PROCEEDINGS OF SCIENCE

Neutrino oscillation physics at JUNO

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JUNO is a multi-purpose neutrino observatory under construction in China. It will host a 20 kt liquid scintillator detector underground with an overburden of 650 m to study the neutrinos from different neutrino sources. With an unprecedented energy resolution of $\sim 3\%$ at 1 MeV, JUNO is designed mainly to detect the anti-neutrinos from the nuclear power plants located ≈ 53 km from the detector. One of the main physics goals of the experiment is to determine the neutrino mass ordering and to precisely measure the neutrino oscillation parameters Δm^2_{21}, $\sin^2\theta_{12}$, and Δm^2_{31} using the reactor anti-neutrino flux. The results from JUNO are expected to improve upon the existing knowledge of precision on these three parameters by almost one order of magnitude. Additionally, JUNO can also detect solar and atmospheric neutrinos, and the neutrinos from supernova explosion. It will also search for a wide range of physics including the study of proton lifetimes, indirect dark matter searches, Geo-neutrinos, etc. This contribution will mainly report on the physics of neutrino oscillations with the reactor neutrinos, and discuss the analysis strategy used to treat the various uncertainties and backgrounds in estimating these parameter sensitivities.

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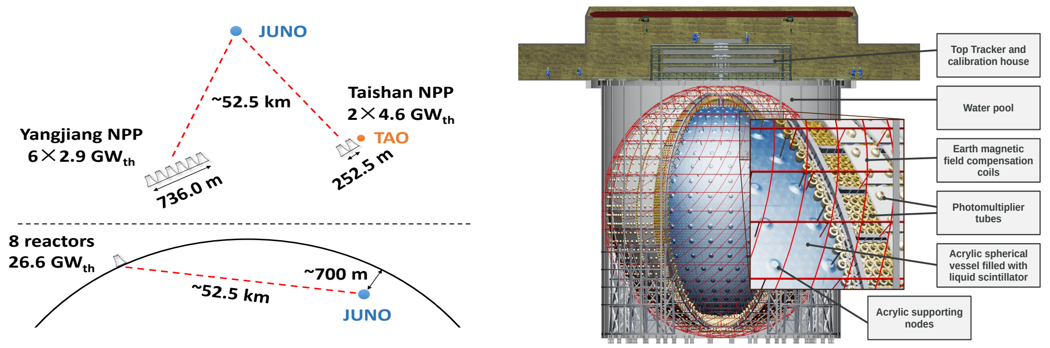
1. Introduction

The standard three neutrino oscillations driven by the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix [1, 2] is well verified by the different neutrino experiments around the globe. Among the parameters which govern the oscillations: two delta mass square terms ($\Delta m^2_{21}, \Delta m^2_{32}$) and their corresponding mixing angles ($\theta_{12}, \theta_{13}, \theta_{23}$) are currently determined within a few percent precision [3]. The sign of Δm^2_{32}, which determines the neutrino mass ordering (NMO), and the value of the Dirac phase ($\delta_{\rm cp}$), which measures the charge-parity (CP) violation in the lepton sector are some of the open questions in neutrino physics. The precise measurements of these oscillation parameters will allow to test the PMNS unitarity by exploring the complimentary measurements between different neutrino experiments.

The Jiangmen Underground Neutrino Observatory (JUNO) is a multi-purpose neutrino observatory under construction in South China [4]. Located approximately 53 km from Yangjiang (17.4 $\rm GW_{th}$) and Taishan (9.2 $\rm GW_{th}$) nuclear power plants, JUNO is primarily designed to observe reactor antineutrinos. Figure 1(a) shows the location of JUNO, its satellite detector called Taishan Antineutrino Observatory (TAO) [5] and the two nuclear power plants. A schematic of the JUNO detector is shown in Fig. 1(b). It is designed to host a large mass of $\sim$ 20 kton liquid scintillator (LS) as the neutrino target, with an overburden of 650 m to reduce cosmic backgrounds. Additionally, the JUNO LS is enclosed within a Water Pool. A Top-Tracker made of plastic scintillators is placed on the top of the Water Pool to veto cosmic muons. About 17612 20-inch and 25600 3-inch photo multiplier tubes (PMTs) will be used in JUNO central detector for light detection, providing $\sim$ 78% photon coverage. Together with a LS attenuation length greater than 20 m, JUNO expects a light yield of 1665 photoelectrons per MeV and an unprecedented energy resolution better than 3% at 1 MeV [7].

