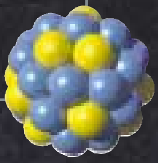
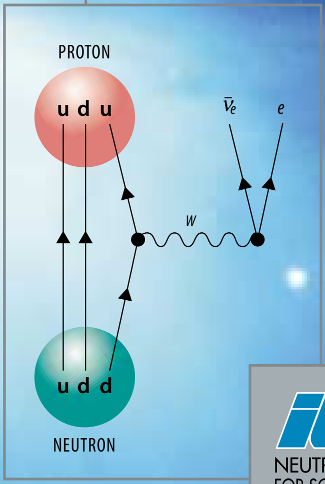
HIGHLIGHTS OF ILL RESEARCH



Neutrons and the Universe

a review of ILL research in fundamental and nuclear physics



NEUTRONS
FOR SCIENCE

This booklet belongs to a series devoted to the application of neutron techniques in different research areas.

We have already published:

Exploring matter with neutrons (May 2000)

Neutrons and life (May 2001)

Neutrons and new materials (May 2002)

The next one will be published in 2004.

Foreword

Our views about the building blocks of Nature – fundamental particles and forces – have evolved dramatically over the past decades. We now have models that attempt to unify the forces and particles, and describe how they came into existence in the very early Universe. Similarly at the next level, theories have been developed which explain how particles interact through forces to form the highly complex nuclei comprising the atoms of everyday matter.

The existing fundamental particles and relevant forces can be described within the framework of the so-called Standard Model. Although highly successful, the Standard Model leaves many questions unanswered and various extensions to the theory have been put forward. To test these models, particle physicists have designed experiments over a wide range of energies. The most ambitious projects aim to collide particles at TeV energies, trying to mimic conditions thought to prevail in the early Universe. The structure of nuclei can also be investigated through collisions, but at a lower energy scale.

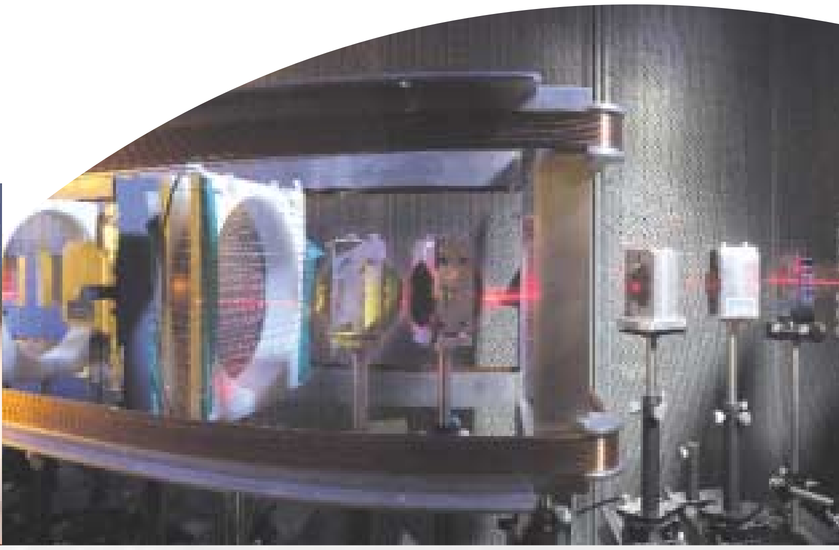
There is another approach, however – which is to search for subtle physical behaviour that reveals itself only at very low energies. This is what the ILL does in uniquely sensitive experiments using neutrons with energies in the sub-eV range. The cold or ultra-cold neutrons produced at the ILL can tell us a great deal about the 'symmetry' characteristics of particles and their interactions – perhaps helping to explain, for example, how the Universe came to contain mainly matter and not antimatter, even though created in equal amounts.

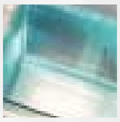
Neutrons at the ILL are also used to investigate the structure and behaviour of nuclei by generating excited nuclear states. Although atomic nuclei have a finite number of constituents – neutrons and protons – they display extremely diverse modes of excitations associated with both single-particle and collective behaviour, and can be regarded as miniature laboratories for studying complex, strongly interacting systems. The ILL is also able to create exotic nuclei with high numbers of neutrons to explore the pathways by which elements are made in the stars.

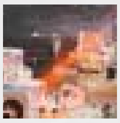
Because neutrons can behave as waves, they can probe the subtleties of quantum behaviour such as nonclassical 'Schrödinger-cat' states – of great significance in current condensed matter and fundamental physics research. As another example, the recent observation at the ILL of the quantisation of neutron states due to the Earth's gravitational field has experimentally confirmed the coexistence of the gravitational force with quantum mechanics, and has opened up a new field of pico-eV spectroscopy.

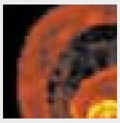
This brochure explains some of the achievements made at the ILL in nuclear and particle physics using neutrons at low energies. The ILL has maintained a diverse suite of neutron sources and instruments to engage in a wide range of scientific topics, and is proud of the advances made in this field. The development and renewal of the ILL's infrastructure will enhance the low-energy neutron sources to contribute to a better understanding and unification of the fundamental forces in Nature. □

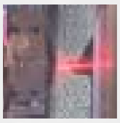
Dr Christian Vettier
Associate Director
Head of Science Division

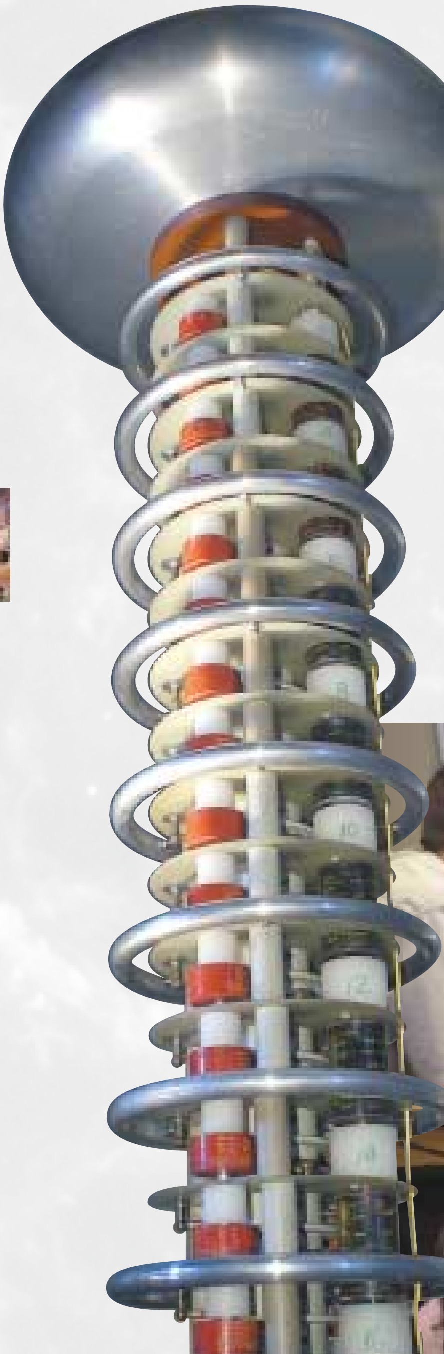












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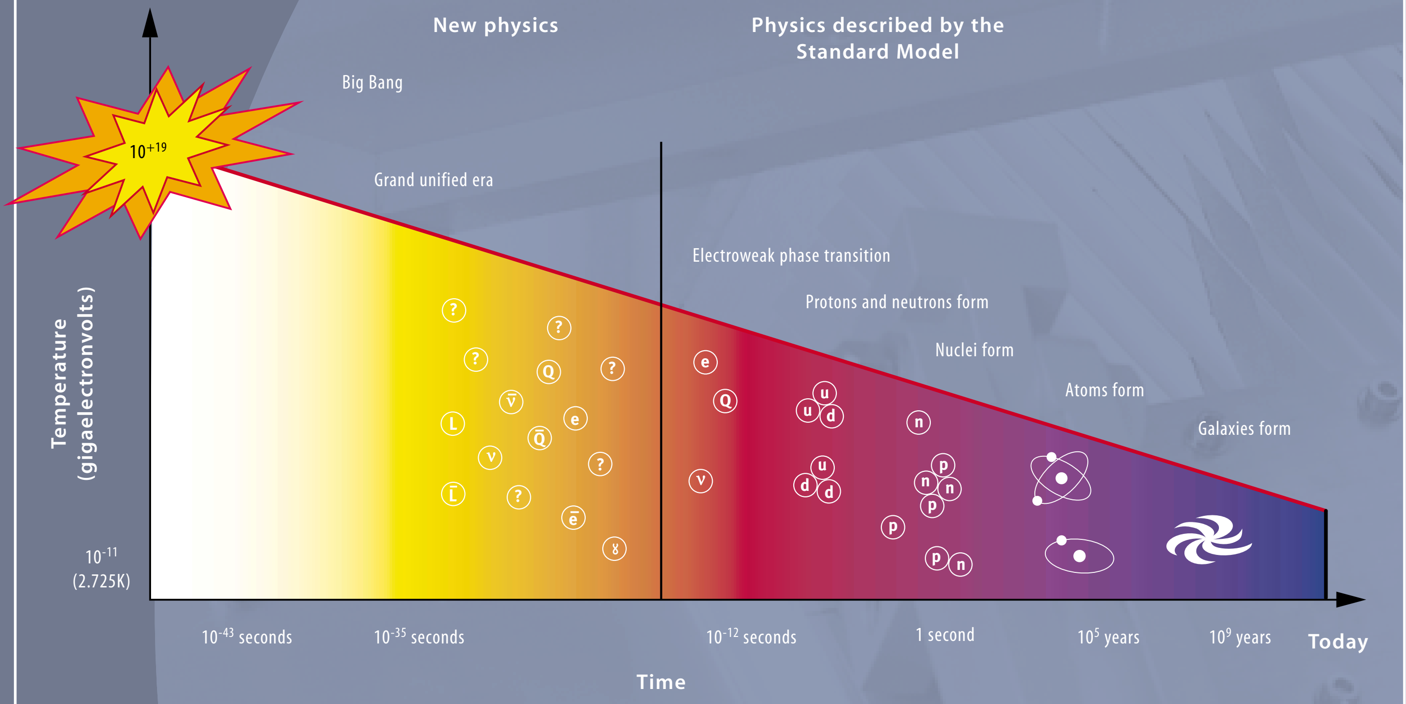
The neutron, the Universe and the fundamental forces

Measurements using low-energy neutrons are leading to a better understanding of the fundamental forces and the nature of the Universe



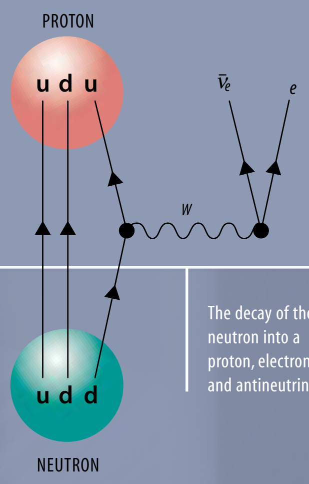
The evolution of matter in the Universe

Most people have heard of the huge machines that accelerate and collide subatomic particles at incredibly high energies in order to study the elementary units of matter and the forces governing their behaviour. However, some important questions about these building blocks of the Universe can be studied by carrying out subtle, very precise experiments at extremely low energies. This is what we do at the Institut Laue Langevin (ILL), using neutrons produced by the research reactor. We make hot, thermal, cold, and ultra-cold neutrons with velocities of between a few kilometres and a few metres per second, corresponding to kinetic energies in the electronvolt-to-nanoelectronvolt range. This is some 20 orders of magnitude less than the energies generated by accelerators.

