EURONS

A new European initiative for nuclear structure research

We still know little about the many exotic nuclei that could exist. To study their structure and behaviour, they must be made in laboratory experiments. This requires large accelerators which fire beams of nuclear particles at high speeds at a target, or at each other. The impact leads to reactions in which nucleons are rearranged and emerge as different nuclei, most of them exotic species. These are collected and, after selection, used in various experiments to study their properties.

Such facilities are complex and large, housing sophisticated equipment. They are, therefore, challenging to build and require effort to maintain. Furthermore, no one facility can accommodate the requirements of every experimental programme, so a variety of accelerators is needed.

A joint European effort

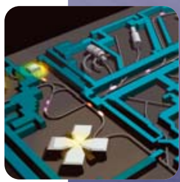
Europe has a strong tradition in nuclear research which has been carried out largely at independent, nationally-run accelerator complexes in different countries. To maximise opportunities for tackling future scientific and technological challenges, the European nuclear structure community has come together to set up a more coordinated framework for research.

The initiative, EURONS – a so-called Integrated Infrastructure Initiative – involves a consortium of nuclear structure scientists from 45 laboratories in 21 countries. Supported by the EU, it comprises three strands:

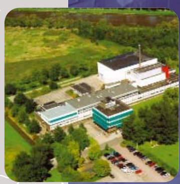
- **Transnational access (TNA) to the facilities**
  Universal access to seven world-class facilities offering complementary experimental resources and strengths, and also one centre for theoretical physics.
- **Joint Research Activities (JRA)**
  Eleven JRAs set up to identify, realise and coordinate the necessary technology development, such as new instruments for improving research infrastructures for particular scientific goals. JRAs involve more than one facility and rely on strong participation of European university groups.
- **Networks (N)**
  Eight networks to coordinate the strategy, including managing the consortium, fostering future collaborations, pooling of resources, broad dissemination of results, promotion of integration of researchers from the new EU member and candidate countries.

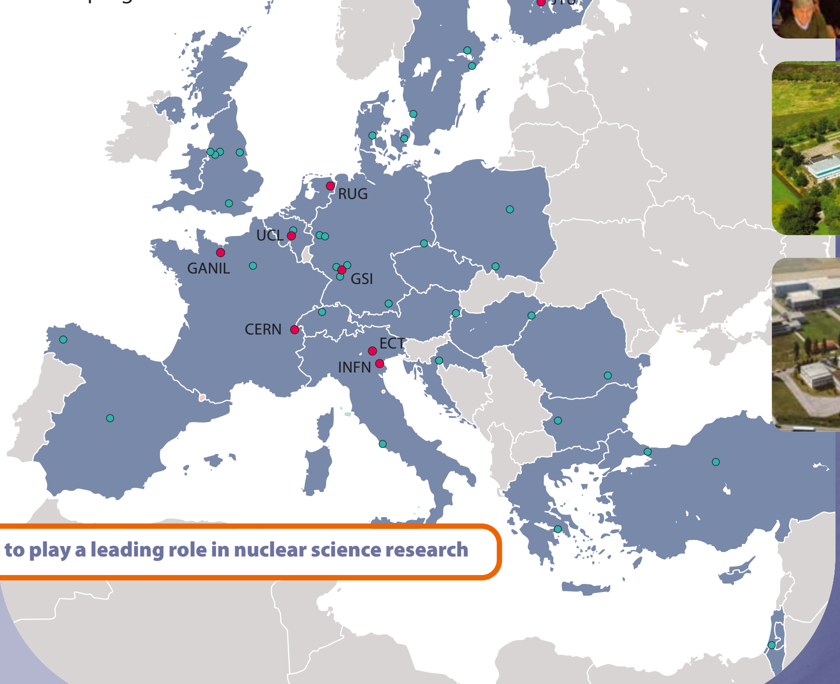
Management structure

EURONS is run by a scientific committee consisting of the coordinators of all activities (TNA, JRA, Networks) and the EURONS management, as well as by an administrative general assembly consisting of one representative from each participating laboratory which ensures feedback to the community and monitors the overall progress.





