STATUS AND PHYSICS POTENTIAL OF THE JUNO EXPERIMENT

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Abstract. The Jiangmen Underground Neutrino Observatory (JUNO) is an underground 20 kton liquid scintillator detector being built in the south of China and expected to start data taking in 2020. JUNO has a physics programme focused on neutrino properties using electron anti-neutrinos emitted from two near-by nuclear power plants. Its primary aim is to determine the neutrino mass hierarchy from the $\nu_e$ oscillation pattern. With an unprecedented relative energy resolution of 3% as target, JUNO will be able to do so with a statistical significance of 3-4 $\sigma$ within six years of running. It will also measure other oscillation parameters to an accuracy better than 1%. An ambitious experimental programme is in place to develop and optimize the detector and the calibration system, to maximize the light yield and minimize energy biases. JUNO will also be in a good position to study neutrinos from the sun and the earth and from supernova explosions, as well as provide a large acceptance for the search for proton decay. JUNO’s physics potential was described and the status of its construction reviewed in my talk at the conference.

1 Introduction

The Jiangmen Underground Neutrino Observatory (JUNO) is a neutrino experiment being built in China, described in [1]. Its primary purpose is to determine the neutrino mass hierarchy (MH) and measure the oscillation parameters using reactor sources. It will consist of a large mass, pure liquid scintillator (LS), placed in an acrylic sphere of 35.4 m of diameter; a system of large-area photo-multipliers of new generation (PMT); a veto system. It will be located at a distance of approximately 50 km from two power plants (Yangjiang and Taishan). The two plants are expected to provide an equal thermal power of about 18 GW, but at the start-up of the experiment only 26.6 GW are expected to be available. The baseline is optimized for maximum $\nu_e$ disappearance, i.e. a minimum of the survival probability (here in the case of normal neutrino mass hierarchy (NH)):

$$P_{NH} (\overline{\nu}_e \rightarrow \overline{\nu}_e) = 1 - \frac{1}{2} \sin^2 2\theta_{13} \left( 1 - \cos \frac{L}{2E_{\nu}} m^2_{atm} \right)$$

$$- \frac{1}{2} \cos^4 \theta_{13} \sin^2 2\theta_{12} \left( 1 - \cos \frac{L}{2E_{\nu}} m^2_{sol} \right)$$

$$+ \frac{1}{2} \sin^2 2\theta_{13} \sin^2 \theta_{12} \left( \cos \frac{L}{2E_{\nu}} (m^2_{atm} - m^2_{sol}) - \cos \frac{L}{2E_{\nu}} m^2_{atm} \right),$$

(the probability for the inverted hierarchy $P_{IH}$ differing only in the coefficient of the last element in the sum, $\cos^2 \theta_{12}$). JUNO will be placed about 700 m
below underground, corresponding to about 1900 m.w.e., in a pit dug in the ground afresh. To pursue its main physics goals JUNO will need to attain an unprecedented resolution on the energy of the $\nu_e$ produced in the reactors. In order to meet such performance extensive studies have been conducted over the past few years concerning various aspects of engineering, detector design, including optical/light collection in the LS and PMT and response of the read-out electronics, software development and background suppression \[2\]. In the talk given at the 18th Lomonosov Conference on Elementary Particle Physics, the main physics case of JUNO was described; the status of the detector design optimization and construction was illustrated and some examples of physics measurements possible, beyond the neutrino oscillations, were presented.

## 2 What drives the detector design....

The experimental signature of the reactor $\nu_e$ in the JUNO detector is given by the inverse beta decay (IBD) process $\nu_e + p \rightarrow e^+ + n$, where the $p$ and $n$ are a proton from the LS and a neutron, respectively. The resulting signal is given by a visible energy from the positron energy loss and annihilation, plus delayed light at a fixed 2.2 MeV energy from the neutron capture. The main goal of JUNO is to determine the MH with at least a 3 $\sigma$ significance within the first 6 years of data taking. The correct MH will be extracted by means of a $\chi^2$ fit to the kinetic energy spectrum of the prompt $e^+$ ($T_{e^+}$), which is directly related to the $\nu_e$ energy ($E_{\nu_e} = T_{e^+} + 2 \times m_e + 0.8$ MeV, where $m_e$ is the $e^+$ mass). From Eqn. 1 one sees that the two hierarchies have a difference in the fine structure of $P_{\nu_e}(\nu_e \rightarrow \nu_e)$, which is illustrated in Fig. 1 left, and was pointed out in \[3\]. The correct MH is determined by constructing the $\Delta \chi^2_{min}(NH - IH)$ from the two fits to the experimental reactor data; this can be translated into a statistical significance of the discrimination. It should be noticed that, with such strategy, a residual ambiguity lingers, associated to the correct value of the atmospheric mass difference $\Delta m^2_{atm}$; this reduces the final sensitivity of the fitting procedure. JUNO estimates that, in order to reach the desired significance, the most important figure of performance is the overall resolution on the event-by-event measurement of $E_{\nu_e}$. In Fig. 1 right, this relationship appears clearly. It is therefore crucial to design a detector which minimizes the statistical uncertainty from stochastic fluctuations in the scintillation light collection, yet keeping linearity and uniformity of the energy response under control. A 3% overall relative energy resolution will yield, for 6 years of data at 36 GW of reactor thermal power, a median significance of 3.4 (3.5) $\sigma$ for NH (IH) \[1\].
To attain this level of precision, the JUNO collaboration has developed a detector made of 3 basic parts, plus the electronics. The central detector is a 20 kton LS target mass, conceived to maximize the photon statistics and minimize the attenuation of the IBD prompt signal. This will be the largest volume of LS to date, composed of a mixture of > 98% LAB (solvent, 1200 photo-electrons/MeV), PPO (solute) and a less-than-per-cent part of bis-MSB (wavelength shifter). The photons are collected by PMT of two different kinds: about 18000 20 inch PMT, most of which of the micro-channel plate (MCP-PMT) type, will guarantee an extended photo-coverage (75%, as per JUNO requirement) and a high overall detection efficiency (expected by the JUNO specifications to be 27% at λ=420 nm); their transit time spread (TTS) being 12 ns. 25000 conventional 3 inch will allow to follow a multi-calorimetric approach, whereby the non-stochastic terms in the energy resolution will be monitored during the calibration runs with known radio-active sources at different energies; the 3 inch PMT will extend the dynamical range in the waveform of large numbers of photo-electrons hitting a localized region and improve time and vertex resolution for muon reconstruction (against cosmic muons). Finally, a veto system will be in place to screen off incoming muons and photons by means of a surrounding water buffer (Cherenkov) and top scintillators. The project of the front-end electronics is also a challenge, because of the many read-out channels, the dark noise rate of the 20 inch PMT and the needed resilience and efficient heat dissipation of an under-water system. A large effort...
from the collaboration is being devoted to this task, but it will not be described here.

