Neutrinos and the hunt for the last mixing angle

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Neutrinos are the Universe's second most common particles after the photons. During their journey through space-time, the elusive neutrinos can change types. Now, researchers at the Daya Bay experiment in China have determined the coveted final mixing angle for this phenomenon, known as neutrino oscillations.

▲ Picture of one of six detectors in the Daya Bay reactor neutrino experiment. The detector captures faint flashes of light that indicate antineutrino interactions. It consists of lines with photomultiplier tubes, and is filled with scintillator fluids. (Photo by Roy Kaltschmidt, Berkeley Lab Public Affairs)

A neutrino is an elementary particle that belongs to the same family of particles as, for example, the electron. These particles are called leptons, and consist of electrons, muons, taus as well as the three associated neutrinos, which below will also be called the three flavor states. There is even speculation that there could exist so-called "sterile neutrinos", but I will not consider such hypothetical particles in this article.

Neutrinos are electrically uncharged, interact only via the weak interaction, and have very small masses; hence they are extremely difficult to detect. Neutrinos are produced e.g. in the soil, in the atmosphere, in the Sun, in supernovae, and in reactions at accelerators and reactors. Among other things, neutrinos are important for the processes that allow the Sun to shine. Although neutrinos are, indeed, very elusive, one has been successful in detecting them (Fig. 1).

Massive and mixed neutrinos

Until June 1998, it was believed that neutrinos were massless, but the results from measurements of atmospheric neutrinos with the Super-Kamiokande experiment in Japan showed that they are most likely massive and mixed (see below for a description of what "mixed" or "mixing" means), which in turn means that oscillations among the different neutrino flavors may occur [1]. The fact that neutrinos are massive and mixed further means that the physical model describing elementary particle physics (the so-called Standard Model) must be modified to include massive and mixed neutrinos. The masses of neutrinos and their mixing angles as well as their ability to oscillate implies that we have evidence for physics beyond the Standard Model.

Neutrino oscillations

The phenomenon of neutrino oscillations arises as a sort of "beats" between the various flavor states, like the beats between two adjacent tones in music. However, this is a genuine quantum mechanical interference phenomenon, which means that the three types of neutrinos oscillate among the three flavor states as they travel through

space-time. Mathematically, one can express it so that the three flavor eigenstates are mixings of the three mass eigenstates, where each flavor state is made up of parts of all mass states, and vice versa. This mixture of neutrinos can generally be parameterized by three so-called 'mixing angles' and three so-called 'CP-violating phases', whose importance will be discussed below. Note that CP-violation means 'broken' CP-symmetry, which is a combination of C-symmetry (charge conjugation symmetry) and P-symmetry (parity symmetry) and states that the laws of physics should be the same if particles and their antiparticles are interchanged (C-symmetry) and left and right are replaced with each other (P-symmetry).

Leptonic mixing parameters

In a simple extended version of the Standard Model, the masses of the three neutrinos and the leptonic mixing parameters (*i.e.*, the three mixing angles and the three CP-violating phases) should be added to the already 19 existing parameters contained in the Standard Model. In what follows, I will only discuss the three mixing angles, often referred to as θ_{12} , θ_{13} , and θ_{23} , where θ_{ij} is a measure on the relative mixing between mass states i and j in the different flavor states. Historically, the three mixing angles θ_{12} , θ_{13} , and θ_{23} , were called the solar mixing angle, the reactor mixing angle, and the atmospheric mixing angle, respectively, but these names are somewhat misleading, as we will see below.

Using the results from the Super-Kamiokande experiment, but also measurements on accelerator neutrinos, one can determine an almost certain value of the mixing angle $\theta_{23} = 45^\circ$ [2], which means that the mass states 2 and 3 are maximally mixed. Furthermore, one can use data from solar and reactor neutrinos to determine a relatively certain value of the mixing angle $\theta_{12} \approx 34^\circ$ [3], saying it is large, but not maximal as is the case for θ_{23} . Until very recently, there has been only an upper limit on the third mixing angle θ_{13} . This upper limit, which restricts θ_{13} to a maximum

◀ **FIG 1:** The Sun in "neutrino light". The Sun as seen by the Super-Kamiokande detector, which is located in an old gold mine a few kilometers below the surface of the Earth. Sun light will never reach the detector, but solar neutrinos will. [Astronomy Picture of the Day (June 5, 1998), NASA. Credit: R. Svoboda and K. Gordan (LSU)]

▲ FIGS 2, 3, AND 4: Pictures of the Daya Bay, Double Chooz, and RENO detectors. (Credits: Daya Bay, Double Chooz, and RENO Collaborations)

of about nine degrees, was a result from the CHOOZ experiment in France in the late 1990's and was featured in a final article by the CHOOZ Collaboration in 2003 [4]. Thus, one has determined two large mixing angles θ_{12} and θ_{23} and one small mixing angle θ_{13} for the neutrinos. These results differ considerably from the values of the corresponding mixing angles in the so-called quark sector, which says that all mixing angles in that sector are small.

The hunt for the third and last mixing angle

The urge to know the values of the parameters of the Standard Model in general and the mixing angles for the neutrinos in particular has spurred particle physicists to also measure and determine a value of the third mixing angle θ_{13} . A non-zero value for θ_{13} would open up a window to eventually be able to measure the above-mentioned CP-violating phases, which provide information about the existing matter-antimatter asymmetry in the Universe.