Europe will continue to play a leading role in nuclear science research

EURONS Networks

EURONS strategies and policies are carried out via eight Networks

- CARINA – *Challenges and Advanced Research in Nuclear Astrophysics*
  Aim: To provide harmonised research in nuclear astrophysics in Europe, identifying the key areas for study, and providing guidance on the optimal development and use of facilities.
- GAMMAPOOL – *Coordination of resources for gamma-ray spectroscopy in Europe*
  Aim: To provide the coordination of the European resources used for high-resolution gamma-ray spectroscopy, particularly for studies of nuclei under extreme conditions.
- EWON – *East-West Outreach – European Nuclear Physics Network*
  Aim: To strengthen links with nuclear physics communities in Eastern Europe, evaluating their scientific potential and perspectives for integration into the European Research Area.
- NuPECC – *Nuclear Physics European Collaboration Committee*
  Aim: To prepare a new Long-Range Plan for research in nuclear physics in Europe, which aims to provide a guideline for future developments.
- PANSI3 – *Enhanced Dissemination of Information on Nuclear Research within* EURONS
  Aim: To encourage public awareness of significant research achievements carried out within EURONS.
- SHE – *Super Heavy Elements Network*
  Aim: To coordinate research into the physics and chemistry of transfermium elements with atomic numbers above 100, and to disseminate information on superheavy elements.
- TNET – *Theory Network for Nuclear Structure and Reactions*
  Aim: To bring together theorists to focus on specific topics in nuclear structure and reaction physics, so as to provide the understanding needed to interpret results from future experiments.
- MANET – *Management Network*
  Aim: To coordinate all technical, scientific, financial, administrative, contractual and legal activities of the EURONS project.

The EURONS PANSI3 team

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MATTER AT EXTREMES

Nuclear structure research in Europe

EURONS

Inside the atomic world

Nuclear matter exists in a wide range of structural forms

All the visible matter in the Universe, including ourselves, consists largely of atomic nuclei – minute building blocks composed of positively charged protons and neutral neutrons (nucleons). The number of protons in a nucleus characterises each of the elements in the Periodic Table – from hydrogen with one proton to uranium with atomic number 92. Nuclei are usually enveloped in an equal number of negatively charged electrons to form atoms whose structure determines the chemical behaviour of elements.

The number of neutrons for each element, however, can vary – giving rise to a plethora of nuclear varieties, each with a different mass, called isotopes. Nuclear scientists estimate that protons can combine with neutrons to give up to 7000 different nuclei; however, only about 300 are stable.

What determines nuclear stability?

Nucleons are bound in a nucleus by the strong force. In addition, they also interact via two other fundamental forces, the weak and electromagnetic forces. All the forces obey the laws of quantum mechanics.

These forces coerce the nucleons into shell-like arrangements such that those nuclei with a full outer shell are the most stable. As nuclei get heavier, a higher proportion of neutrons is needed to keep them glued together.

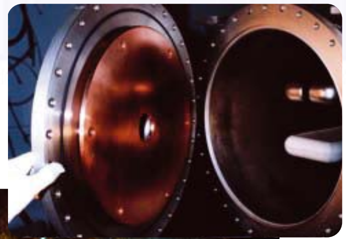
Why is nuclear structure important?

Because the nucleons interact in a complicated way, nuclei possess a rich and fascinating structural diversity, which provides a powerful probe of the fundamental forces. They also offer an ideal laboratory for studying complex self-organising quantum systems.

Perhaps most important, understanding nuclear structure and stability throws light on why the Universe looks the way it does today. The elements are made in nuclear reactions that power stars. These processes are thought to involve exotic nuclei with unusual ratios of protons and neutrons.

Finally, unstable nuclei do have applications as analytical tools and as agents in cancer radio-therapy . Exotic nuclei with unusual structures occur in various processes of present and future forms of power production, and a detailed knowledge of nuclear structure may be exploited one day for increased efficiency and improved safety.

