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Current status and physics prospects of the JUNO experiment(*)

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Summary. — The Jiangmen Underground Neutrino Observatory (JUNO) is a multipurpose neutrino experiment currently under construction in South China. The detector consists of a 20 kton liquid scintillator target, contained inside a 35-meter-diameter spherical acrylic vessel submerged in an ultra-pure water pool. The central detector is equipped with 17612 20-inch photomultipliers and 25600 3-inch photomultipliers, providing a total photocatode coverage of $\simeq 78\%$. The experiment is primarily designed for the determination of neutrino mass ordering, through the measurement of the oscillation pattern of electron antineutrinos emitted from two nuclear power plants, at a baseline of about 52.5 km. In order to achieve high statistical significance ($\sim 3-4\sigma$) in ~ 6 years of data taking, an energy resolution $\leq 3\%$ at 1 MeV is needed. JUNO will play a pivotal role in oscillation physics, measuring three oscillation parameters ($\sin^2(\theta_{12})$, Δm^2_{12}, Δm^2_{32}) with sub-percent precision. Moreover, the experiment will be able to detect neutrinos from several other sources, including solar neutrinos, atmospheric neutrinos, geoneutrinos, and core-collapse supernova neutrinos, opening up many research opportunities in physics and astrophysics. This contribution reviews the physics goals and current status of the JUNO project.

1. – Introduction

The investigation of neutrinos and their properties stands as one of the most dynamic areas in particle physics, both on experimental and theoretical grounds [1]. To date, several experiments, using neutrino and antineutrino beams, produced by natural and artificial sources, and spanning a wide range of energies, have provided compelling evidence of the oscillation phenomenon [1]. In particular, the standard three-neutrino paradigm comprises a total of six parameters to fully describe neutrino oscillations: three mixing angles (θ_{12}, θ_{23}, and θ_{13}), one Dirac CP phase (δ_{CP}), and two independent mass

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Fig. 1.: Location of the JUNO and TAO experiments in South China [3].

squared differences (Δm^2_{21} and Δm^2_{31}, or equivalently Δm^2_{32}). Nevertheless, many questions remain unanswered: the neutrino nature (Dirac or Majorana particle), CP violation in the leptonic sector, the octant problem (*i.e.*, the discrimination between values of θ_{23} lower or higher than $\pi/4$), and the scale of the neutrino mass eigenstates, commonly referred to as Neutrino Mass Ordering (NMO).

The Jiangmen Underground Neutrino Observatory (JUNO) [2, 3], is a multi-purpose liquid scintillator (LS) experiment currently under construction in South China. JUNO is designed primarily for the determination of the neutrino mass ordering with reactor antineutrinos ($\overline{\nu}_e$), emitted from the Taishan and Yangjiang nuclear power plants (NPPs), both located at a baseline of about 52.5 km from the experimental site. JUNO will be able to simultaneously probe the effects of oscillations on both solar and atmospheric scales, standing out as the first experiment to address the NMO measurement through vacuum-dominant oscillations Thanks to this feature, which is illustrated in fig. 2, it will measure four oscillation parameters: Δm^2_{21}, Δm^2_{31}, $\sin^2\theta_{12}$, and $\sin^2\theta_{13}$, reaching a sub-percent precision for the first three parameters [4].

To ensure accurate results, JUNO relies on a deep understanding of the unoscillated reactor antineutrino spectrum shape. To accomplish this, a dedicated small satellite detector called Taishan Antineutrino Observatory [5] (TAO or JUNO-TAO) will be in-

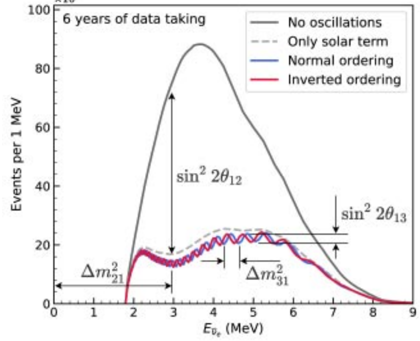

Fig. 2.: Expected reactor antineutrino energy spectrum in JUNO, with and without oscillations. Taken from [4].

Fig. 3.: Support structure of the central detector (as of August 2023).

stalled at a distance of around 40 m from one of the Taishan reactors. TAO will measure the spectrum with sub-percent energy resolution, serving as a data-driven reference to constrain the spectra of the other reactor cores. Figure 1 displays a map illustrating the locations of the JUNO and TAO experiments.

2. – The JUNO experiment

The JUNO detector is deployed in an underground laboratory with approximately 650 m of rock overburden, *i.e.*, 1800 meters-water-equivalent (m.w.e.).

