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Overview of TAO detector and its role for JUNO

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Summary. — The Taishan Antineutrino Observatory (TAO or JUNO-TAO) is a satellite detector of the Jiangmen Underground Neutrino Observatory (JUNO) and will provide a precise measurement of the non-oscillated reactor antineutrino spectra with unprecedented accuracy in energy resolution, improving the sensitivity of JUNO on mass hierarchy study. Furthermore, JUNO-TAO has an extensive research program in various fields: in nuclear databases, in searching the signature of a sterile neutrino, and in the verification of the detector technology for reactor monitoring and safeguard applications. TAO is a detector based on liquid scintillator technology and will be placed near one core of the Taishan Nuclear Power Plant in China, 53 km away from the JUNO site. In this manuscript, TAO's design, its physics potential, and the current status of the R&D will be presented.

1. – Introduction

The Jiangmen Underground Neutrino Observatory (JUNO), with its unique characteristics, in particular the high energy resolution and low systematic uncertainty on neutrino energy, will play an important role in the discovery of the correct neutrino mass hierarchy [1]. To enhance JUNO's discovery potential, a second detector, the Taishan Antineutrino Observatory (named TAO or JUNO-TAO), is under development [2]. The main goal of TAO is to provide the most precise determination of the energy spectrum of electron antineutrinos produced by the nuclear reactions that occur inside the core of the Taishan Nuclear Power Plant (4.6 GW, 53 km away from JUNO), one of the main $\overline{\nu}_e$ sources for JUNO. At the moment, the reference spectrum used for studying the neutrino emitted by nuclear reactors is the one measured by Daya Bay [3], however, for the purposes of JUNO, it will be important to use the spectrum measured by TAO as pointed out by Marrone *et al.* [4].

TAO is a ton-level Liquid Scintillator detector placed 30 m away from the core and will measure the reactor antineutrino spectrum [5]. It will use ∼4000 SiPM tiles working at -50 °C to detect scintillation light.

TAO has multiple physics goals, including: eliminating a model dependence in the determination of the neutrino mass ordering related to possible yet uncovered fine structures in the reactor antineutrino energy spectrum ($S_\nu(E)$); providing a benchmark measurement $S_\nu(E)$ for further tests of the nuclear databases; verifying the detector technology for reactor monitoring and safeguard applications; searching for a hypothetical sterile neutrino state with mass around 1 eV [2].

2. – TAO detector

TAO will measure the antineutrino energy spectrum near the reactor core with 2%@1 MeV (1.5% statistical uncertainty) of resolution. The detector has been designed to reach this goal sensitivity.

TAO is a liquid scintillator detector that detects the electron antineutrinos via the Inverse Beta Decay (IBD) using the following reaction:

$$\overline{\nu}_e + p \rightarrow e^+ + n.$$

The coincidence of the prompt scintillation generated by the positron with the delayed neutron capture provides a distinctive signature for events generated by $\overline{\nu}_e$.

The schematic drawing of the TAO detector is shown in fig. 1. The Central Detector (CD) consists of 2.8 ton gadolinium-doped liquid scintillator (LS) filled in a spherical acrylic vessel and viewed by ∼4000 SiPMs, produced by Hamamatsu, a spherical copper shell that supports the SiPMs and the associated readout electronics, a liquid scintillator buffer and a cylindrical stainless steel tank insulated with 20 cm thick Polyurethane. The outer shielding includes a water tank in the surrounding, High Density Polyethylene on the top, and lead at the bottom. The water tanks, instrumented with Photomultipliers (shown by red circles in the figure), and the Plastic Scintillator on the top, form the

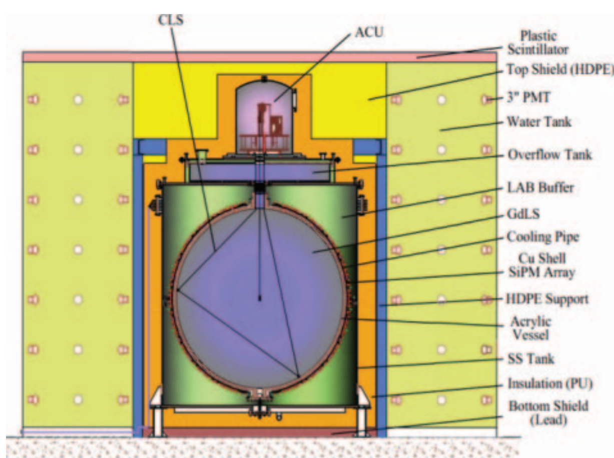

Fig. 1. – Schematic view of the TAO detector, consisting of a Central Detector (CD), the cryogenic system, an outer shielding and veto system. The veto is composed by a water Cherenkov detector and by a plastic scintillator on the top. Automated Calibration Unit (ACU) and Cable Loop System (CLS) are responsible for the daily calibration of the detector.

