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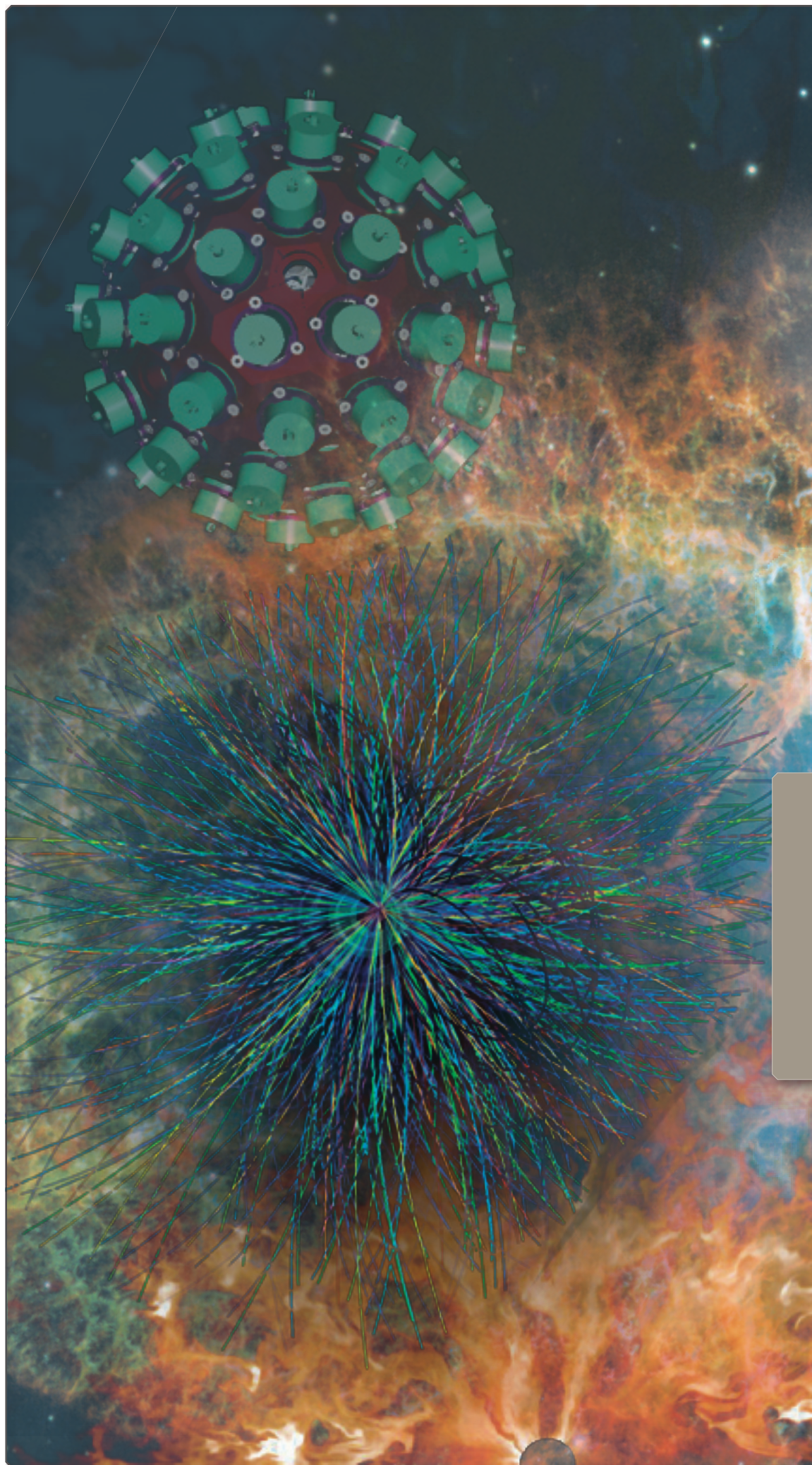
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**EUROPEAN
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SETTING SCIENCE AGENDAS FOR EUROPE

NuPECC

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December 2010





LONG RANGE PLAN 2010

NUCLEAR PHYSICS: SCIENCE AND APPLICATIONS

Perspectives for research in Europe

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THE NUCLEAR PHYSICS EUROPEAN COLLABORATION COMMITTEE IS AN EXPERT COMMITTEE OF THE EUROPEAN SCIENCE FOUNDATION

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Nuclear physicists attend a recent NuPECC conference in Madrid

About NuPECC

The Nuclear Physics European Collaboration Committee (NuPECC) is an Expert Committee of the European Science Foundation (ESF). Its aim is to strengthen European collaboration in nuclear science by promoting nuclear physics, and its trans-disciplinary use and application, in collaborative ventures between European research groups, and particularly those from countries linked to the ESF. NuPECC encourages the optimal use of a network of complementary facilities across Europe, provides a forum for discussing the provision of future facilities and instrumentation, and advises and makes recommendations to the ESF and other bodies on the development, organisation, and support of European nuclear research, particularly on new projects. The Committee is supported by its subscribing Institutions which are, in general, Member Organisations of the ESF involved in nuclear science and research or research facilities.

FOREWORD

The goal of this European Science Foundation *Forward Look* into the future of nuclear physics is to bring together the entire nuclear physics community in Europe to formulate a coherent plan of the best way to develop the field in the coming decade and beyond.

The primary aim of nuclear physics is to understand the origin, evolution, structure and phases of strongly interacting matter, which constitutes nearly 100 per cent of the visible matter in the Universe. This is an immensely important and challenging task that requires the concerted effort of scientists working in both theory and experiment, funding agencies, politicians and the public.

Nuclear physics projects are often 'big science', which implies large investments and long lead times. They need careful forward planning and strong support from policy-makers. This *Forward Look* provides an excellent tool to achieve this. It represents the outcome of detailed scrutiny by Europe's leading experts and will help focus the views of the scientific community on the most promising directions in the field, and create the basis for funding agencies to provide adequate support.

This brochure is a short summary that illustrates highlights from the full *NuPECC Long Range Plan 2010 – Perspectives of Nuclear Physics in Europe*.



Professor Marja Makarow
Chief Executive
European Science Foundation



Professor Günther Rosner
Chair of the Nuclear Physics
European Collaboration Committee



The NuPECC
Committee

INSIDE THE NUCLEUS

Nuclear physics is concerned with understanding atomic nuclei and their constituents

Everyday matter is made of atoms consisting of an electron cloud surrounding an extremely dense core, the nucleus. During the past century, experiments have revealed the nucleus's composite nature in increasing detail. Nuclei consist of positively charged **protons** and neutral **neutrons** (**nucleons**), which make up most of the mass of an atom. Each nucleon is composed of three elementary units called **quarks**. The number of protons in a nucleus defines the basic types of matter with characteristic chemical and physical properties, as classified in the Periodic Table – the elements. Each element can also exist in forms with different masses depending on the number of neutrons in the nucleus – **isotopes**, although many of them are not stable. Around 270 isotopes are found on Earth, but thousands more nucleon combinations could exist – and do exist in the Universe, albeit for fleeting moments. Quarks also form other combinations such as **mesons** (two quarks) and, collectively, all quark combinations are known as **hadrons**.

WHAT HOLDS NUCLEI TOGETHER

Quarks, and thence the nucleons, are bound together by the strong force, one of the four known forces in Nature. It is described by a theory, **quantum chromodynamics (QCD)**, in which fundamental particles called **gluons** mediate the strong interaction between the quarks. Nuclear theory is immensely complicated because gluons also interact with themselves, and the binding between nucleons is not mediated by gluons directly, but by the exchange of **mesons**. Quantum theories are continuously improved to describe nuclear structure up to extreme conditions. Furthermore, the weak force and electromagnetic force, which affects charged particles like protons, also have to be taken into account.

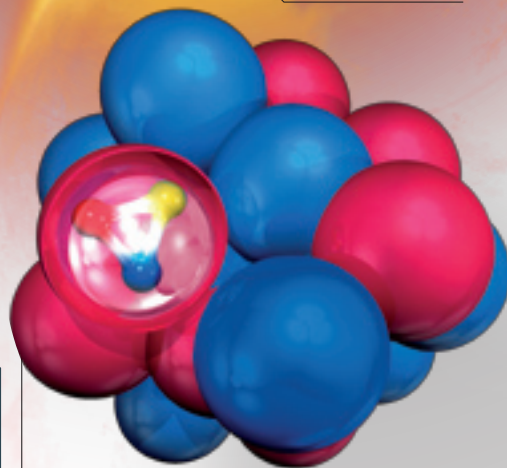
HOW TO STUDY THE SUBATOMIC WORLD

Because the strong force so amply lives up to its name, experiments probing nuclei, and hadrons in general, require accelerators to impart velocity to particles such as electrons, protons or ions (atoms stripped of most of their electrons) up to correspondingly reasonably high energies. These are then collided with a target to produce new particles, which are identified and characterised using large, complex instruments, detectors and spectrometers. Of increasing importance are facilities generating the ion beams of unstable isotopes – **radioactive ion beams, RIBs** – and antimatter particles such as antiprotons and positrons.

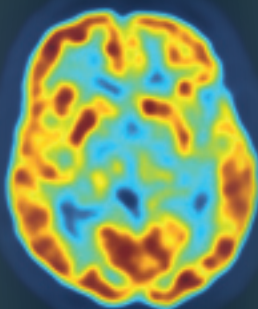
Highly sensitive experiments are also carried out at very low energies, often in specially-designed 'traps'. Advances in infrastructure and instruments crucially depend on a range of innovative technologies, so that research groups from many institutions usually collaborate to develop central facilities to be used by a large number of scientists for a variety of experiments.

Similarly, the complexity of QCD, which encompasses a hierarchy of theoretical approaches depending on scale and energy, means that supercomputers are essential to model interactions – whether between quarks and gluons in hadrons or between nucleons in nuclei.

The energy upon which life depends comes from nuclear reactions deep inside our local star, the Sun

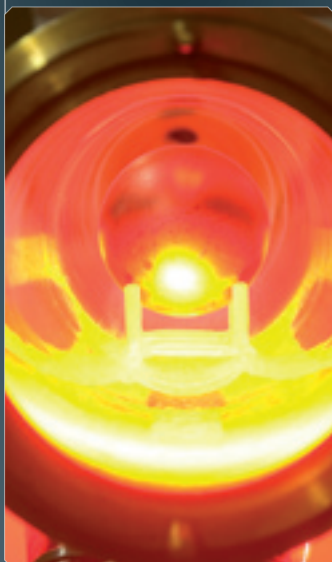


Nuclei consist of protons (red) and neutrons (blue), which are each made up of three elementary quarks held together by gluons



Medical imaging using radioisotopes has become an important diagnostic technique

Advanced nuclear reactors provide clean energy efficiently [PBMR Ltd]



WHY CARRY OUT NUCLEAR EXPERIMENTS?

Nuclear-physics research is a vibrant and vital area of scientific endeavour for many reasons.

1. Nuclear structure is richly varied and complex. How it is generated by the basic forces of Nature is still not well understood (p.8).
2. Nuclei provide an important tool for exploring the fundamental forces (p.14) and the building blocks of matter, in particular hadrons (p.10), and for testing the quantum theories that describe them.
3. Stars are fuelled by nuclear reactions that lead to the build-up of elements, especially in the final stages of a star's life. Such reactions can be studied in the laboratory (p.6).
4. Nuclear experiments can be used to simulate processes in the early Universe that throw light on how it evolved, and also to explore extreme phases of matter thought to exist in massive objects such as neutron stars (p.12).
5. Most significantly, nuclear physics has applications (p.16) in many areas that affect our lives:
 - low-carbon energy generation;
 - medical diagnosis and treatment;
 - analysis for environmental, engineering, biomedical, geological and cultural studies;
 - security and detection of radiation hazards;
 - precision industrial fabrication;
 - high-level training, and knowledge/technology-transfer to other fields.

