Two scientists work on the near detector of the MINOS neutrino experiment at Fermilab in Illinois.

P. GINTER

A MATTER OF DETAIL

AMERICAN NEUTRINO PHYSICISTS ARE GETTING THE MEASURE OF THEIR QUARRY IN ULTRA-HIGH PRECISION.

EUGENIE SAMUEL REICH

“It’s like Christmas shopping at the specialist boutiques,” says Phil Adamson, as he describes his recent US$250,000 buying spree. Adamson, a physicist at the Fermi National Accelerator Laboratory (Fermilab) in Batavia, Illinois, leads a team that has spent the past few months acquiring and installing three ultra-high-precision atomic clocks; six Global Positioning System receivers; more than a kilometre of optic fibre; two auxiliary detectors and at least one pair of timing-interval counters (“kind of fancy stopclocks”, he says) — all to time subatomic neutrinos with nanosecond precision as they pass through the detectors of Fermilab’s Main Injector Neutrino Oscillation Search (MINOS).

The researchers are trying to answer one simple question: do neutrinos travel at or below the speed of light, as required by the theory of relativity, one of the most fundamental tenets of modern physics? Or do they travel just a tiny fraction faster, as suggested with enormous fanfare last September[1] by an experiment in Italy?

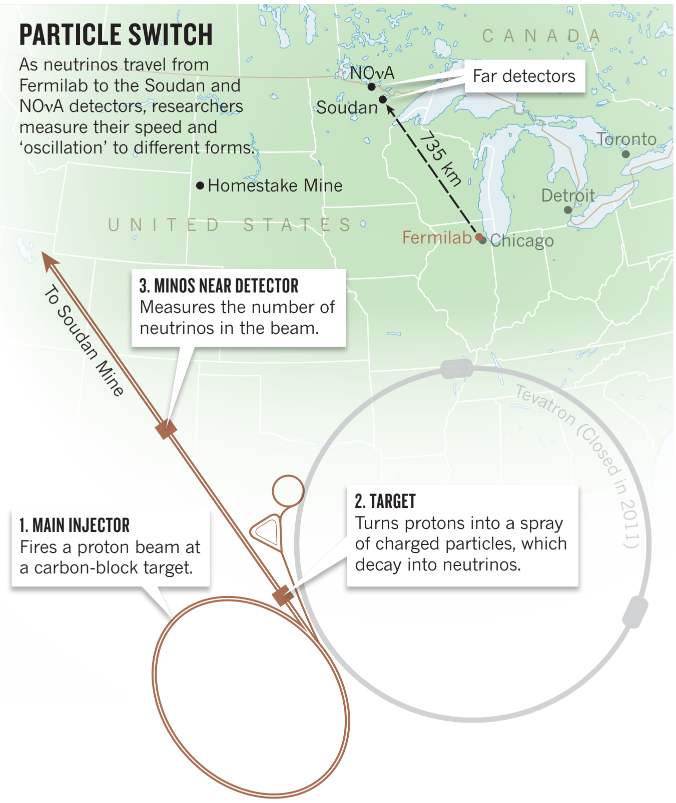
To outsiders, this debate has already been settled. Researchers on the Italian experiment, based at Gran Sasso National Laboratory near L’Aquila, announced in March that they had found the error in their measurement — and two of the team’s leaders resigned (see go.nature.com/xjzhqa). At the same time, physicists working at a different detector at Gran Sasso have published measurements[2] showing that neutrinos do indeed obey the light-speed limit.

Yet neutrino speed is still a prime focus for the MINOS physicists, who are carrying out their own high-precision measurement — not least because they did not do this when they saw hints of a faster-than-light neutrino in their own data some years ago. “This is so much on our front burner,” says Robert Plunkett at Fermilab, a spokesman for MINOS. Around 30 members of the 150-strong collaboration are now working on the search.

Precision is what the MINOS team is all about. In 2008, Fermilab's Tevatron was supplanted as the world's highest-energy particle accelerator by the Large Hadron Collider (LHC) at CERN, Europe's particle-physics laboratory outside Geneva, Switzerland. Since then, US particle physicists have moved from studying collisions at the highest energies to working with beams at the highest intensities, adapting the country's existing accelerator facilities to measure the rates of extremely rare interactions. The hope is that, even at lower energies, forcing theory and experiment into close comparison can turn up anomalies that point to new physics.

Neutrino physics is the centrepiece of that programme. The particles respond only to the aptly named weak force, and mostly stream through solid matter as if there were no barrier. But this aloofness also makes neutrinos potentially a very clean probe of exotic forces: when a neutrino does hit another particle, physicists don't have to disentangle the effects of the much larger strong and electromagnetic forces. Experiments using accelerators, in which physicists can control the energy and direction of the neutrino beam, take maximum advantage of that fact. And MINOS is the most sophisticated experiment of this kind in the United States.

