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Status and progress of the JUNO detector

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The Jiangmen Underground Neutrino Observatory (JUNO) is a neutrino oscillation experiment with a 53 km distance from reactors and a 700 m overburden, currently under construction in South China. The primary goal is to measure the neutrino mass ordering with better than 3σ after 6 years of data taking. Therefore 20 kton high transparency liquid scintillator, high coverage (75%) of photomultiplier tubes and low backgrounds are needed to achieve an energy resolution of 3% at 1MeV and a calibration accuracy better than 1%. This is the most challenging design in the present reactor neutrino experiments throughout the world. Such a large detector also has a huge potential to measure with sub-percent accuracy three neutrino oscillation parameters and detect neutrinos from various terrestrial and extra-terrestrial sources. This talk will present the status and progress of the JUNO detector and of Taishan Antineutrino Observatory (JUNO-TAO), a satellite experiment of JUNO, designed to measure the reactor antineutrino spectrum with sub-percent energy resolution and provide a reference spectrum for future reactor neutrino experiments.

40th International Conference on High Energy physics - ICHEP2020
July 28 - August 6, 2020
Prague, Czech Republic (virtual meeting)

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PoS(ICHEP2020)882

1. Introduction

JUNO [1] is under construction near Jiangmen city in southern China and the main goal is to measure the neutrino mass ordering with better than 3σ after 6 years of data taking [2]. The experiment is about 53 km away from both Taishan and Yangjiang Nuclear Power Plant (NPP) and with an overburden of 700 m rock for shielding of cosmic rays. To achieve energy resolution of $3\%/\sqrt{E(\mathrm{MeV})}$ and calibration error lower than 1%, the high transparency liquid scintillator (LS), high coverage of photomultiplier tubes (PMTs) and low backgrounds are needed. JUNO also has rich physical detection contents like measuring solar neutrino oscillation parameters with highest precision (<1%), and many neutrinos like supernova neutrino, geo-neutrino, solar neutrino, atmospheric neutrino, sterile neutrino, and also is sensitive to a particular proton decay channel.

The central detector (CD) is an acrylic sphere filled with 20 kton Liquid Scintillator (LS) with inner diameter of 35.4 m and thickness of 12 cm; the CD is immersed in a cylindrical water pool operating as a Cherenkov detector and filled with ultra-pure water with diameter and height both 43.5 m (Figure 1). Since LS has a density lower than water, the acrylic shell is supported and held by stainless steel (SS) support structure. There are about 18,000 high quantum efficiency (QE) 20-inch PMTs (LPMTs) closely packed around the LS ball and 25,600 3-inch small PMTs (SPMTs) inserted between the LPMT gaps; finally, 2,400 veto PMTs will be installed on SS structure facing the water pool. The plastic scintillator detector refurbished form the Target Tracker detector of the OPERA experiment will be placed above the water pool as Top tracker (TT) to track cosmic muons.

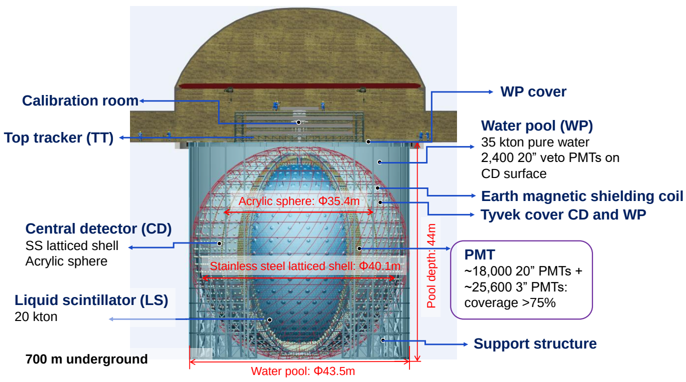

Figure 1: Overview of JUNO detector including central detector, PMTs, water Cherenkov detector, top tracker, etc.

2. The JUNO experiment

JUNO is optimized to have the best sensitivity for neutrino mass ordering at a distance of 53 km both from Yangjiang and Taishan nuclear power plants (NPPs). The thermal power of the NPPs is expected to be 26.6 $\mathrm{GW_{th}}$ at the end of 2020. This section describes the following subsystems of the JUNO detector: the central detector (CD), the PMTs, the calibration system, the veto system, and the Taishan Antineutrino Observatory (TAO, also known as JUNO-TAO).

