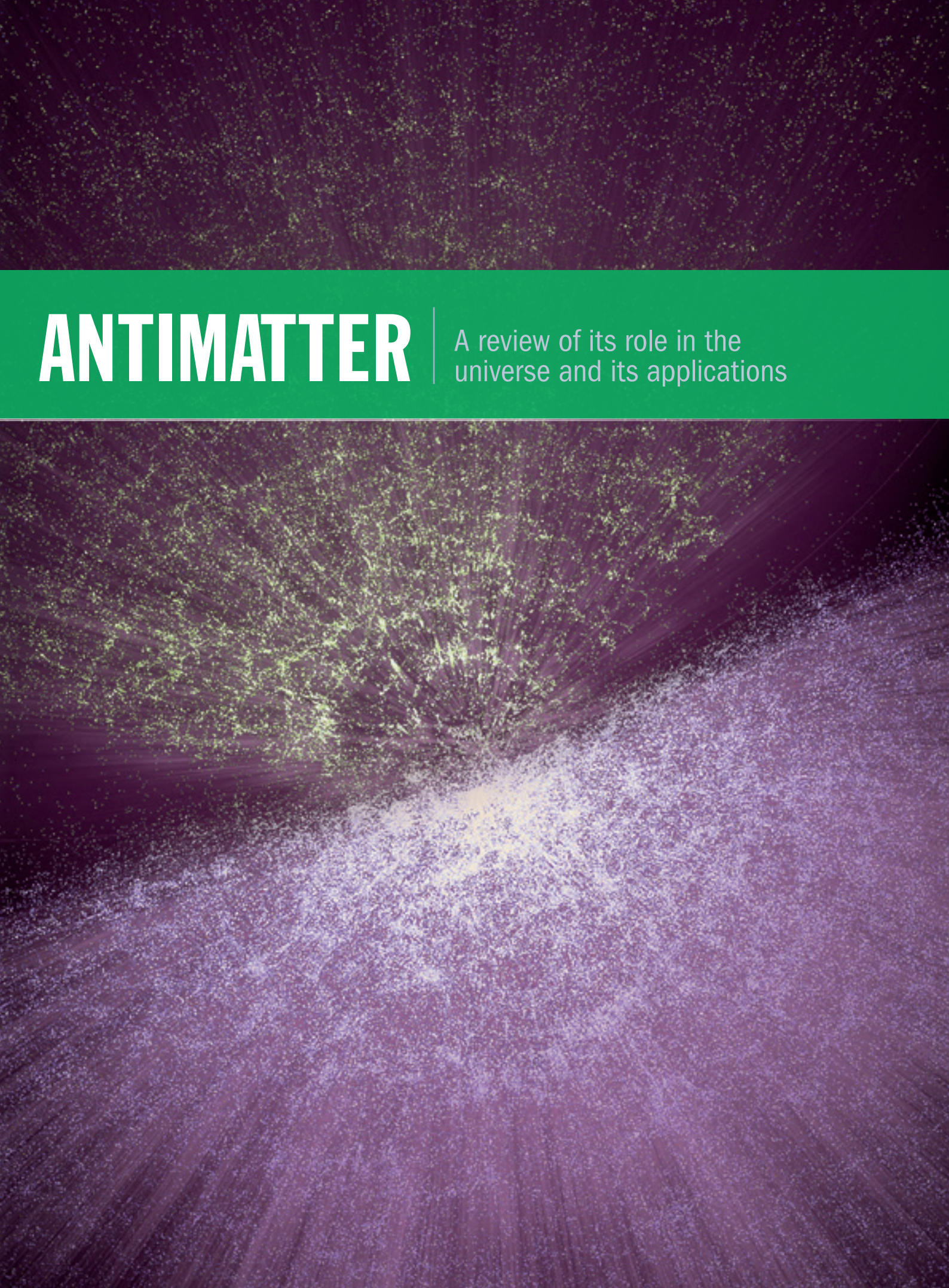
ANTIMATTER

A review of its role in the universe and its applications

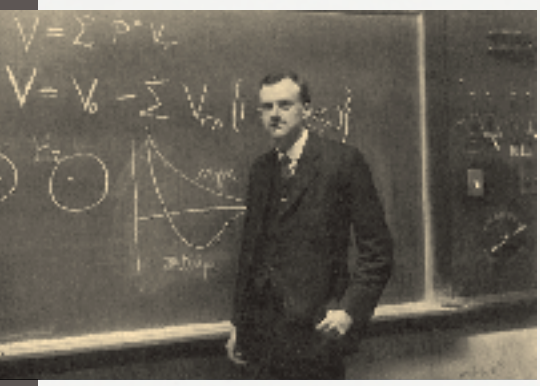


IOP Institute of Physics

Antimatter plays an intrinsic role in our understanding of the subatomic world

THE UNIVERSE THROUGH THE LOOKING-GLASS

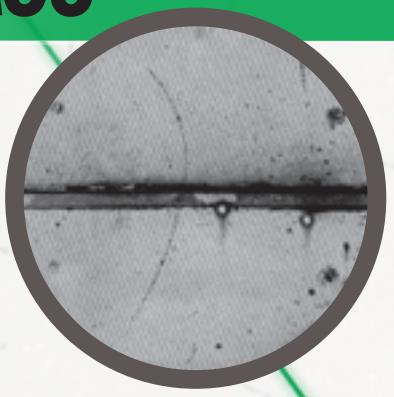
The beginning of the 20th century saw a cascade of brilliant insights into the nature of matter and energy. The first was Max Planck's realisation that energy (in the form of electromagnetic radiation *i.e.* light) had discrete values – it was quantised. The second was that energy and mass were equivalent, as described by **Einstein's special theory of relativity** and his iconic equation, $E = mc^2$, where c is the speed of light in a vacuum; the theory also predicted that objects behave somewhat differently when moving



Paul Dirac's equation of quantum mechanics (right) predicted the existence of antimatter

with velocities close to the speed of light. The third was Niels Bohr's ground-breaking description of matter as composed of atoms consisting of lightweight, negatively charged electrons orbiting a central, positively charged nucleus. The key feature of the model was that the electrons occupied a series of energy levels or quantum states. When an electron jumped from a lower quantum state to a higher one or *vice versa*, it absorbed or emitted quanta of electromagnetic radiation of definite energy, giving rise to a characteristic spectrum of bright or dark lines at specific wavelengths.

