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Why Daya Bay?
In Search of Theta One Three

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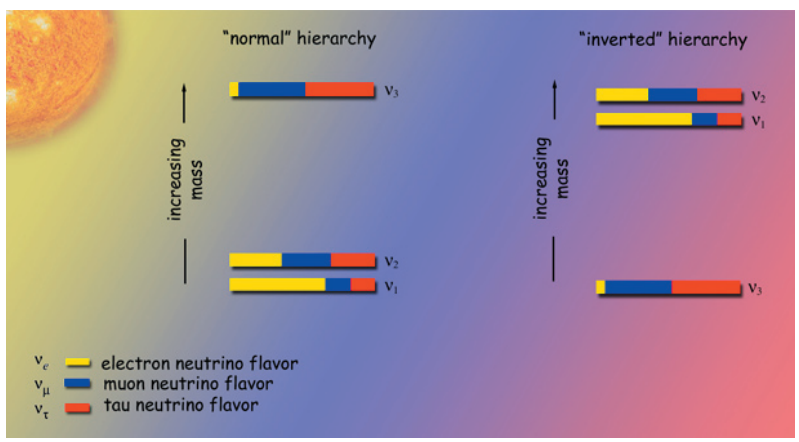
Neutrinos have mass—but only a little, and nobody knows exactly how much. Of the three flavors of neutrino (electron neutrino, muon neutrino, tau neutrino), the heaviest has at least one 10-millionth the electron's mass and could have more than 10 times that much. Which flavor is the heaviest? That too is uncertain.

The hunt for neutrino mass

Neutrinos interact with other particles only through the weak force and gravity, which means hardly at all. Why is knowing their mass important?

For one thing, mass allows neutrinos to change flavors, or oscillate. Neutrino oscillation solved the longstanding mystery of why 1960s experiments designed to count solar neutrinos found only a third of the number expected to be detectable as products of nuclear fusion in the sun. On their way to Earth, electron neutrinos change flavors, many arriving as elusive muon or tau neutrinos.

Neutrinos oscillate at a steady rate because the characteristic masses (mass eigenstates) of each type don't sync up with their characteristic flavors. Every neutrino detected is a mixture of three characteristic masses that continually interfere with one another like different radio frequencies, rhythmically changing their proportions. The probability of finding a given type of neutrino at a certain distance from where it was created depends on values called mixing angles, which express the proportion of mass states 1, 2, and 3 in each kind of neutrino detected.



Neutrinos come in three flavors, but detectors see mixtures of the flavors' characteristic masses. Differences among the three mixed states have been measured, but the masses themselves are unknown. Does the biggest difference mark the heaviest mixed state (the so-called normal hierarchy) or the lightest one (an inverted hierarchy)?

Two of the three mixing angles, θ12 and θ23, have been measured with enough precision to estimate the differences among neutrino masses: there's a modest difference between neutrino 1 (presumably mostly electron flavor) and the slightly heavier neutrino 2 (with a larger proportion of muon flavor), and a much greater difference between these and neutrino 3 (probably mostly tau flavor). But the masses themselves are unknown; even their hierarchy is unknown. Neutrino 3 is very different from the others in mass, but is it the heaviest of them all or the lightest?

Mixing angle θ13 will reveal how much electron flavor is in neutrino 3. Eventually this will help determine whether tau is the heaviest flavor or the lightest, and the actual masses of the other neutrinos as well.

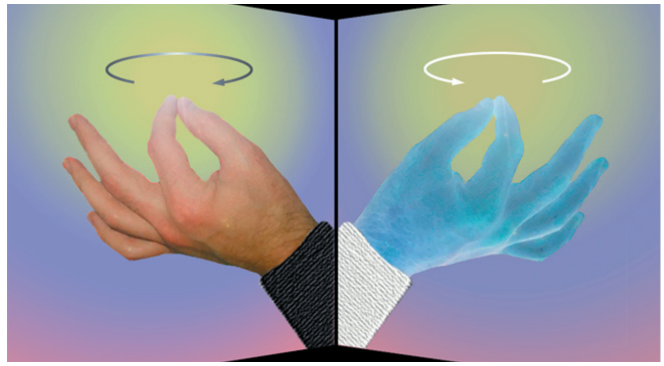
Knowing θ13 will shed light upon several other outstanding puzzles, including that of CP violation.In some way not yet wholly understood, CP violation is responsible for why there is so much matter in the universe and so little antimatter. And a good thing too: if matter and antimatter had been created equally, they would have annihilated each other, and the universe would be empty.

C stands for charge conjugation symmetry—more generally, changing particles into antiparticles and vice versa. Neutrinos "maximally violate" C, because instead of an equal number of left- and right-handed neutrinos and antineutrinos, all neutrinos are left-handed; all antineutrinos are right-handed.

P stands for parity symmetry ("left-right" symmetry), meaning that physical processes should work equally well if the only difference between two particles is their orientation. Neutrinos also maximally violate P.

When C and P are taken together, however, everything seems to come out all right. CP turns a left-handed neutrino into a right-handed antineutrino and a right-handed antineutrino back into a left-handed neutrino.

But do both processes happen with the same probability? The answer affects how matter and antimatter are related, how neutrinos oscillate, and how a great many other fundamental processes proceed.



Both C and P are maximally violated by neutrinos, but taken together, as in the "CP mirror" at right, CP invariance explains the existence of only left-handed neutrinos and only right-handed antineutrinos. Yet are neutrinos really CP invariant?

"Determining neutrino mass will have profound implications for astrophysics and cosmology," says Kam-Biu Luk of Berkeley Lab's Physics Division, a leader in neutrino studies who is also a professor of physics at UC Berkeley.

Digging an Experiment

The first step requires determining the value of θ13. To pin it down with high precision, Luk and colleagues in China, the U.S., and other countries are planning to make use of the powerful nuclear reactors at China's Daya Bay. The project will require three kilometers of tunnels drilled under granite mountains hundreds of meters high; in chambers shielded from cosmic rays by the overlying rock the researchers will install eight identical antineutrino detectors, each weighing 100 metric tons, which can be rolled from location to location inside the tunnel system.

Neutrinos oscillate with a certain frequency, which translates into measurable flight paths characteristic of each mixing angle. At Daya Bay, two detectors in each of two nearby locations will measure the flux and energy of the electron antineutrinos emerging from the reactors. Because of θ13 oscillation, some proportion of these will "disappear" about two kilometers away from where they are created—much as electron neutrinos created in the sun disappear on their way to Earth. The experiment's far detectors, four in all, will be positioned at this distance. The near and far detectors will be exchanged on a regular basis to cancel any systematic detector errors.

By knowing how many electron antineutrinos are produced in the reactors—on the order of a million quadrillion every second! —and the number expected to arrive at each detector—about a thousand per day at the nearby sites, a hundred a day at the far sites—and then comparing how many events are actually detected, θ13 can be determined to the highest precision ever.

"Essentially we measure the difference in flux at two points," says Luk. "Basically it comes down to how many antineutrinos disappear."

Scores of U.S. and Chinese personnel have joined with colleagues in Russia, Taiwan, and the Czech Republic in the Daya Bay experiment, whose scientific spokespersons are Berkeley Lab's Luk and Yi-Fang Wang of the Institute of High Energy Physics in Beijing. The Chinese Academy of Sciences has led the way in committing funds to the project, and the U.S. Department of Energy is sponsoring U.S. research and development.

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