NATURE

50 Years Ago

Whatever advantages the distant future may offer from the manned exploration of space, it is clear that the present benefits of the space race are few and far between … A fortnight's conference is being held … under the title "Space Science and Technology — Benefits to Developing Countries". The introductory pamphlet … describes in a style of sustained optimism the cornucopia of technological blessings which future satellite systems will rain down on the poor and rich alike. In the near future, reflector satellites will shed light on the night earth, the pamphlet says, and "by providing illumination for construction, lumbering, fishing and other outdoor industries, could conceivably have an important effect on the economic growth of the developing nations". The pamphlet does not discuss the catastrophic effect of such a satellite on biological rhythms, nor does it explain in what manner night-time fishing and lumbering will boost any nation's economy.
From *Nature* 17 August 1968

100 Years Ago

The entrance of the United States of America into the war has prompted Mr. A. Hansen to write to *Science* pointing out that the States possess no national floral emblem. France has its fleur-de-lis, England the rose, Scotland the thistle, but America has no flower with which it is associated in people's minds. Mr. Hansen points out the various characteristics required for a national flower, and comes to the conclusion that the columbine, which is in flower from April to July, is probably the most suitable for the purpose. The correspondence of the generic name Aquilegia with the Latin name of the eagle is also considered to be a point in its favour.
From *Nature* 15 August 1918

Vassilikogiannakis, G. *Angew. Chem. Int. Edn* **41**, 1668–1698 (2002).
3. Brown, D. G. & Boström, J. *J. Med. Chem.* **59**, 4443–4458 (2016).
4. Chen, T.-G. *et al. Nature* **560**, 350–354 (2018).
5. Cornella, J. *et al. J. Am. Chem. Soc.* **138**, 2174–2177 (2016).
6. Qin, T. *et al. Science* **352**, 801–805 (2016).
7. Wang, J. *et al. Angew. Chem. Int. Edn* **55**, 9676–9679 (2016).
8. Edwards, J. T. *et al. Nature* **545**, 213–218 (2017).
9. Smith, J. M. *et al. Angew. Chem. Int. Edn* **56**, 11906–11910 (2017).
10. Chen, Y., Tian, S.-K. & Deng, L. *J. Am. Chem. Soc.* **122**, 9542–9543 (2000).
11. Anugu, R. R., Mainkar, P. S., Sridhar, B. & Chandrasekhar, S. *Org. Biomol. Chem.* **14**, 1332–1337 (2016).

This article was published online on 6 August 2018.

PARTICLE PHYSICS

Special relativity validated by neutrinos

Neutrinos are tiny, ghost-like particles that habitually change identity. A measurement of the rate of change in high-energy neutrinos racing through Earth provides a record-breaking test of Einstein's special theory of relativity.

MATTHEW MEWES

The existence of extremely light, electrically neutral particles called neutrinos was first postulated in 1930 to explain an apparent violation of energy conservation in the decays of certain unstable atomic nuclei. Writing in *Nature Physics*, the IceCube Collaboration[1] now uses neutrinos seen in the world's largest particle detector to scrutinize another cornerstone of physics: Lorentz invariance. This principle states that the laws of physics are independent of the speed and orientation of the experimenter's frame of reference, and serves as the mathematical foundation for Albert Einstein's special theory of relativity. Scouring their data for signs of broken Lorentz invariance, the authors carry out one of the most stringent tests of special relativity so far, and demonstrate how the peculiarities of neutrinos can be used to probe the foundations of modern physics.

Physicists generally assume that Lorentz invariance holds exactly. However, in the late 1990s, the principle began to be systematically challenged[2], largely because of the possibility that it was broken slightly in proposed theories of fundamental physics, such as string theory[3]. Over the past two decades, researchers have tested Lorentz invariance in objects ranging from photons to the Moon[4].

The IceCube Collaboration instead tested the principle using neutrinos. Neutrinos interact with matter through the weak force — one of the four fundamental forces of nature. The influence of the weak force is limited to minute distances. As a result, interactions between neutrinos and matter are extremely improbable, and a neutrino can easily traverse through the entire Earth unimpeded. This poses a challenge for physicists trying to study these elusive particles, because almost every neutrino will simply pass through any detector completely unnoticed.

