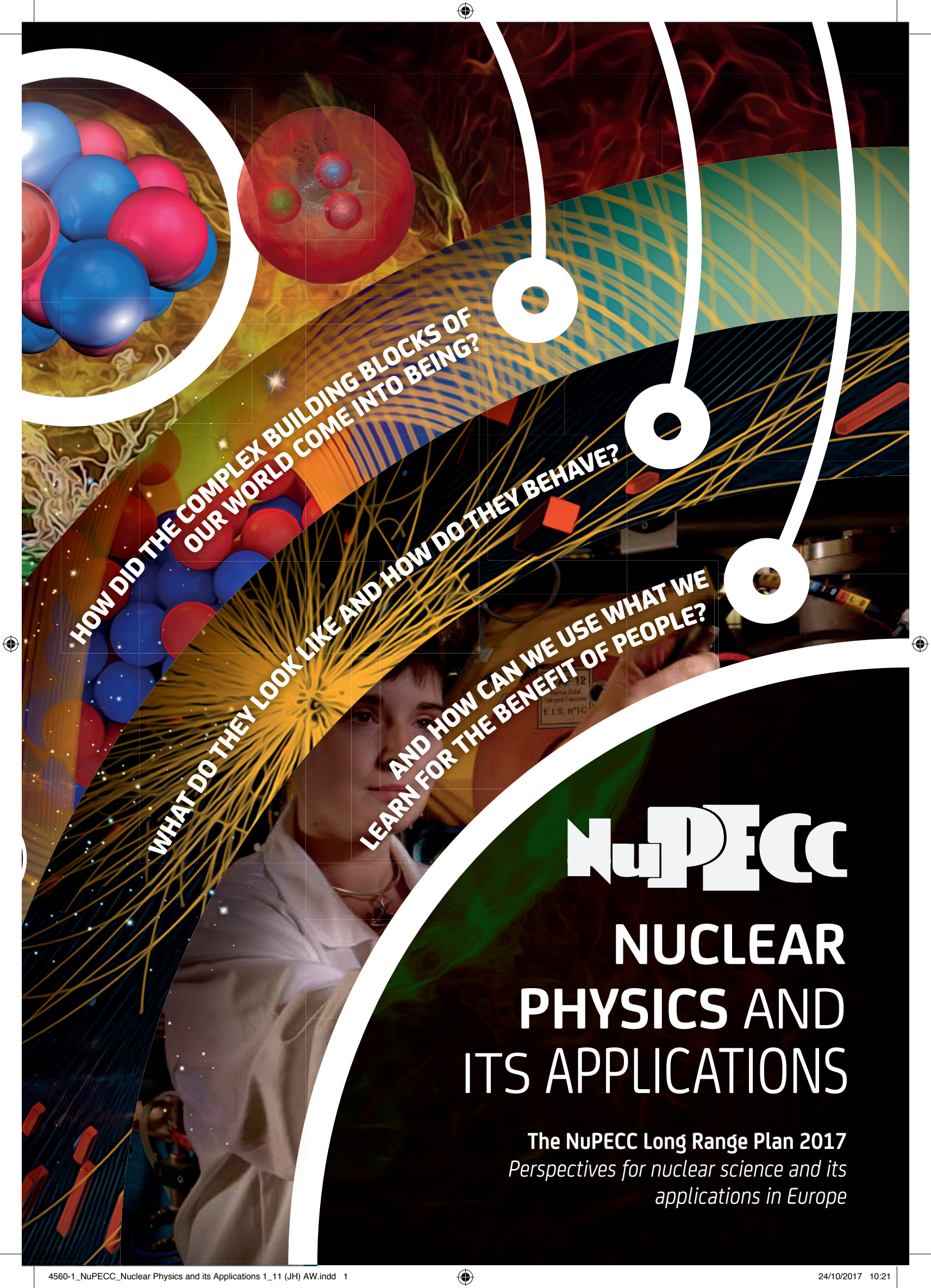




HOW DID THE COMPLEX BUILDING BLOCKS OF
OUR WORLD COME INTO BEING?

WHAT DO THEY LOOK LIKE AND HOW DO THEY BEHAVE?

AND HOW CAN WE USE WHAT WE
LEARN FOR THE BENEFIT OF PEOPLE?

NuPECC

NUCLEAR PHYSICS AND ITS APPLICATIONS

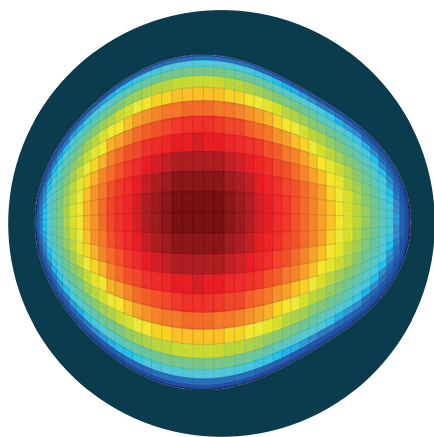
The NuPECC Long Range Plan 2017
*Perspectives for nuclear science and its
applications in Europe*

Introduction

WHAT IS NUCLEAR PHYSICS AND WHY DO WE NEED TO STUDY IT?

THE SCIENCE OF NUCLEAR PHYSICS COVERS THE STUDY OF THE ATOMIC NUCLEUS, WHICH IS WHERE THE MASS OF THE ATOM IS CONCENTRATED. UNRAVELLING THE OFTEN COMPLEX, STRUCTURE AND BEHAVIOUR OF THE NUCLEUS, AND ITS CONSTITUENTS, IS KEY TO UNDERSTANDING HOW THE VARIETY OF MATTER WE SEE ALL AROUND US – AND WHICH UNDERPINS OUR OWN EXISTENCE – IS GENERATED.

Atomic nuclei are hierarchical structures composed of positively charged protons and neutral neutrons, which themselves are made up of fundamental particles, the quarks. These are held together by the so-called strong force, but two of the other fundamental forces, the weak interaction and the electromagnetic force, also play a part in mediating nuclear structure and behaviour. These last two forces also control interactions in the other group of lightweight matter particles, the leptons (see box opposite). The best-understood leptons are the negatively charged electrons, which sit in shells surrounding the nucleus, and dictate an atom's chemical and physical behaviour.



Because all these particles obey the laws of quantum mechanics, nuclei act as miniature laboratories for understanding how Nature works at the most basic level.

A key role of nuclear physics is thus to understand the evolution of matter on this microscopic scale, from the interactions of quarks in the extremely hot, dense, early Universe to create quark combinations called hadrons (the proton and the neutron are by far the most stable hadrons, but other more exotic types can exist), to the

generation, in stars and very compact stellar structures, of a whole 'zoo' of proton–neutron nuclear combinations – atomic nuclei. The intricate structure and varying stability of these nuclei, together with the nuclear reactions they can undergo, dictate their abundance in the Universe and thus on Earth.