2˙1. *Central detector design*. – The Central Detector (CD) consists of a 20 kton liquid scintillator target, contained inside a 35.4-meter-diameter spherical acrylic vessel and submerged in 35 kton of ultra-pure water. Its design is driven by its physics goals: the key prerequisites include achieving an energy resolution of 3% at 1 MeV, ensuring precise control of the energy scale with overall non-linearity effects below 1%, and collecting a substantial amount of antineutrino events [2,3]. The detector incorporates a sophisticated photo-detection system, comprising 17,612 20-inch large PMTs (LPMTs) and 25,600 3-inch small PMTs (SPMTs), attached to the surrounding Stainless Steel (SS) structure. This configuration provides an extensive total photo-coverage of $\simeq$ 78%, securing high photoelectron (PE) statistics. The SS support structure was completed in June 2022, and the installation of the acrylic panels, along with PMTs and their front-end electronics, is presently underway. An actual view of the current status of the CD can be seen in fig. 3, while a schematic representation can be found in fig. 4.

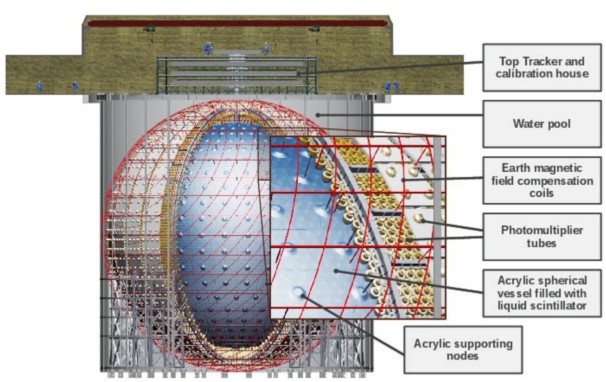

Fig. 4.: Schematic representation of the main JUNO detector. Taken from [4].

2˙2. *Liquid scintillator*. – The LS formula consists of linear alkylbenzene (LAB) as solvent, supplemented with 2.5 g/L of 2,5-diphenyloxazole (PPO) and 3 mg/L of p-bis-(o-methylstyryl)-benzene (bis-MSB) as wavelength shifters. The targeted level of radiopurity is set at 10^{-15} g/g of ^{238}U and ^{232}Th for the NMO analysis, while for the solar neutrino analysis concentrations below 10^{-17} g/g are required [6]. To maintain the proper cleanliness of the LS, a combined system of purification plants, employing different techniques and four stages is planned [3]. A final quality check will be conducted during the CD filling by the Online Scintillator Internal Radioactivity Investigation System (OSIRIS) stand-alone detector [3].

2˙3. *Veto systems*. – The experiment will be equipped with two veto systems providing an efficient reduction of the residual cosmic muon flux crossing the detector. The CD is housed within a cylindrical pool, which is completely submerged in 35 kton of ultra-pure water. The water pool is instrumented with 2400 20-inch PMTs pointing outwards, thereby acting as an active veto Cherenkov detector for cosmic muons. On top of the water pool, a muon tracker with scintillator strips, called Top Tracker [7], will be installed.

3. – Oscillation physics with reactor antineutrinos

The primary physics channel is provided by $\overline{\nu}_e$ emitted by the nearby NPPs, which operate commercial pressurized water reactors, where electron antineutrinos are produced by the β decay of fission products of four major isotopes: ^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu. Reactor antineutrinos are detected in JUNO through the Inverse Beta Decay (IBD) reaction $\overline{\nu}_e + p \rightarrow e^+ + n$. The positron ($e^+$) rapidly deposits its energy and annihilates into two 0.511 MeV photons, producing a *prompt* signal. The neutron thermalizes within the detector medium and after an average time of 220 µs it is captured predominantly on a free proton in the LS, thus emitting a 2.22 MeV γ-ray and giving rise to a *delayed* signal. The positron preserves the majority of the kinetic energy carried by the incoming antineutrino, making it a reliable proxy for the antineutrino itself. Consequently, the energy spectrum generated by the prompt signals serves as a valuable tool for studying the $\overline{\nu}_e$ oscillation pattern.

Positrons interacting with the LS produce photons through scintillation and, to a lesser extent, Cherenkov radiation mechanisms. However, the relationship between the energy deposited by the positron and the number of scintillation photons detected by the PMTs is not linear, mainly due to the quenching effect. A comprehensive calibration program, with a wide range of radioactive sources, is envisaged to measure and understand the intrinsic non-linear behavior of the LS [8]. The visible energy is further smeared because of the finite energy resolution of the detector [8]. Figure 5 depicts the expected prompt energy spectrum in JUNO with and without these detector response effects, *i.e.*, liquid scintillator non-linearity (NL) and energy resolution (Res).