A device using electric and magnetic fields to select particular superheavy nuclei in experiments at GANIL



NASA/ ESA/ J. Hester and A. Loll (Arizona State University)

The Crab supernova remnant. The heavier elements are made and spread through space via supernova explosions

Radioactivity

Unstable nuclei disintegrate in a variety of ways:

- A nucleus may spit out a fragment of two protons and two neutrons (a helium nucleus, or alpha radiation), transmuting itself into the nucleus of an element two atomic numbers lower in the Periodic Table.
- One of the component neutrons may transform into a proton, to give a nucleus one atomic number higher, while releasing an electron (beta radiation) and an antineutrino.
- High-energy electromagnetic radiation (gamma-radiation) is also emitted.
- Very heavy nuclei may simply break apart into lighter nuclei (nuclear fission).

Origin of ancient gold

A knowledge of nuclear energy levels is necessary for an analytical technique called Micro Proton Induced X-ray Emission. This is used to identify trace elements which act as a provenance fingerprint for a material. For example, these Bronze-Age Transylvanian coins were shown to be made from local Carpathian gold

The outer limits

Exploring the frontiers of stability

Protons and neutrons can bind in nuclei in many different combinations, of which only a few are stable, as shown on the nuclear landscape (below). Future experiments aim to probe the stability and structure of nuclei with extreme ratios of protons and neutrons, and with the highest possible numbers of nucleons. In this way, researchers hope to gain a better understanding of the forces that govern the evolution and behaviour of matter.

Research topics to be tackled

When is a magic number no longer magic?
Nuclei with particular numbers of neutrons and protons are exceptionally stable (2, 8, 20, 28, 50, 82). These 'magic numbers' indicate that the nucleons are arranged in closed shells. The magic numbers are well established in stable and near stable nuclei. However, adding neutrons to create heavier isotopes appears to alter the magic numbers. These nuclei are thus of great interest but are difficult to build up.

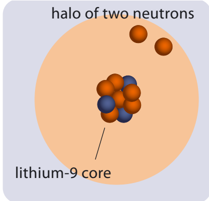
Nuclei with neutron halos or skins
Nuclei with large proportions of neutrons may literally be inflated. In some neutron-rich light nuclei, the outer neutrons are only just hanging on, creating an extended neutron 'halo'. Heavier neutron-rich nuclei may have a low-density neutron 'skin'.

Mirror nuclei
The strong force acts on protons and neutrons in the same way, so we would expect that pairs of nuclei, of which one has the numbers of protons and neutrons reversed, would have identical structures. However, the proton is also affected by the electromagnetic force, resulting in changes that provide insight into the complexities and limits of nuclear binding.

The many shapes of nuclei
While magic nuclei tend to be spherical, some heavier nuclei will settle into a different shape, perhaps flattened or elongated, in order to increase their stability. Thus the nucleons may arrange themselves into modified shell structures with new magic numbers.

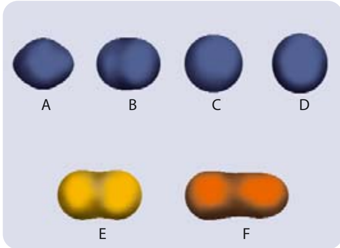
How heavy can a nucleus be?
Although elements with atomic numbers higher than 92 (the proton number) are not stable, theorists have suggested that a range of nuclei starting at 114 protons and 184 neutrons – doubly magic numbers – could be quite long-lived if made.

How are the elements made in Nature?
The elements in our Universe are made in stars by various nuclear reactions. Of key interest are the processes, triggered in supernova explosions, which create the heaviest elements. They are thought to involve highly neutron-rich and proton-rich nuclear species, yet to be studied on Earth.



LAND collaboration/GSI

Lithium-11 is a much-studied neutron halo nucleus – with a lithium-9 (three protons and six neutrons) core surrounded by a halo of two neutrons. However, there are heavier halo nuclei waiting to be explored



