JUNO Experiment: Current Status and Physics

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Abstract. JUNO is a 20 kt liquid scintillator detector located $\sim$650 m underground in Jiangmen, China. The construction will be finished in 2023. Its energy resolution can reach 3% at 1 MeV, which allows it to realize its main goal of determining the neutrino mass ordering (NMO) detecting antineutrinos from two nuclear power plants at 53 km baseline. Mass ordering is expected to have $3\,\sigma$ of significance in 6 years of data taking. Meanwhile the measurement of oscillation parameters $\sin^2\theta_{12}$, Δm^2_{21}, and $|\Delta m^2_{32}|$ will reach sub-percent precision. The Taishan Antineutrino Observatory will be placed $\sim$30 m from the core of one power plant, in order to measure the reactor antineutrino spectrum, as a reference spectrum for the determination of NMO in JUNO, with resolution better than 2% at 1 MeV. The OSIRIS pre-detector is designed to monitor the LS of JUNO during the several months of filling. With its massive LS volume and excellent energy resolution, JUNO will be able to explore many other neutrino, astro, and particle physics topics. For example, detection of supernova neutrinos, atmospheric neutrinos, solar neutrinos, and geoneutrinos. This paper reviews the current status of JUNO and introduces recent studies on JUNO's potential in many different physics topics.

1. Introduction

The Jiangmen Underground Neutrino Observatory (JUNO) [1] is a 20 kt liquid scintillator (LS) underground detector in Jiangmen, China. The detector assembly and installation is expected to be finished in 2023. Its main goal is to determine the neutrino mass ordering (NMO) with the measurement of reactor electron antineutrinos from the two adjacent nuclear power plants (Yangjiang and Taishan) at a baseline of 53 km (Figure 1). The total thermal power is 26.6 GW.

In JUNO central detector, there will be 17,612 20-inch PMTs and 25,600 3-inch PMTs watching the LS with photocathode coverage of 75.2% and 2.7%, respectively. There are additional 2400 20-inch PMTs for the Water Cherenkov Veto. It is expected that JUNO will have an excellent energy resolution of 3% at 1 MeV and an energy nonlinearity uncertainty better than 1%. With 6-year data, the mass ordering can be determined at 3-4 σ significance and the precise measurement of oscillation parameters $\sin^2\theta_{12}$, Δm^2_{21}, and $|\Delta m^2_{32}|$ will achieve at least 0.6% precision [2]. Besides its main goal, JUNO has an excellent ability to explore many other neutrino (astro-) physics topics.

2. Experiment's overview

All the civil construction has been finished in 2022. With about 650 m of rock overburden, the residual cosmic muon rate throught the detctor is 4 / sec with mean muon energy of 207 GeV.

Figure 1. JUNO site is located in Guangdong province, China. Locations of Yangjiang and Taishan nuclear power plants are also shown. [1]

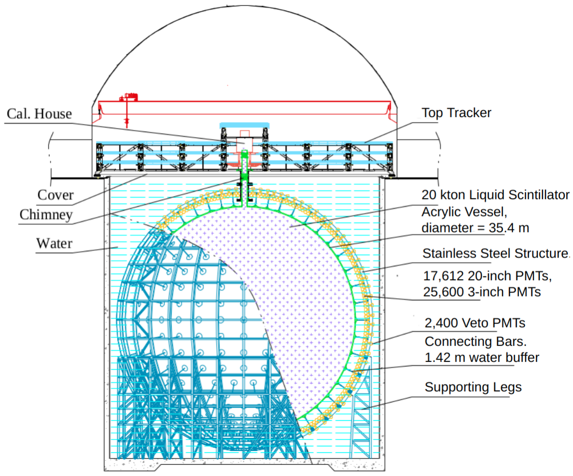

Figure 2. JUNO detector illustration. [1]

2.1. JUNO main detector
As shown in Figure 2, JUNO consists of Central Detector (CD), Water Cherenkov Detector (WCD), and Top Tracker (TT).

The CD holds 20 kton LS in a acrylic vessel with diameter of 35.4 m. The U/Th/K radiopurity of the acrylic vessel is smaller than 1 ppt. The light transparency is larger than 96% at 420 nm. The acrylic vessel is supported by a stainless steel structure which contains 590 connecting bars. The assembly precision is < 3 mm for each node. The PMTs with front-end electronics are mounted on the SS structure. In order to suppress the Earth magnetic field and to minimize its influence on PMT's photoelectron collection efficiency, compensation coils are installed as well.

