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Neutrino Oscillation: Non-Accelerator Experiments

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In recent years, major advances have been seen in neutrino oscillation studies. In this talk, I will cover latest results by using solar neutrinos, atmospheric neutrinos and reactor neutrinos. Improved precision of oscillation parameters, including θ_{12}, ΔM^2_{21}, θ_{23} and $|\Delta M^2_{32}|$ are reported. The last unknown oscillation parameters θ_{13}, ΔM^2_{31} are known now. The next generation reactor neutrino experiments will be able to determine the mass hierarchy and improve significantly the precision of θ_{12}, ΔM^2_{21}, and ΔM^2_{32}. Experiments to study sterile neutrinos are under-planning using reactor neutrinos, radioactive sources as well as accelerator neutrinos.

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[1] Speaker

1. Introduction

Oscillation is a fundamental property of neutrinos, which is related to the neutrino mass and may generate leptonic CP violation to explain the matter-antimatter asymmetry of the Universe. For two-flavor oscillations in vacuum, the oscillation probability is expressed as:

$$P(\nu_1 \rightarrow \nu_2) = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E),$$

where $\sin^2 2\theta$ denotes the oscillation amplitude and $\Delta m^2 L/E$ represents the oscillation frequency. For 3 generations of neutrinos, the oscillation is often described by a 3×3 matrix:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \mathbf{V}_{e1} & \mathbf{V}_{e2} & \mathbf{V}_{e3} \\ \mathbf{V}_{\mu 1} & \mathbf{V}_{\mu 2} & \mathbf{V}_{\mu 3} \\ \mathbf{V}_{\tau 1} & \mathbf{V}_{\tau 2} & \mathbf{V}_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Here the so-called PMNS matrix V can be written as[1,2]:

$$\mathbf{V} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & e^{-i\delta} & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

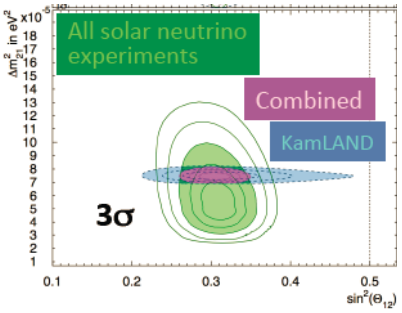
where $c_{ij} = \cos\theta_{ij}$, $s_{ij}=\sin\theta_{ij},$ (i,j=1,2,3).

There are six independent parameters in this matrix: θ_{12}, ΔM^2_{21}, θ_{23} and $|\Delta M^2_{32}|$ are known for more than 10 years, θ_{13} is recently known, while the sign of ΔM^2_{32}, often refered as the mass hierarchy, and the CP phase δ are unknown. In this talk, I will report improved measurements on θ_{12}, ΔM^2_{21}, θ_{23} and $|\Delta M^2_{32}|$ and the lastest known parameters θ_{13} by solar, atmospheric and reactor neutrinos. Future prospects will be given, particularly for the neutrino mass hierarchy. Experiments to study sterile neutrinos using reactor neutrinos, radioactive sources as well as accelerator neutrinos are also introduced.

2. Solar neutrinos

Indications of solar neutrino deficit appeared in 70's from the Homestake experiment and later confirmed by many other experiments, but θ_{12} and ΔM^2_{21} are given with multiple solutions if neutrino oscillation is assumed [1]. The issue was finally settled in 2001 when SNO found that the disappeared solar ν_e actually became ν_μ and ν_τ[3]. KamLAND in 2002 confirmed the solar neutrino oscillation and measured θ_{12} & ΔM^2_{21} unambiguously by using reactor neutrinos[4]. In fact, solar neutrino experiments can very well measure θ_{12} while ΔM^2_{21} has to rely on reactor neutrino experiments such as KamLAND, as shown in Fig. 1.

The main solar neutrino experiments currently operational are the Borexino and SuperKamiokande experiment. Borexino recently measured for the first time the so-called pep neutrinos with a flux of $(1.6\pm0.3)\times10^8$ $cm^{-2}s^{-1}$ [6], as shown in Fig. 2. Hence all solar neutrinos, except that of CNO type, are diretcly observed and in good agreement with the prediction of the Standard Solar Model combined with the MSW-LMA solution. Borexino also saw hints of seasonal variation of solar neutrinos[7], an independent confirmation of solar neutrino obseration. On the other hand, SuperKamiokade observed the Day-Night asymmtry at 2.7 σ level[8], in agreement with the prediction although a 1σ tension still exist.