CURRENT NUCLEAR RESEARCH FACILITIES IN EUROPE



Accelerator laboratory JYFL,
University of Jyväskylä, Finland



Electron accelerator ELSA, University
of Bonn, Germany



European Centre for Theoretical
Studies in Nuclear Physics and
Related Areas, ECT*, Trento, Italy



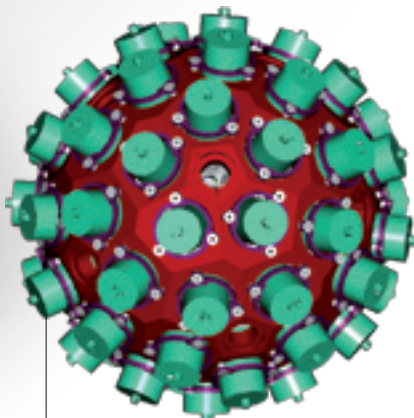
Forschungszentrum Jülich, FZJ
(COSY and HPC), Jülich, Germany



Institut de Physique
Nucléaire, IPNO, Orsay, France



Grand Accélérateur National d'Ions
Lourds, GANIL (SPIRAL), Caen, France



Novel nuclear instrumentation such as the AGATA detector are major European collaborative projects

RESEARCH SUPPORT AND FACILITIES – A VISION FOR EUROPE

Europe continues to play a leading role in nuclear physics research, with more than 6000 scientists and engineers working at facilities and institutions across the continent. At major international facilities such as GSI, GANIL and CERN, researchers can conduct a wide range of experiments covering all the areas mentioned above. However, European nuclear research also benefits from a network of smaller laboratories, which specialise in specific experimental areas, while collaborating in the development of new instrument concepts and providing training for students.

The nuclear physics community, through NuPECC, proposes to build on current successes in tackling the big questions: for example, how did matter in the Universe evolve into what we see today and how it is structured at scales below a million billionth of a metre, and can we exploit what we find out to help humanity solve its energy, health and environmental problems. To this end, NuPECC has formulated a range of recommendations – in particular, the support of new central facilities offering more intense particle beams, the upgrade of current major facilities and full exploitation of existing facilities (p.19)



Helmholtzzentrum für
Schwerionenforschung
GmbH, GSI, Darmstadt,
Germany



European Organisation for
Nuclear Research, CERN
(ALICE, AD, COMPASS
and ISOLDE),
Genève, Switzerland



Kernfysisch Versneller
Instituut, KVI, Groningen,
The Netherlands

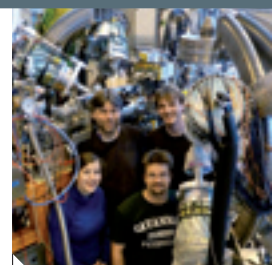
- NuPECC member countries
- FP7 facilities
- Smaller-scale facilities



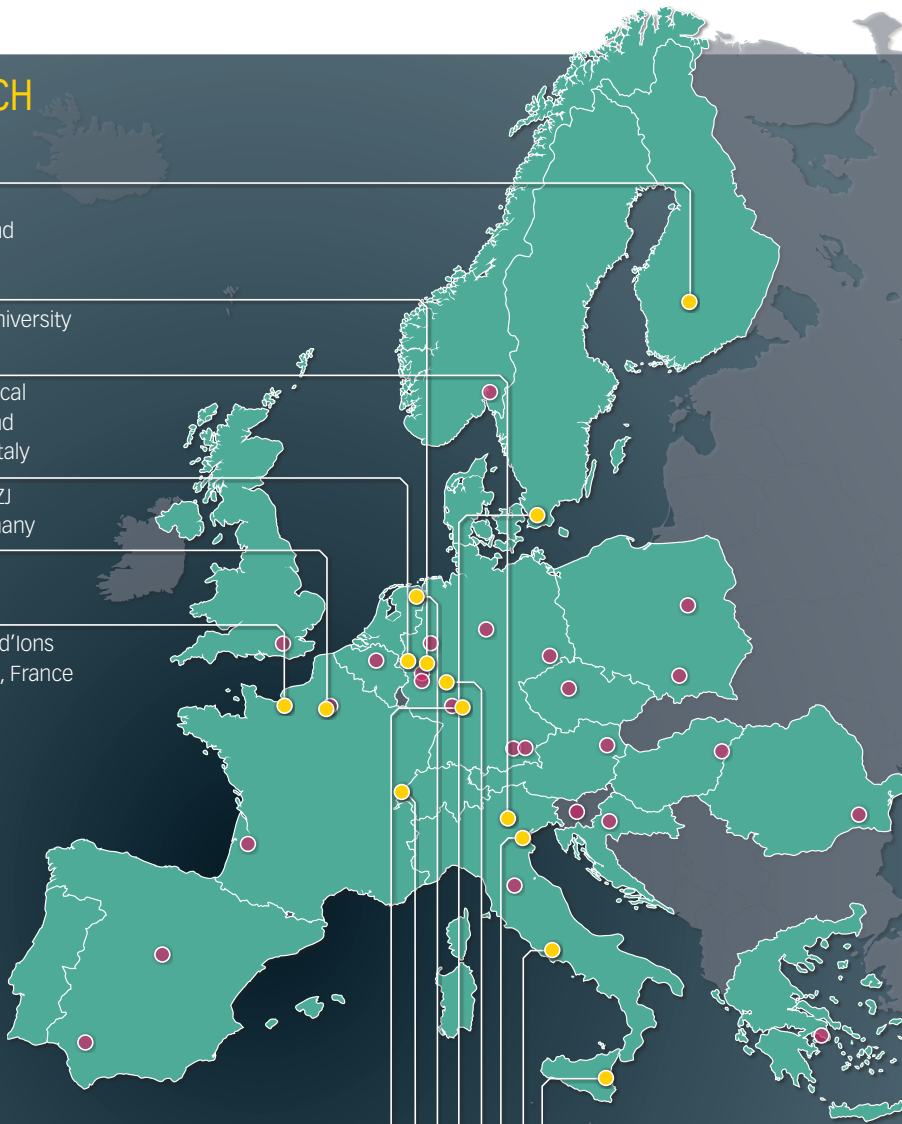
The control room at the GSI
facility in Germany



Part of the cyclotron at GANIL's
radioactive ion beam (RIB)
facility, SPIRAL in France



The Miniball detector
at CERN-ISOLDE
in Switzerland



Laboratori Nazionali
del Sud of INFN, LNS,
Catania, Italy



Laboratori Nazionali
di Frascati of INFN, LNF,
Frascati, Italy



Laboratori Nazionali
di Legnaro of INFN,
LNL, Legnaro (Padova), Italy



Mainzer Mikrotron, MAMI,
University of Mainz,
Germany



Max-lab, University of
Lund, Sweden

WHERE DO THE ELEMENTS COME FROM?

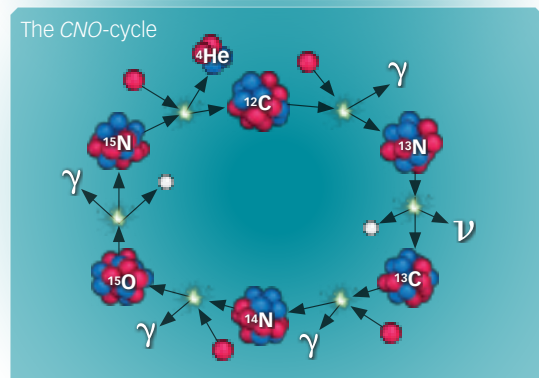
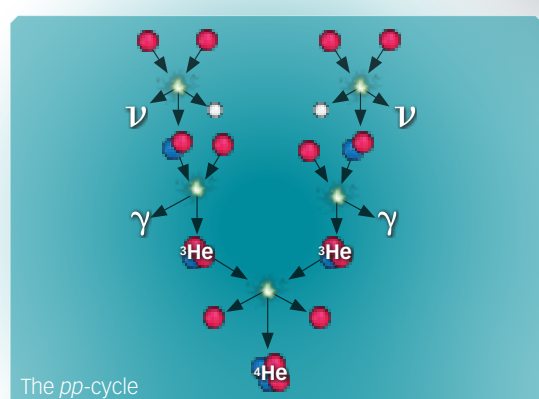
One of most intriguing questions in science is what is the origin of the 92 natural elements that make up our world and all living organisms

While the lightest elements – hydrogen, helium and some lithium and beryllium – were created in primordial processes just after the Big Bang, the heavier elements are continually generated during the life of a star through nuclear reactions. Nuclear physicists try to untangle the complex reaction paths (see nuclear landscape, p.8) thought to occur in stars at different stages of their lives, and match their findings to the element abundances we see.

Life and times of stars

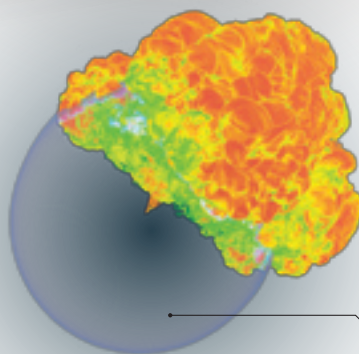
A SLOW BURN

Stars start life producing energy by fusing hydrogen nuclei (protons) into helium – the *pp-cycle*, and via a reaction catalysed by carbon, the *CNO-cycle* (see diagram). As the hydrogen fuel is 'burnt', the helium undergoes fusion reactions to make elements up to oxygen, followed by further element-building processes burning carbon, neon, oxygen and silicon to make elements up to iron. At the same time, neutrons collide and stick to successively larger nuclei, triggering formation of the heavier elements beyond iron. These collisions are rather improbable, so the process is extremely slow – hence the name s-process.



The nuclear reactions building up the lightest elements in stars

- Proton
- Neutron
- Positron
- γ Gamma-ray
- ν Neutrino



A computer simulation, based on theoretical predictions, of the first three seconds of a supernova explosion in which heavy elements are rapidly created
[University of Chicago Flash Center]

A red supergiant star undergoes a supernova explosion after losing part of its mass to a companion star. The heaviest elements are thought to be created in such cataclysmic events

[NASA]

NUCLEAR VAMPIRES

White dwarfs or neutron stars, when part of a binary system, may be resurrected to nuclear life by sucking hydrogen and helium from their stellar companions. The accreted matter may ignite exotic reactions in which protons are captured to create unstable proton-rich nuclei – the *rp*-process.

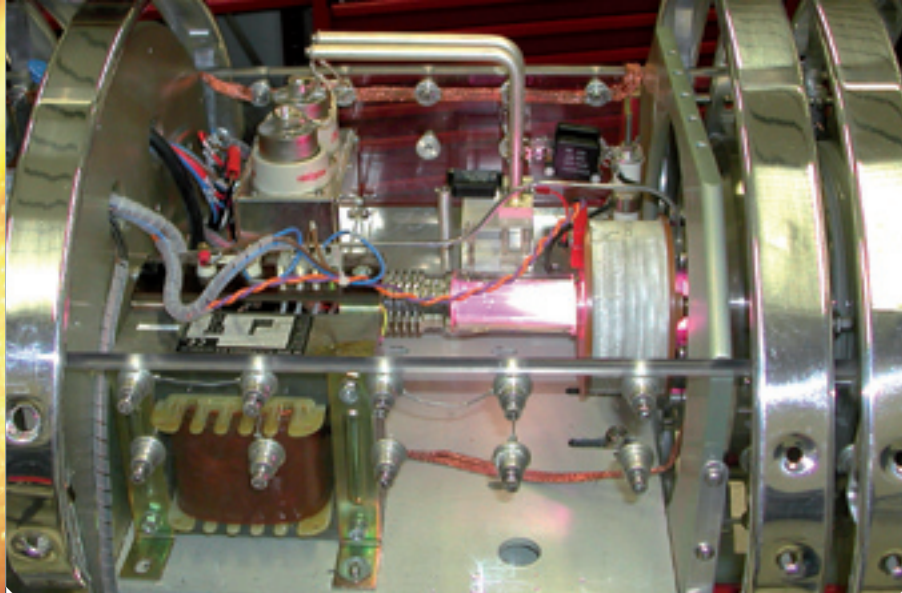
AN EXPLOSIVE DEMISE

Many stars die quietly, continuing to make new elements as they puff out into red giants and then contract into a white dwarf. However, very massive stars end their lives spectacularly in a supernova explosion. The sudden collapse to a neutron star or black hole is thought to trigger cascades of ultra-rapid reactions involving unstable neutron-rich nuclei – the *r*-process. This generates the heaviest elements like uranium.

