Accelerator experiments are closing in on neutrino *CP* violation

It's starting to look like neutrinos and antineutrinos aren't exact mirror images of each other.

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FIGURE 1. WHERE NEUTRINOS ARE MADE. As charged pions created at the J-PARC accelerator in Japan fly through this 96-m-long tunnel, they decay into muons and muon neutrinos. The wall at the end, 5 m tall by 3 m wide, stops the muons and any undecayed pions. The neutrinos, which have no problem traveling through solid metal and rock, keep going toward the detector 295 km away.

Somewhere in the laws of physics, particles must be allowed to behave differently from their antiparticles. If they weren't, the universe would contain equal amounts of matter and antimatter, all the particles and antiparticles would promptly annihilate one another, and none of us would exist.

Violations of *CP* symmetry—the combination of charge conjugation and parity inversion that projects particles onto their antiparticles' mirror images—have already been observed and theoretically accounted for in several flavors of quarks. (See PHYSICS TODAY, August 2019, page 14.) But the extent of that violation is nowhere near enough to explain the imbalance of matter and antimatter in the universe. To make up the shortfall, researchers are looking for an additional source of *CP* violation among the particles of the lepton sector: electrons, muons, taus, all their antiparticles, and their associated neutrinos and antineutrinos.

Unlike most other known particles, neutrinos spontaneously change their identities as they travel. (See PHYSICS TODAY, December 2015, page 16.) A muon neutrino created in one place, for example, might later be detected as an electron neutrino in another. The dynamics of that flavor oscillation can be characterized by three mixing angles—θ_{12}, θ_{23}, and θ_{13}—plus a phase δ_{CP} that captures the amount of *CP* violation, if any. A value of 0 or $\pm\pi$ radians for δ_{CP} means that neutrinos and antineutrinos oscillate identically and *CP* symmetry is conserved; any other value means that the symmetry is broken.

Theory leaves the values of all four of those parameters wide open. And they're extremely difficult to measure experimentally, because neutrino oscillations are extremely difficult to detect. The three mixing angles have been measured to within a few degrees. But the value of δ_{CP} has remained almost entirely unknown.

Now the Tokai-to-Kamioka (T2K) experiment is homing in on δ_{CP}. By smashing protons into a graphite target at the J-PARC accelerator in Tokai on Japan's east coast, the researchers create a powerful, steady beam of either muon neutrinos or muon antineutrinos. At the Super-Kamiokande detector, 295 km to the west, they measure how many of those particles have changed flavor. By comparing the results from neutrino and antineutrino beams, they can estimate δ_{CP}.

After 10 years of data collection—interrupted, unfortunately, by the Tohoku earthquake and tsunami that devastated Japan in 2011 and by an accident on another beamline at J-PARC in 2013—the T2K data suggest that muon neutrinos transform into electron neutrinos more readily than muon antineutrinos transform into electron antineutrinos.[1] It's not yet the end of the story: Whereas some values of δ_{CP} are excluded at a confidence level of three standard deviations (3σ), perfect *CP* symmetry is disfavored only with 2σ confidence. A conclusive answer, by convention, requires 5σ confidence.

But the result suggests that experimental searches for lepton *CP* violation are probably on the right track and could reach that threshold in the coming years as data collection continues and new facilities come on line.

The matter of matter

Neutrinos don't often make their presence felt. Apart from the rare weak interaction, they stream—unseen and untouched—through space, through solid rock, and through the densest plasma of the Sun. Odds are good that none of the atoms in your body will ever interact with a neutrino during your lifetime. How can such an aloof bunch of particles have anything to do with the existence of all the matter in the universe?

A speculative answer lies in the neutrino masses. (See the Quick Study by Rabi Mohapatra, Physics Today, April 2010, page 68, and the article by Helen Quinn, Physics Today, February 2003, page 30.) Each neutrino flavor state is a quantum superposition of the same three mass states, which beat in and out of phase with one another and result in flavor oscillations. The masses' exact values are unknown, but they seem to be on the order of millielectron volts. Neutrinos are thus the outliers among massive fundamental particles, the rest of whose masses are best measured in megaelectron volts or gigaelectron volts.