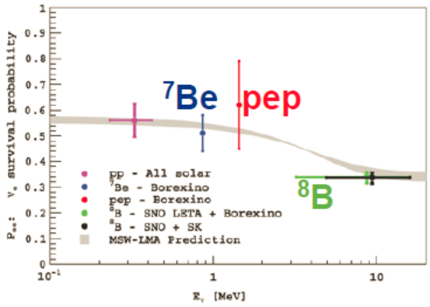


Fig. 1 Combined solar neutrino results with that of KamLAND[5].

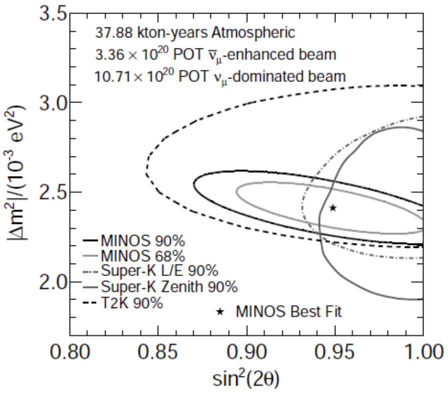
Fig. 2 Latest results from Borexino for pep neutrinos[6].

CNO neutrinos will be searched for by the SNO+ experiment [9], together with a better measurement of solar pep and ^{8}B neutrinos. This is a large (780t) liquid scintillator detector submerged in a water pool. Its construction will be completed in 2014.

Another experiment under planning is LENA which is a huge liquid scintillator detector (50kt) for solar neutrinos, in addition for supernova neutrinos, geo-neutrinos and sterile neutrinos[10]. It can definitely measure CNO neutrinos and can well measure the solar metallicity.

3. Atmospheric neutrinos

The first evidence of the atmospheric neutrino oscillation was observed in 80's by Kamiokande and IMB[1]. In 1998, Superkamiokande observed atmospheric ν_μ disappearance as a function of L/E[11], strongly suggesting that neutrinos do oscillate. Such a major discovery was confirmed by accelerator experiments including K2K, Minos and T2K, and later by the ν_τ appearance experiment, OPERA[1]. SuperKamiokande experiment is contineuing to take data since atmospheric neutrino experiments can well measure θ_{23} while accelerator experiments can better determine $|\Delta M^2_{32}|$, as shown in Fig. 3[12].



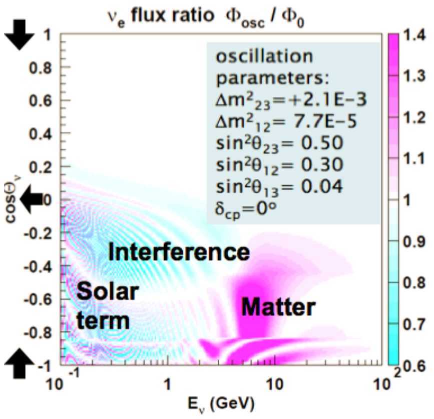


Fig. 3 Latest results of θ_{23} and $|\Delta M^2_{32}|$ from atmospheric and accelerator experiments[12]

Fig. 4 An illustration of the atmospheric neutrino flux ratio ϕ_{osc}/ϕ_0 [13].

Atmospheric neutrinos can be used to determine the sign of $\sin 2\theta_{23}$, the mass hierarchy and the CP phase, thanks to the large θ_{13}. Fig. 4 shows the ratio of the atmospheric neutrino flux with oscillation to that without oscillation[13]. The mass hierarchy comes from the matter effect term, while the CP phase from the interference term.

SuperKamiokande recently reported a slightly preference to the 2nd octant and 1.2σ preference to the inverted hierarchy[13]. Clearly the statistics is not sufficient and there is a need for much larger detectors.

The INO experiment in India is a 50 kt magnetized detector made of RPC and iron plates. Although not very large comparing to SuperKamiokande, its capability to distinguish the charge of muons, hence to distinguish neutrinos from anti-neutrinos, allows it to have a reasonable sensitivity to the mass hierarchy: 3σ after 10 years of operation[14].

