PROCEEDINGS OF SCIENCE

JUNO: A Multi-Purpose LS-based Experiment

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After the discovery of the non-zero neutrino mixing angle θ_{13} by the Daya Bay experiment and confirmed soon by many others, the most pressing question of neutrino physics is the mass hierarchy. We propose a next generation reactor neutrino experiment using the liquid scintillator to precisely measure the reactor neutrino energy spectrum so to determine the neutrino mass hierarchy. This is a multi-purpose experiment, which can also measure precisely neutrino mixing parameters θ_{12}, ΔM^2_{21}, ΔM^2_{32}, and study supernova neutrinos, geo-neutrinos, sterile neutrinos as well as solar and atmospheric neutrinos. This new experiment is now under preparation and its progress is reported here.

XV Workshop on Neutrino Telescopes
March 11-15, 2013
Venice, Italy

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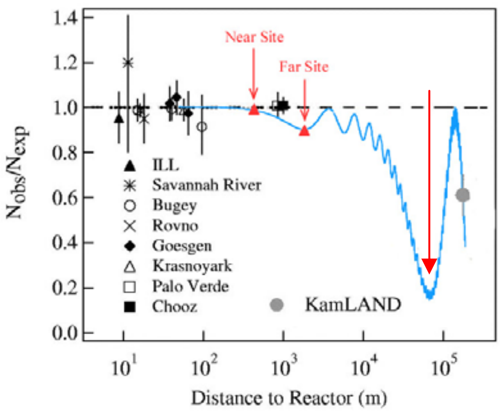
1. Introduction

After the discovery of the non-zero neutrino mixing angle θ_{13} by the Daya Bay experiment[1,2] and confirmed soon by many others[3], there are still many unknowns of the neutrino physics, such as the sign of ΔM^2_{32}, the CP phase δ, the sign of $\sin 2\theta_{23}$, the unitarity of the neutrino mixing matrix, as well as others like the absolute neutrino mass, the Dirac or Majorana nature of neutrinos, etc. Among them, the most pressing question is the the sign ofΔM^2_{32}, often called the neutrino mass hierarchy problem.

We propose a next generation liquid scintillator experiment to measure precisely the energy spectrum of reactor neutrinos[4]. In fact, the shape distortion due to the interference of ΔM^2_{32} and ΔM^2_{31} can actually reveal the information of the mass hierarchy[5]. After a careful analysis, we realized that it is feasible to reach the desired sensitivity by building a detector with a reasonable size and nowdays technology [6]. The unexpected large θ_{13} makes this job much easier and the project can now become a real one. The name of the experiment, previously called Daya Bay II, is now renamed Jiangmen Undergrund Neutrino Observatory(JUNO)

2. Ideas of the experiment and scientific goals

The idea of the experiment can be illustrated in Fig.1. By placing a detector at the oscillation maximum of θ_{12}, as indicated by the arrow, we are not only very sensitive to ΔM^2_{21} and θ_{12}, but also sensitive to the interference of ΔM^2_{23} and ΔM^2_{13}, hence the mass hierarchy [4].



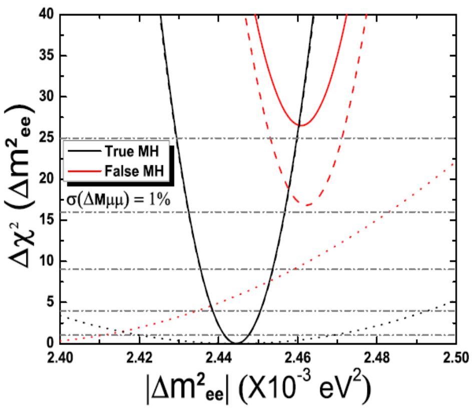


Fig.1 The principle of the JUNO experiment. Fig.2 The sensitivity to the mass hierarchy.

A detailed study shows that the sensitivity to the mass hierarchy depend on the total mass of the neutrino target, the energy resolution of the neutrino detector, the baseline, and the total thermal power. In addition, by using the absolute value of $\Delta M^2_{\mu\mu}$ from muon neutrino disappearance experiment at accelerators, we can improve the sensitivity significantly.

By using the following nominal values: target mass 20 k ton, energy resolution $3\%/\sqrt{E(\mathrm{MeV})}$, total thermal power 36 GW, the baseline 58 km, and 1% uncertainty of

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$\Delta M^2_{\mu\mu,}$ we obtain the sensitivity to the mass hierarchy as shown in Fig.2. In fact, there will be 40 neutrino events per day in this detector, and backgrounds are mainly from random coincidence of about a few percent, and cosmic-rays of less than 1%.

This experiment at the oscillation maximum of θ_{12} can also measure precisely many oscillation parameters. Table 1 shows its capability. In fact, such a precision will be better than that of the CKM matrix, and the unitarity of the neutrino mixing matrix can be tested at a precision better than 1%.

