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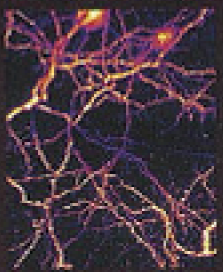

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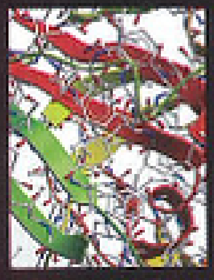

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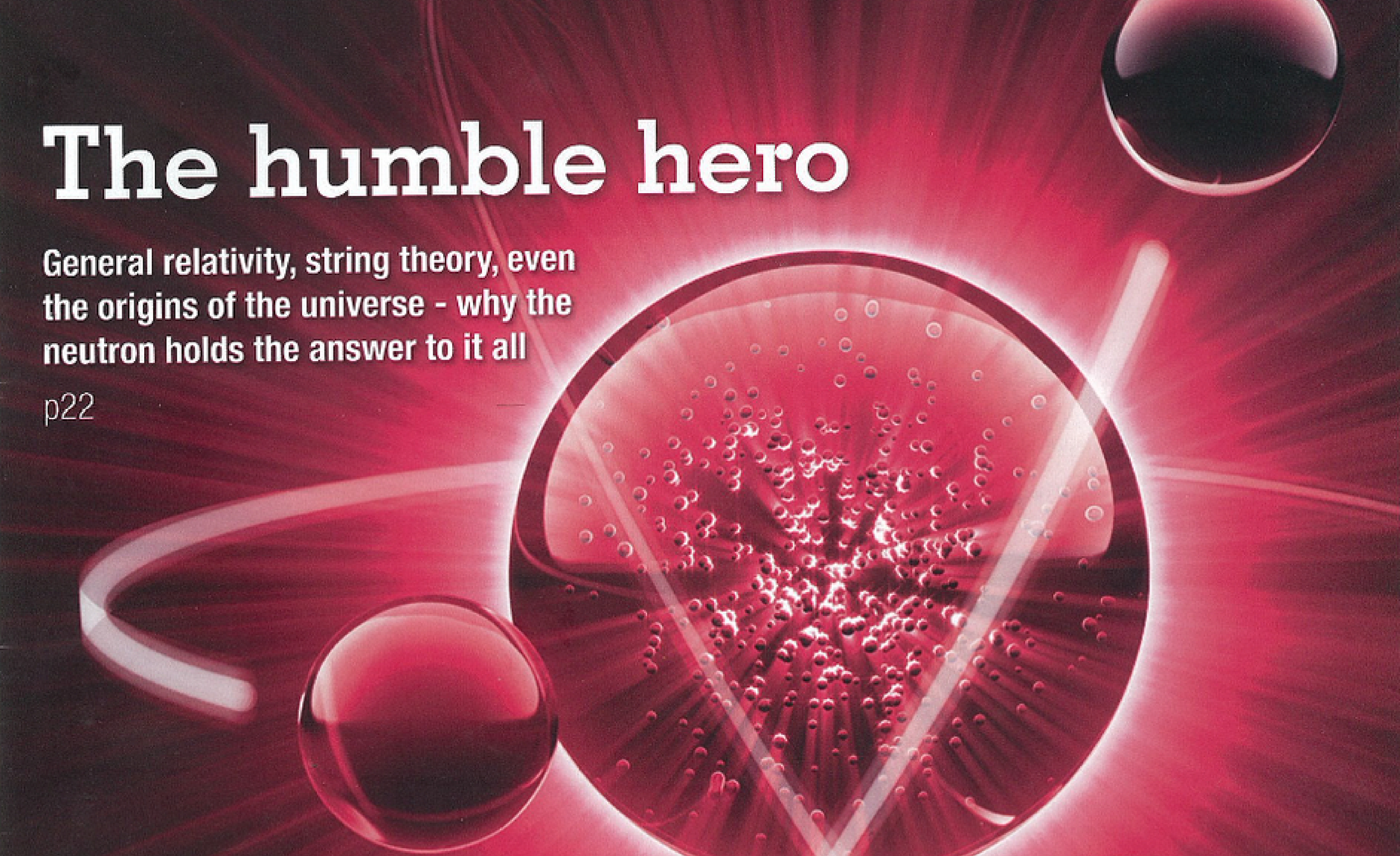