2.1 The central detector

The acrylic spherical vessel with weight of ~ 600 tons is the largest acrylic spherical vessel for a neutrino experiment. It cannot be directly transported into the underground through the tunnel, and will be divided into 265 sheets with the typical sheet size 8 m × 3 m × 12 cm. The sheets will be bonded and annealing will be performed at the JUNO underground site. JUNO has solved all technical problems such as no standards for construction, high precision curved sheet, anti-seismic protection, transparency, low background, fast bonding and annealing, etc. Each acrylic sheet will be supported by stainless steel structure by 2 - 4 support bars. Acrylic vessel panels and SS structure are in production.

In order to achieve the $3\%/\sqrt{E(\text{MeV})}$ energy resolution, the central detector is required to maximize the collection of optical signals from LS and minimize the background from a variety radioactive sources. The LS recipe mainly consists of Linear Alkyl Benzene (LAB) as solvent, with 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, which can emit more than 10,000 photons / MeV. A pilot LS purification system at Daya Bay experiment for R&D has been built [3] and reached the LS attenuation length more than 20 meters at 430 nm wavelength. At ground surface of JUNO site, the purification system is being constructed including Al_2O_3 filtration system, distillation system. LS will be produced on the ground surface and then moved underground. LS will go through water extraction system, steam stripping system and finally fill into the acrylic spherical vessel.

During commissioning and data taking, the LS will be purified using the underground purification system in the purification hall. The LS radio-purity will be essential for the success of the JUNO experiment. JUNO LS radioactive requirements are ^{238}U < 10^{-15} g/g, ^{232}Th < 10^{-15} g/g and ^{40}K<10^{-17} g/g, respectively. In order to monitor the radio-purity during the commissioning of the purification system an Online Scintillator Internal Radioactivity Investigation System (OSIRIS) will be built close to the JUNO detector to control LS radioactivity online with sensitivity of U/Th 10^{-15} g/g per day (Figure 2).

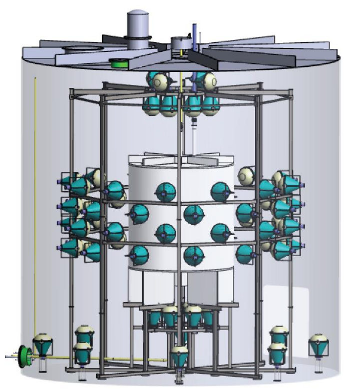

Figure 2: OSIRIS detector design. The detector includes 20 ton LS in the cylinder acrylic tank in center with diameter and height 3 m × 3 m, and ultra-pure water tank 9 m × 9 m, 81 20-inch PMTs around LS and 12 20-inch PMTs around water tank.

2.2 The PMTs

Photon detectors to collect the scintillation light created in interactions of neutrinos with LS are the key components for accomplishing the physical goals of JUNO.

For 20-inch PMTs, 13,000 Micro-channel plate PMTs are produced by North Night Vision Technology Co. (NNVT) and 5,000 dynode PMTs Hamamatsu Photonics [4, 5]. All the PMTs closely packed around CD provide a photo-coverage greater than 75%. Currently, almost all bare PMTs are delivered and acceptance tests are going well. The photon detection efficiency of new MCP-PMT is larger than 30%. Mass production of potted PMT is on going (36%) and in good shape. Implosion protection cover mass production has also started.

In order to improve the energy scale accuracy, in particular, the coupling of non-linearity and non-uniformity, 3-inch PMTs are designed to be inserted in the gaps between LPMTs. These SPMTs together with LPMTs can make double calorimetry system to improve and extend JUNO physics [6]. LPMT and SPMT system both will detect the same inverse beta-decay (IBD) signals

Figure 3: LPMTs and SPMTs are packed closely to each other.

from reactor neutrino interaction, but SPMT area is about 40 times smaller than LPMT and will be almost always work in single photoelectron (SPE) mode for IBD signals. As a result, it will help to constrain the systematics in the LPMT energy reconstruction, improving the energy resolution and the sensitivity of neutrino mass hierarchy measurement. They will also improve the muon reconstruction resolution, help reduce muon-related isotope backgrounds, provide an independent measurement of the θ_{12} and Δm^2_{21} solar parameters with unprecedented precision, and improve the measurement of supernova neutrinos.

25,600 custom made SPMTs (XP72B22) for JUNO are produced by Hainan Zhanchuang Photonics Co. (HZC) [7]. Until now, all bare PMTs already delivered and passed the acceptance test. Performance test data indicates that both LPMTs and SPMTs perform as expected. Others (HV divider, potting, cable, connector, HV splitter, electronics [8], under water box) are all going well.