True, it takes a special kind of researcher to pursue such work — pushing measurements towards the last possible decimal point, over decades if need be. But most of the MINOS physicists share the attitude voiced by team member Nathaniel Tagg, a physicist at Otterbein College in Westerville, Ohio. "I'm one for long shots."



PARTICLE SWITCH

As neutrinos travel from Fermilab to the Soudan and NOνA detectors, researchers measure their speed and 'oscillation' to different forms.

3. MINOS NEAR DETECTOR
Measures the number of neutrinos in the beam.

2. TARGET
Turns protons into a spray of charged particles, which decay into neutrinos.

1. MAIN INJECTOR
Fires a proton beam at a carbon-block target.

COWBOY PHYSICS

Neutrinos' central role in US physics research is a case of historical turnabout, says Tagg. For years the field was considered 'cowboy physics' — a fringe area best left to diehard experimentalists who were willing to drag their detectors down remote mineshafts and into underground bunkers, where the devices could escape the confounding effects of atmospheric cosmic rays.

The archetypal cowboy was Raymond Davis, a radiochemist at Brookhaven National Laboratory in New York, who wanted to make the first direct observations of nuclear fusion reactions in the core of the Sun. He began in 1967 by setting up a 380-cubic-metre tank of perchloroethylene, a dry-cleaning fluid, nearly 1,500 metres down in the Homestake gold mine in Lead, South Dakota. Davis's idea was that neutrinos created in the Sun's nuclear reactions would very occasionally strike a chlorine atom in the tank and turn it into a radioactive isotope of argon, which he could extract and detect by chemical means. But only about one-third of the expected number of neutrinos seemed to be showing up. Either the theorists were wrong about the rate of fusion reactions in the core of the Sun — which didn't seem likely, given the success of their calculations in other areas of astrophysics — or two-thirds of the neutrinos were getting lost.

It took decades for physicists to reach a consensus that this 'solar neutrino problem' was real, not some obscure experimental error, and only in the 1990s did they converge on a probable solution. This started from the hypothesis that neutrinos come in three types, or 'flavours', each of which is the electrically neutral partner of a negatively charged particle with mass — an electron, a muon or a tau. The Sun's fusion reactions produce only electron neutrinos. But as soon as they are produced, according to the theory, these neutrinos begin to 'oscillate', changing from one flavour to another as they travel. By the time they get to Earth, the three flavours have mixed themselves into equal proportions — meaning that just one-third will be electron neutrinos, the only kind that Davis's tank could detect.

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For more on the OPERA neutrino experiment, see:
go.nature.com/eswpxs

This oscillation theory elegantly accounted for the missing solar neutrinos, but posed a new conundrum. The standard model of particle physics held that all three flavours of neutrino have a mass of exactly zero, like that of the photon. But oscillation was possible only if neutrinos have at least a very small mass — which meant that the particles were hinting at some kind of physics beyond the standard model.

This prospect quickly took neutrinos out of the cowboy-physics category (Davis himself would share the Nobel Prize in Physics in 2002). MINOS was one result (see 'Particle switch'). Planning began in the 1990s as physicists looked for a way to verify the oscillation model. In particular, they wanted to create an artificial neutrino beam that would remove one of the biggest uncertainties in solar neutrino experiments, which was the number of neutrinos arriving at the detector. The plan called for Fermilab's accelerator complex to fire protons at a graphite target, producing a spray of short-lived charged particles that would decay into muon neutrinos. The resulting neutrino beam would pass through a 1,000-tonne, train-carriage-sized 'near' detector in the Fermilab grounds, where enough neutrinos would be captured to gauge the total number in the beam. The remaining particles would continue underground on a 735-kilometre, straight-line path to the Soudan Mine in northern Minnesota, where a five-times-larger 'far' detector would measure how many muon neutrinos arrived. If some had oscillated into other forms, the discrepancy would be obvious — and neutrino oscillation would be verified.

COLLISION COURSE

In 1998, however, while MINOS was still on the drawing board, the US project was beaten to this goal by the Super-Kamiokande experiment near Hida in Japan. Through a clever experimental design, the Japanese physicists had been able to verify the existence of oscillation using neutrinos generated by cosmic rays striking the atmosphere[3].

That disappointment took a toll, admits Adamson, one of many particle physicists drawn to the field by a desire to sort out the oscillation phenomenon. But it also proved an opportunity. Rather than being the ones to discover new physics, the MINOS team decided that they would be the ones to carefully characterize the phenomena that the Super-Kamiokande had found. "By the time we started to operate [in 2005] we were trying to make precision measurements," says Adamson.

One obvious question was why neutrinos have mass at all. The standard model can explain the mass of charged particles, such as the electron, as a subtle interaction with the hypothetical Higgs boson. But that mechanism was not supposed to affect neutrinos. The three neutrino varieties have masses so tiny, less than one-millionth that of the electron, that some kind of exotic mass-generating mechanism may be at work, and high-accuracy measurements of the oscillation phenomenon could shed light on what that is.