The humble hero

General relativity, string theory, even the origins of the universe - why the neutron holds the answer to it all

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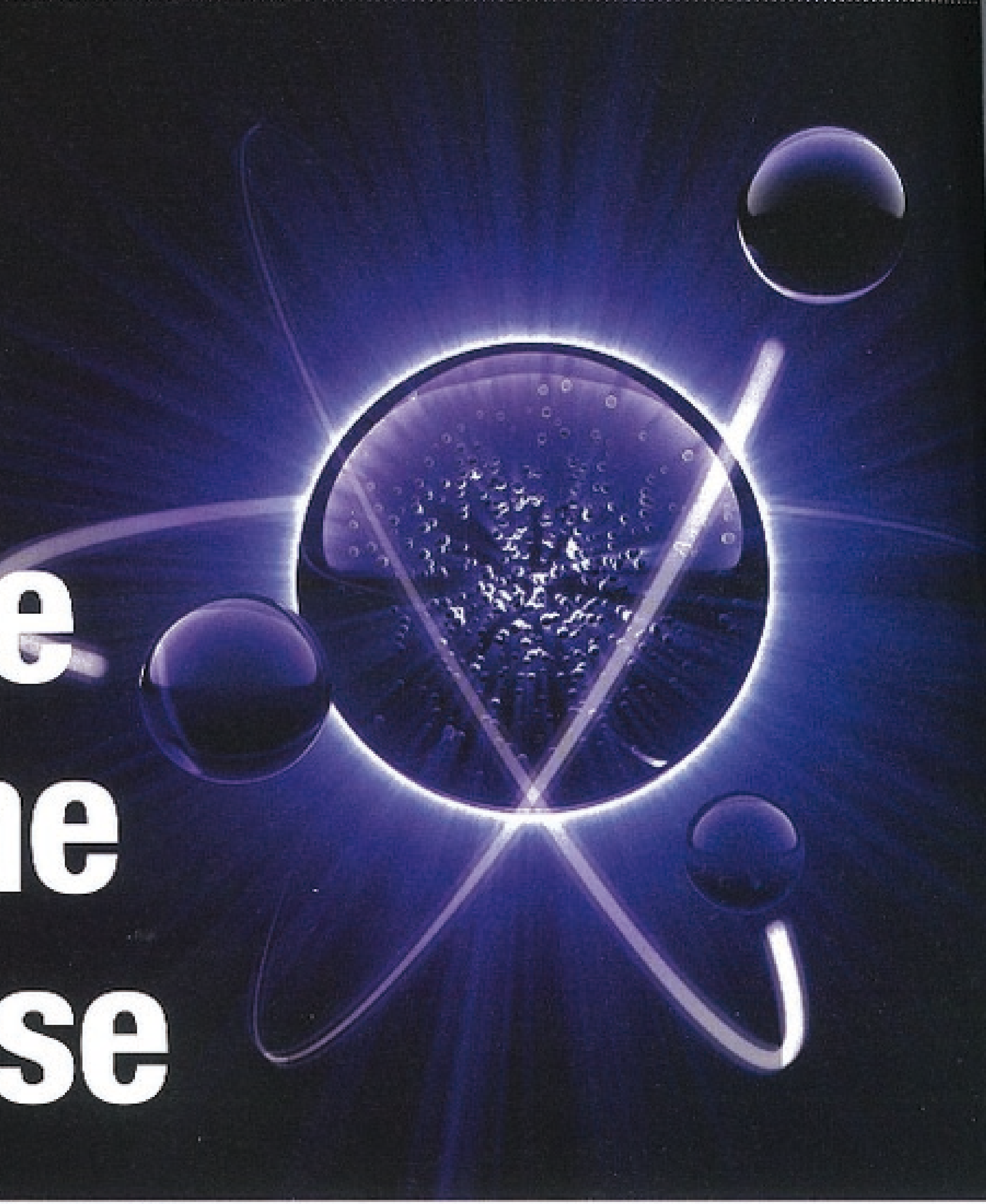


Unveiling the secrets of the early universe

Neutrons are exceptionally powerful tools for answering questions in many scientific disciplines. Ultra-cold neutrons move no faster than you can run but may completely change our understanding of the universe. Dr Peter Geltenbort explains how…

The simple neutron is a uniquely powerful research tool, shedding light on the structure of matter through the recording of its interaction with samples' atomic and molecular structures at neutron science facilities around the world. In over four decades of operation at Institut Laue-Langevin (ILL), the world's flagship centre for neutron science, this most flexible and useful of scientific particles has delivered scientific breakthrough in areas as diverse as nanotechnology and the magnetic phenomena that underpin future computing to biochemical engineering, energy storage, food science, drug synthesis and molecular biology. However there is another string to the neutron science bow which focuses on the study of the particle itself and could answer some of the most fundamental questions about the universe and the very nature of reality.