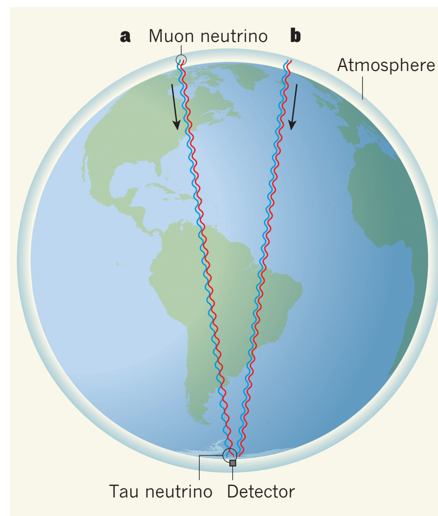

Figure 1 | Propagation of neutrinos through Earth. There are three known types of neutrino: electron, muon and tau. **a**, A muon neutrino produced in Earth's atmosphere can be thought of as the combination of two quantum-mechanical waves (red and blue) that are in phase — the peaks of the waves are observed at the same time. If a principle known as Lorentz invariance were violated, these waves could travel at different speeds through Earth's interior and be detected in the out-of-phase tau-neutrino state. **b**, The IceCube Collaboration[1] reports no evidence of such conversion, constraining the extent to which Lorentz invariance could be violated.

The IceCube Neutrino Observatory, located at the South Pole, remedies this problem by monitoring an immense target volume to glimpse the exceedingly rare interactions. At the heart of the detector are more than 5,000 light sensors, which are focused on 1 cubic kilometre (1 billion tonnes) of ice. The sensors constantly look for the telltale flashes of light that are produced when a neutrino collides with a particle in the ice.

The main goal of the IceCube Neutrino Observatory is to observe comparatively scarce neutrinos that are produced during some of the Universe's most violent astrophysical events. However, in its test of Lorentz invariance, the collaboration studied more-abundant neutrinos that are generated when fast-moving charged particles from space collide with atoms in Earth's atmosphere. There are three known types of neutrino: electron, muon and tau. Most of the neutrinos produced in the atmosphere are muon neutrinos.

Atmospheric neutrinos generated around the globe travel freely to the South Pole, but can change type along the way. Such changes stem from the fact that electron, muon and tau neutrinos are not particles in the usual sense. They are actually quantum combinations of three 'real' particles — ν_1, ν_2 and ν_3 — that have tiny but different masses.

In a simple approximation relevant to the IceCube experiment, the birth of a muon neutrino in the atmosphere can be thought of as the simultaneous production of two quantum-mechanical waves: one for ν_2 and one for ν_3 (Fig. 1). These waves are observed as a muon neutrino only because they are in phase, which means the peaks of the two waves are seen at the same time. By contrast, a tau neutrino results from out-of-phase waves, whereby the peak of one wave arrives with the valley of the other.

If neutrinos were massless and Lorentz invariance held exactly, the two waves would simply travel in unison, always maintaining the in-phase muon-neutrino state. However, small differences in the masses of ν_2 and ν_3 or broken Lorentz invariance could cause the waves to travel at slightly different speeds, leading to a gradual shift from the muon-neutrino state to the out-of-phase tau-neutrino state. Such transitions are known as neutrino oscillations and enable the IceCube detector to pick out potential violations of Lorentz invariance. Oscillations resulting from mass differences are expected to be negligible at the neutrino energies considered in the authors' analysis, so the observation of an oscillation would signal a possible breakdown of special relativity.

The IceCube Collaboration is not the first group to seek Lorentz-invariance violation in neutrino oscillations[5–10]. However, two key factors allowed the authors to carry out the most precise search so far. First, atmospheric neutrinos that are produced on the opposite side of Earth to the detector travel a large distance (almost 13,000 km) before being observed, maximizing the probability that a potential oscillation will occur. Second, the large size of the detector allows neutrinos to be observed that have much higher energies than those that can be seen in other experiments.