Table 1. Precision of neutrino mixing parameters at present and in the future.

	Current	JUNO
Δm^2_{12}	3%	0.6%
Δm^2_{23}	5%	0.6%
$\sin^2\theta_{12}$	6%	0.7%
$\sin^2\theta_{23}$	6%	N/A
$\sin^2\theta_{13}$	14%➔ 4%	~ 15%

The scientific capabilities of the JUNO experiment actually expand to astrophysics. It can be used to study supernova neutrinos, geoneutrinos, solar neutrinos, sterile neutrinos, etc. For example, a 20 kt detector can have thousands of neutrinos if the supernova happens at the core of our galaxy. In addition, liquid scintillator detectors can distinguish different neutrino flavors by reactions like $\bar{\nu}_e + p \to n + e^+$, $\bar{\nu}_e + {}^{12}C \to {}^{12}B* + e^+$, $\nu_e + {}^{12}C \to {}^{12}N* + e^-$, $\nu_x + {}^{12}C \to \nu_x + {}^{12}C*$, etc., hence to obtain energy spectrum of different neutrino flavors. This is very important to understand the details of supernova.

In summary, JUNO is a multi-purpose experiment for neutrino oscillation, astrophysics and geophysics. It will provide unique opportunities for us in the next 20 years.

3. Concept of the experiment

The conceptual design of the detector is shown in Fig.3. A large acrylic central detector contains liquid scintillator with a diameter of 34.5 meters can house 20 kt liquid scintillator. A 37.5 meter diameter stainless steel tank can house all the phototubes and maintain a buffer region to shield radioactive backgrounds from steel and phototube glass. In order to have maximum energy resolution, the whole surface is covered by 20” phototubes, with a total number of 15,000. The whole detector is merged in a water pool to shield backgrounds and stabilize the working conditions. Water will be used as a Cerenkov detector veto cosmic-rays while a tracking detector mounted at the top of the water pool is to tracking cosmic-rays to study backgrounds.

The liquid scintillator is chosen to be LinearAlkali Benzene(LAB) mixed with PPO and BisMSB with no Gd-loading. This is because Gd is often contaminated by Thorium

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so that the radioactive background is too high. It is also because Gd-loaded liquid scintillator is not transparent enough. In fact, LAB is chosen for its very high transparency, very high flush point, environmentally friend and relatively low cost.

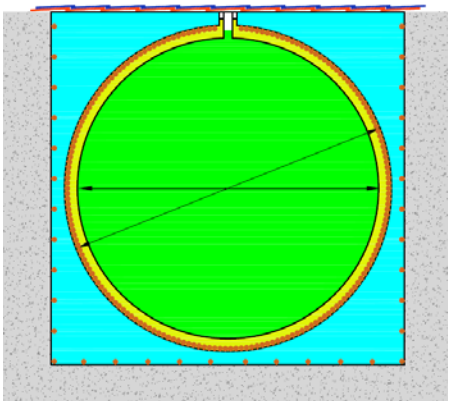

Fig.3 Conceptual design of the JUNO experiment.

JUNO is a technically very challenging experiment since its mass is a factor of 20 larger than that of KamLAND, and the light yield is a factor of 5 higher than that of KamLAND. By a carefully analysis comparing to KamLAND, we concluded that this is feasible taking into account the following considerations: 1) the optical transparency of the liquid scintillator can be increased from 15m to 30m; 2) the light yield of the liquid scintillator can be increased by more than 30% if the concentration of PPO and BisMSB is properly optimized; 3) the photocathode coverage can be increased from 34% to 80%; 4) the quantum efficiency of photocathode can be increased from 25% to 35% thanks to new SBA technology and/or a new type phototubes under development at our institute[7]. The total increase of light yield is a factor of 4.3-5.0, corresponding to an energy resolution of (2.5-3.0)%/ √ E, where E is the visible energy of neutrinos in MeV. The effect of the constant term and the neutron recoil uncertainty will contribute no more than 1%.

