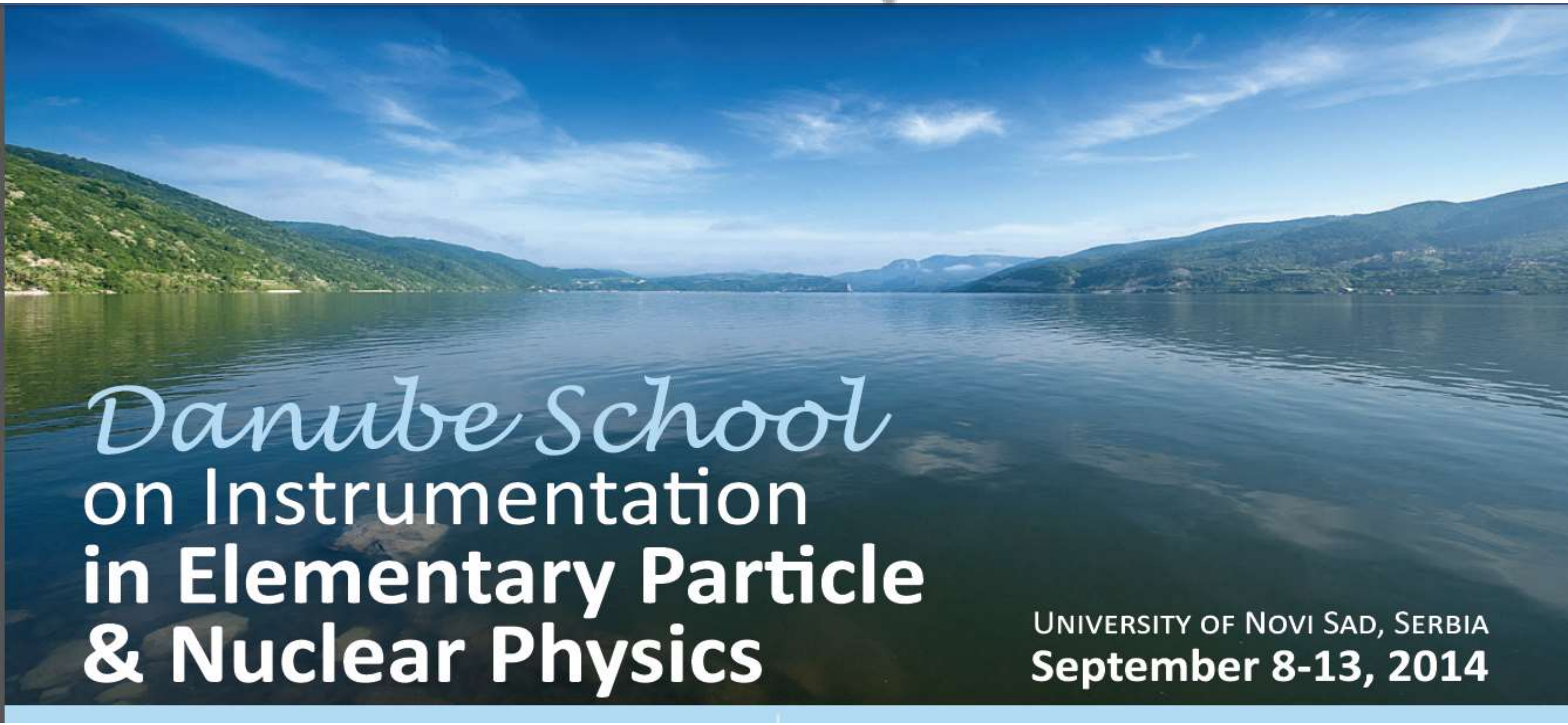
Nuclear Physics



Prof. Miroslav Vesković, Ph.D. **Jovana Nikolov, Ph.D**

Department of Phyiscs, Faculty of Sciences
University of Novi Sad, Serbia

PHYSICS 2010

Nuclear Physics

Exploring the Heart of Matter

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

Nuclear Physics: Exploring the Heart of Matter

The Committee on the Assessment of and Outlook for Nuclear Physics;

Board on Physics and Astronomy; Division on Engineering and Physical Sciences; National Research Council

EUROPEAN
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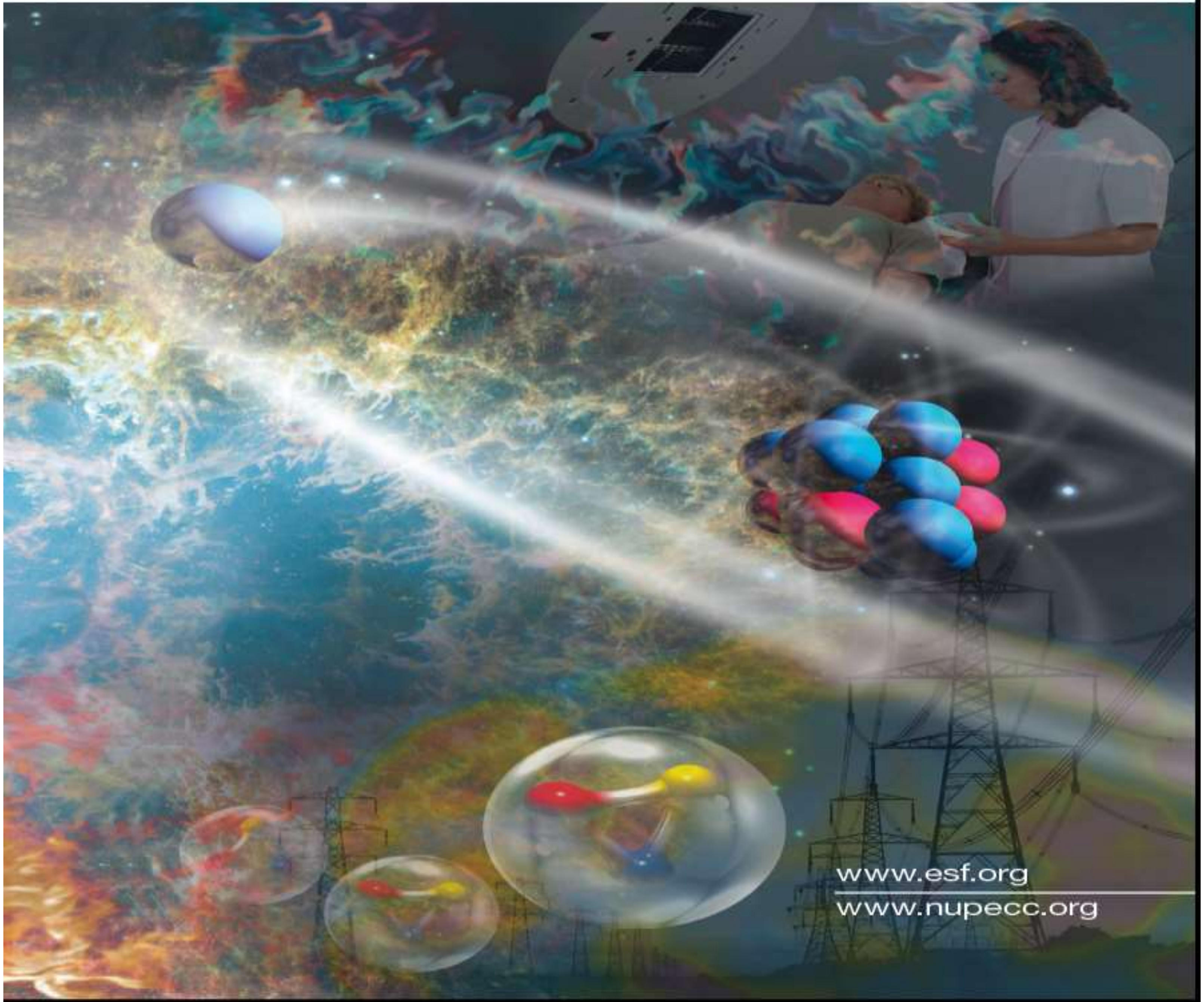
FOUNDATION
SETTING SCIENCE AGENDAS FOR EUROPE

FORWARD LOOK

Perspectives of Nuclear Physics in Europe

NuPECC Long Range Plan 2010

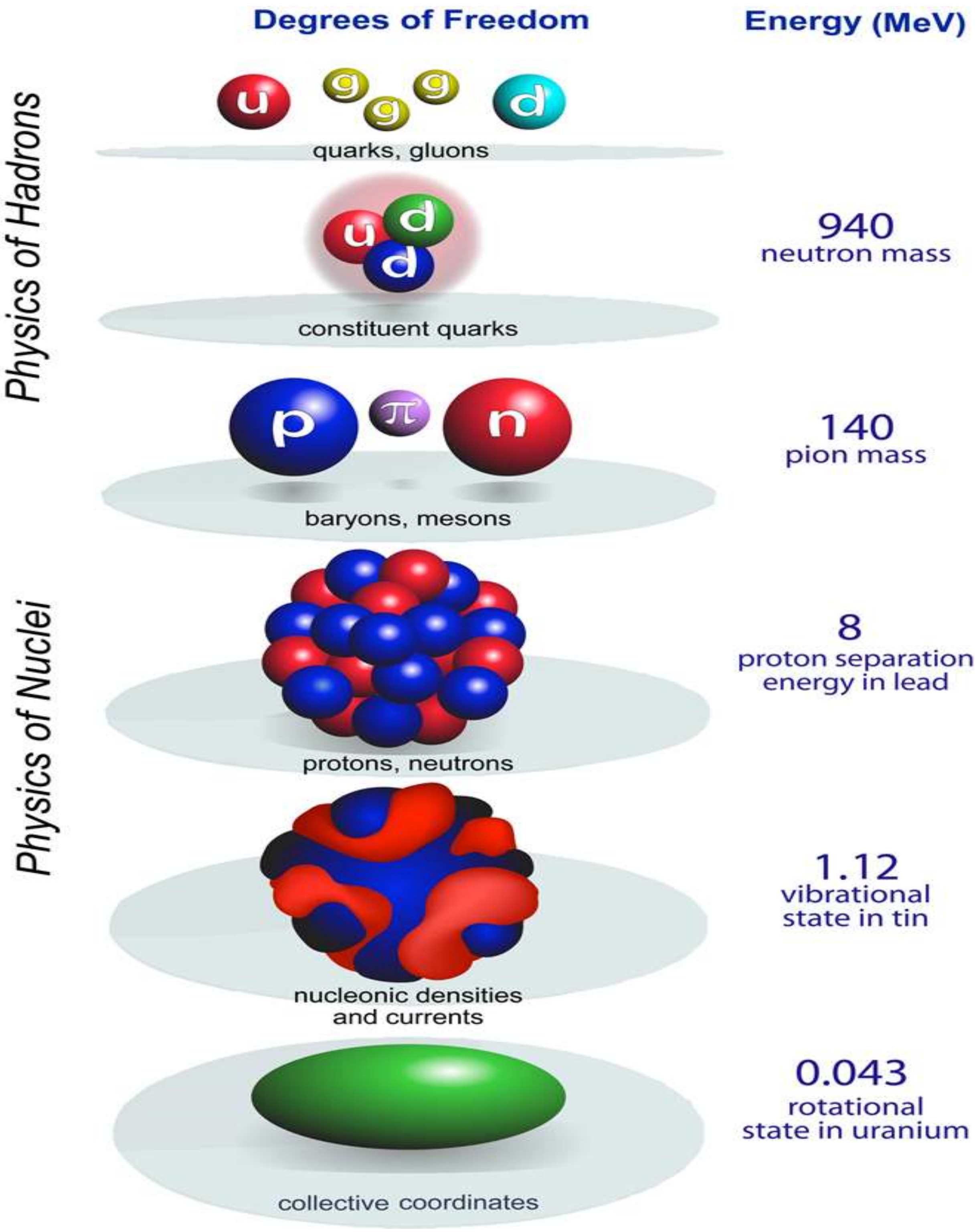


www.esf.org
www.nupecc.org

Perspectives of Nuclear Physics in Europe

NuPECC Long Range Plan 2010

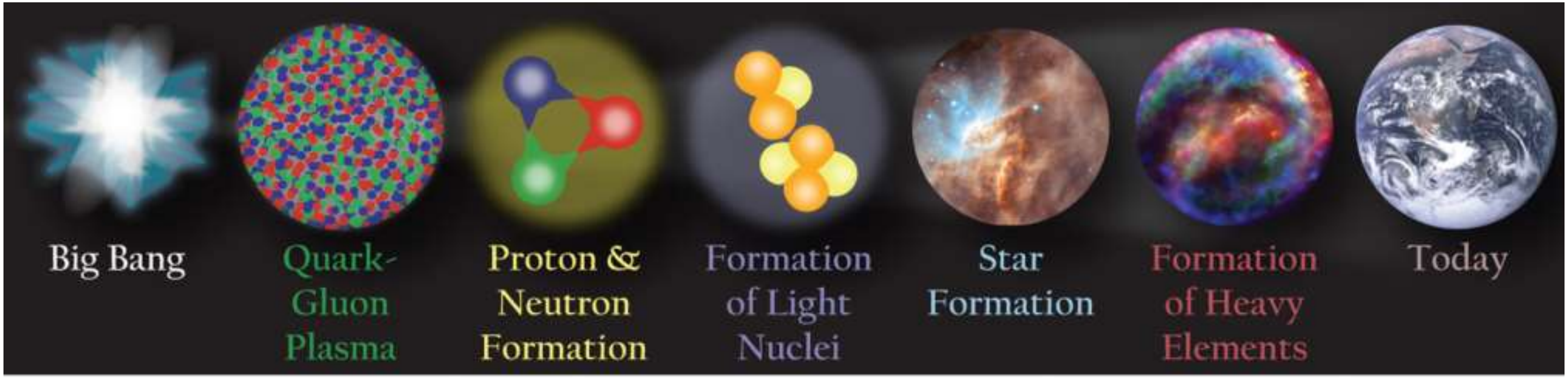
The Nuclear Physics European Collaboration Committee (NuPECC) is an ***Expert Committee of the European Science Foundation***. The aim of NuPECC is to strengthen collaboration in nuclear science by promoting nuclear physics, and its trans-disciplinary use and application,


Degrees of Freedom
Energy (MeV)
Physics of Hadrons
Physics of Nuclei
u
g
g
g
d
quarks, gluons
u
d
d
constituent quarks
940
neutron mass
p
π
n
baryons, mesons
140
pion mass
protons, neutrons
8
proton separation energy in lead
nucleonic densities and currents
1.12
vibrational state in tin
collective coordinates
0.043
rotational state in uranium

Nuclear physics today is a diverse field, encompassing research that spans **dimensions from a tiny fraction of neutrons and protons in the atomic nucleus to the enormous scales of astrophysical objects** in the cosmos.