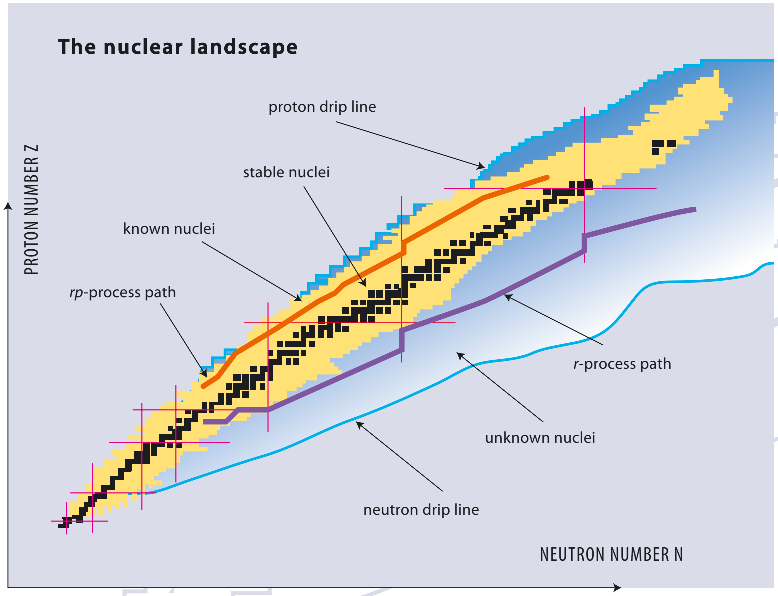
LANL

A Samarium-154
B Tungsten-186
C Lead-208
D Platinum-190

E Plutonium-240
F Thorium-232

Nuclei may adopt different shapes to achieve their minimum energy. Sometimes more than one shape, or isomer, is possible for a particular nucleus

The nuclear landscape
The stability of nuclei can be mapped according to proton and neutron number. The black area indicates the stable nuclei. The yellow indicates the known nuclei. The regions marked in blue show the nuclei that could exist, with the frontiers known as driplines marking the maximum and minimum ratios of protons to neutrons possible. The red and purple lines show the reaction paths (*rp* and *r* processes) by which elements are built up in supernovae



A transnational network of facilities

Many of the major discoveries about the atomic nucleus and its structure have been made in European laboratories

To make full use of complementary strengths of European facilities – equipment and expertise – scientists from across Europe can now benefit from the access to the entire facility network supported by the European Community.

- INFN-LNL *(Legnaro National Laboratory/ National Institute of Nuclear Physics, Legnaro, Italy)* has four accelerators which generate ion beams, and state-of-the-art instruments for experiments on exotic species such as highly deformed nuclei.

- JYU-JYFL *(University of Jyväskylä, Department of Physics Accelerator Laboratory, Jyväskylä, Finland)* offers stable ion beams and special instruments for research into exotic nuclei under a wide variety of experimental conditions.

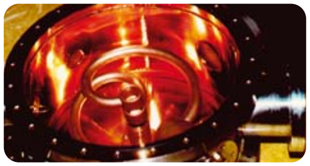
- RUG-KVI *(Kernfysisch Versneller Instituut , University of Groningen, Netherlands)* has the superconducting cyclotron AGOR for the delivery of light and heavy ions to study nuclear structure at low and high excitation energies, which is of importance for astrophysics.

- GSI *(Gesellschaft für Schwerionenforschung, Darmstadt, Germany)* provides high-energy beams of stable and unstable ions up to uranium. The laboratory is famous for making superheavy elements and for developing ion tumour therapy.

- UCL/CRC *(Cyclotron Research Centre, Université Catholique de Louvain, Louvain-la-Neuve, Belgium)* offers high-intensity, low-energy beams of radioactive and stable ions for studying exotic nuclei, in particular those of astrophysical importance.

- GANIL *(Grand Accelerator National d'Ions Lourds, Caen, France)* provides high-energy and high-intensity beams for stable ions – from carbon to uranium. It uniquely provides rare isotope beams using both of the two main methods of production to investigate the unknown territory of the nuclear chart.

- CERN-ISOLDE *(European Organisation for Nuclear Research, Geneva, Switzerland)* is based at the world's largest high-energy laboratory, and is dedicated to the production of radioactive ion beams for experiments on exotic nuclear structure.



- ECT* *(The European Centre for Theoretical Studies in Nuclear Physics and Related Areas, Trento, Italy)* carries out research on nuclear structure theory and fosters links between theorists and experimentalists.