Our existing view of what makes up our Universe at its most basic level is generally described by the Standard Model but this still leaves many questions unanswered. Some of these are being tackled using the highest energy instruments ever constructed such as the Large Hadron Collider to mimic conditions in the early Universe. However, there is another approach: by studying subtle changes in the behaviour of neutrons that only reveal themselves at very low energies, scientists at the ILL lead a global community of researchers who slow neutrons down until they have lost most of their energy.

Known as ultra-cold neutrons, they move no faster than you can run. More importantly they can be stored in special traps, enabling scientists to perform measurements of their fundamental properties with unprecedented high-precision that could in time completely change our understanding of the universe and the story of its birth. Though stable for billions of years within their atoms, if released neutrons quickly decay after about 15 minutes. However, there is significant uncertainty around how long this actually takes. In over 60 years of experiments, interest in this precise value has grown substantially because of a number of fundamental questions it could help answer.

The first concerns the origin of the first matter. During the first moments of the universe, protons and neutrons formed the first elements – hydrogen, a little helium and traces of lithium. However the exact ratios of three elements, vital for testing theories of the early universe, are unknown and can only be calculated by knowing the neutron's true lifetime.

A precise lifetime would also help predict the total amount of matter in the universe and therefore how much mysterious dark matter there must be to make our theories of the universe's evolution work. Finally, as the decay of free neutrons is based purely on the weak interaction, precise measurement of the timescales involved could tell us much about the true strength and structure of this fundamental force.

There are two experiments attempting to improve the accuracy of this measurement. At the ILL our scientists bottle ultra-cold neutrons and count those that survive after different storage times whilst at the National Institute of Standards and Technology in Maryland researchers count the neutrons and then determine the number of protons left behind. So far these two approaches have reduced the uncertainty to roughly two seconds.

The second area of concern lies at the heart of the biggest challenge in physics. The unification of gravity with the other forces predicts some curious effects on extremely small length-scales and Einstein's explanation of the force through General Relativity should start to fall down. Because neutrons have a small mass but are electrically neutral, and are therefore insensitive to electric fields, they are ideal tools for investigating gravity at the microscopic scale.

In 2002 ILL scientists bounced ultra-cold neutrons along a mirror to observe their various quantum energy states. The neutrons were shot between two parallel plates separated by about 25 micrometres – half a hair's width. The upper plate absorbed neutrons, and the lower mirror plate reflected them. They demonstrated that neutrons falling in a gravitational field do not drop like a stone but descend in distinct "quantum leaps".

Last year a research team from the Vienna University of Technology and the ILL modified a similar set up and created a new technique named Gravity Resonance Spectroscopy. By vibrating the underlying mirror at particular frequencies, researchers were able to boost the falling neutrons to higher quantum energy states. Using this technique future research will be able to measure more precisely the energies behind the various quantum states.

