few seconds. By means of all these complex measurements, JUNO will give

PoS(NOW2022)022

important contributions to the complete understanding of the neutrino oscillation mechanism and the neutrino properties, and will use neutrinos as a probe of astronomical objects. Finally, JUNO will also be able to search and constrain the parameter space of beyond-the-standard-model physics processes, like nucleon decay, Lorentz invariance, non-standard interactions, etc. [4, 6].

3. JUNO detector construction progress

The civil works at the JUNO experimental site finished in December 2021, delayed with respect to the preliminary schedule by the unexpected high level of water found during the excavation of the underground laboratory. The water level is now kept under control by a continuous pumping system and the detector construction is rapidly progressing.

The SS structure assembly finished in June 2022 (left side of figure 3). It is made out of SS304 and is divided into 30 longitudinal and 23 latitudinal layers. It is the most important mechanical part of the setup, which supports the loads of: the acrylic vessel, the LS, the LPMTs and SPMTs, the front-end electronics, the light separation plate between CD and WCD, the Earth magnetic field compensation coils (to shield the photomultiplier tubes), etc. It also sustains the upward buoyancy.

The acrylic vessel is the container of the 20 kton of JUNO LS and is sustained by the SS structure by means of 590 connecting rods. Due to its dimensions, it is divided into 265 panels which are produced separately at the company and bonded onsite. There are very stringent requirements on the light transparency of the acrylic, which must be higher than 96% to reach the target energy resolution of JUNO, and on its radiopurity: the concentration of each of the natural contaminants (^{238}U, ^{232}Th, ^{40}K) must be below 1 ppt to keep the accidental background rate within JUNO requirements [8]. Particular attention is paid to the protection of the acrylic surface, which is cleaned with a special procedure and covered with a polyethylene film to prevent Rn implantation during handling and assembly. The construction of the vessel started in July 2022 (right side of figure 3).

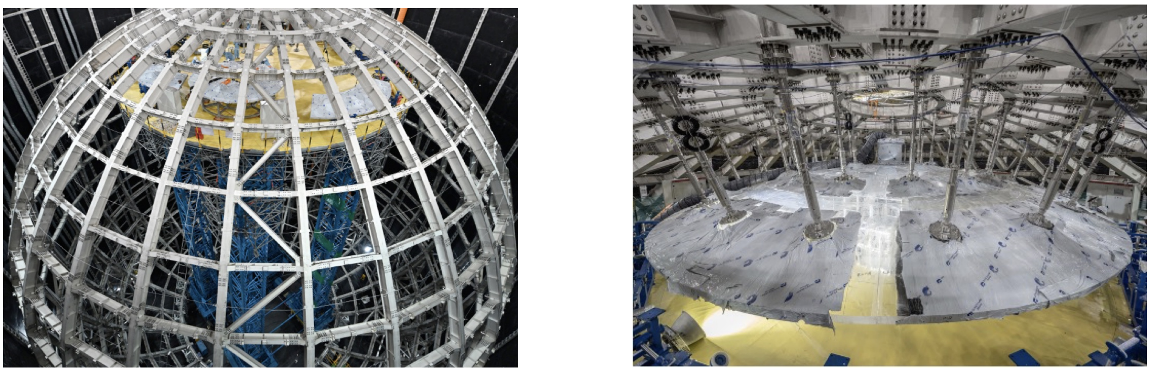

Figure 3: Left: SS structure completely assembled on June 24, 2022. Right: First three layers of the acrylic vessel bonded in August 2022.