WHY IS NUCLEAR ASTROPHYSICS IMPORTANT?

Studying nuclear reactions in stars is essential in:

- probing the evolution of the Universe;
- observing the mysterious 'dark energy' which is accelerating cosmic expansion, as measured via certain supernova observations;
- understanding the energy output of our own star, the Sun, and how it affects our climate;
- employing isotopes that act as 'radioactive clocks' in cosmological and geological dating;
- understanding the role of element abundances in the early evolution of the Earth and of life;
- searching for planets around other stars and exploring the likelihood of extraterrestrial life;
- exploring nuclear processes and conditions potentially useful for energy generation or waste transmutation (p.16).

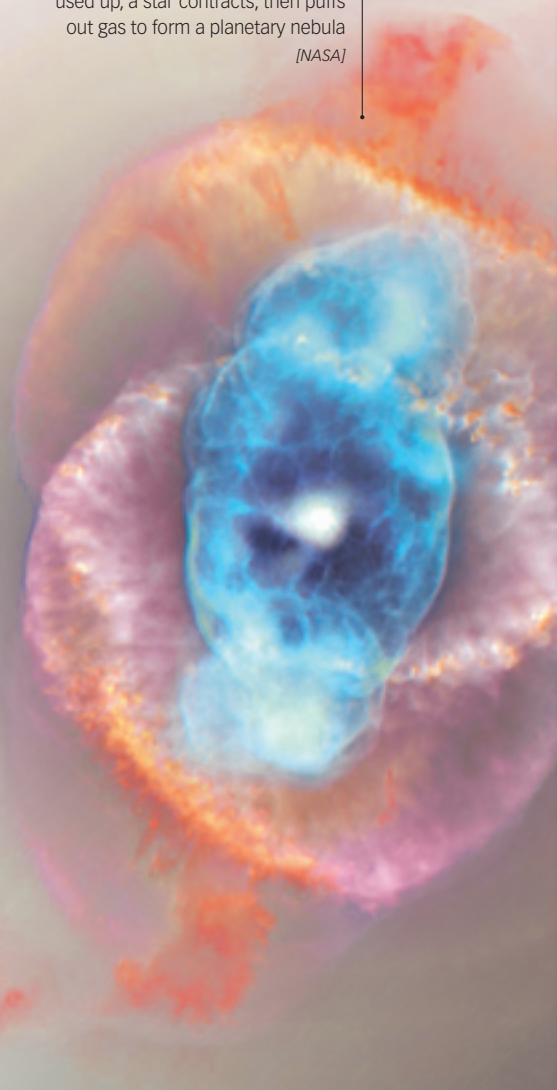


How nuclear astrophysics is studied

Earth-based telescopes measure element abundances across the Universe, while space observatories detect the X-rays and gamma-rays from active and exploding stars, and underground observatories measure the signature neutrino emissions. Of increasing importance are the analyses by cosmochemists of heavy isotopes (using nuclear methods, p.16) found in meteorites that are the pristine remnants of dead stars. Theorists then develop models of the key astrophysical processes and nuclear reaction steps. These are tested through experiments designed to simulate stellar nuclear reactions, and measure their likelihoods and rates, the energies released, and the masses, structure and lifetimes of the isotopes created. Because the fusion reactions of *pp*- and *CNO*-cycles have low probabilities in laboratory conditions, they are investigated underground, protected from interfering radiation, in particular using the LNGS LUNA accelerator facility. Many of the *s*-process elements have been studied with stable isotope beams, but to study the formation of the heavy elements requires beams of unstable isotopes (RIBs).

The LUNA experiment at the Gran Sasso National Laboratory in Italy

Lower-mass stars end their lives as red giants in which some heavy elements are created. As fuel is used up, a star contracts, then puffs out gas to form a planetary nebula [NASA]



RECENT SUCCESSES

◀ A MEASURE OF THE AGE OF THE UNIVERSE

Using LUNA's new accelerator, the reaction converting nitrogen-14 to oxygen-16 has been measured. This is the slowest step in the *CNO*-cycle, and key for understanding stellar evolution and determining the age of the oldest stars in the Universe. The measurement has increased their estimated age by 1 billion years.

▼ UNRAVELLING EXPLOSIVE NUCLEOSYNTHESIS

The masses of more than 1100 transient neutron-rich nuclei that participate in the *r*- and *rp*-processes have been measured in the experimental storage ring (ESR) at GSI. The method is sensitive enough to detect just one nucleus. The new storage ring of FAIR (NESR) will extend studies to very exotic nuclei.



Components of the Experimental Storage Ring at GSI

FUTURE FACILITIES AND INSTRUMENTS REQUIRED

- The next generation of RIB facilities (p.18) – FAIR (NuSTAR), SPIRAL2, HIE-ISOLDE and SPES, and in the longer term, EURISOL – essential for studying explosive nucleosynthesis in stars.
- A new, high-intensity stable-ion beam facility to pursue challenging reaction measurements.
- A higher-energy underground accelerator facility to study rare reactions.
- A complementary network of smaller, stable-beam facilities to make measurements of long-lived nuclei.
- An intense neutron-beam facility to measure neutron-capture reactions.
- Supercomputing facilities for modelling both nucleosynthesis and explosive stellar processes responsible in three dimensions.

OUTSTANDING PROBLEMS TO SOLVE

- The amount of lithium-7 produced primordially does not match calculations, so the rate of its synthesis needs to be measured accurately.
- The conversion of carbon-12 to oxygen-16 needs to be studied in more detail; it plays a crucial role in stellar evolution and in determining the relative amounts of the two most important elements for life.
- Many of the key *CNO*- and *s*-process reactions involving unstable isotopes still need to be investigated, as well as the proton-rich nuclei characterising the *rp*-process.
- Disentangling the complex reaction network of the *r*-process, and exactly where and how the heaviest elements are made are still major questions.

EXPLORING THE NUCLEAR LANDSCAPE

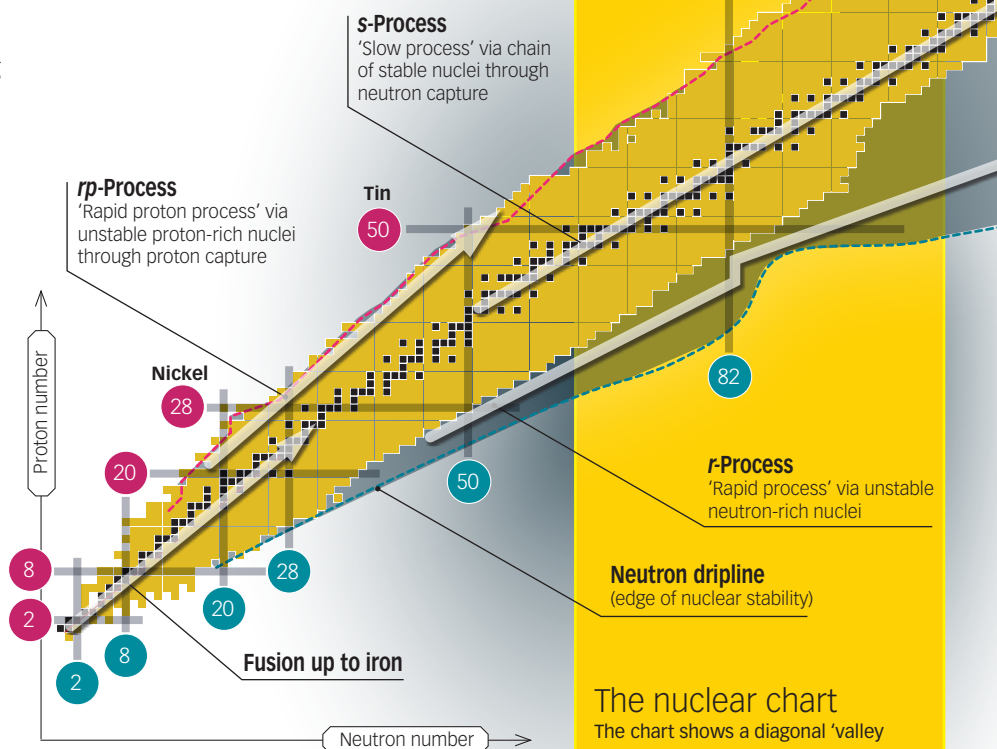
Atomic nuclei represent the most pervasive and significant form of matter in the Universe. Nuclear physicists aim to unravel how these complex quantum systems are arranged

Many thousands of species of atomic nuclei (elements and their isotopes) can exist, containing up to 300 nucleons, though most would be extremely unstable. They can be mapped out on a landscape (see right) according to the ratio and numbers of the constituent protons and neutrons. So far, only about one-quarter of these nuclei have been explored. However, making and studying nuclear species in the unknown regions of the nuclear landscape uncover rich new quantum phenomena of fundamental importance to our understanding of Nature.

BEAUTIFUL COMPLEXITY

The forces binding nucleons interact to produce an extraordinary range of structures. Protons and neutrons arrange themselves in shells such that nuclei with fully filled outer shells are especially stable – ‘magic’ nuclei. However, some lightweight nuclei look like clusters of simpler nuclear species, while heavier nuclei may display collective behaviour, acting like rigid rotors, or as bunches of nucleons that vibrate all together but also possess properties attributed to the behaviour of individual constituent nucleons. This ‘single-particle’ versus ‘collective’ quantum behaviour is a key feature of atomic nuclei.

In the more extreme regions of the nuclear landscape, nuclei may look more exotic, with unusual shapes and new shell configurations with different magic numbers. Those with extreme ratios of neutrons to protons may have a ‘halo’ or ‘skin’ of loosely bound neutrons around a central core. Neutrons and protons prefer to pair up in a nucleus, so just exchanging one proton for a neutron, or *vice-versa* (a parameter called *isospin*) can alter its structure and stability. Studying ‘mirror’ nuclei in which the total numbers of protons and neutrons are swapped over, however, reveals that the nuclear force binding the nuclei does not change much.



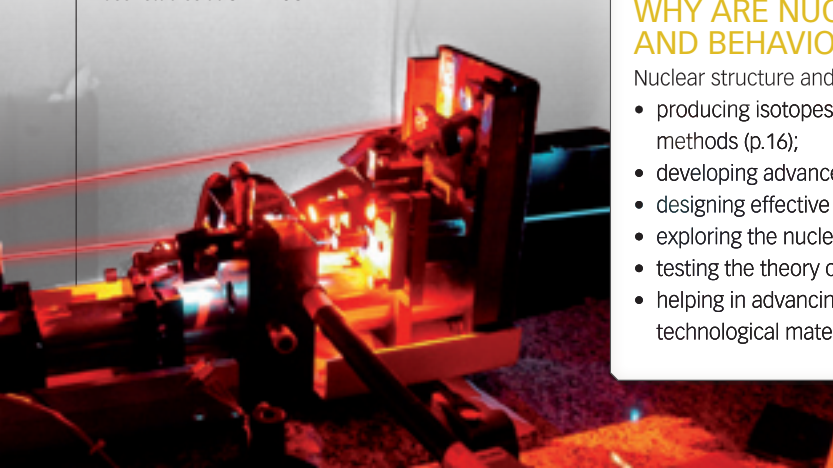
The nuclear chart

The chart shows a diagonal 'valley of stability' (black) inhabited by the familiar stable elements. It is bordered by regions harbouring unstable species that are known (yellow). Beyond, exotic, unknown species with high numbers of neutrons to protons or *vice-versa* survive transiently (grey), the most extreme leaking out nucleons along the proton and neutron 'driplines' (red and blue respectively). At the right-hand corner is a mysterious 'island of stability' of unknown superheavy elements. Zigzagging through the terrain are the nuclear reaction paths by which elements are naturally created in the Universe (p.6).