The next generation water Cerenkov detector for atmospheric neutrinos is the HyperKamiokande with a total mass of 1 million tons, a factor of 20 larger than that of SuperKamiokande. This detector will use 99,000 20” PMTs covering 20% total area. For 10 years operation, it can determine the mass hierarchy up to 3σ, and the CP phase close to 3σ in some cases, as shown in Fig. 5 [15]. The detector is also the target of the neutrino beam from J-PARC with a baseline of 290 km. The sensitivity is actually much better than that of atmospheric neutrinos in most cases, as shown in Fig. 5.

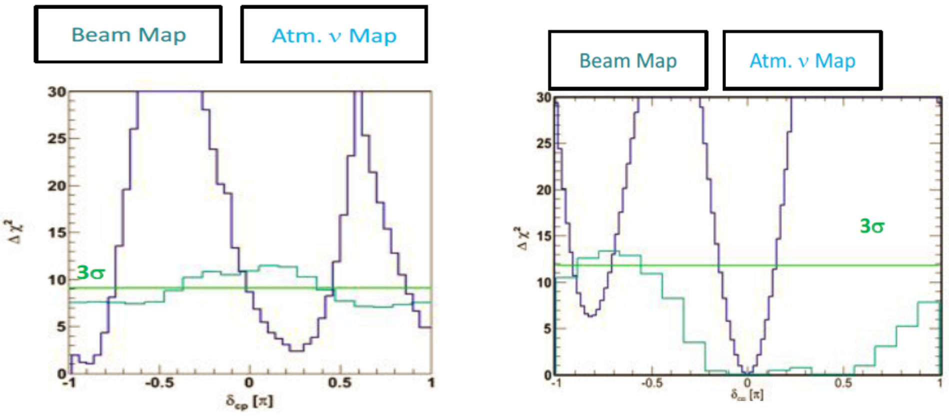


Fig. 5 Sensitivity of HyperK experiment to the mass hierarchy(left) and the CP phase(right)[15].

Even detectors for high energy cosmic-neutrinos such as IceCube can be modified to be sensitive to low energy atmospheric neutrinos by increasing the density of photomultipliers. The mass of such detectors can be easily a factor of ten larger than that of HyperK. One example is PINGU, which will use the existing IceCube detector as the veto and add a “small” core detector for atmospheric neutrino oscillation studies at a threshold of ~GeV. Their sensitivity to the mass hierarchy is easily a factor of ~3 better than that of HyperK if systematic uncertainties can be controlled to a similar level as that of HyperK[16].

4. Reactor neutrinos

Reactor neutrinos are used for the first direct detection in 50’s, and later for oscillation studies and search for magnetic moment[17]. In 2002, the KamLAND experiment observed the reactor neutrino oscillation, and precisely measured the neutrino mixing angle θ_{12} and ΔM^2_{21}[4]. This is the first confirmation of neutrino oscillations using man-made sources. Recently the KamLAND experiment reported latest results on the precision measurement of θ_{12} and ΔM^2_{21} by taking the unique opportunity to measure precisely the backgrounds when all the nuclear reactors in Japan are turned off due to the earthquake accident [18]. It is interesting to see that the measured neutrino rate is following the variation of the reactor power and the fitted results are shown in Fig. 6.

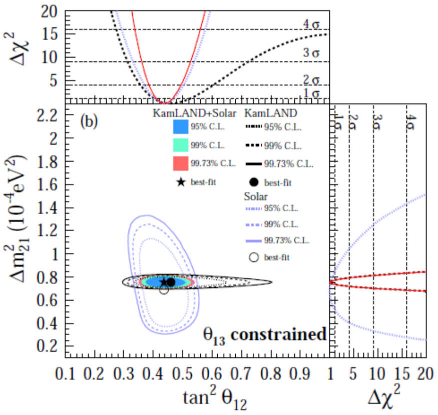


Fig. 6 The best fit of θ_{12} and $|\Delta M^2_{21}|$ from KamLAND and other solar experiments[18].

Very recently, the Daya Bay experiment revealed the last neutrino mixing angle θ_{13}[19], and it is soon confirmed by other experiments[20,21]. Reactor neutrino experiments for θ_{13} started in 2003 with about 8 proposals. In the end, only three experiments, Daya Bay, Double Chooz, and Reno experiments are proved and executed. Table 1 lists their main parameters and expected sensitivities.