Such questions soon began to move the long-term planning for accelerator neutrino facilities to the forefront of US high-energy physics. In 2006, the Particle Physics Project Prioritization Panel of the Department of Energy (DOE) laid out a roadmap for the field that included continued support for MINOS and endorsement of a new experiment known as the NuMI Off-Axis Neutrino Appearance (NOνA). (NuMI, which stands for 'neutrinos at the main injector', is the name of the neutrino beam serving the experiment.)

ACCELERATED DEVELOPMENT

The plans for NOνA called for a boost in the energy of Fermilab's neutrino beam and a new detector farther north in Minnesota. One of its key goals would be to measure how oscillation occurs among neutrinos' three antimatter counterparts, the antineutrinos, and find out whether the process obeys 'charge-parity' symmetry. This symmetry, which basically means that interactions should remain unchanged if particles and antiparticles swap places and everything is viewed in a mirror, is known to be violated in only a few, very rare reactions. Nevertheless, charge-parity violation is thought to be the ultimate explanation for the emergence of much more matter than antimatter from the early Universe, and why stars, planets and living things can exist today. If the symmetry can be violated for neutrinos and antineutrinos, then these ghostly particles could provide unique insights into the processes that have made the Universe the way it is.

At MINOS, meanwhile, the team was busy boosting the intensity of Fermilab's neutrino beam, setting a world record for precisely determining the difference between the masses of the three types of neutrino[4], and measuring a variety of parameters crucial for the design of NOνA.

Then, in June 2010, scientists at MINOS reported early signs of a discrepancy in the rates at which neutrinos and antineutrinos oscillated[5]. This particular discrepancy would have violated another fundamental symmetry of quantum field theory known as CPT, for charge, parity and time. In its way, this would have been just as astonishing as faster-than-light neutrinos. MINOS scientists began to hope for a paradigm-shattering discovery. But these hopes were dashed when further data, reported in February this year[6], suggested that the result was a statistical fluctuation. "It was disappointing," says Justin Evans, a physicist at University College London who is a member of the MINOS team. "We made the world's most precise measurement of antineutrinos' parameters — but everyone wants to be the group that discovers something new."

The faster-than-light neutrino announcement last September from the Oscillation Project with Emulsion-tracking Apparatus (OPERA) experiment in Gran Sasso shook the MINOS team out of its data-collecting routine. The Italian lab reported that neutrinos seemed to be making the 730-kilometre trip from CERN to Gran Sasso some 60 nanoseconds faster than a light beam would. The announcement galled some MINOS collaborators, who back in 2001 had proposed an ultraprecise measurement of neutrino speed only to have the idea nixed by the DOE. The team decided not to resurrect the idea in 2007, when its low-precision measurements hinted that neutrinos might be travelling faster than light[7]. It didn't seem worth fighting that battle again to follow up a result with minimal statistical significance.

So, stung by the hullabaloo from Italy — and aware that MINOS, given the similarity of its set-up to OPERA, was uniquely placed to provide the all-important independent replication of the remarkable finding — the MINOS team was determined to get the measurement right.

> "IT'S A PLEASURE AND PRIVILEGE TO BE IN A POSITION TO SETTLE THIS."

But MINOS was scheduled for a temporary shutdown in March 2012, during which the energy of its neutrino beam would be boosted to serve NOνA. MINOS would also receive some upgrades so that it could look for exotic phenomena such as sterile neutrinos — hypothetical particles that would not participate in any interaction governed by the standard model — and neutrino oscillation into extra dimensions. Yet everyone understood how momentous it would be if neutrinos really did violate Einstein's speed limit, says Adamson. Once the team realized that it had the people and the set-up to check the result in a reasonable time, he says, it felt it had a duty to weigh in.

Fermilab approved a two-month delay in the neutrino beam shutdown, and the MINOS team resurrected and improved its decade-old proposal to do the measurement at high precision. By the time of the shutdown, now scheduled for 1 May, the experiment should have yielded data sufficient to pinpoint the time-of-flight measurement to within 11 nanoseconds, similar to OPERA's uncertainty. And by sometime in 2013, after the neutrino beam is upgraded to higher energy, the increase in event rate should allow MINOS to reach an error of between 2 and 7 nanoseconds.

Physicists at MINOS are determined to make the measurements, even if their chance of a faster-than-light finding is now exceedingly remote given OPERA's admitted error. "There's a chance it will turn out to be really interesting," says Tagg, But if, as looks likely, the measurement simply confirms something that everybody already knows, MINOS will at least have produced a high-precision measurement of a fundamental parameter, something that physicists on the experiment insist is a noble contribution, even if it's not a discovery. "It's a pleasure and privilege to be in a position to settle this," says Plunkett. ■

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