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Status and Prospects of the Jiangmen Underground Neutrino Observatory

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The Jiangmen Underground Neutrino Observatory (JUNO) is a multi-purpose neutrino experiment currently under construction in South China, expecting to start data taking in 2023. JUNO primary goal is the determination of the neutrino mass ordering and the measurement, at a sub-percent level, of three of the neutrino oscillation parameters . The main detector, placed in a cavern about 700 m underground (1800 m.w.e.), will consist of 20 kton of liquid scintillator contained in a 35.4 m diameter acrylic sphere, becoming the largest detector of its kind ever built in the world. JUNO will be instrumented with 17,612 20-inch photomultiplier tubes (PMTs), and 25,600 3-inch PMTs reaching a photo-coverage above 75%. The experiment will achieve an unprecedented energy resolution of $3\%/\sqrt{E(MeV)}$ thanks to a comprehensive calibration system, among others. The acrylic sphere will be submerged in a water Cherenkov detector and covered on the top by layers of plastic scintillator to tag cosmic ray muons, a major source of background. This paper will review the physics potential of JUNO as a medium baseline reactor anti-neutrino experiment, illustrate the technical characteristics of the detector, discuss the technological challenges and present the construction status.

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1. Introduction

The Jiangmen Underground Neutrino Observatory (JUNO) [1] was designed with the determination of the neutrino mass ordering (NMO) as primary physics goal [2]. The relative large value of the neutrino oscillation parameter, θ_{13}, provided an excellent opportunity to resolve the NMO in a medium baseline ($\sim$ 50 km) reactor anti-neutrino $\overline{\nu}_e \to \overline{\nu}_e$ oscillation experiment (JUNO). In contrast to the accelerator (NOνA [3] and DUNE [4]) and atmospheric neutrino experiments (INO [5], PINGU [6], ORCA [7], DUNE[4] and Hyper-K [8]), which rely on the matter effect in neutrino oscillations, JUNO is a unique experiment since it will identify the NMO through the interplay between Δm^2_{31} and Δm^2_{32}; moreover, JUNO NMO sensitivity has no dependence on the CP-violating phase and the θ_{23} octant, playing a key role when combined with other neutrino experiments. The reactor anti-neutrino survival probability in vacuum can be written as

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} \left(\cos^2\theta_{12} \sin^2\Delta_{31} + \sin^2\theta_{12} \sin^2\Delta_{32} \right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\Delta_{21}$$

where $\Delta_{ij} = \Delta m^2_{ij} L/(4E)$, L is the baseline and E is the anti-neutrino energy. Thanks to a baseline $L = 53$ km, JUNO will simultaneously measure oscillations driven by small mass splitting (Δm^2_{21}) and large mass splitting (Δm^2_{31} and Δm^2_{32}). Fig. 1 shows the expected anti-neutrino energy

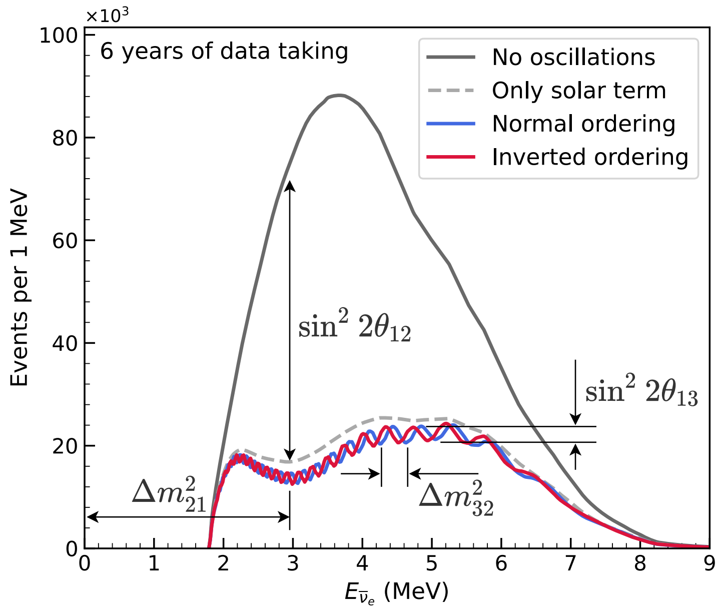

Figure 1: Expected anti-neutrino energy spectrum in JUNO.

