PROCEEDINGS OF SCIENCE

Prospects for Oscillation Physics in the JUNO Experiment

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The Jiangmen Underground Neutrino Observatory (JUNO) is a multi-purpose neutrino experiment currently under construction in South China, in an underground laboratory with approximately 650 m of rock overburden (1800 m.w.e.). The detector consists of a 20 kton liquid scintillator target, contained inside a 35.4-meter-diameter spherical acrylic vessel. The sphere is submerged in an ultra-pure water pool, which acts as a Cerenkov radiation veto system for cosmic rays and ensures minimal environmental radioactivity contamination. The central detector (CD) is equipped with 17,612 20-inch and 25,600 3-inch Photomultipliers Tubes (PMTs), providing more than 75% total photocathode coverage.

JUNO's main goal is the determination of the neutrino mass ordering with reactor antineutrinos, emitted from two adjacent nuclear power plants on a ~ 52.5 km baseline from the experimental site, and detected through the inverse beta decay reaction. The oscillated energy spectrum in JUNO changes subtly depending on the neutrino mass ordering, thus providing sensitivity to this parameter. To achieve a $\sim 3-4\sigma$ significance in about 6 years of data-taking, high energy resolution ($\leq 3\%$ at 1 MeV) and overall non-linearity effects below 1% are needed.

Furthermore, JUNO will be the first experiment to simultaneously probe the effects of solar (Δm^2_{21}) and atmospheric (Δm^2_{31}) oscillations; it will be able to measure four oscillation parameters: Δm^2_{21}, Δm^2_{31}, $\sin^2\theta_{12}$, and $\sin^2\theta_{13}$, achieving a sub-percent precision for the first three parameters.

This contribution will focus on JUNO's oscillation physics potential, with a particular emphasis on the reactor antineutrino analysis.

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1. Introduction

The study of neutrinos and their properties, both on experimental and theoretical grounds, is one of the most active directions within particle physics. To date, the neutrino oscillation phenomenon can be explained within the standard three-neutrino paradigm, where a total of six parameters are needed to fully describe neutrino oscillations: three mixing angles (θ_{12}, θ_{23}, and θ_{13}), one Dirac CP phase ($\delta_{\rm CP}$), and two independent mass squared differences (Δm^2_{21} and Δm^2_{31}, or equivalently Δm^2_{32}). Despite significant advancements in neutrino experiments and their precision in recent years, many properties of neutrinos still remain unknown, including their nature (Dirac or Majorana particles), the existence of CP violation in the leptonic sector, and the scale of the neutrino mass eigenstates, commonly referred to as neutrino Mass Ordering (MO).

The Jiangmen Underground Neutrino Observatory (JUNO) [1], is a multi-purpose liquid scintillator (LS) experiment currently under construction in South China. JUNO is primarily designed for the determination of the neutrino MO with electron antineutrinos ($\overline{\nu}_e$), emitted from six 2.9 GW$_{\rm th}$ and two 4.6 GW$_{\rm th}$ reactor cores in the Yangjiang and Taishan nuclear power plants (NPPs), respectively. Figure 1 shows the location of the JUNO experiment and of its satellite experiment, called Taishan Antineutrino Observatory [2] (TAO or JUNO-TAO) and installed at a distance of around 30 m from one of the Taishan reactors. In order to achieve accurate results, JUNO relies on the precise knowledge of the oscillated reactor antineutrino spectrum shape, and this implies strict requirements on the design of the detector, whose schematic representation is reported in Figure 2. Most importantly, the energy resolution requirement ($\leq$ 3% at 1 MeV) is addressed by securing a total photocoverage of more than 75%, made possible by a sophisticated photo-detection system, comprising 17,612 20-inch large PMTs (LPMTs) and 25,600 3-inch small PMTs (SPMTs).

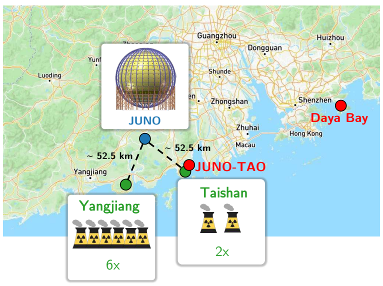

Figure 1: Location of the JUNO and TAO experiments in South China [1].