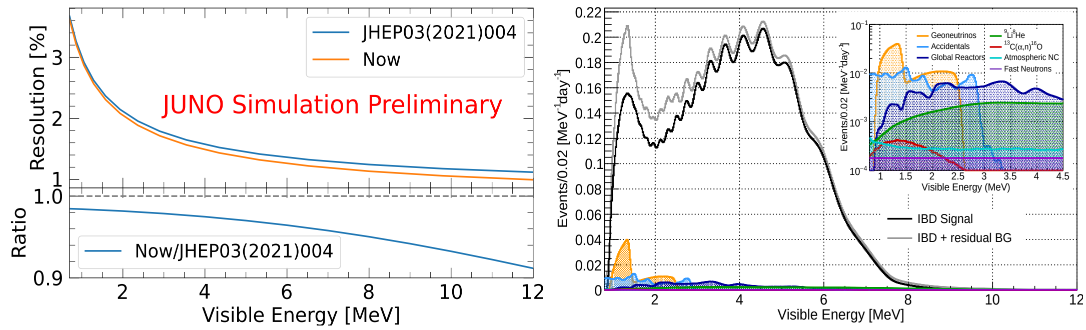


(a) (b)

Figure 1: (a) Layout of JUNO experiment, and (b) schematic of JUNO detector. Taken from [6].

2. Oscillation physics with reactor neutrinos

Pressurized water reactors are the main source of neutrinos for JUNO, where the fission of four fuel isotopes (^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu), and the subsequent β-decay of its daughter isotopes produces electron antineutrinos ($\bar{\nu}_e$). JUNO detects electron antineutrinos via the inverse β-decay (IBD) process, $\bar{\nu}_{\rm e} + {\rm p} \rightarrow {\rm e}^+ + {\rm n}$, where an antineutrino interacts with a proton in the LS producing a positron and a neutron. The positron deposits its kinetic energy and annihilates with an electron in the LS giving a prompt signal. While, the neutron undergoes thermalization and is captured by a proton producing a delayed signal of 2.2 MeV, after approximately 200 µs. Detecting this prompt and delayed coincident signal allows the distinction of neutrino signal from the backgrounds.



(a) **(b)**

Figure 2: (a) Energy resolution of JUNO, and (b) IBD and background spectra per day taken from [6].

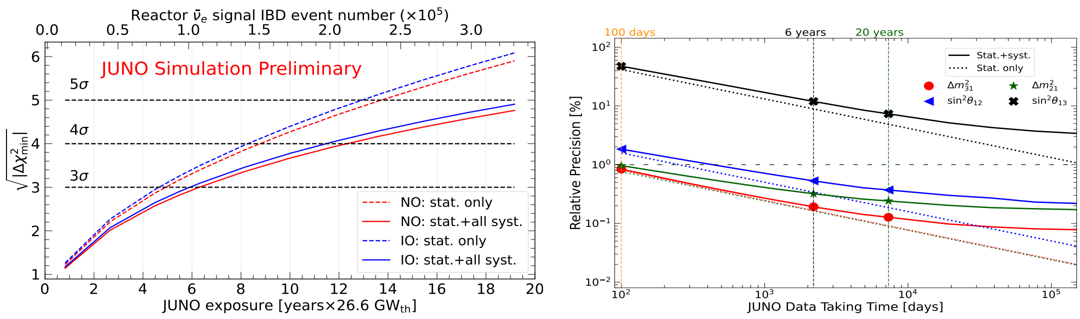
The positron carries the majority of the neutrino energy. However, the expected visible energy of the prompt signal is not linear with respect to the deposited energy. There is a known intrinsic non-linearity, primarily associated with the quenching of scintillation and Cherenkov mechanisms in the LS, called Liquid Scintillator Non-Linearity (LSNL). JUNO will perform dedicated calibrations to estimate this effect [8]. In the present analysis, the effect of LSNL is applied based on the measurements from Daya Bay experiment [9] with the energy scale determined from the JUNO simulations. Further, the visible energy is also smeared to account for other effects influencing the energy resolution such as PMT dark noise, position non-linearity, reconstruction effects, etc. Figure 2(a) highlights a recent update in the estimation of the energy resolution since Ref. [8] (blue line), which described the JUNO calibration program, using a more up to date simulated model of the detector (yellow line). This recent update includes new estimates of the PMT optical model and performance, and updates to the detector geometry, and LS properties to make them match better with the detector under construction.

Figure 2(b) shows the estimated oscillated neutrino spectrum at JUNO, along with the major backgrounds to this analysis: Geo-neutrinos, accidentals, cosmogenic ^{9}Li/^{8}He decays. The major input uncertainty comes from the reactor flux, and a detailed description of event selection, rates and uncertainties used can be found in Ref. [6]. More importantly, JUNO will use the reference neutrino spectrum provided by TAO to perform model independent measurements of neutrino oscillations.