The broad variety of nuclei we see today gives rise to the familiar chemical elements of the Periodic Table, which are defined by the number of protons in their nuclei. However, the number of neutrons can vary to create a range of nuclear species, or isotopes, for each element. Since the number of electrons in a neutral atom is defined by the number of protons present, the make-up of the nucleus has a direct bearing on terrestrial chemistry and biology.

NUCLEAR PHYSICS EXPERIMENTS

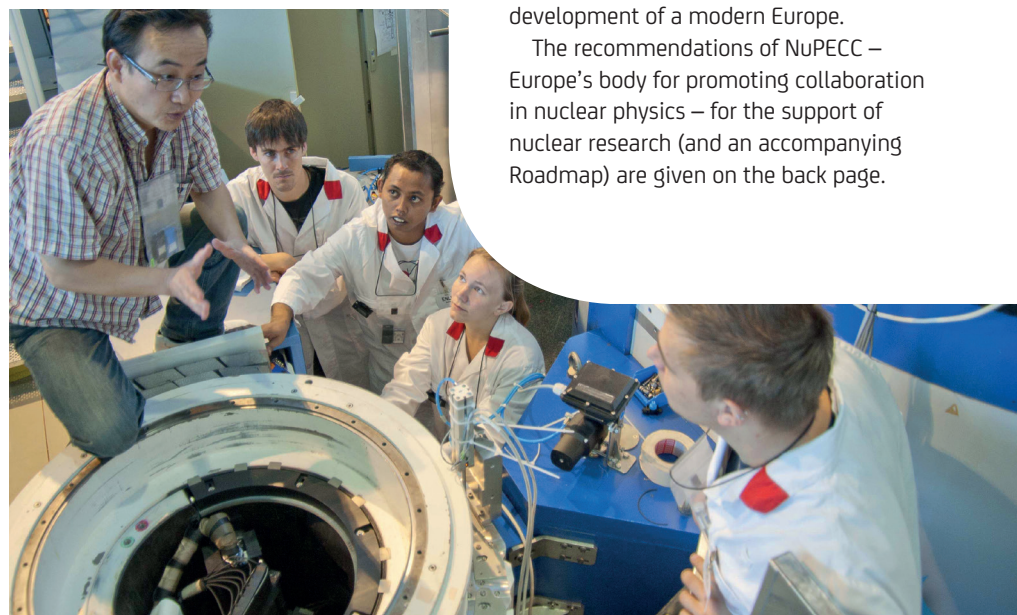
The strong force is so powerful, and the multi-component nuclei have such complex structures, that most studies require experiments carried out under extreme conditions of either very high or very low energies. A typical experiment involves generating beams of particles accelerated

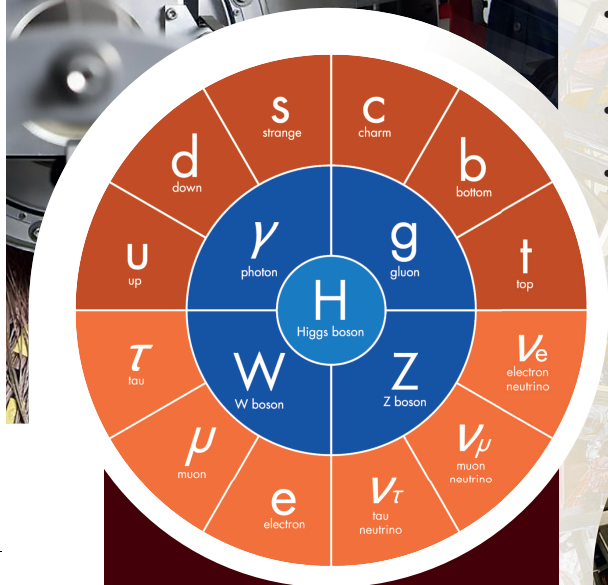
to energies high enough to trigger nuclear reactions in target materials, and the resulting, often exotic, nuclei are detected and studied. The behaviour of nuclei is also studied at ultra-low temperatures in sensitive experiments that look for subtle quantum processes that might indicate new fundamental phenomena.

All these experiments are technically demanding and are increasingly carried out by international teams at large dedicated facilities. Equally important are nuclear theory and high-performance computing infrastructures – not only to interpret results, but also to make predictions about nuclear structure and behaviour.

Such facilities also offer excellent opportunities for training young people in both physics and engineering, equipping them with essential skills to enhance the development of a modern Europe.

The recommendations of NuPECC – Europe's body for promoting collaboration in nuclear physics – for the support of nuclear research (and an accompanying Roadmap) are given on the back page.





Matter particles

- Quarks
- Leptons
- Force carriers
- Higgs boson

The building blocks of Nature

The matter particles consist of six quarks and six leptons, each divided into three generations of increasing mass. Protons and neutrons are made up of the first generation of quarks, called 'up' and 'down'. Each particle has an 'antimatter' partner with opposite electric charge.

The fundamental forces governing nuclei are mediated by the exchange of 'virtual particles'. For the strong force – it is the gluon; the electromagnetic force – the photon; and the weak force – the W and Z bosons. So far, no particle for the fourth force, gravity, has been identified.

THE BIG QUESTIONS

We can summarise 'the big questions' that nuclear physics tries to answer as follows:

- How does the strong interaction of quarks and gluons generate the structures we observe?
- How is the strong force between protons and neutrons in the nucleus (the nucleons) generated from the underlying interactions of quarks and gluons – the particles that carry the strong force?
- How does the complexity of nuclear structure emerge from the interactions between the nucleons?
- What are the limits of nuclear stability in terms of the numbers and proportions of protons and neutrons in a nucleus?
- How and where in the Universe are the chemical elements produced?
- How does quark and nuclear matter behave in extreme conditions – as encountered just after the Big Bang, and in cataclysmic stellar explosions and very dense stellar objects.



We answer these questions by dividing studies into five areas:

- The formation of hadrons from quarks and gluons;
- The behaviour of quarks and hadrons under extreme conditions of temperature, pressure and density;
- Nuclear structure and reactions – the complex behaviour of nuclei, especially unusual, very unstable ones;
- Nuclear astrophysics – how the elements came into being;
- Fundamental interactions – what nuclear science tells us about the fundamental laws of Nature;
- Finally, the knowledge gained from these studies offers many applications of benefit to society.

These are described in the following pages, along with the advanced European facilities where ground-breaking research is carried out.

ABOUT NuPECC

The Nuclear Physics European Collaboration Committee (NuPECC) is an Expert Committee associated with the European Science Foundation. The Committee is supported by its Subscribing Institutions, which are involved in nuclear science and research or research facilities, and nominate the NuPECC Members.

The objective of NuPECC is to strengthen European Collaboration in nuclear science through the promotion of nuclear physics, and its trans-disciplinary use and application in collaborative ventures between research groups within Europe. In pursuing this objective, the Committee shall:

- define a network of complementary facilities within Europe and encourage the optimisation of their usage;
- provide a forum for the discussion of the provision of future facilities and instrumentation; and
- provide advice, and make recommendations on the development, organisation, and support of European nuclear research and of particular projects.