The 35 kton ultrapure water of WCD around the CD vessel can shield the outer γs. The Radon concentration in water is expected to be about 10 mBq/m^3 With 2400 20-inch veto PMTs, WCD will detect and veto cosmic muons with an efficiency greater than 99.5%. The TT covers 60% of the area above the WCD. Using its plastic scintillator array, TT can precisly measure the muons across it, with angle resolution at 0.2°, corresponding to 20 cm at the bottom of CD.

2.2. JUNO PMTs
JUNO will be equipped with two kinds of Large 20-inch PMTs (LPMTs): 5k Hamamatsu PMTs and ∼15k MCP-PMTs produced by NNVT. All LPMTs have been produced, tested, and instrumented with waterproof potting. The mean photon detection efficiencies are 28.5% and 30.1% respectively for the two types of LPMTs. The total coverage of PMTs is 75%. With high detection efficiency and high PMT coverage, JUNO will be able to reach the designed energy resolution of 3% at 1 MeV. Small 3-inch PMTs (SPMTs) are installed in the space among LPMTs. SPMTs will provide a complementary set of sensors for the same events as LPMTs.

2.3. Liquid Scintillator and OSIRIS pre-detector
The liquid scintillator of JUNO consists of three components: Linear Alkyl Benzene (LAB) as solvent plus 3 g/L of 2,5-diphenyloxazole(PPO) and 15 mg/L of 1,4-bis(2-methylstyryl) benzene (bis-MSB) as wavelength shifter. The attenuation length at 430 nm is 20 m. In order to meet the stringent LS radio-purity requirements of U/Th at 10^{-15} g/g (NMO), and 10^{-17} g/g (Solar neutrinos), a scintillator processing system has been built. The LS system includes four purification stages (Al_2O_3 column, distillation, water extraction, steam stripping) as well as storage and mixing tanks [3]. After that, the LS of JUNO will arrive at the OSIRIS (Online Scintillator Internal Radioactivity Investigation System) pre-detector. From there, LS

will continue go to the JUNO central detector.

The setup of OSIRIS (Figure 3) has been optimized for the purpose to detect the residuals of natural U/Th contamination of the LS. It can hold 18 tons of LS in its acrylic vessel. There are 64 LPMTs watching the LS and 12 outer LPMTs facing towards the water shielding to veto muons. It will search for the fast coincidence decays of ^{214}Bi-^{214}Po and ^{212}Bi-^{212}Po in the decay chains of ^{238}U and ^{232}Th, respectively. For the JUNO solar requirement, a measurement of 2-3 weeks is needed. OSIRIS could be possible to be upgraded to Serappis (SEarch for RAre PP-neutrinos In Scintillator) detector [4], dedicated to the precision measurement of the flux of solar pp neutrinos on the few-percent level.

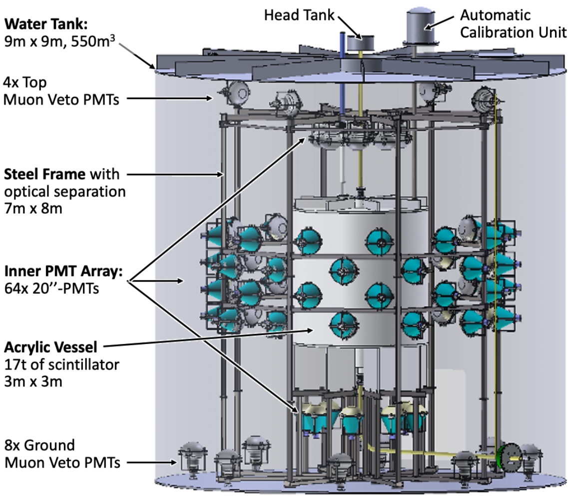

Figure 3. Schematic view of OSIRIS. [3]

