Overview of the Jiangmen Underground Neutrino Observatory (JUNO)

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1. Introduction

After the discovery of non-zero $\theta_{13}$ in latest reactor$^{12,34,56}$ and accelerator$^{67}$ neutrino oscillation experiments, the neutrino mass hierarchy (i.e., the sign of $\Delta m^2_{31}$ or $\Delta m^2_{32}$) and lepton CP violation are the remaining oscillation parameters to be measured in the near future. The methods of determining the neutrino mass hierarchy (MH) include the matter-induced oscillations in the long-baseline accelerator neutrino experiments$^{8,9,10}$ and atmospheric neutrino experiments$^{11,12}$, and the vacuum oscillations in the medium baseline reactor antineutrino experiments$^{13,14,15,16}$.

The Jiangmen Underground Neutrino Observatory (JUNO) is a multipurpose liquid scintillator (LS) neutrino experiment, whose primary goal$^{15}$ is to determine the neutrino mass hierarchy using reactor antineutrino oscillations. The layout of JUNO is shown in Fig. 1, where the candidate site is located at Jiangmen in South China, and 53 km away from the Taishan and Yangjiang reactor complexes. The overburden for the experimental hall is required to be larger than 700 meters in order to reduce the muon-induced backgrounds.

2. Physics potential

Because the relative size of two fast oscillation components is different ($|\Delta m^2_{31}| > |\Delta m^2_{32}|$ or $|\Delta m^2_{31}| < |\Delta m^2_{32}|$), the interference between the two oscillation frequen-
Fig. 1. Layout of the JUNO experimental design. Current site makes use of the Taishan and Yangjiang reactor complexes, where the previous site is not considered because the third reactor complex (Lufeng) is being planned.

pecies in the reactor antineutrino energy spectrum gives us discrimination ability of two different MHs (normal or inverted). The discrimination power is maximized when the $\Delta m_{21}^2$ oscillation is maximal (see Figure 1 of Ref. [15]).

To calculate the sensitivity of MH determination at JUNO, we assume the following nominal setups. A LS detector of 20 kton is placed 53 km away from the Taishan and Yangjian reactor complexes. The detailed distance and power distribution of reactor cores summarized in Table 1 of Ref. [15] is used to include the reduction effect of baseline difference. In the simulation, we use nominal running time of six years, 300 effective days per year, and a detector energy resolution $3\%/\sqrt{E(\text{MeV})}$ as a benchmark. A normal MH is assumed to be the true one while the conclusion won’t be changed for the other assumption. The relevant oscillation parameters are taken from the latest global analysis [17]. To illustrate the effect of energy non-linearity and the power of self-calibration, we assume a residual non-linearity curve parametrized in Figure 3 of Ref. [15] and a testing polynomial non-linearity function with 100% uncertainties for the coefficients. Taking into account all above factors in the least squares method, we can get the MH sensitivity as shown in Fig. 2 where the discriminator is defined as

$$\Delta \chi^2_{\text{MH}} = |\chi^2_{\text{min}}(\text{Normal}) - \chi^2_{\text{min}}(\text{Inverted})|,$$

and $\Delta m_{ee}^2$ and $\Delta m_{\mu\mu}^2$ are the effective mass-squared differences in the electron and muon neutrino disappearance experiments, respectively. From the figure we can learn that a confidence level of $\Delta \chi^2 \simeq 11$ is achieved for the reactor-only analysis, and it will increase to $\Delta \chi^2 \simeq 19$ by using a prior measurement of $\Delta m_{\mu\mu}^2 (1\%)$.

Other important goals of JUNO include the precision measurement of oscillation parameters and unitarity test, observation of supernova neutrinos, geo-neutrinos, solar neutrinos and atmospheric neutrinos, and so on. Using reactor antineutrino oscillations, we can measure three of the oscillation parameters (i.e. $\sin^2 \theta_{12}$, $\Delta m_{21}^2$
Fig. 2. MH sensitivity of JUNO using reactor antineutrino oscillations. The vertical difference of the curves for the true and false MHs is the discriminator defined in Eq. (1). The solid and dashed lines are for the analyses with and without the prior measurement of $\Delta m^2_{\mu\mu}$.

and $|\Delta m^2_{31}|$ better than 1%.

3. Design concepts

The design of the central detectors is still open for different options. One basic option is shown in Fig. 3, where the concept of three separated layers is used for better radioactivity protection and muon tagging. The inner acrylic tank contains 20 kton linear alkylbenzene (LAB) based LS as the antineutrino targets. 15,000 20-inch photomultiplier tubes (PMTs) are installed in the internal surface of the outer stainless steel tank. 6 kton mineral oil is filled between the inner and outer tanks as buffer of radioactivities. 10 kton high-purity water is filled outside the stainless steel tank. It serves as a water Cherenkov detector after being mounted with PMTs. Other design concept contains the balloon option, single tank option, PMTs module option and mixtures among them. The energy resolution, radioactivity level and technical challenges are the main concerns of different options.

To obtain an unprecedented energy resolution level of $3%/\sqrt{E(\text{MeV})}$ (or 1,200 photon electrons per MeV) is a big challenge for a LS detector of 20 kton. Much better performance for PMTs and LS is required. R&D efforts to overcome the above challenges are being developed within the JUNO working groups. A new type of low-cost high-efficiency PMTs is being designed, which uses the micro channel plate (MCP) as the dynode and receives both the transmission and reflection light using the reflection photocathode. A coverage level of 80% can be realized with a careful consideration of the PMTs spacing and arrangement. Moreover, highly transparent LS with longer attenuation length (>30 m) is also being developed.
Both the method of LS purification by using Al$_2$O$_3$ and the distillation facility and the method to increase the light yield are considered.

4. Conclusion

JUNO is designed to determine the neutrino MH ($3\sigma - 4\sigma$ for six years) and measure three of the oscillation parameters better than 1% using reactor antineutrino oscillations. It can also detect the neutrino sources from astrophysics and geophysics. It has strong physics potential, meanwhile contains significant technical challenges. This program is supported from the Chinese Academy of Sciences and planned to be in operation in 2020.

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