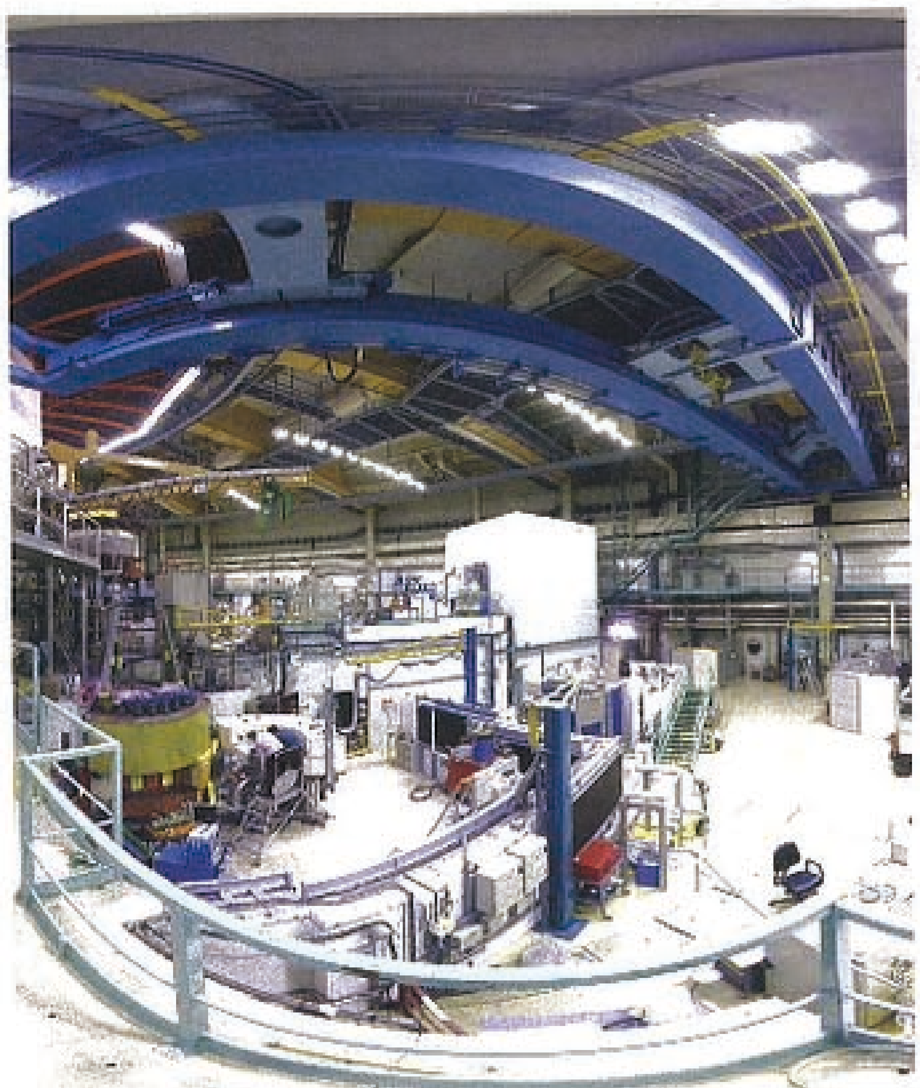
Some physicists believe these measurements will reveal a slight divergence with those of Newtonian gravity, a disparity that could provide evidence of dark matter particles known as axions or the extra dimensions suggested by string theory.

It could also test the equivalence principle that states gravity accelerates all objects equally, regardless of their mass. In 1971, it was famously demonstrated on the moon by Apollo astronaut Dave Scott who dropped a hammer and feather which landed simultaneously. Researchers hope to use this new technique to test the principle's accuracy for elementary particles with unprecedented accuracy.

The unification of gravity with the other three fundamental forces would take us far beyond current particle physics as described by the Standard Model. Here lies a highly active research area and there are several classes of theories being considered. Many are based on a concept favoured by many physicists, that of symmetry. A number of symmetries predicted by the Standard Model are broken by experimental or theoretical evidence. One is time reversal which suggests that time is symmetrical whether it is run forward or backwards. Though key to the Standard Model, many scientists agree that it must be violated in order to explain the survival of matter at the expense of antimatter after the Big Bang (thus securing our existence).

With neutrons, a number of hypothetical new channels for this 'T-violation' are being investigated. One of these is the search for the electric dipole moment of the neutron. Though the neutron appears neutral overall, there are still small opposing electric charges deep within it. If the average positions of these charges do not coincide the neutron would have an electric dipole moment (EDM) meaning it would be affected by an electric field, and would provide the violation required to explain the abundance of matter in the universe. If the neutron does contain an EMD we can guarantee it will be tiny. If we blew a neutron up to the size of the Earth, the maximum charge separation of a proton and an electron would be less than a hair's width. Experiments with ultra-cold neutrons can look for a signal that the EDM would give by storing the neutrons in a cell that is submitted to a combination of a weak magnetic and strong electric field. So far the EDM remains elusive but the search continues at ever more precise scales.