The characteristic double spatial and temporal signature provided by the IBD reaction enables efficient tagging signal candidates while reducing background contamination. For this purpose, multiple selection criteria are devised to perform event selection. The resulting energy spectrum, comprising the reactor antineutrino signal and all residual backgrounds is reported in fig. 6 [4].

3˙1. *Precision measurement of oscillation parameters and NMO determination*. – To extract the neutrino oscillation parameters and evaluate the sensitivity to the NMO, the analysis involves comparing the nominal spectrum, which stands as a representation of

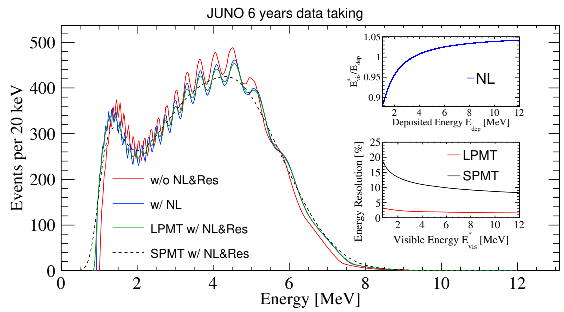

Fig. 5.: Expected prompt energy spectrum with and without the different detector response effects. Taken from [4].

the spectrum JUNO is expected to measure, as depicted in fig. 6, with a theoretical model linked to the standard three-flavor framework. An Asimov pseudo-dataset is constructed to simulate the nominal energy spectrum at JUNO for both the Normal Ordering (NO) and Inverted Ordering (IO) hypotheses. Then, the median sensitivity discriminator is defined as:

$$\Delta\chi^2 \equiv |\chi^2_{\text{min}}(\text{NO}) - \chi^2_{\text{min}}(\text{IO})|. \tag{1}$$

The resulting median $\Delta\chi^2$ is reported in fig. 7 as a function of JUNO data taking time for both NO (red) and IO (blue) hypotheses. It is determined that with ~ 6.7 years of data taking at 26.6 GW_{th} reactor power, JUNO can determine the NMO with 3σ significance [9]. Furthermore, ongoing research is exploring the possibility of enhancing this level of significance by integrating additional information from the detection of atmospheric neutrinos [3, 9]. Moreover, JUNO is foreseen to already exceed global precision on Δm^2_{21}, Δm^2_{31}, and $\sin^2\theta_{12}$ within the first months of data acquisition [4]. Within six years, these three parameters will be determined to a precision of 0.2%, 0.3%, and 0.6%, respectively, representing almost an order of magnitude enhancement over the precision attained by existing measurements. Figure 8 shows the relative precision of the oscillation parameters as a function of JUNO data taking time.

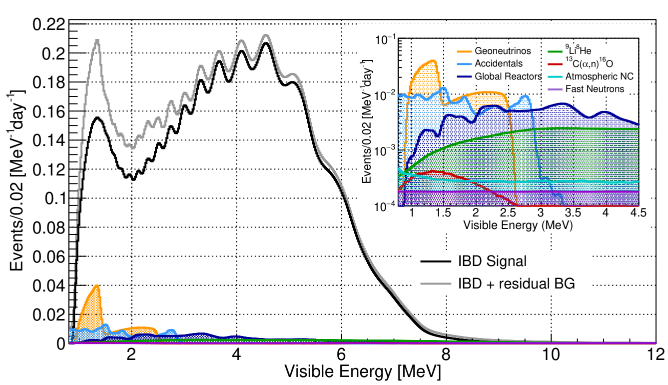

Fig. 6.: Expected energy spectra in JUNO, with all spectral components. Taken from [4].

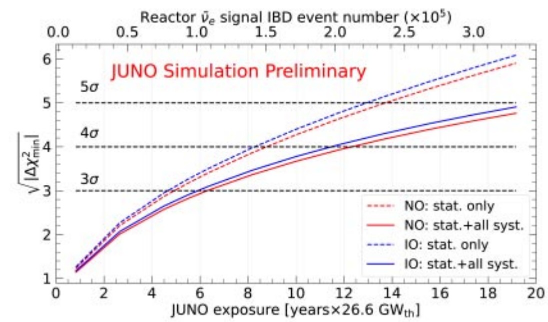

Fig. 7.: NMO median sensitivity as a function of JUNO exposure. Taken from [9].

4. – JUNO physics program

Due to its remarkable target mass and expected performance, JUNO has an extensive physics program [2,3], ranging from studying neutrinos from other sources, such as solar and supernova neutrinos, to exploring Beyond the Standard Model (BSM) physics, such as the search for proton decay.

