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Future of neutrino based reactor experiments

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The last angle of the PMNS mixing matrix has been measured by the neutrino reactor experiments. This important result opens the door to the precision era in the neutrino oscillation landscape. In this context, the next generation of reactor experiments at the kilo ton scale will significantly improve the measurements on the oscillation parameters and will give an answer on the mass hierarchy (MH) in the next decades. After a brief summary of the last results, these experiments will be presented with their technological challenges to reach the required sensitivity.

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1. Introduction

During numerous years, the best limit on the last mixing angle θ_{13} has been given by the neutrino reactor experiments, in particular by CHOOZ[1]. In 2012, three experiments based on multi detector sites, Daya Bay[2], RENO[3] and Double Chooz[4] have considerably improved the detection technique and measured this parameter. In the general framework of neutrino oscillation physics, the flavor states $\{\nu_\ell\}$ are related to the mass states $\{\nu_i\}$ thanks to the PMNS[1] mixing matrix which can be expressed by the product of matrices depending on the mixing angles θ_{ij}:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}.e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}.e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

with $c_{ij} = cos(\theta_{ij})$, $s_{ij} = sin(\theta_{ij})$ and δ_{CP} the CP phase. The oscillation probability between two flavor states ν_ℓ and $\nu_{\ell'}$ is given by:

$$P_{\nu_\ell \to \nu_{\ell'}} = \left| \sum_i U_{\ell i} U^*_{\ell' i}.e^{\frac{-m_i^2}{2E}.L} \right|^2 = \left| \sum_i U_{\ell i} U^*_{\ell' i} \right|^2 + 2Re \sum_i \sum_{i \neq j} U_{\ell i} U^*_{\ell' i} U^*_{\ell' j} U_{\ell j}.e^{\frac{|m_i^2 - m_j^2| L}{2E}}$$

where E is the neutrino energy, L the distance from the source. This transition probability also depends on the differences of the squared masses of the neutrino mass states $\Delta m^2_{ij} = |m_i^2 - m_j^2|$. In the three active neutrino scenario, two mass hierarchy configurations are possible: the Normal Hierarchy (NH) and the Inverted Hierarchy (IH) as shown in Figure 1 in which the mass states appear in normal or inverted ordering.

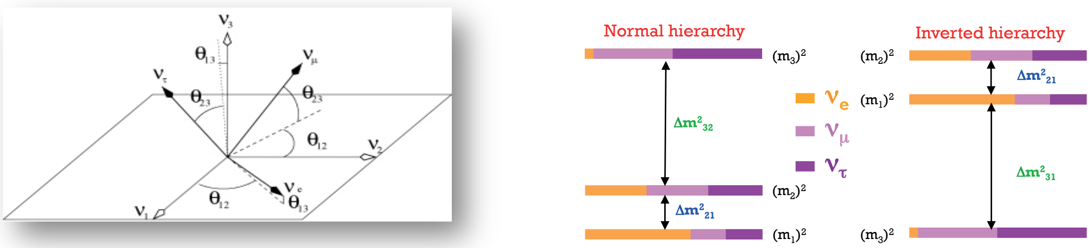


Figure 1: Geometrical interpretation of the mixing angle (left) Normal/Inverted mass hierarchy (right)

One of the next challenge in neutrino physics will be to determine the correct mass hierarchy scheme. Long baseline experiments with accelerator based beam and neutrino telescopes are able to address this question through matter induced effect on the oscillation probability. But a complementary approach consists to look precisely at the energy spectrum of the antineutrinos coming from nuclear reactor at a medium baseline [5, 6]. Taking into account the success on the recent reactor experiments, a new generation of detectors based on the same detection technique is proposed to answer this fundamental question.