Here, we describe how the neutron is a suitable tool for investigating the four known fundamental forces of Nature – electromagnetism, the weak and strong forces, and gravity. The first three forces, as well as all the known fundamental particles, are described by a very successful theory called the Standard Model of Particle Physics. The matter particles are divided into a series of three families, each consisting of two quarks (such as the up and down quarks found in protons and neutrons) and two leptons (such as electrons and neutrinos). The forces are mediated by carrier particles – the photon (the carrier of light) for the electromagnetic force, the W and Z particles which carry the weak force, and the gluon which carries the strong force. However, the theory is by no means complete; for instance, gravity is not yet included. Physicists would like to unify all the forces into a single theoretical description that would explain fully how the particles and forces came into being when the Universe was created in the Big Bang about 15 billion years ago. Experimentalists are looking for phenomena that provide evidence of physics going beyond that explained by the Standard Model. Neutron studies are not only providing us with precise information on the ideas we already have but may well also shed light on these new theories.

Electromagnetism

The electromagnetic force acts between all electrically charged particles, such as the negatively charged electrons and positively charged protons making up the atoms of everyday matter. This force is responsible



The decay of the neutron into a proton, electron and antineutrino

>> **TORSTEN SOLDNER AND DIRK DUBBERS**

for chemical bonding and electrical conduction, and controls all living processes – even how our muscles move. Neutrons, also found in atoms, are themselves electrically neutral; nevertheless they provide some important results concerning electromagnetism.

In fact, according to the Standard Model, there is no reason why the neutron's charge should be zero. However, new theories unifying the forces do require the neutron to be exactly neutral. Indeed, a high-precision experiment carried out at the ILL has proved this to be the case (up to 21 decimal places after the zero!), as required by the new theories beyond the Standard Model.

The neutron can also be used to determine the basic strength of the electromagnetic interaction, which is given by a quantity called the fine-structure constant α. This has to be determined experimentally by linking very precise data from atomic and nuclear physics to a similarly accurate measurement of the velocity of free neutrons with a well-defined wavelength. The product of velocity and wavelength is equal to the ratio of Planck's constant h (another important constant in fundamental physics, which relates the energy of a particle to its wavelength) to the mass of the neutron, h/m_n. From this ratio and the other data, α can be derived. Such a measurement of h/m_n at the ILL gave a relative accuracy of 3.9×10^{-8} for α. This result can be compared with other measurements of the fine-structure constant, for example, based on the magnetic moments of electrons and muons (the latter are particles similar to electrons but heavier). Such comparisons make it possible to examine closely the theory of electromagnetism in the framework of the Standard Model.

The weak force

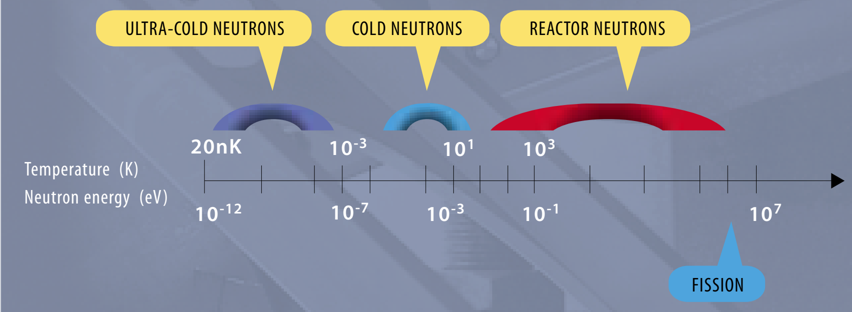
The weak force does not appear to play a noticeable part in everyday life, mainly because it has an extremely short range. Nevertheless, the weak interaction is actually vital to our existence. It determines the rate of the nuclear fusion processes that make the Sun and other stars burn, and thus their temperature.

We have known for about 20 years that the weak force and the electromagnetic force are components of a more fundamental, unified force called the electroweak interaction. We believe that the two forces separated when the Universe cooled down just after the Big Bang (see the 'electroweak phase transition' in the diagram opposite). Unlike the electromagnetic interaction, the weak force retained a number of exotic properties. For example, it is the only fundamental force that distinguishes between left and right-handedness, and between particles and their 'antimatter' partners (which are identical but have the opposite charge): it exclusively acts on left-handed particles and right-handed antiparticles.

These peculiar characteristics of the weak interaction manifest themselves in the behaviour of neutrons, so they make an excellent probe of this fundamental force. A neutron is stable when bound in the nuclei of atoms, but when free, it decays on average after about a quarter of an hour into a proton, an electron and a particle called an antineutrino (see the diagram above). This decay is based purely on the weak interaction, and the free neutrons produced in large numbers at the ILL can be used in experiments to determine precisely the lifetime of the neutron (see p.9) and several other neutron decay parameters, which tell us about the strength and structure of the weak force.

The decay of the free neutron also plays an important role in precision tests of the weak interaction that may reveal physics beyond the Standard Model. One topical example examines whether the Standard Model's description of the effect of the weak interaction on the various quark families ('quark mixing') is correct (see p.10).

The range of neutron energies produced at the ILL



The neutron, the Universe and the fundamental forces

New equipment for measuring the neutron electric dipole moment

The neutron's lifetime is significant in cosmological theories seeking to explain the origin and evolution of the Universe. The lightest elements, hydrogen, helium and lithium, are thought to have formed in the first three minutes after the Big Bang, and their predicted relative amounts compared with what is actually observed in the Universe is one of the strongest pieces of evidence for the Big Bang model. The neutron lifetime influences significantly the abundances of the light elements. It is only in recent years that measurements of the lifetime have been sufficiently accurate to allow researchers to make reliable calculations.

Two other important values can be derived from these element abundances. The first relates to the number of particle families that exist. This number strongly influences the expansion of the early Universe and with it the abundances of the lightest elements. Calculations of the abundances showed that the number of particle families is limited to three, and only three – a figure confirmed with high precision shortly afterwards in high-energy particle physics experiments.

The second significant quantity is the density of baryonic matter in the Universe. This is the ordinary matter we know – the nuclear matter consisting of protons and neutrons – which makes up all the stars and planets in galaxies. Research in this area has produced surprising results, namely that only around one-tenth of this baryonic matter is visible in the stars, and that the rest must be hidden in exotic invisible objects such as black holes or neutron stars, or in intergalactic space. Furthermore, various recent astrophysical observations indicate that the baryonic matter makes up only about 4 per cent of the total matter-energy density of the Universe. The rest seems to consist of about one-third unknown 'dark exotic matter' and two-thirds unknown 'dark energy'.

The strong force

The strong interaction affects only the quarks, binding them into particles like protons and neutrons. It too has a short range and has one peculiar characteristic: the particles that carry the strong force, gluons, also interact with one another via the strong force. As a result, quantitative predictions about the strong interaction are extremely difficult. Such calculations have to be verified experimentally. For example, we would like to know the strength of the force needed to pull quarks apart (they are never found singly). This can be done by measuring the electric polarisability of the neutron. Here, the quarks are pulled apart by a strong electric field which acts on the electric charges of the quarks. Nuclear structure studies also provide very detailed qualitative information about the properties of the strong force (see p.18).

Gravitation

Although gravitation is the most familiar of the fundamental forces, its theoretical description does not as yet fit with that of the other interactions. The most successful theory to date is Albert Einstein's General Theory of Relativity, which interprets gravitation as the curvature of space-time. This geometrical approach is fundamentally different from the description of the other three forces which is based on quantum field theories. Ideally, theorists would like to find a quantum theory of gravity.

Neutrons have a mass so feel the gravitational force. They are ideal particles for studying gravity at the microscopic level: they are electrically neutral; easy to detect; have a relatively long lifetime; and reflect well off mirrors. Recently at the ILL, quantum states of the neutron in the Earth's gravitational field were successfully observed for the first time (see p.14).

Why are such experiments important? Until now, gravitation has been tested only on a large scale by observing the movements of stars and galaxies or in

Measuring the polarisation of cold neutrons

Earth-bound experiments such as Galileo's famous free-fall tests. However, some theories for unifying gravity with the other forces predict some curious effects on extremely small length-scales which may throw new light on the nature of the Universe. The ILL experiment studied gravity in the free fall of single particles at a length-scale of micrometres and an energy scale of picoelectronvolts, in other words, in a significant regime not accessible with conventional gravitation experiments.

The neutron and new physics

Unification is an important concept in understanding physical laws and the existence of the Universe. It has been successfully achieved for the electromagnetic and weak forces. However, unification of all the forces would take us far beyond current particle theories. Beyond-the-Standard-Model physics is a highly active research area and there are several classes of theories being considered. These are based on a concept favoured much by physicists, that of symmetry.

In the Standard Model we have two symmetries that are completely broken by the weak interaction, namely parity *P* (between left and right-handed particles) and charge conjugation *C* (between matter and antimatter). How we can understand the origin of these symmetry violations? Most popular today are theories that start with a highly symmetric Universe, in which left and right-handed particles are equivalent at the prevailing very high energies. The asymmetries in our present low-energy Universe are then explained by 'spontaneous symmetry breaking' during one of the 'phase transitions' between different states of the Universe, as depicted in the diagram on p.4. Experiments searching for evidence of such left-right symmetric theories can be carried out using neutrons (see p.11).

Another symmetry, time reversal *T*, is broken only to a very small degree in the Standard Model. *T*-violation turns out to be necessary to explain the survival of matter at the expense of antimatter after the Big Bang (thus securing our existence). This mechanism, called baryogenesis, however, cannot be accommodated into present-day theories. It may even require as yet unknown *T*-violating effects and is a very strong motivation for probing 'new physics' beyond the Standard Model. With neutrons, hypothetical new channels of *T*-violation are investigated by searching for an electric dipole moment (see p.13) and for small asymmetries in the neutron decay (see p.12).

These neutron experiments may reveal the faint traces of 'new physics'. Thus the neutron can be used not only to test very precisely our current knowledge of fundamental physics but also as a delicate probe in uncovering a deeper understanding of how our Universe works. ■

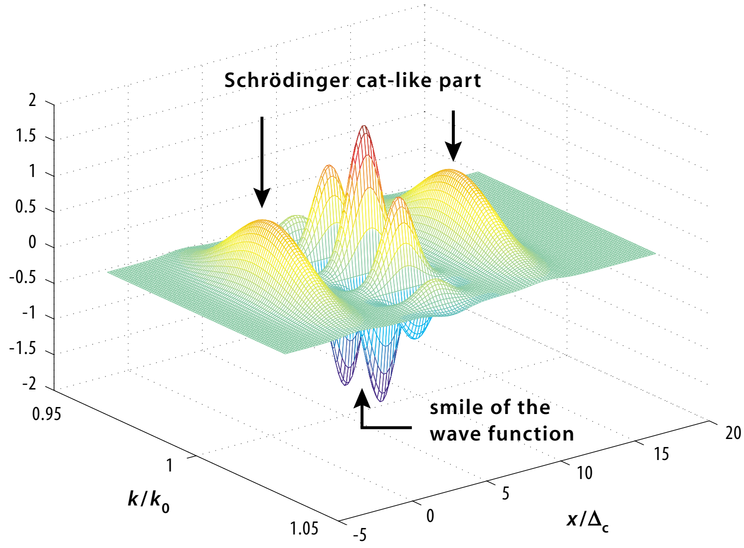
The particle families

I	II	III	
u up	*c* charm	*t* top	
d down	*s* strange	*b* bottom	quarks
ν_e e-neutrino	ν_μ μ-neutrino	ν_τ τ-neutrino	
e electron	μ muon	τ tau	leptons

The dancing neutron

Interferometry experiments
are revealing the strange
quantum heart of the neutron

>> **HELMUT RAUCH**

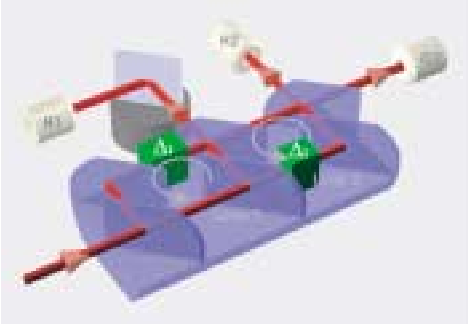


The Wigner function representing a neutron behind the first interferometer loop when a large phase shift is applied, and the neutron wave function becomes separated in space indicating a Schrödinger cat-like quantum state

Quantum theory is one of the most successful theories of Nature that we have. It can be used to describe the behaviour of a variety of objects: elementary particles such as electrons and photons, nuclear constituents (protons and neutrons), atoms and even molecules. Some characteristics predicted by quantum theory are not easy to understand however. For example, microscopic objects can behave as either particles or waves. Since quantum mechanics is a general theory, the wave-like characteristics of a particle can be thought of as representing the probability distribution of where the particle can be found. Another peculiar aspect is that a quantum system changing from one state to another actually exists as an entangled state, or 'coherent superposition', of those states until measured in some way. This idea is famously illustrated by Schrödinger's famous paradox: a cat locked in a box with a lethal chemical poison triggered by a radioactive source (whose decay is governed by quantum probability) remains in an indeterminate, alive-and-dead superposition of states until the box is opened.