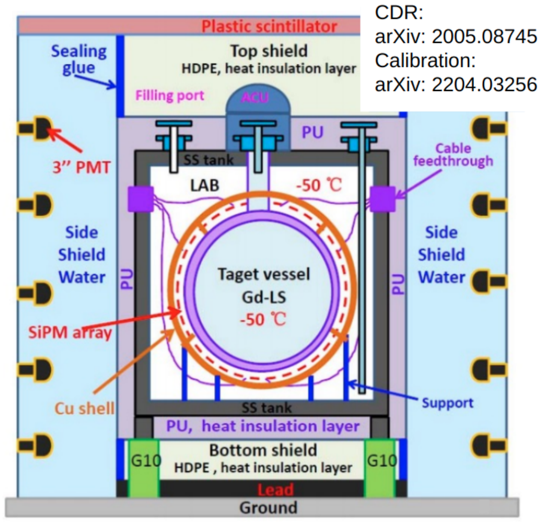

Figure 4. Schematic view of TAO. [5]

2.4. Taishan Antineutrino Observatory

Taishan Antineutrino Observatory (TAO) is located ~30 meters from a reactor core of the Taishan Nuclear Power Plant (4.6 GW_{th}). TAO will precisely measure the reactor neutrino spectrum, as a model independent reference spectrum for JUNO, with resolution better than 2% at 1 MeV. TAO will also provide benchmark tests for nuclear database.

The schematics of the detector is shown in Figure 4. TAO can hold 2.8 tons of Gadolinium-doped Liquid Scintillator (GdLS). It uses silicon PM for light collection and works at -50 °C. The photon detection efficiency is larger than 50%, coverage is ~94%, and dark count rate is only ~100 Hz/mm^2. Such that the detected light level can reach 4500 PE (photoelectron)/MeV.

3. Physics with JUNO

According to the standard 3-flavour neutrino oscillation model, the flavour eigenstates and mass eigenstates of neutrinos are not identical. The Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix is used to describe the mixing between the eigenstates and it can be decomposed into different components that correspond to atmospheric, reactor, solar sectors, and Majorana phases. Since the discovery of neutrino oscillation, there arised many open questions. Neutrino mass ordering is one the main topics of the next generation neutrino detectors: is the third mass eigenstate (ν_3) heavier or lighter than the first two (ν_1 and ν_2). In the normal ordering (NO) case: $m_1 < m_3$; in the inverted ordering (IO) case: $m_1 > m_3$.

JUNO will be able to detect electron antineutrinos (reactor, geoneutrinos, supernova neutrinos) through the Inverse Beta Decay (IBD): $\bar{\nu}_e + p \rightarrow e^+ + n$. An IBD event happening in JUNO will induce a prompt signal: 1) annihilation of positron and a delayed signal: 2) neutron capture after ~200 μs. JUNO will search for coincidence of these two signals. The IBD threshold is 1.8 MeV. Besides, JUNO is also able to detect neutrinos through elastic scattering off electrons in both charge current and neutral current channels. Solar neutrinos are detected by this method.

This section will discuss about varieties of physics goals and sensitivities of JUNO with different neutrino sources.

3.1. Neutrino mass ordering

Figure 5 shows the expected energy spectrum of the reactor antineutrino in the cases of NO, IO, and no oscillation. The curves that correspond to oscillation are obtained by applying survival probability of $\bar{\nu}_e$ on the original energy spectrum of $\bar{\nu}_e$, with different oscillation parameters and 53 km baseline as inputs. The small oscillation peaks contain NMO information, which is independent of $\delta_{\rm CP}$, and θ_{23}. Matter effect adds maximally 4% correction at roughly 3 MeV. Hence JUNO is complementary to other experiments that are based on matter-effect on long baseline oscillations of accelerator neutrinos and atmospheric neutrinos.

An Asimov data set was generated for both NO and IO assumptions. The corresponding minimum chi-squared are obtained by fitting to the data set. Then the median sensitivity discriminator of NO and IO is defined as: $\Delta\chi^2_{\rm NMO} = |\chi^2_{\rm min}({\rm NO}) - \chi^2_{\rm min}({\rm IO})|$. JUNO will reach its reactors-only sensitivity on NMO of $3\,\sigma$ at 6 yrs * 26.6 $\rm GW_{th}$ exposure.