[1] Pontecorvo-Maki-Nakagawa-Sakata

1.1 Mass hierarchy determination

The reactor experiments take benefit from the large amount of antineutrinos $\bar{\nu}_e$ flux emitted by the nuclear reactor cores of power plants. The mass hierarchy will be determined thanks to the precision measurements of their survival probability which can be expanded into the following equation:

$$
\begin{aligned}
P_{\bar{\nu}_e \to \bar{\nu}_e} &= 1 - sin^2\theta_{13}.(cos^2\theta_{12}.sin^2\Delta_{13} + sin^2\theta_{12}.sin^2\Delta_{32}) - cos^4\theta_{13}.sin^2\theta_{12}.sin^2\Delta_{21} \\
&= 1 - 2s_{13}^2c_{13}^2 - 4c_{13}^2s_{12}^2c_{12}^2sin^2\Delta_{21} + 2s_{13}^2c_{13}^2\sqrt{1 - 4s_{12}^2c_{12}^2sin^2\Delta_{21}}.cos(2\Delta_{32} \pm \phi)
\end{aligned}
$$

where $\Delta_{ij} = \frac{\Delta m_{ij}^2}{4E}$ and $\tan\phi = \frac{c_{21}^2.sin^2\Delta_{21}}{c_{21}^2.cos^2\Delta_{21} + s_{21}^2}$. In this expression, a phase ϕ appears in the probability. The sign is related to the mass hierarchy configurations and results in a shift on the oscillation as shown in Figure 2. The determination of the mass hierarchy will be done by measuring the oscillation pattern. However, the smallness of the shift will impose important constraints on the energy resolution of the detector which has been estimated at 3% for 1 MeV and under the reasonnable assumption that uncertainty on the oscillation parameters, especially on Δm_{23}^2 , will be improved by the current running experiments [7]. In this context, liquid scintillator based detectors appear to be good candidates to perform this measurement with a very good energy resolution. Nevertheless, the energy response requires to be well calibrated to understand non linearity effects (due to quenching effect, Cherenkov light, electronics...) and keep them under control at the subpercent level.

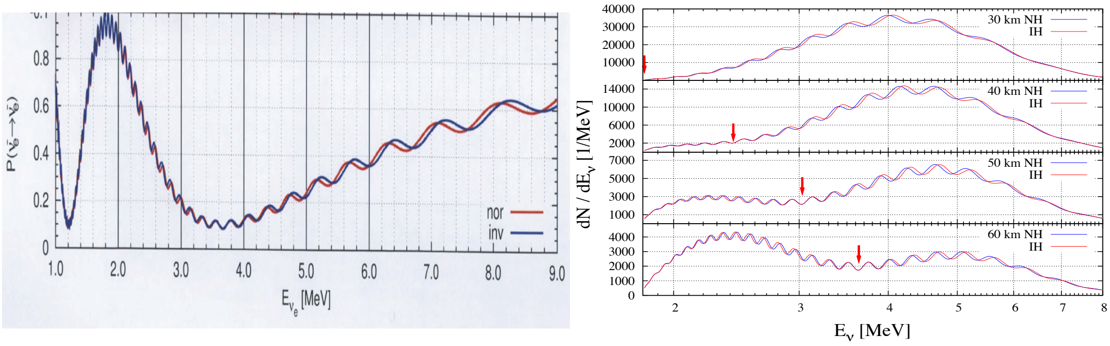


Figure 2: Phase shift induced by the normal/inverted hierarchy on the oscillation probability (left) Energy spectra for several detector baselines (right).

Among the simulated baselines, the most favorable baseline is defined as 60 km long defining the so called medium baseline. The sensitivity on the mass hierarchy determination requires large statistics with reduced systematic errors. A large research program based on liquid scintillator detectors at a kilo ton scale is under development [8].

2. Nuclear reactor experiments.

The detection principle of a reactor experiment is based on the Inverse β-decay process ($\bar{\nu}_e + p \longrightarrow e^+ + n$) produced by the $\bar{\nu}_e$ interaction in the neutrino target filled with liquid scintillator. It produces a clear signature consisting of a prompt signal coming from the positron annihilation and followed by a delayed one due to the neutron capture on hydrogen. The liquid scintillator can also be loaded with gadolinium element to enhance the neutron signature.

