Constraint on the matter–antimatter symmetry-violating phase in neutrino oscillations

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For a century, physicists assumed the universe began with equal amounts of matter and antimatter. If that were true, everything would have annihilated everything else in the first moments after the Big Bang, and we wouldn't be here. Nothing would be here. The fact that we exist — that there are stars and planets and people — means matter won that battle. And we still don't know why. The T2K Collaboration, firing a beam of neutrinos across two hundred ninety-five kilometers of Japan, found the first significant crack in that symmetry. The answer came from the ghostliest particle we know.

The physicist Andrei Sakharov identified, decades ago, one necessary ingredient for matter to dominate: the laws of physics must treat matter and antimatter differently. That's called charge-conjugation parity-reversal symmetry breaking, or CP violation, if you want the full name. We've seen it in quarks, but only weakly. The quark-sector Jarlskog invariant, which measures the magnitude of CP violation, sits

at about three times ten to the negative five. That's far too small to explain the universe we observe. So physicists went looking elsewhere. Neutrinos — the lightest, most ghostly members of the particle family called leptons — carry a potential source of CP violation that could be orders of magnitude larger. And that's what T2K set out to measure.

Here's the mechanism. Neutrinos come in three flavors: electron, muon, and tau. But the flavor states and the mass states don't match up neatly — they're quantum mixtures of each other. As a neutrino travels, those mixed mass states interfere, and the flavor composition shifts. A muon neutrino can arrive at a detector looking like an electron neutrino. This is neutrino oscillation. The mathematics of this mixing is encoded in a four-parameter matrix called the Pontecorvo-Maki-Nakagawa-Sakata matrix, or PMNS matrix: three mixing angles and one complex phase called delta-CP. That phase is the key. When delta-CP is nonzero, neutrinos and antineutrinos oscillate at different rates. The leptonic Jarlskog invariant — the measure of CP violation in this sector — is approximately zero point zero three three multiplied by the sine of delta-CP. When delta-CP sits near plus or minus ninety degrees, that factor reaches its maximum. And crucially, for the T2K baseline and energies, changing delta-CP from positive ninety to negative ninety degrees can shift the expected number of electron-neutrino events at the far detector by roughly forty percent. That's a large, measurable difference.

The T2K experiment is built around exploiting exactly that difference. Start at J-PARC on Japan's east coast, where a thirty gigaelectronvolt proton beam slams into a graphite target and produces a spray of secondary particles. Magnetic horns focus those particles into a beam: set the horns one way and you get a muon-neutrino beam; flip the polarity and you get a muon-antineutrino beam. The beam is aimed two and a half degrees off-axis from the far detector, which produces a narrow energy spectrum peaking at about zero point six gigaelectronvolts — right where the oscillation effect is largest. The beam is remarkably pure: in neutrino mode, ninety-seven point two percent of it is muon neutrinos at the source, with electron-neutrino contamination of just zero point four seven percent.

Two hundred eighty meters from the target sits the near-detector complex. The key component is ND280, an off-axis magnetized detector that characterizes the beam before any oscillation has had a chance to happen. Because it's magnetized, it can distinguish particles from antiparticles — critical when you're separately measuring neutrino and antineutrino interactions. ND280's job is to pin down the flux and interaction-model uncertainties before they propagate to the far detector. That near-far strategy is central to the whole enterprise: without it, systematic uncer-

tainties alone would swamp the signal. With it, the uncertainty on predicted event counts at the far detector drops from thirteen to seventeen percent down to four to nine percent across the main signal samples.