EXOTIC TRANSFORMATIONS

Also of great interest are the changes in shape and structure when a nucleus is excited into a higher quantum energy state. Some nuclei may distort from a spherical to an oblate or prolate shape with a new shell configuration – *shape isomers*. Certain heavy nuclei, when set spinning fast, elongate into a 'super- or hyper-deformed' shape. The most exotic nuclei may also decay in unusual ways; for example, proton-heavy iron-45 decays by emitting two protons simultaneously.

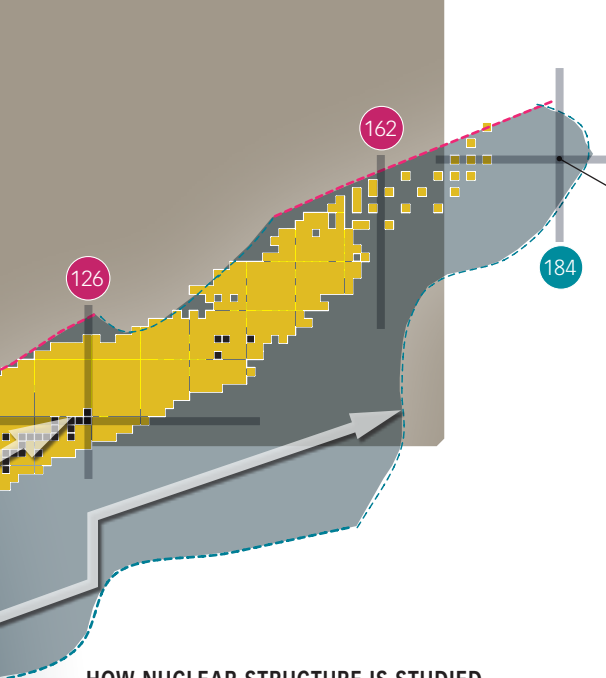
Laser studies at CERN-ISOLDE



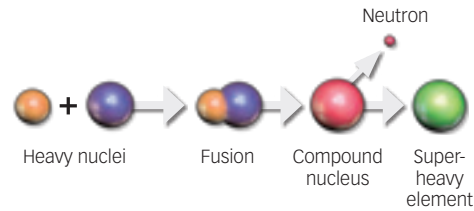
WHY ARE NUCLEAR STRUCTURE AND BEHAVIOUR IMPORTANT?

Nuclear structure and stability measurements are essential for:

- producing isotopes efficiently for medical treatment and diagnosis, and analytical methods (p.16);
- developing advanced nuclear-energy schemes (p.16);
- designing effective nuclear-waste transmutation strategies;
- exploring the nucleosynthetic pathways that generate the elements (p.6);
- testing the theory of the strong force and fundamental theories of matter (p.10 & 14);
- helping in advancing theories of complex quantum behaviour relevant to new technological materials.



Superheavy island of stability



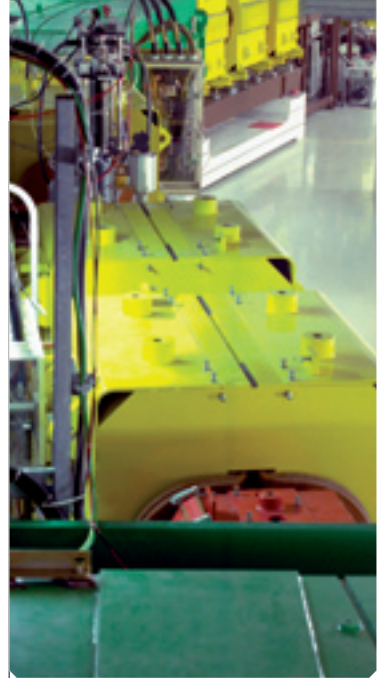
Superheavy elements are made when heavy nuclei collide. They fuse to produce an excited compound nucleus, which may then transform into a new element by losing some neutrons

HOW NUCLEAR STRUCTURE IS STUDIED

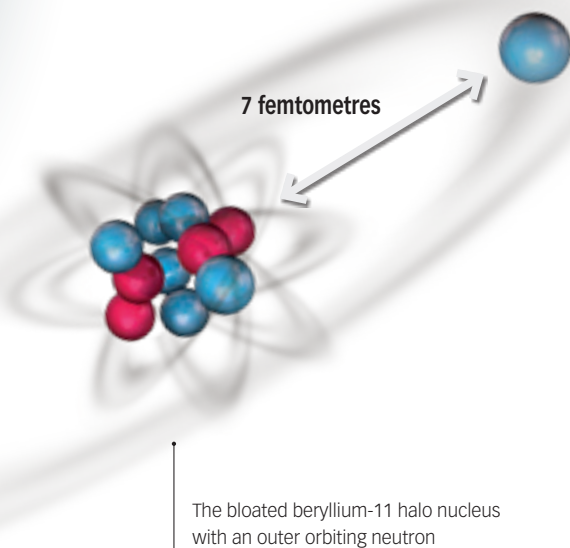
New nuclei are created during reactions of accelerated particles or ions with a target. The interacting nuclei can fragment, fission or fuse, giving rise to exotic species, which are carefully selected and transported towards the area where measurements are carried out. Depending on the equipment installed, **lifetimes**, **masses** and **decay properties** can be measured, or the exotic nuclei can induce further reactions on a secondary target. Lasers are also used as probes. Together, these approaches provide a coherent picture of the nuclear structure.

SCIENTIFIC CHALLENGES

- Can we describe the rich variety of nuclear structures and reactions in terms of the fundamental interactions between the constituent particles?
- How do regular and simple patterns emerge in the structure of complex nuclei?
- What are the key variables governing the dynamics between colliding nuclei?
- Can we predict how collective and single-particle properties in nuclei vary with mass, isospin, spin and nuclear temperature (measured in units of MeV corresponding to 10 billion degrees)?



The fragment separator at GSI, used in the generation of unstable isotopes



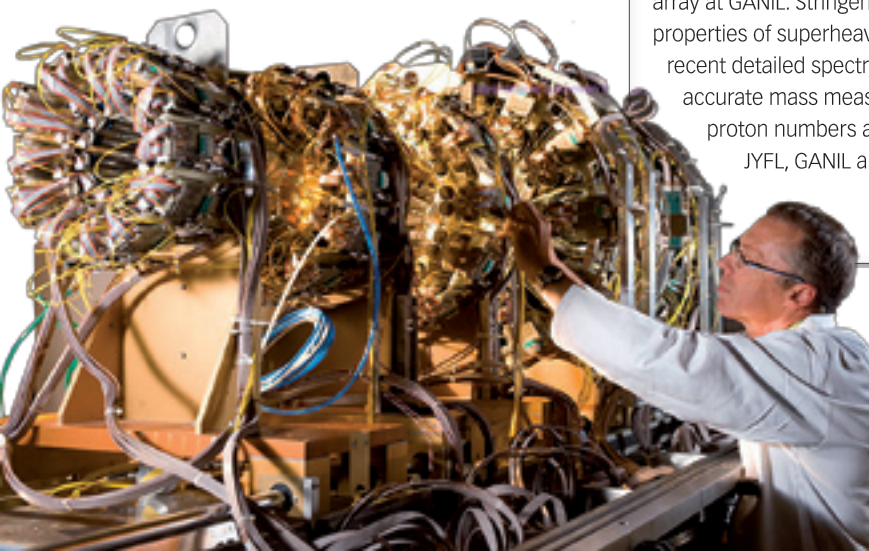
RECENT SUCCESSES

◀ EXTREMELY NEUTRON-RICH SYSTEMS

Researchers at GSI and GANIL have produced extremely neutron-rich isotopes of lithium with seven, nine and 10 neutrons. These systems cannot hold onto their outer neutrons, but live long enough to be observed. At the CERN-ISOLDE facility, researchers used lasers to measure very precisely the size of the bloated neutron halo of beryllium-11, showing that the outer neutron orbits the core at three times its distance.

▼ NEW SUPERHEAVY NUCLEI

Superheavy elements containing up to 116 protons have been synthesised at GSI's SHIP facility. Evidence for the island of stability comes from long fission times for compound nuclei with 120 and 124 protons measured with the INDRA array at GANIL. Stringent tests for predicting properties of superheavy elements come from recent detailed spectroscopic studies and accurate mass measurements of nuclei with proton numbers around 102, carried out at JYFL, GANIL and GSI.



The INDRA detector at GANIL

FUTURE FACILITIES AND INSTRUMENTS REQUIRED

Nuclear structure experiments are carried out at large and small facilities, using both beams of stable and unstable nuclei. However, to make enough very rare nuclei for study, facilities capable of generating intense radioactive ion beams (RIBs) are essential. Of equal importance are new detectors, ion traps and spectrometers (p.18) for making measurements.

- The major in-flight (p.18) RIB facility for nuclear structure studies will be the FAIR-NuSTAR facility.
- SPIRAL2 at GANIL, HIE-ISOLDE at CERN and SPES at LNL offer a complementary network of advanced ISOL (p.18) RIB facilities that are paving the way for the ultimate European ISOL facility EURISOL.
- Intense stable-ion beams are needed to probe nuclei at the proton dripline, as well as to make and study superheavy elements.
- The wide variety of state-of-the-art instrumentation is needed to make the best use of the new accelerator facilities.

EXPLORING THE FIRST LEVEL OF COMPLEXITY IN MATTER

Hadrons, which include the protons and neutrons in nuclei, represent the simplest form of observable matter in the Universe

The constituents of nuclei belong to a wider class of particles, **hadrons**, which are composed of elementary quarks and gluons. Because these building blocks are never seen in isolation, hadrons represent the first observable level of complexity in the construction of matter in the Universe. Quarks and gluons can bind in pairs (**mesons**) and threesomes (**baryons**), and even in more complex structures (see Box). Hadron physics aims to study how this complexity is generated through the action of the strong force.

WHY STUDY HADRONS?

To understand the fundamental theory of the strong interaction, QCD – A variety of mathematical approaches is used to describe the strong force depending on the scale and energy of the system being studied. For example, at high energies, quarks and gluons are regarded as interacting points and links on a space-time lattice – **lattice QCD**. The predictions are then compared with experimental results.

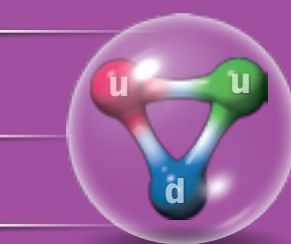
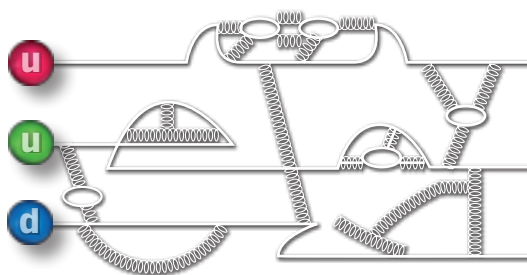
To understand the structure and behaviour of nuclei (p.8) – Studying hadrons provides a deeper understanding of even more complex systems that interact through the strong force, such as nuclei. Nucleons combine in nuclei via the exchange of virtual pions rather than directly via gluons.

To provide information relevant to experiments in fundamental physics – High-energy physics such as that being carried out at the Large Hadron Collider (LHC), CERN depends on hadron collisions. Precision data on hadron physics are essential for interpreting results.

To understand how hadron properties like the mass of the proton are generated – The detailed construction of hadrons is not understood. Simply adding up the properties of the individual components cannot explain the observations.

To understand the role of exotic matter like glueballs – QCD predicts that particles solely composed of gluons, glueballs, or particles where the properties of gluons play a major role, hybrids, should exist. The unique self-interaction of these force-carriers might have far-reaching consequences in explaining the Universe.

To improve applications of hadrons – Proton, antiproton, neutron, pion and nuclear beams are employed to treat cancer, and as analytical probes (p.16).