Its research objectives include the desire not only to better understand the nature of matter interacting at the nuclear level but to describe the liquid state of the Universe that existed at the big bang—a phenomenon that can now be replicated in the most advanced colliding-beam accelerators. ***Its discoveries impact other fields such as astrophysics, particle physics, and cosmology, while the tools developed by nuclear physicists not only are employed by other basic sciences but have found wide-spread applications in a range of technologies that benefit society.***

Nuclear physics in the universe



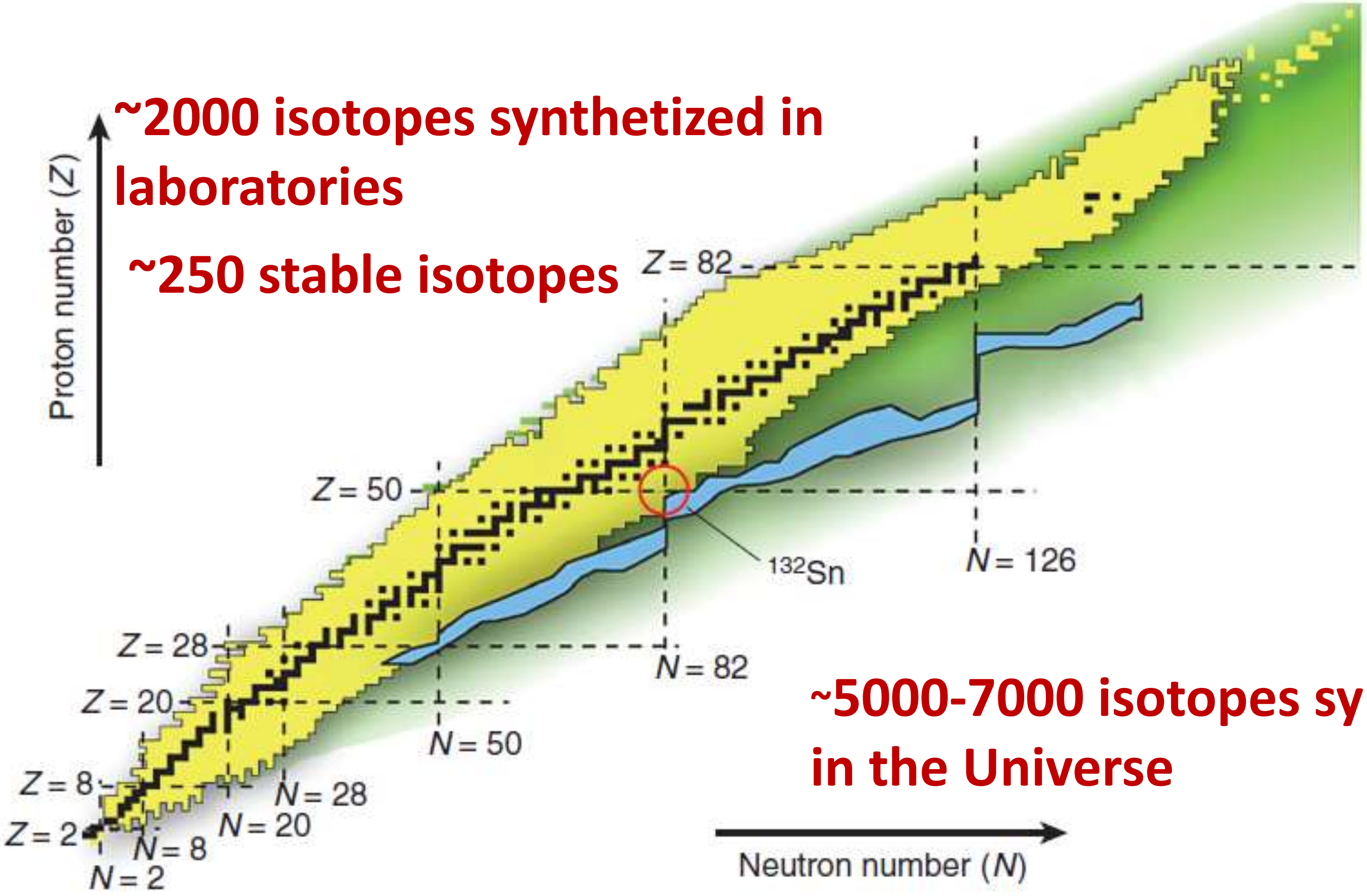
Over 99.9 percent of the mass of all the matter in all the living organisms, planets, and stars in all the galaxies throughout our universe comes from the nuclei found at the center of every atom. These nuclei are made of protons and neutrons that themselves formed a few microseconds after the big bang as the primordial liquid known as quark-gluon plasma cooled and condensed. The lightest nuclei (those at the centers of hydrogen, helium, and lithium atoms) formed minutes after the big bang. Other elements were formed later in nuclear reactions occurring deep within the early stars. Cataclysmic explosions of these early stars dispersed these heavy nuclei throughout the galaxy, so that as the solar system formed it contained nuclei of carbon, nitrogen, oxygen, silicon, iron, uranium, and many more elements, which ended up forming our planet and ourselves.

SOURCE: Adapted from the Nuclear Science Wall Chart, developed by the Nuclear Science Division of the Lawrence Berkeley National Laboratory and the Contemporary Physics Education Project. Available at http://www.lbl.gov/abc/wallchart/index.html. Last accessed on May 30, 2012. Star Formation image: NASA/ESA and the Hubble Heritage Team (AURA/STScI/HEIC); Formation of Heavy Elements image: NASA/ESA/JHU/R. Sankrit and W. Blair; Today image: NASA.

From quarks to neutron stars

- At the shortest distance scales, relativistic heavy ion collisions are used to study quark-gluon plasma and how protons and neutrons and other hadrons condense from it as it cools.
- Electron-scattering experiments are used to study the complex structure of those protons and neutrons, with varying spatial resolution.
- Rare isotope beams are used to understand the patterns and phenomena that emerge as protons and neutrons form larger and larger nuclei.
- Nuclear phenomena occur on truly macroscopic distance scales in stars, in the nuclear reactions that drive certain classes of cataclysmic stellar explosions and in the description of the structure, formation, and cooling of neutron stars, which are basically gigantic nuclei.

- SOURCE: Courtesy of Witold Nazarewicz, University of Tennessee.

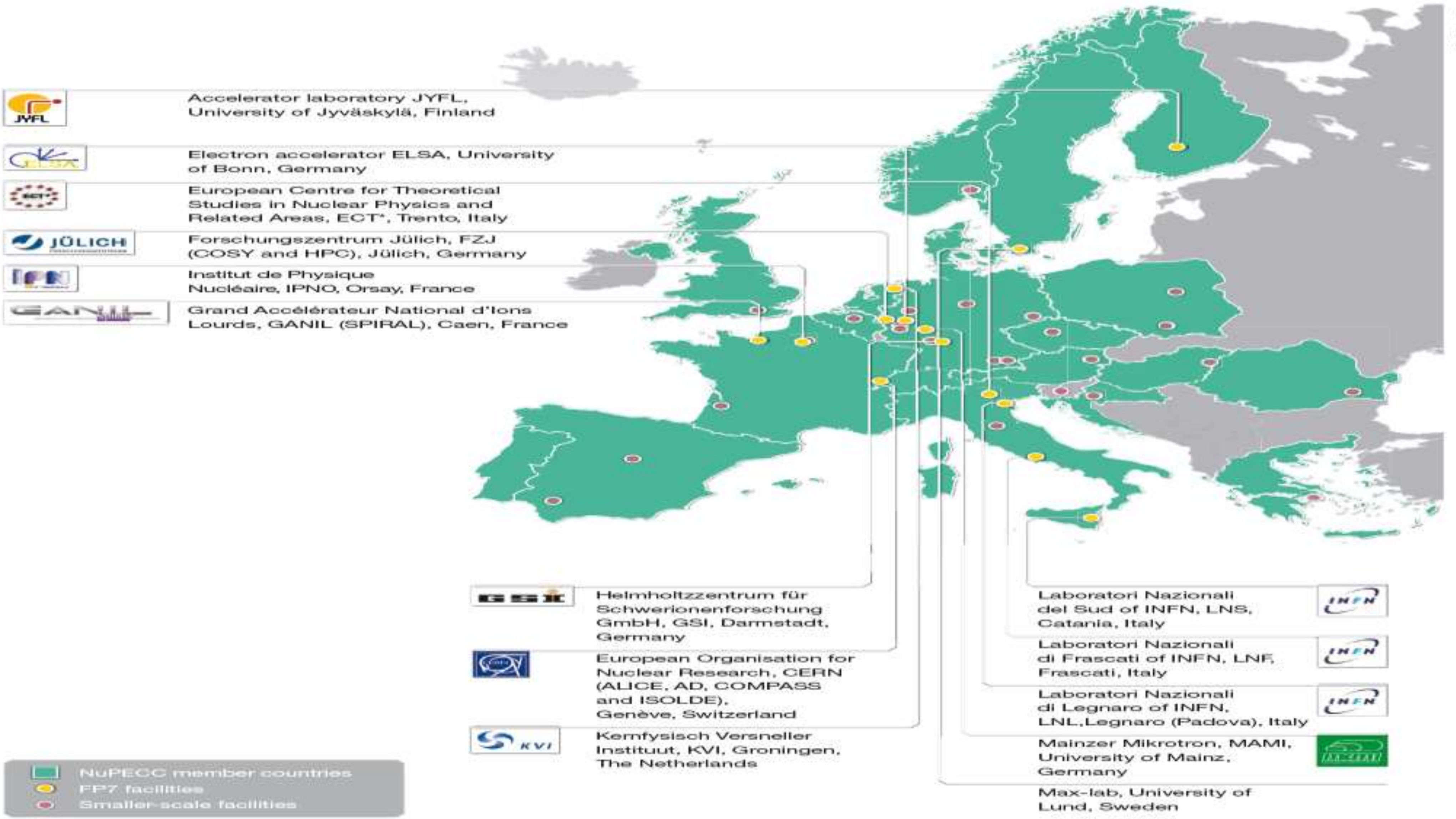


~2000 isotopes synthetized in laboratories

~250 stable isotopes

~5000-7000 isotopes synthetized in the Universe

Research Infrastructures,Networking and Upgrades



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

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

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

🟩 NuPECC member countries
🟡 FP7 facilities
🔴 Smaller-scale facilities

h2o-Creative

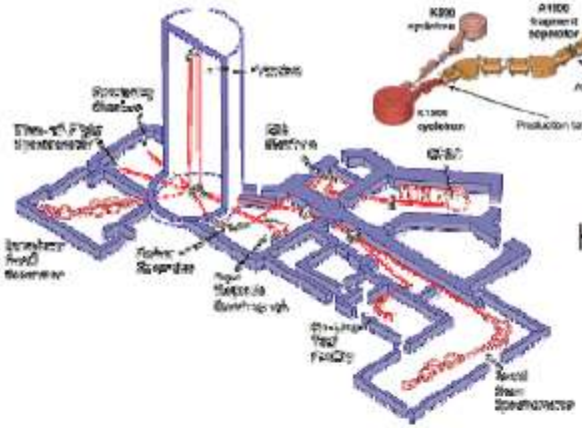
United States

5 midsize university facilities
FSU, ND, TUNL, UoW, Yale
2 large university facilities,
TAMU, NSCL/MSU
2 national laboratory facilities
ATLAS/ANL, HIBRF/ORNL

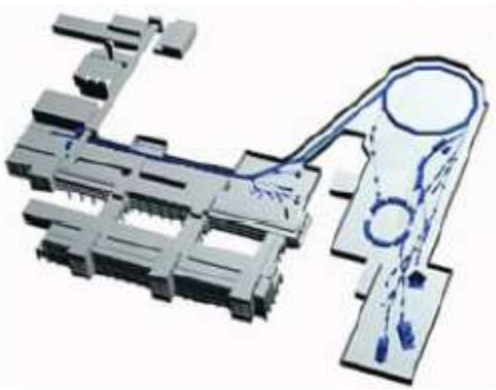
International Community

Several universities
GANIL, France
GSI, Germany
INFN Legnaro, Italy
i-Themba, South Africa
Lanzhou, China
RCNP Osaka, Japan
RIKEN, Japan
Saha Institute, India
ISAC TRIUMF, Canada