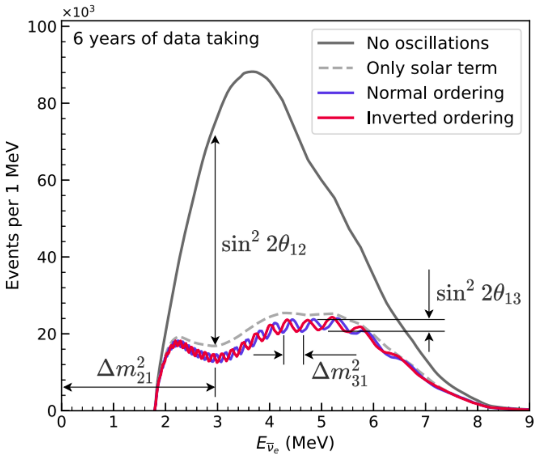

Figure 5. The expected antineutrino energy spectrum after 2000 days of data taking, assuming NO, IO, and no oscillation. Features of dependence on the four oscillation parameters are highlighted. [2]

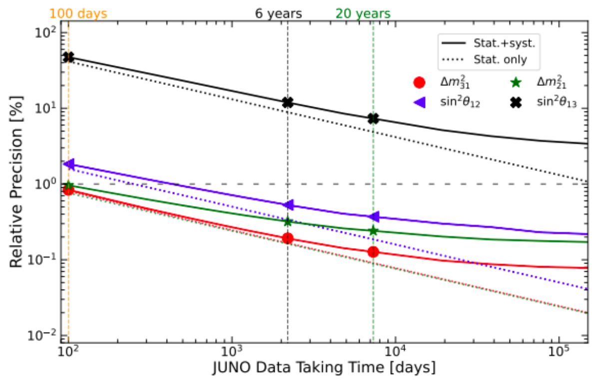

Figure 6. Relative precision level of the four oscillation parameters with respect to data taking time. [2]

3.2. Precision measurement of neutrino oscillation parameters

JUNO will be the first experiment ever to measure solar and atmospheric oscillation effects simultaneously. Because of extraordinary detector performance and large statistics of reactor antineutrino, the $\sin^2\theta_{12}$, Δm^2_{21}, and $|\Delta m^2_{32}|$ oscillation parameters will be determined to better than 0.6% precision in six years of data collection [2]. The precision will reach sub-percent even just after one year.

3.3. Supernova neutrinos

A core-collapse supernova emits 99% of the energy via neutrinos. With large target mass, JUNO is capable to detect all flavors of supernova neutrinos through many different channels. For a typical supernova at 10 kpc, the energy spectra of events from different channels are shown in Figure 7. A multi-messenger trigger system will be built to provide alert of supernova on the global network.

Diffuse Supernova Neutrino Background (DSNB) neutrinos are also possible to be detected by JUNO. They represent an integrated flux from the past supernova in the visible Universe. The main background would be reactor neutrinos above 10 MeV and NC atmospheric neutrinos. The influence of the latter can be suppressed by pulse shape discrimination. The signal to background ratio can then reach 3.5. And DSNB discovery potential is $3\,\sigma$ in 3 years of data taking with nominal models.

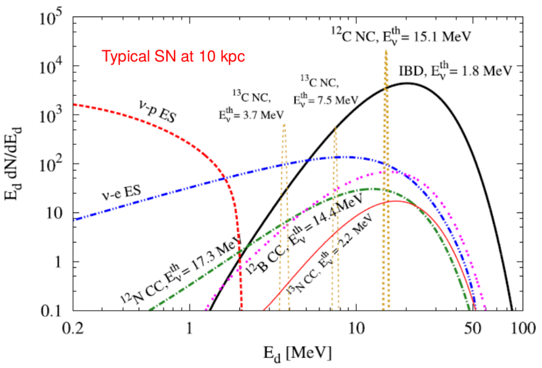

Figure 7. Supernova (at 10 kpc) neutrino event rates in different channels, as a function of visible energy E_d. [6]

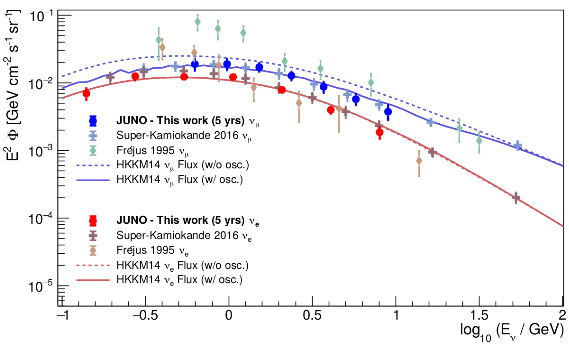

Figure 8. Atmospheric neutrino energy spectrum [7] of JUNO for ν_μ (blue) and ν_e (red), compared with two other experiments [8, 9].