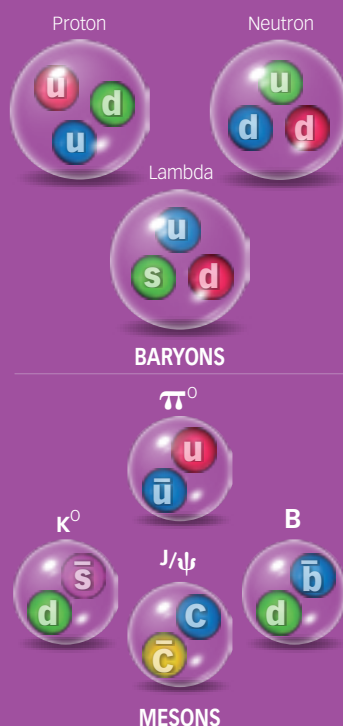


A hadron is composed of quarks that interact via the strong interaction. The gluons carrying the strong force also self-interact, so that trying to understand the structure and dynamics of hadrons is horrendously complicated

THE WORLD OF QUARKS AND GLUONS

Quarks come in six 'flavours' of increasing mass: **up**, **down**, **strange**, **charm**, **bottom** and **top**, which combine to form hadrons through the strong force carried by gluons.

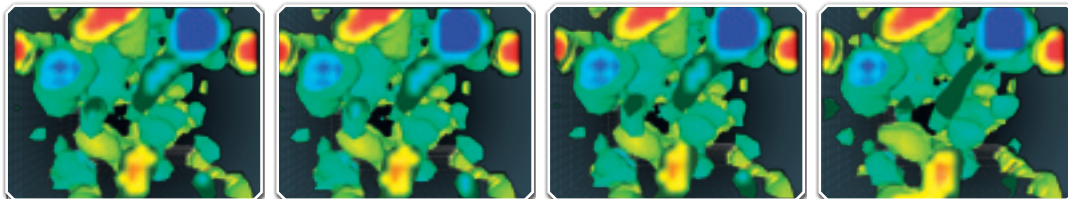
- Mesons consist of a quark-antiquark pair – of which the **pion** is the lightest; others include the kaon containing a strange quark, **charmonium** consisting of a charm quark and its antimatter partner, and the **B-meson** containing a bottom quark.
- Baryons are composed of three quarks. While the familiar protons and neutrons consist of three up and down quarks, baryons containing heavier quarks, **hyperons**, have also been identified.
- Hadrons with **four** and **five** quarks have been predicted, as well as a spectrum of exotic mixtures of quarks and gluons, **hybrid mesons** and quark 'molecules'.
- In addition, because gluons are self-interacting, they are predicted to form all-gluon ensembles called **glueballs**.



Some typical particles studied in hadron experiments. Many combinations of quark flavours are possible

The three-spectrometer facility at the 'race-track' Mikrotron, MAMI, which provides a continuous polarised electron beam, and is one of several European facilities carrying out research into hadron structure and dynamics

The spin of the proton is made up of the spins and motions of the constituent quarks and possibly other 'virtual' quarks



Collaborations of theorists use lattice QCD to model quark-gluon interactions on powerful supercomputers
[D. Leinweber/CSSM/University of Adelaide]

The Compass experiment at CERN investigates hadron structure and spectroscopy, as well as the spin of the proton



HOW ARE HADRONS STUDIED?

- **Hadron structure:** the structure of the proton is a defining problem for hadron research. It is explored using beams of leptons – electrons, positrons (anti-electrons) or muons – which are scattered off protons to reveal the constituent quarks and their motions.
- **Hadron spectroscopy:** spectroscopy is a proven tool in physics to study Nature. Hadron physics utilises electron, pion, photon, proton or deuteron beams to explore the hierarchy, or 'spectrum' of rare quark/gluon structures that form at different energies and under various conditions.
- **Hadron interactions,** particularly involving pions and kaons, and the study of hyperons and hypernuclei (nuclei containing hyperons) created provide important information on the strong force.

RECENT SUCCESSES AND PROBLEMS STILL TO SOLVE

MYSTERY OF THE MISSING SPIN

The individual spins of quarks in the proton account for only about one-third of its total spin. Theorists had predicted that gluons and a 'sea' of transiently existing strange quarks could contribute. Recent experiments using polarised beams (all spins aligned) have shown that the strange sea does not participate, so that one-third of the spin is still unaccounted for. Another suggestion is that the way quarks move around could play a role and should be studied in the future.

UNEXPECTED CHARM

The complex spectrum of hadrons containing charm quarks has been explored extensively recently, revealing new charm particles with unusual properties and unknown structure, which indicate that our previous view of Nature was much too simple.

MORE COMPLEX STRUCTURES

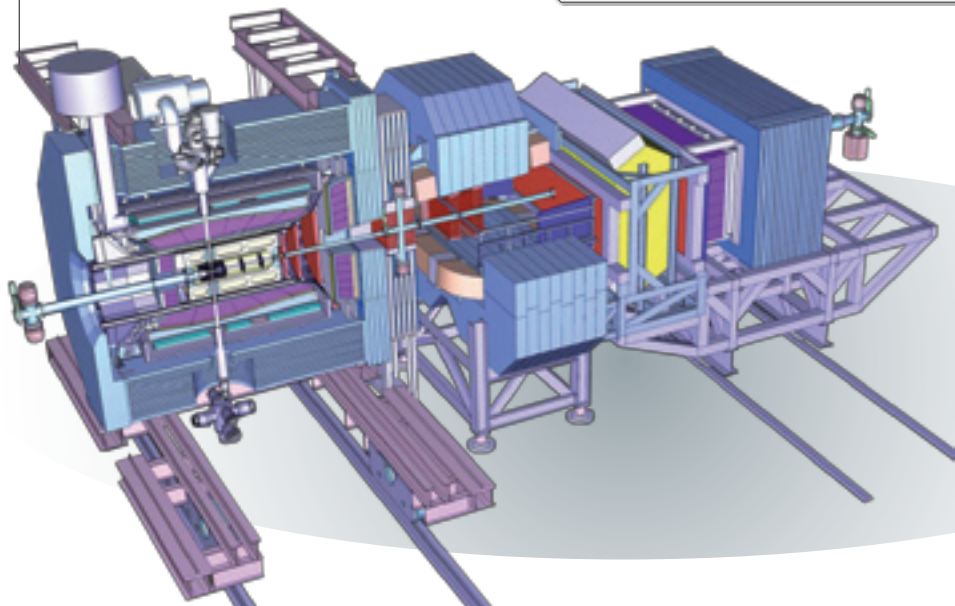
Although a great deal of work has been done on identifying and studying exotic mesons and baryons that helps to test QCD, there are still huge gaps in our knowledge. For example, definitive evidence for glueballs, tetraquarks and pentaquarks has not yet been obtained.

FUTURE FACILITIES AND INSTRUMENTS REQUIRED

Dedicated accelerators generating high-quality beams are needed for hadron experiments.

- PANDA at FAIR will be the flagship experiment using antiprotons stored in a high-energy storage ring, HESR. They will be directed at a proton-rich target to create and study in detail many quark-gluon structures previously inaccessible.
- Europe has led the way in hadron science. Existing smaller facilities should be fully exploited and improved on to provide expertise and specialist input.
- Continual support of theory activities, which require high-performance computing are essential, combined with close interplay with experiments.
- To extract more information on hadron structure, the HESR ring could be upgraded to provide access to a polarised proton-antiproton collider or a polarised electron-proton/ion collider. A future electron-ion collider, LHeC, using the LHC at CERN, could investigate the little-understood role of gluons in hadrons.

The PANDA detector at FAIR will use high-energy antiproton beams to study many aspects of hadron physics



FROM NUCLEAR LIQUID TO QUARK-GLUON PLASMA

Quark-gluon matter shows a rich variety of behaviour under different conditions

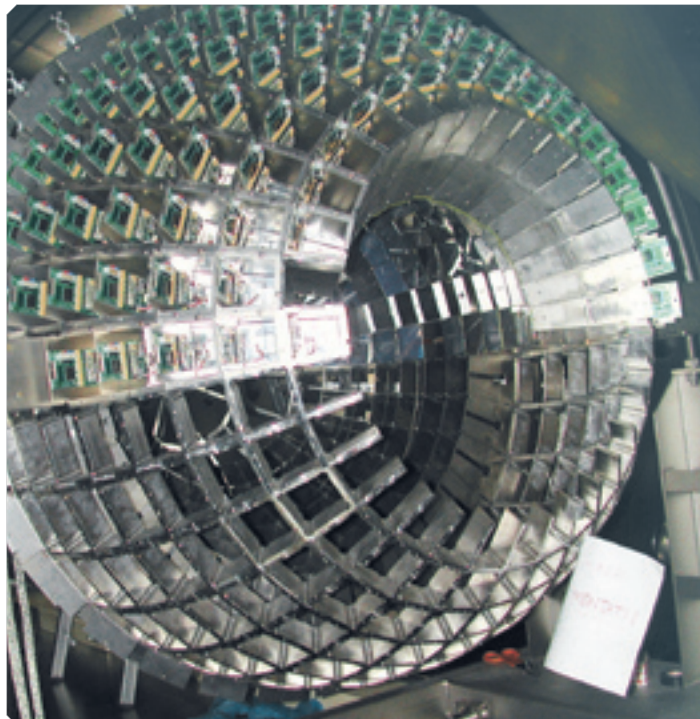
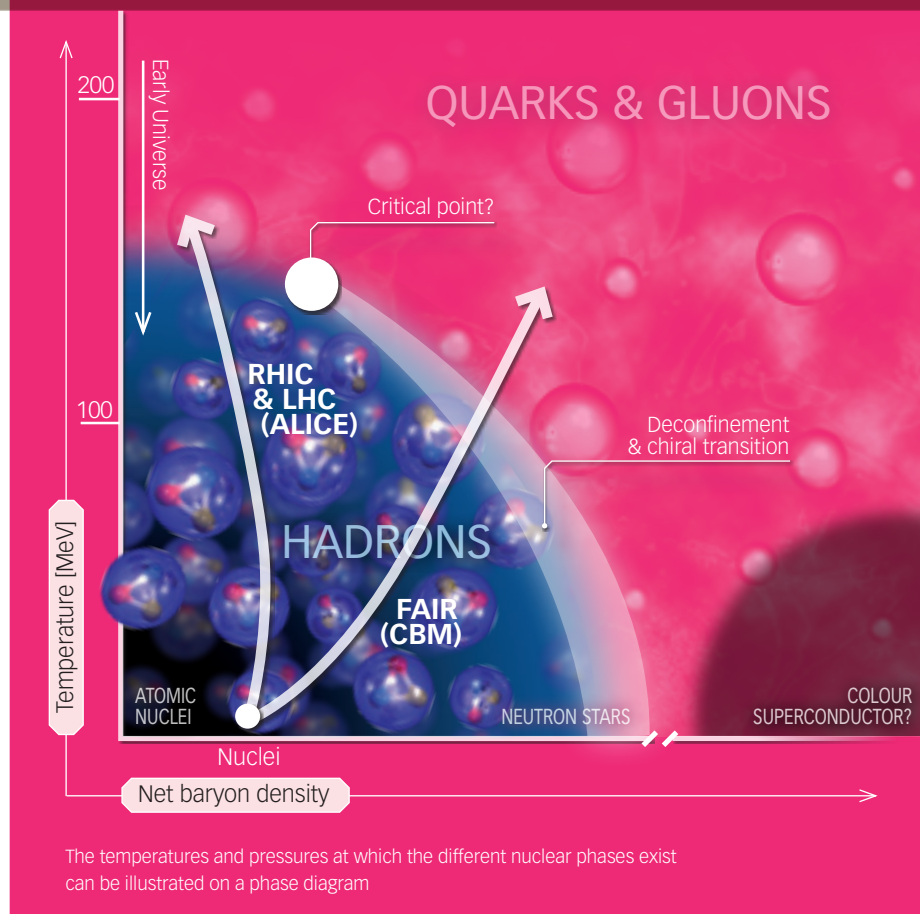
Just as water exists in different phases – solid, liquid or gas – so does nuclear matter. In everyday matter, protons and neutrons have coalesced into nuclei, which are regarded as drops of nuclear liquid. At an increased temperature and density, they ‘boil’ to form a hadron gas. At even higher temperatures, the matter continues to change: excited states called baryonic resonances appear and particle-antiparticle pairs form. Finally, at temperatures 100,000 times hotter than the Sun and densities 10 times higher than ordinary atomic nuclei, the hadrons ‘melt’ to form a quark-gluon plasma (QGP). At low temperatures but extremely high densities, the QGP system is predicted eventually to form a colour superconductor in which quarks behave similarly to the electrons in conventional superconducting materials.