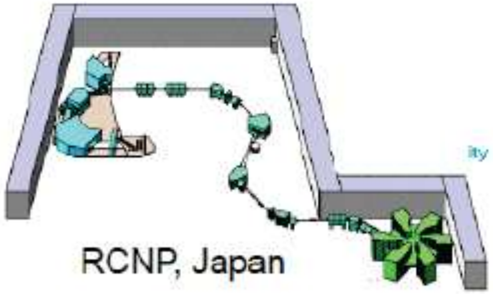
CCF/NSCL/MSU



HRIBF/ORNL



GSI, Germany



RCNP, Japan

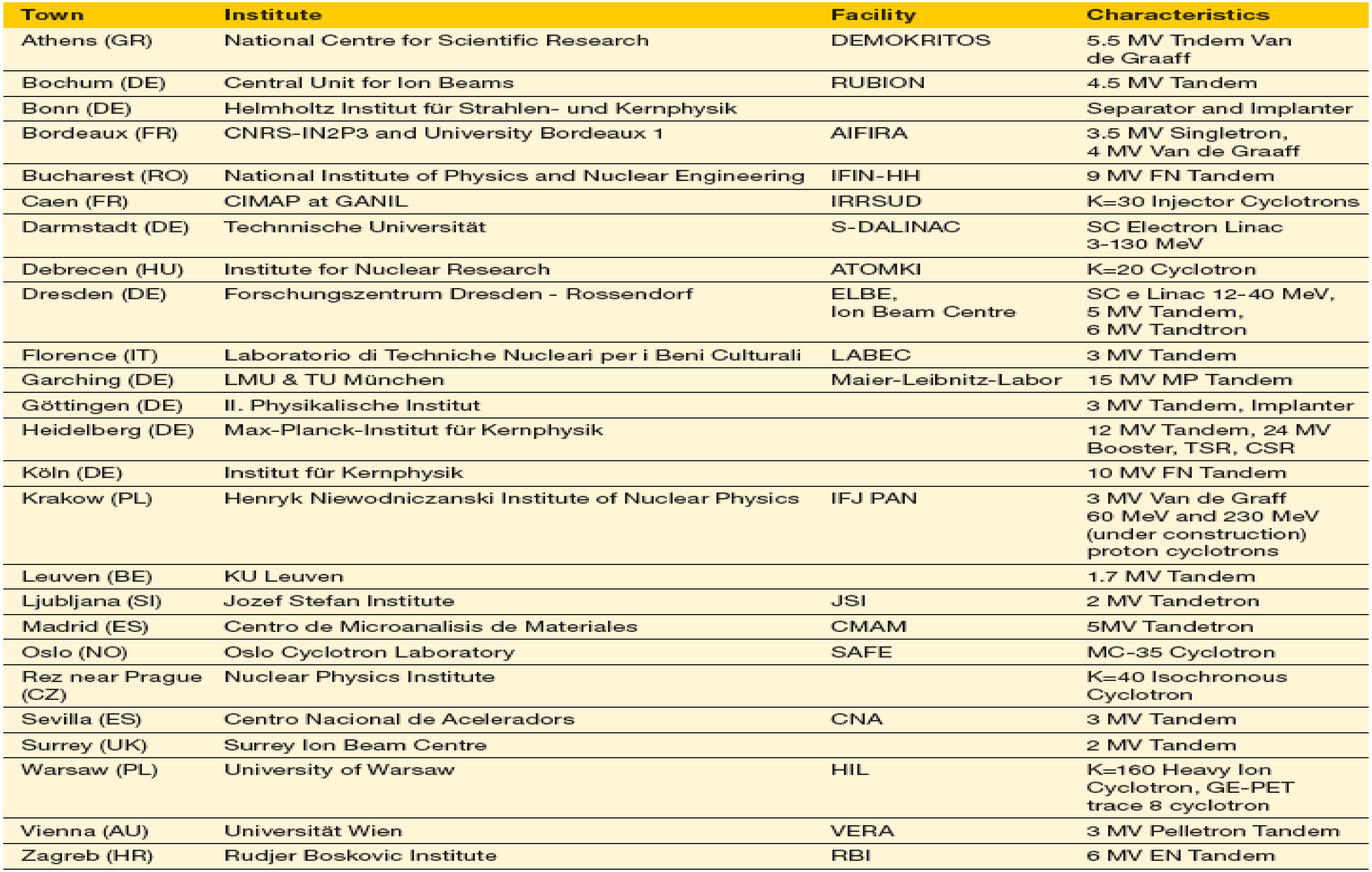
Lepton Beam Facilities

- MAX-lab, Lund, Sweden
- ELSA, Bonn, Germany
- MAMI, Mainz, Germany
- COMPASS at CERN, Geneva, Switzerland
- INFN-LNF, Frascati, Italy

Hadron Beam Facilities

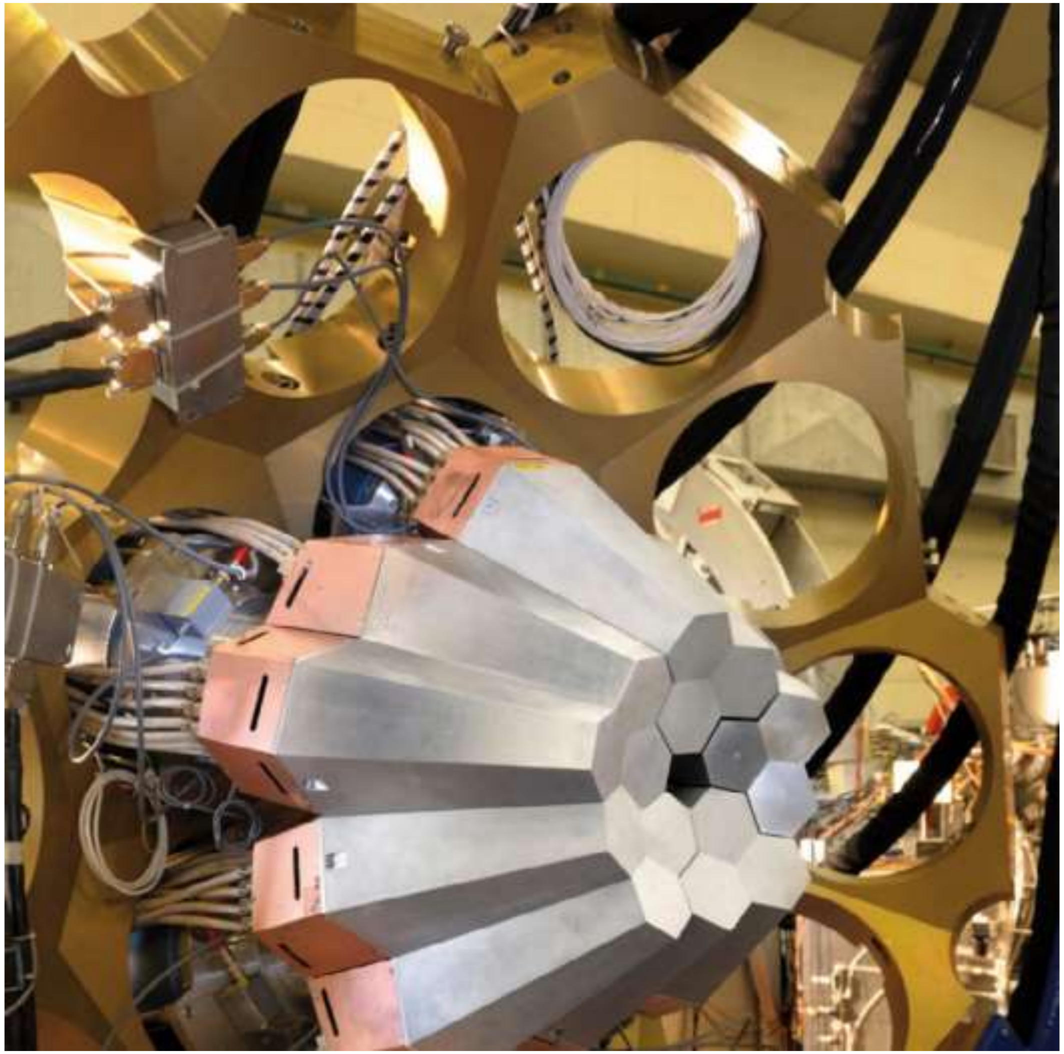
- JYFL, Jyväskylä, Finland
- KVI, Groningen, The Netherlands
- COSY at FZ Jülich, Germany
- GSI, Darmstadt, Germany
- GANIL, Caen, France
- IPN, Orsay, France
- ISOLDE at CERN, Geneva, Switzerland
- ALICE at CERN, Geneva, Switzerland
- Antiproton Decelerator AD at CERN,
- Geneva, Switzerland
- INFN-LNL, Legnaro, Italy
- INFN-LNS, Catania, Italy
- Neutron Facilities in Europe

Smaller-Scale Facilities



Town	Institute	Facility	Characteristics
Athens (GR)	National Centre for Scientific Research	DEMOKRITOS	5.5 MV Tndem Van de Graaff
Bochum (DE)	Central Unit for Ion Beams	RUBION	4.5 MV Tandem
Bonn (DE)	Helmholtz Institut für Strahlen- und Kernphysik		Separator and Implanter
Bordeaux (FR)	CNRS-IN2P3 and University Bordeaux 1	AIFIRA	3.5 MV Singletron, 4 MV Van de Graaff
Bucharest (RO)	National Institute of Physics and Nuclear Engineering	IFIN-HH	9 MV FN Tandem
Caen (FR)	CIMAP at GANIL	IRRSUD	K=30 Injector Cyclotrons
Darmstadt (DE)	Technnische Universität	S-DALINAC	SC Electron Linac 3-130 MeV
Debrecen (HU)	Institute for Nuclear Research	ATOMKI	K=20 Cyclotron
Dresden (DE)	Forschungszentrum Dresden - Rossendorf	ELBE, Ion Beam Centre	SC e Linac 12-40 MeV, 5 MV Tandem, 6 MV Tandtron
Florence (IT)	Laboratorio di Techniche Nucleari per i Beni Culturali	LABEC	3 MV Tandem
Garching (DE)	LMU & TU München	Maier-Leibnitz-Labor	15 MV MP Tandem
Göttingen (DE)	II. Physikalische Institut		3 MV Tandem, Implanter
Heidelberg (DE)	Max-Planck-Institut für Kernphysik		12 MV Tandem, 24 MV Booster, TSR, CSR
Köln (DE)	Institut für Kernphysik		10 MV FN Tandem
Krakow (PL)	Henryk Niewodniczanski Institute of Nuclear Physics	IFJ PAN	3 MV Van de Graff 60 MeV and 230 MeV (under construction) proton cyclotrons
Leuven (BE)	KU Leuven		1.7 MV Tandem
Ljubljana (SI)	Jozef Stefan Institute	JSI	2 MV Tandetron
Madrid (ES)	Centro de Microanalisis de Materiales	CMAM	5MV Tandetron
Oslo (NO)	Oslo Cyclotron Laboratory	SAFE	MC-35 Cyclotron
Rez near Prague (CZ)	Nuclear Physics Institute		K=40 Isochronous Cyclotron
Sevilla (ES)	Centro Nacional de Aceleradors	CNA	3 MV Tandem
Surrey (UK)	Surrey Ion Beam Centre		2 MV Tandem
Warsaw (PL)	University of Warsaw	HIL	K=160 Heavy Ion Cyclotron, GE-PET trace 8 cyclotron
Vienna (AU)	Universität Wien	VERA	3 MV Pelletron Tandem
Zagreb (HR)	Rudjer Boskovic Institute	RBI	6 MV EN Tandem

Travelling Detectors



The AGATA demonstrator mounted at INFL-LNL in Legnaro, Italy.

It is well established that experiments using complex arrays based on Germanium detectors (such as EUROBALL, EXOGAM, MINIBALL and RISING) have delivered important scientific results and developed new technical methods.

Theory and Computing

- ECT*, Trento, Italy;

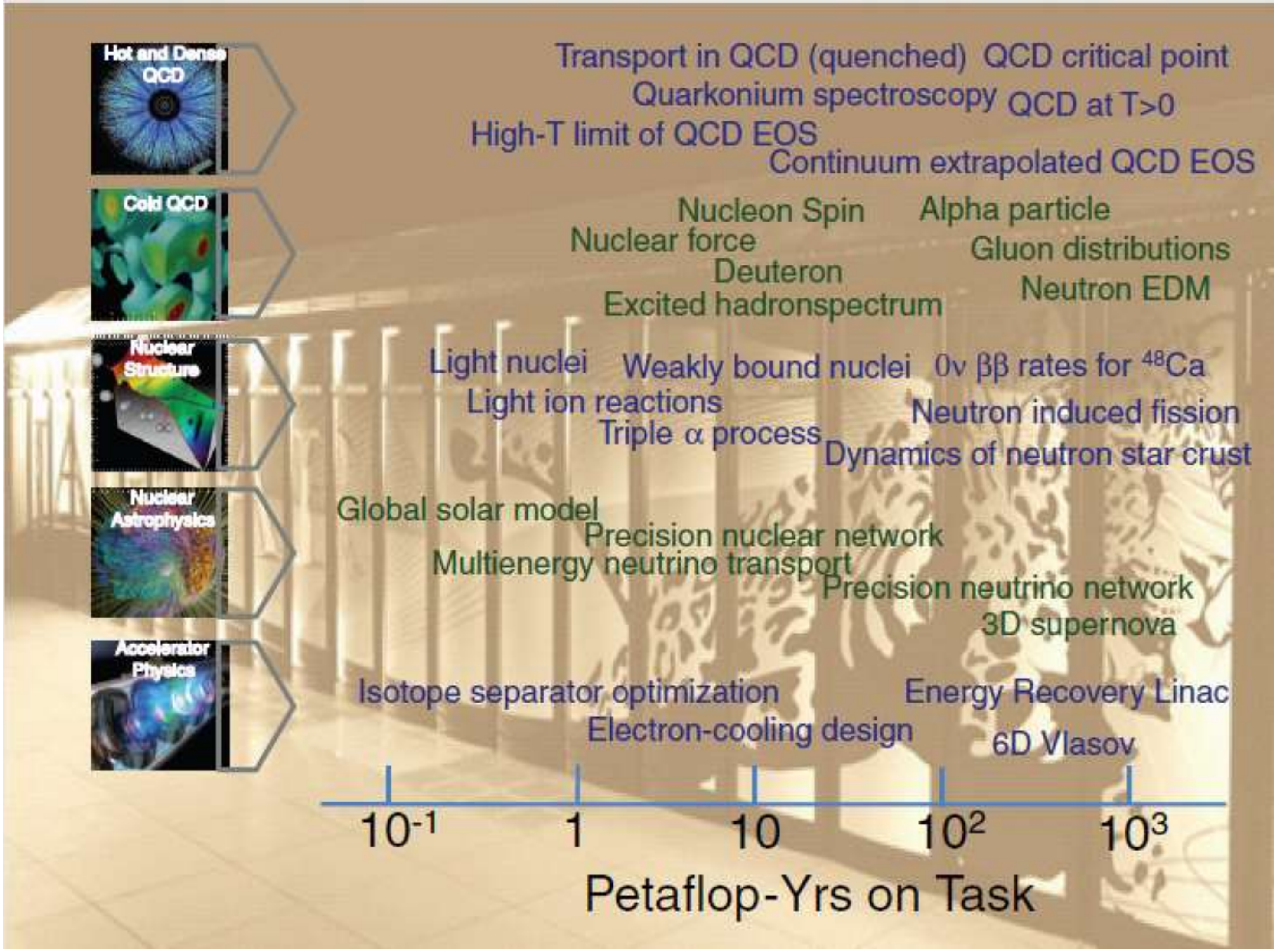
- Jülich Supercomputer Centre, Germany;

Box 2.3
High-Performance Computing in Nuclear Physics

One of the trends in science today is the increasingly important role played by computational science. Yesterday's terascale computers, capable of a trillion calculations per second, are being replaced by petascale computers, which are a thousand times faster, and scientists are even now working toward exascale computers, which will be a thousand times faster again (at a million trillion calculations per second). All of this computing power will provide an unprecedented opportunity for nuclear science (see Figure 2.3.1). Scientific computing, including modeling and simulation, has become crucial for research problems that are insoluble by traditional theoretical and experimental approaches, too hazardous to study in the laboratory, too time-consuming, or too expensive to solve.