After over half a century of experiments, the field of ultra-cold neutron research is still going strong. A variety of new sources are planned or under construction and together with the ILL, the global leader in the field, this growing community is only just starting to shine a light on the secrets these extremely cold particles hold about the nature of the universe and the origin of everything within it. LN



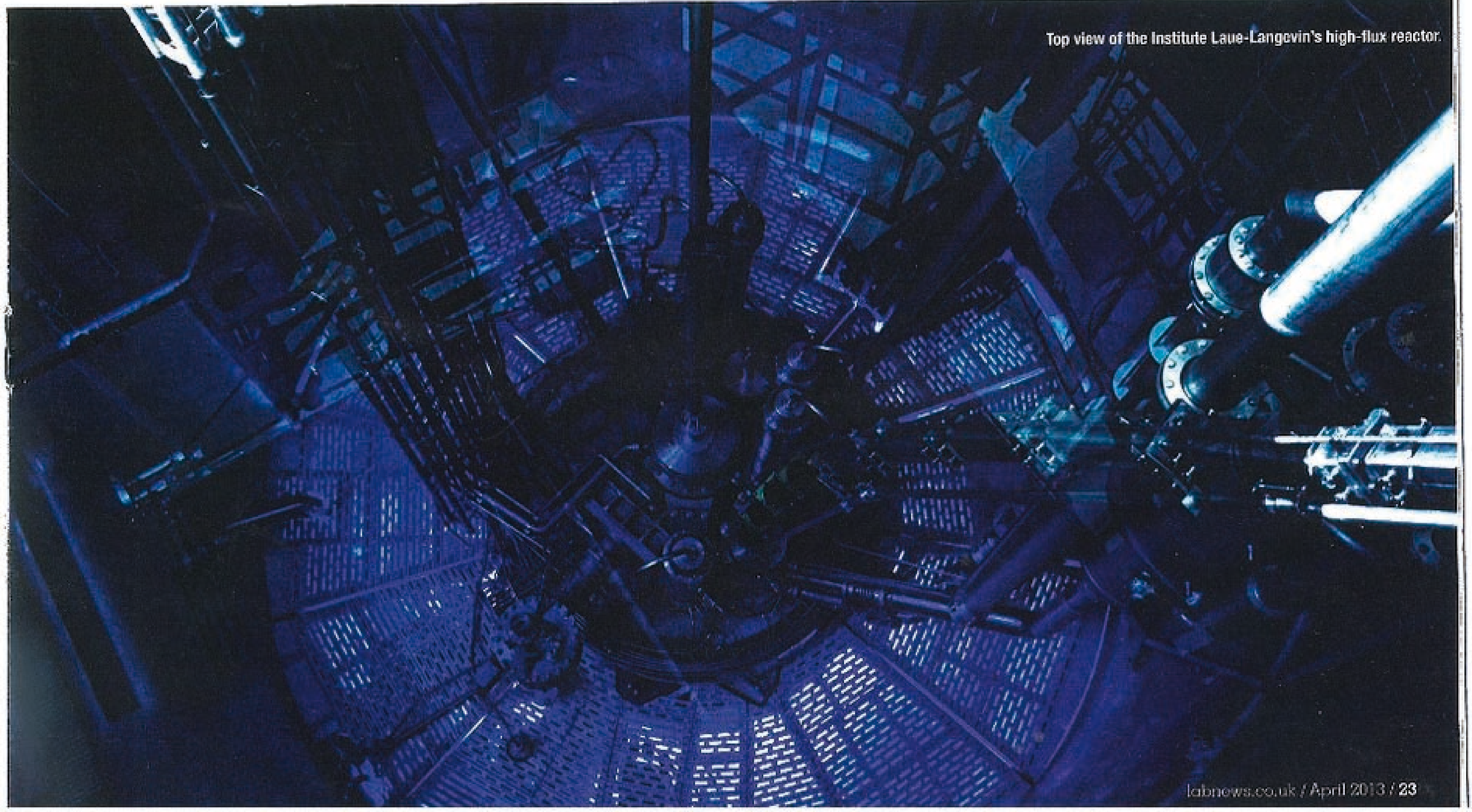
The high-flux reactor at the ILL.

THE AUTHOR

Dr Peter Geltenbort is a physicist at the Institut Laue-Langevin

CONTACT

+33 4 76 20 72 42



Top view of the Institute Laue-Langevin's high-flux reactor.