NUPECC MEMBER COUNTRIES

AUSTRIA	ITALY
BELGIUM	THE NETHERLANDS
CROATIA	NORWAY
CZECH REPUBLIC	POLAND
DENMARK	PORTUGAL
FINLAND	ROMANIA
FRANCE	SPAIN
GERMANY	SWEDEN
GREECE	SWITZERLAND
HUNGARY	UNITED KINGDOM

INSTITUTIONAL MEMBERS

ECT* (Trento, Italy)
FAIR (Darmstadt, Germany)
JINR (Dubna, Russia)
SPIRAL2 (GANIL, Caen, France)

OBSERVERS

ALAFNA (Latin American Nuclear Physics and Applications)
ANPhA (Asian Nuclear Physics Association)
EPS (European Physical Society)
NSAC (US Nuclear Science Advisory Committee)

Website: www.nupecc.org

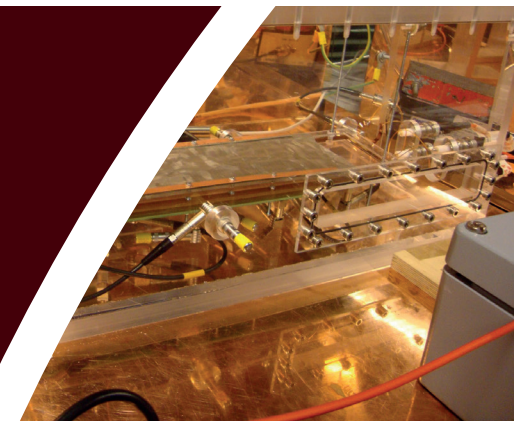
A LEADING NETWORK OF NUCLEAR RESEARCH FACILITIES

EUROPE OFFERS AN EXTENSIVE, WELL-STRUCTURED NETWORK OF NUCLEAR RESEARCH FACILITIES, UNPARALLELED ELSEWHERE IN BREADTH AND SCOPE. IT IS NOT SURPRISING, THEREFORE, THAT THE INNOVATIVE SCIENCE CARRIED OUT IS NOT ONLY PUSHING BACK THE FRONTIERS IN OUR UNDERSTANDING OF MATTER AND THE UNIVERSE, BUT IS ALSO CREATING OPPORTUNITIES FOR NEW TECHNOLOGIES AND WEALTH CREATION.

European countries from west to east, and north to south, have traditionally maintained a diverse range of laboratories hosting the particle accelerators and instruments needed to investigate nuclear matter. Some facilities are small, often specialising in particular areas of nuclear science, or in applied research such as analytical services for industry, healthcare applications, or R&D on novel nuclear power schemes.

Increasingly, it is recognised that to make ground-breaking discoveries, investment is needed in advanced international facilities, which researchers can visit from across the globe to collaborate. However, the research activities at both national and trans-national laboratories are complementary and interdependent, especially in providing student training and instrument development.

The strategies for taking forward nuclear research across Europe in this way is supported and assessed by ESFRI, the European Strategy Forum on Research Infrastructures, which has set out a Roadmap.



ELI-NP The ESFRI-supported 'Extreme Light Infrastructure' (ELI) project has a nuclear physics component to be located near Bucharest in Romania. It comprises a very high-power laser system, delivering brilliant gamma-ray beams powerful enough to probe nuclear structure, and even how fundamental interactions and particles emerge from the vacuum.

EURISOL-DF This Distributed Facility represents a future collaborative strategy aimed at combining the scientific research programmes and technological R&D of European nuclear physics laboratories that utilise the so-called ISOL method when generating rare nuclei. The GANIL-SPIRAL2, ISOLDE/CERN and SPES-INFN facilities have ambitions to become the core members of this new initiative. The long-term goal is to develop EURISOL on a single site that, together with FAIR, will provide nuclear physicists with unmatched experimental facilities.

LARGE-SCALE FACILITIES

EUROPE HAS A NUMBER OF WELL-ESTABLISHED LARGER RESEARCH ORGANISATIONS, WHICH PROVIDE THE FOCUS FOR A BROAD RANGE OF NUCLEAR STUDIES, AND THE DEVELOPMENT OF CUTTING-EDGE EXPERIMENTAL SETUPS AND INSTRUMENTATION.

CERN in Geneva, hosts several accelerator systems producing a variety of particle beams that enable phenomena, including many in nuclear physics, to be explored across a spectrum of energies. The ALICE experiment on the famed Large Hadron Collider (LHC) studies the generation of hadrons from the hot quark-gluon plasma that existed in the early Universe; it now is being upgraded with new equipment to take more precise measurements. The COMPASS experiment probes hadron structure and behaviour at lower energies, while ISOLDE produces various radioactive ion beams for experiments in the fields of nuclear and atomic physics, materials and the life sciences, it is also being upgraded (HIE-ISOLDE) to expand research on significant nuclear reactions. The Antiproton Decelerator (AD), together with a new decelerator ring, ELENA, provides antiprotons at the lowest energies for sensitive, precision experiments on the fundamental forces.

GANIL in Caen, France provides another major international heavy-ion accelerator complex, dedicated to exploring nuclear structure and reactions; plans are going ahead to expand and improve this facility (see above right). It is currently hosting the internationally developed instrument, AGATA. This is an advanced gamma-ray spectrometer that will detect and measure, with unprecedented positional accuracy, the characteristic energies of gamma-rays emitted by rare, unstable nuclei. The instrument configuration is gradually growing, and will be deployed at various nuclear physics laboratories across Europe for given periods.

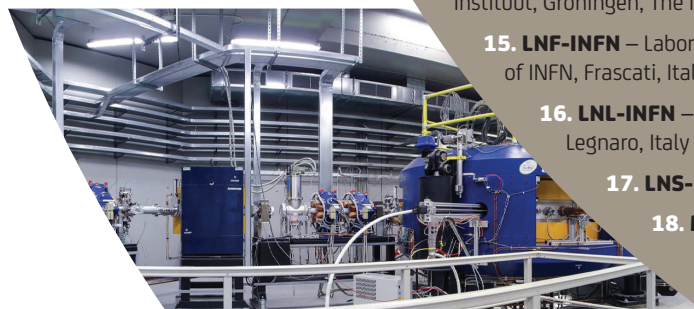
GSI in Darmstadt, Germany operates a large accelerator complex that generates nuclei from hydrogen to uranium (as ions) for experiments investigating the nature of very exotic nuclear species. This setup will now be the injector system for a major new nuclear facility, FAIR (see above right).

INFN (Italy's Istituto Nazionale di Fisica Nucleare) comprises four laboratories in Catania, Frascati, Legnaro and Gran Sasso, which between them carry out a wide range of studies in nuclear science and its applications. The Legnaro laboratory is building a new accelerator (SPES) for creating neutron-rich nuclei, which are of astrophysical relevance, and contribute to our understanding of nuclear binding and stability.