WHY EXPLORE NUCLEAR PHASES?

- **Understanding the strong force:** in ordinary matter, the strong interaction always binds quarks in hadrons like the proton (quark confinement) but in hot, dense matter, the strong force is thought to be modified, becoming weak enough to allow isolated quarks to exist.
- **Understanding the evolution of the Universe:** about 10 microseconds after the Big Bang, matter would, indeed, have existed as a plasma of free quarks and gluons, which combined into hadrons as the Universe cooled.
- **Understanding extreme astrophysics:** in supernovae, and in even more dense neutron stars, quark matter is predicted to behave in exotic ways, which require a knowledge of the nuclear phase diagram.

HOW NUCLEAR PHASES ARE STUDIED

Experimentalists explore the nuclear phase diagram by colliding nuclei at various energies to simulate the behaviour of matter under particular conditions. They then analyse how the hot, dense nuclear systems fragment, measuring the energies and flow of the resulting particles. Theorists predict the behaviour of particles using QCD calculations on supercomputers, particularly during the onset of a transition from one phase to another.



Collision experiments with the Chimera detector at LNS Catania, Italy explore the liquid-gas transition of the nuclear phase diagram



Students work on the NA60 experiment at CERN which has been searching for the production of transient particles that form during high-energy collisions to create a quark-gluon plasma

A computer simulation of collisions in the ALICE detector at the LHC, CERN

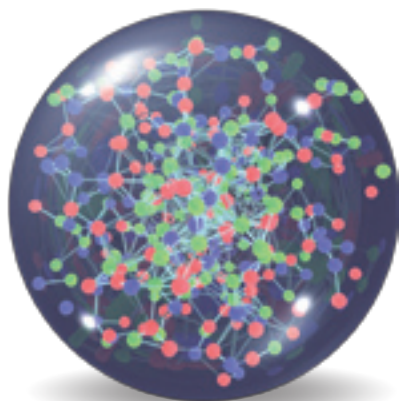
RECENT SUCCESSES

▲ PROBING MASS CHANGES

One of the goals of heavy-ion experiments is to probe the conditions in which quarks acquire mass through chiral symmetry-breaking (see right). Recent experiments at CERN measured intriguing mass changes in short-lived particles called rho-mesons, which transiently form when heavy indium nuclei are collided at very high energies to create conditions close to a quark-gluon plasma.

▼ THE PERFECT FLUID?

Experiments colliding gold ions at the Relativistic Heavy Ion Collider, RHIC (a US project with European participation), revealed fascinating new features of the hot and dense matter created in the collisions: the constituent particles move all together, 'flowing' like a liquid that is almost friction-free. Particularly exciting is the fact that this is the first unexpected experimental observation that was anticipated by string theory – the most fundamental theory of matter.



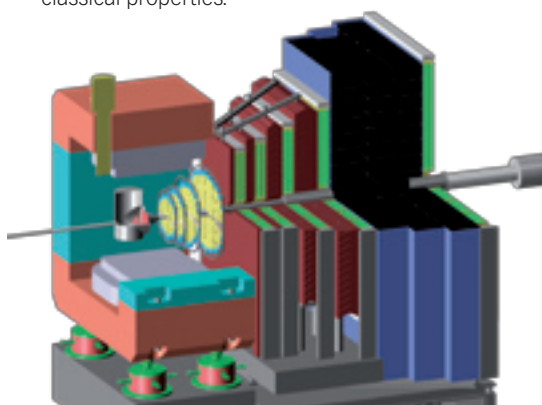
EXTREME DENSE MATTER

Experiments at RHIC have also shown that the matter produced in heavy-ion collisions is so dense that even the most energetic and penetrating probes (jets) get stuck within a few femtometres. This opens up a wide array of novel techniques at collider energies using 'hard' processes as differential probes of the properties of hot QCD matter.

The CBM experiment at FAIR will explore many aspects of the transition to a quark-gluon plasma

QUESTIONS TO ANSWER

- Non-interacting quarks should be almost massless, so where do the masses of protons and neutrons come from? Quark masses appear to be generated via the breaking of a fundamental symmetry (p.14) called **chiral symmetry**. Creating a QGP tests this theory – quarks should be de-confined and chiral symmetry restored.
- Large areas of the nuclear phase diagram have not been explored and many theoretical predictions need to be tested. For example, the liquid-gas transition is deeply influenced by the ratio of protons and neutrons present, which is also thought to determine whether neutron stars collapse into **black holes**. Further experiments require collisions involving rare proton-rich or neutron-rich nuclei.
- Whether phase transitions are gradual or sharp is not well understood, particularly at very high pressures and temperatures. A critical point in the phase diagram is predicted, where the transition between hadronic matter and quark-gluon matter changes from a sharp to a smooth transition.
- It is not certain if quarks undergo a chiral transition to acquire mass at the same time as they become confined in hadrons. Furthermore, at lower baryon densities, there are experimental hints that phases can exist containing both baryons and quarks, which may or not be chirally symmetric.
- What the QGP looks like at different energies and densities is proving intriguing. Although it acts as a **perfect liquid** at temperatures currently reachable, it is unclear whether that will hold at still higher temperatures. In addition, theorists predict that at very high energies, the density of gluons rises to create a slowly changing 'gluon glass' with classical properties.



FUTURE FACILITIES AND INSTRUMENTS REQUIRED

The next generation of high-energy experiments aim to explore the fundamental nature of matter under conditions of pressure and temperature never observed before.

- The ALICE experiment at the LHC will collide lead nuclei at unprecedented energies to create a much hotter QGP, reaching a new domain in which qualitatively new features are expected to appear. Experiments colliding nuclei and protons will also allow extreme gluon densities to be studied. A programme of further upgrades to the detector will open new windows of observation, to exploit fully the opportunities arising in the new energy regime.
- The Compressed Baryonic Matter (CBM) experiment at FAIR will map the nuclear phase diagram around the transition to a QGP. It will measure the proportions of exotic hadrons associated with de-confinement and the modification of hadron masses, and will search for the predicted critical point.
- Experiments with RIBs at FAIR, SPIRAL2, SPES and FRIBS (LNS-Catania) are needed to study the nuclear liquid-gas transition.
- A new high-energy electron-ion collider (LHeC) at CERN will open up an entirely new regime for studying extreme QCD matter.
- Petaflop supercomputers are needed to model the QCD phase diagram in the regions that experiments will explore.
- The huge amounts of data created will require a **GRID infrastructure** to process and analyse.

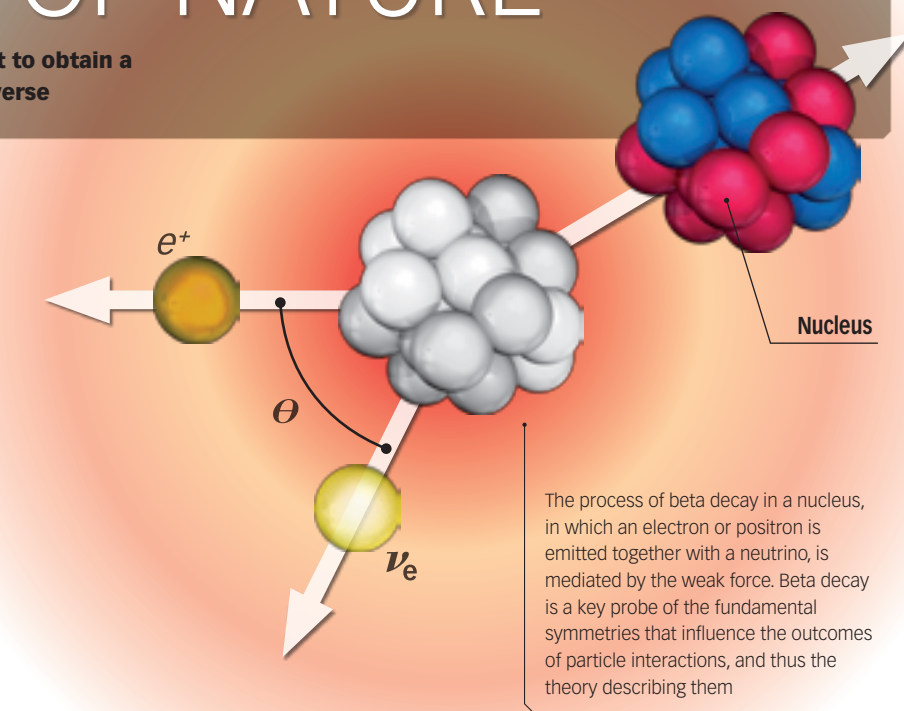
THE FORCES OF NATURE

Nuclear systems play a significant role in the quest to obtain a complete picture of the building blocks of the Universe

A major goal of physicists is to devise a unified quantum theory of the basic forces and particles that accounts for their origins. As the Universe cooled in the first fraction of a second after the hot Big Bang, it underwent a series of phase changes from a unified 'symmetrical' state, to one in which the force and matter components were separated out. **Symmetry** is a key mathematical tool for describing the deepest relationships between the fundamental particles, and it is the processes of 'symmetry breaking' that characterise these phase transitions. Fundamental symmetries of crucial significance include **charge (C)**, which changes particles into antiparticles, **parity (P)** which reflects the spin, or handedness, of a particle, **time (T)**, which reverses the direction of a process, and **Lorentz symmetry**, by which the laws of physics remain the same for all directions in space-time.

THE STANDARD MODEL AND ITS EXTENSIONS

The key concepts are enshrined in a successful quantum description called the **Standard Model (SM)**, but which is far from complete (see box). Theorists are extending the SM to unify the known matter and force particles. One way to search for evidence of such **SM extensions** is to look for tiny signature deviations in predicted nuclear properties and processes that would be caused by new particles and interactions arising from these extensions. Low-energy precision experiments offer the most powerful route to measuring these effects, so testing the validity of established and also novel theories.



SOME QUESTIONS TO ANSWER

Studying the subtleties of nuclear behaviour can help to answer important questions about fundamental interactions and their role in the evolution of the Universe:

- Which fundamental symmetries are conserved in Nature?
- A basic symmetry is that matter particles have antimatter partners, so why is there very little antimatter in the Universe?
- Are there other than the four known fundamental forces?
- What are the precise values of the fundamental constants of Nature?

The arrival of the giant spectrometer in Karlsruhe, Germany for the KATRIN experiment, which will carefully analyse the beta decay of the hydrogen isotope, tritium. This will provide information about the absolute mass of the neutrino, one of the most elusive particles in the Standard Model and extremely difficult to study

Quarks	u up	c charm	t top	γ photon
	d down	s strange	b bottom	Z Z boson
Leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson
	e electron	μ muon	τ tau	g gluon

The Standard Model

Two families of three generations of matter particles exist – six flavours of quark (p.10) and six leptons of increasing mass (electron, muon and tauon, and their respective neutrinos). Each particle has an antimatter partner with opposite charge. Four basic interactions are known: electromagnetism and the weak force (now unified into the electroweak interaction), the strong force, and gravity (not yet part of the Standard Model). The first three are mediated by known particles: the photon, the W and Z bosons, and the gluon. The particle associated with gravity, the graviton, has not yet been directly observed.



WHAT ARE THE EXPERIMENTS?

Nuclear physics experiments exploring these questions are often small-scale, requiring extremely precise, usually protracted measurements on one particular phenomenon, sometimes at very low temperatures, or away from contaminating radiation or electromagnetic fields.

One property of both quarks and leptons, used to test the SM, is that their quantum states are rarely pure but have other particle ‘flavours’ mixed in. For example, it is now known that **neutrinos** have a small mass and that the three neutrino types mix or ‘oscillate’. Experiments based on the radioactive decays of selected isotopes aim to measure the neutrino masses and the amount of mixing, which can then be compared with theoretical predictions. The decay of the **neutron**, and a number of well-chosen isotopes that decay in a similar way, also offer a range of subtle measurements that explore symmetry-breaking processes and the presence of new forms of weak interactions predicted by SM extensions.



