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Particle physics

Neutrino secrets could be revealed close to home

Josh Spitz

Scientists typically look at the skies or take to the laboratory to probe the neutrino's properties. But neutrinos produced in Earth's atmosphere could reveal this long-sought information — and the experiments are already well under way.

Neutrinos outnumber electrons, protons and neutrons in the Universe by a factor of about one billion — but they barely interact with other matter. A typical neutrino produced in the core of the Sun could zip through one light year (around ten trillion kilometres) of lead without hitting anything. This makes neutrinos difficult to study, and yet their prevalence has given them a key role in shaping the cosmos. Writing in *Physical Review X*, Argüelles *et al.*[1] suggest that measurements of neutrinos created in Earth's atmosphere could be used to determine the properties of this elusive particle, which can then offer clues about the formation of the entire Universe.

There are three types of neutrino — electron, muon and tau — and the type is set when a neutrino is generated or detected. For example, in a nuclear process called β decay, an unstable nucleus converts a neutron to a proton, and in doing so emits an electron and an electron antineutrino. Intriguingly, a neutrino can change type after some time. This quantum phenomenon is known as mixing, and it depends on the distance that the neutrino travels, what it moves through and its energy. Mixing also implies that neutrinos have mass, with each of the three types forming a combination of three distinct, but currently unknown, masses.

Precision measurements to determine the rules that govern mixing could reveal how neutrino properties relate to the nature of the cosmos — one of the big questions in astroparticle physics, in which scientists connect the smallest aspect of the Universe to the largest. Several experiments are currently being planned or undertaken around the world to determine these rules, using neutrinos produced from the Sun, particle accelerators, energetic events in space and radioactive decay.

But, because the properties of neutrinos are so crucial to our understanding of the Universe and measuring them is so difficult, scientists are continually looking for other ways to probe these fascinating particles. One such route involves the neutrinos that are readily produced when cosmic rays interact with Earth's atmosphere (Fig. 1). For example, a supernova in a distant galaxy can generate energetic cosmic-ray protons that travel all the way to Earth, and then hit a molecule in the upper atmosphere, producing a shower of secondary particles that can include neutrinos.

These atmospheric neutrinos were used to discover mixing[2], together with neutrinos from the Sun[3]. But Argüelles *et al.* suggest that further precision measurements of atmospheric neutrinos could also definitively find how the three neutrino masses are ordered, from lightest to heaviest. And such measurements are already in the works at a quartet of facilities that either have or will have devices that detect neutrino interactions occurring in water. These include Japan's Super-Kamiokande[4] and Hyper-Kamiokande[5] detectors, the IceCube Neutrino Observatory in Antarctica[6] and the ORCA detector, located deep in the Mediterranean Sea[7].

Together, these devices will collect about one million atmospheric neutrinos over the next decade, and each detector has a unique capability. For example, the IceCube detector features one cubic kilometre of ice fitted with light sensors, with its enormous size making it particularly sensitive to neutrinos with extremely high energies. But it is blind to the lower-energy interactions that are easily observed by the Japanese detectors, both of which involve tanks of liquid water spanning tens of metres. The combined measurements from all the detectors will feature both muon and electron neutrinos with energies ranging from around 0.1 to 100 gigaelectronvolts (GeV; 10^9 electronvolts) and that have travelled

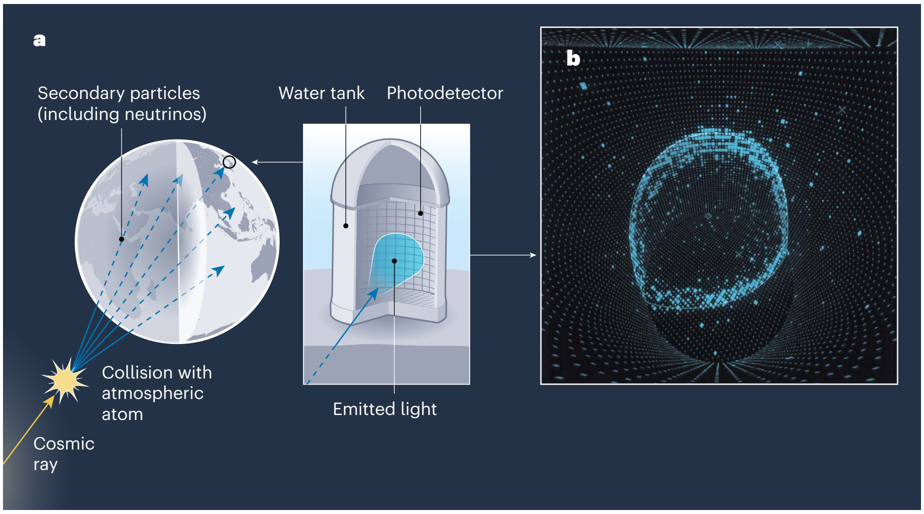

Figure 1 | Detecting neutrinos generated in Earth's atmosphere. a, A cosmic ray entering Earth's upper atmosphere can collide with an atom or molecule, producing a shower of secondary particles, which can include neutrinos. Experiments around the world are set up to detect these neutrinos when they interact with water or ice. For example, the Super-Kamiokande detector near Hida, Japan, consists of a water-filled tank lined with photodetectors that capture the flashes of light produced during these interactions. **b**, Scientists use the light pattern detected to determine the type of neutrino (the pattern of a muon neutrino is shown here), as well as its energy and the distance it has travelled. Collecting a large sample of events can reveal further information, such as the intrinsic properties of the particle itself. Argüelles *et al.*[1] performed an analysis suggesting that such data will enable researchers to determine, by 2030, how the neutrino masses are ordered, from lightest to heaviest.

