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Neutrino Oscillation Physics in JUNO

D. Navas-Nicolás on behalf of the JUNO collaboration[a,*]
[a] *IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405 Orsay, France*
E-mail: navas@ijclab.in2p3.fr

The Jiangmen Underground Neutrino Observatory (JUNO) is a 20 kton liquid scintillator detector that will study reactor antineutrinos emitted primarily from two nuclear power plants in the south of China at a baseline of about 53 km. Thanks to its two photon detection systems (17612 20" PMTs and 25600 3" PMTs), JUNO will achieve an unprecedented 3% energy resolution at 1 MeV with an energy scale calibration uncertainty of 1%. Such a powerful detector capability will resolve, for the first time, the interference pattern between the solar and atmospheric oscillation modes. Therefore, the primary physics goals of JUNO include the determination of the neutrino mass ordering at a 3-sigma confidence level and the measurement of three neutrino oscillation parameters, $\sin^2\theta_{12}$, Δm^2_{21} and Δm^2_{32}, with sub-percent precision. This document will cover the JUNO expected sensitivity in terms of neutrino oscillation physics, showing the impact of JUNO future results within the global neutrino framework.

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*Speaker

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1. Introduction

During the last decades, the precision of the best-known neutrino oscillation parameters has been improved thanks to a new generation of neutrino experiments that have allowed the compilation of new data from long-baseline accelerators or nuclear reactors [1]. These oscillations are governed by six independent parameters: 3 mixing angles θ_{12}, θ_{23} and θ_{13}, two mass squared differences Δm^2_{21} and Δm^2_{31} or Δm^2_{32} and a δ_{CP} phase responsible for the CP-violation in the leptonic sector. However there are still open challenges in the three-neutrino picture, as the value of δ_{CP} or the sign of Δm^2_{31}, the latter giving rise to the so-called neutrino mass ordering (NMO) problem.

The Jiangmen Underground Neutrino Observatory (JUNO) is a multi-purpose reactor neutrino experiment which aims to determine the neutrino mass ordering and measure the oscillation parameters with sub-percent precision [2], [3]. The JUNO experiment, under construction, is located in the Guandong province (China), at equal distances of ~53 km from the Yangjiang and the Taishan nuclear power plants, and has been optimized to have the best sensitivity for determining the NMO.

The detector, schematically depicted in Fig. 1, consists of a neutrino target mass of a sphere of 20 kton liquid scintillator, surrounded by 17.612 large 20-inch photomultiplier tubes (PMTs), referred to as LPMTs, and 25.600 small 3-inch PMTs or SPMTs, yielding an integral 77.9% photocathode coverage . The intrinsic dual-calorimetry of JUNO is crucial to achieve an unprecedented energy resolution of ≤3% at 1 MeV energy resolution, required for the NMO determination [4].

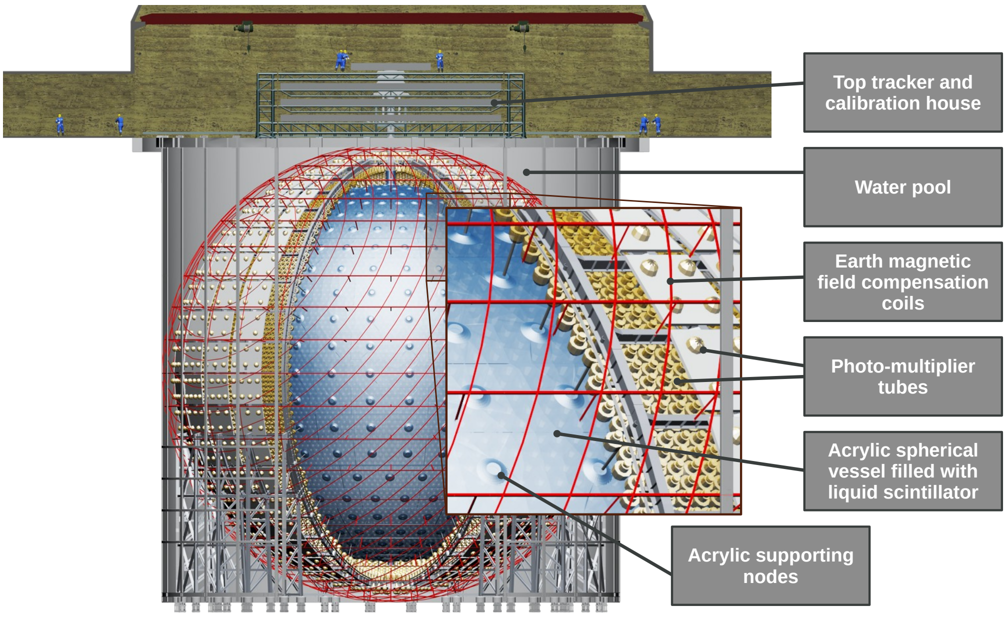

Figure 1: Schematic view of the JUNO detector.

