PROCEEDINGS OF SCIENCE

Empowering JUNO physics by means of an ancillary photodetection system

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JUNO is a liquid scintillator detector currently under construction in the south of China. JUNO aims to detect the disappearance of reactor antineutrinos at an average baseline of 53 km, with the primary goal of determining the neutrino mass ordering and performing a sub-percent measurement of three of the neutrino oscillation parameters. This physics program is rooted in the detector's unprecedented capability to detect 1345 photoelectrons (p.e)/MeV of deposited energy, yielding a 3% energy resolution at 1 MeV. The main photodetection system comprises 17,612 20-inch "large" photomultipliers (LPMTs), each of which experiences an illumination varying over two orders of magnitude. To help calibrating the LPMT response in such a demanding environment, JUNO will be instrumented with additional 25,600 custom-made 3" "small" photomultipliers (SPMTs). They will operate in photon-counting regime by detecting at most 1 PE per neutrino interaction, hence providing a complementary energy estimator with a novel dual calorimetry technique. In addition, the SPMT system is designed to provide a semi-independent measurement of the "solar" oscillation parameters, to aid the measurement of supernova neutrinos, to study the proton decay and to improve the muon track reconstruction, whose performance is pivotal for background rejection. Like the LPMTs, the SPMTs together with their power and readout systems, will have to operate under water for over 20 years, posing challenging constraints on the design, reliability and implementation of this major subsystem of JUNO. In this talk, we will present the innovative design of the JUNO SPMT system, its impact on physics, and the current status of SPMT production and testing.

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Introduction

In 1998, the first evidence of neutrino oscillation was reported by the Super Kamiokande Collaboration with the detection of atmospheric neutrinos[1]. Since then, many different neutrino experiments also claimed it by detecting neutrinos from various sources (the Sun, nuclear reactors, accelerators). The neutrino oscillation implies that the flavor eigenstates (ν_e, ν_μ and ν_τ) are a linear combination of three mass eigenstates (ν_1, ν_2 and ν_3). This linear combination can be described with a unitary mixing matrix (PMNS)[2]. This matrix includes 7 parameters: three mixing angles (θ_{12}, θ_{23} and θ_{13}), three mass splitting (Δm^2_{21}, Δm^2_{32} and Δm^2_{31}) as well as a Charge-Parity (CP) violating phase δ_{CP}. During the last twenty years, all of these parameters have been measured except the sign of Δm^2_{32} and δ_{CP}. The relatively high value of θ_{13} measured by the Daya Bay[3], Double Chooz[4] and RENO[5] experiments confirmed that the sign of Δm^2_{32} can be extracted from the nuclear reactor electron anti-neutrinos ($\overline{\nu_e}$) energy spectrum at a medium baseline[6]. The proposal of the JUNO experiment[7] stems from this finding. The JUNO detector will be the largest liquid scintillator (LS) detector ever built so far, with 20 kton of scintillating material in total. It is currently under construction in the Guangdong province, in China. The determination of the sign of Δm^2_{32}, also refered to as the neutrino Mass Ordering (NMO) problem, will be based on the detection of the $\overline{\nu_e}$ from the Yangjiang and Taishan nuclear power plants *via* the Inverse Beta Decay (IBD) interaction channel. The Normal or Inverted Ordering will be inferred from the fine structure of the $\overline{\nu_e}$ spectrum, which requires a 3% energy resolution at 1 MeV[8]. The 3σ confidence level shall be reached in six years of data taking[7][8]. In addition, synergies between JUNO and other experiments (JUNO+T2K+NOνA[9], JUNO+ORCA[10] and finally JUNO+IceCubeUpgrade[11]) will boost its sensitivity to the NMO. JUNO is also designed to measure three neutrino oscillation parameters at the sub-percent level: θ_{12}, Δm^2_{21} and $|\Delta m^2_{32}|$ and is also sensitive to θ_{13}. Thanks to its detection volume and performances, JUNO will also be able to detect a burst of neutrinos from a core-collapse supernova event in our galaxy or its vincinity, as well as to put new stringent limits on the Diffuse Supernovae Neutrino Background (DSNB), detect solar neutrinos, atmospheric neutrinos etc. The physics program of JUNO is fully reviewed in[7][8]. In order to minimise its energy resolution and thus maximise its sensitivity to the NMO, JUNO will be instrumented with two different photomultiplier tube (PMT) systems. Indeed, the "large PMT" (LPMT) system - made of 20" PMTs - will be the main photodetection system. The addition of a "small PMT" (SPMT) system - made of 3" PMTs - will help to better control the energy resolution systematics term using the dual calorimetry technique and will also enchance the physics potential of JUNO. This contribution is focused on the SPMT system. The section 1 describes the detector and briefly details the impacts of the SPMT system on the JUNO physics. The section 2 gives an overview of the SPMT system, its features and the status of its development.