Schrödinger-cat states of neutrons

Can these so-called Schrödinger-cat states be studied for particles like neutrons? Even though neutrons are massive, they do show wave-like behaviour, which means that neutron waves out of phase can either reinforce or cancel each other to produce an interference pattern. Using neutron interferometry, a coherent superposition of neutron states can be created and observed. A neutron (wave) is split into two beams by diffraction from a perfect silicon crystal. Even though the beams are separated by several centimetres, their quantum states remain inextricably linked (another peculiarity of quantum systems). One of the beams is passed though devices (marked in green opposite) that delay or accelerate the neutron wave so that it is out of phase with the other beam. The beams are now in different states yet still entangled, so when they are then recombined they reveal a quantum superposition which can be detected and measured.



A double-loop interferometer in which nonclassical neutron states can be produced and analysed

The quantum states can be visualised as a kind of probability distribution called a Wigner function (above). It shows the two Schrödinger-cat states as separate peaks, and in between a series of wiggles, called 'the smile of the wave function,' which point to how the states are coupled. By varying the phase shifts between the beams and the timing of recombination, the wiggles and the position of the peaks can be varied in a wide variety of ways.

This 'dancing' Wigner function of the neutrons shows how much information can be stored in these dead-and-alive Schrödinger-cat states. More complex Wigner functions can be produced with more smile regions, so providing a pathway to the production of quantum-engineered neutron states. These 'nonclassical' states behave quite differently from the normal neutron states and give us new insights into the behaviour of matter.

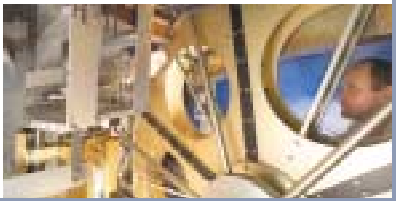
Another closely related phenomenon has recently been explored at the ILL which also shows the nonlocal nature of quantum mechanics. When a neutron, tiny though it is (confinement radius about 0.7 femtometres), passes through a narrow slit system it seems like the neutron 'feels' the walls. The explanation of this intriguing effect is as follows. The slits cause the transverse motion of the particle to be quantised (forming a series of energy levels as would happen if a particle were confined in a box or an atom). This produces a longitudinal phase shift which can be measured by neutron interferometry. This effect exists even if the neutron classically does not touch the walls at all.

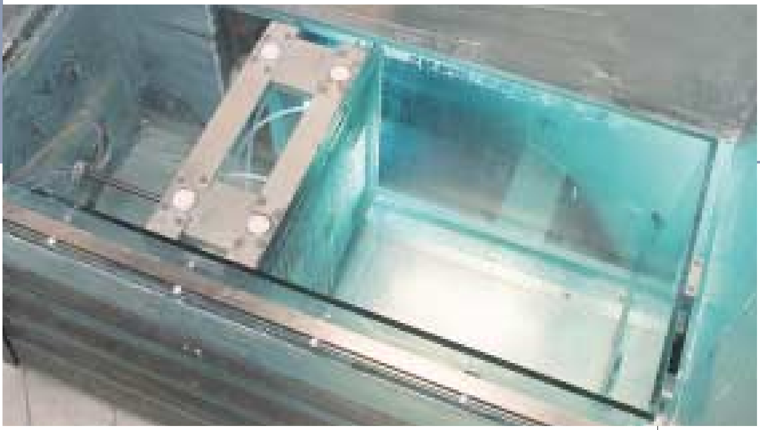
These two examples offer a small glimpse into the broad range of neutron interferometry experiments possible. And even after almost 30 years of research in this exciting field, still new ways of exploring questions of fundamental physics with neutrons open up. ■

Research team H. Rauch, G. Badurek and M. Baron (*Atomic Institute of the University of Vienna*)

The lifetime of the neutron is a key factor in explaining the evolution of the Universe – and our existence

Neutrons are not forever





Fomblin-coated storage volume (made of glass) of the MAMBO II lifetime experiment

>> JAMES BUTTERWORTH AND PETER GELTENBORT

Although most of the neutrons in the world around us are bound into the nuclei of atoms which have been stable for billions of years, once released from this environment, they rapidly decay into protons, electrons and antineutrinos (called beta decay). The lifetime of the free neutron is about 15 minutes (or more precisely, 886 seconds).

Knowing this number is important for understanding the creation of elements in the Universe. Neutrons, with protons, would have been made in the first instances after the Big Bang. Had the neutron lifetime been much smaller, the Universe would consist almost entirely of hydrogen – much larger and it would contain only helium. Luckily, the half-life is such that the early Universe contained both hydrogen and helium, which were then able to combine inside stars to form all the other elements which are vital for life. The precision to which the relative abundance of these elements can be calculated (see pp.16 and 17) is limited by the uncertainty in the measurements of the neutron lifetime, currently about 2 seconds.

Beyond the Big Bang, the neutron lifetime also has implications for our lives today. It is an important parameter governing the rate at which two hydrogen nuclei can fuse to form deuterium – a crucial step in the energy-releasing cycle that fuels the Sun.

Finally, precise measurement of the neutron lifetime combined with results obtained from other neutron beta-decay experiments (see p.11) can give us information about the fundamental forces acting inside the neutron itself.

Peter Geltenbort and Thomas Brenner

Measuring the lifetime

The first neutron lifetime measurements were performed with neutron beams obtained from nuclear reactors such as the ILL. Although it is almost impossible to observe the antineutrino emitted during neutron decay, the electron and proton can be readily detected. If we know the number of neutrons in a given volume at a given moment, the rate at which electrons and protons are emitted from this volume gives us directly the neutron lifetime. The problem arises in knowing exactly how many neutrons are in the volume and even the size and shape of the volume to which our detectors are sensitive.

In the 1970s, techniques were developed for obtaining ultracold neutrons with such low energies that they could be confined inside a bottle for periods approaching their lifetime. In a perfect bottle, relative measurements of the number of neutrons remaining after two different storage times are sufficient to determine the lifetime.

In reality, a few neutrons are lost when they encounter the bottle wall, so that their number decreases slightly faster than expected from beta decay alone. Several methods have been employed to adjust for this error. One involves performing the experiment several times using bottles of different sizes. As the size of the bottle is increased, the rate at which the neutrons collide with the walls is reduced. By extrapolating the data to the point where the collision rate is zero (an infinitely big bottle!) we can eliminate the effect of the walls.

A more recent approach is to confine ultra-cold neutrons using magnetic fields (neutrons have a magnetic moment so respond to a magnetic field). In the absence of material walls the losses can be eliminated and the decay can be followed in real time. This method has been demonstrated at the ILL and the National Institute of Standards and Technology in the US, and will probably form the next generation of measurements. ■

Research team J. Butterworth, P. Geltenbort and Th. Brenner (*ILL*), *in collaboration with TU Munich, PNPI* (*Gatchina, Russia*) *and the Kurchatov Institute* (*Moscow*)

Part of the neutron decay experiment, PERKEO II

>> **HARTMUT ABELE**

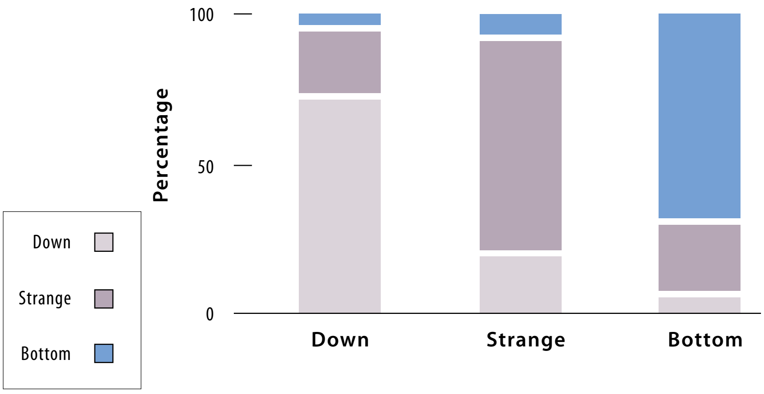
The ILL's unique source of cold neutrons is ideal for probing the strength of the weak interaction – and looking for new physics beyond the Standard Model

Quark mixing in neutrons

According to the accepted theory of particles and fields, the Standard Model, matter is built from two types of fundamental particles – quarks and leptons (see p.4). Quarks come in six varieties or flavours called up (u), down (d), charm (c), strange (s), top (t) and bottom (b). The familiar neutrons are built from two d-quarks and one u-quark, whereas protons are built from two u-quarks and one d-quark. Thus, ordinary matter is made exclusively from up and down quarks, whereas the other quark flavours are observed in particles made in high-energy collider experiments.

Quarks interact, among other things, via the strong and weak forces (see p.4). The weak interaction has the peculiar effect of allowing one type of quark to change into another type. This is what happens when a neutron decays via beta decay into a proton, an electron and an antineutrino (see p.5) – a d-quark (in the neutron) changes into a u-quark (in the proton). In this process, quantum theory predicts that the quark states are not 'pure' – the decaying down quark carries small contributions from strange and bottom quarks (similarly, a decaying bottom quark has small contributions from a down and a strange-quark, and so on). The strengths of the 'quark mixings' can be laid out in a useful mathematical way in a three-by-three array called the Cabibbo-Koyabishi-Maskawa (CKM) matrix. The Standard Model requires that the mixing ends up as a zero-sum – in other words, each quark gives as much as it takes (technically, the CKM-matrix is said to be unitary). Probing this unitarity condition is thus an important test of the Standard Model.

Mixing of down, strange and bottom quarks. Here in this mixture, every quark gives as much as it takes



Measuring asymmetry

At the ILL, we have been doing just this, by studying the mixing of the down quark (first element in the CKM matrix) in the beta decay of cold, free neutrons. The principle is to prepare a highly-polarised neutron beam (with 100 per cent of the neutron spins aligned). As explained in the article opposite, the electrons are preferentially emitted in a direction opposite to the spin of neutron in a proportion predicted by the Standard Model. Applying a magnetic field separates the differently oriented electrons, sending one kind to detectors located on the left and the other to detectors on the right. The count rate of electrons measured by the left and right detectors differs by several per cent (beta-asymmetry). Combining this asymmetry, which in effect measures the strength of the weak interaction, with the neutron lifetime gives values directly related to the CKM quark-mixing matrix, in particular the first element.

Using recently upgraded equipment – the PERKEO II spectrometer which employs superconducting magnets – we were surprised to find that the data indicated a significant 1-per-cent deviation from the requisite zero-sum value for quark-mixing. This effect cannot be explained by the Standard Model. Similar results had been seen in experiments examining beta decay in nuclei, but no-one believed them because of the complication of having to introduce corrections relating to nuclear structure. However, our experiment avoids this issue, relying solely on neutrons and electrons to give a cleaner result.