The LS is a Linear Alkyl Benzene (LAB) solvent mixed with 2.5 g/L PPO fluor and 3 mg/L bis-MSB wavelength shifter. To fulfil JUNO demanding requirements, it must have a very high light yield (> 1345 p.e./MeV), a long attenuation length (> 20 m), and extremely high radiopurity ($< 10^{-17}$ g/g for ^{238}U and ^{232}Th, $< 10^{-18}$ g/g for ^{40}K, $< 10^{-24}$ g/g for ^{210}Pb) [8]. An industrial scale purification process was designed, and is under construction at the JUNO site. It foresees four main steps: i) alumina column filtration, ii) distillation, iii) water extraction, and iv) steam stripping (more details in [6]). Only when the radiopurity requirements are met, as determined by the JUNO Online Scintillator Internal Radioactivity Investigation System (OSIRIS [9]), the LS will be allowed to enter the acrylic vessel.

The detector filling with LS is a very delicate operation, for the possible mechanical stress to the acrylic vessel and the high risk of contaminating the scintillator itself. Especially the background issue is particularly serious for JUNO, since there is no possibility of recirculating the LS back to the purification plants, given the unprecedented volume. For this reason we are carefully planning this final step of the detector commissioning with strict requirements on the possible leakage of pumping and connecting lines and by including a special cleaning step of the inside of the acrylic vessel before removing the protective film. We chose the water exchange scheme for the detector filling, where the pool and the vessel will be filled in parallel with water, and then the LS will be inserted from the top while removing the water from the bottom. Special efforts are put in the design of the ultra-pure water supply system, to reduce at minimum the contamination transfer from the water to the LS, as well as in the environmental control of all areas of the underground laboratory.

All photomultiplier tubes are produced, tested and instrumented with waterproof potting. The final photon detection efficiency of the LPMTs turned out to be higher than designed, and its mean value now amounts to 29.6% [10].

Further details on the JUNO detector can be found in [6] and references therein. The JUNO collaboration plans to finish the detector construction by the end of 2023.

4. Updates on JUNO physics sensitivity

The original estimate on JUNO sensitivity to NMO was discussed in [4]. Since then, the total reactor thermal power available to JUNO decreased of ~26% (from 35.8 GW to 26.6 GW) because only two of the planned four Taishan reactors have been built; moreover, the expected muon flux is now ~33% higher (from 3 to 4 Hz) because of the shallower location of the JUNO experimental hall due to the underground water problem. On the other hand, we expect a ~3% improvement of the detector energy resolution (from 3% to 2.9% at 1 MeV), thanks to the higher photon detection efficiency of the LPMTs, to an improved understanding of the PMT optical model, and to a more accurate simulation of the detector geometry; moreover, we expect a ~10% improvement of the muon veto efficiency (from 83% to 91.6%), and we have more realistic estimations of the expected backgrounds from the detector materials [8]. Finally, we expect an improved reactor spectral shape uncertainty thanks to the combined analysis with the Taishan Antineutrino Observatory (TAO) [11], a 1 ton LS satellite detector placed at 30 m distance from one of the Taishan reactor cores to measure the unoscillated antineutrino flux with high precision. The new sensitivity of JUNO to NMO after these updates is reported in figure 4: with ~6 y of data taking, a sensitivity of 3σ is expected using only reactor neutrinos in a combined analysis with JUNO-TAO and including all systematic effects. Further improvements are expected by the inclusion of the atmospheric neutrino analysis (under preparation).

For the oscillation parameters, ~ 1% precision on the measurement of the two mass splittings Δm^2_{21} and Δm^2_{31} is expected after only ~100 d of data taking, while a precision < 0.5% on $\sin^2 2\theta_{12}$, Δm^2_{21}, and Δm^2_{31} is expected in 6 y using only reactor neutrinos (figure 5) [5]. This is the best