JINR in Dubna, Russia, is well-known for its programme to create and study new, superheavy elements (SHE) via collisions of heavy ions. A SHE factory is now being constructed, and there are plans for a new, large collider facility NICA (see above right).

FAIR The Facility for Antiproton Research (FAIR) is the flagship project on the ESFRI Roadmap. With 10 partner countries, it will provide a unique accelerator complex for the experimental programmes of its four scientific pillars: APPA (atomic, plasma and applied physics); CBM (quarks and hadrons in extreme conditions); NUSTAR (nuclear structure, reactions and astrophysics); and PANDA (exotic hadron structure and behaviour).

NICA (Nuclotron-based Ion Collider Facility) is a new accelerator complex that will enhance JINR's position as a world-class nuclear physics facility. It will enable the study of various states of hot dense nuclear matter via heavy-ion collisions.



NEW FACILITIES BEING BUILT OR PLANNED

NUPECC HAS IDENTIFIED THESE COLLABORATIVE PROJECTS AS BEING KEY TO MAINTAINING EUROPE'S LEADING POSITION IN NUCLEAR PHYSICS RESEARCH.

SPIRAL2 is a multi-purpose international facility being built at GANIL, aimed at delivering intense beams of rare nuclei, some right on the edge of stability.

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

2. CCB – Cyclotron Centre Bronowice (IFJ PAN) Kraków, Poland

3. ELSA – Electron accelerator, Bonn, Germany

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

5. FZJ – Forschungszentrum Jülich (COSY and HPC), Jülich, Germany

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

7. GSI – Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany

8. HIL – Heavy Ion Laboratory, Warsaw, Poland

9. IFIN-HH Horia Hulubei – National Institute of Physics and Nuclear Engineering, Bucharest, Romania

10. ILL – Institut Laue–Langevin, Grenoble France

11. IPN – Institut de Physique Nucléaire, Orsay, France

12. JYFL – Accelerator Laboratory, University of Jyväskylä, Finland

13. JINR – Joint Institute for Nuclear Research, Dubna, Russia

14. KVI-CART – Kernfysisch Versneller Instituut, Groningen, The Netherlands

15. LNF-INFN – Laboratori Nazionali di Frascati of INFN, Frascati, Italy

16. LNL-INFN – Laboratori Nazionali di Legnaro of INFN, Legnaro, Italy

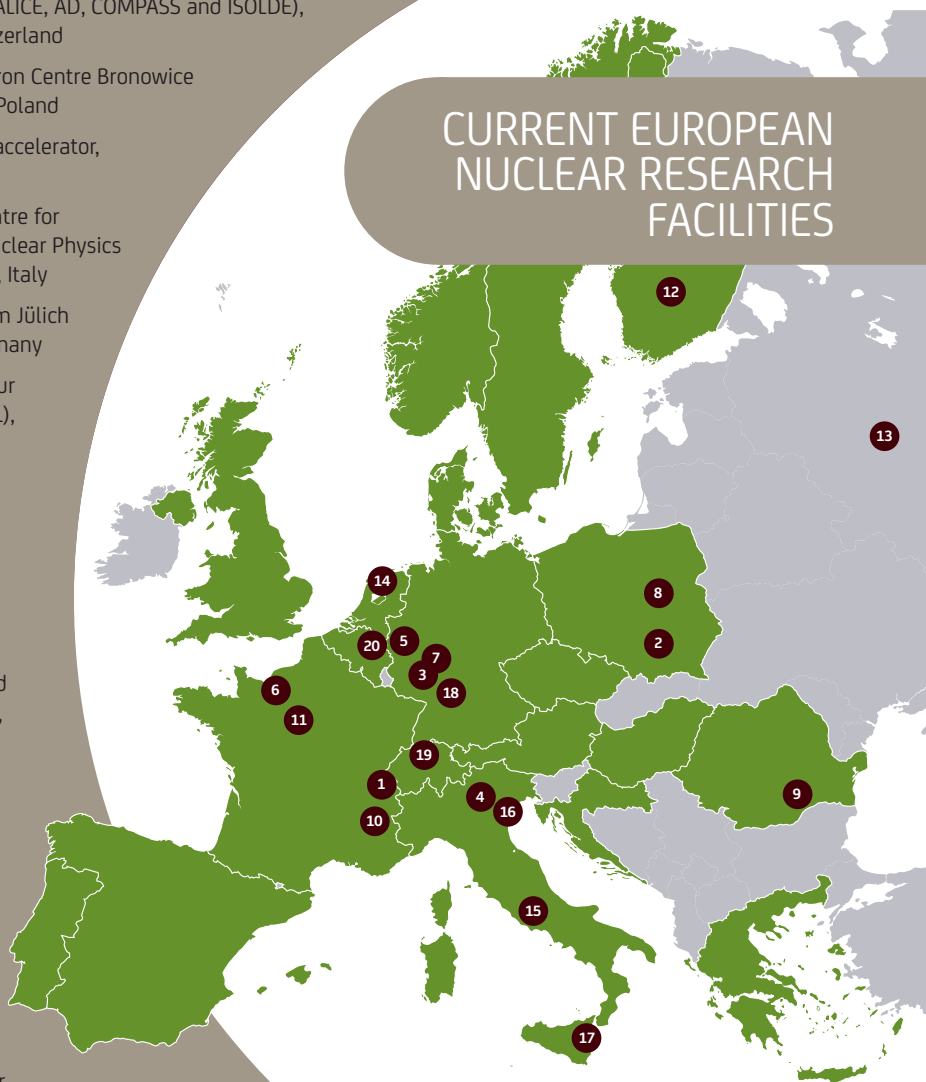
17. LNS-INFN – Laboratori Nazionali del Sud of INFN, Catania, Italy

18. MAMI – Mainzer Microtron, Institute for Nuclear Physics, Mainz, Germany

19. PSI – Paul Scherrer Institute, Villigen, Switzerland

20. SCK•CEN – Mol, Belgium

CURRENT EUROPEAN NUCLEAR RESEARCH FACILITIES



IN TODAY'S UNIVERSE, QUARKS NEVER EXIST ON THEIR OWN; THEY ARE ALWAYS BOUND INTO PAIRS (MESONS, LIKE THE PION OR KAON) OR TRIOS (BARYONS, LIKE THE PROTON AND NEUTRON), HELD BY THE EXCHANGE OF GLUONS CONSTITUTING THE POWERFUL STRONG FORCE. OF THESE, ONLY THE PROTON AND NEUTRON HAVE LONG LIFETIMES. OTHER, MORE COMPLEX COMBINATIONS ARE POSSIBLE, SUCH AS TETRAQUARKS, PENTAQUARKS, VARIOUS HYBRID STRUCTURES AND EVEN ENTITIES COMPOSED OF JUST GLUONS – SO-CALLED GLUEBALLS. HADRON PHYSICS INVOLVES STUDYING THE INTRICATE PATTERNS OF THE HADRON STRUCTURES THAT EMERGE, THE SPECTRA MAPPING THEIR ENERGIES, AND THEIR INTERACTIONS.

