

Detector design and current status of JUNO experiment

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The Jiangmen Underground Neutrino Observatory (JUNO) is a multi-purpose experiment, which is under construction in South China. Thanks to the 20 ktons of ultra-pure liquid scintillator (LS), JUNO will be able to perform innovative and groundbreaking measurements like the determination of neutrino mass ordering (NMO). Beyond NMO, JUNO will measure the three neutrino oscillation parameters with a sub-percent precision. Furthermore, the JUNO experiment is expected to have important physics reach with solar neutrinos, supernova neutrinos, geoneutrinos, and atmospheric neutrinos. The experiment is being constructed in a 700m underground laboratory, located about 53 km from both the Taishan and Yangjiang nuclear power plants. The JUNO central detector (CD) will be equipped with 17612 20-inch photomultiplier tubes (PMTs) and 25600 3-inch PMTs. The central detector will be surrounded by a water tank that will provide passive shielding from radioactivity decays and serve as a water Cherenkov detector to tag cosmic muons. Additionally, a plastic scintillator detector is located above the central detector to veto cosmic muons from the top. The JUNO CD detector is expected to have an energy resolution better than 3% at 1 MeV and to have an absolute energy scale uncertainty better than 1% over the whole reactor antineutrino energy range. The detector construction is expected to be completed in 2023. In this manuscript, I will present the detector design and the installation status of the various JUNO subsystems.

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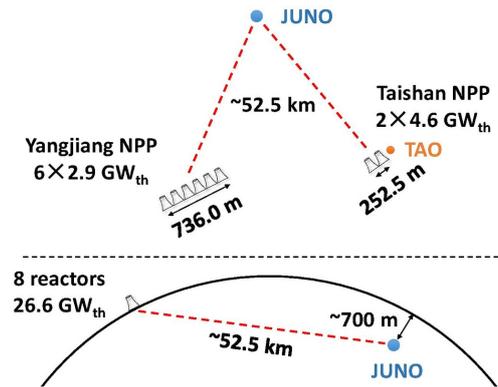


Figure 1: JUNO detector is located near the city of Kaiping, Guangdong province in southern China. It has a baseline of 52.5 km to the two nearest nuclear power plants, Taishan and Yangjiang. The central detector is ~ 700 m under the ground level. Close to one core of the Taishan NPP will be mounted JUNO-TAO to measure the reactor neutrino spectrum [1].

1. Introduction

Jiangmen Underground Neutrino Observatory (JUNO) is a multipurpose neutrino experiment under construction in southern China. With a baseline of 52.5 km to the two nearest nuclear power plants (NPP), Yangjiang and Taishan as shown in figure 1, and ≈ 700 m under ground level, it mainly aims to measure the neutrino mass ordering (NMO) using reactor antineutrino. The measurement relies on the small difference in the oscillation patterns for normal ordering and inverted ordering, as shown in figure 2. Along with the NMO measurement, JUNO will reach sub-percent precisions in measuring the oscillations parameter in the reactor sector [2]. JUNO is also sensitive to neutrinos emitted by other sources: solar neutrinos, Core Collapse SuperNova (CCSN) neutrinos, geoneutrinos and atmospheric neutrinos. To have sufficient sensitivity to NMO, the JUNO detector is required to have an energy resolution of $< 3\%$ at 1 MeV. The central detector is made of an acrylic sphere of 35.4 m diameter, containing 20 kton of linear alkylbenzene (LAB) based liquid scintillator blended with PPO and bis-MSB as the wavelength shifters. It is surrounded by a water pool filled with 35 kton high-purity water and instrumented with 2000 20-inch PMTs to veto muons and covered by a plastic scintillator on the top as a cosmic muon tracker. To collect photons emitted by the scintillator, 17612 20-inch PMTs, namely large PMT or LPMT, will be employed. In addition, 25600 3-inch PMT, called small PMT or sPMT, will be installed for calibrating the non-linearity of the LPMTs utilizing a laser calibration system. In total, the photocathode coverage is 78%. A sketch of the detectors is shown in figure 3. Currently, the JUNO detector is under construction and the data-taking will start in 2024.

2. JUNO detector

JUNO was proposed with the determination of neutrino mass ordering as a primary physics goal [3]. However, JUNO offers the possibility of studying neutrinos from various sources both