The detector is designed to provide an efficiency background reduction. The target is the central part of the inner detector, it is surrounded by a first region filled with unloaded liquid scintillaton (gamma catcher) collecting the light escaping the target, followed by a second one filled with mineral oil (buffer) allowing the shield against environmental radioactivity coming from materials such the photomulipliers located around the sensitive volume as shown in Figure 3. An important component of background is due to the cosmic muons and making correlated background, emitting fast neutrons produced by the muons in the surrounding rock and beta/neutron delayed signal coming from cosmogenic long lived nuclei (^{9}Li,^{8}He) produced by inelastic interaction on ^{12}C. Even if a large rock overburden is necessary to limit the cosmic rays flux at the detector level, an active shielding performed by a veto placed around the sensitive volume is required. This is an important point which has to be taken into account for the next generation of reactor experiments at a kilo ton scale.

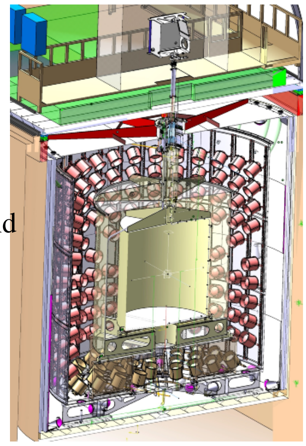


Figure 3: Internal view of a Double Chooz detector.

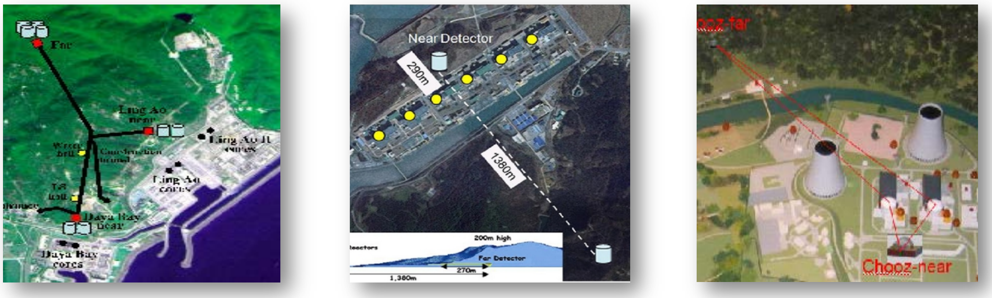


Figure 4: Nuclear reactor sites: Daya Baya (left), RENO (middle) and Double Chooz (right).

Three major experiments, Daya Bay, RENO and Double Chooz shown in Figure 4, are based on multi site detector techniques allowing to drastically reduced the systematic errors, and have successfully measured the last mixing angle θ_{13} as summarized in Figure 5.

Experiment	Thermal Power (GW_{th})	Baseline (m)	Overburden
Daya Bay	17.4	363 Daya Bay - (Near) / 1985 (Far) 481 Ling Ao I - (Near) / 1615 (Far) 526 Ling Ao II - (Near)	98/350 m 112/350 m 112 m
Reno	16.5	290 (Near) / 1380 (Far)	110 / 450 mwe
Double Chooz	8.5	400 (Near) / 1050 (Far)	120 / 300 mwe

Table 1: Nuclear reactor experiments configuration Near/Far detectors .

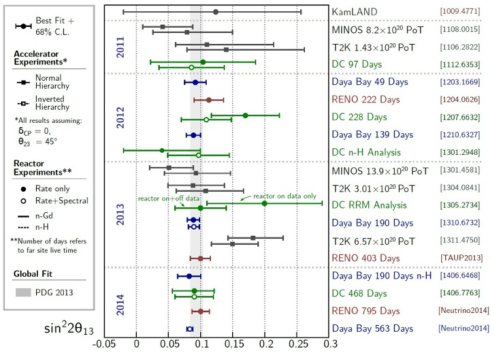


Figure 5: Summary on $sin^2(\theta_{13})$ reactor measurements.

The next steps on the analysis is to perform a combined analysis on θ_{13} to reach an unprecedent precision of its measurement.