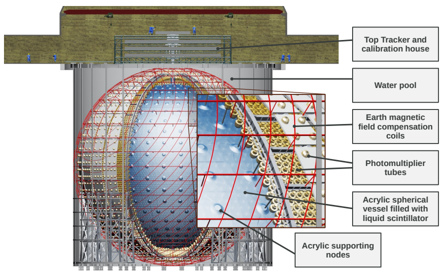

Figure 2: Schematic representation of the main JUNO detector [1].

2. Oscillation physics with reactor antineutrinos

The primary $\overline{\nu}_e$ signal is provided by the nearby NPPs, which operate commercial pressurized water reactors (PWRs), where electron antineutrinos are produced by the β decay of fission products of four major isotopes: ^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu. Reactor antineutrinos are detected in JUNO through the Inverse Beta Decay (IBD) reaction $\overline{\nu}_e + p \rightarrow e^+ + n$. The positron ($e^+$) rapidly deposits its energy and annihilates into two 0.511 MeV photons, thus producing a *prompt* signal. The neutron undergoes thermalization within the detector medium through multiple scatterings. After an average time of 220 µs it is captured predominantly on a free proton in the LS, thus emitting a 2.22 MeV γ-ray and giving rise to a *delayed* signal. A schematic representation of the IBD reaction

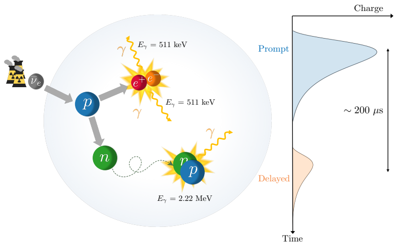

Figure 3: Schematic illustration of an IBD reaction in the LS, with corresponding time-charge diagram (not in scale).

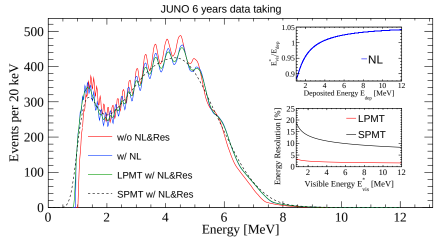

Figure 4: Expected prompt energy spectrum with and without the different detector response effects.

is depicted in Figure 3. The positron retains nearly all of the incoming antineutrino kinetic energy, making it a reliable proxy for the latter. As such, the energy spectrum generated by prompt signals provides a valuable means to investigate the $\overline{\nu}_e$ oscillation pattern. When positrons interact with the LS, they generate photons through scintillation and sub-dominant Cherenkov radiation mechanisms. However, the relationship between the energy deposited by the positron ($E_{\rm dep}$) and the number of scintillation photons detected by the PMTs is not strictly linear, primarily due to the quenching effect. To account for deviations from linearity, the Liquid Scintillator Non-Linearity (LSNL) is characterized by the equation: $E_{\rm vis} = f_{\rm LSNL}(E_{\rm dep}) \cdot E_{\rm dep}$, where $E_{\rm dep}$ represents the deposited energy, $E_{\rm vis}$ is the visible energy under the assumption of perfect energy resolution, and $f_{\rm LSNL}(E_{\rm dep})$ denotes the LSNL function. As the composition of the LS in Daya Bay and JUNO is similar, we have adopted the Daya Bay non-linearity curves [3], with appropriate adjustments to ensure consistency with the energy scale derived from JUNO simulations [4]. The visible energy $E_{\rm vis}$ is further smeared because of the finite energy resolution of the detector [4]. Figure 4 reports the expected prompt energy spectrum in JUNO with and without the aforementioned detector response effects, i.e., liquid scintillator non-linearity (NL) and energy resolution (Res). The IBD reaction provides a characteristic double spatial and temporal signature, enabling the identification of signal candidates while effectively mitigating background contamination. Consequently, several selection criteria are devised to efficiently perform event selection. The resulting energy spectrum, comprising the reactor antineutrino signal and all residual backgrounds is reported in Figure 5. More detailed information can be found in [5].

