is to establish Asgard model organisms with genetic and imaging potential. In the meantime, we should marvel at the beauty of a new world that has been discovered.

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Particle physics

Nuclear reaction rules out neutrino hypothesis

Jun Cao

An anomalous measurement from a nuclear reactor triggered a three-year campaign to find an elusive particle called the sterile neutrino. The search shows definitively that sterile neutrinos don't exist — but the anomaly persists. **See p.257**

Neutrinos are among the most abundant elementary particles in the Universe, but they have zero electric charge and interact only weakly with matter, so are difficult to detect in experiments. They have therefore been implicated as the reason behind some of the key gaps in our current understanding of the Universe. The long-held idea[1] that there are only three types of neutrino was challenged in 1996 (ref. 2) by evidence suggesting the possibility of a fourth type, called the sterile neutrino. Further support for this proposal came in 2011 (ref. 3), when the total number (the flux) of antineutrinos — the antimatter counterpart of neutrinos — produced in a nuclear reactor differed significantly from that predicted. A dedicated search ensued. And now, on page 257, the STEREO collaboration[4] confirms the flux anomaly, but reports that this discrepancy cannot be explained by the existence of a sterile neutrino.

In 1989, experiments[1] on the Large Electron–Positron Collider (LEP) at CERN, Europe's particle-physics laboratory near Geneva, Switzerland, determined precisely that there were three types (or 'flavours', in particle-physics terms) of neutrino. The three confirmed flavours are the electron neutrino, the muon neutrino and the tau neutrino. Neutrinos are generated when cosmic rays interact with Earth's atmosphere, and also through nuclear fusion occurring in the Sun's core. Experiments designed to detect these atmospheric[5] and solar[6] neutrinos established the curious fact that neutrinos oscillate — they change spontaneously from one flavour to another as they travel.

Neutrino oscillation can occur only if neutrinos have mass, and their mass is difficult to measure. An electron neutrino (or any other flavour) is a quantum mixture of three states that have different masses. When this neutrino moves through space, quantum interference between the three states leads to the periodic flavour transformations that constitute neutrino oscillation.

Although scientists do not know the exact values of the neutrino masses, they can measure the differences between them; these are called 'mass splittings' and are proportional to the oscillation frequencies. The three frequencies corresponding to the three mass splittings have all been observed with various neutrino sources, including solar and atmospheric neutrinos, as well as with sources produced in particle accelerators and nuclear reactors.

An abnormal neutrino oscillation with a new frequency was detected[2] in 1996, triggering the proposal of the sterile neutrino. This hypothetical neutrino should have a much larger mass than those of the other three and yet it was not detected in the LEP experiments. The name comes from the fact that it is not expected to participate in the weak interaction — the interaction between subatomic particles that leads to the radioactive decay of atoms. Certain fundamental-physics theories suggest the existence of the sterile neutrino, and there are experimental hints that support these theories, one of the strongest hints being a result known as the reactor antineutrino anomaly[3].

Electron antineutrinos are produced in abundance by nuclear-fission reactions in the cores of nuclear reactors. This type of

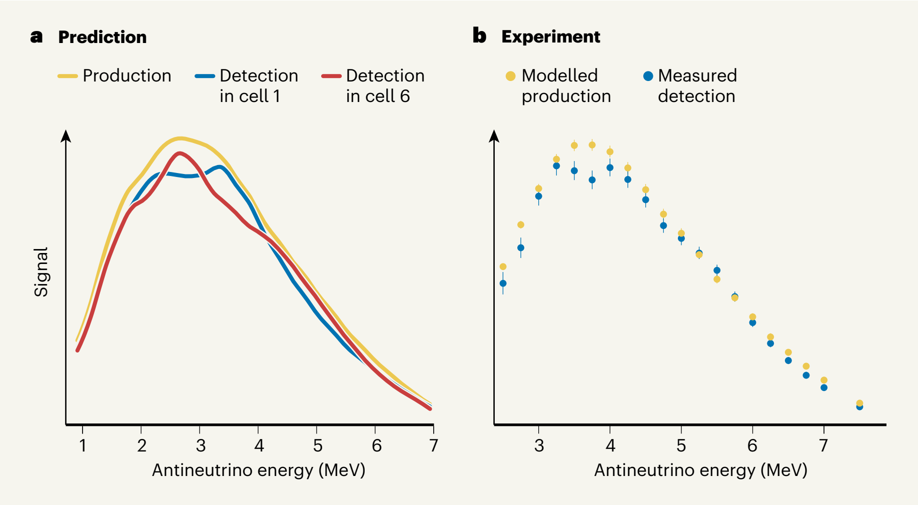

Figure 1 | The search for sterile neutrinos using a nuclear reactor. Neutrinos come in different 'flavours', including electron, muon and tau neutrinos. Electron antineutrinos (the antimatter counterparts of electron neutrinos) are produced in fission reactions in nuclear-reactor cores, and it was previously found[3] that the average number of these particles (their flux), measured by detectors close to such reactors, is about 6% less than that predicted. This anomaly was proposed to result from some neutrinos changing into a hypothetical fourth flavour, known as the sterile neutrino. The STEREO collaboration[4] measured the flux and energy spectra of antineutrinos in 6 detector cells positioned between 9 and 11 metres from a nuclear reactor. **a**, The existence of the sterile neutrino would have resulted in the shape of the detected energy spectra varying between cells. **b**, This spatial variation was not detected, but the authors measured lower flux than that predicted, thus confirming the anomaly, and excluding the possibility that it is caused by a sterile neutrino. (Adapted from Figs 1 and 2 of ref. 4.)