High-performance computing provides answers to questions that neither experiment nor analytic theory can address. As such, it becomes a third leg supporting the field of nuclear physics. Nuclear physicists perform comprehensive simulations of strongly interacting matter in the laboratory and in the cosmos. These calculations are based on the most accurate input, the most reliable theoretical approaches, the most advanced algorithms, and extensive computational resources. Until recently working with petascale resources was hard to imagine, and even at the present time such an ambitious endeavor is beyond what a single researcher or a traditional research group can carry out. To this end, collaborative software environments have been created under the DOE's Scientific Discovery Through Advanced Computing (SciDAC) program, where distributed resources and expertise are combined to address complex questions and solve key problems.[1] In each partnership, mathematicians and computer scientists are collaborating with nuclear physicists to remove barriers to progress in nuclear structure and reactions, QCD, stellar explosions, accelerator science, and computational infrastructure. Computational resources required for these calculations are currently obtained from a combination of dedicated hardware facilities at national laboratories and universities, and from national leadership-class supercomputing facilities.

Although significant advances have been achieved in computer hardware as well as in the algorithms used in today's computations, the forefront computational challenges in nuclear physics require resources that can only be achieved in national supercomputing centers or by dedicated special-purpose machines. Collaborative frameworks such as SciDAC will need to continue in order to prepare for, and to fully utilize, computing resources beyond the petascale when they become available to nuclear physicists. As the nature of the computers will be quite different from that of today's computers, the codes and algorithms will need to evolve accordingly. Given the scale of the computational facilities, it is clear that one should view these numerical efforts like experiments in their style of operation. Currently, the nuclear physics community can efficiently use between 1 and 10 sustained petaflop resources; hence a staged evolution to the exascale seems appropriate.


Hot and Dense QCD
Transport in QCD (quenched)
QCD critical point
Quarkonium spectroscopy
QCD at T>0
High-T limit of QCD EOS
Continuum extrapolated QCD EOS
Cold QCD
Nucleon Spin
Alpha particle
Nuclear force
Gluon distributions
Deuteron
Neutron EDM
Excited hadronspectrum
Nuclear Structure
Light nuclei
Weakly bound nuclei
0ν ββ rates for ^{48}Ca
Light ion reactions
Neutron induced fission
Triple α process
Dynamics of neutron star crust
Nuclear Astrophysics
Global solar model
Precision nuclear network
Multienergy neutrino transport
Precision neutrino network
3D supernova
Accelerator Physics
Isotope separator optimization
Energy Recovery Linac
Electron-cooling design
6D Vlasov
10^{-1}
1
10
10^2
10^3
Petaflop-Yrs on Task

Future Research Infrastructures

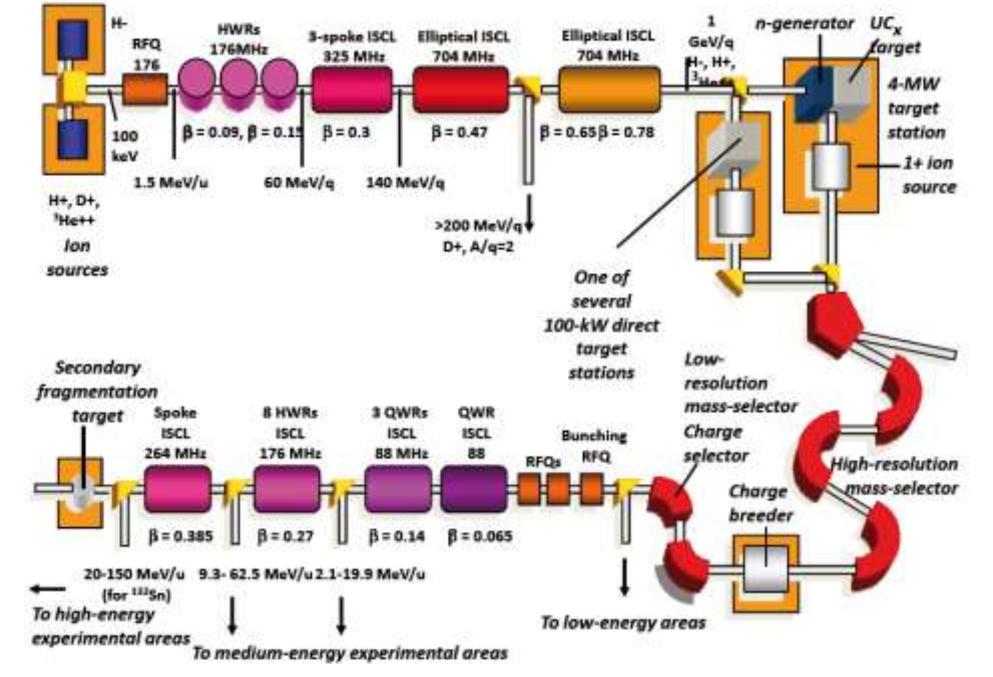
- ESFRI Roadmap Facilities: FAIR, Darmstadt, Germany; SPIRAL2 at GANIL, Caen, France;
- MYRRHA, Mol, Belgium; ELI, Bucharest, Romania
- Major Upgrades of Existing Facilities:HIE-ISOLDE at CERN, Geneva,Switzerland; SPES at INFN-LNL, Legnaro, Italy; Superconducting Linac at GSI,Darmstadt, Germany

Artist's view of the European Spallation Source, ESSS, in Lund, Sweden.

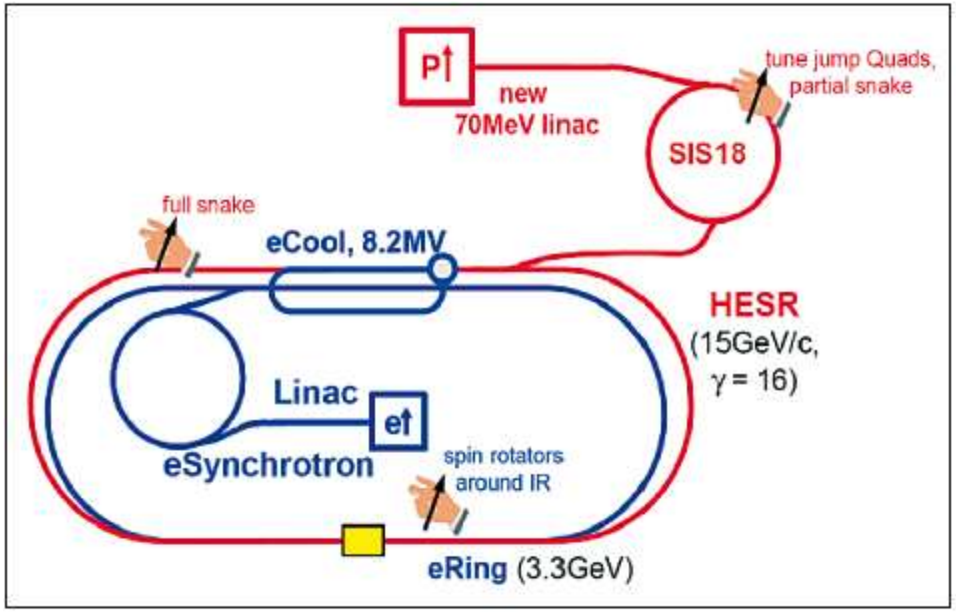
Layout and architectural view of ELI-NP facility

Projects & Design Studies

- EURISOL; ENC at FAIR, Darmstadt, Germany; PAX at FAIR; LHeC at CERN, Geneva, Switzerland



Block diagram of the EURISOL facility.

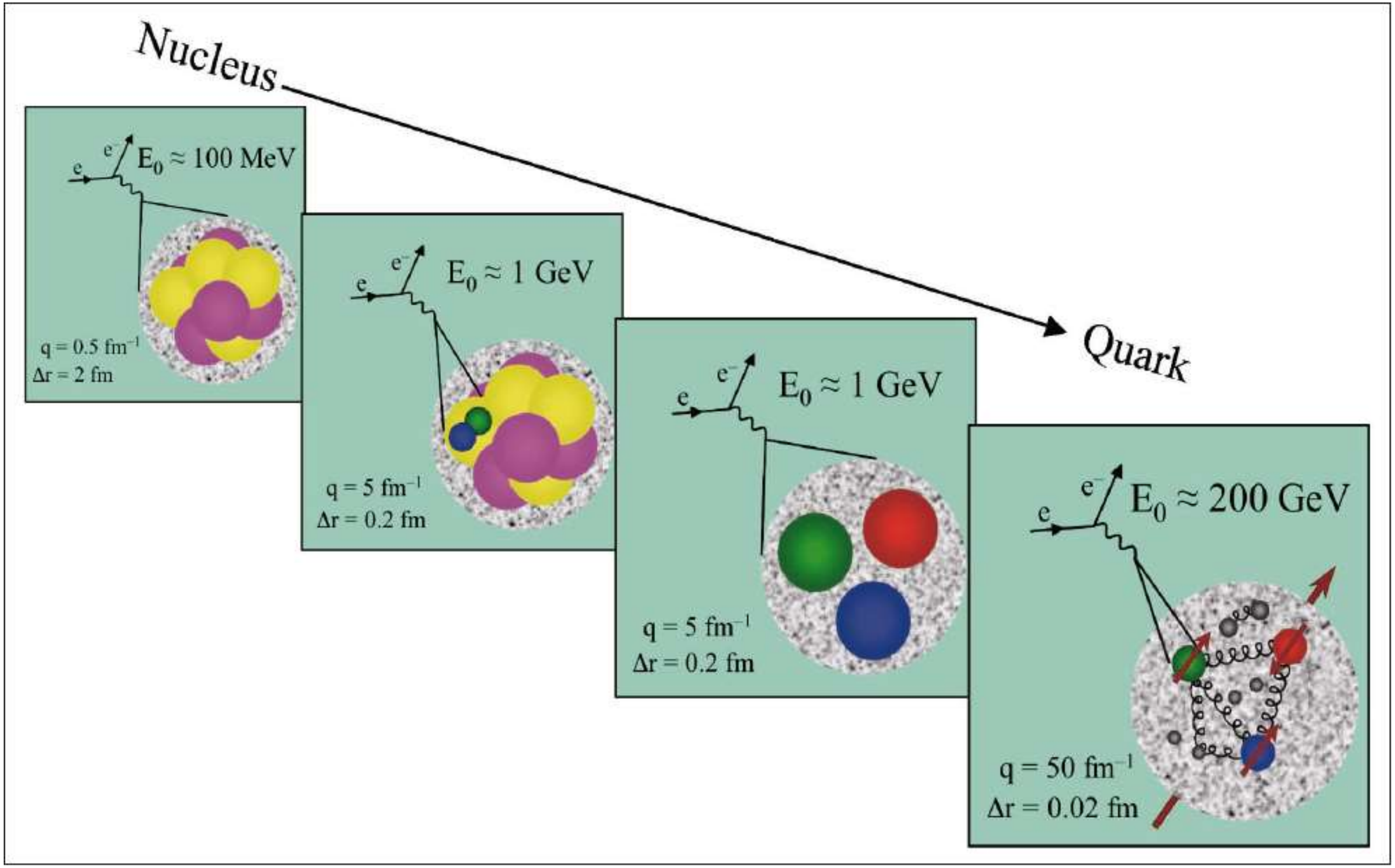


Layout of ENC@FAIR.

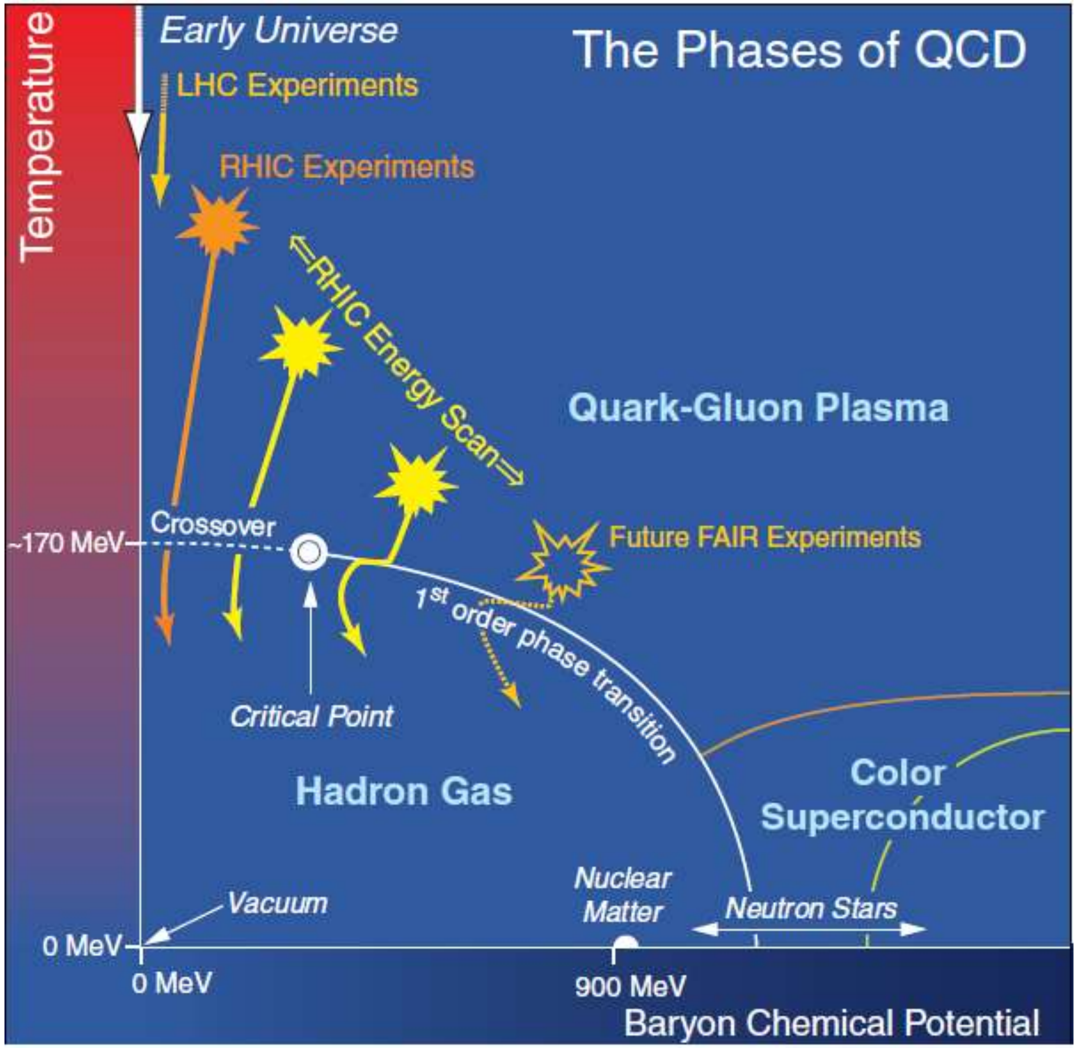
Scientific Themes

- Hadron Physics
- Phases of Strongly Interacting Matter
- ***Nuclear Structure and Dynamics***
- Nuclear Astrophysics
- Fundamental Interactions
- ***Nuclear Physics Tools and Applications***