The Austrian physicist, Erwin Schrödinger laid down a more precise mathematical formulation of this behaviour based on wave theory and probability – **quantum mechanics**. The Schrödinger wave equation could predict the spectrum of the simplest atom, hydrogen, which consists of a single electron orbiting a positive proton. However, the spectrum featured additional lines that were not explained. In 1928, the British physicist Paul Dirac realised that because the



C.D. Anderson, Emilio Segrè Visual Archives

The first image of a positron track found in cosmic rays

or **positron**; when an electron met a positron, they would annihilate according to Einstein's equation, generating two gamma rays in the process. The concept of **antimatter** was born.

$$(c\boldsymbol{\alpha} \cdot \hat{\mathbf{p}} + \beta mc^2)\,\psi = i\hbar \frac{\partial \psi}{\partial t}$$

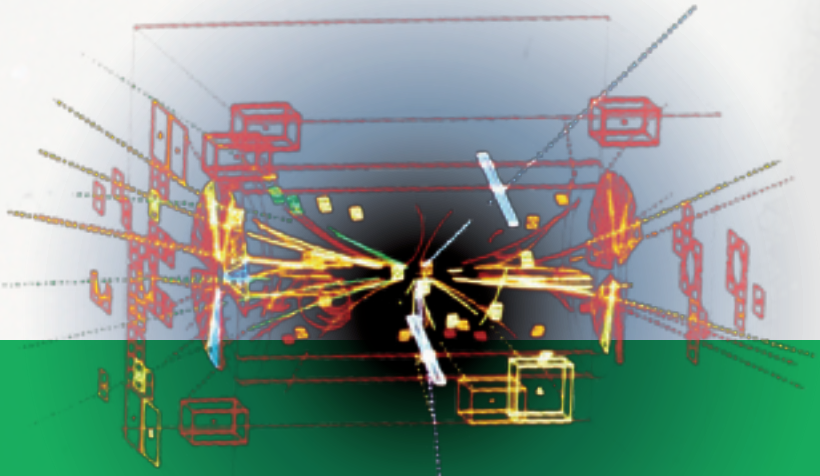
electron was very light and moved very quickly, special relativity needed to be incorporated into the equation to explain this fine structure.

Dirac produced a more complicated wave equation that revealed the electron's true character. First, it predicted that electrons had spin, which could be right- or left-handed. The second, more bizarre characteristic was that the electron could have a range of negative as well as positive energies. This suggested that this concept predicted the existence of a positively charged electron –

THE IMPORTANCE OF DIRAC'S IDEAS

Today, it is accepted that all subatomic particles can have a "mirror" or antimatter counterpart with opposite **charge** and right- or left-handed **spin**. Furthermore, our understanding of particles and forces – the fundamental building blocks of the universe – is built on these kinds of mirror **symmetries**, which are reflected in the powerful mathematical framework of quantum mechanics. The concept of symmetry is now used throughout physics to explain and classify phenomena.

Another important idea to emerge

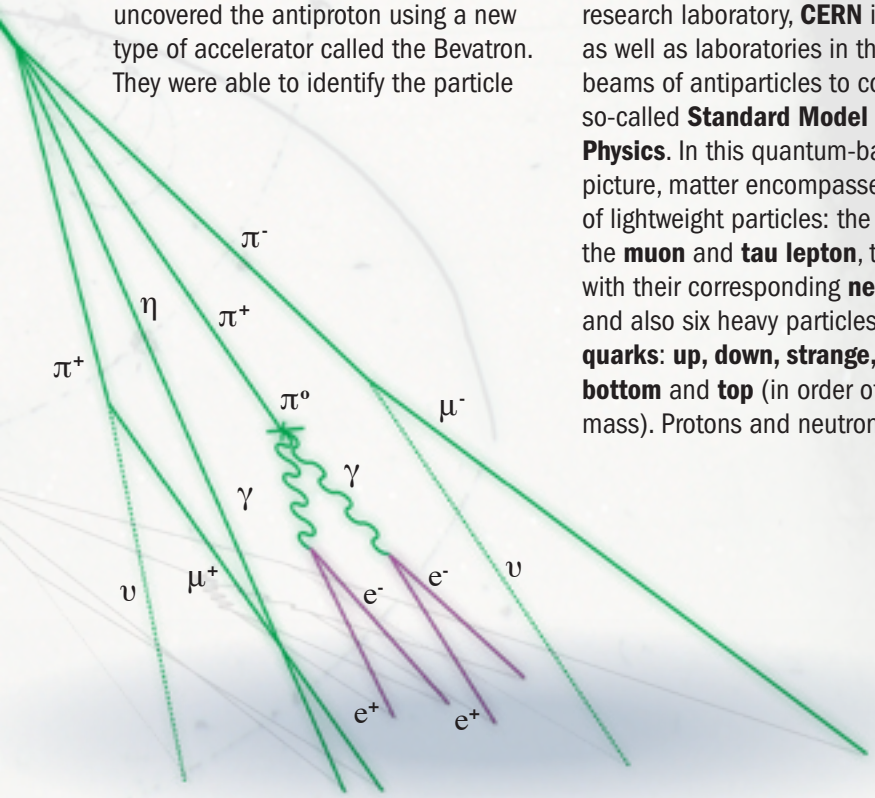


The first detection in 1983 of a carrier of the weak force, the Z particle, in CERN's ground-breaking proton–antiproton collider (the Super Proton Synchrotron), which was later superseded by the Large Electron–Positron collider, LEP (top right)

from Dirac's equation is that the vacuum is not empty space but a sea of virtual particles. According to quantum probability, particles can pop in and out of existence, allowing **particle–antiparticle pairs** to be generated from the vacuum according to Einstein's equation.

THE DISCOVERY OF ANTIPARTICLES

The existence of positrons was confirmed when they were discovered in cosmic rays using a cloud chamber, in 1932 by Carl Anderson at the California Institute of Technology. Then in 1955, a team led by Owen Chamberlain and Emilio Segrè at the University of California at Berkeley uncovered the antiproton using a new type of accelerator called the Bevatron. They were able to identify the particle from its momentum and negative charge, and show that it annihilated in a characteristic way when it hit a proton or neutron in ordinary matter.



THE ROLE OF ANTIMATTER IN PARTICLE PHYSICS

Experiments employing or generating antimatter particles have played a key role in formulating ideas about the fundamental particles and forces. Particle collisions at very high energies may generate particle–antiparticle pairs, which provide information about the characteristics of the elementary units of which the universe is composed.