2.3 Comprehensive calibration system

In order to achieve an energy scale uncertainty of better than 1%, an efficient calibration system is very important. As is shown in Figure 4, the calibration system consists of several complementary subsystems which have different dimension functions [9]:

1. 1D: Automatic Calibration Unit (ACU)

2. 2D: Cable Loop System (CLS) and Guide Tube Calibration System (GTCS)

PoS(ICHEP2020)882

3. 3D: Remotely Operated Vehicle (ROV)
4. Auxiliary systems: Calibration house, Ultrasonic Sensor System (USS), CCD and A Unit for Researching Online the LSc tRAnsparency (AURORA)

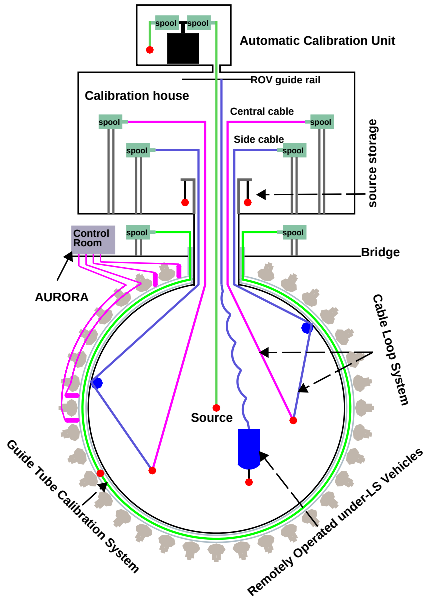

Figure 4: Overview of the calibration system (not drawn to scale), including the ACU, two CLSs, the GT, the ROV and the AURORA.

2.4 Veto system

In order to reduce the experimental background, the neutrino detector is not only placed in deep underground but also covered with veto detectors. The JUNO veto detector consists of a water Cherenkov detector and a top tracker detector.

JUNO water Cherenkov detector is a cylindrical water pool filled with about 35 kton ultra-pure water to passive shield rock neutrons, material radioactivity and active veto muons that go through LS and water pool. 2400 20-inch MCP-PMTs are installed on CD surface toward outside. Earth magnetic shielding coils are around CD to shield the earth magnetic and obviously increase the LPMT photoelectron collections. Residual magnetic field intensity <10% of local earth magnetic field for CD PMTs, <20% for Veto PMTs. Tyvek is not only around CD but also around water pool wall, bottom and top with fully coverage to increase the water pool veto system Cherenkov light. 5 mm thick high-density polyethylene plate (HDPE) lining around water pool wall and bottom to prevent diffusion of radon from rocks and keep water clean. Water circulation system not only keeps the ultra-pure water clean but also can control in (21 ± 1) °C

Top Tracker (TT) is designed to reuse the target tracker walls of the OPERA experiment and put 3-layers XY plastic scintillator strips to tag muon tracking, which is not only for veto, but also for muon tracking validation. The modules are already at JUNO site. Electronic front-end boards are all produced and other electronic boards in production and test well.

2.5 Taishan Antineutrino Observatory

The Taishan Antineutrino Observatory (JUNO-TAO), a ton-level with high energy resolution Gadolinium doped LS (Gd-LS) detector at 30 m from one of the Taishan reactor cores is a satellite experiment of JUNO [10]. The reactor antineutrino spectrum will be measured with sub-percent energy resolution, to provide a reference spectrum for future reactor neutrino experiments, and to provide a benchmark measurement to test nuclear databases. The detector includes 2.8 ton Gd-LS, 10 m^2 95% coverage with silicon photomultipliers (SiPMs) whose photon detect efficiency > 50%. The detector will Operate at -50 °C to decrease SiPM dark noise. The photoelectron yield is 4500 p.e./MeV, an order higher than any existing large-scale LS detectors. TAO can detect 2000 reactor antineutrinos per day and will start operation in 2022.

3. Summary

JUNO is a multipurpose experiment, not only to measure mass ordering, but also to measure solar oscillation parameters, supernova neutrinos, solar neutrinos, geo-neutrinos, atmospheric neutrinos, nucleon decay, etc. All of subsystems are in good production progress. The experiment is expected to start operation in 2022.

4. Acknowledgments

This work was supported by the National Natural Science Foundation of China No. 11975258, the Strategic Priority Research Program of the Chinese Academy of Sciences, Grant No. XDA10011200, and Special Fund of Science and Technology Innovation Strategy of Guangdong Province.

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