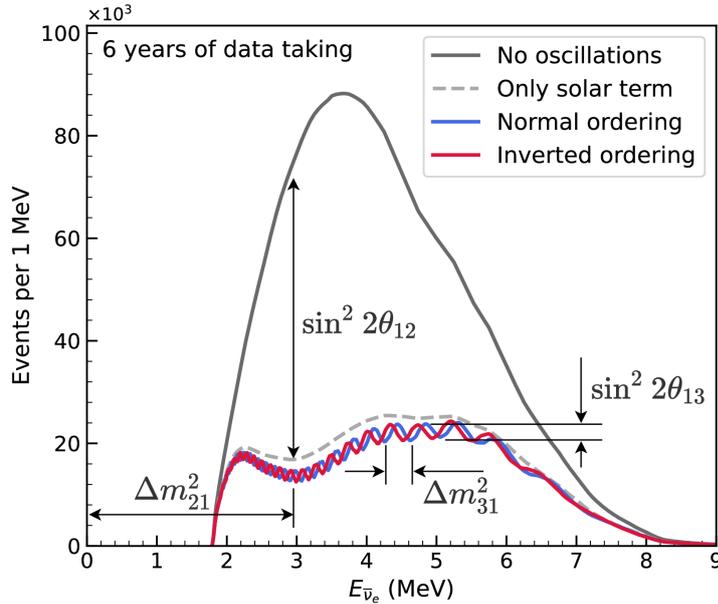


Figure 2: JUNO aims to measure the mass ordering using the small differences in the neutrino energy spectra assuming normal ordering (blue line) and inverted ordering (red line).

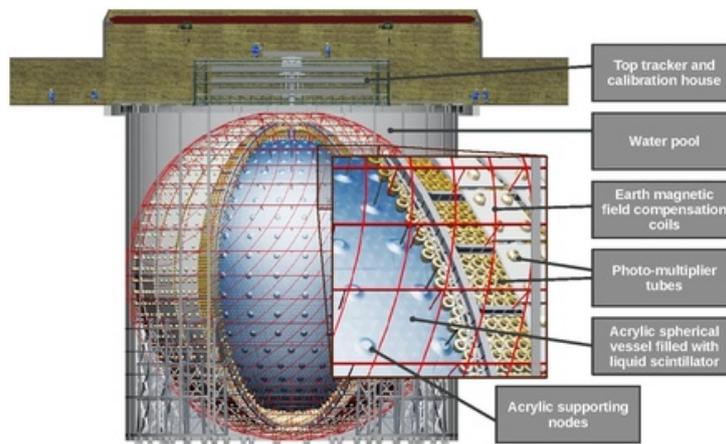


Figure 3: Schematic of the main JUNO detector. An acrylic sphere filled with 20 kton of liquid scintillator is immersed in a water tank and surrounded by 17612 large (20-inch) and 25600 small (3-inch) PMTs. The water pool is instrumented with 2400 20-inch PMTs providing shielding and cosmic-ray muon tagging. A top tracker system consisting of three layers of plastic scintillator covers roughly 60% of the surface above the water pool and provides precision tracking of cosmic-ray muons entering the central detector. A calibration house on the top of the central detector is used to store the corresponding instruments deployed in the detector. Two sets of large coaxial coils surround the central detector, largely suppressing any effects the Earth’s magnetic field could have on the 20-inch PMTs’ collection efficiency.

artificial (nuclear reactor) and natural (e.g. the sun, the atmosphere, the center of the earth, and astrophysical).

JUNO detects the reactor antineutrino signal mainly via Inverse Beta Decay (IBD) reaction, $\bar{\nu}_e + p \rightarrow e^+ + n$. However, JUNO can detect neutrinos and antineutrinos via elastic scattering on protons or electrons and via weak interaction on carbon nuclei.

2.1 JUNO Central Detector

The central detector (CD) consists of an acrylic sphere of 35 m of diameter filled with 20 kton of liquid scintillator (LS) and is surrounded by a water pool (WP) equipped with LPMTs to work as a water Cherenkov detector (WC) and by a plastic scintillator on the top to work as a muon top tracker (TT). The cylindrical water pool has a diameter of 43.5 m and a height of 44 m. The spherical acrylic vessel is sustained by a stainless steel structure. The light emitted by the LS is collected by both LPMTs and sPMTs, which are installed on the inner surface of the Main Structure. A water buffer of 1.42 m thickness between the acrylic vessel and the PMT surface protects the LS from the PMT glass's radioactivity. The water buffer is connected with the outer water Cherenkov detector but is optically separated. A chimney for calibration operations is connected to the top of the acrylic vessel. Special radioactivity shielding and a muon tracker will cover the chimney and the calibration system on the top. The JUNO LS is composed of Linear alkylbenzene used as the detection medium due to its excellent transparency, high flash point, and low chemical reactivity. In addition, the LS will contain 2.5 g/L 2,5-diphenyloxazole (PPO) as the fluor and 3 mg/L p-bis-(o-methylstyryl)-benzene (bis-MSB) as the wavelength shifter.