2.1 Neutrino mass-ordering and parameter sensitivities

To determine the NMO, the JUNO and TAO experiment models are analyzed in a simultaneous fit to an Asimov data set. The data from TAO is used to constrain the reactor antineutrino energy spectrum since the effects from neutrino oscillations are negligible, while the NMO is determined from the oscillation pattern in JUNO data. Figure 3(a) shows the estimated median NMO sensitivity for both normal ordering (NO) and inverted ordering (IO) hypothesis. JUNO can determine the NMO with 3σ significance for an exposure of $\sim$ 6 years at 26.6 $\mathrm{GW_{th}}$ reactor power [10].

The oscillation parameter sensitivities are determined in an equivalent method. It is estimated that using 6 years of data, JUNO can determine the parameter Δm^2_{31}, Δm^2_{21} and $\sin^2\theta_{12}$ with a precision of $\sim$ 0.2%, $\sim$ 0.3% and $\sim$ 0.5% respectively. Within 100 days of data taking, JUNO is



(a) **(b)**

Figure 3: Estimation of JUNOs sensitivity to (a) neutrino mass-ordering, and (b) oscillation parameters taken from Ref. [6]

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expected to lead the global precision on these three parameters [6]. Figure 3(b) shows the relative precision on these parameters and the precision to measure $\sin^2\theta_{13}$.

3. Oscillation physics with solar and atmospheric neutrinos

Independent of reactor neutrinos, JUNO is also expected to study neutrino oscillations with ^{8}B solar neutrinos. Thanks to an excellent signal to background ratio expected at JUNO, the parameters $\sin^2\theta_{12}$ and Δm^2_{21} can be estimated with a precision of 8% and 20% respectively for 10 years of data taking. It can be further improved by adding informative priors on the ^{8}B flux from global data measurements. A detailed description on the analysis strategy can be found in Ref. [11, 12].

Complimentary to reactor neutrino measurements, JUNO is also capable of estimating the NMO exploiting the matter effects in atmospheric neutrino oscillations. Further, studies are in progress to combine the complimentary measurements from reactor and atmospheric neutrinos to improve the NMO sensitivity.

4. Conclusion

JUNO is a multipurpose liquid scintillator neutrino experiment currently under construction in China. With its large volume and excellent energy resolution of ~ 3% at 1 MeV, JUNO is expected to determine the NMO with a significance of 3σ for an exposure of ~ 6 years at 26.6 GW$_{\text{th}}$ reactor power. It is also estimated that within 6 years of data taking, JUNO can improve the relative precision on the oscillation parameters Δm^2_{31}, Δm^2_{21} and $\sin^2\theta_{12}$ by almost one order of magnitude (~ 0.2%, ~ 0.3% and ~ 0.5% respectively). JUNO is also capable of studying neutrino oscillations with solar and atmospheric neutrinos and further studies are also in progress to combine the atmospheric and reactor neutrinos.

References

[1] B. Pontecorvo, *Mesonium and anti-mesonium*, Sov. Phys. JETP **6**, 429 (1957).

[2] Z. Maki, M. Nakagawa, S. Sakata, *Remarks on the unified model of elementary particles*, Progress of Theoretical Physics **28**, 870 (1962).

[3] R.L. Workman et al., *Review of Particle Physics*, Prog. Theor. Exp. Phys. **2022**, 083C01 (2022).

[4] Angel Abusleme et al., *JUNO physics and detector*, Progress in Particle and Nuclear Physics **123**, 103927 (2022).

[5] Angel Abusleme et al., *TAO Conceptual Design Report: A Precision Measurement of the Reactor Antineutrino Spectrum with Sub-percent Energy Resolution*, arXiv:2005.08745 (2020).

[6] Angel Abusleme et al., *Sub-percent precision measurement of neutrino oscillation parameters with JUNO*, Chinese Physics C **46**, 123001 (2022).

[7] G. Huang, *Vertex and Energy Reconstruction in JUNO with Traditional Methods*, Zenodo, doi: 10.5281/zenodo.6804556 (2022).

[8] Angel Abusleme et al., *Calibration Strategy of the JUNO Experiment*, J. High Energ. Phys. **2021**, 4 (2021).

[9] D. Adey et al., *A high precision calibration of the nonlinear energy response at Daya Bay*, Nuclear Instruments and Methods in Physics Research Section A **940**, 230-242 (2019).

[10] J. Zhang, *JUNO Neutrino Mass Ordering Sensitivity*, Zenodo, doi: 10.5281/zenodo.6775074 (2022).

[11] Angel Abusleme et al., *Feasibility and physics potential of detecting ^{8}B solar neutrinos at JUNO*, Chinese Phys. C **45**, 023004 (2021).

[12] Jie Zhao et al., *Model Independent Approach of the JUNO ^{8}B Solar Neutrino Program*, arXiv:2210.08437 (2022).