1. The JUNO detector

The JUNO detector consists in three parts. The main part is the **C**entral **D**etector (**CD**), a 35.4 m diameter spherical acrylic vessel containing 20 kton of LS. The CD is instrumented with 17,612 20" PMTs (LPMT) that will allow to achieve a 75% photo-coverage. In addition, 25,600 3" PMTs (SPMT)[12] will be placed in alternation with the LPMTs as shown on Fig.2. The corresponding photo-coverage of the SPMT system is 3%.

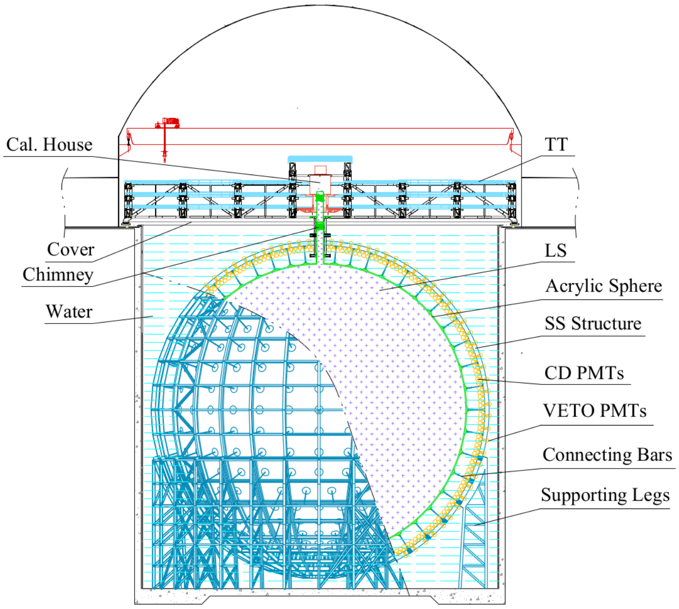

Figure 1: *Schematic view of the JUNO detector.*

The LPMTs will allow to collect a great amount of light to reach ~1345 photoelectrons (p.e)/MeV. This will keep the stochastic term of the energy resolution <3%. The SPMTs will have ~40 p.e/MeV and will work in photo-counting regime. It means that even for the most energetic reactor electron antineutrinos (~10 MeV), the great majority of the SPMTs fired will have only 1 p.e. Thus, they will ensure a better control of the energy resolution systematics term by mitigating the potential non-linearity in the LPMTs, thanks to the Dual Calorimetry calibration (DCC)[13]. The DCC consists in comparing the response of two different PMT systems to a single light source. In practice, the response of a single LPMT will be compared to that of the 25,600 SPMTs in order to correct its potential non-linearity at high charge. Two complementary light sources will be used, a laser (MeV~GeV) and radioactive sources (<10 MeV). Also, the LPMTs could suffer from saturation effects in case of high energy events (muons with an average energy $\overline{E} \simeq 200$ GeV), for events at the detector borders (saturation of the PMTs in the vicinity of the vertex) or even when the event rate is too high. We expect the SPMTs not to suffer from such saturation. In addition, the SPMTs will allow to perform quasi-independent physics analyses (solar parameters measurement, core-collapse supernova neutrinos detection and proton decay) as well as enhance the muon-tracking capability.

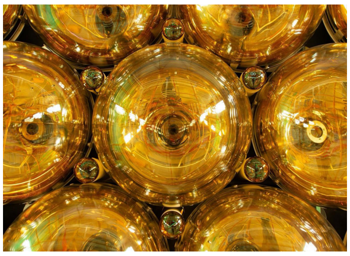

Figure 2: *Photograph showing a real size mock-up of the 3" PMTs placed in-between the 20" PMTs.*

The CD is immersed in the **W**ater **P**ool (**WP**) a cylindrical vessel with a diameter of 43.5 m and a height of 44.0 m. The WP will contain ~35 kton of ultra pure water (< 0.2 Bq/m^3) and will be instrumented with 2,400 20" PMTs (veto PMTs). This sub-detector will be used to reconstruct the tracks of the incoming cosmic muons and will also constitute a shield against the surrounding rock radioactivity. The third part of the detector is the **T**op **T**racker (**TT**). It is made of three planes of plastic scintillator (47.0 m x 20.0 m each) placed on top of the CD and WP. The TT will also be dedicated to the reconstruction of part of the cosmic muons tracks with an expected median angular resolution of ~0.20°[14]. Indeed, the muons interactions represent a non-negligible source of correlated background for the NMO analysis[7][8]. It needs to be carefully addressed.