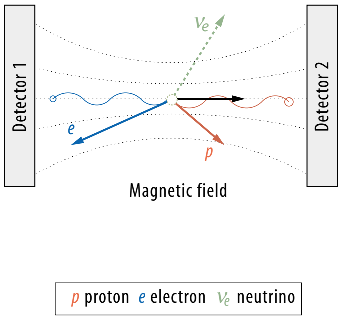
Again, the experiment nicely shows how low-energy measurements of neutrons can point the way to new fundamental physics. ■

Research team H. Abele, M. Astruc-Hoffmann, D. Dubbers, U. Müller and J. Reich *(University of Heidelberg)*, V. Nesvizhevsky *(ILL)*, S. Bässler and F. Glück *(University of Mainz)*, O. Zimmer *(TU Munich)*

When neutrons look into a mirror

No-one has seen a right-handed neutrino but highly accurate neutron decay experiments may reveal what happened to them in the early Universe

>> MICHAEL KREUZ



The inner detector chamber of PERKEO II. You can see the carrier for one of the proton detectors and the electric shielding of the decay volume. The electron detector had to be removed to gain access to the installation

When we look into a mirror, we see an exact image of our world, but with everything reversed – for example, a right-handed person becomes a left-handed one. What happens if a particle like a neutron looks into a mirror? Like all fundamental particles, the neutron can also be left or right-handed, depending on the direction of its spin to its momentum. We might expect, therefore, the spin to reverse in the mirror – a right-handed particle becoming left-handed and vice versa.

However, Nature is not so simple. The mirror relating to particle spin, which is called parity (*P*), is not symmetrical for particle behaviour governed by the weak force, such as neutron beta decay (see p.9). Whether right-handed or left-handed, a neutron always produces a right-handed antineutrino when it decays. So the symmetry is said to be broken.

This 'parity violation' distinguishes the weak force from the three other fundamental forces. Physicists have never been happy with this concept because there is no reason why Nature should prefer a particular handed particle. It had to be artificially introduced into the Standard Model of particle physics (see p.4).

Many theories going beyond the Standard Model, which attempt to explain how the forces arose in the early Universe suggest, however, that in the high-energy environment just after the Big Bang, the weak interaction was completely left-right symmetric. As the Universe cooled, this symmetry was broken. Although the left-handed W particle responsible for carrying the weak force has been discovered in high-energy experiments mimicking the conditions in the early Universe, no right-handed W particle has been seen, probably because it is too massive to be detected at the energies so far available. It might be possible, however, to detect its ghostly traces in neutron beta decay. A discovery of such remnants would then offer a natural basis for the asymmetry in the Standard Model and help us to understand the processes in the early Universe.

Looking for right-handedness

The neutron, through its decay, offers an ideal laboratory for investigating the weak force and left-right symmetry breaking. At the ILL, we conducted an experiment using polarised neutrons and the same spectrometer, PERKEO II, as described opposite, to count the decay particles in the right and left detectors, but in a slightly different configuration, allowing both the electron and the proton from the decay to be detected. The principle of the experiment is simple. It consists of measuring the asymmetry in the neutrino emission. Parity violation means that the neutron decay products – the electron, the proton and the antineutrino – are not emitted in just any direction. The antineutrino tends to be emitted in the direction of the neutron spin, while the electron tends to go in the opposite direction. Because the neutrino has virtually no mass and interacts only weakly with matter, it cannot be detected directly, but its orientation and energy can be derived from the measurements of the other two particles.

The count rates of the two detectors will differ depending on the direction of the neutron spin. These count rates can be compared with those predicted by the Standard Model. If different, then they might indicate right-handed contributions as predicted by theories going beyond the Standard Model. With increasing accuracy, the experiments have drawn closer to the outer edge of the Standard Model, and new measurements with even higher accuracy are now being planned. ■

The mounted and aligned spectrometer PERKEO II

Research team M. Kreuz (*ILL and University of Heidelberg*), H. Abele, C. Vogel, D. Mund, U. Mayer and M. Brehm (*University of Heidelberg*), T. Soldner, A. Petoukhov and V. Nesvizhevsky (*ILL*)

Installing the detector used in the experiment (the TRINE detector)

>> TORSTEN SOLDNER AND KLAUS SCHRECKENBACH

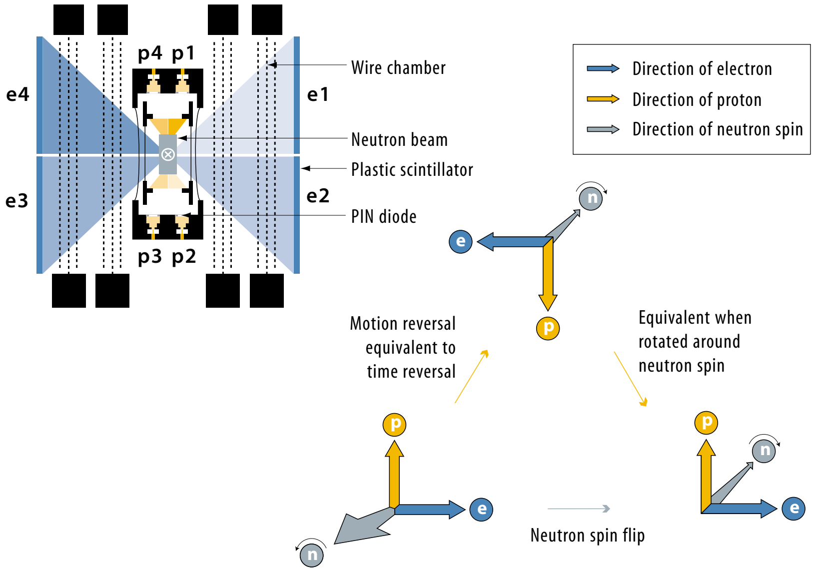
How to go backwards in time

An experiment at the ILL is looking for tiny differences in processes that can go forwards and backwards in time

We know that in daily life time only goes forward – we get older, no matter what we do to stay young. Time never runs backward for us. Nevertheless, the laws of physics at a fundamental level seem happy for time to go in both directions. Take a process like one particle bouncing off another: like a movie, the reaction can usually be run forwards or backwards. Such a process cannot be used to identify whether the time is running forwards or backwards and so is symmetrical with respect to time reversal.

This behaviour, called time-reversal symmetry (*T*), is related to two other so-called discrete symmetries, and they are all vitally important in our understanding of elementary particles and forces. One symmetry, parity (*P*), states that Nature does not distinguish between the behaviour of a particle and that of its mirror image (as described on p.11). The other is called charge conjugation (*C*) and exchanges particles by their antiparticles – it converts matter to antimatter and *vice versa*. Nevertheless, the weak force violates these symmetries. For example, the decay of the neutron, which is a weak process (see p.4), violates *C* and *P*. The violation of these first two symmetries has been known for 40 years, but *T*-violation, discovered in accelerators with particles called kaons, has not yet been observed in neutron decay.

A neutron decays into a proton, electron and neutrino. Time reversal inverts the directions of particle movements and spins. This is equivalent to a simple spin flip of the neutron. The detector scheme (below) has electron detectors left and right, e1-e4 (plastic scintillators and wire chambers), proton detectors up and down, p1-p4 (PIN diodes), and the neutron spin is perpendicular to the plane of the drawing. Comparing the concidence count rates of the protons and electrons detected for the two directions of the neutron spin can uncover whether the system of the decaying neutron is symmetric under time reversal



Reversing time in a spin

We tested for time reversal when a neutron decays (into a proton, an electron and an antineutrino) by effectively reversing the motions of the particles involved. This is done in a subtle way by measuring the numbers of electron-proton couples emitted in certain directions for two sets of neutrons spinning in opposite senses. Flipping the spin in this way is equivalent to reversing the motions of all particles involved in the decay and thus reversing time (if the film ran backwards the spins would reverse). Of course, we are not reversing the decay process itself but theoreticians say that this does not matter at our current level of experimental precision.

The actual experiment counts the electron–proton couples in a fixed detector geometry, and compares the count rates for the two opposite directions of the neutron spin. If they do not agree, then this would indicate time-reversal violation. Highly sophisticated detectors have had to be developed to ensure that the two sets of count rates are measured under identical conditions and that other effects like the known parity violation cannot adulterate the measurement. To achieve sufficient precision, a huge number of decays have to be counted – only possible using a high-flux reactor such as that at the ILL. Our experiments have so far shown that Nature's preference for one direction of time is less than one in a thousand events.

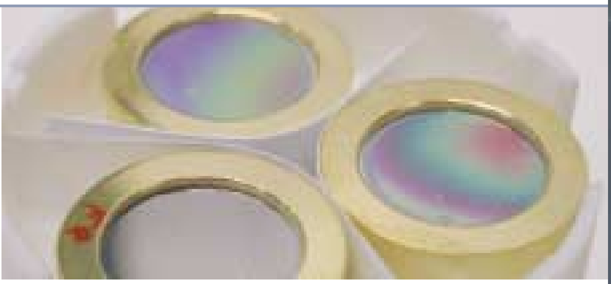
Should we go further? Although, the Standard Model of Particle Physics (see p.4) describes most physical phenomena quite precisely, there are still open questions. For example, in a symmetric world of particles and forces, equal amounts of matter and antimatter would have been created in the Big Bang, but we see no signs of antimatter now. Theorists think that a process involving the violations of *C* and *T*-symmetry was the key factor. However, this process cannot be explained by the tiny breaking of time-reversal symmetry already incorporated in the Standard Model, so alternative models have been proposed which need to be tested experimentally. Some of these models contain a violation of *T*-symmetry that may show up in neutron decay. ■

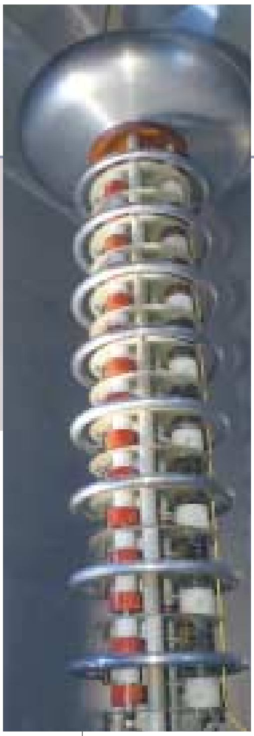
Research team C. Plonka, K. Schreckenbach and O. Zimmer (*Technical University of Munich*), L. Beck (*University of Munich*), P. Liaud (*ISN Grenoble*), A. Bussière and R. Kossakowski (*LAPP Annecy*), A. Petoukhov and T. Soldner (*ILL*)

Living in a material world

A project at the ILL led by a team of UK researchers is addressing some of the most fundamental questions of our existence

>> **MAURITS VAN DER GRINTEN**





Equipment used to measure the neutron EDM: an array of ultra-cold neutron detectors and the high voltage stack

The Big Bang is believed to have generated equal populations of particles and anti-particles but our Universe contains predominantly matter, so why is our Universe made of matter? Is the standard theory of particles and forces used to describe our world complete, or are there, for example, additional particles yet to be discovered?

Experimental searches to answer these questions are normally the privilege of accelerator laboratories operating at extremely high energies. At the ILL, however, we are seeking to address these issues from the opposite extreme: a unique source of very low energy neutrons, so-called ultra-cold neutrons, is being exploited to observe the behaviour of neutrons as they are submitted to a combination of weak magnetic and strong electric fields. In these extreme conditions, the neutron can expose a violation of time-reversal symmetry (*T*-violation, see p.4) to a level that could explain the particle nature of our Universe. *T*-violation would be revealed by the presence of a permanent neutron electric dipole moment (EDM). This experiment is pursuing the search for the neutron EDM. Although the neutron is an electrically neutral particle, there are small positive and negative charges deep within it. An EDM would arise if the average positions of the positive and negative charge do not coincide. The neutrons also have a spin, and while an EDM would remain unchanged under *T*-reversal, the spin would be reversed – in other words, time symmetry is broken.

