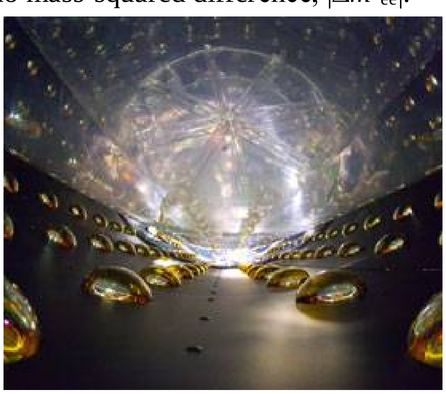
# Daya Bay Neutrino Experiment

The observation of neutrino oscillation in experiments involving solar, atmospheric, accelerator, and reactor neutrinos has demonstrated that the masses of neutrinos are nonzero, and neutrinos with different flavors can mix with each other to form the mass eigenstates. Neutrino oscillation has provided the only compelling evidence thus far for new physics beyond the standard model (SM). The smallness of the neutrino masses (< 2 eV) and the surprisingly large mixing angles ($\theta_{12} \approx 34^\circ$ and $\theta_{23} \approx 45^\circ$) have already provided intriguing clues for extensions to the SM. However, many outstanding questions on the properties of neutrinos remain to be answered. The large antineutrinos flux available at the nuclear power plants offers significant opportunities for addressing many important issues in neutrino physics, including the mixing parameters for neutrino oscillations, the neutrino mass hieracrchy, and the possible existence of sterile neutrinos.

Among the three mixing angles required for describing neutrino oscillation, the mixing angle $\theta_{13}$ was unknown as of 2011, and an upper bound of $\sin^2 2\theta_{13} < 0.17$ at 90% confidence level was determined from the Chooz reactor neutrino experiment. Besides determining the content of the electron neutrino in the third neutrino mass eigenstate, knowledge of the precise magnitude of $\theta_{13}$ was crucial for future study of CP violation in the neutrino sector. The Daya Bay, RENO, and Double Chooz, are the three reactor neutrino experiments designed for sensitive searchers for the smallest mixing angle in the neutrino sector, $\theta_{13.}$ The UIUC group has been a member of the Daya Bay experiment since its inception in 2006. The design goal of the Daya Bay experiment was to reach a sensitivity of 0.01 at 90% confidence level for $\sin^2\theta_{13}$. To achieve this high level of sensitivity, a total of eight identically designed 20-ton Gd-doped liquid scintillators antineutrino detectors are placed at three experimental halls to minimize systematic uncertainties originating from the reactor antineutrino flux and the detector efficiency.

The Daya Bay collaboration started taking data with six Antineutrino Detectors (ADs) in December 2011, and with all eight ADs in October 2012. Figure 1.a shows the top view of the interior of the AD and Figure 1.b shows two identical AD placed in a water pool acting as shield to various backgrounds. Daya Bay announced the discovery of the $\theta_{13}$ mixing angle in March 2012, having observed clear neutrino oscillation signals with a $5.1\sigma$ significance. This first physics result[1] from Daya Bay has attracted much attention and has been cited ~1000 times. Very recently, from the combined analysis of 621 days of 6AD plus 8AD data, the mixing angle and mass-squared difference are determined with high precision, i.e., $\sin^2 2\theta_{13} = 0.084 \pm 0.005$ and $|\Delta m^2_{ee}| = 2.44 \pm 0.11 \times 10^{-3}$ eV$^2$. This corresponds to the most precise measurements of $\theta_{13}$ and $|\Delta m^2_{ee}|$ to date, and the mixing angle $\theta_{13}$ is determined to be non-zero at a significance of ~17 $\sigma$. Figure 2 shows the electron antineutrino survival probability versus propagation distance $L$ over antineutrino energy $E_\nu$. An oscillating pattern with the amplitude of the oscillation ~$\sin^2 2\theta_{13}$ is clearly seen. The location of the oscillation minimum also allows a first determination of the electron antineutrino mass-squared difference, $|\Delta m^2_{ee}|$.



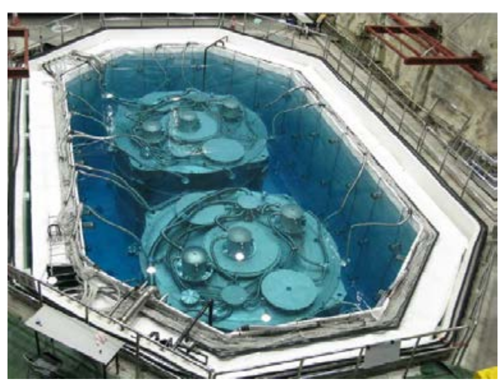


Figure 1: a) Top view of the interior of the Daya Bay Antineutrino Detector. b) View of one of the three Daya Bay experimental hall after the two ADs were installed in the water pool.