Such high energies imply that the quantum-mechanical waves have tiny wavelengths, down to less than one-billionth of the width of an atom. The IceCube Collaboration saw no sign of oscillations, and therefore inferred that the peaks of the waves associated with ν_2 and ν_3 are shifted by no more than this distance after travelling the diameter of Earth. Consequently, the speeds of the waves differ by no more than a few parts per 10^{28} — a result that is one of the most precise speed comparisons in history.

The authors' analysis provides support for special relativity and places tight constraints on a number of different classes of Lorentz-invariance violation, many for the first time. Although already impressive, the IceCube experiment has yet to reach its full potential. Because of limited data, the authors restricted their attention to violations that are independent of the direction of neutrino propagation, neglecting possible direction-dependent violations that could arise more generally.

With a greater number of neutrino detections, the experiment, or a larger future version[11], could search for direction-dependent violations. Eventually, similar studies involving more-energetic astrophysical neutrinos propagating over astronomical distances could test the foundations of physics at unprecedented levels. ■

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1. The IceCube Collaboration. *Nature Phys.* https://doi.org/10.1038/s41567-018-0172-2 (2018).
2. Colladay, D. & Kostelecký, V. A. *Phys. Rev. D* **58**, 116002 (1998).
3. Kostelecký, V. A. & Potting, R. *Phys. Rev. D* **51**, 3923–3935 (1995).
4. Kostelecký, V. A. & Russell, N. Preprint at https://arxiv.org/abs/0801.0287v11 (2018).
5. LSND Collaboration. *Phys. Rev. D* **72**, 076004 (2005).
6. The MINOS Collaboration. *Phys. Rev. D* **85**, 031101 (2012).
7. Double Chooz Collaboration. *Phys. Rev. D* **86**, 112009 (2012).
8. MiniBooNE Collaboration. *Phys. Lett. B* **718**, 1303–1308 (2013).
9. Super-Kamiokande Collaboration. *Phys. Rev. D* **91**, 052003 (2015).
10. T2K Collaboration. *Phys. Rev. D* **95**, 111101 (2017).
11. IceCube–Gen2 Collaboration. Preprint at https://arXiv.org/abs/1412.5106 (2014).

GENOME EDITING

Chromosomes get together

Genome-editing approaches have been used to fuse 16 yeast chromosomes to produce yeast strains with only 1 or 2 chromosomes. Surprisingly, this fusion has little effect on cell fitness. SEE ARTICLE P.331 & LETTER P.392

GIANNI LITI

The genomes of nucleus-bearing organisms are divided into linear chromosomes. The number of chromosomes ranges from one to hundreds across species. But why is there such variation? Do specific chromosome numbers hold an advantage for particular species? Shao *et al.*[1] (page 331) and Luo *et al.*[2] (page 392) independently manipulate the genome of the budding yeast *Saccharomyces cerevisiae* by systematically fusing chromosomes, enabling the researchers to explore the consequences of chromosome-number reduction.

Normal *S. cerevisiae* genomes have 16 distinct chromosomes ($n = 16$), which range from 230 to 1,532 kilobases in length[3]. To function correctly, yeast chromosomes need protective structures called telomeres at both ends, and only one centromere — a region that ensures the accurate segregation of chromosomes into mother and daughter cells during cell division. Simply fusing the ends of two chromosomes is therefore not a viable strategy for reducing chromosome number because it would produce chromosomes containing two centromeres.

To solve this problem, the two groups used genome-editing tools to fuse sequences found adjacent to one of the telomeres in each chromosome, and to simultaneously remove one of the two centromeres (Fig. 1). Using this approach, they reduced the chromosome number step by step, producing strains that had progressively lower values of n. The fusion strains comprised genomic material that is almost identical to that of normal *S. cerevisiae*, differing only in chromosome number and by a few non-essential genes that were deleted during strain creation.

Luo *et al.* produced an $n = 2$ strain containing chromosomes that were each about 6,000 kb long. However, they were unable to fuse the two chromosomes into one as part of a viable cell. By contrast, Shao *et al.* successfully fused the entire *S. cerevisiae* genome into a single chromosome in a functional yeast.

Given that each group used similar strategies, it is interesting to consider why only one of the teams could fuse the final two chromosomes. A possible explanation is that