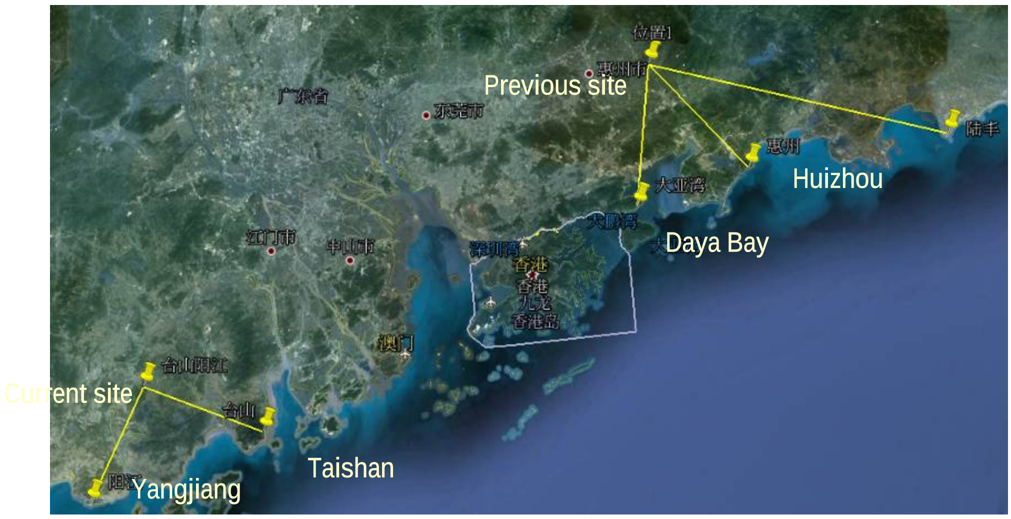

Fig. 4 The arrangement of the experiment

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The experiment is located at a site with an equal distance to two reactor complex. One is called Taishan which will have 4 reactor cores with a total thermal power of 18.4 GW. Two of them are now under construction. Another one is called Yangjiang which will have 6 reactor cores with a total thermal power of 17.4 GW, four of them is now under construction. Fig. 4 shows the configuration of the experiment. In fact, we had chosen a few years ago another site close to Daya Bay, but later we realized that the power plant changed plans, and the configuration is not ideal.

4. Current status

This experiment established its concept in 2008 and got boosted in 2012 thanks to the large θ_{13} and the success of Daya Bay experiment. The site was selected and the geological survey was started. From a simulation study, it is concluded that the detector has to have an equal distance to reactors within 500 m. Fortunately, there is a mountain at the desired location with an elevation of 270m, and preliminary geological survey shows that this mountain is made of a piece of granite with a diameter of about 2 km.

A conceptual design of the civil construction was completed and reviewed. Our plan was to build a 600 m vertical shaft and a 1.3 km sloped tunnel to access the experimental hall. After all, the overburden of the detector is more than 700 m rock.

The experimental hall will have a diameter of about 50m and height of 80m, the largest in the country. Detailed engineering analysis shows that it is stable in the given granite. Fig. 5 shows a preliminary study of the cavern with a grid analysis of rock mechanics.

A detailed geological survey is going on now as well as the detailed civil design. We expect to complete the preparation work up to 2014 and start the civil construction in 2015.

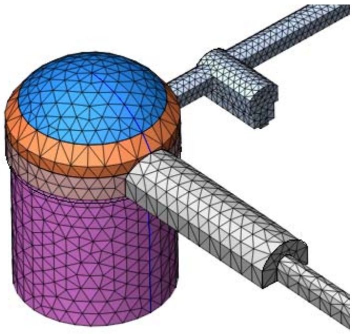

Fig. 5 The conceptual design of the experimental hall

The detector design and the related R&D are started. There are three major issues to be resolved. One is the central detector design: how to build such a large detector to hold different liquid? Currently there are several options, mainly classified as a) steel frame plus spherical acrylic tank, b) spherical steel tank plus acrylic box, c) spherical steel tank plus balloon, d) steel tank only. There are also combinations of these options. Studied of all options are in parallel and a decision is to be made by the end of 2013 to limit to no more than two options. Prototypes of the selected options will be

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manufactured to understand technical and installation issues until a final decision is to be made.

The second issue is high transparent liquid scintillator. We need to improve the attenuation length of the LAB from currently about 15m to about 30 m. The plan is to improve the purification process, improve the production process and improve the quality of raw materials in close collaboration with the manufacturer. The best results we obtained now are already exceeding 25 m.

The third issue is the high quantum efficiency photomultipliers. We can purchase photomultipliers with a Quantum Efficiency (QE) more than 35% from Hamamatsu and possibly other manufacturers. We are also developing a new type of MCP-PMT with an expected QE of more than 35%[7]. Prototypes of 8" PMT have been made with good single photon electron signal and a reasonable QE. Prototypes of 20" PMT will be available soon.

The detector is also instrumented with other components, such as muon veto detectors, calibration systems, readout electronics, trigger and DAQ, etc. All of them are progressing well.

The experiment is approved by the Chinese government for R&D and funding is available for the next two years. International collaboration will be established soon and new comers are welcome. The experiment is expected to start operation in 2020.

5.Summary

Thanks to the large θ_{13}, we can now plan a medium baseline reactor neutrino experiment to determine the neutrino mass hierarchy. A large liquid scintillator-based experiment, called JUNO, is proposed to determine the mass hierarchy at 4-5 sigma level with 6 years of data taking. This detector can also precisely measure the neutrino oscillation parameters and study supernova neutrinos, geo-neutrinos, etc. The JUNO experiment is under preparation and the data taking is planned for 2020.

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