Precision experiments at CERN aim to search for minute differences in the quantum energy levels of hydrogen (proton, electron), antihydrogen (antiproton and positron) that might indicate *CPT* symmetry-breaking

Direct symmetry-breaking phenomena are sensitive probes of SM extensions. The *C*, *P* and *T* symmetries can be violated in specific circumstances, resulting in the preponderance of a particle or antiparticle with a particular charge and spin. Again, experiments are carried out on neutrons and selected nuclei, and also on atoms including antihydrogen (composed of an antiproton and positron). Of particular interest are experiments searching for an electric dipole moment in leptons, neutrons and nuclei, which is forbidden by these symmetries, but might be essential to explain the missing antimatter. Other experiments test the combined *CPT* symmetry and Lorentz invariance.

Stringent tests of our current descriptions of the electromagnetic and strong interactions are also carried out, measuring the magnetic moments of the electron and muon, investigating the properties of highly charged ions, and studying the quantum states of exotic atoms containing muons, pions, kaons and their antiparticles. Experiments on antimatter atoms aim to establish whether gravity acts equally on matter and antimatter.



RECENT SUCCESSES

▲ TRAPPING NEW PHYSICS WITH WITCHCRAFT

Exotic nuclei can be confined by electrical and magnetic fields in laser and/or ion traps. These provide intense, pure sources for experiments observing the products of nuclear beta decay. Precision experiments of this type allow us to investigate the basic properties of the weak interaction, and search for physics beyond the Standard Model. For example, the WITCH (Weak Interaction Trap for Charged Particles) experiment at CERN-ISOLDE studies beta decay in different nuclei, analysing various details that are influenced by the physics of the weak interaction.



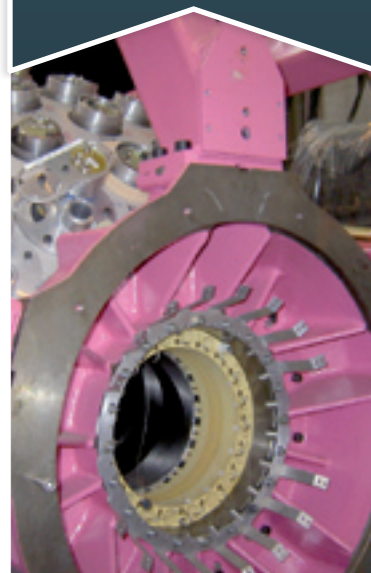
▲ A HINT OF NEW PHYSICS?

European physicists, together with international colleagues, have carried out an exciting experiment at the Brookhaven National Laboratory in the US which might be revealing physics associated with extensions of the SM. It measures a subtle parameter of the muon called the ‘anomalous’ magnetic moment. The latest experimental value appears to differ considerably from that expected from SM theory, despite significant improvements of our theoretical understanding of this parameter that were mainly driven by European physicists.

Part of the detector system for measuring pion decay at the Paul Scherrer Institut in Switzerland

RECOMMENDATIONS FOR FUTURE SUPPORT

- Continuous support of laboratories and university groups that develop equipment for small, precise experiments, or carry out the necessary complementary theoretical work.
- Construct low-energy antiproton facilities such as FLAIR at FAIR, and carry out the ELENA upgrade to the Antiproton Decelerator at CERN for novel experiments on interactions.
- Improve facilities in underground laboratories for highly sensitive nuclear-decay experiments.
- Upgrade existing facilities producing RIBs.
- Build dedicated new facilities providing continuous access to RIBs (such as ISOL@Myrrha at Mol, Belgium), high-intensity neutron sources (such as the European Spallation Source, ESS, in Lund, Sweden) and coherent X-ray sources (free electron laser facilities).



REWARDS FROM NUCLEAR SCIENCE

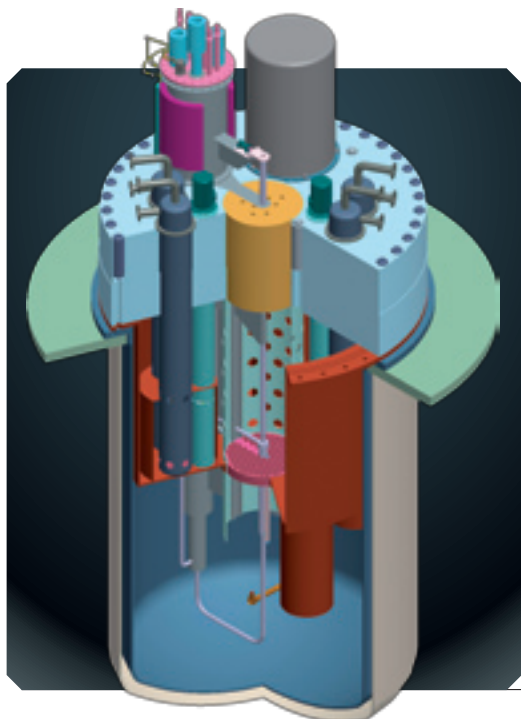
Carbon-free energy sources, better healthcare and improved national security are just a few of the benefits of studying the nucleus

Nuclear physics, and the tools developed to study it, offer a wealth of enabling knowledge and innovative technologies that are benefiting society in crucial ways.

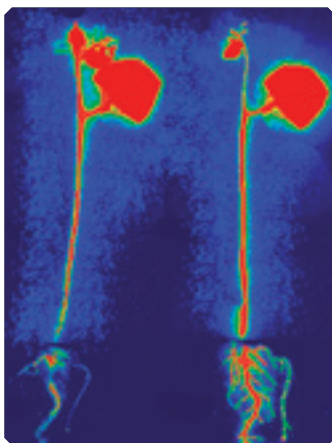
ENERGY AND CLIMATE CHANGE

Advanced technologies based on nuclear reactions offer the prospect of providing sustainable energy that is almost carbon-free. The next generation of fission reactors (Generation IV) promises to be much more efficient, safe, cost-effective and proliferation-proof, and will produce much less waste. Accelerator-driven systems (ADS), based on proton-accelerator technology and sub-critical reactors, have the potential to transmute radioactive waste into less hazardous isotopes. New fuel cycles could also be developed in the future, for example, using thorium. Finally, progress towards practical nuclear fusion has received a boost with the construction of the international ITER reactor in France.

Nuclear physics studies across Europe are providing the essential data for the development of Gen-IV reactors, for minimising waste, and for evaluating materials and processes in both fission and fusion reactors. The nuclear reactions underpinning new fuel cycles and transmutation processes are also being investigated at current and new research facilities.



The Antiproton Cell Experiment (ACE) at the Antiproton Decelerator (AD) at CERN to test the use of antiprotons in cancer therapy



A positron radiograph showing the distribution of carbohydrate (high concentrations shown in red) in a poplar sapling following incorporation of carbon dioxide labelled with positron-emitting carbon-11, via the process of photosynthesis

[Brookhaven National Laboratory]

The concept of transmuting nuclear waste safely will be tested with the MYRRHA ADS research reactor in Mol, Belgium

HEALTH – Particle therapy and radioisotopes are increasingly being employed as both diagnostic and therapeutic tools.

Diagnosis – Short-lived radioisotopes act as tracers in biomedical research and also highlight disease processes in the body. Body-imaging techniques rely on the position-sensitive detection of gamma-rays to create a three-dimensional image. The gamma-rays are emitted by an injected radioactive tracer in single photon emission computed tomography (SPECT), or originate from the disintegration of a positron in positron emission tomography (PET). Advanced gamma-ray detectors combined with fast digital electronics that were developed for basic nuclear physics experiments, are enabling increasingly high-resolution imaging to be carried out in real time.

Therapy – Radioisotopes are increasingly being used to treat tumours that are resistant to other types of treatment. In recent years, accelerated beams of hadrons – both protons and carbon ions – are being deployed clinically, with 25 new dedicated facilities being planned or under construction in Europe.

Radioprotection – Examining the effects of nuclear radiation on living tissue, especially at low-dose levels, is an important area of research. This is particularly relevant to nuclear power-plant safety, radiotherapy and diagnostics, and high-altitude and space travel.

ENVIRONMENT

The increasing sensitivity of analytical methods using isotopes makes them invaluable tools for investigating and monitoring the environment, for example, in climate-change studies. Two methods in particular are employed: accelerator mass spectrometry (AMS), and neutron activation analysis. Such techniques find use, for instance, in analysing and dating geological samples for paleo-climatology studies, or monitoring water resources, following carbon-dioxide exchange between the ocean and atmosphere, and measuring atmospheric and water pollution.

Electricity use across Europe. Nuclear energy plays a key role in keeping the lights switched on sustainably

Proton and carbon-ion therapy can save the lives of patients with difficult-to-treat cancers
[Heidelberg University Hospital]

[INFN/LABEC]



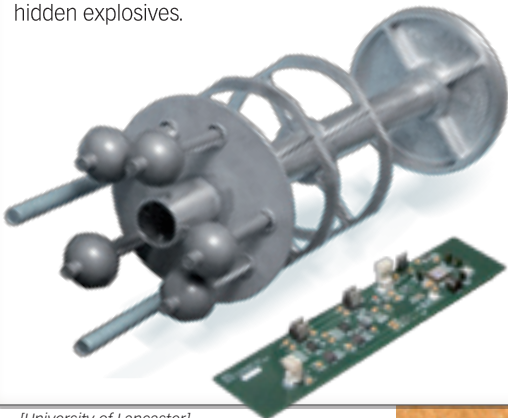
RECENT SUCCESSES

▲ THE TUNIC OF ST FRANCIS IDENTIFIED

Radiocarbon-dating using AMS at the Laboratory of Nuclear Techniques for Cultural Heritage (LABEC) in Florence has revealed that the tunic of St Francis of Assisi, preserved in the town of Cortona, was truly woven during his lifetime, whereas another tunic, attributed to the 12th-century saint and preserved in Florence, was woven several decades later.

▼ COMBATting TERRORISM

A UK consortium, Distinguish, is building an imaging system based on neutron activation. It exploits new germanium detectors, developed for nuclear physics research, to scan cargo and baggage in transit for hidden explosives.



[University of Lancaster]

SECURITY

National security has become a major issue in most countries, and nuclear analytical techniques, in particular those involving neutron and gamma-ray interrogation, are playing a major part in detecting or tracking radioactive, strategic nuclear materials and explosives. Portable systems are being developed for border control, including high-resolution and extremely sensitive detector techniques originally developed for nuclear-structure studies. Nuclear systems to detect neutrinos are being investigated as probes of fissile materials inventories for non-proliferation control.

MATERIALS SCIENCE

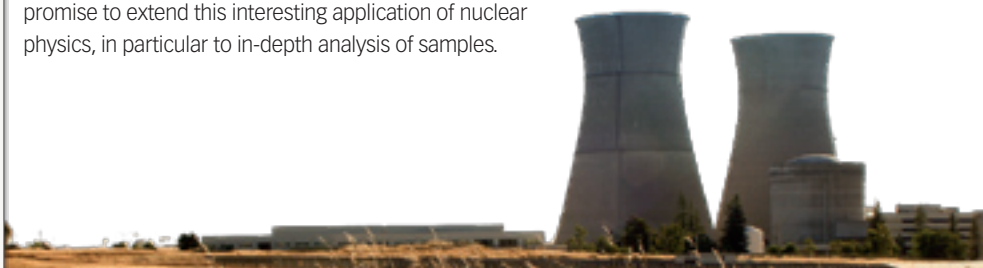
The availability of accelerated beams of both stable and unstable isotopes over a wide range of energies provides new opportunities in characterising and fabricating advanced materials. Progress in ion-beam analysis techniques allows a more fundamental understanding of material properties at the nano-scale, opening the way for the fabrication of novel materials with specific properties. Materials under extreme physical conditions or high-radiation environments for innovative reactors or space applications, for example, are extensively studied. Micro-beams provide excellent tools for shaping and structuring thin-layer materials.