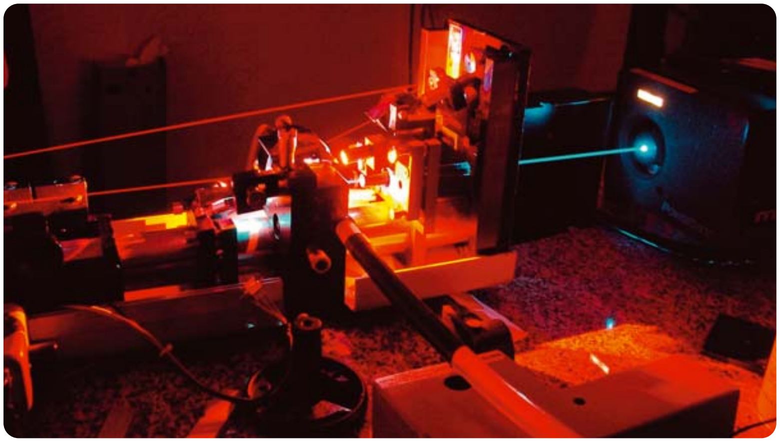
How do you investigate the nucleus?

Nuclear structure experiments require beams of fast-moving atoms which have been stripped of electrons to produce charged ions. They can be accelerated, and then collided with a target to generate further, secondary beams of stable and unstable nuclei.

Experiments involve measuring the masses of the nuclei made, their lifetimes, modes of decay, and also the energy spectra of the gamma-radiation and decay particles produced. Experiments may involve collisions with further nuclear beams, and the use of lasers to measure nuclear energy levels.

Exploring the nuclear landscape

Investigating nuclei at the frontiers of stability has revealed some fascinating effects



Laser studies at CERN-ISOLDE on magic nuclei

Changing magic numbers

Adding extra neutrons to a nucleus can probe how and why magic numbers change. Researchers at CERN-ISOLDE recently created magnesium-33 which has seven more neutrons than the heaviest stable isotope. Laser studies showed that the excess neutrons tend to sit in the outer nuclear orbits. Experiments at other laboratories like LNL, GANIL and GSI have investigated dozens of these fascinating neutron-rich nuclei. They include iron-66 with eight more neutrons than the heaviest stable isotope, and gallium-82 which has eleven more than its heaviest stable relative.

Bloated with neutrons

The heaviest – and weirdest – isotope of hydrogen with one proton and *six* neutrons has been made at GANIL by smashing a beam of exotic helium-8 ions (with six neutrons) into a detector containing isobutane gas (a carbon-rich target). Helium-8 is a halo nucleus made in GANIL's radioactive beam facility SPIRAL.

Breaking the nuclear mirror

Recent studies at LNL compared the energy-level schemes of two mirror nuclei, sulphur-31 (16 protons and 15 neutrons) and phosphorus-31 (15 protons and 16 neutrons). It was observed that these nuclei, with interchanged proton and neutron numbers, show a difference in the decay patterns which indicates that the mirror symmetry is broken.

Nuclear shape-shifters

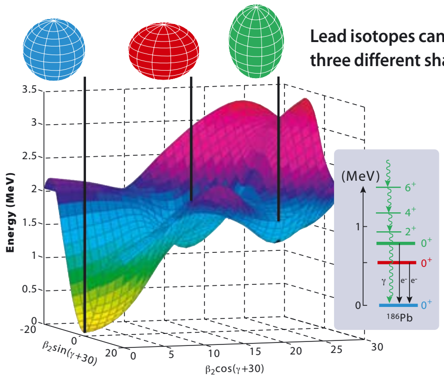
Nuclei may change shape when given some extra energy. One magic nucleus, lead-186 (82 protons), is normally spherical, but can also adopt either a pumpkin or melon shape. Recently, a collaboration at JYFL studied polonium nuclei which have a similar number of neutrons. Needing just a tiny amount of energy to change shape, these special nuclei can easily choose between three different kinds of quantum structures.

Superheavy *and* doubly magic

In 2006, an international team at GSI made four atoms of a new superheavy isotope, hassium-270 (108 protons) by smashing magnesium-26 ions at high speed into a target of curium-248. Hassium-270 is unusually long-lived and is thought to be doubly magic.