3.4. Atmospheric neutrinos

JUNO will detect atmospheric neutrinos via CC and NC interactions. Electron and muon neutrinos discrimination can be done according to hit time pattern. Figure 8 shows the expected atmospheric neutrinos spectrum reconstructed by JUNO, assuming 5-year of exposure. Measurement of energy spectrum can reach 25% precision after five years. Due to matter effect, atmospheric neutrinos across the Earth can be used to study NMO, totally independent from reactor antineutrinos. JUNO sensitivity on NMO is expected to be: $0.7{\sim}1.4\,\sigma$ (atmospheric only) at ~ 6 years exposure [7].

3.5. Solar neutrinos

Detection of neutrinos from the Sun is important for both solar physics and neutrino oscillation physics. Knowing that there is 200 tons ^{13}C in the LS of JUNO volume, the solar ^{8}B neutrinos will be model independently observable in all three interactions of CC, NC on ^{13}C, and elastics scattering on electrons. The measurement of ^{8}B solar neutrino can easily reach 5% of precision.

Sensitivity of ^{7}Be, pep, and CNO solar neutrinos highly depends on radio-purity level of JUNO. Several radio-purity scenarios are assumed: from the Borexino level up to the "IBD" one (minimum required for the NMO). For ^{7}Be neutrinos, after one year of data-taking JUNO can reach and overcome current best result (2.7% [10]). For pep neutrinos, after two year of data-taking (except for IBD scenario) JUNO can reach and overcome current best result (14.8% [10]). For CNO neutrinos, constraint on pep-ν is crucial for the CNO detection. CNO neutrinos can be identified with precision better than 20% (except for IBD scenario), without ^{210}Bi constraint (used in the Borexino measurement [11]). A collaboration paper about these solar neutrinos is under preparation.

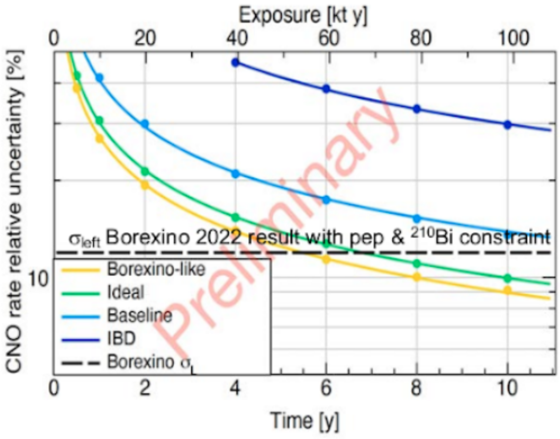

Figure 9. CNO neutrino precision with the pep constraint. [12]

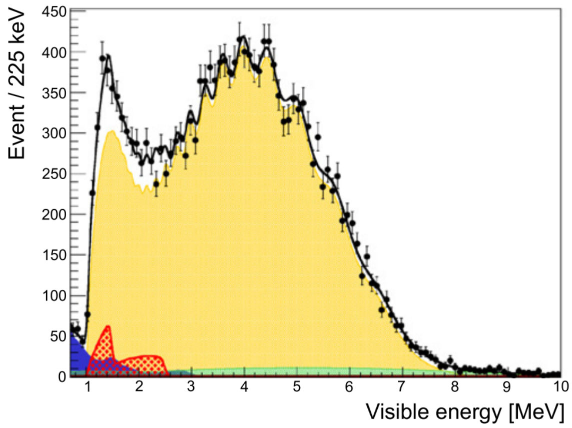

Figure 10. $\bar{\nu}_e$ from ^{238}U and ^{232}Th decay chains in the Earth. [1]

3.6. Geoneutrinos

Geoneutrino is a unique tool to study the Earth and can bring insights about its formation and radiogenic heat. The signal in JUNO is expected to be: 39.7+6.5-5.2 TNU (∼400 geoneutrinos per year). JUNO can reach the precision of current Borexino and KamLAND measurements in about one year. And JUNO will be sensitive to U/Th ratio. Figure 10 shows the energy spectrum of IBD candidates prompt signals from geoneutrinos (red), reactor antineutrinos (orange), and other accidental and radioactive backgrounds.

4. Conclusion

Construction of JUNO will be completed by the end of 2023. JUNO's sensitivity on neutrino mass ordering will reach 3σ after ∼6 years with 26.6 GW_{th} exposure. Besides its main goal, there are many exciting results in particle physics and astrophysics to be encountered from JUNO's data in the future.

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