Physics prospects of the JUNO experiment

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Abstract. JUNO is a 20 kton multi-purpose liquid scintillator detector currently being built in China in a dedicated underground laboratory and expected to complete the detector construction in 2021. JUNO primary physics goal is the determination of the neutrino mass ordering, with a significance of 3-4 sigma in six years of data taking, by measuring the oscillation pattern of electron antineutrinos coming from two nuclear power plants at a baseline of about 53 km. Besides this fundamental aim, its large target mass, unprecedented energy resolution of 3% at 1 MeV, and vertex reconstruction capability will provide vast opportunities in particle physics and astrophysics. JUNO will have a very rich physics program, which includes the precise measurement at a sub-percent level of the solar neutrino oscillation parameters, the detection of low-energy neutrinos coming from galactic core-collapse supernova, the measurement of the diffuse supernova neutrino background, the detection of neutrinos coming from the Sun and the Earth (geo-neutrinos). In this paper I will give an overview on the JUNO physics potential and discuss the performance of the JUNO detector for the various proposed measurements.

1. Introduction

The Jiangmen Underground Neutrino Observatory (JUNO) will be the largest liquid scintillator detector placed in an underground laboratory [1]: its main physics goal is the disentangling of the neutrino mass ordering but, thanks to its dimensions, JUNO may perform many other competitive measurements in the neutrino field, serving in fact as a sensitive neutrino observatory. It will be also useful to measure the nucleon decay and study other exotic searches [1].

The detector is designed as 20 kton of liquid scintillator – Linear Alkyl Benzene (LAB) as solvent, with 2.5 g/l PPO as fluor, and 3 g/l bis-MSB as wavelength shifter – contained in an acrylic sphere of 35.4 m of diameter, supported by a stainless steel truss. The scintillation light will be detected by a double photomultiplier (PMT) system: a large (20 inch) PMT array – both for signal and veto events – made by about 15000 microchannel plate PMTs produced by Northern Night Vision Technology, and about 5000 dynode PMTs produced by Hamamatsu Photonics; and a small (3 inch) PMT array made by about 26000 PMTs produced by HZC Photonics, to be operated in photon counting mode. The detector will be immersed in 35 kton of ultra-pure water instrumented with 2000 of the large PMTs to serve as water Cherenkov muon veto, and will be equipped with a Top Tracker, made of 3 plastic scintillator layers, for a precision muon tracking covering about half of the top area. Great attention is devoted to material selection and production protocols to restrict the radioactive background to the stringent requirements of the JUNO design [1].

According to the JUNO construction schedule, the detector will be ready by the end of 2021.
2. Neutrino mass ordering sensitivity

To disentangle the neutrino mass ordering (νMO), JUNO will use a method proposed by Petcov and Piai in 2002 [2], who suggested that reactor experiments placed at medium baseline distance – where the solar oscillation probability is at its maximum – could profit from the interference effect between the solar and atmospheric oscillation frequencies to infer the actual νMO. The large value of the $\theta_{13}$ mixing angle [3, 4, 5] has made the proposed method feasible.

JUNO is located in the South of China, in Guangzhou region, at about 53 km distance from the Yangjiang and Taishan nuclear power plants. A total power of 26.6 GW will be available at the start of the data taking (35.8 GW are foreseen at regime operation). Reactor neutrinos will be detected by means of their Inverse Beta Decay (IBD) reaction on the protons of the liquid scintillator: $\nu_e + p \rightarrow e^+ + n$. This reaction offers the coincident signature between the two 511 keV $\gamma$-rays, following the $e^+$ annihilation, and the 2.2 MeV $\gamma$-ray, following the neutron capture by a proton, with a characteristic time delay of $\sim 200\mu s$.