spectrum in JUNO. The contributions of the mass splitting and oscillation is clearly visible: the small oscillation peaks in the oscillated spectrum is the way to determine the NMO. Additional key ingredients are a large active mass (20 kton) and an excellent energy resolution (σ_E/E equal or better than 3% at 1 MeV) Thanks to these challenging requirements, besides neutrino mass ordering, JUNO will address several additional topics in neutrino and astro-particle physics: the precise measurement of the reactor anti-neutrino spectrum will also lead to the precise determination of the neutrino oscillation parameters $\sin^2\theta_{12}$, Δm^2_{21} and $|\Delta m^2_{32}|$ as can be inferred from Fig. 1. Finally, the

JUNO detector is not limited to detect anti-neutrinos from reactors, but also observes neutrinos from terrestrial and extra-terrestrial sources, like supernova burst neutrinos, diffuse supernova neutrino background, geoneutrinos, atmospheric neutrinos [9], and solar neutrinos [10].

2. The JUNO Experiment

The JUNO experiment is located in Jinji town, about 43 km South-West of Kaiping city, in Guangdong province, China. The experimental site is at equal distance (about 53 km) from the YangJiang and TaiShan nuclear power plants. The detector is being constructed in an underground laboratory, under the Dashi hill, with a rock overburden of about 700 m (1800 m.w.e.). The JUNO detector is made of a Central Detector (CD), a water Cherenkov detector and a Top Tracker (TT). The CD, a spherical Acrylic Vessel with inner diameter of 35.4 m and 12 cm thickness is supported by a stainless steel shell structure (SS) and contains 20 kton of highly transparent Liquid Scintillator (LS). The SS supports 17,612 20-inch PMTs and 25,600 3-inch PMTs with the photocathode facing toward the center of the acrylic sphere. Another 2,400 20-inch PMTs are directed towards the water pool to detect the Cherenkov light produced in water. The CD and water Cherenkov detectors are optically separated. The SS provides an additional support for the front-end electronics, cables and the coils designed to compensate the geomagnetic field. To satisfy the requirements for the reactor and solar neutrino program, the CD must be made of selected radio-pure materials. The surfaces of the CD components, including the Acrylic Vessel, pipes, pumps, and valves, are required to be extra clean and LS/water-compatible [11]. The JUNO LS recipe is the following: Linear Alkyl Benzene (LAB), 2,5-diphenyloxazole (PPO), and 1,4-bis(2-methylstyryl)benzene (bis-MSB). The optimal LS composition was determined to be the purified solvent LAB with 2.5 g/L PPO and 3 mg/L bisMSB [12]. A combined system of purification plants has been designed to improve the optical and radio-purity properties of the LS [1]. An Online Scintillator Internal Radioactivity Investigation System (OSIRIS) [13] has been designed and assembled as a stand-alone detector to monitor the LS radio-purity during JUNO CD filling with LS. OSIRIS aims to guarantee that the concentrations of ^{238}U and ^{232}Th in the LS do not exceed the given limits (10^{-15} g/g or 10^{-16} g/g) required for reactor anti-neutrino or solar neutrino measurements, respectively.

The design [14] and R&D program [15] for the 20-inch PMT electronics have been driven by requirements of reconstructing the deposited energy in the LS with high resolution and a good linearity response over a wide dynamic range: from 1 p.e. for low energy events to 1000 p.e. for showering muons and muon bundles. In addition, a precise measurement of the photon's arrival time is mandatory [14]. The 20-inch PMT electronics is split into two parts: the 'wet' electronics located very close to the PMTs inside a custom Stainless Steel box (UWbox), and the 'dry' electronics in the electronics rooms. Since it is almost impossible to repair the 'wet' electronics underwater in the water pool during operation, its loss rate is required to be $< 0.5\%$ in 6 years. This requirement has generated important constraints on the reliability of the 'wet' electronics (see the discussion in [15]). As can be seen from Fig. 2, three PMT output signals are fed to the front-end and readout electronics located inside the UWbox. The PMT high voltage is provided for each PMT by a custom High Voltage module [15] located inside the UWbox. The analog signal is amplified and converted to digital with a 14 bit, 1 GS/s, custom ADC. The signal is further processed (local trigger generation, charge reconstruction and timestamp tagging) and stored temporarily in a local memory before