Such design, especially the large mass and control of the energy scale, will also allow JUNO to perform measurements of the neutrino solar parameters with uncertainties well below 1%, not attained to date.

4 Current status of the detector project

After a careful design phase, the construction of the various elements is underway. About 15000 MCP-PMT were ordered from the NNVT (North Night Vision of Technology CO., LTD, China) manufacturer and are being tested at a dedicated centre in the region around the JUNO site. Further technical details on the design and production of the MCP-PMT was the subject of a dedicated contribution by S. Qian at this conference. Additional 5000 conventional dynode 20 inch PMT were commissioned to Hamamatsu, of the type R12860, in order to complement the leading PMT lay-out and provide a faster TTS (3 ns). All the large-area PMT will be equipped with protective masks to reduce propagation of shock waves if one PMT explodes under water pressure: their design has been finalized after extensive pressure tests. The bidding of the 3 inch PMT was completed last spring and the elements ordered from HZC-Photonics. These are custom-made based on the KM3NeT design, with improved TTS for better muon tracking. It is desirable that the LS be purified to a good degree from radioactive isotopes, to reduce the intrinsic background of the detector. The set level are $10^{-15}$ g/g for $^{238}$U and $^{232}$Th and $10^{-17}$ g/g for $^{40}$K. The attenuation length (AL) that JUNO requires is greater than 20 m at $\lambda = 430$ nm (for 3 g/l of PPO in LAB). A strategy has been developed by JUNO aimed at obtaining an optimal admixture of solvent and solutes in optical and radio-active terms. The purification will go through four parallel and complementary processes: an Al$_2$O$_3$ (alumina) column, a distillation plant, water extraction and gas stripping. A pilot plant has been established in one of the LS halls of the Daya Bay experiment in China to monitor the AL and level of purification, which uses the alumina method. Results are displayed in Fig. 2 and show a good stability and that the desired level of AL has been surpassed.

5 Calibration of energy and vertex position reconstruction

As stressed, a good and understood energy response is paramount for the main aims of the JUNO experimental programme. While the large mass, photo-coverage and detection efficiency ensure small statistical fluctuations in the light yield, systematic misestimation from non linearity and non uniformity of the detector response can quickly spoil the precision. Keeping the uncertainty
on the energy scale determination at less than 1% over the energy interval is crucial to keep the total $\sigma(E)/E \leq 3\%$. Together with that, reconstructing the position at which the event took place in the LS will play a very useful role in suppressing the backgrounds, mainly related to diffuse radioactivity and cosmic ray muon scattering. To this end JUNO will deploy a redundant calibration system. Complementary methods are envisaged across the detector and for various energy loss mechanisms: an Automatic Calibration Unit (ACU) will place several known radioactive sources along the vertical axis in the sphere; a Cable Loop System (CLS) will move across vertical planes by means of pulleys, while a Guide Tube Calibration System (GTCS) will be in use to probe the outer CD surface. Finally a Remotely Operated under-LS Vehicle (ROV) will provide events of known energy across the whole detector volume. The calibration strategy (in particular number of points in the scan and occurrence of the calibration scans) is being worked out.

6 Other physics possible with JUNO

JUNO’s features make it an excellent detector also for other physics topics, including non-reactor neutrino measurements such as solar and supernova neutrino fluxes and geo-neutrino isotopical origin. In many of these case, the main challenge will be to control the intrinsic background activity and the cosmogenic cascades (muons interacting with carbon in the LS and creating Lithium). The latter are expected to be of high occurrence in the relatively shallow JUNO pit (about 250000 per day as opposed to 60 IBD events, tens to thousands of solar neutrinos and about 1 geo-neutrino per day). JUNO will also be complementary to large Cherenkov detectors (e.g. SK, HK) in the search for proton
decays. The proton will come from the hydrogen in the LS and should decay to a neutrino and a kaon, with subsequent semi-leptonic meson decays. The initial decay is sub-threshold for Cherenkov light in water but the kaon kinetic energy of about 105 MeV is well visible as scintillation light. Thanks to the peculiar time pattern of the tiered decay, JUNO will be competitive (and complementary) soon after switching on. Additional information on all the programme can be found in [1].

7 Conclusions

The JUNO experiment is on course to start operations within the next few years. Its challenging and multi-faceted physics programme (on and beyond reactor neutrino oscillations) demands a very careful detector design and the use of novel technologies. At the same time, with its unprecedented size and energy resolution, JUNO is poised to have an impact on many areas of neutrino physics. A few selected figures were provided drawn from the many design/technical improvements and tests being put in place to achieve both unprecedented performance and reliability for a large and underwater system.

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