Europe's main particle physics research laboratory, **CERN** in Geneva, as well as laboratories in the US, used beams of antiparticles to confirm the so-called **Standard Model of Particle Physics**. In this quantum-based picture, matter encompasses six types of lightweight particles: the **electron**, the **muon** and **tau lepton**, together with their corresponding **neutrinos**; and also six heavy particles called **quarks**: **up, down, strange, charm, bottom** and **top** (in order of increasing mass). Protons and neutrons are composed of the two lightest quarks. Each particle has an antimatter partner. The four fundamental forces, the electromagnetic force, strong and weak forces, and gravity, are also described as being mediated by particles, known as bosons (although gravity is still not incorporated into the Standard Model).

In the 1980s, experiments at CERN colliding beams of protons and antiprotons confirmed the existence of W and Z bosons, which carry the weak force. These new particles were later studied throughout the 1990s using the **Large Electron–Positron** collider, **LEP**. A new electron-positron collider is being planned to probe the Higgs-boson-like particle that has now been discovered in the Large Hadron Collider (LHC) at CERN.

Another high-energy project at Darmstadt in Germany, **FAIR** (Facility for Antiproton and Ion Research), will use high-intensity antiproton beams to investigate the strong force, and how matter first formed and evolved in the universe.

THE UK ROLE

The UK has always been a world-leader in particle physics. It has participated in most of the major international experiments involving antimatter, particularly through its membership of CERN. The UK has invested in technologies for future collider designs and experiments. It plans to become an Associate Member of FAIR.

The high-energy FAIR facility in Germany will generate intense antiproton beams for many experiments

We live in a universe made mostly of matter, so where did all the antimatter go?

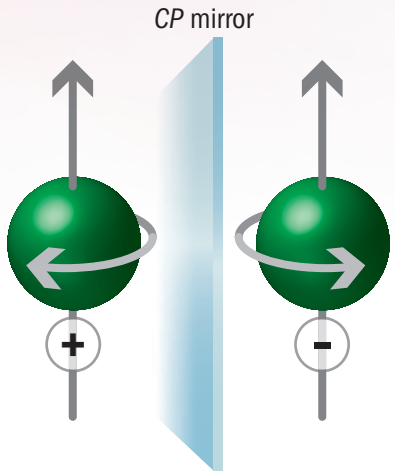
LOST WORLDS OF ANTIMATTER

Physicists now believe that the Universe was born some 13.75 billion years ago in a unified high-energy state that rapidly expanded and cooled, coalescing into the matter and force carriers responsible for our existence. Matter and antimatter particles should have been created in equal numbers and should have annihilated. Somehow, some matter – but no antimatter – survived; observations indicate that all the stars and galaxies we see are made of the same version of matter as our own solar system and ourselves.

Theoretical physicists think that an imbalance between particles and antiparticles must have developed during the primordial expansion, and that there must be some inherent asymmetrical difference in the behaviour of matter and antimatter that favoured the survival of matter. However, no one is sure what those processes were and how they worked. Identifying subtle effects associated with the **matter–antimatter asymmetry** is now one of the main research areas in fundamental physics.

SEARCHING FOR ASYMMETRY

As explained on p2, physicists classify the quantum properties of particles according to various symmetries: in particular, their **electrical charge (*C*)**, which can be positive or negative; their "**parity**" **(*P*)**, which describes what happens when they are inverted in space (as in a mirror) and gives the particles "right- or left-handedness"; and the reversibility of their behaviour in **time (*T*)** – the film of a particle interaction looks the same whether run forwards or backwards. Particles and their antiparticles with opposite charge and handedness should behave in the same way, that is – symmetrically. To search for any asymmetry, researchers probe *C*, *P* and *T*, either separately or combined (*CP* or *CPT*), by comparing how particles and their anti-versions behave.



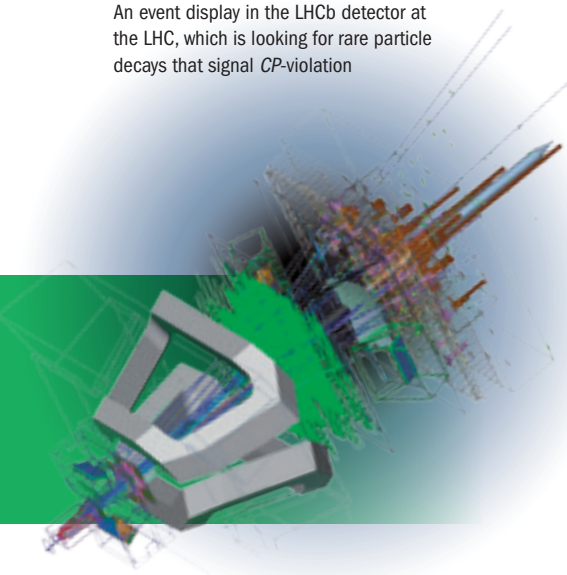
Symmetry inherent in quantum mechanics shows how the *CP* (charge–parity) "mirror" (a mathematical operation) reverses the basic attributes of fundamental particles like electrons: the electric charge transforms from negative to positive or *vice-versa*; and the direction of the particle's motion reverses with respect to the sense of its spin so that its "handedness" changes

The first hints of asymmetry were seen in 1964 when scientists at the Brookhaven National Laboratory in the US observed a tiny difference in the

The CPLEAR experiment at CERN investigated the "breaking" of the *CP* mirror (*CP*-violation) in the early 1990s, using particles called kaons

decays of exotic composite particles known as **neutral kaons (K^0)**. These consist of a down quark and a strange quark (p3) but exist in two forms that are each "quantum mixtures" of both the matter and antimatter versions. The two forms decay at different rates, and are known as K-long and K-short. Tiny discrepancies in their decay patterns indicated that the constituent quarks and antiquarks were behaving slightly differently in terms of their parity, and were in fact "violating *CP* symmetry". More precise experiments at CERN using the **Low Energy Antiproton Ring (LEAR)** and at other laboratories confirmed that *CP* and *T* symmetries were violated.

In the 1990s, physicists turned to the decays of a heavier particle called the **B-meson**, which contains a bottom quark. A major experiment at the Stanford Linear Accelerator Center



An event display in the LHCb detector at the LHC, which is looking for rare particle decays that signal *CP*-violation

in California, called **BaBar**, together with a Japanese experiment, **Belle**, extensively measured various aspects of *CP*-violation in Bs and anti-Bs. These measurements have continued at the LHC with the **LHCb** experiment (upgrade planned for 2018), which is currently measuring very rare B-meson decays.