2.2 Osiris

To achieve its important physics goals, JUNO has set stringent upper limits of 10^{-15} g/g on the contamination level of the LS for uranium and thorium chain isotopes and 10^{-17} g/g for solar neutrinos [4]. To achieve these radiopurity requirements an extensive purification program needs to be performed on the liquid scintillator before filling the acrylic vessel. The Online Scintillator Internal Radioactivity Investigation System (OSIRIS) will verify the efficiency of the purification plants and monitor the radiopurity of the produced LS for the filling of the JUNO Central Detector. The setup is divided into an Inner Detector (ID), containing the LS volume and surrounding PMTs, and an Outer Detector (OD), equipped with a few PMTs and utilizing the water shielding as a Cherenkov muon veto. The cylindrical vessel (Acrylic Vessel, AV) of 3 m in height and diameter, with a thickness of 3 cm, holds the liquid scintillator at the center of the detector. The 8 m high Steel Frame (SF) with a diameter of 7 m provides mechanical support for the AV, the photomultipliers, and the calibration system. To collect the scintillation light produced by the LS 64 20"-PMTs will be used. All the structures will be surrounded by a Water Tank (WT), 9 m in height and diameter, as shielding from external gamma rays emitted by the rocks. The water tank is instrumented with 12 LPMTs to collect Cherenkov light produced by muons using the WT as a veto detector. On the top of the structure is the calibration system composed of a picosecond laser pulse coupled with optical fiber and an automated calibration system able to deploy radioactive sources and an LED directly into the LS volume. The layout of the OSIRIS detector is shown in figure 4.

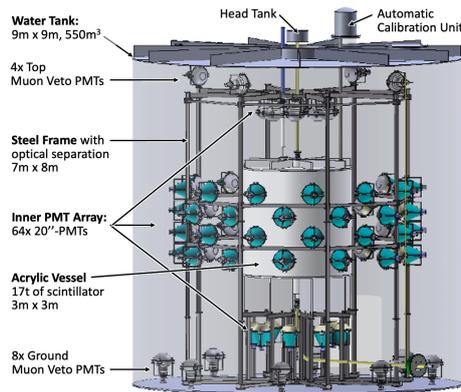


Figure 4: Layout of the OSIRIS detector. It is possible to divide OSIRIS into the Inner Detector (ID) which is formed by the LS volume and the inner PMT array and the Outer Detector (OD) which uses the shielding water as a Cherenkov muon veto.

2.3 JUNO Calibration System

Non-uniformity and non-linearity could compromise the measurement of the antineutrino energy spectrum. Therefore, both effects need to be corrected by calibration to achieve the 1% energy accuracy and $3\%/\sqrt{MeV}$ energy resolution for the NMO [5]. The calibration system is composed of three sub-systems: the Automatic Calibration Unit (ACU), the Guide Tube System (GT), and the Cable Loop System (CLS). The ACU is developed to do calibration along the central vertical axis z of the CD and it's composed of four independent spools mounted on a turntable. Each spool is capable of unwinding and delivering the source via gravity through the central chimney of the CD, with a positioning precision in z better than 1 cm. Three sources will be deployed regularly, including a neutron source (AmC), a gamma source (^{40}K), and a pulsed UV laser source carried by an optical fiber with a diffuser ball attached to the end [6]. The GT is a tube looped outside of the acrylic sphere along a longitudinal circle. Within the tube, a radioactive source with cables attached to both ends gets driven around with a positioning precision of 3 cm allowing to calibrate the central detector non-uniformity at the boundary. The CLS will deploy sources to off-axis positions. Two cables are attached to the source, which also form a loop to deliver and retract the source. Different sources can be interchanged on the CLS. To reach other positions not covered by the CLS a Remotely Operated Vehicle (ROV) capable of deploying a radioactive source in almost the entire LS volume was developed. Independent laser devices known as AURORA, are used to make measurements of the attenuation length and Raleigh scattering length of the LS using detected light patterns on the PMTs. A scheme of the calibration systems is shown in figure 5.

3. Conclusion

JUNO detector is currently under construction and will start taking data in 2024. A full R&D program was developed to reach an energy resolution of 3% at 1 MeV with an energy uncertainty of less than 1%. To satisfy the strict requirements on energy resolution three independent calibration systems, named ACU, GT, and CLS, were developed while the OSIRIS detector will monitor the radiopurity level of the liquid scintillator before and during data taking.

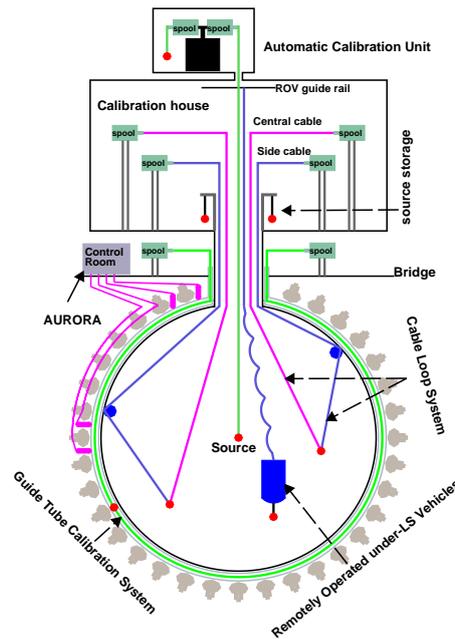


Figure 5: Overview of the calibration system (not to scale), which includes the Automatic Calibration Unit (ACU), Cable Loop Systems (CLS), the Guide Tube (GT), and the Remotely Operated Vehicle (ROV). The AURORA is an auxiliary laser diode system to monitor the attenuation and scattering length of the LS.

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