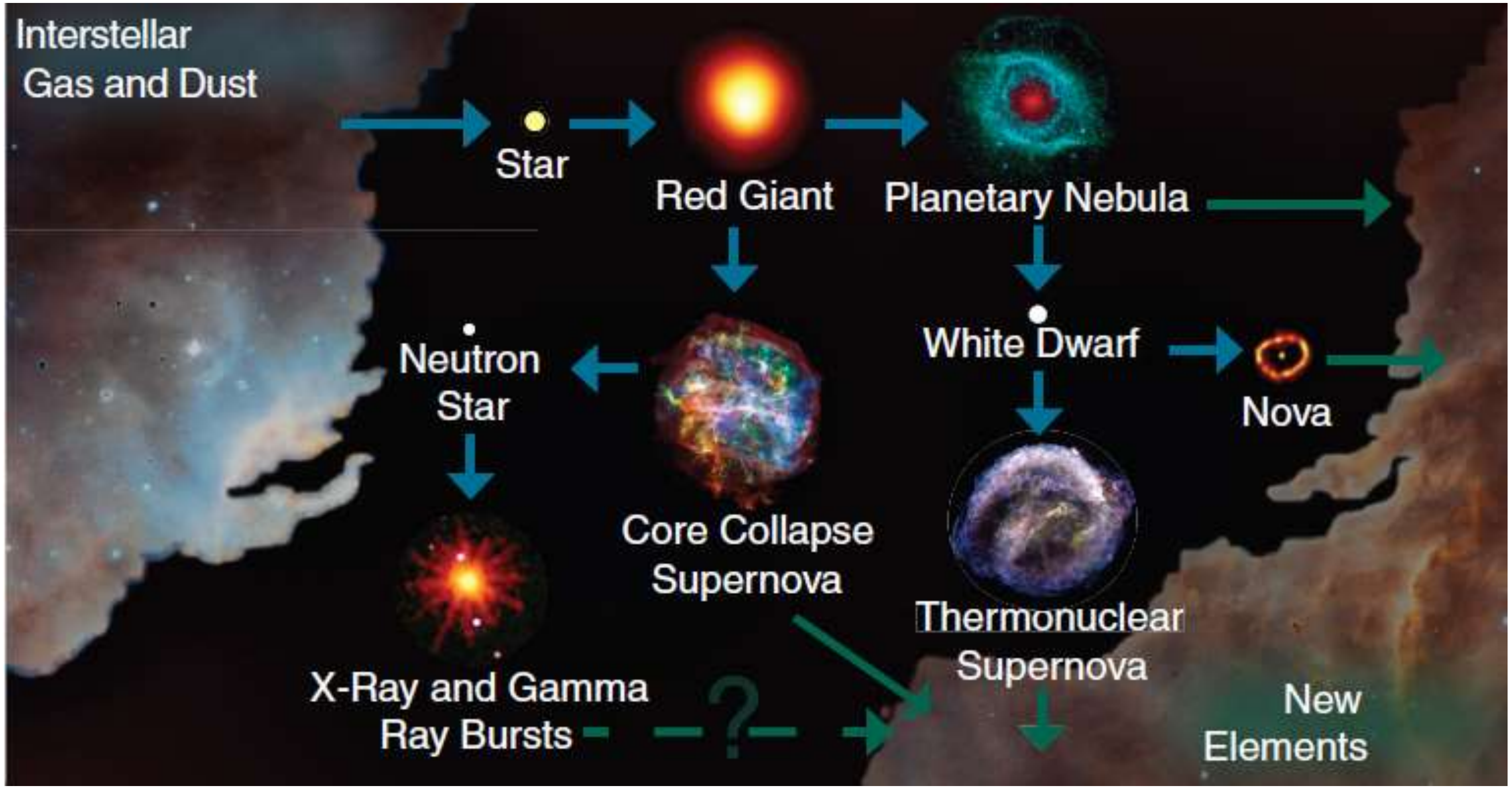
Hadron Physics



Phases of Strongly Interacting Matter



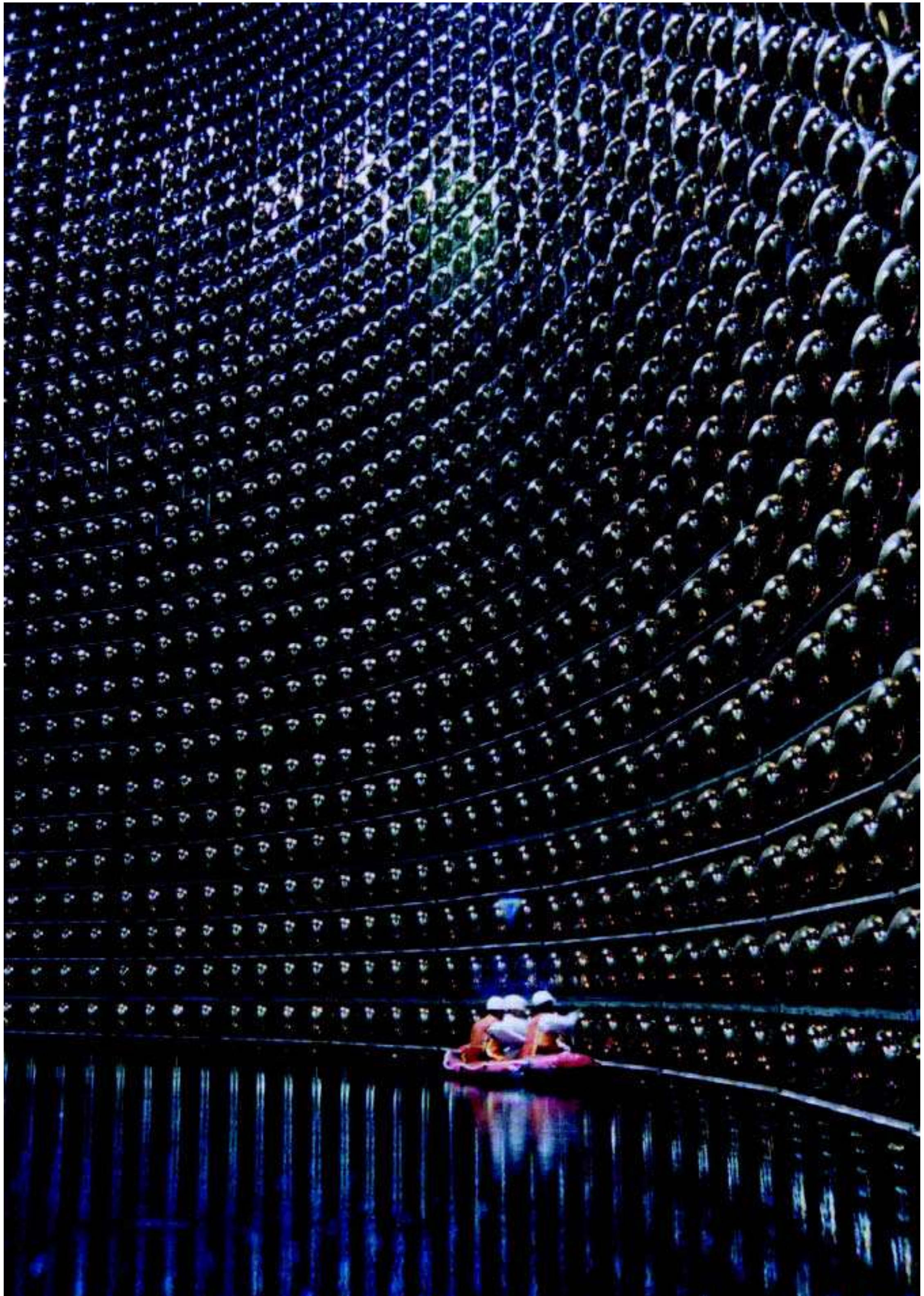
Nuclear Astrophysics



Fundamental Interactions

The SNO detector viewed with a fisheye lens. The central acrylic vessel containing 1,000 tons of heavy water (D2O) is 12 m in diameter and surrounded by 9,500 photomultipliers.

SOURCE: Courtesy of SNO.



The Super-Kamiokande detector. Here, scientists (in a rubber raft) inspect the large photomultiplier tubes as the enormous tank is filled with water.

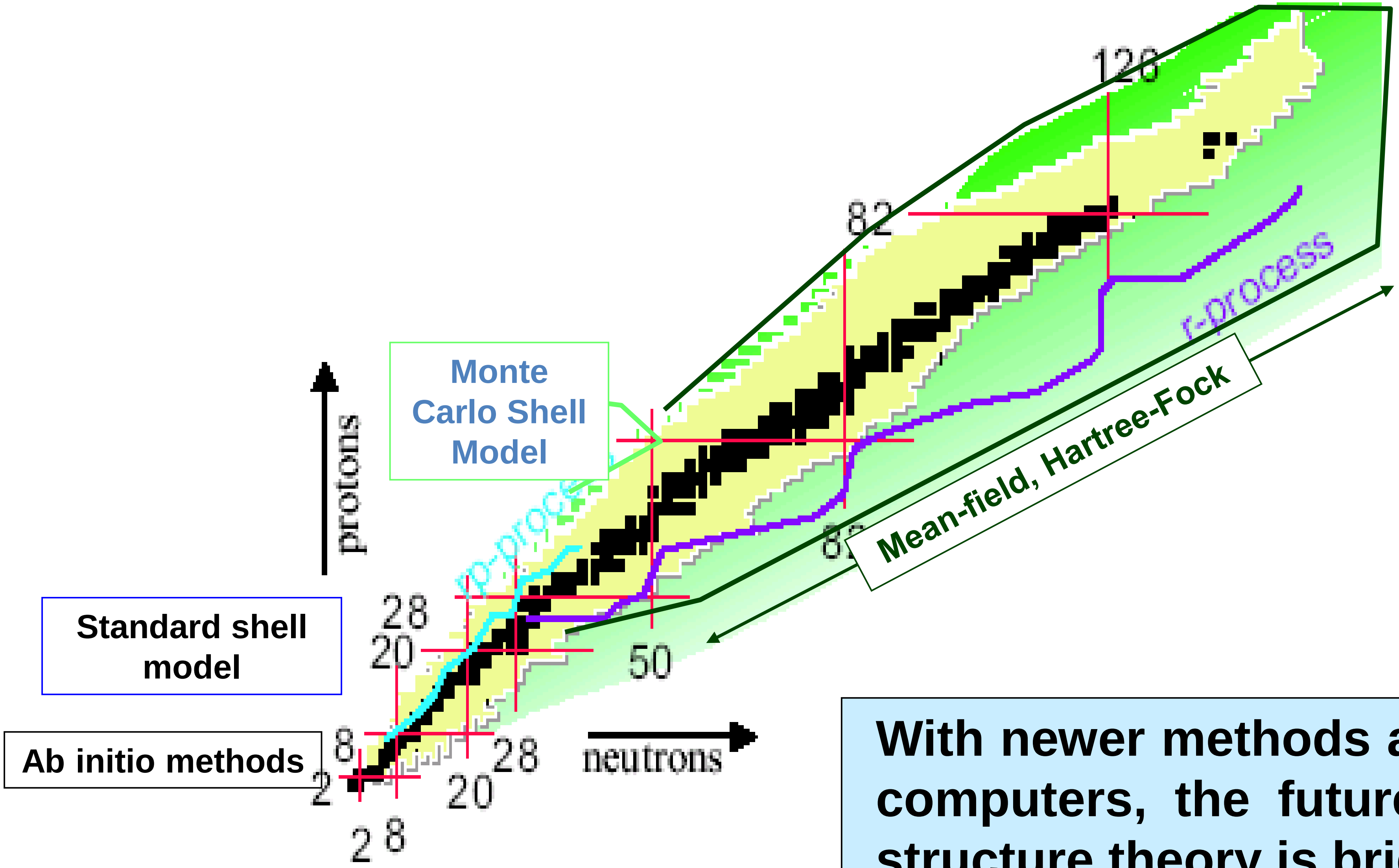
Image courtesy of the Institute for Cosmic Ray Research, University of Tokyo.

PERSPECTIVES ON THE STRUCTURE OF ATOMIC NUCLEI

The overarching questions guiding nuclear structure research have been expressed as two general and complementary perspectives: ***a microscopic view focusing on the motion of individual nucleons and their mutual interactions, and a mesoscopic one that focuses on a highly organized complex system exhibiting special symmetries, regularities, and collective behavior.***

Open questions:

- What are the limits of nuclear existence and how do nuclei at those limits live and die?
- What do regular patterns in the behavior of nuclei divulge about the nature of nuclear forces and the mechanism of nuclear binding?
- What is the nature of extended nucleonic matter?
- How can nuclear structure and reactions be described in a unified way?