NEUTRINOS TO THE RESCUE?

So far, none of the *CP*-violating phenomena seen is large enough to explain the disappearance of antimatter. Physicists are now turning to another particle, the **neutrino**, which may just provide some answers. Neutrinos are electrically neutral and have hardly any mass, but reveal themselves in the radioactive decay of some unstable nuclei. All three neutrino types, the electron-neutrino, muon-neutrino and tau-neutrino, appear to oscillate from one type to another. Recent experiments on neutrinos produced in nuclear reactors, which measure the rate of one type of neutrino oscillation predicted to involve *CP*-violating processes, indicate that the effect could be measured.

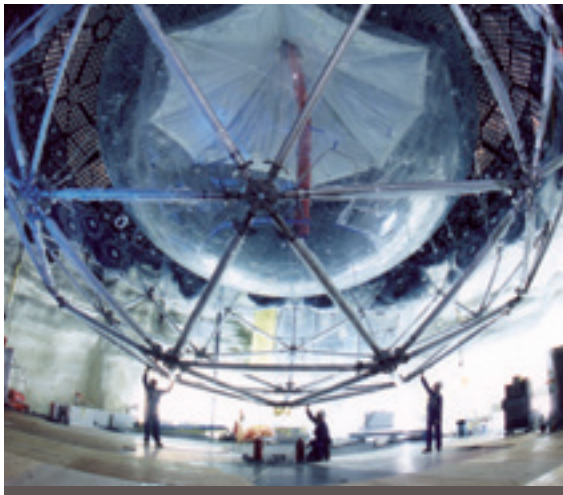
Even more significant is that the spin of lightweight neutrinos is always left-handed. Theorists postulate that a right-handed, much heavier neutrino could have existed in the high-energy primordial universe, and could have generated the necessary imbalance in particle–antiparticle numbers through *CP*-violation. However, for such *CP*-violation to exist, the neutrinos and antineutrinos (which have no charge) would have to be identical, as predicted by the Italian physicist Ettore Majorana in 1932.

This attribute of neutrinos may reveal itself in a rare type of radioactivity called **neutrinoless double beta decay**. In normal beta decay, an electron and an antineutrino are emitted. However, double beta decay can happen in some isotopes, and it is possible that the two neutrinos generated could just cancel each other out – if they behave both as particles and antiparticles. A number of high-precision experiments are searching for this, as yet unseen phenomenon.

Neutrino *CP*-violation will also be studied in a future international **neutrino factory** producing intense neutrino beams.

DETECTING ANTIMATTER IN SPACE

No antimatter galaxies have been detected in the universe, but single antiparticles do rain down on the Earth as cosmic rays, probably produced in high-energy processes such as those occurring around black holes, in supernovae or the annihilation of dark matter. Several satellites including the European mission, **Pamela** (Payload for Antimatter Exploration and Light-nuclei Astrophysics) launched in 2006, and the AMS (Alpha Magnetic Spectrometer) installed on the International Space Station in 2011, have been sifting through cosmic rays for antimatter. If any antimatter nuclei, such as helium nuclei, were detected, it might indicate the existence of bulk antimatter somewhere in the cosmos.



The huge Sudbury Neutrino Observatory (SNO) in a mine in Canada is being upgraded to search for a rare particle event (neutrinoless double beta decay) that may uncover *CP*-violation in neutrinos

THE UK ROLE

UK researchers participated in *CP*-violation experiments, CPLEAR and BaBar, and are now collaborating in LHCb. In addition, they are carrying out subtle experiments on neutrons at the Institute Laue-Langevin in Grenoble, France that may also uncover *C*, *P* and *T* asymmetries. The UK also has a strong presence in neutrino research: in two projects searching for neutrinoless double beta decay: **SNO+** at the Sudbury Neutrino Laboratory in Canada, and **SuperNEMO**, located in the Modane Underground Laboratory in the French Alps; and in the search for neutrino *CP*-violation at the **T2K** experiment (JPARC facility) in Japan. The UK is also hosting new technology needed for a neutrino factory, called **MICE (Muon Ionisation Cooling Experiment)**.

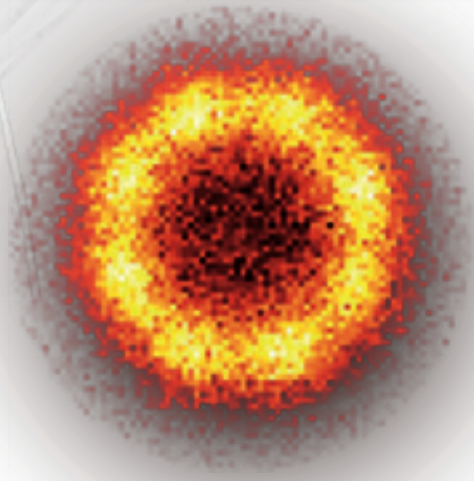
Part of the international SuperNEMO experiment to detect neutrinoless double beta decay, being developed at the University of Manchester

Antimatter is extremely difficult to make and store

CREATING ANTIMATTER IN THE LABORATORY

COLD ANTIHYDROGEN

While subatomic antiparticles can be generated in high-energy experiments, synthesising even the simplest form of everyday atomic antimatter is a major challenge. To make antihydrogen (an antiproton bound to a positron) requires supplies of positrons and antiprotons that are moving slowly enough to combine into atoms without annihilating. The first few antihydrogen atoms were not produced until 1995. Using LEAR, CERN physicists passed decelerated antiprotons through a jet of xenon gas. Some of the antiprotons' energy was converted into electron–positron pairs – and, occasionally, a positron formed a transient bond with an antiproton.



Top and left: antihydrogen atoms are held in magnetic traps at CERN; untrapped atoms are seen here annihilating on the inner surface of the ALPHA trap

Such a set-up was not suitable for studying antihydrogen, and in 1999, CERN built a new facility, the **Antiproton Decelerator (AD)**, to decelerate antiprotons down to a speed one-tenth that of light. The low-energy antiprotons could then be transferred to experimental set-ups designed for antiatom studies.

Two international collaborations, **ATHENA** and **ATRAP**, employed novel technology to slow the antiprotons further and capture them in a trap using magnetic and electric fields. The antiprotons were then carefully introduced into a second trap containing chilled positrons so that both sets of antiparticles could combine into atoms. In 2002, the ATHENA team announced it had detected 50,000 antihydrogen atoms. Using a slightly different trap configuration and method of detecting antihydrogen, ATRAP reported equally impressive results. Soon after, both experiments were making millions of antihydrogen atoms.