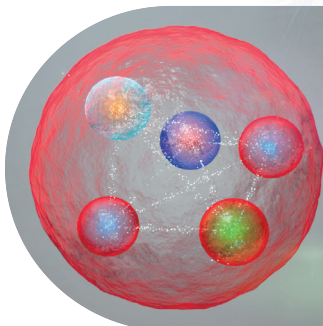
THE PHYSICS OF HADRONS

Of crucial importance, is to formulate a quantitative description of what we might expect to see. The basic theory of the strong force is quantum chromodynamics (QCD). It is extremely complicated and different theoretical approaches are adopted for different energy regimes. A particularly powerful method, which requires a huge amount of computing power, is to calculate quark–gluon interactions on a space-time lattice of points (lattice QCD).

THE COMPLICATED PROTON

Because there are six quarks, the number and variety of hadron permutations possible are large, and laboratory experiments involve creating and studying them. Beams of particles such as protons, antiprotons, pions, and kaons can be used to study the spectra of hadrons, their internal structure and interactions – particularly those composed of the heavier quarks. Such hadrons are rare and exotic, yet tell us about how the strong force works.

Some of the most interesting problems in hadron physics are how the characteristics – mass, spin and size – of hadrons like the proton are generated, since they cannot be explained just by adding together the same properties of the individual constituent quarks. QCD predicts that the interactions of gluons and small contributions from other kinds of quark make hadrons a lot more complicated. Only recently, studies have uncovered large discrepancies in measurements of the proton radius made in different experiments. New experiments at PSI and MAMI/MESA aim to find out whether QCD can explain it or whether new physics must be invoked.

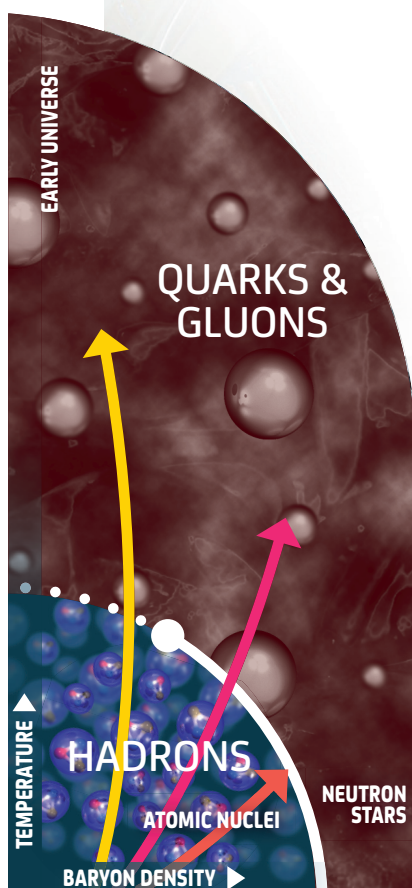


European hadron facilities

- The COMPASS experiment at CERN (Geneva) uses muon and hadron beams. It has been probing how the spin of the proton is generated from its constituents. The new NICA facility at Dubna will investigate nucleon spin further.
- ELSA (Bonn) and MAMI/MESA (Mainz) deliver electron beams to study many complexities of hadron structure and behaviour.
- The LHCb experiment at the LHC (CERN), is designed to study b-quark decays, but also recently confirmed the existence of a very exotic hadron, the pentaquark.
- GSI operates the HADES detector system to investigate quark–antiquark pairs produced in heavy-ion collisions. Their identification is helping researchers to understand their modifications within the nuclear medium.
- The PANDA experiment, one of FAIR's cornerstone experiments, will collide antiprotons with a proton-rich target to provide a wide range of hadron studies, especially of particles composed of heavier quarks.

Recommendations for hadron research

- Complete the PANDA experiment at FAIR.
- Support the experimental programmes at the laboratories mentioned, which carry out detailed measurements complementary to those that will be made at FAIR.
- Support work on the underlying theory of hadron interactions, in particular employing methods requiring high-performance computing.

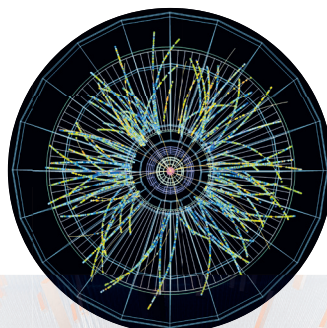


The phase diagram showing the types of matter existing up to very extreme temperatures and densities

- LHC
- FAIR
- NICA

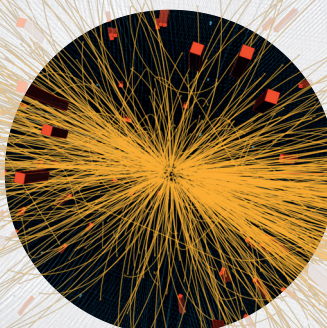
MATTER AT EXTREMES

STUDYING NUCLEAR MATTER AT VERY HIGH TEMPERATURES AND DENSITIES NOT ONLY REVEALS THE HIGH-ENERGY PROCESSES THAT DROVE THE EVOLUTION OF THE UNIVERSE JUST AFTER ITS BIRTH, BUT ALSO ITS VERY EXOTIC NATURE IN MASSIVELY COMPRESSED STELLAR CORPSES – NEUTRON STARS. COLLISIONS BETWEEN THE DENSE NUCLEI OF HEAVY IONS AT HIGH ENERGY PROVIDE THE MAIN TOOL FOR SIMULATING THESE EXTREME CONDITIONS.



HIGH-TEMPERATURE MATTER

Observational evidence indicates that the Universe started in a hot compressed, uniform state in the Big Bang. It then expanded, cooling and condensing into quarks, leptons and the force particles. The quarks formed in the first trillionth of second in a hot fluid-like droplet – the quark–gluon plasma (QGP). After around a microsecond, the QGP had expanded enough for the quarks to bind into hadrons (the strong force gets stronger with widening distance). The first hadrons forming would have been transient exotic pairs of the heavier quarks, charm and bottom (mesons), but eventually the familiar protons and neutrons formed, which became the building blocks of nuclei in stars and galaxies.



HIGH-DENSITY MATTER

Supermassive stars end their active nuclear lives exploding as supernovae, and then contract under gravity into dense cores of hadronic matter, mostly neutrons. However, the density of matter in the centre of a neutron star is thought to be so high that more exotic types of quark matter can exist such as hyperons, which are like protons but contain strange quarks.

All these forms of nuclear matter can be plotted on a phase diagram of temperature *versus* density of particles (see top left). To understand fully how quarks and hadrons behave, we would like to explore as much of the phase diagram as is possible, since theory indicates that some very exotic behaviour could exist.



European heavy-ion facilities

CURRENT

- The ALICE experiment at the LHC collides lead ions at very high energies, and then detects the production of exotic mesons and other particles that are the signature of a QGP. Measurements so far indicate that a QGP acts like a frictionless superfluid.
- NA61/SHINE experiment at CERN fires particles at a fixed target to probe the region of the phase diagram just before quarks become ‘de-confined’ in a QGP.
- HADES at SIS-18, GSI, studies lower-energy collisions of dense matter. It collides heavy nuclei to generate strange mesons and hyperons that might be found in neutron-star cores.