Monte Carlo Shell Model

Mean-field, Hartree-Fock

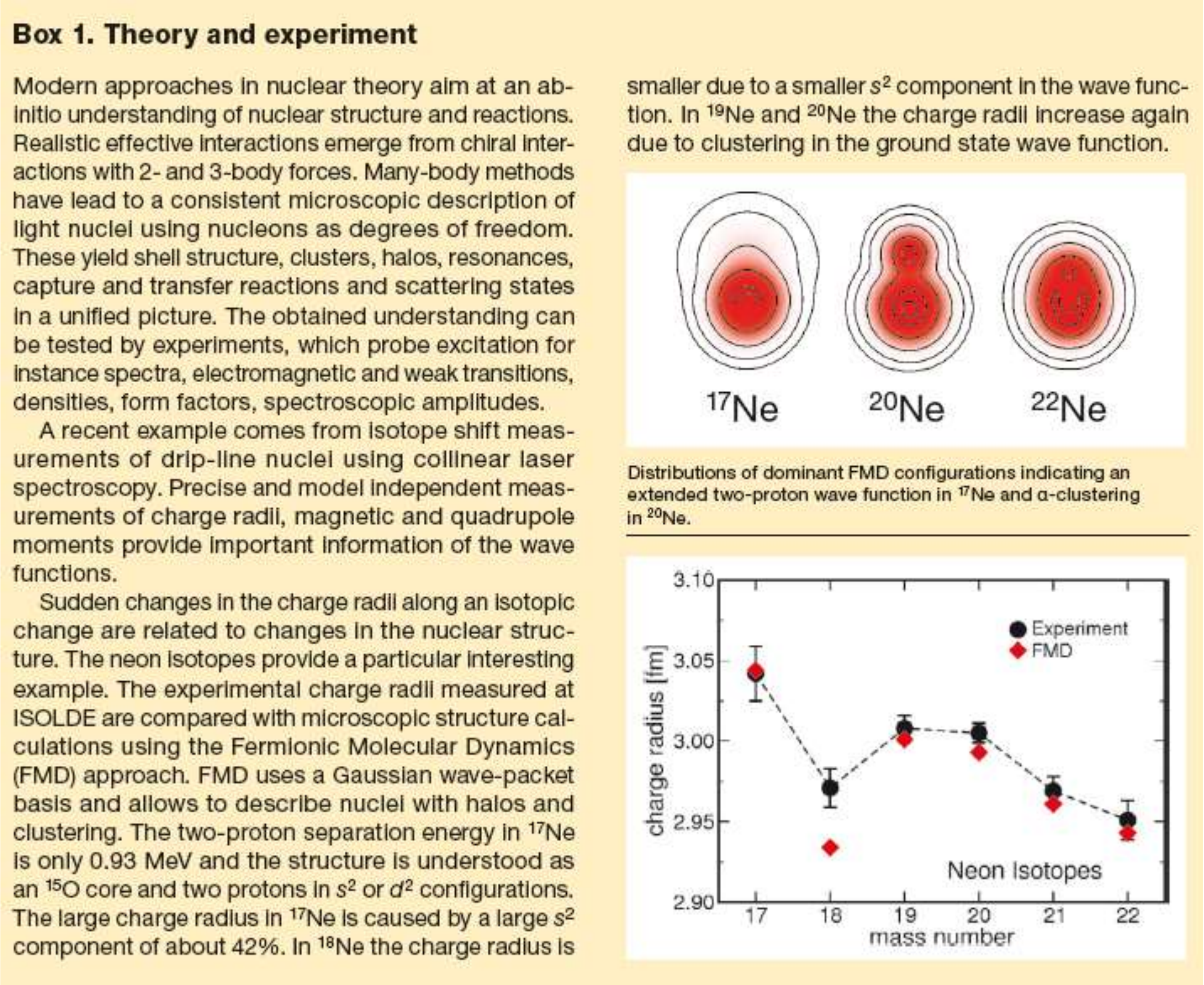
Standard shell model

Ab initio methods

With newer methods and powerful computers, the future of nuclear structure theory is bright!

Nuclear Structure and Dynamics

- Theoretical Aspects: Ab Initio methods



Box 1. Theory and experiment

Modern approaches in nuclear theory aim at an ab-initio understanding of nuclear structure and reactions. Realistic effective interactions emerge from chiral interactions with 2- and 3-body forces. Many-body methods have lead to a consistent microscopic description of light nuclei using nucleons as degrees of freedom. These yield shell structure, clusters, halos, resonances, capture and transfer reactions and scattering states in a unified picture. The obtained understanding can be tested by experiments, which probe excitation for instance spectra, electromagnetic and weak transitions, densities, form factors, spectroscopic amplitudes.

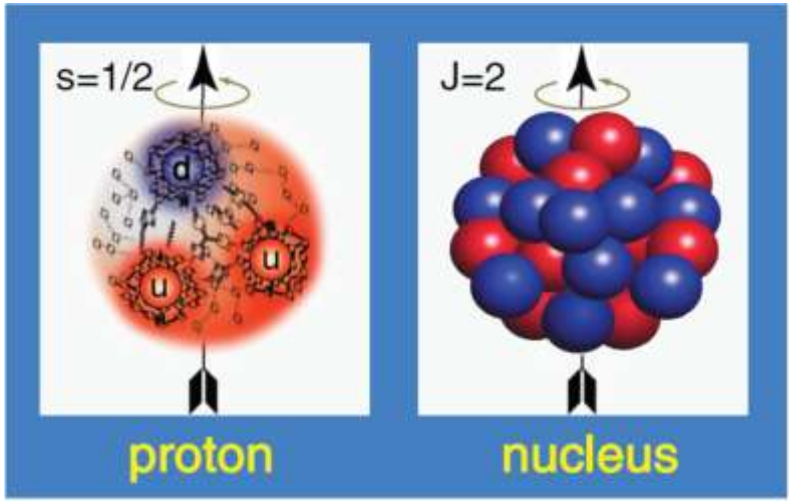
A recent example comes from isotope shift measurements of drip-line nuclei using collinear laser spectroscopy. Precise and model independent measurements of charge radii, magnetic and quadrupole moments provide important information of the wave functions.

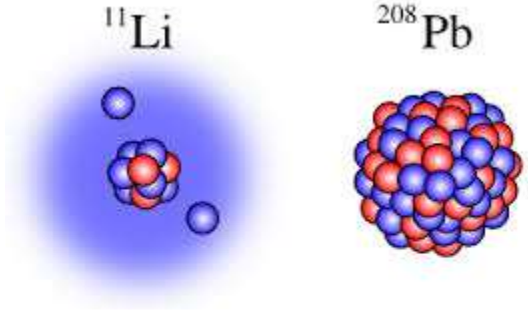
Sudden changes in the charge radii along an isotopic change are related to changes in the nuclear structure. The neon isotopes provide a particular interesting example. The experimental charge radii measured at ISOLDE are compared with microscopic structure calculations using the Fermionic Molecular Dynamics (FMD) approach. FMD uses a Gaussian wave-packet basis and allows to describe nuclei with halos and clustering. The two-proton separation energy in ^{17}Ne is only 0.93 MeV and the structure is understood as an ^{15}O core and two protons in s^2 or d^2 configurations. The large charge radius in ^{17}Ne is caused by a large s^2 component of about 42%. In ^{18}Ne the charge radius is smaller due to a smaller s^2 component in the wave function. In ^{19}Ne and ^{20}Ne the charge radii increase again due to clustering in the ground state wave function.

Distributions of dominant FMD configurations indicating an extended two-proton wave function in ^{17}Ne and α-clustering in ^{20}Ne.

- **Linking quarks, nucleons and nuclei**

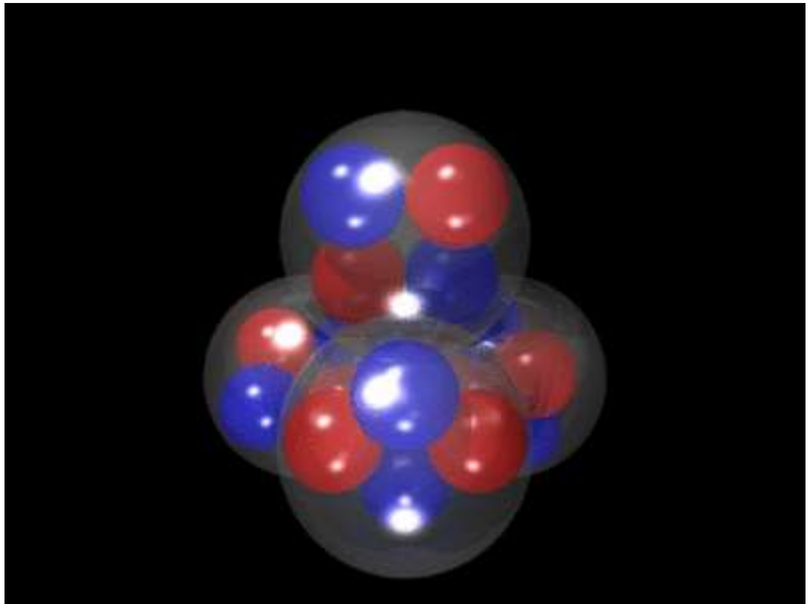
The spin of the proton is the sum of contributions from the spins and motions of all the quarks (u and d), quark-antiquark pairs (little circles), and gluons (connecting lines) within it. Recent experiments indicate that the sum of the orbital motion contributes more than the sum of all the spins, much as the total angular momentum of a large nonspherical nucleus is primarily the sum of contributions from the orbital motion of hundreds of protons (red) and neutrons (blue). SOURCE: (left) Lawrence S. Cardman, JLAB; (right) Witold Nazarewicz, University of Tennessee.





- **Weakly bound and unbound states**

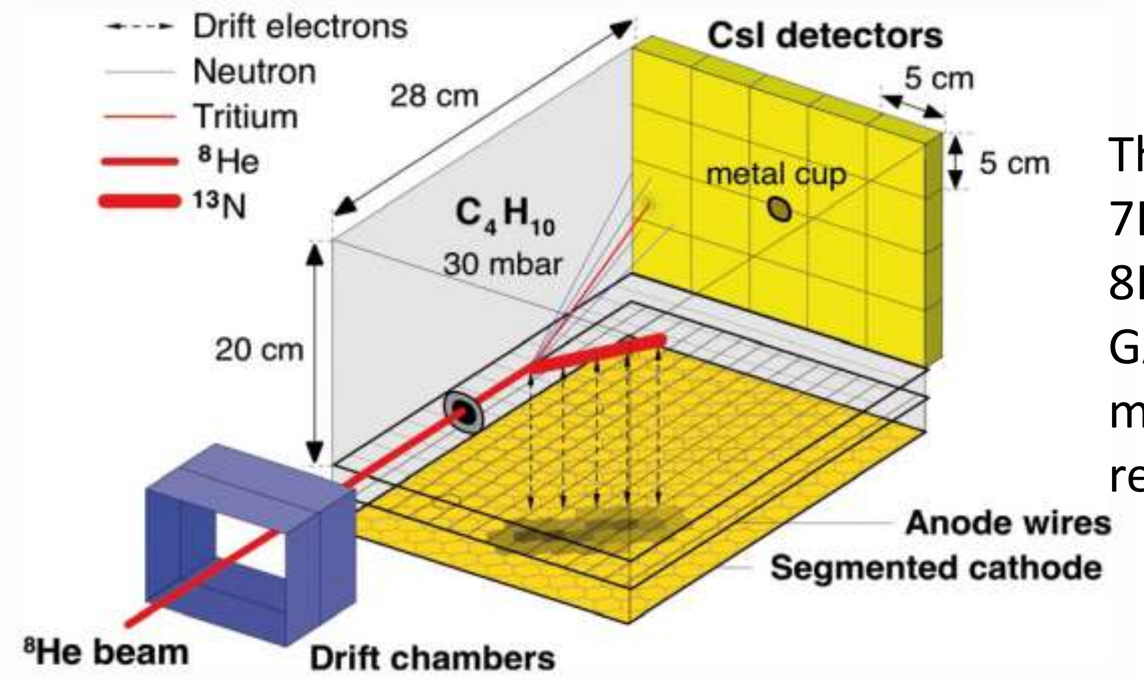
- **Halos, clusters and few-body correlations**



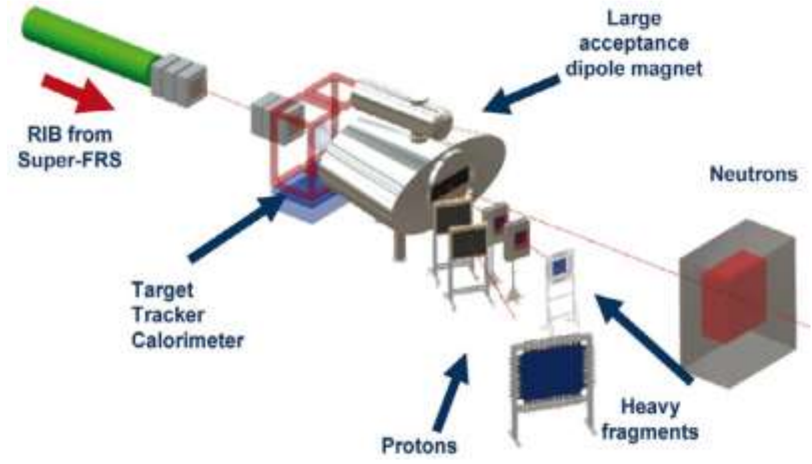
Specific instrumentation for studies of exotic light nuclei:

Since most experiments are on the limit of what is possible both concerning ion production and detection, ***an integral approach is often necessary where the accelerator and separation facilities are parts of the experimental set-up***. In addition to the generic state-of-the-art detection systems for charged particles and gamma rays, systems specific to studies of light nuclei are active targets for low-momentum transfer experiments as well as high-efficiency, high-granularity neutron detectors for reaction and neutron-decay studies. A wealth of spectroscopic information has become available by the advancement of high-granularity detectors for charged particles; the potential for similar studies through neutrons is at least as large, but as of yet has hardly been possible to address.

Versatile instrumentation for nuclear reactions



The system with the highest N/Z ever produced is 7H. It was identified as a resonance in the 8He(12C,13N) reaction at 15MeV/nucleon at GANIL. The active target MAYA was employed to measure kinematical correlations of the reaction residues.



Schematic view of the R3B setup comprising the calorimeter CALIFA, a target-recoil tracking system, a large acceptance super-conducting dipole, the neutron detector NeuLAND, as well as tracking systems for charged particles and heavy ions.

Superheavy elements

Box 3. Superheavy elements

New elements

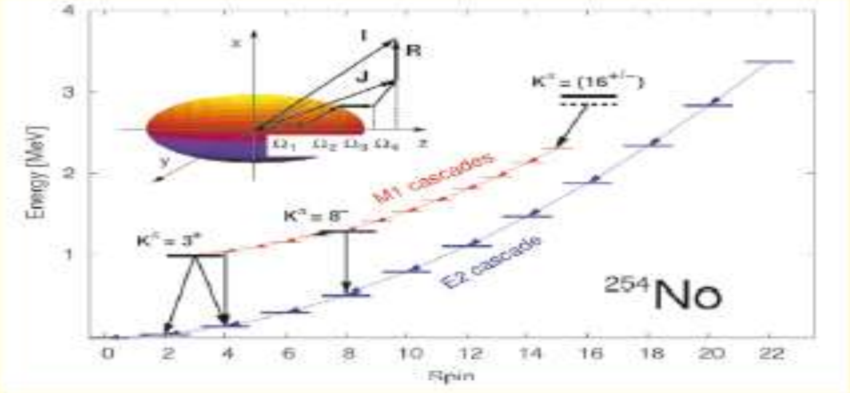
The long-standing quest for superheavy elements (SHE) has led to exciting results during the past decade claiming synthesis of elements up to $Z = 118$. Confirmation of these results obtained in Dubna, synthesis of new elements with $Z > 118$ and to reach the predicted neutron shell closure at $N = 184$ will be the great challenges for the next decade.