Experiment	Power (GW)	Baseline(m) Near/Far	Detector(t) Near/Far	Overburden (MWE) Near/Far	Designed Sensitivity (90%CL)
Daya Bay	17.4	470/576/1650	40//40/80	250/265/860	~ 0.008
Double Chooz	8.5	400/1050	8.2/8.2	120/300	~ 0.03
Reno	16.5	409/1444	16/16	120/450	~ 0.02

Table 1 Main parameters of reactor neutrino experiments and their sensitivities to $\sin^2 2\theta_{13}$.

The Daya Bay experiment was initially proposed in 2003 while the construction started in 2007. The description of the experiment and detector systematic errors can be found in ref. [22]. The civil construction completed at the end of 2010 and the detector installation completed in 2011. At the end of 2011, all the detectors in three experimental halls are operational and physics results are reported in March 8, 2012, using data from Dec. 24, 2011 to Feb. 17, 2012, a total of 55 days[19]. An updated result is reported later using 137 days of data[23]. The observed number of events over that of expected assuming no neutrino oscillation is $R=0.944\pm0.007(\text{stat})\pm0.003(\text{syst})$, showing a deficit at a statistical significance of more than 7σ. Assuming neutrino oscillation with three generations, a combined χ^2 fit yields a new value of $\sin^2 2\theta_{13}$ as the following:

$$\sin^2 2\theta_{13} = 0.089 \pm 0.010(\text{stat}) \pm 0.005(\text{syst}).$$

The statistical significance of $\sin^2 2\theta_{13}$ being non-zero is 7.7σ. Fig. 7 shows the number of observed events vs that of expected as a function of the weighted baseline. Clearly the pattern is consistent with neutrino oscillations.

An independent prove of neutrino oscillation is the distorted energy spectrum of neutrinos from reactors at far detectors, as shown in Fig. 7. The ratio of the spectrum of far detectors to that of near detectors is consistent with that of neutrino oscillation. A detailed analysis is in progress and will be reported at the NuFACT 2013 workshop soon[24].

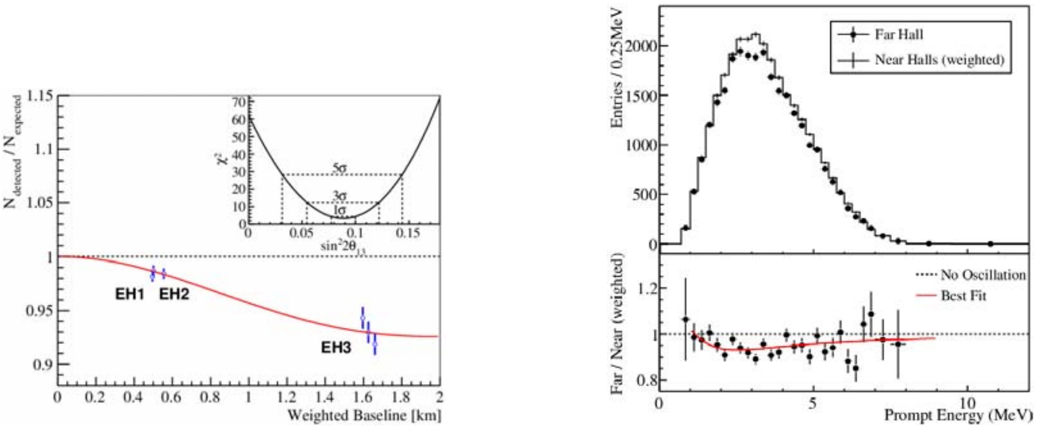


Fig. 7 Results from the Daya Bay experiment. Left: the number of observed events vs that of expected as a function of the weighted baseline(EH1, EH2, EH3 denote detectors in different experimental halls). Right: Energy spectrum of reactor neutrinos at near and far detectors, and their ratios.

The Daya Bay experiment completed the summer maintenance and a comprehensive calibration program using both automatic and manual calibration system. The full detector is operational since Oct. 2012 and the data taking will continue for the next 3-5 years. The precision to $\sin^2 2\theta_{13}$ is expected to reach 3-4 % level at the end of the experiment.