To study the antihydrogen produced, the atoms needed to be stored. ATHENA was replaced by **ALPHA (Antihydrogen Laser Physics Apparatus)** which had a magnetic trap specially designed to confine the neutral atoms at a temperature close to absolute zero. By 2010, 38 antihydrogen atoms had been stored for one-fifth of a second, with the number increasing to hundreds of atoms for many minutes in the following year.

The ALPHA antihydrogen facility

HOW DO YOU MAKE ANTIMATTER PARTICLES?

Positrons

Positrons are produced naturally in the radioactive decay of some elements. Sodium-22 is the isotope most used to create positron beams. However, a shortage of sodium-22 has meant that new methods of production are being studied. For example, bombarding a target with an electron beam, or gamma rays from a reactor, generates electron–positron pairs that can then be separated. The

The positron beam facility at FRMII, Technical University of Munich

FRMII research reactor at the Technical University of Munich provides an intense positron beam for a variety of experiments (p11). Irradiating a target with a powerful, ultra-intense laser, such as the new European facility being planned, the **Extreme Light Infrastructure (ELI)**, offers a potential route to generating billions of electron–positron pairs for antimatter experiments.

Antiprotons

Antiprotons are produced via pair production by firing protons at a target made of a heavy metal such as nickel or iridium. They are then collected using a magnetic field.

A device that will transport antiprotons in a new low-energy decelerator, ELENA, to replace the existing AD set-up that serves the ALPHA and ASACUSA experiments

QUARK ANTIMATTER

High-energy experiments in the US (the Relativistic Heavy Ion Collider, RHIC, at the Brookhaven National Laboratory) and in Europe (the ALICE experiment at the LHC) are studying collisions of heavy nuclei in order to simulate conditions in the universe when ordinary matter was first crystallising out of the primordial quark–antiquark soup. Detecting particles consisting of quark–antiquark pairs that would have been initially generated throws light on the processes involved, and how matter came to form rather than antimatter. Atomic nuclei made of antiprotons and antineutrons such as antideuterium, antihelium-3 and antihelium-4, as well as exotic nuclei containing heavy antiquarks, have also been observed by the STAR collaboration at RHIC. Their study probes the nature of the forces that made our universe what it is today.

Part of the STAR detector at the RHIC facility, which has detected the generation of antimatter nuclei

WHY STUDY ANTIHYDROGEN?

Comparing the spectra of antihydrogen and hydrogen offers a unique probe of the combined *CPT* symmetry described on p4. Any violation would mean a drastic revision of fundamental physics ideas. In 2011, the ALPHA team made its first spectroscopic measurements, which are being continued using a laser to excite the atoms. Another CERN experiment called **AEGIS** is being built to test whether the effect of gravity on antihydrogen and hydrogen is the same, which again will provide insight into theories describing the fundamental forces and the universe.

The success of the AD experiments has spurred on CERN to develop a new antiproton source to be ready in 2017. **ELENA (Extra Low Energy Antiproton Ring)**, will slow antiprotons to under a one-fiftieth of the current energy of the AD, which will increase the trapping efficiency by up to 100 times. The FAIR facility (p3), which will provide much more intense antiprotons beams, also plans to carry out antihydrogen experiments.

THE UK ROLE

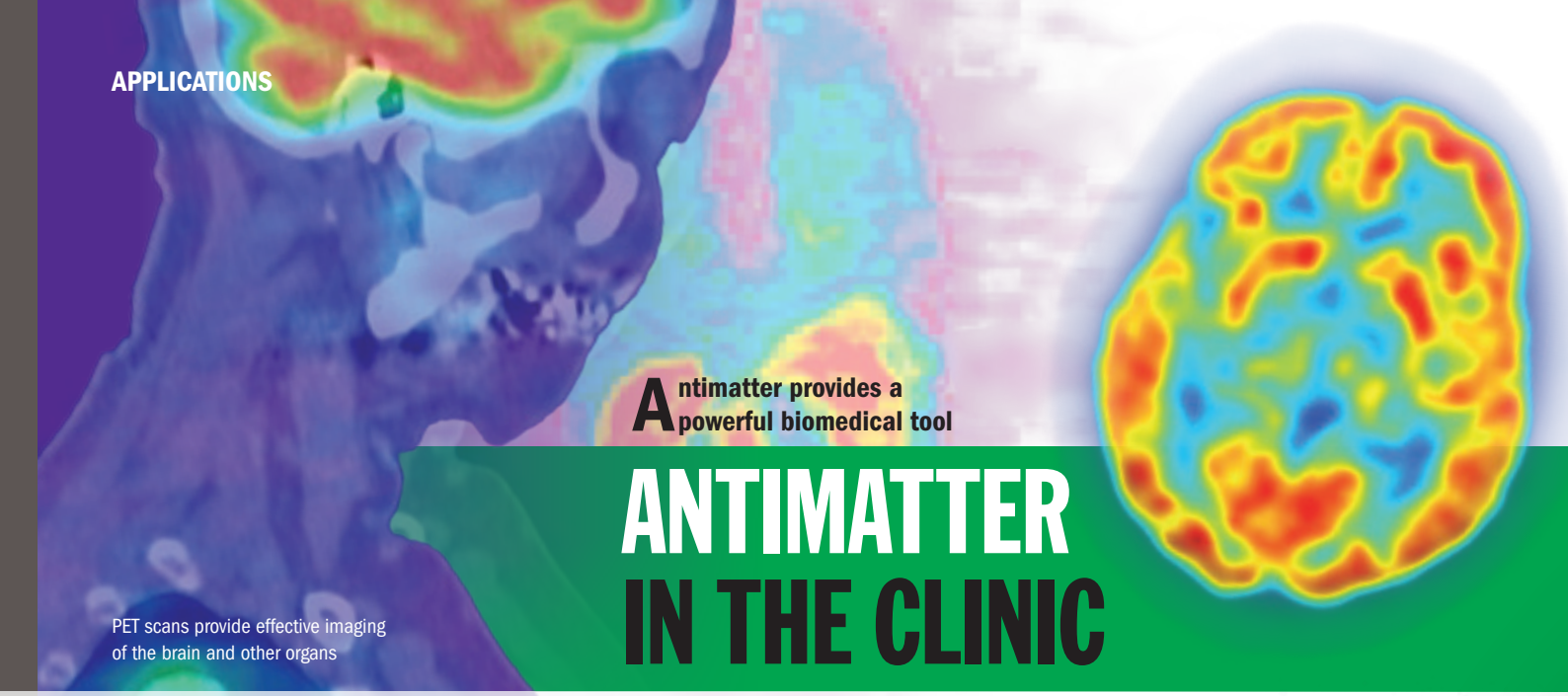
Mike Charlton leads a team from Swansea University collaborating in the ALPHA experiment. His team and researchers from Queen's University Belfast have also been involved in ASACUSA.