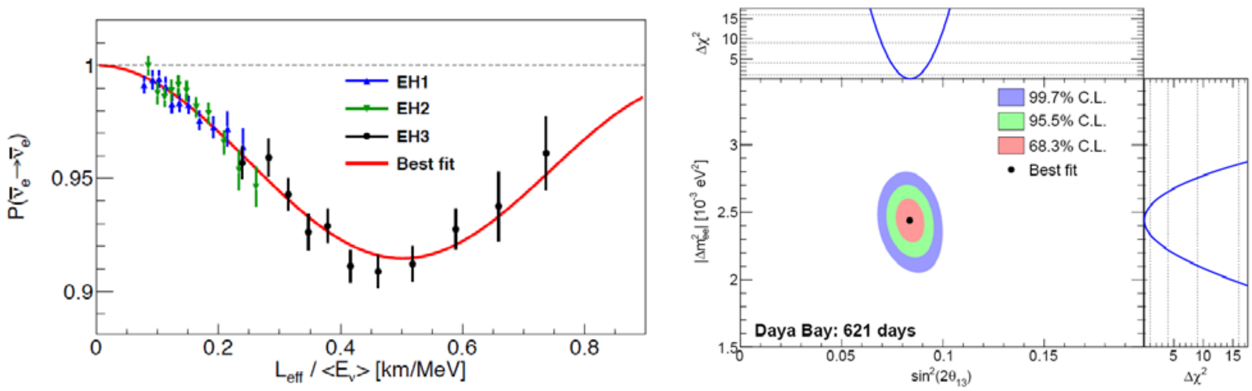



Figure 2: a) The electron antineutrino survival probability vs. propagation distance *L* over antineutrino energy $E_\nu$. b) Best-fit values of $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$ from Daya Bay.

The precise measurement of $\theta_{13}$ from the reactor experiments has major implications on the future search for CP violation in the lepton sector. First, the magnitude of CP violation is proportional to $\sin\theta_{13}$, and the non-zero value of $\theta_{13}$ would allow CP violation to be observed (provided that the CP phase is non-zero). Second, the precise value of $\theta_{13}$ determined from the reactor experiments is needed for extracting the CP-violation phase in the long-baseline $\nu_\mu \to \nu_e$ appearance experiment. Indeed, the $\nu_\mu \to \nu_e$ result from the T2K experiment combined with latest Daya Bay result on $\theta_{13}$ already indicates a preference of non-zero CP phase. The prospect for observing CP violation in future long baseline neutrino experiments is quite promising.

While precise measurement of the width of *Z* boson has limited the number of light active neutrino flavors to three, there is still room for other types of neutrinos which do not participate in the standard left-handed V-A interaction. These neutrinos, referred as the "sterile" neutrinos, often arise in extensions of the SM that incorporate neutrino masses. They are also among the leading candidates for resolving some puzzles in astronomy and cosmology. If sterile neutrinos mix with the active neutrinos, their existence can then be detected through the deviation of the neutrino oscillation pattern from that expected for three active neutrinos alone. Although tentative evidences for sterile neutrinos with $|\Delta m^2| > 0.1$ eV$^2$ have been reported in $\nu_\mu \to \nu_e$ appearance experiment, they are in tension with the limits derived from disappearance experiments. Jiajie Ling, an UIUC postdoc, led the effort to search for evidence of a light sterile neutrino using the 6AD Daya Bay data. With multiple detectors deployed at three different baselines collecting a large number of antineutrino events, the Daya Bay experiment offers a unique opportunity to search for sterile neutrino in the mass range of $10^{-3}$ eV$^2 < |\Delta m^2_{41}| < 0.3$ eV$^2$, which was largely unexplored until now. The presence of the sterile neutrino could be detected through the deviation of the measured antineutrino energy spectra from those expected from the mixing of three active neutrinos. Stringent limits on the mixing angle $\theta_{14}$ and $|\Delta m^2_{41}|$ have been obtained. Figure 3 shows the exclusion contour for the neutrino oscillation parameters $\sin^2 2\theta_{14}$ and $|\Delta m^2_{41}|$. Ling is the corresponding author of a recent PRL[2] paper, which was selected as the ``Editor's Suggestion". Even better sensitivity is expected with a combined analysis of the 6 and 8 AD data.

The Daya Bay experiment will continue to take data until at least the end of 2017. Many other physics topics are currently being studied based on the large amount of data collected so far.

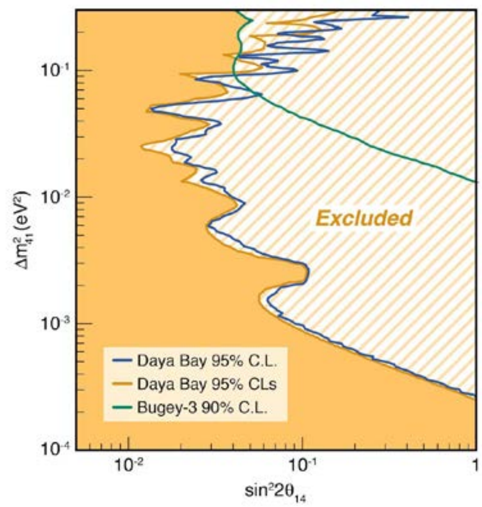



Figure 3: The exclusion contours for sterile neutrino oscillation parameters $\sin^2 2\theta_{14}$ and $|\Delta m^2_{41}|$ from Daya Bay.

[1] F. P. An et al., Daya Bay Collaboration, ``Observation of electron-antineutrino disappearance at Daya Bay", Phys. Rev. Lett. 108, 171803 (2012).

[2] F. P. An et al., Daya Bay Collaboration, ``Search for a Light Sterile Neutrino at Daya Bay", Phys. Rev. Lett. 113, 141802 (2014).