3. Next generation of reactor experiments

The success of the nuclear reactor experiments have proven that the detection technique can be applied for mass hierarchy determination by requiring and unprecedent effort to scale the detector at a kt fiducial volume scale. In addition, to go further and to collect enough statistics to reach the required sensitivity, a large R&D program are required to develop a high efficiency photomultiplier coverage and good scintillator properties to keep the systematics under control. In this context, two experiments are proposed.

3.1 RENO-50

The Reactor Experiment for Neutrino Oscillation experiment shown in Figure 6. will be located at 50 km from the Hanbit nuclear power plant and will be placed in a underground laboratory with 450 m overburden at the Guemseong mountain in Korea. The detector consists of a 18 kton ultra low radioactivity liquid scintillator based detector.

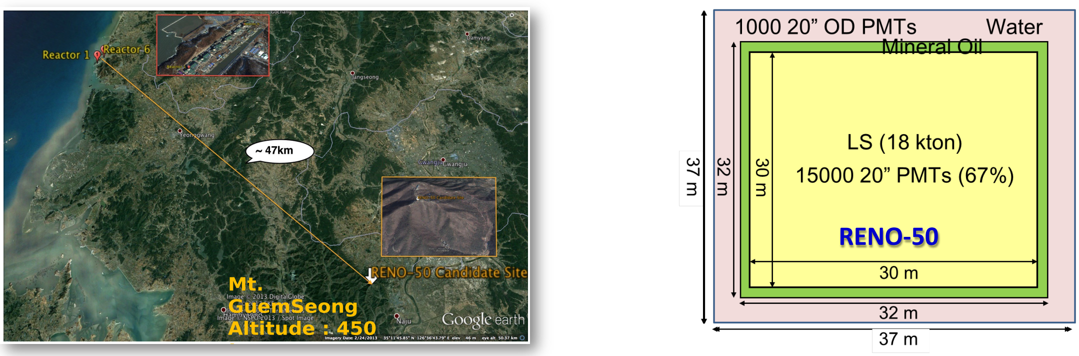


Figure 6: RENO 50 location (left) Detector design (right)

The scintillation light is read by 15000 photomultipliers (20") with an effective coverage of 67%. The detector will also have an outer detector filled with water and read by 1000 photomultipliers (20"). According to sensitivity studies, within the optimal detector working conditions (3% on energy resolution, good transparency,...) a significative answer on the mass hierarchy should by accessible within 10 year of running [9]. A proposal of the experiment has been submitted, if construction is approved the experiment could start by 2021.

3.2 JUNO

The Jiangmen Underground Neutrino Observatory (JUNO) is another kilo ton scale proposed experiment. The detector will be located 53 km far from two nuclear power plants Yangjiang and Taishan with 36 GW of thermal power as shown in Figure 7. The detector will be located down in a mine with 700 m overburden.

Figure 7: JUNO location (left) Detector design (right)

JUNO should be able to significantly improve the measurement of the oscillation parameters at the percent level as shown in Table 2. and hence allow for the unitarity tests of the PMNS mixing matrix.

	Current value	JUNO
Δm^2_{12}	4%	0.6%
Δm^2_{23}	5%	0.6%
$sin^2(\theta_{12})$	5%	0.7%
$sin^2(\theta_{23})$	10%	N/A
$sin^2(\theta_{13})$	6%	15%

Table 2: Evolution of the precision on the oscillation parameters.

The target consists in a 20 kt of liquid scintillator inside a huge water pool. The baseline option for the tank is the use of an acrylic material with 35 m of diameter supported by stainless steal (SS) structure. Another option is also under investigation with stainless steal tank with 38 m diameter with a balloon. The scintillation light will be read by 15000 photomultipliers (20″) with high quantum efficiency providing an high coverage (80%) of the sensitive volume. Other possibilities are under investigation by considering additionnal photomultipliers to improve photocathode coverage. A new type of high quantum efficiency photodetectors are under development using MCP as mutliplication stage and allowing a 4π collection efficiency[10]. Technical issues have been successfully resolved with $8''$ prototypes and allow to go further with $20''$ prototypes.The liquid scintillator is a key material of the detector and an important research and development program is on going to improve the quality to reach the required sensitivity on mass hierarchy shown in Figure 8.