Although the main JUNO contribution to neutrino oscillations comes from the analyses of reactor electron antineutrinos, JUNO's rich physics program also includes studies of neutrinos originated in the Sun and the atmosphere that provide complementary measurements [3].

2. JUNO physics with reactor antineutrinos

Reactor antineutrinos $\bar{\nu}_e$ are detected in JUNO through their interaction via the inverse beta decay (IBD) with a proton of the liquid scintillator: $\bar{\nu}_e + p \rightarrow e^+ + n$. Reactor neutrino experiments use the IBD interaction to detect $\bar{\nu}_e$ due to two major reasons: the charged current interaction has a larger interaction cross section for $\bar{\nu}_e$ with energy of a few MeV than any other processes, and the final state particles (positron and neutron) can be detected in coincidence, which largely suppresses backgrounds compared with the single signal detection. After applying the IBD selection criteria to suppress any radiogenic or cosmogenic events, as well as any possible geoneutrinos from the U and Th decay chain decays in the Earth, JUNO will be able to detect around 47 $\bar{\nu}_e$ per day, with a high selection efficiency of ~82%.

In JUNO location, the neutrino energy spectrum will be distorted by a slow (low frequency) oscillation driven by Δm^2_{21} and modulated by $\sin^2\theta_{12}$, as well as a fast (high frequency) oscillation driven by Δm^2_{31} and modulated by $\sin^2\theta_{13}$, as shown in Fig. 2. JUNO will be the first experiment to observe these two modes of oscillation simultaneously.

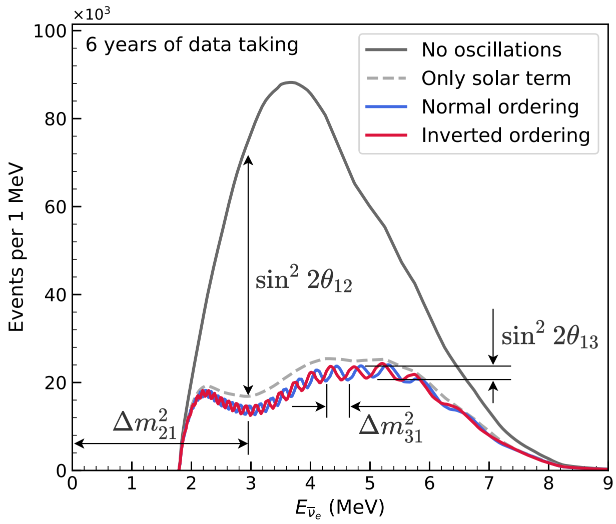

Figure 2: JUNO reactor antineutrino energy spectrum weighted by IBD cross-section without (black) and with the effect of neutrino oscillation for normal ordering (blue) and inverted ordering (red) assuming 2000 days of data-taking.

In order to eliminate any possible model dependance on the reactor antineutrino spectrum due to fine structure, the Taishan Antineutrino Observatory (TAO, also known as JUNO-TAO) [5] is proposed as a satellite experiment of JUNO to measure the reactor antineutrino spectrum with sub-percent energy resolution. The JUNO-TAO liquid scintillator detector is located 30 m from one of the Taishan NPP reactor cores and will provide an energy spectrum with an energy resolution of less than 2% at 1 MeV, helping in addition to reduce the reactor flux shape uncertainty.

2.1 NMO determination

As previously mentioned, disentangling the two oscillation modes (normal and inverted) requires the detector to have the ability to measure the fast atmospheric oscillations. The sensitivity of

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JUNO to the NMO is calculated using an Asimov sample. The positron spectrum is fitted assuming the normal or inverted ordering with the χ^2 method and the correct ordering is then determined by constructing the estimator $\Delta\chi^2_{\text{NMO}} = |\chi^2_{\text{min}}(\text{NO}) - \chi^2_{\text{min}}(\text{IO})|$.

Since JUNO sensitivity is based on the vacuum oscillations, the NMO determination has no dependence on the unknown CP-violating phase and the θ_{23} octant, adding unique information when combined with other neutrino experiments. After 6 years of data taken, the expected sensitivity would be larger than 3σ by fitting JUNO's data alone. However by using an external 1% constraint from ν_μ disappearance measurements, the NMO sensitivity can be improved to 4σ [2]. Furthermore the combined sensitivity of JUNO together with accelerator experiments has the potential to yield the first resolved ($\geq 5\sigma$) measurement of the NMO [6].

2.2 Precision Measurement of Oscillation Parameters

Besides the determination of the NMO, JUNO is expected to give a precise measurement of three neutrino oscillation parameters, including $\sin^2\theta_{12}$, Δm^2_{21} and Δm^2_{31} or Δm^2_{32}. The precision measurement of these parameters is a powerful tool to test the standard three-flavor neutrino picture and discover physics beyond the Standard Model.