NEW

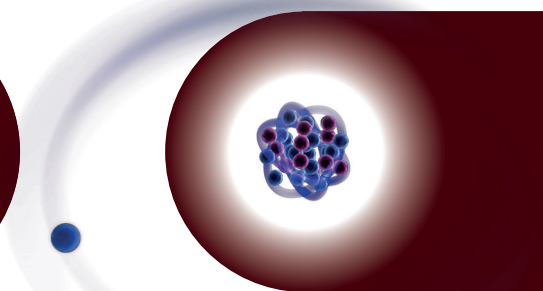
- The CBM (Compressed Baryonic Matter) experiment at FAIR will be the flagship experiment to explore a range of hadron behaviour in conditions signifying the transition to a QGP, or in a neutron star.
- The MPD and BM@N heavy-ion experiments at NICA (JINR) will scan various areas of the phase diagram.
- NA60+ experiment at CERN, still being planned, would make complementary measurements to those taken with the CBM and other experiments.

Recommendations for matter at extremes research

- Continue with current heavy-ion programmes at the LHC (ALICE), NA61 at the CERN SPS, and GSI (HADES).
- Give priority to the development of the CBM experiment at FAIR to investigate very dense nuclear matter.
- Complete the NICA facility and its experiments to study heavy-ion reactions.
- Develop plans for future heavy-ion projects.
- Continue collaboration on theoretical support to interpret results and the development of underlying QCD theory.

PROTONS AND NEUTRONS CAN BIND TOGETHER VIA THE NUCLEAR FORCES TO CREATE AS MANY AS 7000 DIFFERENT NUCLEAR SPECIES. THEY INCLUDE THE 300 OR SO STABLE, OR LONG-LIVED, ISOTOPES THAT CHARACTERISE THE FAMILIAR ELEMENTS. MOST OTHER NUCLEI ARE CALCULATED TO BE VERY UNSTABLE, WITH THE LIMITS OF STABILITY GOVERNED BY THE EXTREMES OF PROPORTIONS OF THE TWO TYPES OF NUCLEON, PROTONS AND NEUTRONS, AND THEIR NUMBER IN A NUCLEUS.

NUCLEAR STRUCTURE AND REACTIONS



European facilities studying nuclear structure

• STABLE ION AND NEUTRON BEAM FACILITIES

Europe possesses a range of nuclear facilities, some based at universities, able to provide moderately intense beams of stable nuclei for studying superheavy nuclei, very unstable nuclei, and neutron-rich nuclei of astrophysical significance.

• RADIOACTIVE ION BEAM (RIB) FACILITIES

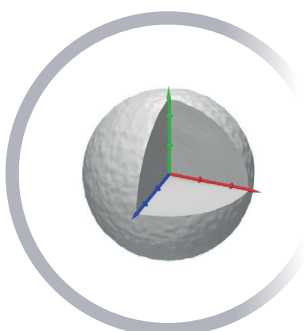
Larger facilities such as GSI, GANIL (with the addition of SPIRAL2) and HIE-ISOLDE (CERN) generate beams of unstable nuclei (as ions) that enable a wider range of much more exotic nuclei to be prepared. NUSTAR at FAIR will become the experiment for such studies, and eventually will be complemented by upgraded facilities of the EURISOL distributed programme. ISOL@MYRRHA at SCK•CEN in Mol, Belgium and SPES (LNL) will also provide radioactive ion beams, and the ELI-NP laser facility will be able to study very exotic neutron-rich nuclei.

• INSTRUMENTS

AGATA is a unique and world-leading device able to detect gamma-rays, measure their energies and pinpoint their origin with very high sensitivity. This internationally-supported, germanium-based detector array has been successfully used at LNL, GSI and GANIL.



An early experiment using the AGATA detector at LNL showed that the calcium-42 nucleus, when set spinning, elongates into a triaxial 'super-deformed' state

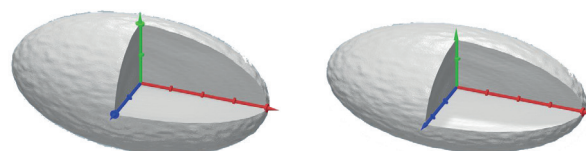


Many rare and unusual nuclei can be created and then studied using accelerator facilities. The result has been the discovery of a wondrous variety of complex structures and shapes – from lightweight 'halo' nuclei in which an outer neutron orbits far from the central structure, through nuclei arranged in smaller clusters of nucleons, or in concentric shell-like structures, which when fully occupied by nucleons are very stable ('magic' nuclei), to dense, heavyweight nuclei with unusual shapes that behave more like wobbling liquid droplets.

Experiments probing these nuclei attempt to understand how these various structures emerge as the numbers and proportions of protons and neutrons change across the nuclear landscape (see right), and what controls their stability and behaviour. Of particular interest are nuclei with neutron–proton proportions that are only just bound, and are on the edge of shedding neutrons or protons (the neutron or proton 'driplines'), and 'superheavy' nuclei containing up to 300 nucleons.

GENERATING EXOTIC NUCLEI

These exotic nuclei are generated by colliding beams of particles (some unstable nuclei themselves) with a target. They can be identified, and their properties characterised by the gamma-rays and other particles that they emit as they decay. Also of significance is what happens when they are 'heated', made to spin, or undergo nuclear reactions. Such systems composed of many interacting particles are challenging to describe theoretically, so theorists must rely on a series of models to explain these experimental results. The eventual aim is to create a unified description of atomic nuclei.



Recommendations for nuclear structure research

- Complete FAIR and NUSTAR.
- Continue support for upgrades at SPIRAL2, HIE-ISOLDE and SPES that will underpin EURISOL.
- Complete and operate ELI-NP.
- Support to the completion of AGATA in full geometry.
- Continue support to existing facilities (ALTO, GANIL, GSI-FAIR, IFIN-HH, ISOLDE, JYFL, KVI-CART, LNL-LNS, NLC Warsaw-Krakow), including support to smaller facilities in developing their specific research programmes, instruments and in training researchers.
- Support work developing a unified theory of nuclear structure and interpreting nuclear data.

THE COMPLEX PHYSICS OF THE ATOMIC NUCLEUS HAS NOT ONLY SHAPED OUR UNIVERSE BUT ALSO OURSELVES. NUCLEAR ASTROPHYSICS AIMS TO UNDERSTAND THE EVOLUTION OF MATTER IN ALL ITS COMPLEXITY ACROSS COSMOLOGICAL TIME – IN THE FIRST MINUTES JUST AFTER THE BIG BANG, DURING THE LIFE-CYCLES OF STARS WHEN THE PRIMARY ELEMENTS NEEDED FOR LIFE WERE CREATED, AND IN VIOLENT COSMIC EVENTS THAT DELIVERED THE HEAVIEST ELEMENTS.