Searching for the EDM

How do you measure the neutron EDM? First, the neutrons are placed inside a quartz storage cell in a weak magnetic field. The neutrons are spin-polarised, and precess in the magnetic field with a frequency that depends on the neutron magnetic moment and the magnetic field strength. In addition to the weak magnetic field, a very high electric field is applied over the quartz storage cell by putting 100,000 volts on its lid. The interaction of the neutron EDM with the electric field will shift the precession frequency slightly – by just a few parts per billion. Measuring this tiny shift to high precision thus gives us evidence for a neutron EDM. The precision with which we are searching for the EDM is unprecedented: if you can imagine scaling up the neutron to the size of the Earth, our experiment is equivalent to looking for a single positive and negative electric charge separated by only a few micrometres (less than one-tenth of the thickness of a human hair) at its centre.

To achieve the required experimental sensitivity, we employ a variety of technologies. The experiment relies on an atomic mercury magnetometer that can measure the magnetic field in the storage cell to a precision of one-billionth of the Earth's magnetic field. Nuclear magnetic resonance techniques are used to measure the neutron precession frequency. Advanced materials are also exploited: diamond-like coatings to optimise neutron-storage properties; and a special alloy, mu-metal, to shield the experiment from the Earth's magnetic field.

Searches for particle electric dipole moments take a prominent place in modern particle physics because of their bearing on the origin of symmetry violations and the implication these have on understanding the Universe as we experience it today. The puzzle of what exactly did happen to matter and antimatter after the early days of the Universe remains yet to be solved. This search for the neutron EDM may well bring us a step closer to the understanding of why we are living in a material world. ■

The quartz storage cell for the measurement of the neutron EDM

Research team K. Green, P. S. Iaydjiev and S. N. Ivanov (*RAL*), M. G. D. van der Grinten (*RAL/Sussex*), P. G. Harris, J. M. Pendlebury and D. B. Shiers (*Sussex*), P. Geltenbort (*ILL*)

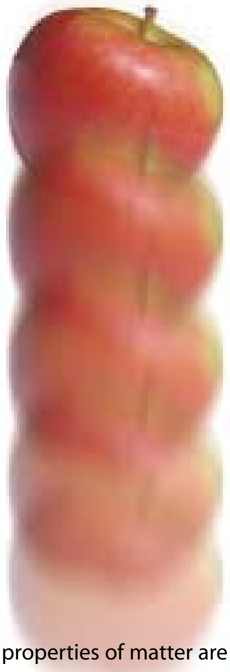
For the first time, ultra-cold neutrons have revealed quantum states due to gravity

Quantum states of matter in a gravitational field

>> VALERY NESVIZHEVSKY

Serge Claisse

Participants in the ILL experiment: from the left, Valery Nesvizhevsky, Hans Börner and A. K. Petoukhov



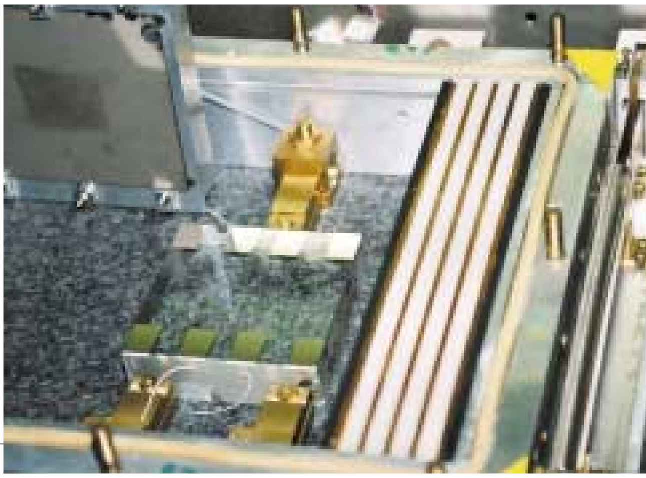
Quantum, or discrete, properties of matter are manifest in a variety of phenomena in Nature, particularly at the microscopic level. Quantum mechanics, the theory that describes the very small, predicts that subatomic particles can have only certain energy values, described as quantum states. This rule should hold for all matter under the influence of Nature's four fundamental forces – the strong and weak nuclear forces, electromagnetism and gravity (see p.4). We can, for example, observe the quantum states of electrons in an electromagnetic field, and these indeed give rise to the well-defined structure of atoms. Similarly, the quantum states of nucleons (protons and neutrons) in the strong nuclear field, responsible for the structure of atomic nuclei, can be detected.

By analogy, gravity should also lead to the formation of gravitational quantum states in particles, which affect their behaviour in a gravitational field such as that of the Earth. However, it is by far the weakest of the four forces (for an electron in an atom, for instance, the electromagnetic field is about 40 orders of magnitude stronger than the gravitational field), so measuring such phenomena is extremely challenging.

Bowling ultra-cold neutrons

Nevertheless, we have for the first time observed such states in an experiment with ultra-cold neutrons carried out at the ILL. We demonstrated that the vertical motion of very slow neutrons in the Earth's gravitational field proceeds in discrete steps. In the experiment, the ultra-cold neutrons were sent on a gentle parabolic trajectory through a baffle and onto a horizontal mirror. They had horizontal and vertical velocity components of metres per second and centimetres per second, respectively.

Neutrons at such low energy are totally reflected by the mirror. They arrive at grazing angles (in trajectories very close to the mirror's surface) and are reflected upwards until gravity forces them to descend again. Gravity acts on the vertical velocity component only. The experiment shows that there is a minimum energy corresponding to the vertical motion of matter in the gravitational field. For neutrons at the surface of the Earth, this was measured to be as small as about one picoelectronvolt, which corresponds to the jumping height of about 10 micrometres. This energy is 13 orders of magnitude smaller than the binding energy of an electron in the hydrogen atom, which might demonstrate why it is not easy to observe this effect. Thus, the classical motion of ultra-cold neutrons actually becomes discrete, when you observe them at sufficiently low energies. ■



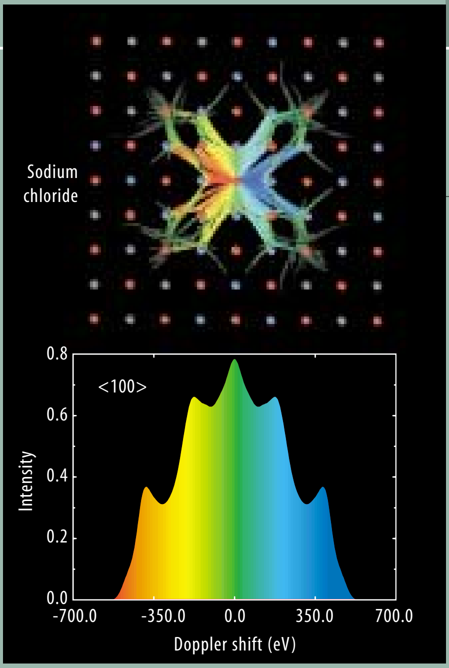
The equipment for measuring quantum states of a neutron in a gravitational field

Research team V. V. Nesvizhevsky, H. G. Börner and A. K. Petoukhov (*ILL*), A. M. Gagarski (*PNPI, Gatchina*), H. Abele, S. Bässler and A. Westphal (*University of Heidelberg*), A. V. Strelkov (*JINR, Dubna*)

The intense source of neutrons offered by the ILL is an excellent tool for investigating nuclei and nuclear reactions, leading to a better understanding of the structure of nuclei and how they are made in the stars

Understanding the nucleus

>> **HANS BÖRNER**



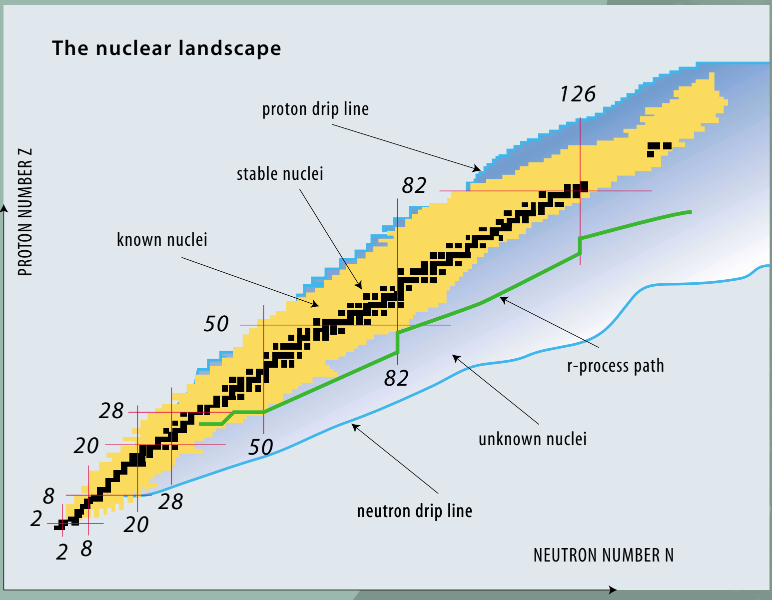
The lifetimes of nuclear states can be measured using the GRID technique. The top image is a simulation of atoms recoiling in a single crystal of sodium chloride (the recoil is induced by gamma emission); the bottom image shows the measured shift in energy induced by the recoil

Most of the visible matter in the Universe is made up of nuclei – collections of protons and neutrons which form the tiny, but dense cores of all atoms. Although nuclei are extremely small, only about one million millionth of a centimetre across, they can contain up to a couple of hundred protons and neutrons (collectively called nucleons) which interact through the electromagnetic and nuclear forces (see p.4).

The familiar elements of everyday life are built from nuclei with a characteristic number of protons (atomic number) and at least an equal but often slightly varying number of neutrons (to give isotopes of the element). It is also possible, however, to create nuclei containing vastly varying proportions of protons and neutrons which can survive for a short time. Physicists believe that around 7000 different proton-neutron combinations are possible. These can be plotted on a kind of nuclear landscape (see opposite). The chart shows a long valley of stability marked in black going diagonally across, which encompasses the isotopes making up everyday matter, but on either side are areas inhabited by unstable nuclei with increasing numbers of protons or neutrons. These areas are bounded by so-called driplines, marking where the proportions of protons or neutrons in the nucleus are so high that they just leak away. We know where the proton dripline is but only the lower part of the neutron dripline has so far been investigated.

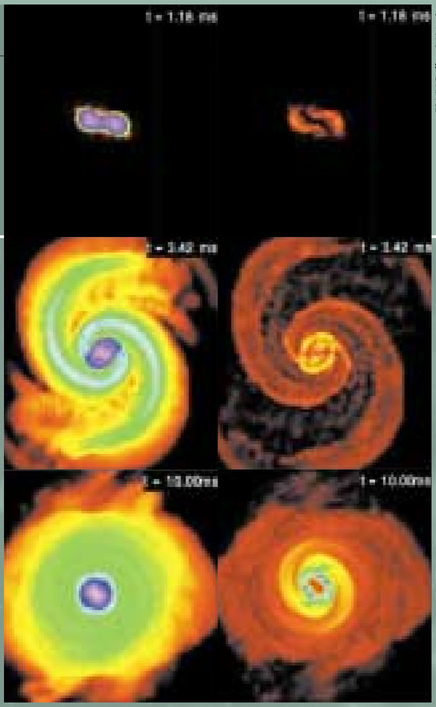
Nuclear models

Why are these more extreme nuclei interesting? The interplay of the forces between many nucleons within these minuscule systems ensures that they behave in very complex ways – we have really only just scratched the surface in our understanding of nuclear structure! Nuclei, like atoms, obey the laws of quantum mechanics but there is as yet no single quantum description of nuclear structure. One characteristic that researchers first noticed in the 1930s and 1940s was that nuclei with certain numbers of protons and neutrons were particularly stable. These co-called magic numbers were explained by a nuclear model, introduced In 1948 by Otto Haxel, Hans Jensen, Hans Suess and Maria Meyer, in which each nucleon moves in an orbit under the influence of a spherically symmetrical central field of force calculated from the


The nuclear landscape

Understanding the nucleus

Merging neutron stars could be one of the sites of heavy element synthesis



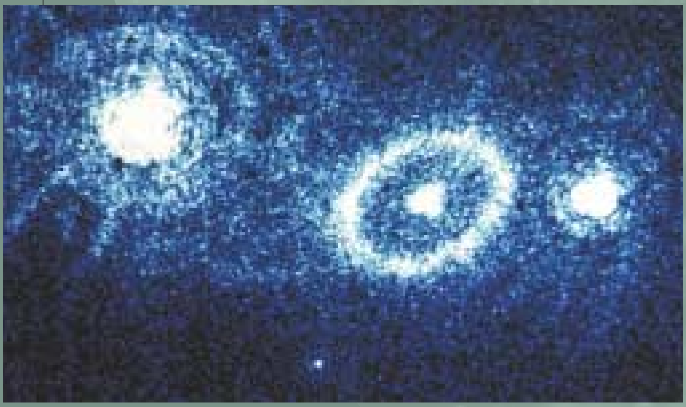
ESA/M.Ruffert & H.Janka

average effects of all the nucleons. As for electrons in atoms, the nucleons build up in shells according to quantum mechanical principles. This approach, the so-called shell model, successfully predicted that the magic numbers represented fully occupied 'closed' stable shells of protons or neutrons. Any nucleons orbiting outside the outermost closed shell behave as 'valence' nucleons. Like valence electrons in atoms, they can be excited through a range of higher energy states, as predicted by quantum theory.