CULTURAL HERITAGE

Nuclear analytical techniques, play a rewarding role in determining non-invasively the provenance, date and even the method of manufacture of archaeological and art objects. Many European museums and art galleries have their own facilities. About 25 AMS facilities in Europe carry out routine carbon-14 dating. New generations of systems exploiting neutrons, protons or alpha particles (helium-4 nuclei) – some portable – promise to extend this interesting application of nuclear physics, in particular to in-depth analysis of samples.

RECOMMENDATIONS

- **Energy** – the continued development of facilities and resources needed to obtain information about the relevant nuclear reactions.
- **Health** – continued programmes in developing new methods for radio-pharmaceutical production, imaging for particle therapy, in radiobiology, and in the development of compact methods of particle acceleration for cancer therapy.
- **Analysis** – the implementation of European networks of AMS and particle-beam facilities for dating and analysis.
- **Training** – further training in all aspects of applied nuclear science and the encouragement of interdisciplinary programmes.



STIMULATING TECHNOLOGIES FOR THE FUTURE

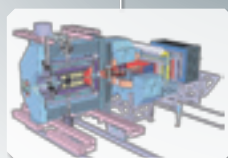
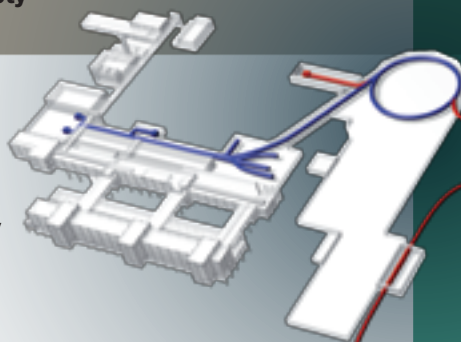
The demands of nuclear physics research lead to technological advances that benefit society

To tackle the future scientific challenges, a network of facilities offering exquisitely tailored, intense beams of a wide range of particles – electrons and hadrons – is essential, along with sensitive methods of identifying and characterising the products of interactions. This requires a range of highly innovative technologies, including new acceleration methods, detectors, computer techniques and data-storage.

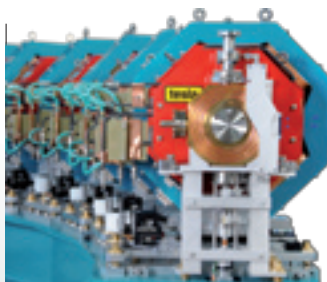
A BETTER PARTICLE BEAM

Of key importance for nuclear physics studies is the efficient production of rare, very unstable isotopes and exotic hadrons (see box, right). This requires investing in the development of a variety of technologies including:

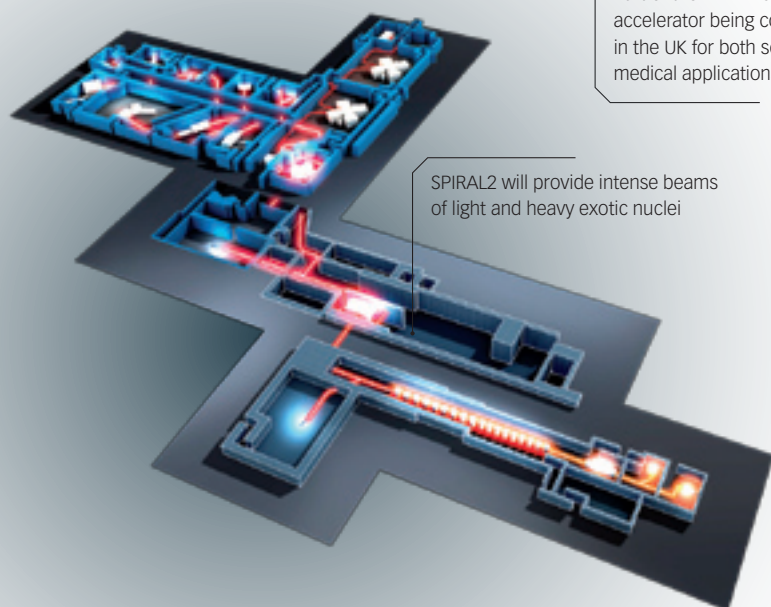
- New ion sources to improve the numbers and varieties of species that can be generated.
- Advanced accelerator devices such as superconducting accelerating radio-frequency cavities and fast-cycling magnets to guide beams.
- Novel accelerating approaches, using new, compact machine designs (such as the fixed-field alternating gradient accelerator being developed in the UK) – or in the longer term, lasers to accelerate particles – may offer inexpensive routes, while also being suitable for applications outside the nuclear and fundamental-science field.
- Advanced devices such as ‘active targets’ containing a gas (hydrogen or helium) that acts as both target and detector.



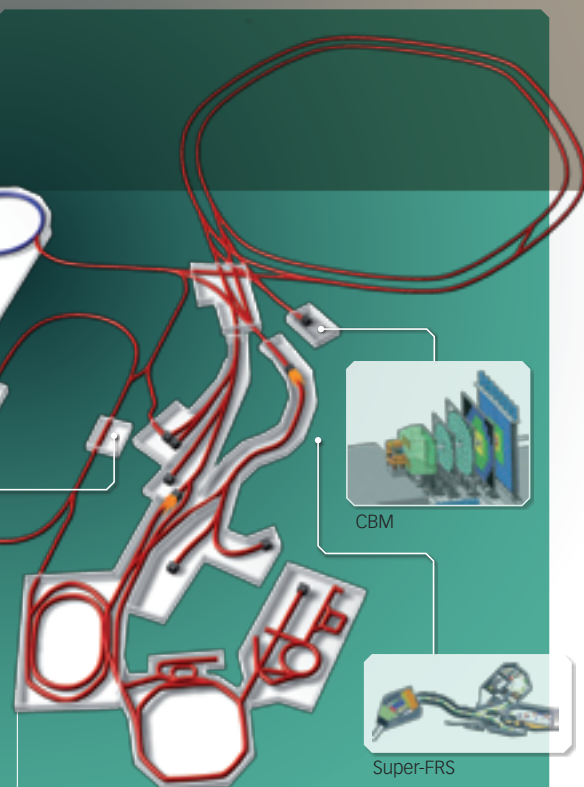
PANDA



Part of the EMMA compact accelerator being constructed in the UK for both science and medical applications



SPIRAL2 will provide intense beams of light and heavy exotic nuclei



CBM

Super-FRS

The FAIR will enable a wide range of nuclear physics experiments to be carried out, using novel technology with broader applications

A new era of facilities

The new FAIR (Facility for Antiproton and Ion Research) Facility to be built on the GSI site will be Europe's leading centre for research into strong-interaction physics. A key feature is the production of an intense antiproton beam to study exotic matter. FAIR's complex accelerator system will also generate a wide range of high-precision, high-intensity beams of stable and unstable nuclei, from protons to uranium.

The new SPIRAL2 accelerator at GANIL will produce exotic nuclei at extremely high intensities. FAIR and SPIRAL2 employ different but complementary set-ups to produce such beams: the ‘in-flight’ and ‘ISOL’ systems. Both involve passing the accelerated particles through a target and separating the new nuclear species generated, before either directing them towards a secondary target or accumulating them in a storage ring (in-flight method) or re-accelerating them (ISOL method) for experiments.

Supercomputers such as the Aurora system managed by ECT* in Trento are essential for theoretical studies in nuclear physics



The new cyclotron being installed in the accelerator laboratory at the University of Jyväskylä, Finland

DETECTORS

Experiments involve detecting a variety of particles and gamma-rays. Spherical detectors composed of germanium devices are used to trace the path of gamma-rays emitted from events, and to measure their energies. A new detector array, **AGATA**, which can precisely track a gamma-ray trajectory is being developed by a European consortium to be used across future facilities. Collaborative teams are also developing **position-sensitive detectors** based on other semiconductor materials, such as silicon pixel and microstrip devices – as well as gas-based detectors. For the most extreme experimental environments, new devices must be developed that are ‘radiation-hard’. For low-temperature experiments and applications, detectors based on cadmium, zinc and tellurium (CZT) are being designed, as well as radiation-hard synthetic diamond detectors.

The advances being made are already being transferred to other fields which benefit – particularly industry, health provision and energy generation. Many young researchers trained in computer methods, and in designing and developing the new technologies, go on to employ their skills in industry.

EXAMPLES OF TECHNOLOGY TRANSFER

- **Ion-beam technology** for industrial applications such as chip production.
- **Compact, cost-effective accelerators** for medical therapies and medical isotope production (there is currently a major world shortage of such facilities).
- **New detectors, software and radiation-hard chips** for applications in remote imaging and security.
- **Advanced computer codes** for modelling complex tasks such as traffic control.



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RECOMMENDATIONS

We wish to make the following recommendations of how best to develop the field of nuclear physics in Europe during the next decade and beyond.

ESFRI FACILITIES

Complete in a timely fashion the construction of the nuclear physics facilities on the ESFRI list of large-scale research-infrastructure projects in Europe:

- **FAIR** at the GSI site, including its four pillars, the PANDA antiproton experiment (hadrons, p.10), the NuSTAR radioactive ion beam (RIB) facility (nuclear structure, p.8), the CBM experiment (nuclear phases, p.12), and the atomic, plasma, and applied physics programme APPA;
- **SPIRAL2** at GANIL, including high-intensity stable ion beams and ISOL RIBs to study exotic nuclei (p.18).

MAJOR UPGRADES

Carry out major upgrades of the following complementary large-scale nuclear physics facilities:

- **HIE-ISOLDE** at CERN (RIBs);
- **SPES** at INFN-LNL (RIBs);
- The **AGATA** gamma-ray detector (p.18) to be used at the above facilities;
- The new **Superconducting Linac** to provide high-intensity stable beams at GSI, for example, to search for superheavy elements (p.8);

ALICE FACILITY

Upgrade the nuclear beams programme and the ALICE detector at CERN to extend the physics reach in investigations of quark-gluon matter (p.12).

THEORY

Strengthen theory support to experiment by developing collaboration between national theory groups through new transnational programmes:

- Strengthen the financial basis of the theoretical research infrastructure **ECT*** to increase its involvement in European theory initiatives;
- Strongly support **advanced studies** related to the above experimental recommendations and improve the link between nuclear theory and quantum chromodynamics (p.10);
- Invest in **high-performance computing facilities** dedicated to nuclear-physics projects.

EXISTING FACILITIES

Fully exploit and upgrade existing large-scale research infrastructures (see map, p.5) to exploit fully past investment:

- The **lepton-beam facilities** (electrons/positrons, muons) at ELSA, MAMI, COMPASS (CERN) and DAΦNE (INFN LNF);
- The **hadron-beam facilities** at COSY (FZ Jülich), and GSI;
- The **heavy-ion beam facilities** at JYFL, KVI, GSI, GANIL, IPN, CERN-ISOLDE, INFN-LNL and INFN-LNS;
- The **nuclear astrophysics** underground accelerator LUNA at INFN Gran Sasso;
- The **ELENA** upgrade of the Antiproton Decelerator at CERN.

Fully exploit smaller-scale national and university nuclear physics laboratories (see map, p.5).

APPLICATIONS AND EDUCATION

Secure and further develop the nuclear-physics skills-base in view of current and future needs, in particular regarding:

- Novel developments in energy generation (nuclear fission and nuclear fusion), medicine (such as imaging and tumour therapy) and security (p.16);
- Development of novel sources, micro-beams, high-power targets and radiation detection instrumentation that will also be used in other fields of science and engineering, and in the life sciences (p.16 and p.18).

FUTURE FACILITIES

Continue the scientific and technical assessments for building new large-scale nuclear physics facilities in the future, and specifically promote:

- The inclusion of the high-intensity ISOL facility, **EURISOL**, in future updates of the ESFRI list, based on the successful EURISOL Design Study in FP7.
- Technical Design Studies for intense RIBs at **ISOL@MYRRHA**, a polarised proton-antiproton collider (**PAX**) and an electron-nucleon/ion collider (**ENC**) at FAIR, and a high-energy electron-proton/ion collider (**LHeC**) at CERN;
- The inclusion of nuclear physics programmes at the multi-purpose facilities, **ELI** (Extreme Light Infrastructure) and **ESS**.