Researchers at the University of Birmingham are participating in ALICE, and, with STFC Daresbury Laboratory in Cheshire, in the STAR experiment at RHIC.

The ASACUSA facility at CERN

ANTIPROTONIC HELIUM

A further CERN experiment, **ASACUSA (Atomic Spectroscopy and Collisions Using Slow Antiprotons)**, makes precision measurements on helium atoms in which one of the two orbiting electrons has been replaced with an antiproton. A small amount of **antiprotonic helium** is created when antiprotons are mixed with helium gas at very low temperatures. Laser spectroscopy again is used to provide another test of *CPT* symmetry.



PET scans provide effective imaging of the brain and other organs

Antimatter provides a powerful biomedical tool

ANTIMATTER IN THE CLINIC

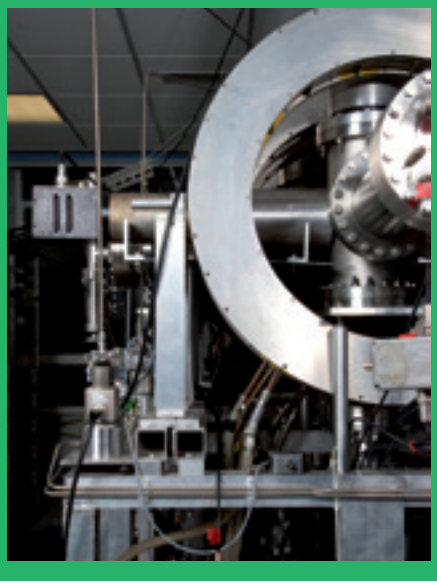
THE POWER OF POSITRONIUM

A positron may combine with an electron to form **positronium**. Positronium comes in two forms: **parapositronium** with the positron and electron having oppositely aligned spins, which has a lifetime of 125 picoseconds; and **orthopostronium** with spins parallel, which survives for 142 nanoseconds in a vacuum (though only about a nanosecond in a molecular solid).

Positronium is interesting for several reasons:

- Very cold positronium temporarily forms when positrons are fired at a silicon surface so that they combine with electrons in the semiconductor. This offers a way of generating the resulting low-energy positrons in a controlled way for antihydrogen experiments (p6).
- Positrons also combine with electrons in organic molecules to form positronium states before annihilation. This is important in influencing the effectiveness of PET imaging: when the positrons interact with biological tissue, the initial formation of positronium increases the positron lifetime.
- Positrons are produced in many astrophysical processes such as supernovae explosions, and may well play a role in mediating interstellar chemistry via positronium formation.

How positrons and positronium interact with matter is also of fundamental interest and is revealed by studying their collisions with single atoms and molecules. Recently, researchers at University College London led by Gaetana Laricchia found, somewhat surprisingly, that positronium scatters off various atoms and molecules in a similar way to an electron moving at the same speed. As described by theorist, James Walters, at Queen's University Belfast, the positron appears to be "cloaked". Although the reason is not fully understood, it does mean that the large library of electron data available can be used in understanding how positronium interacts with matter – ranging from the human body to interstellar clouds.



Part of the equipment used at University College London to make and study the behaviour of positronium

IMAGING

Antimatter annihilation provides one of the main imaging techniques used in hospitals today. **Positron emission tomography (PET)** relies on short-lived positron-emitting isotopes (of carbon, oxygen, nitrogen and fluorine) which act as tracers when incorporated into selected pharmaceuticals introduced into the body. The pairs of gamma rays emitted, when the positrons annihilate as they come into contact with surrounding tissues, are detected by a position-sensitive detector array (largely developed as a spin-off from high-energy physics and astronomy research). The signals are used to construct a series of visual "slices" through the body that are then combined into a 3-D image, in a similar fashion to a computerised X-ray tomography (CT) scan.

The ACE experiment investigating the effectiveness of antiproton therapy at CERN

PET scans can follow biological processes such as blood flow, metabolism, neuronal transmission, tumour growth and are employed by the pharmaceutical industry to monitor the behaviour of drugs in the body. It is particularly successful at imaging structure and activity in the brain. Although the images are not as detailed as those from CT or magnetic resonance imaging (MRI) scans, they have the potential to measure biomolecular changes in a quantitative way. The recent development of new tracers, together with higher-resolution detectors, have allowed physiological changes to be followed such as those associated with Alzheimer's disease. PET is increasingly used to provide rapid and accurate 3-D images of tumours for radiotherapy planning.

ANTIPROTON CANCER THERAPY

Targeted proton beams are already employed as a therapeutic tool to kill tumours without damaging the surrounding tissue. They are particularly effective for difficult-to-treat head and neck tumours. The beam energies of protons and antiprotons can be adjusted so that they deposit most of their energy over a very short range that matches the size of a living cell. However, antiprotons also annihilate when in contact with protons in the cellular matter, so deliver much more energy over the same range. Antiproton therapy is currently being investigated at CERN in the **ACE experiment**, which has shown that the rate of destruction of cancer cells is four times higher with antiprotons than protons. This means that the radiation dose can be much smaller, and therefore safer and more effective. Antiprotons are, of course, more expensive to produce, but researchers in the US are already working on the development of a portable trap capable of holding and transporting antiprotons, which might make the procedure more economic.