Some theories postulate that whatever mechanism gives neutrinos their anomalously small masses also creates another set of particles with anomalously large ones. The hypothetical particles would be too massive ever to be seen today, even in the most powerful of particle accelerators, but they could have been abundant in the energetic environment of the early universe. If they existed, and if their decays into other particles violate *CP* symmetry, they could be responsible for the present-day matter–antimatter imbalance. And if ordinary neutrinos and their ultraheavy counterparts behave the same way with respect to *CP* symmetry, then studying neutrinos could open a window onto the dynamics of the early universe.

That's a lot of ifs, and not all theoretical models accommodate that line of reasoning. But for those that do, looking for neutrino *CP* violation is a place to start.

Neutrino beam

Much of what we know about neutrinos comes from experiments that monitor the neutrinos coming from nuclear reactors. (See, for example, Physics Today, May 2012, page 13.) When the unstable fission fragments made in a nuclear reaction undergo beta decay, they spew out multitudes of electron antineutrinos in all directions. Accelerator experiments offer an additional degree of control: the ability to create an intense beam of neutrinos that all travel in approximately the same direction.

Neutrino creation at J-PARC is efficient. The accelerator protons colliding with the graphite target create a multitude of charged pions, almost all of which decay into muons and muon neutrinos as they pass through the tunnel shown in figure 1. The pions and muons propagate through the free space of the tunnel but are stopped by the solid wall at the end, leaving only the neutrinos to continue the trip west to Super-Kamiokande. A 40-m-tall water tank lined with photomultiplier tubes, Super-Kamiokande is one of the best neutrino detectors in the world.

When a neutrino passing through Super-Kamiokande chances to undergo a weak interaction with one of the water molecules, it produces a charged lepton—an electron or muon—according to the neutrino's flavor. (Taus take too much energy to produce, so tau neutrinos mostly go undetected.) From the Cherenkov light the lepton generates as it speeds through the water, the researchers can determine the neutrino's flavor and, crucially, exactly when it arrived. Super-Kamiokande got its start detecting neutrinos coming from the Sun and from Earth's atmosphere, and those neutrino sources are still there. J-PARC creates neutrinos in precisely timed pulses; based on their time of arrival, Super-Kamiokande distinguishes the neutrinos coming from the accelerator and those from all other sources.

Only a small fraction of the neutrinos from J-PARC get detected. Most miss the target—on its trip across Japan, the neutrino beam expands to a cross-sectional area almost a million times the size of Super-Kamiokande. Only a few per trillion of the neutrinos that do pass through the detector undergo a weak interaction there, and only a few percent of those are electron neutrinos, the valuable products of the flavor oscillation T2K seeks to measure. All told, it takes some 10^{21} accelerator protons to produce the few dozen electron neutrinos that the experiment has detected.

Super-Kamiokande can distinguish muon neutrinos from electron neutrinos, but not neutrinos from antineutrinos. Fortunately, that ambiguity can be resolved at J-PARC's end. The pions produced by the accelerator protons come in both positively and negatively charged varieties, with π^+ decaying into antimuons and muon neutrinos, and π^- decaying into muons and muon antineutrinos. By steering either π^+ or π^- into the decay volume, the researchers can produce a nearly pure beam of either neutrinos or antineutrinos. Since 2014, T2K has been alternating between neutrino and antineutrino modes, with approximately the same number of accelerator protons spent on each.

Symmetry violation

Even without any *CP* violation, T2K's data for neutrinos and antineutrinos aren't expected to be identical. The neutrinos propagate through rock made of matter, not antimatter, and they're measured by a detector made of matter. Both of those so-called matter effects bias the relative probabilities of neutrinos and antineutrinos oscillating and being detected. Furthermore, the oscillation and detection rates depend on the neutrino's kinetic energy, which can't be directly controlled or measured; it can only be inferred from the energy of the Cherenkov radiation in the detector through a complicated nuclear-physics calculation.

Once those effects are taken into account, T2K's observations—90 electron neutrinos and 15 electron antineutrinos over 10 years—suggest not only that muon neutrinos transform more readily than muon antineutrinos do but that the imbalance is close to as large as it could possibly be. Theory predicts that if δ_{CP} were $-\pi/2$, the value that produces maximal *CP* violation in favor of antineutrino oscillation, the experiment should have seen 82 electron neutrinos and 17 electron antineutrinos. A *CP*-conserving δ_{CP} of 0 would yield 68 electron neutrinos and 20 electron antineutrinos. And a δ_{CP} of $\pi/2$ would result in 56 electron neutrinos and 22 electron antineutrinos.