To extract the neutrino oscillation parameters, the expected spectrum that JUNO will measure, illustrated in Fig. 3, is compared against the hypothesis model obtained using the nominal oscillation parameters from [1]. In table 1, it can be seen how JUNO will improve today's precision by measuring three out of six neutrino oscillation parameters to the per mile precision. In fact, JUNO is expected to dominate the world precision on those parameters with only about 100 days of data taking, although more statistics will improve the results.

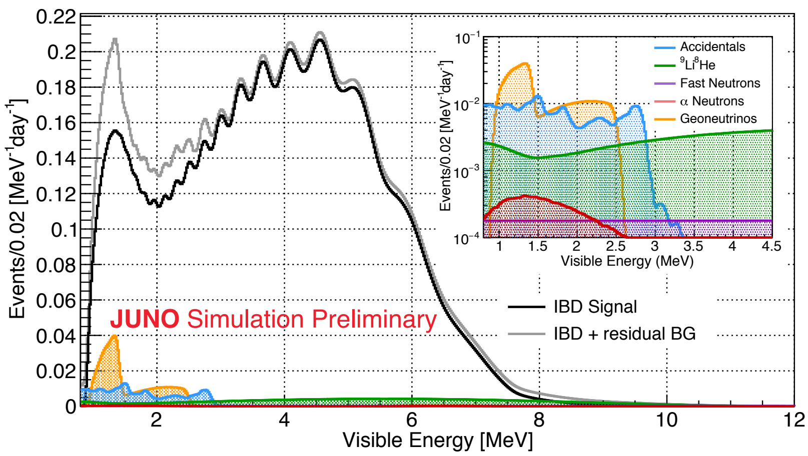

Figure 3: Visible energy spectrum and background spectra expected in JUNO detector.

3. JUNO physics with solar and atmospheric neutrinos

The low-energy threshold, the high energy resolution and the large target mass makes JUNO an excellent detector for tagging ^{8}B solar neutrino via the neutrino-electron elastic scattering process. With ten years of data taking, about 60,000 signal events are expected with a signal to background

	Δm^2_{31}	Δm^2_{21}	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$
JUNO 6 years	~0.2%	~0.3%	~0.5%	~12%
PDG 2020	1.4%	2.4%	4.2%	3.2%

Table 1: JUNO precision levels for the oscillation parameters after 6 years of data taken. The current knowledge (PDG2020 [1]) is shown for comparison. No external constrain is applied for $\sin^2\theta_{13}$ in the JUNO results.

ratio equal to two. This large sample of data will provide the opportunity to measure the day-night-asymmetry with 0.9% sensitivity. Moreover, JUNO can simultaneously measure the oscillation parameters Δm^2_{21} to 20% precision and $\sin^2\theta_{12}$ to 8% precision [7]. In fact a comparison of the solar and reactor Δm^2_{21} measurement from the same detector will help to shed light on the current tension between the value of Δm^2_{21} reported by solar neutrino experiments and the KamLAND experiment.

On the other hand, JUNO will be also able to detect several atmospheric neutrinos per day given the large detector volume. The atmospheric flux measurements will allow to investigate the NMO (with more than 1σ significance for 6 years of data) and the θ_{23} octant [3]. Although JUNO's design is not optimized for atmospheric neutrino physics, the extremely good performances as the large active volume and the fine energy resolution allow to reconstruct the energy spectrum with competitive precision. This way the atmospheric neutrino energy spectrum can be reconstructed in the energy range [100MeV-10 GeV], separately for ν_e and ν_μ, assuming a 5 years detector livetime [8].

4. Summary and conclusions

JUNO is a new generation neutrino experiment based on the world's largest liquid scintillator detector with an unprecendented energy resolution, aiming primarily for the high precision reactor neutrino oscillation measurements. Its major scientific prospects include the neutrino mass ordering determination and the unprecedented precision measurement of the oscillation parameters. Beyond the detection of reactor neutrinos, JUNO is capable to observe also solar and atmospheric neutrinos that will provide independent and complementary measurements of the oscillation parameters. Therefore JUNO will provide a unique opportunity to address some unsolved crucial questions in particle physics and astrophysics.

References

[1] P. A. Zyla *et al.* [Particle Data Group], PTEP **2020** (2020) no.8, 083C01

[2] F. An *et al.* [JUNO], J. Phys. G **43** (2016) no.3, 030401

[3] A. Abusleme *et al.* [JUNO], Prog. Part. Nucl. Phys. (2021) 103927

[4] A. Abusleme *et al.* [JUNO], JHEP **03** (2021), 004

[5] A. Abusleme *et al.* [JUNO], [arXiv:2005.08745 [physics.ins-det]].

[6] A. Cabrera *et al.* [arXiv:2008.11280 [hep-ph]].

[7] A. Abusleme *et al.* [JUNO], Chin. Phys. C **45** (2021) no.2, 023004

[8] A. Abusleme *et al.* [JUNO], Eur. Phys. J. C **81** (2021), 10