TOMASZ BARSZCZAK/SUPER-KAMIOKANDE COLLABORATION/SPL

distances from 15 to 12,700 kilometres.

These experiments will study the number of muon and electron neutrinos detected as a function of their energy and distance travelled. Each interaction that a neutrino undergoes in water or ice produces a flash of light, and the neutrino is judged to be muon-like or electron-like on the basis of the shape of the light pattern that is captured by thousands of photon detectors. The neutrino's energy can be determined by the size of this pattern and, by using the pattern to reconstruct the angle of the incoming neutrino, scientists can estimate the distance that it travelled after being generated in the atmosphere, including how much of its path went through Earth.

The behaviour of the neutrino as it travels is intimately tied to the fundamental properties of the particle. For example, muon neutrinos that are generated in the atmosphere with intermediate energy (1–10 GeV) are more likely to change into electron neutrinos after travelling through Earth if the lowest mass component of the neutrino is mostly electron-type. This mass ordering corresponds to what scientists refer to as 'normal' (as opposed to inverted) ordering, because the electron is the lightest of the three charged particles after which the neutrino types are named, followed by the muon and the tau.

Argüelles *et al.* estimated the sensitivity associated with the four experiments and ran computer simulations of the processes involved. Their study suggests that a combined analysis of atmospheric-neutrino data from all these detectors should, by 2030, give rise to statistically meaningful information about the ordering of neutrino masses. Particle-accelerator[5,8–10] and reactor-based[11] projects will also have key roles in this determination.

Incorporating the results of other experiments could offer even more insight. Telescopic observations of large-scale structure – the 'clumpiness' of galaxy networks – can provide a measure of the total sum of the neutrino masses[12], which is closely related to the ordering. This is because near-light-speed neutrinos tend to carry their mass away from objects that are coalescing under gravity. Observing less clustering than expected would therefore indicate a more massive neutrino. Some laboratory-based nuclear experiments are also sensitive to neutrino mass, including those involving the β decay of the hydrogen isotope tritium, and an ultra-rare process called double β decay, in which an unstable nucleus exchanges two neutrons for two protons.

The researchers' analysis confirms the enormous potential of atmospheric-neutrino studies. Despite the many approaches to understanding neutrinos all being complementary, the teams involved in these diverse experiments are in competition with each other to determine the mass order. And yet, in an amazing coincidence, their efforts are all expected to converge on current estimates for the range of neutrino masses in the next decade or so. Scientists might expect that the results will be compatible across these wildly different probes, pointing to a clear and consistent picture of neutrinos on Earth, in the atmosphere and in space. However, any kind of inconsistency between the measurements could be viewed as an exciting indication of both new particle physics and new cosmology.

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The author declares no competing interests.

Neuroscience

Mysterious ultraslow brain activity observed in mice

Gilles Laurent

Neurons with a role in navigation fire sequentially in mice, forming patterns that repeat every minute or so – but which are neither spatially organized, nor related to any visible behaviour. **See p.338**

Brain oscillations result from the rhythmic and coordinated activity of groups of neurons. Most of the types that have been recognized so far (for example, alpha, theta and gamma oscillations) occur on timescales of less than 1 second; that is, at frequencies of 1 to around 100 cycles per second. On page 338, Gonzalo Cogno *et al.*[1] provide evidence for sequential and periodic events in the mouse medial entorhinal cortex (MEC) – a region of the brain involved in navigation – that extends these timescales to the minute range.

Advances in brain recording and analysis techniques have enabled scientists to study the activity of many neurons simultaneously[2,3]. When applied to organisms with small nervous systems, these methods have revealed ordered patterns of activity in populations of neurons, which relate to sensory inputs[4] or to the animal's behaviour[5] and cannot be detected from single-neuron recordings. Relatively ordered dynamics have also been shown to exist in larger brains; for example, in the mammalian motor cortex during preparation for movement[6].

These insights provide an overarching framework to understand the sometimes puzzling properties of single neurons, such as those in the neural circuits involved in navigation[7,8]. Moreover, they emphasize that the brain is a 'dynamical system' – a system with properties that result from interactions between its components over time – and that interesting things happen in it over a wide range of timescales. Periodic synchronization and sequential activation of neurons are examples of these kinds of dynamics.

In their experiments, Gonzalo Cogno *et al.* took measurements from the brains of awake mice, which were running or standing on a rotating wheel in the dark so that they were not influenced by their visual surroundings. The authors used two-photon calcium imaging, an optical technique that measures the increase in cytoplasmic calcium in electrically active neurons, to look at the activity of hundreds of MEC neurons simultaneously. After processing the resulting data, Gonzalo Cogno *et al.* were able to examine the calcium signals in each individual neuron. They found that the signals oscillated with periods (the duration of a full cycle) ranging from tens of seconds to minutes – producing a range of frequencies that the authors refer to as 'ultraslow'.

Having established that most simultaneously recorded neurons tended to undergo similar ultraslow oscillations, Gonzalo Cogno and colleagues observed that the neurons did not all oscillate at the same time. Instead, they were activated sequentially, forming a string