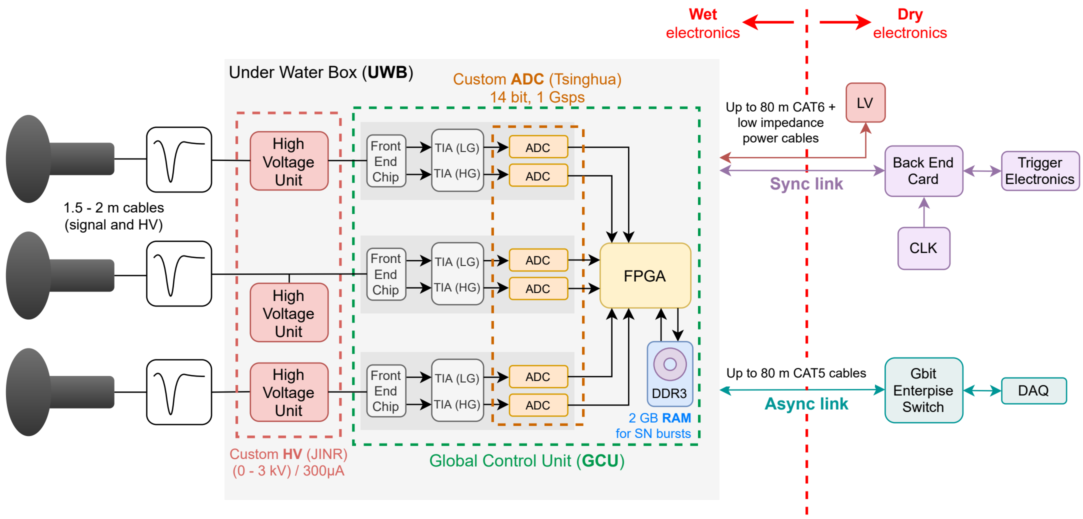

Figure 2: Large PMT electronics logical scheme.

being sent to the data acquisition (DAQ), once validated by the global trigger electronics. Besides the local memory available in the readout-board FPGA, a 2 GBytes DDR3 memory is available and used to provide a larger memory buffer in the exceptional case of a sudden increase of the input rate, which overruns the current data transfer bandwidth between the 'wet' electronics and the DAQ. This situation will certainly happen in case of a supernova explosion not very far from the Earth, when the rate of neutrino interactions in the LS is expected to increase suddenly and for a short time. The readout electronics is connected to the 'dry' electronics through a so-called 'synchronous link', which provides the clock and synchronization to the boards and handles trigger primitives, and an 'asynchronous link' which is fully dedicated to the DAQ. Both cables connecting the UWbox to the PMTs and the UWbox to the 'dry' electronics run inside a stainless steel bellow, which completely isolates the cables from the water in which the electronics is submerged. While the length of the bellow connecting the UWbox to the PMTs is less than 2 m, those connecting the UWBox to the back-end electronics have variable length form 30 m to 100 m to fulfill the installation constraints.

To precisely determine the neutrino mass ordering, the JUNO central detector requires a better than 1% energy linearity and a 3% effective energy resolution. Multiple calibration sources and multiple dimensional scan systems are developed to correct the energy non-linearity and spatial non-uniformity of the detector response [16].

3. Conclusion

JUNO, thanks to the 20 kton LS target mass and $3\%/\sqrt{E(MeV)}$ effective energy resolution, is expected to resolve the neutrino mass ordering at 3σ with about 6 years of data taking of reactor anti-neutrino coming from the nearby nuclear power plants. Moreover, due to the large mass and advanced detector technologies, many other important topics in neutrino physics will be measured. JUNO completed the excavation of the tunnel and the underground experimental hall at the end of 2020. The detector design has been finalized and all challenges regarding the detector technologies have been solved. The detector component production and facility and the detector installation is underway. The detector construction is expected to be completed by the end of 2022.

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