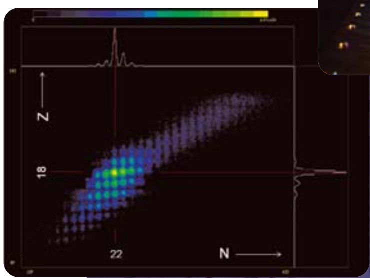
Element formation in supernovae

Measurements of key nuclear reactions, usually involving short-lived nuclei, are needed to improve our understanding of the build-up of elements in supernovae. Reactions in which protons or deuterons (one proton and one neutron) are fired at a target, causing a neutron in a target nucleus to change into a proton, or the capture of two neutrons from the nucleus by a proton projectile, have been performed at KVI and UCL/CRC with unprecedented precision.



Lead isotopes can adopt three different shapes

GSI's COMPACT detector used in experiments making superheavy elements



Plot showing the production of isotopes by the collision of argon-40 ions impinging with an energy of 252 MeV on a lead-208 target at LNL

Joint Research Activities

A fundamental aim of EURONS is to identify and develop new technologies and techniques for improving nuclear structure research infrastructures

New sources of radioactive charged ions to make exotic nuclei

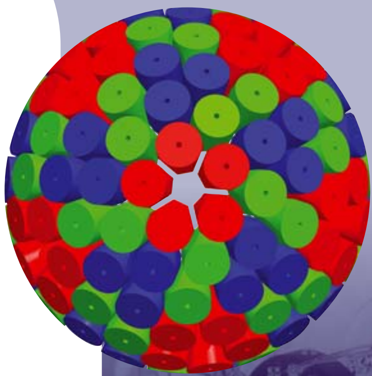
- ISIBHI – *Ion Sources for Intense Beams of Heavy Ions*
  The next generation of intense heavy ion beams requires new ion sources. The goal is to improve the flux of ions and the variety of isotopes available for acceleration.
- Advanced charged breeding
  New methods for creating exotic isotopes as highly charged ions (by stripping electrons from the atoms) are under study, which allow for precision experiments at low beam energies and further acceleration in compact accelerators.
- LASER – *Laser techniques for Exotic Nuclei Research*
  Lasers are used in radioactive ion beam sources to ionise the atoms, and also to measure atomic energy levels. Systems are being designed to select target nuclei, and to tailor and evaluate their properties.

New particle and radiation detectors

- INTAG – *Instrumentation for Tagging*
  New methods are being developed for identifying heavy nuclei from their mass and atomic number. These include hi-tech separators for sorting out different nuclei and detectors for identification.
- DLEP – *Detection of Low Energy Particles from Exotic Decays*
  Nuclei may decay at low energies by emitting neutrons and light charged particles. New detectors, combined with advanced electronic and computer methods, are being developed to detect and identify the particles.
- AGATA – *Advanced Gamma Tracking Array*
  Measuring the energies of gamma-rays produced in the reactions of nuclei is an essential probe of their structure. A spherical spectrometer capable of measuring the faintest emission of gamma-rays is being developed. Position-sensitive germanium detectors enable the paths of individual gamma-rays to be tracked.

- TRAPSPEC – *Ion traps, spectrometers and detectors*
  Exotic nuclei can be studied by capturing them in magnetic devices. New technologies are being developed to slow down and stop fast-moving nuclei in order to measure their masses and spectra.

- SAFERIB – *Radiation Protection Issues related to Radioactive Ion Beam Facilities*
  Targets producing radioactive beams must conform with European safety standards. Radiation protection issues for existing and future facilities are being addressed through a coordinated strategy.



The AGATA array

Reactions between exotic heavy nuclei and light-weight nuclear targets

- EXL – *Exotic Nuclei studied with Light Hadronic Probes*
  Unstable heavy nuclei can be studied by accumulating them in a special storage ring and colliding them with targets of light ions. Improved preparation methods and detection systems are being explored.
- RHIB – *Reactions with High-Intensity Beams of Exotic Nuclei*
  Reactions with high-energy, rare-isotope beams are a powerful tool for nuclear astrophysics, and for investigating properties of neutron-rich nuclei and nuclear matter. Advanced experimental instrumentation is developed for pushing the limits of this method towards heavier nuclei and also more complex reactions.
- ACTAR – *Active target detectors for the Study of Extremely Exotic Nuclei using Direct Reactions*
  Experiments creating rare exotic nuclei are expected to benefit from the development of a highly novel system containing a gas (helium) that acts as both target and detector.

Addressing radiation protection

EXL detector component