Edited after Nature and T2K suggestions:

Behind the paper: CP violation in neutrino oscillations

In 1967, Andrei Sakharov proposed conditions required in the early universe for generating matter and anti-matter at different rates, to explain the abundance of matter in our universe today. Charge-Parity (CP) violating processes are essential under these conditions. Measurements of the CP violation in quarks, first performed in 1964, are too small to explain the difference, and finding other sources of CP violation is an ongoing quest in the physics community. In April 2020, the T2K collaboration published a paper in Nature suggesting large CP violation in the leptonic sector, namely in neutrino oscillations. Some of the researchers involved in the project tell us their story.

A guest post by Ciro Riccio (Scientist, Stony Brook University), Patrick Dunne (Scientist, Imperial College London), Pruthvi Mehta (Ph.D. student, University of Liverpool), Sam Jenkins (Ph.D. student, University of Sheffield), Tomoyo Yoshida (Graduated PhD student, Tokyo Institute of Technology), Clarence Wret (Scientist, University of Rochester)

The oscillation analysis, whose results were recently published in Nature, is the last link in a long chain of work. It amalgamates the effort of the entire collaboration, from those designing and constructing the experiment 20 years ago, to the countless hours of detector operations taken by people all over the world, to the development of the analyses.

The project

There are over 400 people working on T2K, in 12 countries, at 69 institutes. Many of us have spent years building our bit of the experiment, from physical objects like detector or beamline instrumentation, to abstract items like data analysis frameworks. Looking at the author list, you'll see that T2K consists of collaborators from all over the world. Our daily communications happen online; in video meetings, emails, and chats. It's sometimes a challenge to find good time-slots for connecting people over 16 time zones, and it's not uncommon to sign-off from a meeting with a good-night, only to be met with a good-morning, and vice versa.

Our international collaborators frequently fly to Japan to spend a week or two monitoring the experiment in Tokai—on the east coast—where the neutrino beamline and Near Detectors are, or Kamioka—just west of the Japanese alps—where the Far Detector is. In addition to the flashing computer screens and sounding alarms, we get to witness a very different side of Japan from the bright lights of Tokyo, from the beautiful mountains and rivers of rural Japan, to the delicious local specialities. Avoiding the risk of data loss often occurs at the cost of sleep for the operations experts (as the contributors to this blog post can attest)—but all is forgotten after a morning visit to the local *onsen* (hot-spring).

It's impossible to overemphasise the fantastic experience of Japanese culture as an added bonus of partaking in T2K. Many of the restaurants in the Tokai and Kamioka areas are familiar with members of the collaboration, and are very accommodating to international collaborators. The owner of one particular restaurant in Tokai often recognises Sam and remembers that he can speak a small amount of the language (*chotto*), and indulges him to order in broken Japanese (we like to think it's good for practice, and not solely their entertainment). A favourite annual event is the sweet potato festival (*imo matsuri*), a community event in Tokai held in November to celebrate the root vegetable that the Ibaraki prefecture is renowned for.

The measurement

The Super-Kamiokande Far Detector started construction in 1991 in Kamioka, and operates 24 hours a day, 365 days a year, so as not to miss rare astrophysical events, such as supernova bursts. The neutrino beam and the Near Detectors started construction 2001 (beam) and 2007 (Near Detectors) in Tokai, and are continuously operating when we have pre-allocated beam time, sometimes up to seven months per year.

To make our measurement we not only need the neutrino beam and the detectors, but also a computer-simulated model of the entire experiment, painstakingly quantifying how we think each component behaves and how certain we are of that description. This includes everything from the neutrino beam (and the proton beam collisions that creates it), to the neutrino interactions in our detectors, to the density of the Earth between Tokai and Kamioka, to how good our detectors are at measuring the neutrinos.

To characterise the neutrino beam, we have two detectors ("ND280" and "INGRID") 280m from the neutrino source, which have a staggering amount of neutrinos passing through them. Occasionally these neutrinos interact at the Near Detectors, occasionally they interact 300km later in Super-Kamiokande, but most of the time they continue out through Earth's atmosphere, propagating deep into space. To put things into perspective, this analysis used about $3x10^{21}$ (3,000,000,000,000,000,000,000) proton interactions to create the neutrino beam. Roughly one neutrino is created per proton interaction, but due to their rare interaction rate with matter, we observe a mere 120,000 neutrino events at ND280 (60,000 of which were used in our analysis) and about 500 at Super-Kamiokande over the course of nine years. In the early neutrino beam experiments of the 1970s, the data are often on less than 500 neutrino events, with the experiments sitting right next to the neutrino source for tens of years. Today we have about the same number of neutrino events in a similar amount of time, but sitting 300km away from the source at Super-Kamiokande. It's only recently that we have the technology, international funding support from governments, and scientific community in place to produce such powerful neutrino beams, which are the backbone of these precise measurements.

Once the neutrinos are characterised at the Near Detector, the oscillation analysis takes all the models of the neutrino beam, the detectors, the neutrino interaction, and neutrino oscillations, combines them with their constraints, and blends them together to describe our observations. The analysis and all of its inputs turns PhD students', scientists' and professors' daily work into many cycles of communication-implementation-validation, over the course of more than a year. When validations and tests are satisfied, we finally get to look at the data and make our measurement of the neutrinos' oscillations. That last link in the long chain has the privilege to see the final result first in the collaboration. The moment when the plot pops onto your screen and you're the only person who knows what it shows is pretty special. For this result, published in April 2020, we first saw the results internally in Autumn 2018, and spent the time between then and now extensively validating and testing alternate explanations.

Looking ahead

T2K is currently in the process of updating the analysis using more data taken during 2019/2020, and using better models of the experiment, all thanks to the continuing dedicated work of all our collaborators. Many of us are also working on upgrades of the neutrino beamline, the Near Detectors and the Far Detector, to squeeze out more science from the neutrino beam. Our results published in Nature are the strongest constraint on the CP violating phase in neutrinos to date, but we have only taken about half of our allocated data. There is much more to come and the prospects are truly exciting for all of us. As we continue, we're including the work of even more people than the analyses that came before; new students, scientists and professors. We hope they, like us, get their share of the pleasant, stressful, lovely, frustrating, and ultimately rewarding experience of being on an international science collaboration such as ours.