THE UK ROLE

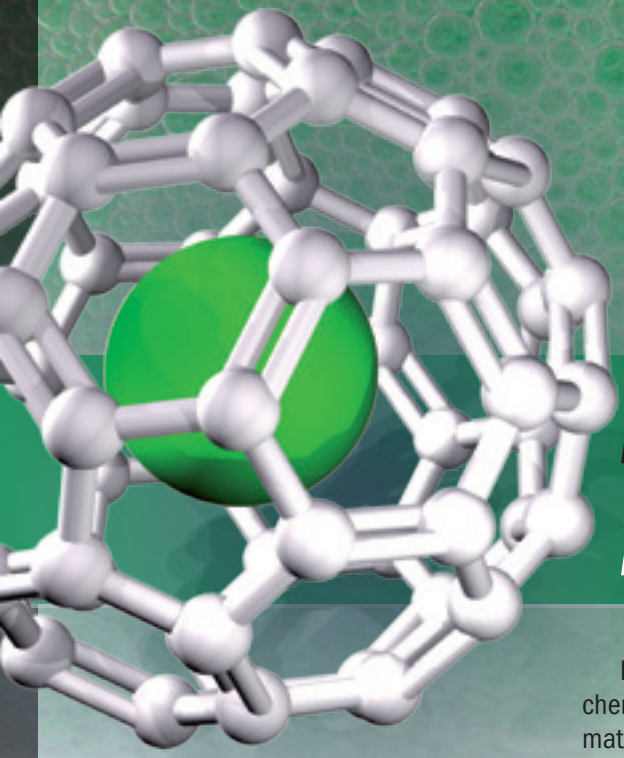
Several universities are working with hospitals to improve PET equipment and extend applications. These include Imperial College London (Hammersmith Hospital), the University of Manchester, Cardiff University and King's College London.

Both University College London and Swansea University have extensive programmes studying positron interactions and positronium, while theoretical work on positron–molecule scattering and positronium formation is also carried out at the University of Nottingham and Queen's University Belfast.

ENERGY FROM ANTIMATTER?

Although matter–antimatter annihilation generates large amounts of energy, it is unlikely that it would ever be a practical source of power (or used for making bombs), simply because antiprotons, or positrons, are so difficult and expensive to make (p8). With today's technology, it is impossible to synthesise large amounts of antimatter: the CERN accelerator would have to run for 100 billion years to produce a single gramme. Nevertheless, an antiproton beam could, in theory, start a nuclear reaction that is useful for energy generation. Such **antiproton drivers** have been suggested for **inertial confinement fusion**.

The intense gamma-ray beam from a **positronium laser** could also initiate nuclear reactions such as fusion. Theoretically, this could be achieved if a cloud of positronium atoms held at room temperature could form what is known as a Bose–Einstein condensate (BEC), in which all the atoms fall into the same quantum energy state and behave as a single entity. The positrons would then collectively annihilate to emit a coherent beam of gamma rays. One way to achieve this is to trap the positrons in a thin film of porous silica, as explained on p8. Researchers in the US have shown that double positronium "molecules" can form, which is the first step towards a BEC.

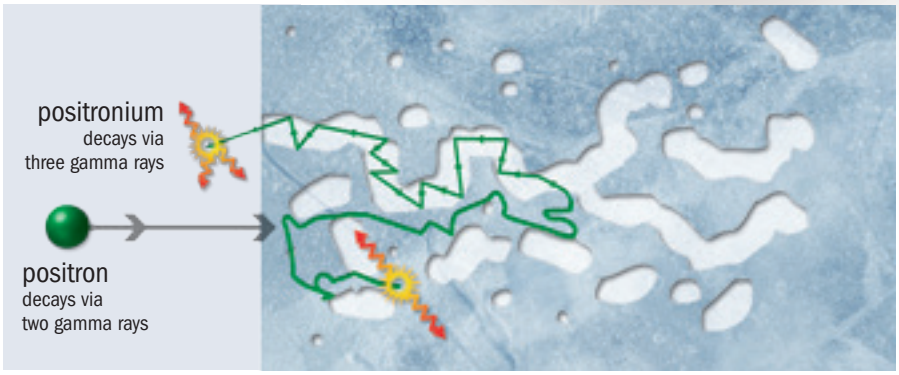


Antiparticles interact with matter in unique ways to provide a useful analytical tool for materials science and technology

ANTIMATTER PARTICLES AS PROBES

Details of the physical and chemical nature of the surfaces of materials and thin films are revealed through precision measurements of the gamma-ray pairs emitted when positrons annihilate with electrons in samples, sometimes first binding with them to form positronium (p8) – this is **positron annihilation spectroscopy (PAS)**. Using low-energy positron beams, the technique is ideal for studying surfaces, near-surface layers, and thin films. PAS encompasses three types of measurement. The most used method is the measurement of the **Doppler broadening of the gamma-ray energy spectrum**, which reflects the change in momentum of the electrons when bound to positrons. This in turn depends upon the immediate atomic environment – indicating, for example, whether there are structural defects. The method can probe the presence of missing atoms and pores in the crystal structure of semiconductors and other solids, and follow changes with temperature and over time. Paul Coleman at the University of Bath is currently using this method to study the behaviour of ice films, which is important for a range of astrophysical processes, as well as the freezing of biological tissues. He is also developing a variant of PAS using polarised positrons (with spins all pointing in the same direction) to study

Positron emission can be used as a tracer technique to track fast moving particles such as detergent powders in washing machines and dishwashers