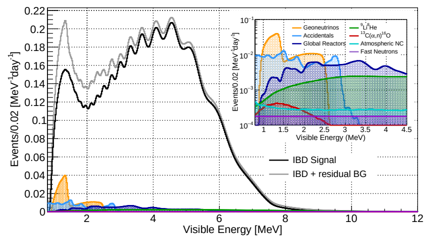

Figure 5: Expected energy spectra in JUNO, with all spectral components.

2.1 Precision measurement of oscillation parameters and MO determination

To extract the neutrino oscillation parameters and assess the sensitivity to the MO, the analysis involves comparing the nominal spectrum, which serves as a proxy for the expected spectrum that JUNO will measure, illustrated in Figure 5, with a hypothesis model based on the standard three-flavor framework. An Asimov pseudo-dataset is constructed to represent the nominal energy spectrum at JUNO under both the Normal Ordering (NO) and Inverted Ordering (IO) hypotheses. Then, the median sensitivity discriminator is defined as: $\Delta\chi^2 \equiv |\chi^2_{\rm min}({\rm NO}) - \chi^2_{\rm min}({\rm IO})|$.

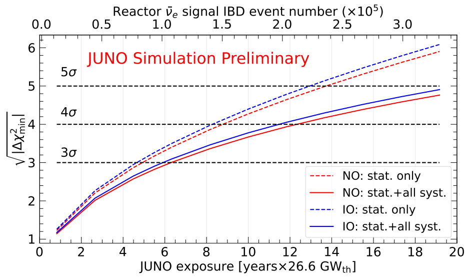

Figure 6: MO median sensitivity as a function of JUNO exposure [6].

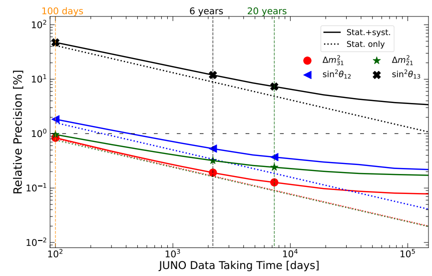

Figure 7: Relative precision on oscillation parameters as a function of JUNO exposure [5].

The resulting $\Delta\chi^2$ is reported in Figure 6 as a function of JUNO data taking time for both NO (red) and IO (blue) Asimov datasets. It is determined that with $\sim$ 6.2 years of data taking at full 26.6 GW$_{th}$ reactor power, JUNO can determine the neutrino MO with 3σ significance [6]. Furthermore, ongoing research is exploring the potential for enhancing this significance by incorporating additional information from the detection of atmospheric neutrinos [1, 6].

The obtained relative precision on the oscillation parameters [5] is reported in Table 1, and compared with state-of-the-art knowledge. JUNO is foreseen to already exceed global precision on three parameters within the first months of data acquisition. Figure 7 shows the relative precision of the oscillation parameters as a function of JUNO data taking time.

	PDG 2020	100 days	6 years
Δm^2_{21}	2.4%	0.6%	0.3%
Δm^2_{31}	1.3%	0.4%	0.2%
$\sin^2\theta_{12}$	4.2%	1.1%	0.6%
$\sin^2\theta_{13}$	3.2%	26.2%	12.0%

Table 1: Relative precision on oscillation parameters from PDG 2020 and JUNO (projected).

3. Conclusions

JUNO is a next-generation liquid scintillator neutrino observatory currently under construction in South China. Thanks to its unprecedented size and energy resolution, it will be able to perform a precise measurement of the $\overline{\nu}_e$ oscillated spectrum and to measure Δm^2_{31}, Δm^2_{21}, $\sin^2\theta_{13}$, and $\sin^2\theta_{12}$. The experiment is projected to attain sub-percent precision [5] for Δm^2_{31}, Δm^2_{21}, and $\sin^2\theta_{12}$, marking a milestone in the oscillation physics field. Moreover, JUNO stands out as the only experiment currently capable of resolving the MO through dominant vacuum oscillations of reactor antineutrinos. The expected sensitivity reaches the 3σ level in about 6.2 years of operation at 26.6 GW$_{th}$ reactor power.

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