A step forward in understanding the universe: The latest results from the Daya Bay experiment

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Why is the current universe dominated by matter when there should have been equal amounts of matter and anti-matter at the beginning? One of the keys to answering this question is to find out a currently undiscovered charge-parity (CP) violation in the lepton sector. The CP violation can be tested through studies of the phenomenon called neutrino oscillation. Neutrino oscillation occurs because the weak eigenstates, $|\nu_i\rangle (i = \text{e, } \mu, \tau)$, and mass eigenstates, $|\nu_i\rangle (i = 1, 2, 3)$, are mixed, as follows:

$$|\nu_i\rangle = \sum_i (U_{PMNS})_{ij} |\nu_j\rangle,$$

where $U_{PMNS}$ is the $3 \times 3$ Pontecorvo-Maki-Nakagawa-Sakata mixing matrix, which is defined with three mixing angles, $\theta_{12}, \theta_{23},$ and $\theta_{13}$, and one complex Dirac CP phase, $\delta_{\text{CP}}$. The weak eigenstates define how neutrinos interact through the weak interactions, while their time development is defined by the mass eigenstates. Because the weak eigenstates are described as superpositions of three different mass eigenstates, flavors of neutrino (i.e., the weak eigenstates) can “oscillate” while a neutrino is traveling.

The Daya Bay experiment was designed to discover the value of $\theta_{13}$, which was the only mixing angle left unknown until 2012, by observing the disappearance of electron antineutrinos produced by nuclear reactors with a ~1 km baseline. The disappearance probability can be approximately written as

$$P(\bar{\nu}_\text{e} \rightarrow \bar{\nu}_\text{e}) = 1 - \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta m^2_{32} L}{4E}\right),$$

where $\Delta m^2_{32} = m^2_3 - m^2_2$ is the squared mass difference between the third and the second mass eigenstates, $L$ is the traveled distance, and $E$ is the energy of neutrinos. The experiment consists of eight functionally identical antineutrino detectors deployed at three underground experimental halls near the Daya Bay nuclear reactor complex in southern China. These detectors precisely measured the flux of reactor antineutrinos and discovered the non-zero value of $\theta_{13}$ by a significance of more than 5σ in 2012. Since then, the Daya Bay experiment has been leading precision measurements of reactor antineutrinos with by far the largest dataset and continuous efforts to reduce systematic uncertainties.

At the Neutrino 2022 conference, the Daya Bay reactor antineutrino experiment presented its latest results for measuring the neutrino mixing angle $\theta_{13}$ and the absolute value of the mass squared difference $|\Delta m^2_{32}|$ using all the data collected from 2011 to 2020. The precision of $\sin^2 2\theta_{13}$ now reaches 2.8%, as shown in Figure 1, and that of $|\Delta m^2_{32}|$ is 2.3%, both of which are at the world’s best

Figure 1. Schematic picture for Daya Bay reactor antineutrino experiment. The inset shows the latest results of $\sin^2 2\theta_{13}$ in comparison with other experiments. The error bars indicate statistical and systematic uncertainties.
precision. Furthermore, given that there are currently no planned projects to measure \( \theta_{13} \) at a similar or improved precision, this value of \( \sin^2 2\theta_{13} \) by the Daya Bay experiment will be the “standard” in the foreseeable future. This is an extraordinary achievement from decades-long efforts by the collaboration.

This precision was achieved not just by accumulating a large set of data, but also by continuously improving detector calibration and background identifications. Calibrating the response of this large-scale detector at a sub-percent level is not an easy job at all. The Daya Bay collaboration precisely characterized the response of its detectors using a wide variety of calibration data, including data with deployed radioactive sources, natural radio activities, and dedicated measurements of electronics responses. This led to unprecedented 0.5% uncertainty on the absolute energy scale and 0.2% uncertainty on the relative energy scale. Benefitting from the high-statistics data, Daya Bay also improved the measurements of the background processes and identified rare backgrounds that were not accounted for before. All these components were indispensable for their latest results.

The Daya Bay experiment also made important measurements of the absolute flux of reactor antineutrinos. From the detailed analysis of the time evolution of the antineutrino flux and by the joint analysis with the PROSPECT collaboration, they found that the flux due to the fission products of \(^{239}\text{Pu}\) is in reasonable agreement with the conventionally used model, while a significant tension for the flux is due to the fission products of \(^{235}\text{U}\).\(^3\)\(^4\) This result is now posing a doubt on the sterile neutrino hypothesis as a solution to the so-called reactor antineutrino anomaly. In addition, Daya Bay found the first evidence of reactor antineutrinos at above 10 MeV.\(^2\) This high-energy component of the reactor antineutrinos flux is of interest for future searches for diffuse supernova neutrino backgrounds (DSNB), as they are one of the most significant backgrounds for the DSNB.

I was fortunate to have the opportunity to join some of the past measurements at Daya Bay while I was a Chamberlain Fellow at Lawrence Berkeley National Laboratory from 2011 until 2016. I am proud of the results we produced at Daya Bay, not just because of their significance but also because of the process of extracting physics results through the efforts of carefully examining the data with many wonderful collaborators. Since the beginning of the analyses, we had multiple groups performing the analyses independently for nearly all the components. These efforts, sometimes viewed as redundant, provided us important benefits of cross-checking one another, understanding the advantages and limitations of each method, and eventually producing improved results. I also liked our spirit of carefully evaluating the data from all the possible aspects to make the most out of it. From the results presented at Neutrino 2022, I see that the culture and spirit of the collaboration that I enjoyed are still lively present to this date. I sincerely congratulate the Daya Bay collaboration for these monumental results.

Among three mixing angles in the \(\text{UPMNS} \) matrix, \(\theta_{13} \) is now the most precisely measured one. This precise value of \(\theta_{13} \) is a key ingredient for searching for CP violation by the long-baseline neutrino oscillation experiments, such as currently running T2K and NOvA experiments, as well as future projects such as Hyper-Kamiokande and DUNE experiments. It is also an important stepping stone for further precision measurements of reactor antineutrinos at the JUNO experiment. Results of the Daya Bay will remain in history, as the standard of the value of \(\theta_{13} \), and also as a standard of how precision measurements should be made.

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DECLARATION OF INTERESTS
The authors declare no competing interests.