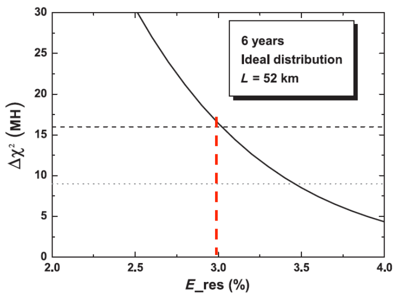
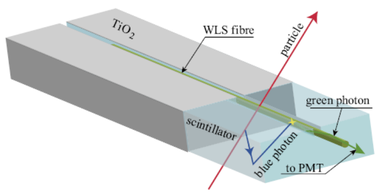


Figure 8: Energy resolution requirement.

The scintillator will be composed with Linear Alkali Benzene (LAB) mixed with PPO and bisMSB and should have a good transparency over several tens of meters covering the diameter of the sphere. An intrinsic single rate below 3 Hz (above 0.7 MeV) is expected under the assumption on the radiopurity is maintain below ^{40}K/U/Th <10^{-15} g/g. The medium will be no gadolinium loaded allowing also to prevent from additionnal radioimpurities and keep a high transparency of the medium. The purification will be maintained by a filtration system keeping a good quality, water extraction ...
The JUNO top tracker is a fundamental element of the experiment allowing to precisely characterize the cosmic muon flux crossing the detector.



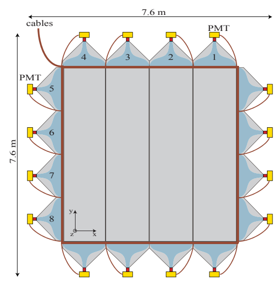


Figure 9: Plastic scintillator equipped with WLS optical fiber (left) Element of a the top tracker (right)

Several technologies have been envisaged like RPC's[11], liquid scintillator tubs...The baseline is to reuse the OPERA target tracker[12] whose the technology used is based on plastic scintillator. A tracker module consists of 64 strips equipped with optical WLS fibers[2] whose detection principle is illustrated in Figure 9 (left). On each side, the 64 fiber ends coming out of the strips are coupled

[2]Wave Length Shifting fibers

to the photocathode of a multianode photomultiplier thanks to an optical device. Each 64 channel multanode photomultipliers will be read with MAROC3 front end chips[13].

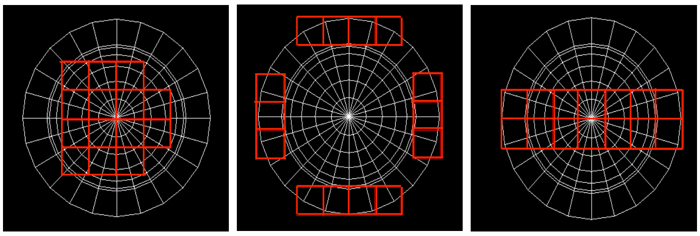


Figure 10: Possible configurations of the JUNO Top Tracker.

A Top Tracker (TT) element will be composed by four modules (4×64 scintillaror strips) in X direction versus by four others (4×64 scintillaror strips) in Y direction represented in Figure 9 (right). An active area of about 2783 m^2 can be covered with the 56 elements (6.7m$\times$6.7m each). However, the TT cannot cover the whole area of the detector, several configurations of the JUNO top tracker based on several layers are under inverstigation. Possible configurations based on four layers are shown in Figure 10. and can cover an area of about 630 m^2. JUNO is in the civil engineering phase and should be able to start taking data by 2020.

4. Summary and perspectives

These next generation of nuclear reactor experiments at kt scale will be able to probe the neutrino mass hierarchy and perform precision measurement on the oscillation parameter at the percent level opening the door to the PMNS unitarity test. It opens also the possibility to cover a wide research program including geoneutrinos, solar neutrinos, supernovae and astrophysics field searches.

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