This 'single-particle' approach works effectively only for light nuclei and those with numbers of neutrons and protons near a closed shell. Because nucleons, unlike atomic electrons, interact strongly with each other through the nuclear forces, individual interactions become too complicated to calculate for heavier nuclei with nucleons not near a magic number. Theorists have therefore resorted to another class of models in which the nucleons are treated collectively as a liquid drop, held together by surface tension. When excited, the nucleons all move together causing the nucleus to vibrate or rotate, or even change shape.

The shell and liquid drop models represent two extreme pictures of nuclear behaviour. In the 1950s, Aage Bohr, Ben Mottelson and James Rainwater combined aspects of both descriptions, pioneering a collective model which couples the motions of individual nucleons to nuclear surface oscillations. The theory accounts for the complex spectra seen in nuclei as sets of vibrationally and rotationally excited quantum states. They also showed that both protons and neutrons like to couple in pairs. Later in the 1970s, Akito Arima and Francesco Iachello built on the idea of paired nucleons to develop a model in which an inert core is surrounded by pairs of valence nucleons, which are treated as 'bosons' (see p.18). This 'interacting boson' model describes nuclei in terms of dynamic symmetries corresponding to particular nuclear shapes such as spherical, deformed axial symmetric (rugby ball-shaped), or deformed axial asymmetric. A small change in the number of nucleons in a nucleus can indeed result in a rapid change in its shape (see p.20).

Supernova 1987A



Hubble Space Telescope/ESA

Not surprisingly, nuclear quantum states are extremely complex. Measuring their lifetimes may indicate which model best predicts the properties of a particular class of nuclei, and the often subtle interplay between single-particle and collective behaviour (see p.18). Excited states which are quite long-lived (called isomers) are good probes of nuclear models. They may arise because certain quantum rules (which are model-sensitive) do not allow the excited nucleus readily to fall back to its lowest energy level, or because compatibility between collective and single-particle behaviour impedes the transition (see p.19).

Nucleosynthesis

Studies of extreme nuclei provide stringent tests not only for these models but also for the theories of the underlying nuclear forces. Another important application is in understanding how the elements came to be made in Nature. We know that all elements heavier than boron are made in stars through nuclear reactions. The lighter elements are synthesised via nuclear burning during the normal lifetime of stars, while the elements heavier than iron are made either in gaseous envelopes of ageing red giants or in supernova explosions. The main processes involve a nucleus capturing a neutron. Nuclei with an excess of neutrons are 'beta-unstable'. This means that a neutron from the nucleus decays into a proton, emitting a beta particle (electron) and a neutrino in the process, so increasing atomic number by one, thus climbing up the nuclear chart by one element. The capture reaction may go very slowly as in red giants (the slow, or *s*-process, see p.21) or explosively fast as in supernovae (the rapid, or *r*-process, see p.22).

These processes involve the creation of unstable neutron-rich nuclei. Experiments studying the spectra of such nuclei, measuring lifetimes of their excited states and determining the probability of capturing a neutron, allow us to contribute to predictions about the expected abundances of the elements and thus the most likely route by which they are made.


The interferometers used in the GAMS5 high-resolution gamma-ray spectrometer

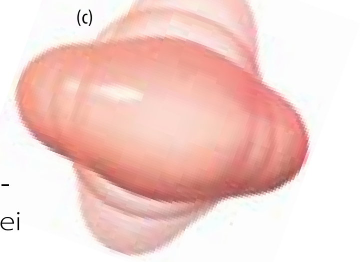
The ILL's unique role

The ILL has been carrying out nuclear research for the past 30 years. Its reactor provides an intense neutron source for studying neutron-capture reactions and the structure of the nuclei they form. When a nucleus captures a neutron, it is excited to the binding energy of the neutron (typically about 10 megaelectronvolts). As the excited nucleus returns to lower energy levels, it emits a cascade of characteristic gamma rays. Precise measurement of these gamma rays allows us to determine the sequence of the excited states through which the nucleus descends and so determine the path of de-excitation.

It is also possible to measure the lifetimes of the excited nuclear states using technology pioneered at the ILL, called GRID (Gamma Ray Induced Doppler broadening). Gamma rays emitted when the nuclei are in flight shift slightly in wavelength due to the Doppler effect. This results from nuclear motion induced by the emission of gamma rays preceding the ones being measured. The recoils are extremely small in energy and the Doppler effect can only be detected by spectrometers with a resolution of one part per million. This is possible with the ILL's crystal spectrometers GAMS which have 1000 times better resolving power than conventional semiconductor gamma-ray detectors.

With the GAMS spectrometers we can study nuclei in the region of stability, or at least close to it. If we want to do gamma-ray spectroscopy of nuclei far from stability, however, we need an additional tool. By firing neutrons at heavy nuclei such as uranium they can be induced to fission into neutron-rich fragments. Not only can we then study the fission process itself, but we can also investigate the properties of very neutron-rich nuclei. The fission fragments are directly extracted from the reactor using the ILL's unique mass separator Lohengrin in about a microsecond. Electromagnetic fields separate the charged fragments according to their mass, charge and kinetic energies, and an array of germanium detectors then detects the emitted gamma rays. These instruments are used to study a wide variety of nuclei, giving insights into nuclear structure and nucleosynthesis as is shown in examples in the following pages.

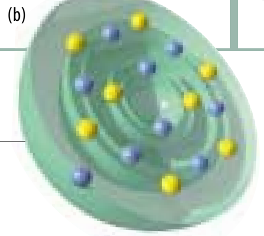
Finally, nuclear physics techniques have many applications in areas such as medical imaging and cancer therapy. In addition, accurate knowledge of fission yields studied with a special set-up (called Mini Inca) at Lohengrin are essential ingredients for studies of the destruction by transmutation of long-lived radioactive waste produced by nuclear power stations. ■



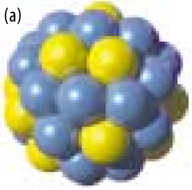
Groundbreaking experiments at the ILL are probing the complex interplay between single-particle and collective behaviour in heavy nuclei

>> JAN JOLIE AND HANS BÖRNER

From shells to liquid drops



(a) A typical nucleus consisting of protons (yellow) and neutrons (blue), (b) the shell model of the nucleus and (c) the liquid drop model



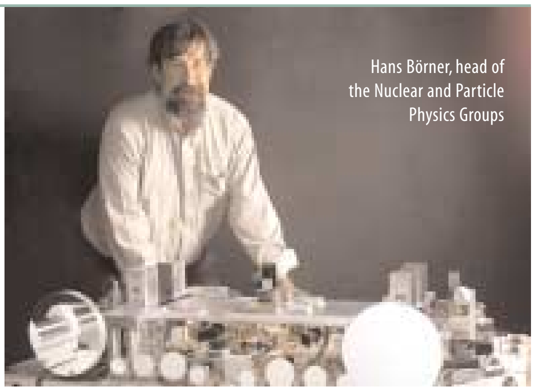
The atomic nucleus is made up of densely packed nucleons – protons and neutrons, held in the firm grip of the strong nuclear force (see p.6) so that they interact strongly with each other. Because of the strength and complexity of the strong force, physicists have had to rely on a series of approximate pictures of what atomic nuclei look like and how they behave (see p.16).

These models are, of course, based on quantum mechanics which means that the nucleons in the nucleus exist in defined quantum energy states. The way these states are filled up depends on another quantum property by which all particles are divided into two kinds called fermions and bosons. Fermions obey the Pauli exclusion principle whereby no two particles can occupy the same quantum state, whereas bosons will happily all sit in the same energy level.

Nucleons, like electrons, are fermions, and so can be considered to sit in orbits of defined energy in the nucleus – in the same way that electrons do in atoms. However, for the nucleus there are two sets of orbits – one for protons, one for neutrons. This description, which works well with nuclei containing not too many nucleons, is called the shell model. The orbits form shells – or groups of orbits having similar energies – with large energy gaps between shells. Nuclei with a closed (full) shell of protons, or a closed shell of neutrons (and especially those with both) are much more stable. For nuclei with a few additional nucleons beyond a closed shell, the nucleons in the closed shell can mostly be neglected, and only the interactions between the outermost nucleons – called residual interactions – must be taken into account.

Quantum liquid

In heavy nuclei with many nucleons outside the last closed shell, the calculations become prohibitively complex even with modern computers, so a different model is used called the collective model or liquid drop model. The model views the nucleus as a droplet of quantum liquid with typical features such as density and surface tension.


Hans Börner, head of the Nuclear and Particle Physics Groups

The liquid drop also has defined quantum states which appear as surface vibrations and rotations of the deformed droplet. These quantum excitations, called phonons, behave as bosons, and can exist collectively in the same vibrational mode. By studying these multiphonon states, nuclear physicists hope to find out how the bosonic collective excitations are related to their single-particle shell model constituents – the fermionic nucleons.

One approach is to expose atomic nuclei to neutrons from the ILL reactor core so that they capture the neutrons, forming a statistical population of excited (higher energy) nuclear states. When they return to their lowest energy state they emit gamma radiation which can be measured using the world's most precise gamma-ray spectrometers, the ILL's crystal spectrometers – GAMS.

Over the past decade, we have observed the first multiphonon states in the heavy nucleus erbium-168, followed up by studies of further multiphonon excitations in other heavy, deformed nuclei. In classical solids, multiple vibrations pile on top of one another at will. In nuclei, however, the finite number of particles and the Pauli exclusion principle significantly impede the creation of such modes. Indeed, the existence of multiphonon vibrational excitations in nonspherical nuclei is a long-standing issue. To characterise these states involves measuring their very short lifetimes which last less than one million millionth of a second. A powerful method known as the GRID technique (see p.17) pioneered at the ILL has enabled us to measure their lifetimes. In this way, we can probe how inherent loners, the fermionic nucleons, are transformed into collective excitations which are the jovial phonons. This provides a deeper understanding of the residual interactions mentioned earlier. ■

Research team J. Jolie (*University of Cologne*), H. G. Börner (*ILL*), R. F. Casten and V. Zamfir (*Yale University, USA*), A. Aprahamian (*University of Notre Dame, USA*).

Very neutron-rich nuclei far from stability are excellent testbeds for nuclear theory

Probing exotic nuclei

>> GARY SIMPSON

The Lohengrin team (clockwise from the left: Antonella Scherillo, Gary Simpson, Herbert Faust, Igor Tsekhanovich and Riccardo Orlandi)

The array of gamma-ray detectors positioned at the Lohengrin focal point

Nuclei make up more than 90 per cent of the known mass of the Universe, so it is important to understand their properties and structure. Although researchers have been studying the nucleus for about 50 years, we are still a long way from having an all-encompassing description – a 'Standard Model'. At the moment, nuclear behaviour is explained in terms of two extreme types of model, shell models which treat the constituent protons and neutrons as single particles, and collective models which treat the nucleus as a macroscopic system (see p.16). The behaviour of many nuclei can be explained in terms of the interplay of single-particle and collective behaviour.