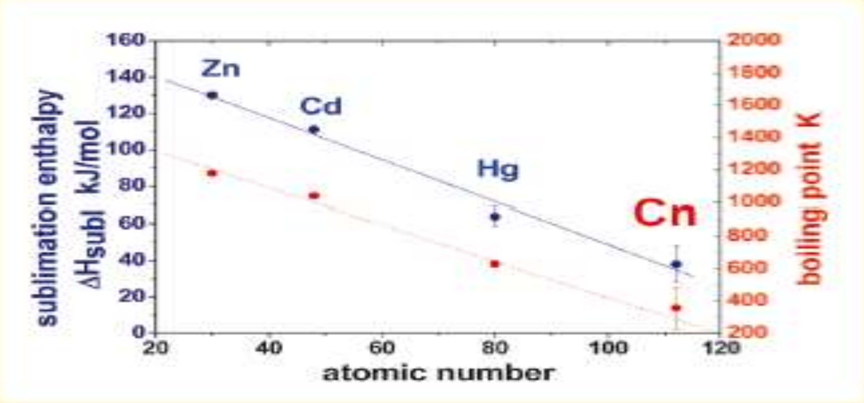
Masses and atomic structure

Masses of $^{252-254}$No, ^{255}Lr were measured with SHIPTRAP at GSI. The fundamental challenge is to extend these mass measurements to neutron rich long-lived transactinides, which terminate the α-decay chains starting at $Z > 113$, as well as investigating the complex atomic structure of stored super-heavy nuclides by means of laser spectroscopy.

Nuclear structure

Transfermium nuclei can be produced with cross-sections of >10nb enabling in-beam and focal-plane studies in tagging experiments. In addition to the ground-state rotational band, bands built on high-K isomers have been observed in ^{254}No and adjacent nuclei, in experiments carried out at JYFL and GSI.





Chemistry

Strong relativistic effects on the electronic structure of SHE make them extremely interesting objects for chemical studies. Copernicium (Cn) is a noble metal as its sublimation enthalpy and boiling point follow the trend of the lighter group-12 elements towards high volatility.

Shell model

The SM is based on an effective interaction acting within a limited model space of valence nucleons. The computational requirements of the SM are heavy and the applicability of the method relies on the availability of large-scale computational resources. ***One can expect that the size of the model spaces that can be handled by the SM will continue to increase in the coming years, thanks to computational and to conceptual developments.*** This will make this method one of the main tools to understand the physics of medium mass nuclei far from stability.

Revising the Paradigms of Nuclear Structure

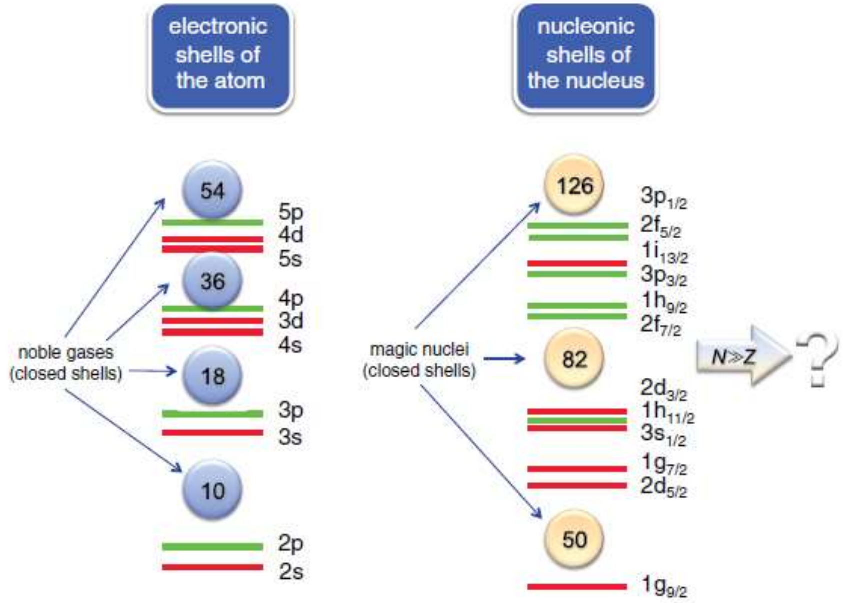


FIGURE 2.1 Shell structure in atoms and nuclei. *Left:* Electron energy levels forming the atomic shell structure. In the noble gases, shells of valence electrons are completely filled. *Right:* Representative nuclear shell structure characteristic of stable or long-lived nuclei close to the valley of stability. In the "magic" nuclei with proton or neutron numbers 2, 8, 20, 28, 50, 82, and 126, which are analogous to noble gases, proton and/or neutron shells are completely filled. The shell structure in very neutron-rich nuclei is not known. New data on light nuclei with N >> Z tell us that significant modifications are expected. SOURCE: Adapted and reprinted with permission from K. Jones and W. Nazarewicz, 2010, *The Physics Teacher* 48 (381). Copyright 2010, American Association of Physics Teachers.

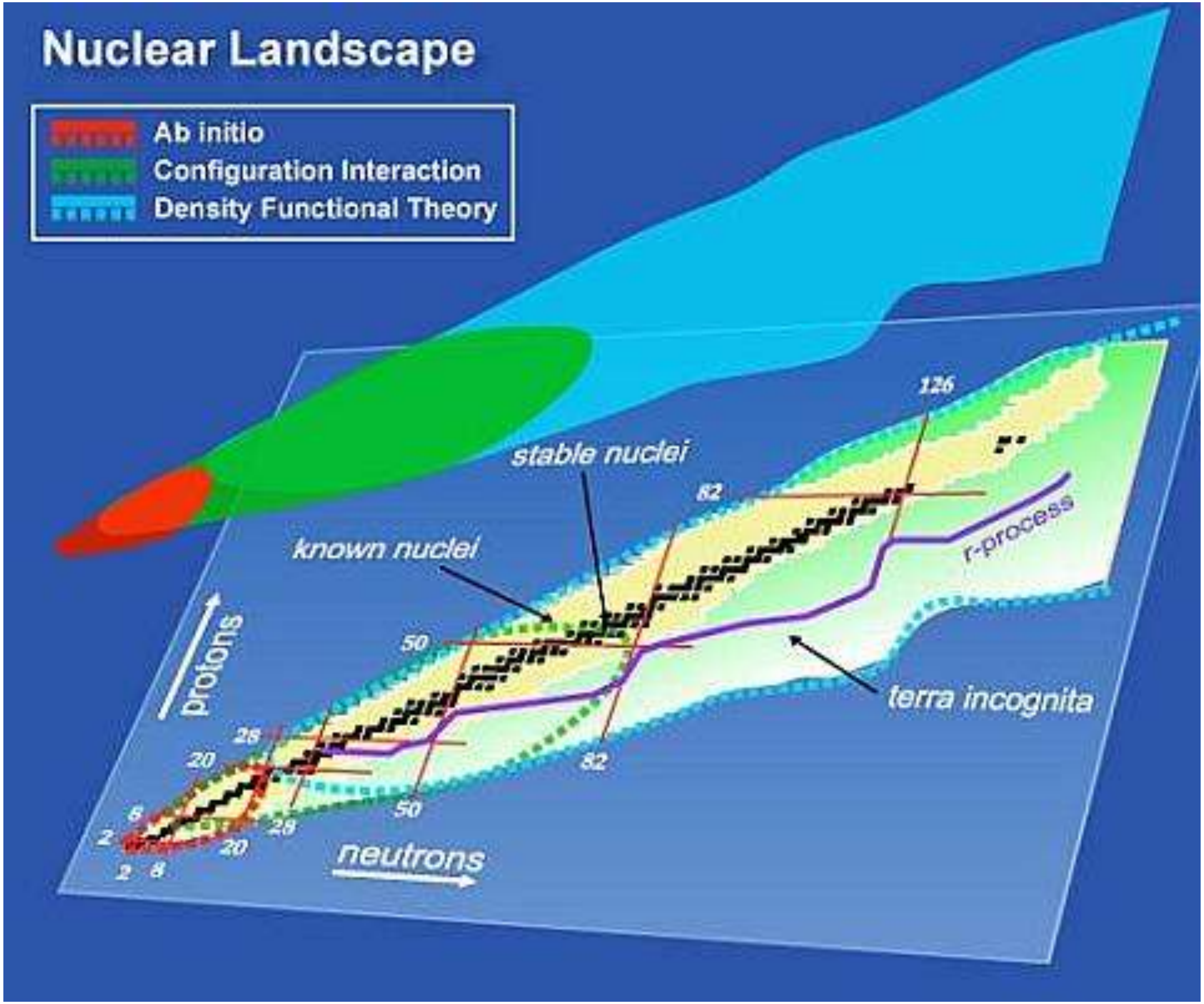
The modification of shell gaps far from stability raises doubts about one of the firmest paradigms of nuclear structure – the universality of magic numbers throughout the nuclear chart. Recently, the traditional magic numbers underwent major revisions as previously unavailable species became accessible. ***The shell structure known from stable nuclei is no longer viewed as an immutable construct but instead is seen as an evolving moving target.*** Indeed the elucidation of changing shell structure is one of the triumphs of recent experiments in nuclear structure at exotic beam facilities worldwide.

Energy density functional methods

- ***The family of microscopic approaches based on nuclear Energy Density Functionals (EDF) provides a complete and accurate description of ground-state properties and characteristic excitations over the whole nuclide chart.***

- The main goal of the EDF approach to nuclear structure in the next decade will be the construction of a consistent microscopic framework that describes ground-state properties, nuclear excitations and reactions at a level of accuracy comparable with experimental results, and provide reliable predictions for systems very far from stability, including data for astrophysical applications that are not accessible in experiments.

Nuclear Landscape



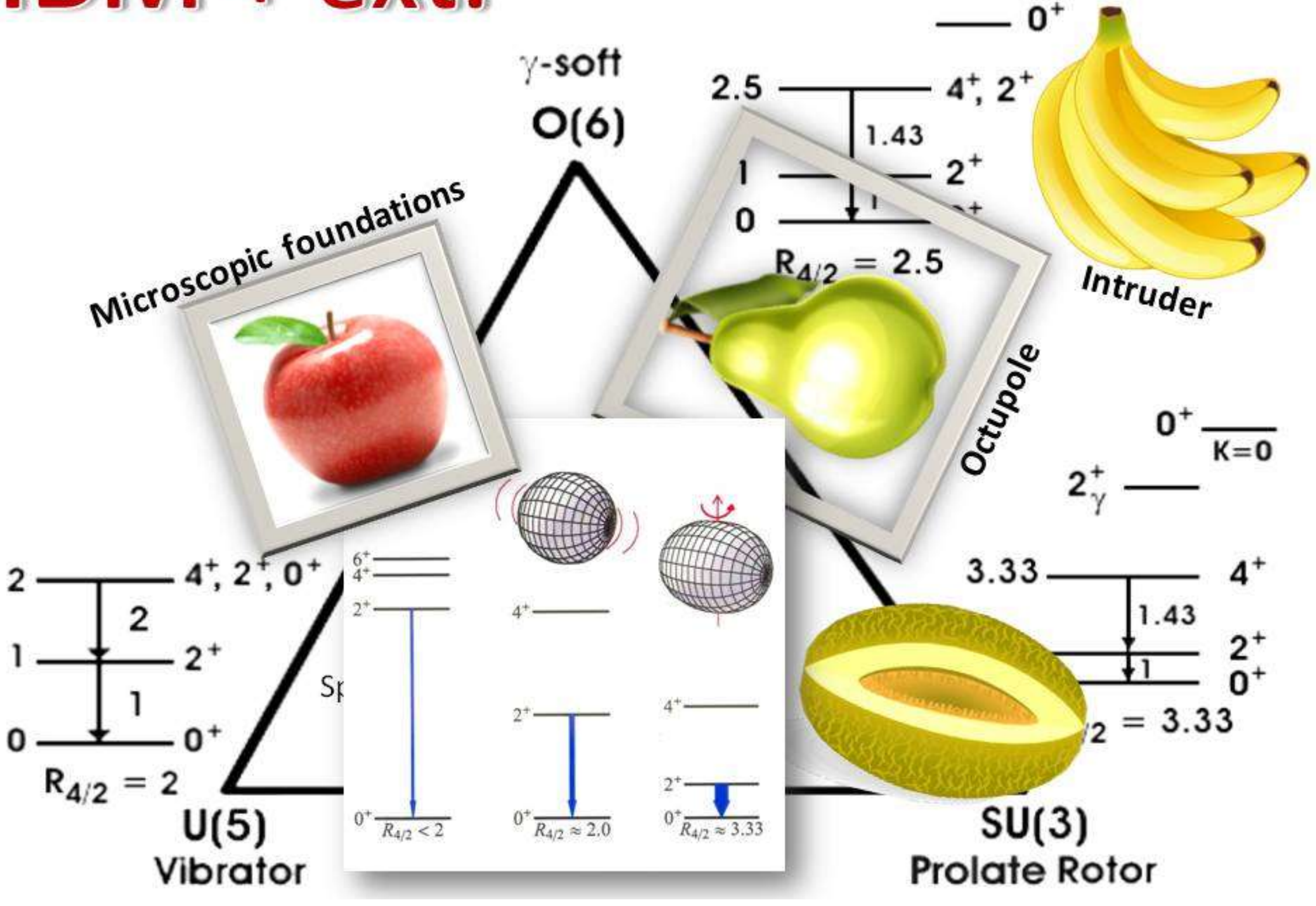
Symmetries in nuclei and phase transitions

One fundamental goal of nuclear structure physics is to evidence regularities and simple features of nuclear spectra, providing a comprehensive understanding of the origin of such regularities in the complex nuclear many-body systems.