JUNO will be the first experiment to measure simultaneously the slow oscillations (driven by the solar frequency $\Delta m_{21}^2 \sim 7.5 \times 10^{-5} \text{eV}^2$) and the fast oscillations (driven by the atmospheric frequency $\Delta m_{32}^2 \sim 2.5 \times 10^{-3} \text{eV}^2$), as well as their tiny interferences which contain the νMO information (see Figure 1 – oscillation parameters are taken from best fit values in [6] for each ordering). To discriminate the actual ordering, the detector must achieve unprecedented levels of energy resolution (of the order of $\Delta m_{21}^2 / \Delta m_{32}^2 \sim 3\%$ at 1 MeV) and energy scale precision < 1%. These challenging performances are expected to be achievable with the high photocathode coverage and highly transparent scintillator on one side, and the accurate energy calibration on the other (see [7]). Figure 2 shows the oscillated spectra at JUNO in both hypotheses of normal and inverted νMO smeared by the designed energy resolution of $3\%/\sqrt{E(\text{MeV})}$. Other important experimental parameters which contribute to sensitivity loss in the νMO determination are the actual distributions of the reactor cores, the $\nu_e$ fluxes coming from far reactors (e.g. Daya Bay and Huizhou nuclear power plants), and the radioactive background rate and spectral shape uncertainties. Detailed studies about the sensitivity of determining the νMO, assuming those systematic uncertainties and $10^5$ $\nu_e$ events in 6 years of data taking, demonstrated that a median sensitivity of 3 $\sigma$ can be achieved [1]. Additional sensitivity can be gained by combining with precision measurement of $|\Delta m_{\mu\mu}^2|$ from future long baseline experiments (T2K and NOvA): a confidence level from 4 to 5 $\sigma$ can be obtained for a $|\Delta m_{\mu\mu}^2|$ uncertainty of $\sim 1\%$.

Figure 1. Reactor $\nu_e$ spectrum expected at JUNO for no oscillations (black) and for different hypothesis on the νMO, normal (red) or inverted (blue) [8].

Figure 2. Same oscillated spectra of Figure 1 for $10^5$ $\nu_e$ events detected at $\sim 53$ km from the source: in this case the expected energy smearing of $3\%/\sqrt{E(\text{MeV})}$ is applied [8].
Another important issue is the precise knowledge of the reactor $\bar{\nu}_e$ spectrum. Large scale sub-structures have been constrained by the Daya Bay experiment [9]: the available informations are sufficient not to degrade JUNO sensitivity [10]. On the other hand, unknown fine structures may have a larger impact [11]: for this reason, the Taishan Antineutrino Observatory (TAO) – a satellite experiment of JUNO – is under construction with the aim of reaching the unprecedented energy resolution of less than $2\%/\sqrt{E\text{(MeV)}}$, in order to provide a model-independent reference spectrum for JUNO. TAO is planned to be ready for data taking in 2021.

3. Precision measurement of oscillation parameters

JUNO can measure very precisely the neutrino mixing parameters as well as provide a test of the standard three-neutrino framework. The oscillation parameters $\sin^2\theta_{12}$, $\Delta m_{21}^2$, and $\Delta m_{ee}^2$ [1] can be determined with remarkable precisions of 0.7%, 0.6%, and 0.5%, respectively. Moreover the unitarity of the neutrino mixing matrix $U_{\text{PMNS}}$ can be probed by JUNO to 1% level.

4. JUNO: a neutrino underground observatory

The superior detector properties as well as the unprecedented dimensions of JUNO provide great opportunities in studying neutrinos from Supernovae, the Sun, and the Earth’s interior, atmospheric neutrinos, sterile neutrinos, Nucleon decays, neutrinos from Dark Matter, and other exotic searches. In the following, JUNO potentialities in a selection of physics issues are briefly introduced. Further details and discussions can be found in [1].

4.1. Supernova burst neutrinos

A core-collapse Supernova (SN) emits almost all of its energy in the form of neutrinos. In our galaxy, 3 core-collapse SN per century are expected. JUNO, being a 20 kton detector, is a good observatory of a SN neutrino burst and, by measuring both the energy spectrum and the time evolution of the burst, will be very useful to test the different existing theoretical models. A liquid scintillator detector can measure all neutrino flavors via charged current (CC) and neutral current (NC) interactions or via elastic scattering, and the energy threshold can be as low as 0.2 MeV. The dominant signal will come from Inverse Beta Decay (IBD) CC interactions – the same channel of the neutrino mass ordering measurement – and the detection will be practically background-free since the SN event duration is very short ($\sim 10$ s). About 5000 IBD events are expected in JUNO from a core-collapse Supernova located at 10 kpc distance. JUNO will be able to make a real time detection of a SN neutrino burst, therefore being eligible to participate at the international SN alert networks (e.g. SNEWS).