These theories have so far been rigorously tested only with stable or near-stable nuclei, of roughly similar numbers of neutrons and protons. However, these constitute less than 10 per cent of all nuclei that could exist (see the nuclear chart on p.15). Nevertheless, by studying exotic species with extreme neutron-to-proton ratios, we can verify the validity of our nuclear models, and advance nuclear theory.

Nuclei with high ratios of protons to neutrons can be obtained relatively straightforwardly using accelerators. Obtaining neutron-rich nuclei is more difficult, and only a handful of facilities worldwide can produce reasonable amounts. One of these is Lohengrin at the ILL. A target of a fissile isotope is placed close to the ILL reactor core, in this unique instrument. The isotope fissions into a range of neutron-rich nuclei which are separated by Lohengrin (see p.17). Decays of excited nuclear states can then be detected by germanium gamma-ray detectors, to give information about the nucleus. The properties of these neutron-rich, unstable species are expected to deviate from those near stability. For instance, neutron-rich nuclei with a mass of around 100 rapidly change shape from being spherical to deformed by adding just two neutrons. Similarly, shell structure changes and new closed shells appear, and other shells disappear, in very neutron-rich regions.

Side-on view of the Lohengrin mass separator when it was being constructed

Neutron-rich tin-132

One example is the structure of the neutron-rich tin-132 nucleus which has 50 protons and 82 neutrons – eight beyond stability; its lifetime is about 40 seconds. It is 'doubly magic', meaning it has both full proton and neutron shells. Doubly-magic nuclei are tightly bound, so tin-132 and similar nuclei were expected to have a relatively simple structure, making them excellent for testing nuclear models on the exotic, neutron-rich side of the nuclear landscape.

Studies at Lohengrin on nuclei in the region of tin-132 have measured the lifetimes of long-lived excited (isomeric) states of these nuclei, to verify whether the excited states in the doubly-magic tin-132 region do have a pure single-particle nature. ■

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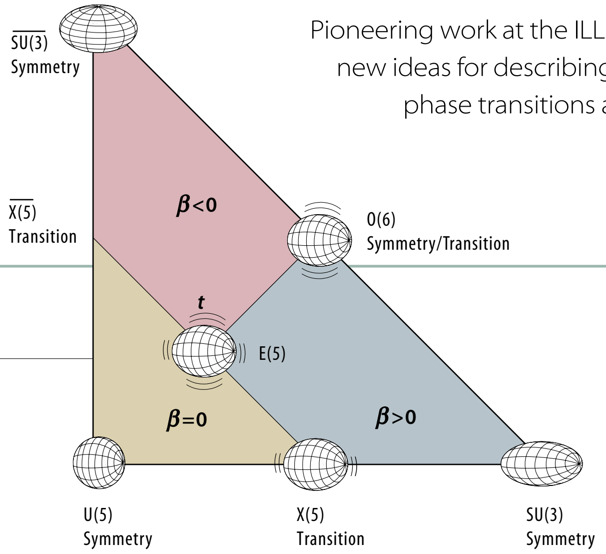
Phase transitions in nuclei

Pioneering work at the ILL has led to the development of new ideas for describing nuclear structure, in particular phase transitions associated with shape changes

>> RICK CASTEN AND VICTOR ZAMFIR



The equilibrium phase diagram for nuclei. Nuclear models typically span the triangle using two variables which are analogous to pressure and temperature in Landau theory

The structure of atomic nuclei depends sensitively on the numbers of protons and neutrons in the outermost orbits – active nucleons – near the surface of the nucleus. Physicists have known for half a century that, in many regions of the nuclear chart (see p.15), nuclei change structure and shape from spherical to deformed (ellipsoidal) as the number of active nucleons increases. However, nuclei in these shape-transitional regions have been the most difficult to describe theoretically, because they involve intense competition between single-particle and collective behaviour (see p.18). Nevertheless, a useful approach is to think of the change in shape as a phase transition, rather like that between water and ice, or between two different crystal structures. We can apply this idea even though nuclei are small, finite objects with a limited number of particles.

Precision studies of shape changes

This perspective has recently been explored and enhanced in exciting new ways by studying shape transitions in a particular group of nuclei, through precision gamma-ray studies at the ILL and other laboratories. Using the GRID method (p.17), ILL researchers measured the lifetimes of nuclear excitations in the picosecond (million millionth of a second) range of the heavy nucleus samarium-152, considerably revising our knowledge of this and similar nuclei with 90 neutrons. The studies showed that the structure changes abruptly at that point – the nuclei can simultaneously take on both spherical and deformed shapes in different quantum states. These observations confirm that finite nuclei do undergo phase transitional behaviour depending on the number of nucleonic constituents.

This work has inspired two ground-breaking developments. In the first, Francesco Iachello at Yale University developed a new concept for describing nuclear phase transitions. Again, just as the shapes of different crystal structures can be described mathematically in terms of symmetries, so can nuclear shapes. This leads to the idea of 'critical point' nuclear symmetries where the shape changes from one symmetry to another depending on a small change in the number of nucleons that the nucleus contains. These symmetries are simple, easy to calculate and are parameter-free. They are classified according to the type of phase transition, and have an underpinning in the mathematical language of group theory. One of these symmetries called X(5) describes a rapid spherical-to-deformed phase transition. Supported by recent ILL data, samarium-152 emerges as the first empirical example of this symmetry. This is not the first time that the ILL has pioneered the study of symmetries in nuclei, however. In 1978, ILL researchers discovered the first example of the then newly proposed symmetry, O(6), in platinum-196.

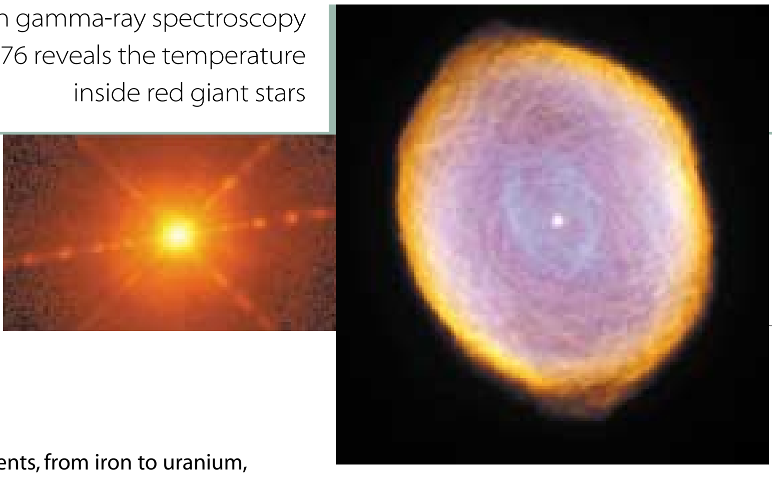
The second development in this area is the application, by Jan Jolie, Pavel Cejnar and their colleagues, to nuclei in their lowest energy state, of a well-known theory in physics – Landau theory. This is used classically to describe changes in, for example, crystal structure in terms of parameters like pressure and temperature which can be shown as a phase diagram. When applied to nuclear shape, the resulting phase diagram (see above) shows that nuclei have three shape phases at low energy – spherical (denoted by $\beta = 0$), prolate deformed (rugby ball-shaped, β greater than 0), and oblate deformed (disc-like, β less than 0) and that the phase transitions that separate these phases meet at the triple point *t*. ■

Members of the Yale Nuclear Structure Group (left to right) Rick Casten, Libby McCutchan, Victor Zamfir and Mark Caprio, looking at a GRID spectrum for an isotope of samarium

Research team R. F. Casten, V. Zamfir and M. Caprio (*Yale University, USA*), J. Jolie (*University of Cologne*) and H. G. Börner (*ILL*)

A stellar thermometer

High precision gamma-ray spectroscopy of lutetium-176 reveals the temperature inside red giant stars



Hubble Space Telescope/STScI

>> FRANZ KÄPPELER AND HANS BÖRNER

A red giant (left) is the final stage of a star like the Sun. It ejects its outer layers into space to form a beautiful planetary nebula (right)

The heaviest elements, from iron to uranium, are made when a star becomes a red giant or when, if very massive, it explodes as a supernova. The abundances of elements we see in Nature are roughly an equal mix of the ashes of these two scenarios.

The origin of lutetium-176 and of about 30 other nuclei, however, can be completely ascribed to red giants. The process involves the slow capture of a neutron (the *s*-process) by a nucleus followed by beta decay in which one of its neutrons converts into a proton with the emission of an electron and a neutrino to give the element with the next highest atomic number. The nucleosynthesis associated with this process is now quite well understood, and by determining experimentally the rates at which neutrons are captured, the resulting abundances of these so-called *s* isotopes can be quite accurately described.

Having a clear picture of how lutetium-176 is made and being able to predict its natural abundance is of particular interest because it has a half-life of 36 billion years decaying, via beta emission, to hafnium-176. This decay could, in principle therefore, be used as a clock to determine the age of the *s* elements – the original *s*-production of lutetium-176 could be compared with its abundance today (as in the familiar radioactive carbon-dating process).

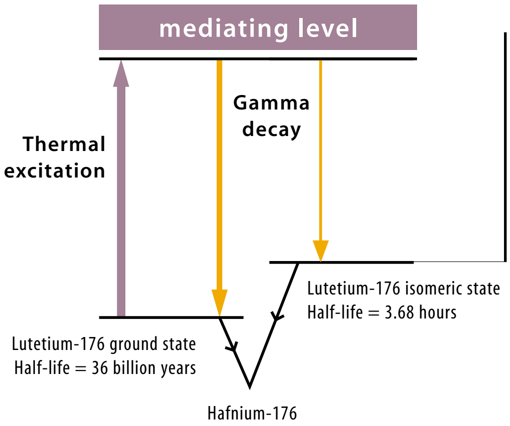
However, attempts along these lines encountered an unexpected obstacle. Whilst behaving as a perfect clock under laboratory conditions, the decay of lutetium-176 was suspected to change at the extremely high temperatures inside red giants. The reason for this exotic behaviour is subtle. Lutetium-176 is formed, through neutron capture, in an excited state. This, however, can de-excite back to the lowest energy state (ground-state) by emitting gamma-rays, or to another so-called isomeric state which decays with a half-life of only 3.68 hours. The overall lifetime of lutetium appears therefore shorter. Nevertheless, under laboratory conditions, the rates of the two processes can be measured and taken into account.

Normally the two families of energy levels associated with these two processes do not influence each other. However, the question was whether this remained the case in the hot, energetic red giant environment. The ground-state would be excited thermally to a series of higher states, which may decay to the short-lived isomer. The exact population of these higher states depends on the temperature, which then influences the rate at which lutetium-176 is lost via the short-lived isomer. The overall, apparent decay rate of lutetium-176 would thus also depend on temperature (see figure below).

Probing the stellar interior

We explored this question using high-resolution gamma spectroscopy, which allowed us to study the two families of states with unsurpassed sensitivity. We found that, while the half-life of lutetium-176 remains at its laboratory value up to 150 million degrees, it drops to about 1 year at its production site in a red giant.