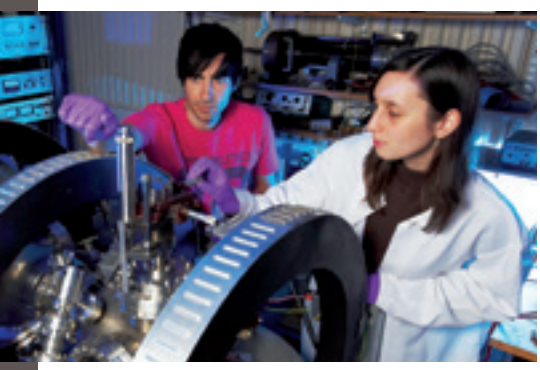


Paul Coleman/University of Bath

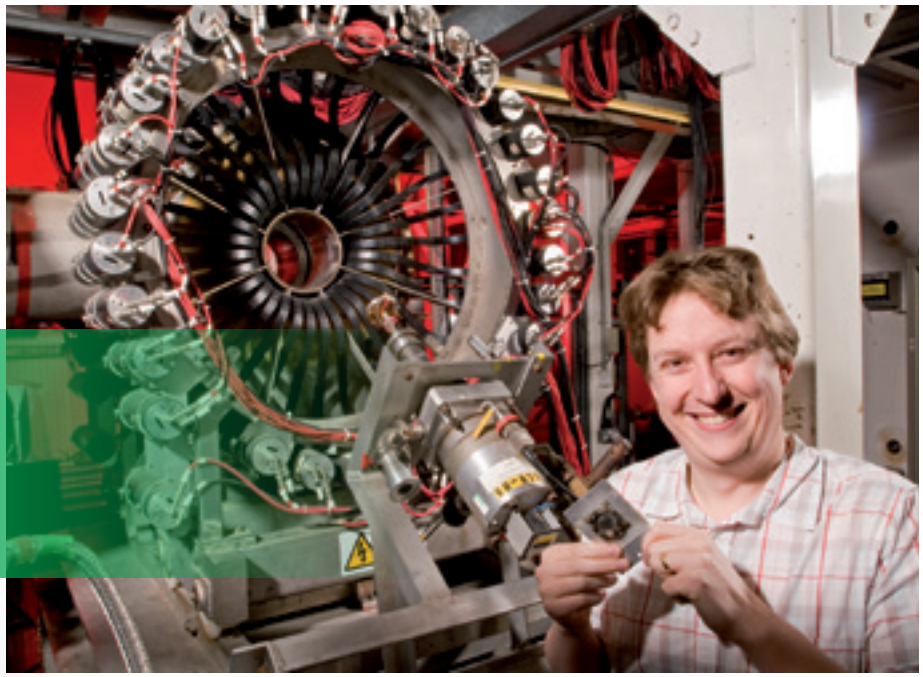
The lifetimes of positrons and positronium trapped in nanoporous materials reveal information about their structure

ANALYSIS WITH POSITRONS

Positron emission tomography is employed to image materials and processes of industrial importance, such as the flow of oil or water through rocks, lubricants in engines, and radioactive waste in nuclear storage materials. A new variant of the technique developed by David Parker at the University of Birmingham, **positron emission particle tracking (PEPT)**, can track tracer particles accurately in fast-flowing granular materials as they mix. His team has developed a portable PEPT gamma camera that enables them to carry out studies on working commercial systems such as fluidised beds (where pressurised fluids are forced through a vessel containing particulate material) used in coal gasification, chemical processing and food manufacture.



Researchers at the University of Bath working with positron beams



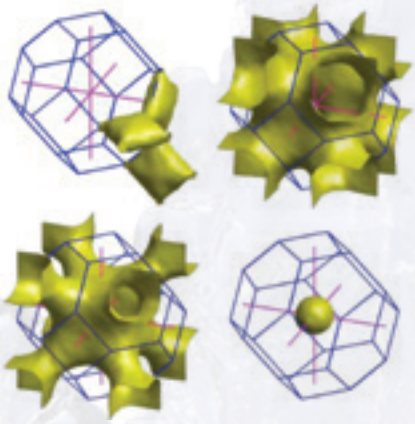
Ashraf Alam/University of Bristol

Left and right: antimuons implanted into C_{60} fullerenes form a hydrogen-atom-like state in the cage-like structure of the molecules, as revealed in muon spin rotation experiments at the UK facility, ISIS

thin magnetic films relevant to the next generation of magnetic devices.

Measuring the **variation in angles between the emitted gamma rays** provides even more precise information about the electronic structure of a material. Ashraf Alam, Stephen Dugdale and colleagues at the University of Bristol employ this approach to explore the fundamental properties of electronic and magnetic compounds of technological interest such as high-temperature superconductors and shape-memory alloys.

Finally, the **lifetime of the implanted positrons/positronium atoms** depends on the density of electrons at the annihilation site and gives information about the size and nature of open defects in materials. In condensed matter, atomic vacancies normally trap positrons, but there is not enough space for positronium formation, and the positrons annihilate directly with the electrons in the material. The lifetimes are therefore short, typically less than 500 picoseconds. David Keeble at the University of Dundee uses positron lifetime spectroscopy (using the positron beam at the FRMII Munich Research Reactor, p7) to study complex oxides with technologically important properties such as ferroelectricity, superconductivity and magnetoresistance, as well as semiconductor materials used in solar cells and other electronic devices. The Bristol group employs lifetime measurements to probe subnanometre-scale open volumes in biopolymers, with the aim – in conjunction with the pharmaceutical and food industries – of designing tailor-made vehicles for drugs and nutrients. They also utilise the lifetime technique to relate the physical characteristics of polymer–nano-composites to these open volumes.



Ashraf Alam/University of Bristol

The electronic structures of technologically important materials can be constructed with the aid of positron annihilation spectroscopy

ANALYSIS WITH ANTIMUONS

The heavier version of the positron, the positively charged antimuon, is also extensively employed as an analytical probe. Positive muons readily implant themselves in solids and liquids, and combine with electrons to form **muonium**, which behaves like a lightweight hydrogen atom. Like protons, muons have a spin, so behave like tiny magnets.

Once implanted in a sample, the magnetic environment around the muon affects its spin direction in a way that provides information about the local chemical and magnetic behaviour. The technique, **muon spin rotation (μSR)**, relies on polarised muons and is analogous to the well-known analytical method of nuclear magnetic resonance (NMR). Muons survive for just over 2 microseconds before they decay into positrons that are then detected. The technique is ideal for studying the role of hydrogen impurities in semiconductors, exotic molecular magnets, superconductors, and many other electronic materials.

THE UK ROLE

Analysis using positrons is carried out at the Universities of Birmingham, Bath, Bristol and Dundee, and Imperial College London.

The ISIS pulsed muon facility at the STFC Rutherford Appleton Laboratory near Oxford is the UK centre for μSR experiments. Muon beams are generated from an energetic proton beam when it collides with a target to generate intermediate particles called pions. These quickly decay to muons.

The IOP thanks the researchers who helped with the preparation of this booklet.

Not all UK research on or using antimatter could be mentioned.

Further information on antimatter

1. *Antimatter,* Frank Close, OUP, Oxford, 2009

2. Antimatter: Mirror of the Universe – LIVEfromCERN
   http://livefromcern.web.cern.ch/livefromcern/antimatter

3. In London, King's College, Imperial College, University College and the Medical Research Council (MRC) have formed a PET imaging consortium, Imanova Ltd (www.imanova.co.uk), based at the Hammersmith Hospital where most PET research is now concentrated.

4. http://en.wikipedia.org/wiki/Antimatter

For further information, contact:

Tajinder Panesor
IOP Institute of Physics
76 Portland Place
London W1B 1NT
Tel +44 (0)20 7470 4800
Fax +44 (0)20 7470 4848
E-mail tajinder.panesor@iop.org
www.iop.org
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Front cover image
The distribution of galaxies across the universe from the Sloan Digital Sky Survey

Research and text: Nina Hall ninah@ealing.demon.co.uk Design: **h2o-creative**