antiparticle has been studied extensively, and it had a key role in the 1956 discovery of the neutrino[7]. To use reactor-generated electron antineutrinos to investigate neutrino oscillation, it is crucial to know both the flux of antineutrinos emitted in these nuclear reactions and how many antineutrinos are produced at particular energies (the energy spectrum). The precision with which these quantities are measured and theoretically predicted has improved markedly since the 1950s. And in 2011, it was found that the average antineutrino flux detected in these experiments was about 6% less than that predicted[8].

One possible explanation[8] for this reactor antineutrino anomaly is that some neutrinos morph into sterile neutrinos after they leave the reactor core. Dedicated experiments were designed to investigate this possibility by installing detectors close to the reactor, usually at a distance of around 10 metres, where an oscillation into sterile neutrinos might show up in the observed energy spectrum. However, these experiments made the picture only messier: some reported that such a signature was observed[9,10], and others reported a negative result[11,12].

The STEREO experiment settles at least part of this debate with a relative measurement in 6 detector cells that are positioned between 9 and 11 metres from a nuclear reactor generating electron antineutrinos (Fig. 1). If these antineutrinos were to oscillate into sterile antineutrinos, then one would expect to see the 2011 antineutrino flux deficit confirmed, but also to see the antineutrino energy spectrum vary with distance from the reactor. Although the flux measured by the authors was indeed 5.5% lower than the model prediction, the expected oscillation pattern did not show up in their results. Its absence indicates that the reactor antineutrino anomaly cannot be explained by the sterile-neutrino hypothesis.

Because neutrinos are so difficult to detect, signals from sources other than the reactor can be many times more abundant than real neutrino signals if the detector is not well shielded. These false signatures are called background signals, and they can blur or distort the measurements. The authors were able to avoid many uncertainties by using their comparative measurement. The background signals were well controlled with relatively good shielding, and were measured when the reactor was switched off.

In addition to the flux deficit, the authors observed that the energy spectrum was distorted with respect to the model predictions — with a 'bump' between 5 and 6 megaelectronvolts, which was also detected in previous experiments[13–15]. This anomaly in the spectrum is not fully understood, but could be a result of imperfect nuclear data. The STEREO experiment used the uranium-235 isotope, and offers the most precise antineutrino spectrum measured so far for this isotope. The study will therefore be of interest to scientists benchmarking nuclear data for reactor physics, and to those predicting the antineutrino spectrum for other reactor experiments.

The reactor antineutrino anomaly has been confirmed, but its source remains a mystery. However, the impressive precision of the STEREO experiment has ensured that the sterile neutrino is no longer a viable explanation, putting to rest one hypothesis and opening the field for others. The search for an explanation continues.

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Developmental biology

Radiation damage in male worms skips a generation

Ronald Cutler & Jan Vijg

Radiation-damaged paternal DNA has been found to cause embryos of the second generation of nematode worms, but not the first, to die. The proposed mechanisms help to explain the observed lack of such an effect in humans. **See p.365**

Exposure to radiation causes DNA damage that predisposes individuals to mutations and cancer[1]. However, whether this damage, or its effects acquired in adulthood, can be passed on to future generations has remained controversial. There is a lack of evidence in humans for transgenerational effects of radiation from the atomic bombs at the Japanese cities of Hiroshima and Nagasaki in 1945 (ref. 2), or from the 1986 nuclear accident at Chernobyl, Ukraine[3]. Wang *et al.*[4] show on page 365 that exposing male nematode worms (*Caenorhabditis elegans*), but not females, to ionizing radiation results in the death of embryos produced by subsequent generations. The proposed mechanism for these transgenerational effects might explain why similar outcomes are not seen in humans exposed to radiation.

DNA damage is ubiquitous in physiological conditions and is a likely cause of ageing[5]. Most of this damage either is repaired accurately through one of multiple intertwined DNA-repair pathways, or prompts severely damaged cells to undergo a form of programmed cell death known as apoptosis. However, DNA repair is occasionally erroneous, promoting cell survival but resulting in the formation of mutations. Mutations in germline cells (eggs and sperm) are the source of evolutionary variation, but they are also responsible for embryonic lethality and genetic disease[6].

It is now well documented that the main source of genetic variation in humans is mutations in sperm[6]. Germline mutation frequency increases with the father's age, and paternal age at reproduction has been associated with increased risk of genetic disease and a decrease in the lifespan of daughters[6,7]. We would therefore expect that adult exposure to radiation or other known DNA-damaging agents would increase the number of mutations and produce adverse effects in subsequent generations. But, as noted earlier, there is little evidence for such transgenerational effects of radiation in humans[2,3].

Wang and colleagues used nematodes to study how exposing parents to ionizing radiation affects the first (F_1) and second (F_2) generations of progeny. *Caenorhabditis elegans* has two sexes, hermaphrodite and male. In the experiments, male *C. elegans* or 'females' (mutant hermaphrodites that produce only eggs) were irradiated and then immediately mated with healthy worms of the opposite