The RENO experiment in Korea started data taking with both near and far detectors in Aug.1, 2011. The first result is reported in April, 2012 by using 220 days of data, with a statistical significance of 4.9σ[20]. An updated result with 403 days of data is reported in March, 2013 at the NeuTel workshop[25]. They measured the neutrino oscillation amplitude as

$$\sin^2 2\theta_{13} = 0.100 \pm 0.010(\mathrm{stat}) \pm 0.015(\mathrm{syst}).$$

The energy spectrum and the ratio of near to far spectrum are shown in Fig. 8. The RENO experiment plan to take data for the next 5 years and the expected precision to $\sin^2 2\theta_{13}$ is 7%.

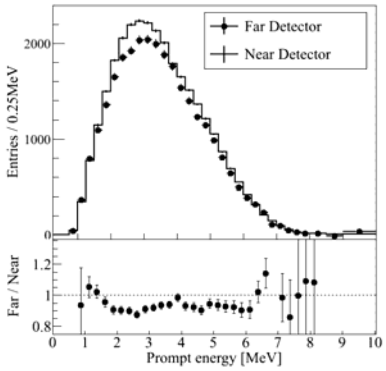


Fig. 8 Results from the RENO experiment: Energy spectrum of reactor neutrinos at near and far detectors, and their ratios.

The Double Chooz experiment started the far detector data taking at the beginning of 2011 and the near detector will be completed in 2014. They reported first hint of non-zero θ_{13} at the end of 2011, and later various updates[26,27,28]. Without the near detector, Double Chooz experiment used several different methods, taking advantages that a single reactor may turn-off completely, so backgrounds can be measured precisely. By using combinations of rate plus shape analysis, the reactor rate modulation analysis, the Gd capture and Hydrogen capture analysis, the Double Chooz experiment obtained consistent results of $\sin^2 2\theta_{13}$, all at a statistical significance of about 3σ level[26,27,28]. Once the near detector is operational in 2014, the final precision of $\sin^2 2\theta_{13}$ can reach the 10% level.

It is clear that a combined fit of $\sin^2 2\theta_{13}$ from three reactor experiments is desired by the community. But a simple average is not adequate since some uncertainties are correlated and some are estimated by a different standard. The three reactor experiments agreed to work together to produce an appropriate average so that a best value of $\sin^2 2\theta_{13}$ can be available.

Reactor neutrino experiments will not stop here. A next generation experiment, called JUNO, is now under planning in China[29]. The idea of the experiment can be illustrated in Fig.9. 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 between ΔM^2_{32} and ΔM^2_{31}, hence the mass hierarchy [30].

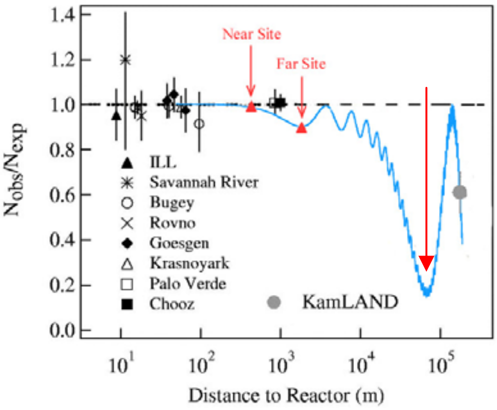


Fig.9 The principle of the JUNO experiment.

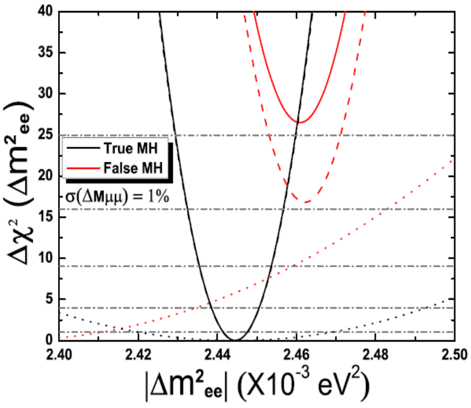


Fig.10 The sensitivity to the mass hierarchy.

By using the following nominal values: target mass 20 kton, energy resolution 3%/√E(MeV), total thermal power 36 GW, the baseline 58 km, and 1% uncertainty of $\Delta M^2_{\mu\mu}$, we obtain the sensitivity to the mass hierarchy as shown in Fig.10[31]. In fact, there will be 40 neutrino events per day in this detector, and backgrounds are mainly from random coincidence at a level of about a few percent, and cosmic-ray-related backgrounds of less than 1%.

This experiment, at the oscillation maximum of θ_{12}, can also measure precisely many oscillation parameters. Table 2 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%.