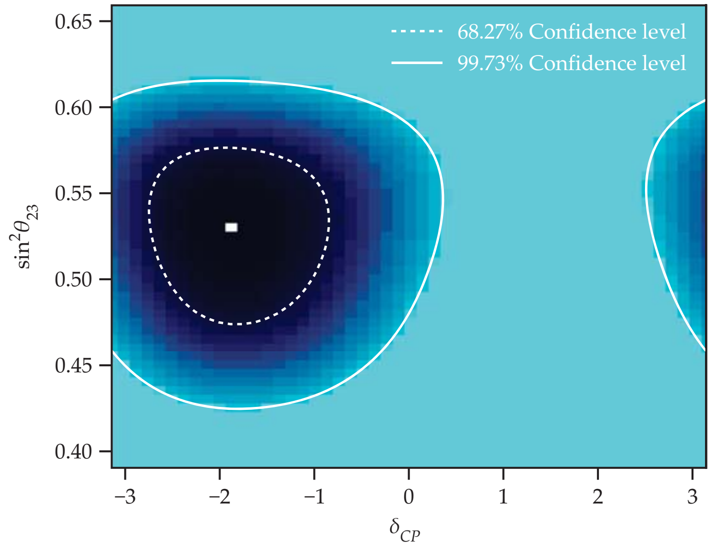

FIGURE 2. CONFIDENCE LIMITS on neutrino oscillation parameters derived from the T2K experiment's data. The plot shows constraints on the mixing angle θ_{23} and the *CP*-violating phase δ_{CP} at the 68.27% (1σ) and 99.73% (3σ) confidence levels; the result marks the first time that any possible values of δ_{CP} have been excluded with 3σ confidence. (Adapted from ref. 1.)

The small numbers and complicated physics make for large uncertainties. Figure 2 shows the confidence limits at 1σ (68.27%) and 3σ (99.73%) on δ_{CP} in conjunction with θ_{23}, another parameter that affects the oscillation probability. The data are most consistent with a negative δ_{CP}, and most of the positive values are excluded with 3σ confidence.

That analysis assumes the so-called normal mass order, in which m_3, the neutrino mass that differs the most from the other two, is the largest of the three masses. The inverted order, in which m_3 is the smallest, predicts different oscillation dynamics that are less consistent with the data. The true order of the neutrino masses remains an open question, but the T2K results make the normal order look a bit more likely.

Next generation

T2K isn't the only accelerator experiment looking for signs of neutrino *CP* violation. There's also NOνA (NuMI Off-Axis ν_e Appearance), which generates muon neutrinos at Fermilab in Illinois and detects electron neutrinos in northern Minnesota. The NOνA collaboration's most recent results, published last year, also favor the normal over the inverted mass order.[2] Although the NOνA data are best fitted by a δ_{CP} of 0, they can't yet exclude any δ_{CP} values with even 1σ confidence, and they're compatible with T2K's findings.

Both the T2K and NOνA experiments are ongoing, and they'll continue to collect data in the coming years to pin down δ_{CP} and other neutrino properties. At the same time, the next generation of experiments is in the works. In Japan, the planned Hyper-Kamiokande detector, a water tank even larger than Super-Kamiokande, will allow data collection 20 times as fast as T2K currently achieves. And in the US, DUNE (Deep Underground Neutrino Experiment) will pair neutrinos generated at Fermilab with a liquid-scintillator detector in western South Dakota.

Both the new experiments are due to come on line in 2026 or 2027, although that schedule reflects the plan before the outbreak of COVID-19. Once they're up and running, how long they'll take to get definitive results depends on what δ_{CP} turns out to be. A large symmetry violation is easier to spot than a small one. If *CP* violation is maximal, as the T2K results suggest it might be, DUNE and Hyper-Kamiokande could reach a 5σ measurement in as little as two years of operation.

Johanna Miller

References

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2. M. A. Acero et al., NOνA collaboration, *Phys. Rev. Lett.* **123**, 151803 (2019).