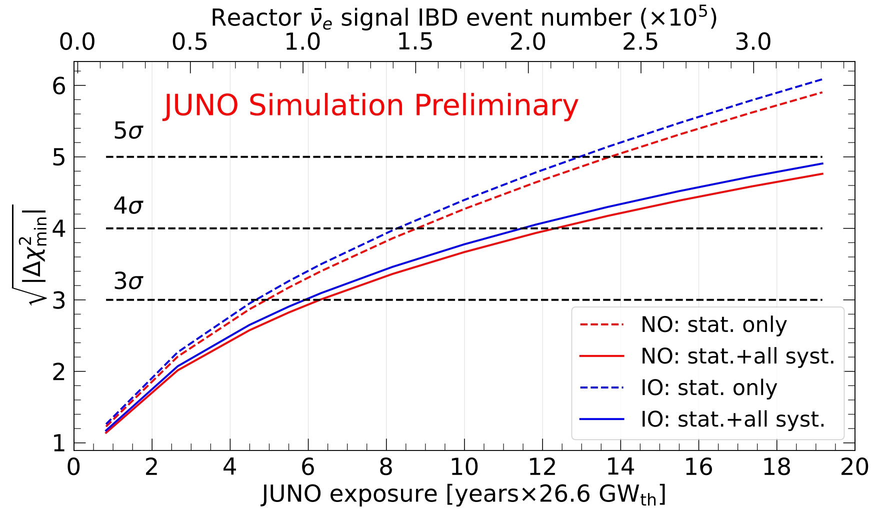

Figure 4: Predicted JUNO sensitivity to NMO as a function of exposure; with an antineutrino selection efficiency of 82%, the resulting reactor antineutrino rate at JUNO is 47/day.

measurement of the oscillation parameters in the foreseeable future. Further, JUNO is unique for the fact that the two solar parameters can be constrained also by means of ^{8}B solar neutrinos, therefore exploiting neutrinos and antineutrinos in the same detector.

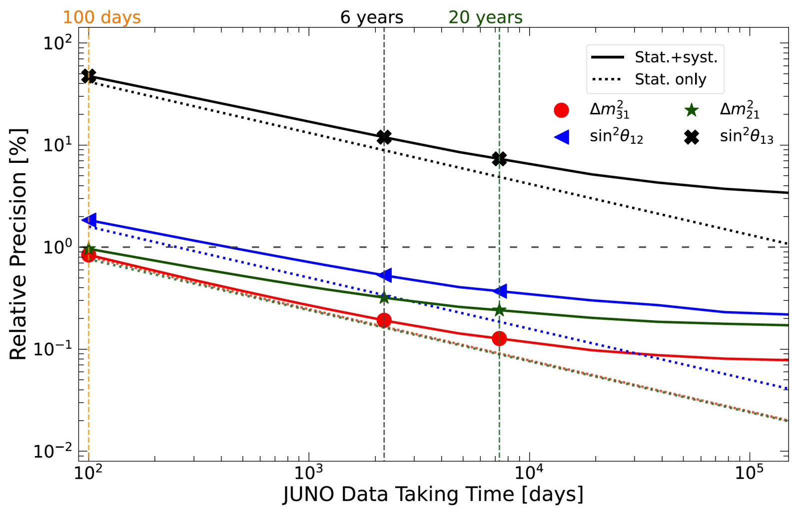

Figure 5: Relative precision of different oscillation parameters as a function of JUNO data taking time (taken from [5]).

^{8}B solar neutrinos will be measured by JUNO via elastic scattering on electrons with the unprecedented energy threshold of 2 MeV. In addition, by exploiting the 200 t of ^{13}C of the LS, JUNO will detect ^{8}B neutrinos also via charged current and neutral current interactions on ^{13}C, and thus will study ^{8}B neutrinos in a model independent way. The sensitivity of JUNO to lower energy solar neutrinos (i.e. ^{7}Be, pep, and CNO) will crucially depend on the final internal background level of the LS. Detailed publications on the expected sensitivities for the different solar neutrino channels are in preparation.

Finally, an improved sensitivity for the discovery potential of the DSNB with JUNO was obtained by means of accurate background evaluation, increased signal efficiency via pulse shape discrimination, and updated DSNB signal model. JUNO can reach a discovery potential significance of 3σ for 3 years of data taking, and achieve better than 5σ after 10 years, for a reference DSNB model. Details are discussed in [12].

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