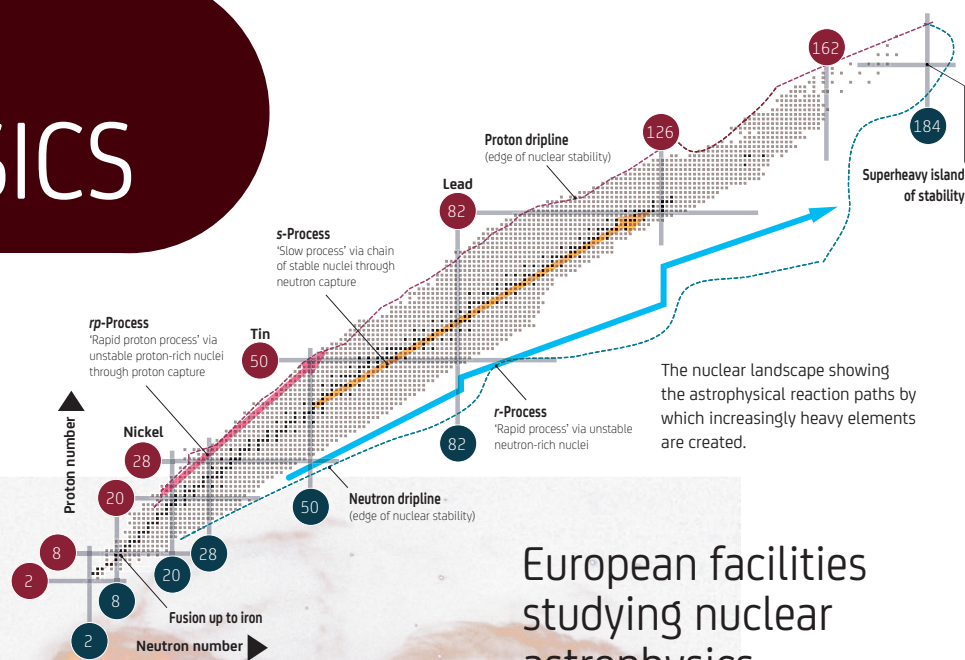
NUCLEAR ASTROPHYSICS

Theories of 'nucleosynthesis', by which the chemical elements were created, are tested by experimentally probing and measuring nuclei of interest, and simulating specific nuclear reactions. Results are also assessed against observations of stellar behaviour and of element distributions across the Cosmos. The story is intriguing and there is still much we do not know.

The lightest elements, hydrogen, helium, and lithium, were made from primordial Big-Bang matter, before the first stars formed. The rest of the elements are thought to be built up in stellar processes through complex chains of nuclear reactions (shown by the coloured arrows in the diagram). In this way, during a typical star's lifetime, its supply of hydrogen fuel is 'burnt' to helium, followed by burning to carbon, nitrogen and oxygen. Eventually the heavier elements such as silicon and finally iron and nickel are reached. The reaction chains can be mapped on a landscape charting the nuclei species that form with increasing numbers of protons and neutrons. It climbs slowly up along the central 'valley' of stable nuclei, continuing until all the star's nuclear fuel has been consumed and it eventually collapses.

HOW WERE THE HEAVIEST ELEMENTS MADE?

We know little about how the heavier elements beyond iron in the Periodic Table are created. Theory suggests that many of them are generated in extremely violent environments such as the supernova explosion that ends the life of a very massive star, followed by its core collapse into a neutron star or black hole; or when a white dwarf in a binary star system is explosively resurrected by drawing off gas from its companion. Even more violent events like the merger of two neutron stars or black holes may also trigger these rapid nucleosynthetic processes. They are thought to follow paths up the nuclear landscape involving thousands of unstable nuclear species on both sides of the valley of stability.



The nuclear landscape showing the astrophysical reaction paths by which increasingly heavy elements are created.

European facilities studying nuclear astrophysics

Nuclear astrophysics requires the same facilities as those for studying nuclear structure (see opposite), making use of stable ion and neutron beams to investigate nuclear reactions of astrophysical significance, and radioactive ion beams to make nuclei far from the valley of stability.

- **NUSTAR** at **FAIR** in particular will provide studies of unstable nuclei relevant to explosive nucleosynthesis. In addition, studies at the other FAIR experiments, **CBM**, **PANDA** and **APPA**, will shed light on nuclear reactions in the neutron-star interior and in the hearts of dense gas giants like Jupiter.
- The **LUNA** deep underground facility in Gran Sasso, Italy (**LGNS**) is the only laboratory with an accelerator particularly well suited to studying the hydrogen-burning reactions that take place in the main phases of stellar life. It will be joined by a second accelerator **LUNA-MV** which will investigate the next stages of helium and carbon burning.

Additional recommendations for nuclear astrophysics research

- Follow the same recommendations as for nuclear structure research.
- Complete the upgrade of the LUNA underground facility (LUNA-MV).
- Support the work at ECT* (Trento) in theoretical nuclear astrophysics.

THE BASIC LAWS OF THE UNIVERSE MANIFEST THEMSELVES AT ALL LEVELS – FROM THE QUANTUM BEHAVIOUR OF THE BUILDING BLOCKS OF NATURE TO THE EVOLUTION AND DYNAMICS OF STARS AND GALAXIES. PHYSICISTS LOOK FOR THE UNIFYING PRINCIPLES, OR PATTERNS, THAT BEST DESCRIBE THESE LAWS.

SYMMETRIES AND FUNDAMENTAL INTERACTIONS

An important principle underlying our understanding of Nature is that of symmetries and symmetry-breaking. The history of the Universe contains a series of symmetry breakings leading to the pattern of fundamental particles and forces we observe today. High-sensitivity tests of symmetries improve our insight into the relevant processes and shape new theoretical developments.

Atomic nuclei provide excellent laboratories for probing these symmetries. Ingenious experiments using low-energy beams of particles, or very cold ions confined in magnetic traps, can make incredibly precise measurements of properties such as magnetic moments, electric charge and modes of decay. While symmetry principles are embedded in current quantum descriptions used to predict the results, physicists look for minute effects that hint at symmetry-breaking pointing to some deeper unifying theory. Such measurements are complementary to those made in high-energy particle colliders.

DO MATTER AND ANTIMATTER BEHAVE IN THE SAME WAY?

To look for such symmetry-breaking can involve comparing the behaviour of matter particles with their antimatter counterparts in terms of charge–parity and time-reversal. Experiments on antimatter, for example antihydrogen (an antiproton combined with a positive electron) held in a trap, will determine whether matter and antimatter behave in a similar way, especially in a gravitational field. Other sensitive experiments investigating whether the neutron has an electric dipole moment, or the ghostly neutrino has a measurable mass, could uncover a more fundamental description of Nature.