4.2. Solar neutrinos

There are currently three open issues in the solar neutrino field, of great relevance for astrophysics and elementary particle physics, where JUNO contribution could become crucial: i) the tension between the solar and the reactor experimental data in the measurement of the $\Delta m_{21}^2$ oscillation parameter; ii) the solar metallicity problem, regarding a discrepancy between the Standard Solar Model (SSM) predictions and the solar data which would require either a revision of the SSM inputs or a modification of the core abundances of some elements in the Sun; iii) the analysis of the energy dependence of the $\nu_e$ survival probability to study the transition between the vacuum-dominated and the matter-dominated oscillation regions.

Concerning i), as observed in Section 3, JUNO can measure $\Delta m_{21}^2$ with sub-percent precision using reactor neutrinos. Moreover, if the measurement of the solar neutrino oscillations could be improved by JUNO, for the first time one single detector could test the tension on $\Delta m_{21}^2$ by detecting reactor and solar neutrinos at the same time. For the metallicity problem, a more accurate measurement of the $^7\text{Be}$ and $^8\text{B}$ neutrino fluxes would give important informations to
solve this central problem of nuclear astrophysics. Moreover, the continuous solar $^8\text{B}$ neutrino spectrum is a perfect tool to study the transition from vacuum- to matter-dominated oscillations in the relevant energy region between 1 and 3 MeV.

The main detection channel for solar neutrinos of all flavors (via neutrino oscillations) is the elastic scattering on electrons, with the observable being the electron kinetic energy. The impact of JUNO in the solar neutrino field will depend crucially on the achieved background level since, in contrast to IBD reaction, no coincident signature is foreseen. For details refer to [1].

4.3. Atmospheric neutrinos

Thanks to its low energy threshold ($< 500 \text{MeV}$), JUNO can measure atmospheric neutrinos with good energy resolution, good particle discrimination and good capabilities to reconstruct the direction of the charged leptons. JUNO measurements can therefore help improving the predictions on the atmospheric neutrino fluxes at low energy, being complementary to other type of detectors (e.g. water Cerenkov detectors). Moreover, atmospheric neutrinos are a very important source to study neutrino oscillations and can therefore provide an independent measurement of the $\nu_{\text{MO}}$ (via matter effects). Finally, precise measurements of atmospheric neutrinos play an important role since they constitute the main background for other rare event searches to be performed with JUNO [1].

4.4. Geoneutrinos

Geoneutrinos are an important tool to explore the composition of the Earth and to estimate the amount of radiogenic power driving the Earth’s engine. The expected geoneutrino signal at JUNO will mostly come from the Earth crust and present different compositional models of the bulk silicate of the Earth predict different mantle neutrino fluxes. On the other hand, the detector cannot discriminate the mantle contribution from the crust one: therefore an interdisciplinary team of physicists and geologists are presently at work to develop a local refined crust model around the JUNO site. About 400-500 IBD events are expected from $^{238}\text{U}$ and $^{232}\text{Th}$ geoneutrinos (IBD reaction threshold of 1.8 MeV prevents from detecting $^{40}\text{K}\,\bar{\nu}_e$), with the reactors’ $\bar{\nu}_e$ being the main background source. The unprecedented precision in the measurement of the oscillation parameters should strongly reduce the error on the expected antineutrino flux, thus allowing a measure of U/Th ratio at percent level.

5. Conclusions

The neutrino mass ordering determination as well as the vast physics potential of large liquid scintillator detectors, are the main motivations for the JUNO experiment, designed to mark significant breakthroughs in the neutrino field and define the missing properties of these elusive particles. JUNO construction is proceeding well and the detector is planned to be ready for data taking by the end of 2021.

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