To correct this defect, we would need to know the temperature history to which lutetium-176 is exposed. Since this is not currently possible, the idea of using lutetium-176 as a cosmic clock has had to be abandoned for now. Instead, the argument can be turned around to obtain an estimate for the temperature at which lutetium-176 is produced – between 200 and 300 million degrees. This information thus provides a probe for the interior of red-giant stars completely independent of the yet uncertain stellar models. ■

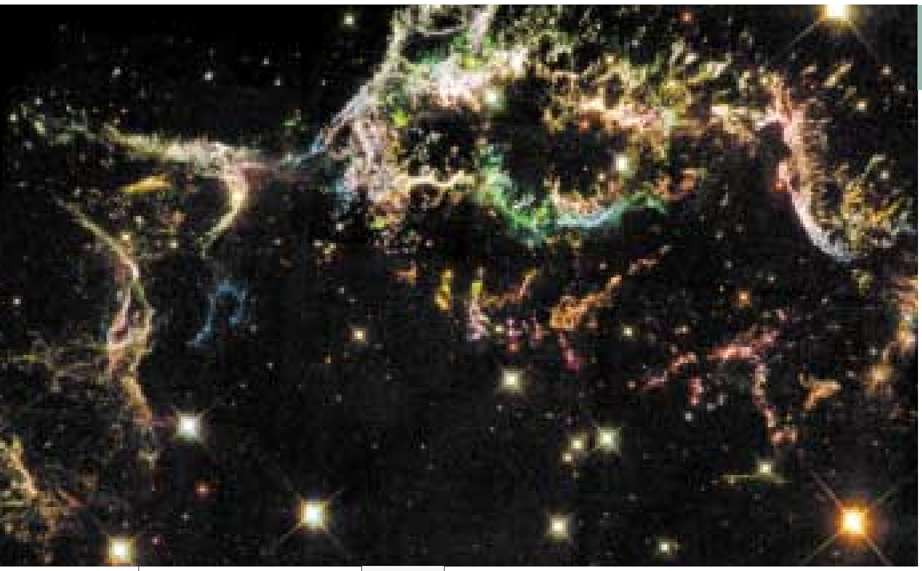


Excitation of a mediating state in the hot stellar photon bath provides a link between the incompatible isomer and the ground state of lutetium-176, resulting in a drastic reduction of the half-life

Research team N. Klay, H. Beer and F. Käppeler (*Karlsruhe Research Centre, Germany*), H. G. Börner and C. Doll (*ILL*)

Researchers at the ILL are investigating how the heaviest elements are made in the Universe

Where do the heavy elements come from?



The remnants of a supernova explosion in which heavy elements are built up and spread across the Galaxy

>> HERBERT FAUST AND JEAN-ALAIN PINSTON

We know that all but the lightest elements in Nature are made in stars via nuclear reactions. Understanding the path by which the heaviest elements are synthesised is a current challenge. Half of the elements above iron are thought to be created by a process called the rapid neutron capture (*r*) process, whereby a nucleus captures a large number of neutrons and decays to the element of the next highest atomic number, by emitting an electron and an antineutrino (beta decay).

Our observational knowledge of the r-process is based on the relative abundances of elements as analysed in the Sun and distant stars. They reveal that the process must occur in environments where neutron densities are extremely high – at least 10^{20} neutrons per cubic centimetre – and at temperatures of more than a billion degrees. The site of the *r*-process is not yet known, despite huge efforts on the astrophysics side. It may happen in explosive events of so-called type II supernovae, or in the merger of two neutron stars. The resulting debris of the *r*-process goes on to form the next generation of stars such as our Sun.

The path of the *r*-process is very exotic. Iron nuclei, first made in stars by other processes which stop at iron, undergo successive neutron captures, going up to nuclear masses where the high temperatures result in neutrons being knocked loose from nuclei by gamma-rays at the same rate as they are captured. The nuclei then have to wait for beta decay to happen to continue the climb up the elemental ladder. Eventually, elements up to the actinides are created.

Even though we don't yet know the astrophysical circumstances of the *r*-process, in nuclear physics terms its path must occur on the very neutron-rich side of the nuclear chart, almost 10 to 20 mass units away from the valley of stability (see p.15). We can indeed calculate the path, assuming particular neutron densities and temperatures, and using what we know about neutron-rich nuclei.

Investigating *r*-process nuclei

The ILL is investigating neutron-rich nuclei located near to the *r*-process path. These nuclei are created by nuclear fission, and then separated and analysed by the Lohengrin spectrometer (see p.17). Their mass range covers a considerable part of the region where the *r*-process is thought to proceed.

An important area of the nuclear chart to investigate is that surrounding neutron-rich nuclei with so-called magic numbers of protons and neutrons (see p.15). These have increased stability due to full shells of nucleons. For example, we investigated the excited high-spin states in antimony isotopes which have a nearly closed shell with about 82 neutrons and 50 protons. These long-lived nuclear states are single-proton excitations, and such measurements are important for testing aspects of nuclear structure needed to fix parameters relevant to the *r*-process. More experiments are planned in this direction.

The fission process itself is also a rich source of information: the abundances of the fission fragments produced and their excited states depend on their nuclear structure. Recently, we have proposed an empirical model in which the excitation and kinetic energies of the fragments are calculated from their ground-state masses and the so-called level density parameter, which determine how the nuclei behave at higher temperatures. These parameters, which are easy to measure, also probe nuclear models, and are directly linked to values needed in *r*-process calculations. ■

Inside the Lohengrin spectrometer

Research team H. Faust, G. Simpson and I. Tsekhanovich (*ILL*), J. A. Pinston and J. Genevey (*ISN Grenoble*)

Glossary

Antimatter
The equation in quantum mechanics describing subatomic particles predicts that each matter particle has an antimatter partner (of opposite electrical charge, if the particle is charged).

Antineutrino
The antimatter partner of the neutrino; some theories suggest the neutral neutrino is its own antiparticle.

Baryonic matter
Matter made of baryons – particles consisting of three quarks, such as neutrons and protons.

Beta decay
A type of radioactive decay in which a neutron converts into a proton, an electron and an antineutrino.

Big Bang
The Universe is believed to have been born in a fireball explosion about 15 billion years ago.

Boson
A quantum particle which has a spin of integer value (0,1,2....*etc*). Bosons include the particles that mediate the fundamental forces.

Critical point
The point at which phases are in equilibrium (see Phase transition).

***C*-violation (violation of charge conjugation)**
The phenomenon in which matter and antimatter particles behave differently.

Deuterium
An isotope of hydrogen containing a neutron as well as a proton.

Dripline
The boundary on the nuclear chart marking the edge of nuclear stability at which neutrons or protons 'drip out' of the nucleus.

Electric dipole moment
The quantity describing the electric field of an object due to the spatial separation of positive and negative charges inside the object.

Electron
An elementary particle which is a significant constituent of atoms and is also emitted by unstable nuclei as beta radiation.

Electronvolt
The energy required to accelerate an electron through a potential of 1 volt.

Fermion
A particle which has half-integer spin. Examples are quarks and leptons as well as composite particles like neutrons and protons.

Femto
Unit of scale10^{-15}.

Fine structure constant
A fundamental constant of Nature that describes the strength of the electromagnetic force.

Fundamental forces
All known forces present in the Universe can be reduced to four fundamental forces: the gravitational and electromagnetic force we know from everyday life, and the weak and strong forces which are responsible for the existence of the material world we live in.

Gamma ray
Very high energy electromagnetic radiation. Gamma rays are emitted in nuclear transitions.

Group theory
A mathematical approach, based on the concept of symmetry, and applied extensively in the physical sciences to classify the properties of systems.

Gluon
The particle (boson) that mediates the strong force.

Isomer
An excited nuclear state which decays with a relatively long half-life.

Lepton
A type of elementary particle predicted by the Standard Model. They comprise the electron, muon, tau and their corresponding neutrino partners. They interact via the electromagnetic and weak forces.

Liquid drop model
One of the theoretical descriptions of the nucleus which regards the constituent nucleons as acting collectively in a fluid drop with density and surface tension.

Magic number
The number of protons or neutrons in a nucleus which denotes a particularly stable configuration with a closed outer shell of protons or neutrons.

Magnetic moment
Property characterising the magnetic field of a spinning electric charge.

Muon
An elementary particle belonging to the lepton family – a heavier version of the electron with a half-life of 2.2 microseconds.

Neutrino
A neutral elementary particle with hardly any mass.

Neutron
One of the two particles making up the nucleus. Free neutrons decay into a proton, an electron and an antineutrino.

Neutron star
A small star consisting largely of densely packed neutrons that is the end-product of a supernova explosion.

Nuclear chart
A map showing the range of possible nuclei in terms of numbers of protons and neutrons. It marks both stable and short-lived nuclei.

Nuclear fission
Process by which heavy nuclei break up to produce smaller nuclei.

Nuclear magnetic resonance
A process in which the spin of a nucleus interacts with magnetic and electromagnetic fields causing it to precess like a spinning top does in the Earth's gravitational field.

Nucleon
A constituent of the nucleus, usually a proton or a neutron.

Glossary

Nucleosynthesis
The processes by which increasingly heavy nuclei are built up from protons and neutrons (mainly in stars) to create the elements of Nature.

Nucleus
A constituent of atomic matter consisting of protons and neutrons.

Pauli exclusion principle
Fundamental quantum law which distinguishes fermions from bosons. It says that no two fermions can occupy the same quantum state; bosons can occupy the same quantum state.

Phase transition
The point in terms of, for example, temperature or pressure at which a defined structure or set of properties of a system suddenly changes.

Phonon
Name used for a vibrational mode in quantum mechanics; phonons behave as bosons.

Pico
Unit of scale, 10^{-12}.

Planck's constant
The fundamental constant of Nature that relates the energy and wavelength of quantum particles.

Proton
One of the constituents of the nucleus. The number of protons characterises the chemical and physical properties of an element.

***P*-violation (parity violation)**
A phenomenon by which right and left-handed particles behave differently.

Quantum mechanics
The theory that describes matter and energy in terms of particles with wave-like behaviour.

Quantum state
Systems obeying the laws of quantum mechanics, such as particles or nuclei, exist in defined energy states.

Quark
The elementary particle making up particles such as protons and neutrons. There are six kinds of quark and they interact via the strong, weak and electromagnetic forces.

Red giant
An ageing star that has expanded to form a large volume of cool, tenuous gas (the volume of our inner Solar System) with a small core, after all its hydrogen fuel has been exhausted, and it has begun to burn helium into carbon and oxygen.

***r*-Process (rapid process)**
The explosive process thought to occur in supernovae (type II) whereby nuclei rapidly capture neutrons on a time-scale that is fast compared with the process of beta decay so that several neutrons are captured before beta decay occurs to give the element of the next highest atomic number.

Shell model
A theoretical description of the nucleus in which the constituent nucleons are arranged in filled shells under the influence of an averaged central force. Outer 'valence' nucleons in the outermost shell control the behaviour of the nucleus.

***s*-Process**
The process of nucleosynthesis in red giants whereby nuclei capture neutrons on a timescale that is slow compared with the subsequent beta decay to give the element of the next highest atomic number.

Standard Model of Particle Physics
The accepted theoretical description of the elementary building blocks of matter and three of the four forces of Nature in terms of matter particles – six quarks and six leptons and force particles – the photon (electromagnetism), W and Z bosons (weak force) and the gluon (strong force).

Strong interaction
One of the four fundamental forces; it affects only quarks and gluons.

Supernova type II
Massive stars (10 to 30 times the mass of our Sun) end their life in a gigantic explosion as bright as an entire galaxy.

Symmetry
A mathematical concept used throughout physics to describe the state and degree of order in systems.

Symmetry breaking
A process by which a system changes to a state of lower symmetry with more complex structural or dynamic characteristics.

***T*-violation (time-reversal violation)**
The phenomenon whereby a forward-going process differs from the same process going in reverse.

Ultra-cold neutrons
Neutrons cooled to energies so low that they can not penetrate through material walls.

Uncertainty Principle
An intrinsic characteristic of quantum behaviour whereby the precision with which linked variables such as position and momentum, or energy and time, can be determined simultaneously is limited.

Weak interaction
One of the four fundamental forces; it is responsible for phenomena such as beta decay.

W particle
One of the particles that mediate the weak interaction.

Z particle
One of the particles that mediate the weak interaction.

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The Boomerang Nebula – a planetary nebula formed by a fierce wind blowing ultra-cold gas at half a million kilometres an hour from a dying central star. The heavier elements are created by the process of nucleosynthesis (see p. 16) in such stars

The inset shows the path of neutron decay

NEUTRONS
FOR SCIENCE

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