4·1. *Atmospheric neutrinos.* – JUNO will have the capability to detect neutrinos generated by cosmic-ray showers interacting in the Earth's atmosphere, covering both the MeV and GeV energy ranges [3]. Although the detector is not specifically designed for atmospheric neutrino measurements, simulations have revealed its significant potential for reconstructing low-energy events [3]. Additionally, by leveraging matter effects that occur as neutrinos propagate through the Earth, atmospheric neutrinos offer a complementary sensitivity to the NMO, independent of reactor antineutrinos. In addition to direct NMO measurements, ongoing studies aim to combine the sensitivity to NMO using both reactor and atmospheric neutrinos within the JUNO experiment [9].

4·2. *Solar neutrinos.* – Solar neutrinos are electron neutrinos produced by thermonuclear reactions taking place in the core of the sun. About 99% of energy comes from

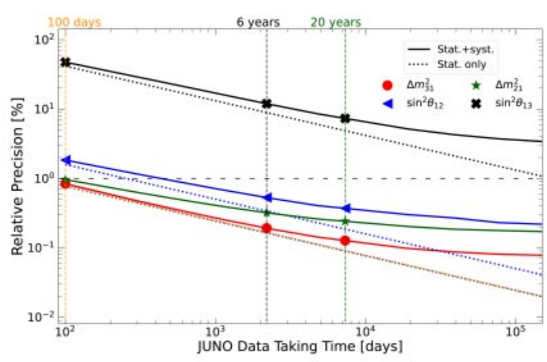

Fig. 8.: Relative precision on oscillation parameters as a function of JUNO exposure. Taken from [4].

the so called *pp* chain, yielding *pp*, *pep*, ^{7}Be, ^{8}Be, and *hep* neutrinos with different energy spectra. The remaining smaller portion of the Sun's energy is produced through the CNO cycle. The primary detection channel for solar neutrinos in JUNO [3] is the elastic scattering (ES) on electrons $\nu_e + e^- \to \nu_e + e^-$. The main source of background arises from the intrinsic natural radioactivity in the liquid scintillator, gamma rays from external detector materials, and unstable isotopes produced by cosmic ray muons that traverse the detector. The sensitivity of JUNO to higher energy ^{8}B solar neutrinos, characterized by a low flux and an energy spectrum that extends up to approximately 15 MeV, is discussed in ref. [10]. Furthermore, this detection channel serves as a complementary method for measuring the oscillation parameters $\sin^2\theta_{12}$ and Δm^2_{21}. On the other hand, JUNO's capability to measure lower-energy solar neutrinos (*i.e.*, those with visible energy below 2 MeV) is highly reliant on the level of radiopurity. A recent study considered various radiopurity scenarios and detailed information is available in ref. [11].

4˙3. *Geoneutrinos*. – Geoneutrinos are antineutrinos released during the decay of long-lived radioactive elements within the Earth. They offer a valuable means to explore the Earth's formation and chemical composition. The detection of geoneutrino signals relies on the IBD reaction, and the kinematic threshold of 1.806 MeV allows for the measurement of neutrinos produced along the ^{238}U and ^{232}Th decay chains. Thanks to the considerable size of the detector, JUNO is expected to surpass the statistics collected by previous LS-based experiments within just one year of data-taking, with an anticipated rate of 400 events/year. Over several years of measurements, JUNO also has the potential to provide constraints on the Th/U ratio in the observed signal, as detailed in [2, 3].

4˙4. *Other physics topics in JUNO*. – In addition to the physics channels outlined above, JUNO will also play a key role in the detection of core-collapse supernovae. Its substantial target mass and dedicated data acquisition system [2, 3], provide excellent capabilities for detecting MeV-scale supernova neutrinos of all flavors and through various interaction channels. Furthermore, JUNO offers the opportunity to address a broad range of unresolved questions in the fields of particle physics, nuclear physics, astrophysics, and cosmology. In-depth details can be found in ref. [3].

5. – Conclusions

The construction of the JUNO detector is proceeding and advancing towards its final stages. JUNO's outstanding capability to measure the oscillated reactor antineutrino spectrum allows it to exceed the current global precision on three oscillation parameters. This scientific endeavor marks the beginning of a new era of sub-percent precision in the neutrino sector [4]. Moreover, the expected sensitivity for NMO determination reaches the 3σ level in roughly 6 years of operation at 26.6 $\mathrm{GW_{th}}$ reactor power [9]. Beyond these achievements, JUNO holds the potential to investigate various other aspects of neutrinos and oscillations, using them as valuable probes to explore the Sun, Earth, and supernovae explosions.

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