Then the beam travels two hundred ninety-five kilometers through Earth's crust to Super-Kamiokande — a fifty thousand ton tank of ultrapure water buried under a Japanese mountain, lined with photomultiplier tubes. When a neutrino interaction produces a charged particle, that particle travels faster than light moves through water and emits a cone of Cherenkov radiation — a ring of light on the detector wall. Electrons produce blurry, diffuse rings; muons produce sharp, clean ones. That ring morphology is how Super-Kamiokande identifies what flavor of neutrino just interacted. T2K built five signal samples from these events — single muon-like and single electron-like rings in both beam modes, plus a neutrino-mode electron-like sample with evidence of a pion — and looked for the pattern that CP violation would leave in those counts.

Extracting delta-CP from those counts is not simple. The signal — extra electron-neutrino appearance — sits on top of backgrounds from misidentified events, pion production, and the small intrinsic electron-neutrino contamination in the beam. T2K handles this with a joint statistical analysis: ND280 data constrain the flux and interaction models first, and then those constrained parameters feed into the far-detector prediction. The collaboration used two independent statistical frameworks — a frequentist approach building Neyman confidence intervals with Feldman-Cousins corrections derived from at least twenty thousand simulated datasets per tested value of delta-CP, and a Bayesian approach using Markov-chain Monte Carlo sampling with a uniform prior on delta-CP. Both methods agreed on the answer.

The result is striking. T2K observed significantly more electron-neutrino appearance than electron-antineutrino appearance — exactly the pattern large CP violation would produce. The best-fit value of delta-CP for the normal mass ordering is negative one point eighty-nine radians, with an uncertainty of plus zero point seventy minus zero point fifty-eight. For the inverted ordering it's negative one point thirty-eight, plus zero point forty-eight minus zero point fifty-four. Both of those sit close to negative pi over two — maximal CP violation. The ninety-nine point seventy-three percent confidence interval — that's the three sigma level — for the normal ordering runs from negative three point forty-one to negative zero point zero three, excluding forty-six percent of the full possible range. The CP-conserving values — delta-CP equals zero, delta-CP equals plus or minus pi — are excluded at the ninety-five percent confidence level. That's significant. It means the data are mean-

ingfully inconsistent with a universe where neutrinos and antineutrinos oscillate identically.

The other measured parameters tell a consistent story. The atmospheric mixing angle theta-twenty-three came in at sine squared equals zero point fifty-three, plus zero point zero three minus zero point zero four — consistent with maximal mixing, meaning neutrinos mix almost perfectly between muon and tau flavors. The fit also preferred the normal mass ordering, where the two lighter mass states are clustered together and the third is heavier, with a Bayesian posterior probability of eighty-nine percent and a Bayes factor of eight. The team tested alternative neutrino-nucleus interaction models and found no significant bias in the delta-CP best-fit values. Any biases seen in other parameters were folded into the quoted uncertainties.

Three sigma, though, is not a discovery. In particle physics, the gold standard is five sigma — a one in three point five million chance of seeing your result if the effect isn't real. Three sigma is roughly one in a thousand. Compelling. Suggestive. But not settled. The collaboration is explicit about this: the result is a strong indication, not a confirmed observation.

What would confirmation require? More data and bigger detectors. The dataset here spans two thousand nine to two thousand eighteen, with exposures of one point forty-nine times ten to the twenty-first protons on target in neutrino mode and one point sixty-four times ten to the twenty-first in antineutrino mode. Statistical uncertainty still dominates. A next-generation instrument with roughly ten times the water volume would accumulate signal far faster, and independent long-baseline experiments approaching the same measurement from different baselines and energies would provide the cross-checks that a discovery demands.

The deeper prize is leptogenesis — the theoretical chain by which CP violation in the lepton sector, through early-universe processes, could generate the matter excess we observe today. T2K doesn't directly probe leptogenesis; that requires additional physics beyond what any oscillation experiment can reach. But what T2K does probe is the first, necessary link in that chain: are neutrinos and antineutrinos actually different? The answer, at three sigma, is: probably yes. A two hundred ninety-five kilometer beam, a tank of water, and a faint asymmetry in how neutrinos and antineutrinos show up at a detector. That may be where the answer to why we exist begins.

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