In the search of θ_{13} , global fits to all available neutrino data to indirectly determine the mixing angles belong to the efforts [5]. Of course, one has also examined various theoretical models that predict values for these mixing angles. Many models lead to so-called tribimaximal ($\theta_{12} \approx 35.3^\circ$ and $\theta_{23} = 45^\circ$) or bimaximal ($\theta_{12} = 45^\circ$ and $\theta_{23} =$

45°) mixing, but both mixing patterns provide $\theta_{13} = 0$. Therefore, one has also discussed models that predict so-called bilarge mixing, which means large, but not necessarily maximal values for θ_{12} and θ_{23} and no restriction on θ_{13} . Examples

of such models are also found in the literature [6].

The hunt for θ_{13} has mainly been taken up by three neutrino experiments: the Daya Bay experiment in China, the Double Chooz experiment in France at the Franco-Belgian border (which is the successor to the CHOOZ experiment), and the RENO experiment in South Korea (see Figs 2, 3, and 4, respectively). All three are reactor neutrino experiments, which examine electron antineutrinos from nuclear power plants to directly determine the value of θ_{13} .

For example, the Daya Bay experiment consists of six reactors and six antineutrino detectors at distances of 0.5 to 1.5 kilometers from the reactors.

It should be noted that in early 2011 two experiments, the T2K experiment in Japan and the MINOS experiment in the United States, found results which indicated that the hypothesis that θ_{13} equals zero is not true. At last, in November 2011, the Double Chooz experiment came with its first result: the value of the third mixing angle is probably just in between eight and nine degrees [7]. However, it was a result of great uncertainty, since it was not possible to exclude that the result was a statistical fluctuation. So, in March 2012, the Daya Bay experiment presented its initial findings in an article [8]. With good statistical significance, they measured $\sin^2(2\theta_{13}) = 0.092 \pm 0.017$ (see Fig. 5), which gives $\theta_{13} \approx 8.8^\circ$, *i.e.*, just below the upper limit originally determined by the CHOOZ experiment. Thus, the Daya Bay experiment has won the hunt for the third mixing angle! A month after the Daya Bay experiment, also the RENO experiment came with its first result (with even better statistical significance than the Daya Bay experiment), $\theta_{13} \approx 9.8^\circ$ [9], which is slightly larger than the value of the Daya Bay experiment. There are now three independent measurements from three different experiments, Daya Bay, Double Chooz, and RENO, which all indicate that the value of the third mixing angle is about nine degrees. Thus, the value of θ_{13} is distinct from zero, but small. Therefore, both the tribimaximal and bimaximal mixing patterns are ruled out by data. At the "Neutrino 2012" conference in Kyoto, Japan, three experiments reported on updated best-fit values: $\theta_{13} \approx 8.7^\circ$ (Daya Bay), $\theta_{13} \approx 9.4^\circ$ (T2K), and $\theta_{13} \approx 9.6^\circ$ (Double Chooz).

The CP-violating phase and the matter-antimatter asymmetry in the Universe

One of the three CP-violating phases, the so-called Dirac CP-violating phase δ , can be measured using neutrino oscillation experiments. This phase appears only in combination with the third mixing angle in the leptonic mixing matrix as $\sin(\theta_{13}) \exp(\pm i\delta)$. Thus, a non-zero value of θ_{13} means that it is, in principle, possible to determine δ . As a matter of fact, accelerator-based neutrino oscillation experiments will provide the most promising

This could have implications for the matter-antimatter asymmetry in the Universe. ▶▶

opportunity to observe CP violation [10]. In order to measure CP violation, such experiments will study both neutrino and antineutrino oscillations. If antineutrinos do not oscillate in the same way as neutrinos do, then this is a signal of CP violation, and in turn, this could have implications for the matter-antimatter asymmetry in the Universe. For example, note that the lepton asymmetry in the mechanism known as leptogenesis [11] depends on the Dirac CP-violating phase [12]. Especially, the oscillation channels between electron and muon neutrinos (or antineutrinos) are best suited to study CP violation, since it is easier to create and detect such neutrinos compared to tau neutrinos. In fact, two neutrino oscillation experiments, the NOvA experiment [13] between Fermilab and Ash River, Minnesota, USA and the NuMI experiment [14] between Fermilab and the Soudan mine, Minnesota, USA, will search for muon neutrino-electron neutrino oscillations as well as muon antineutrino-electron antineutrino oscillations to measure CP violation in the neutrino sector. In addition, the NOvA experiment may be able to provide a measurement of the neutrino mass hierarchy – another important neutrino parameter. For the future, there exist proposals for the Long-Baseline Neutrino Experiment (LBNE) [15], which aims to find out if neutrinos are the reason why we exist (since their interactions could explain why matter is more abundant than antimatter), and a so-called Neutrino Factory that will be the ultimate producer of precision neutrino data.

Summary

In summary, the measurement of θ_{23} by the Super-Kamiokande experiment resulted in one of the first indications of physics beyond Standard Model, the measurement of θ_{12} was the first precision measurement in neutrino physics, and the hunt for the value of the third and final mixing angle θ_{13} was the beginning of the end of the measurements of the mixing angles for the neutrinos, but the beginning of the continuation of measurements of the remaining neutrino parameters. ■

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Picture taken by Mats Wallin.

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▼ FIG 5: The ratio of measured and predicted no-oscillation spectra. The red curve is the best-fit solution with $\sin^2(2\theta_{13}) = 0.092$ obtained from the rate-only analysis. The dashed line is the no-oscillation prediction. This figure has been adapted from Ref. [8].