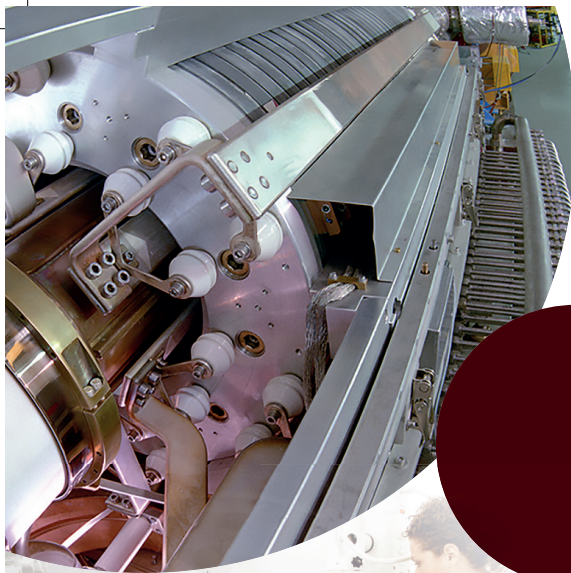
European facilities studying symmetries and fundamental interactions

Many of the experiments carried out are table-top, and so can be conducted in university laboratories. Others may require intense sources of particles and specialised equipment available only at the larger facilities. These include:

- [AD/ELENA](#) at [CERN](#) creates cold antiprotons to search for matter–antimatter asymmetries.
- [APPA](#) at [FAIR](#) will carry out low-energy experiments with antiprotons and heavy ions to test the current quantum theories of particles and forces.
- [DAFNE](#), the electron–positron collider at [LNF-INFN](#), generates kaons to study aspects of the strong force.
- Europe's neutron facilities carry out experiments with cold and ultra-cold neutrons to probe a range of fundamental properties and look for new physics. The new high-intensity neutron source, ESS in Lund, may continue this work.
- [Radioactive ion beam](#) facilities, mentioned on p8, provide unstable nuclei for experiments on fundamental interactions.
- [PSI](#) provides the highest-intensity pion and muon beams for fundamental and applied physics.
- [Underground facilities](#) ([LNGS](#)) in Europe allow highly sensitive experiments such as those trying to determine the mass of the neutrino.

Recommendations for research in symmetries and fundamental interactions

- Continue strong support for the above facilities.
- Continue funding of innovative work by university groups.
- Continue development of traps and cold beams to improve sensitivity and accuracy.
- Strongly support theoretical research groups working in this area.



NUCLEAR SCIENCE PLAYS A SIGNIFICANT ROLE IN MANY ASPECTS OF DAILY LIFE, FROM HEALTHCARE TO AIRPORT SECURITY. FURTHER ADVANCES BENEFITTING SOCIETY DEPEND ON CONTINUING INVESTIGATION INTO THE PROPERTIES OF NUCLEI AND THE ADVANCED TECHNOLOGIES INTRINSIC TO NUCLEAR PHYSICS RESEARCH.

APPLICATIONS AND SOCIETAL BENEFITS



HEALTH One of the most exciting developments is the use of carefully shaped hadron beams (protons and heavier ions) to kill cancer cells. Proton therapy is already well-established, while carbon-ion therapy is also now being taken forward in several

European centres. The precision in dose delivery makes hadron

therapy ideal for treating resistant tumours in sensitive tissues. Other candidates for therapy, such as oxygen and helium ions, are also being studied.

Diagnostic imaging using injected radioactive tracers is a well-established clinical procedure. Improved imaging methods are continually being explored, together with new isotopes giving better resolution, and advanced ion-beam technology that can combine imaging and therapy.

A huge variety of radioisotopes are produced in nuclear facilities for injected therapeutic procedures. There is currently particular interest in highly targeted therapy combining isotopes with selected antibodies, and the development of pairs of isotopes of the same element that allow imaging and therapy to be carried out simultaneously – ‘theranostics’.

ENERGY Advanced nuclear energy offers the most effective solution to countering global warming, whether from next-generation fission or from future fusion reactors. Some of the most promising options include new fission-fuel cycles and accelerator driven systems (ADS) – subcritical systems driven by a proton beam that can be switched off at will. Encouragingly, the latter setup could be used to destroy radioactive waste. All these systems require data about nuclear reactions such as yields and decays, obtained at research facilities.

ENVIRONMENT A whole series of analytical techniques based on ion beams, or radio-tracers, are employed in many aspects of environmental studies – in particular, in gathering evidence of pollution and environmental changes such as ocean acidification or increases in radioactivity.

MATERIALS SCIENCE Similar techniques are also used to characterise new materials. Ion beams can also be deployed in fabrication processes involving surface modification such as nano-structuring or ion implantation.

SECURITY Terrorist attacks employing radioactive materials are of increasing concern, so sensitive and portable radiation detection systems (based on those used in nuclear research) are essential in border control. A relatively new nuclear technique, nuclear resonance fluorescence, is now being used to detect isotopes in materials relevant to nuclear security.



HERITAGE SCIENCE Ion-beam techniques provide a host of methods for determining the elemental composition of delicate artefacts and paintings non-destructively, while neutron radiography generates 3D images revealing the inner structure and composition of objects.

European facilities with a role in applications development

- RIB and neutron facilities will carry out a wide range of programmes relevant to applications including measurements for nuclear data libraries and isotopes.
- The MYRRHA reactor at SCK•CEN is a demonstration ADS.
- The ITER fusion test device being constructed in Caderache, France, will generate fusion energy over a sustained period.
- Low-energy facilities such as the LABEC laboratory in Florence, and the AGLAE laboratory at the Louvre, Paris, carry analytical work relevant to environmental analysis and heritage science.
- FAIR will provide unique opportunities for materials and biophysics research with heavy ions.
- A number of European laboratories are actively pursuing R&D in the application of various kinds of hadron therapy.

Recommendations for applications development

- Promote access to large-scale facilities, and support small and dedicated facilities.
- Continue to develop new clinical techniques such as theranostics.
- Develop compact systems for medical radioisotope production.
- Develop and disseminate accurate nuclear data for nuclear-energy generation.
- Promote expertise in areas with potential applications.
- Strengthen communications between the nuclear physics community and end-users.

RECOMMENDATIONS



FOR MORE INFORMATION CONTACT:

NUPECC

Professor Angela Bracco
The NuPECC Chair
 Università degli Studi
 Dipartimento di Fisica and INFN sez.
 via Celoria 16, 20133 Milano Italy
Tel: (39) 02 50317252
Email: bracco@mi.infn.it

Dr Gabriele-Elisabeth Körner
The NuPECC Scientific Secretary
 c/o Physik-Department E 12
 Technische Universität München
 85748 Garching Germany
Tel: (49) 89 2891 2293
Mob: (49) 172 89 15 011
Email: sissy.koerner@ph.tum.de
www.nupecc.org

**EUROPEAN
SCIENCE
FOUNDATION**

EUROPEAN SCIENCE FOUNDATION

Science and Support Office
 European Science Foundation
 1 quai Lezay-Marnésia, BP 90015
 67080 Strasbourg cedex France
Tel: (33) 388 767 100 (reception)
Fax: (33) 38 837 0532
www.esf.org