active muon veto system necessary for the ground based detector. The calibration system consists of the Automated Calibration Unit (ACU) and a Cable Loop System (CLS).

Since SiPMs are afflicted by a high dark noise value at laboratory temperature, all the central detector will operate at -50 °C to reduce the dark noise background, mandatory to reach an energy resolution lower than 2% at 1 MeV.

The liquid scintillator composition is similar to the one used in JUNO, but is optimized for low temperatures, in particular: LAB (Lynear Alkyl Benzene) doped with Gadolinium, 2 g/L diphenyloxazole (PPO), 1 mg/L p-bis-(o-methylstyryl)-benzene (bis-MSB) and a small fraction of Ethanol.

3. – The calibration system used in JUNO-TAO

A correct energy reconstruction with high energy resolution is a very important TAO goal to achieve. Two important effects can introduce a non-linearity in the liquid scintillator response to the propagation of a charged particle: Ionization quenching and Chrenkov radiation [6].

Vertex reconstruction depends on the number of detected photons which may vary due to a variation of absorption and scattering of photons across the detector medium, photon's incident angles and their reflections. This effect is known as the detector nonuniformity. To study non-linearity and non-uniformity effects, a dedicated calibration system was developed [7].

The calibration system contains the Automated Calibration Unit (ACU) which is based on the one used in Daya Bay experiment and a Cable Loop System (CLS). The ACU, shown in fig. 2, can be used to calibrate TAO's energy response precisely on the Z-axis, while the CLS will allow off-axis calibrations [8].

The ACU can deploy three different sources inside the detector alongside the z-axis, while a turntable revolves to a specific angle. In particular, sources are:

- an ultraviolet (UV) light source, for timing measurements and SiPMs monitoring;
- ^{68}Ge source;
- a combined source that contains multiple gamma sources and one neutron source.

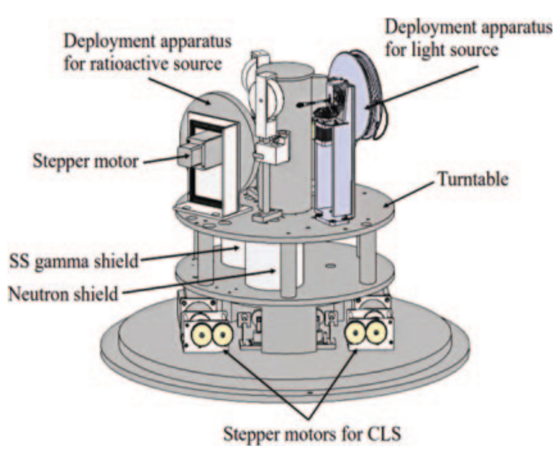

Fig. 2. – Schematic view of the Automatic Calibration Unit.

The Cable Loop System (CLS) was designed with a single ^{137}Cs radioactive-source, that can be deployed to an off axis position. This system is based on the JUNO CLS [7]. The radioactive source is positioned in a small area of the stainless steel cable, which is coated with Teflon to prevent contamination of the Gadolinium doped liquid scintillator. The cable passes through two anchors glued to the inner surface. Two stepper motors can pull the cable in either direction to position the radioactive source into the detector with a good positional accuracy.

Thanks to ACU and CLS, it will be possible to deploy different radioactive sources on and off the central axis and then mapping the response of the entire detector. The energy resolution degradation and energy bias will be controlled within 0.05% and 0.3% respectively, making TAO able to achieve the required energy resolution [8].

4. – Conclusion

TAO will provide a high precision energy spectrum of reactor electron antineutrino useful for JUNO neutrino mass ordering determination. To satisfy the strict requirements on energy resolution, two independent calibration systems, named ACU and CLS, have been developed. With ACU and CLS and the calibration strategy developed, TAO is able to measure high-precision reactor antineutrino spectrum.

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