	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%

Table 2. Precision of neutrino mixing parameters at present and in the future.

The scientific capabilities of the JUNO experiment can actually expand to astrophysics, covering supernova neutrinos, geo-neutrinos, solar neutrinos, and sterile neutrinos, etc.

The conceptual design of the detector is shown in Fig.11. A large acrylic central detector 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 a maximum energy resolution, the whole surface is covered by 20" phototubes, counting 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 to veto cosmic-rays while a tracking detector mounted at the top of the water pool is to track cosmic-rays to study backgrounds.

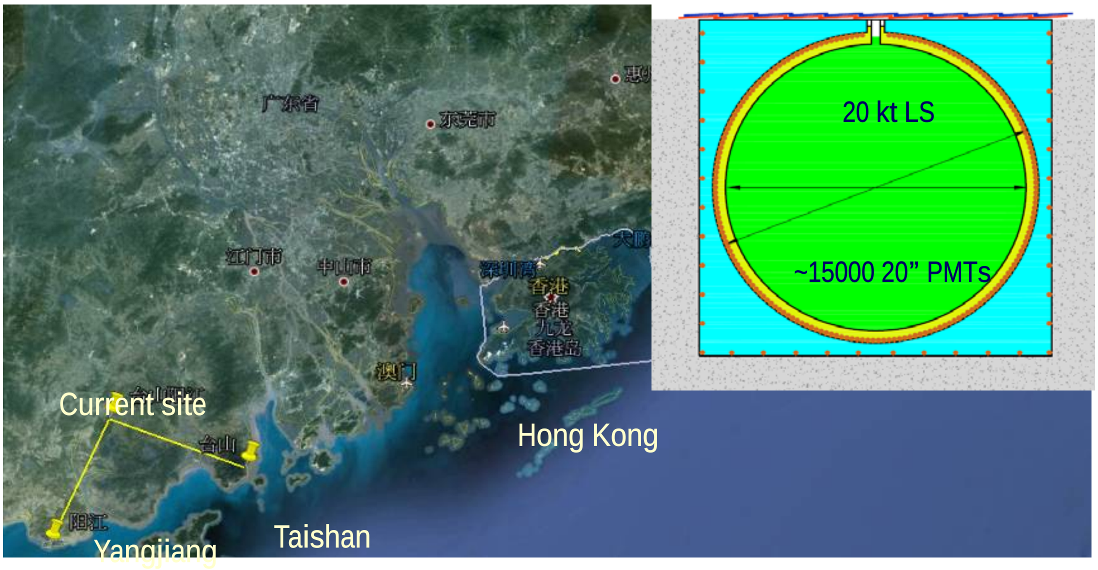


Fig. 11 The arrangement of the experiment

The experiment is located at a site with an equal distance to two reactor complexes. One is called Taishan which will house 4 reactor cores with a total thermal power of 18.4 GW. Two of them are now under the 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. The JUNO experiment is approved by the Chinese government for R&D and funding is available for the next two years. A detailed geological survey is now going on as well as the detailed civil design. We expect to complete the preparation work up to 2014 and to start the civil construction in 2015. An international collaboration will be established soon and new comers are welcome. The experiment is expected to start operation in 2020.

A similar proposal by the RENO group, called RENO-50, is also under planning now.

5. Sterile neutrinos

It has been pointed out a few years ago that reactor neutrino fluxes may have been under-estimated so that the measured reactor neutrino flux may have a deficit, indicating a possible reactor neutrino oscillation with sterile neutrinos[32]. Subsequently, a number of new calculations confirmed the calculation while some argued that the significance of the deficit is not sufficient[33]. Indications of the oscillation with sterile neutrinos are also claimed by other experiments but global fits show that they are not the "same oscillation"[34].

Clearly there is a need to have more experimental evidence. Proposals include short baseline(<10m) reactor experiments, accelerator experiments, and very strong radioactive source experiments[35].

6. Summary

After the discovery of the neutrino oscillation, we now finally know all the neutrino mixing angles. Thanks to the large θ_{13}, we can plan next generation experiments. In a few years from now, we will know all of the mixing angles and mass differences precisely. The unknown parameter, mass hierarchy, will be known in about 10 years, while the most important parameter, CP phase, will be probably known in about 10-20 years. This is an exciting field and exciting moment.

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