2. The 3" PMT system

The 25,600 SPMTs will have to operate under water for 20 years. They will be grouped by 128 and each group will be connected to a single cylindrical Underwater Box (UWB) (40 cm in height and 30 cm in diameter) containing the electronics and power (Fig.3). The electronics comprises a "splitter board" which aims to separate the signals coming from the SPMTs and the power signal, an ASIC Battery Card (ABC), and a Global Control Unit (GCU). The ABC board contains the CATIROC[15] chips which will read-out and digitise the charge and time of the PMTs signal. The GCU will transfer the digitised signals to the Data Acquisition (DAQ). In total, 200 UWBs, 400 splitter boards, 200 ABCs and 200 GCUs will be produced. The production is in progress. All boards will be tested before shipping to the JUNO experimental site.

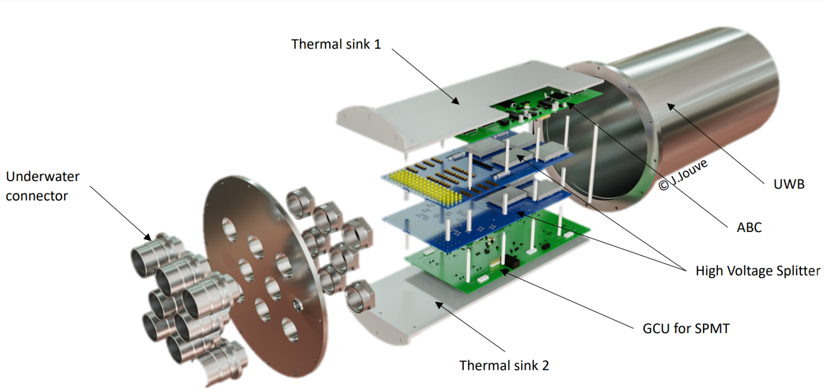

Figure 3: *Schematic view of an underwater box containing electronics.*

The production of the JUNO 3" PMTs represents the largest sample of PMTs ever produced. All the SPMTs have been produced by the HZC-Photonics$^{\copyright}$ company. The company monitored 15 performance parameters of all SPMTs - all along the production - including the dimensions of the PMT glass bulb, the quantum efficiency (QE), the Transit Time Spread (TTS), the Dark Counting Rate (DCR) etc. Indeed, in order to achieve the physics goals fixed by the JUNO collaboration, precise requirements were determined before the start of production. As an example, the measured TTS of the SPMTs is $\sim$1.6 ns (σ) and the Dark Counting Rate (DCR) is $\sim$500Hz at 0.25 p.e (in average, over the full production sample). In addition, the JUNO collaboration has performed complementary tests on random samples of the freshly produced SPMTs all along the production. The Fig.4 lists the parameters, the requirements and the results of the tests operated by the HZC-Photonics$^{\copyright}$ company and the JUNO collaboration.

Parameters	Class	Requirement		Test fraction		Tolerance	Results
		(limit)	(mean)	HZC	JUNO	of diff.	(mean)
Φ (glass bulb)	A	(78, 82) mm	-	100%	10%	-	OK
QE@420 nm	A	>22%	>24%	100%	10%	<5%	24.9%
High Voltage	A	(900,1300) V	-	100%	10%	<3%	1113 V
SPE resolution	A	<45%	<35%	100%	10%	<15%	33.2%
PV ratio	A	>2	>3	100%	10%	-	3.2
DCR@0.25 PE	A	<1.8 kHz	<1.0 kHz	100%	10%	-	512 Hz
DCR@3.0 PE	A	<30 Hz	-	100%	10%	-	7.2 Hz
TTS (σ)	B	<2.1 ns	-	-	3%	-	1.6 ns
Pre-pulse	B	<5%	<4.5%	-	3%	-	0.5%
After-pulse	B	<15%	<10%	-	3%	-	3.9%
QE non-uniformity	B	<11%	-	-	3%	-	5%
Φ (eff. cathode)	B	>74 mm	-	-	3%	-	77.2 mm
QE@320 nm	C	>5%	-	-	1%	-	10.2%
QE@550 nm	C	>5%	-	-	1%	-	8.6%
Aging	D	>200 nA·years	-	-	3 PMTs	-	OK

Figure 4: *Summary of the SPMTs acceptance criteria and test results for different parameters.*

The performed tests are detailed in [12] showing that the deliverables fulfill the JUNO technical requirements and quality control level. Before the commissioning of JUNO, all the SPMTs will be tested again, after cabling and potting, with a dedicated test-bench which includes the JUNO SPMT system electronics.

Conclusion

The JUNO detector is currently under construction in China with the primary objective of determining the NMO. For this purpose, a 3% energy resolution at 1 MeV (E_{vis}) is required. In order to maximise its sensitivity to the NMO, the JUNO CD will be instrumented with 25,600 additional 3" PMTs that will ensure a better control of the energy resolution systematics term and will enhance the physics potential of JUNO. The PMT production is finished and the PMT system hardware production is ongoing.

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