These features are known to be associated with the so-called dynamical symmetries, which include both symmetries of the mean field and symmetries of the residual interactions among the particles, and which are characterized by definite underlying algebraic structures.

The issue of quantum phase transitions in nuclei is far from being fully explored and great steps are expected in the coming years on the theory side. The major extensions will concern the explicit treatment of the nucleus as a fluid with two components (protons and neutrons) the treatment of excited states, a generalization to odd-even systems (treated as a mixture of bosons and fermions).

IBM + ext.


γ-soft
O(6)
2.5
4+, 2+
1.43
1
2+
0
R4/2 = 2.5
0+
Intruder
Microscopic foundations
Octupole
0+
K=0
2γ+
2
4+, 2+, 0+
2
1
2+
1
0
0+
R4/2 = 2
U(5)
Vibrator
Sp
6+
4+
2+
0+
R4/2 < 2
4+
2+
0+
R4/2 ≈ 2.0
4+
2+
0+
R4/2 ≈ 3.33
3.33
4+
1.43
2+
1
0+
/2 = 3.33
SU(3)
Prolate Rotor

Reactions

The availability of low- and high-energy radioactive beams and, in particular the discovery of halo-nuclei, has brought out a renewed interest in the modeling of nuclear reactions.

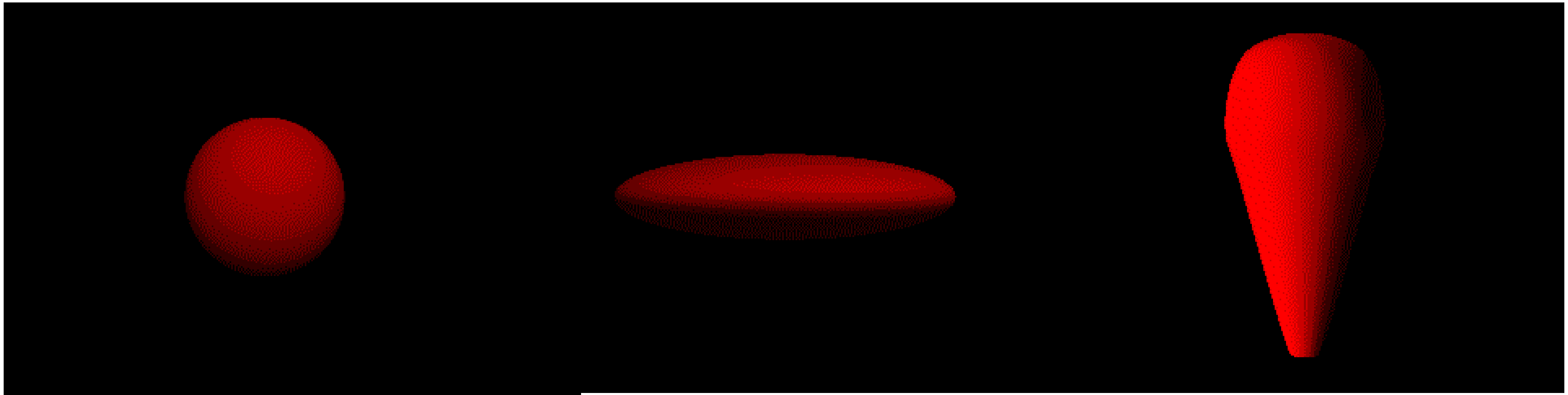
To take into account the complexity of the many-body problem, current approaches to reaction theory involve different approximations whose validity needs to be checked, in particular when applied to exotic light nuclei. There are two major issues in any reaction approach: first, to ensure that sufficiently detailed microscopic structure information of the interacting nuclei is incorporated (via optical potentials, form-factors, spectroscopic factors, etc.) and, second, a proper treatment of the relevant dynamics. These two aspects are often intertwined and need to be carefully addressed.

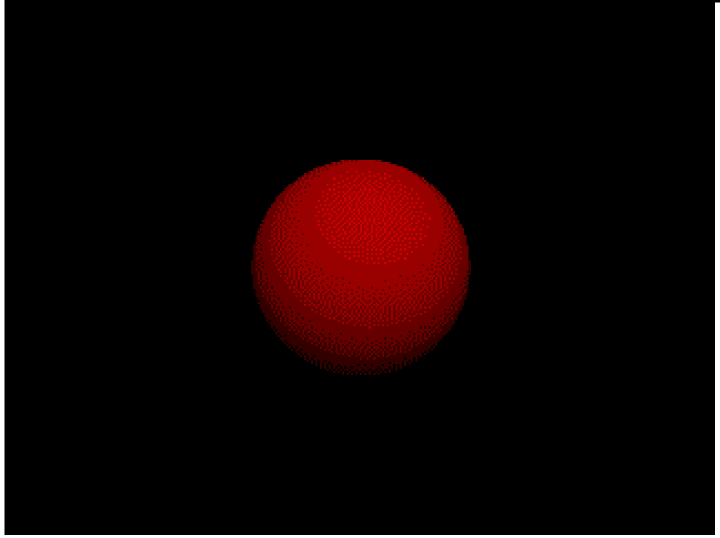
Toward a unified description of nuclear structure and reactions

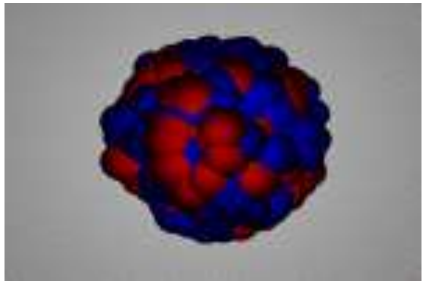
Nuclear theory is rapidly evolving from studies of nuclei close to the valley of beta-stability towards a description of vast regions of short-lived and exotic nuclei far from stability and at the nucleon drip-lines. Such an expansion imposes stringent constraints on microscopic structure and reaction models that are being developed.

The goal for the next decade will be to develop a microscopic description of nuclear structure and reaction phenomena that can be extrapolated very far from beta-stability, and simultaneously provide reliable error estimates.

Onset of Complexity- Nature and Origin of Simple Patterns in Complex Nuclei







- **Collective response of nuclei**

The nuclear collective responses reveal information on the bulk properties of nuclei and nuclear matter. This response is characterized by the ***giant resonances*** of various multipolarities with most of the strength well above the particle separation energy.

- **Evolution of nuclear collective properties with spin and temperature**

The investigation of nuclear properties as a function of spin and temperature plays a crucial role in the study of nuclear structure beyond the mean field description. Experiments exploring the nucleus at the highest possible spins have shown that a nucleus while spinning faster and faster can undergo several shape changes before terminating in a single-particle like configuration, where the nucleonic spins of all valence nucleons are aligned. In order to produce even higher-spin states the nucleus can regain a collective motion by acquiring more valence nucleons (see box). In this way it is expected to observe new shape phenomena like the long sought hyperdeformation.

- **Shape coexistence, phase transitions and dynamical symmetries**

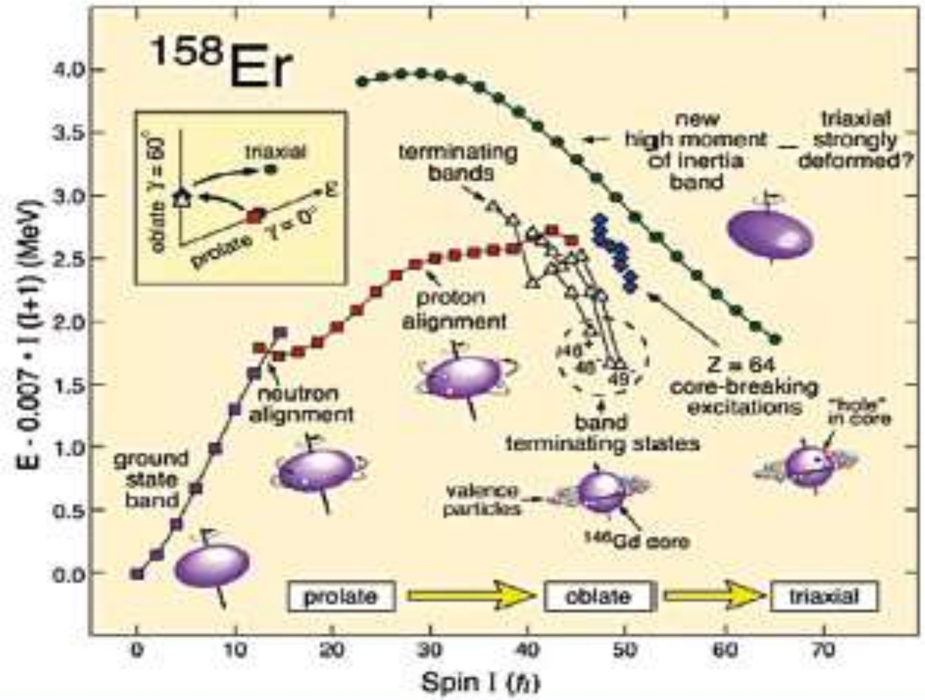
The future programme using the new and more intense heavy RIBs will shed light on the phenomena related to nuclear shapes and dynamical symmetries. The occurrence of new ***exotic shapes*** such as proton-neutron triaxiality or tetrahedral deformation and new dynamical symmetries associated with the critical points characterizing the quantum phase transitions will be elucidated in particular by measuring their electromagnetic transition properties.

- Instrumentation

Box 4

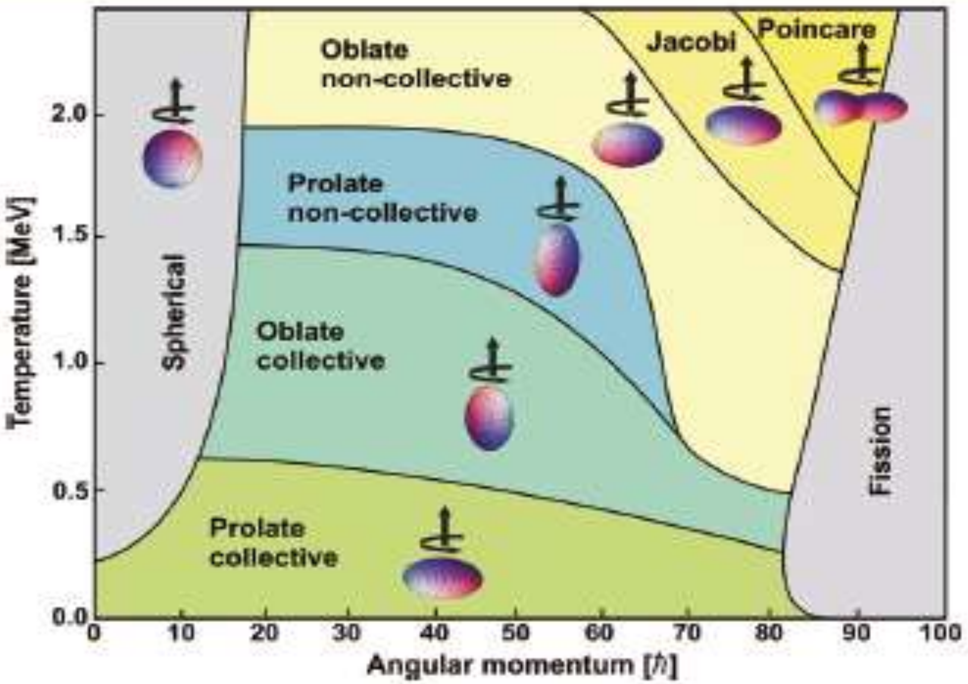
Nuclear rotation

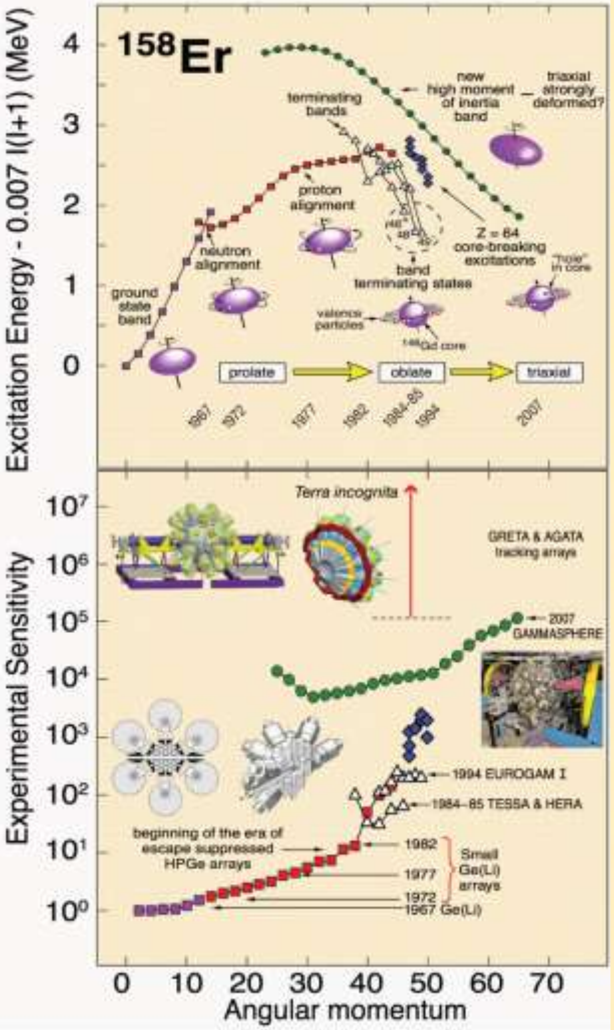
The response of atomic nuclei to rotation at increasing angular-momentum values, is a fundamental and fascinating phenomenon. A new frontier of discrete-line γ-ray spectroscopy has been opened with the possibility of identifying rotational bands at ultra-high spins, in spite of their very weak population. The figure illustrates the spectacular evolution of nuclear structure with increasing angular momentum. This evolution is matched with the dramatic changes in nuclear shape that occur, i.e. from prolate collective at low spin, to oblate non-collective at the "band terminating" spins near 50ħ, and now to strongly deformed triaxial shapes up to 65ħ (adapted from PRL 98 (2007) 012501)



High temperature regime

At finite temperature T the nucleus behaves as a charged liquid drop which under the stress of rotation manifests different shapes. This is illustrated in the temperature-angular momentum diagram. At low T one expects a tri-critical point, around which oblate or prolate, rotating along the symmetry axis (non-collectively), as well as oblate shapes, rotating perpendicularly to the symmetry axis (collectively), coexist. At higher T several scenarios are predicted. The Jacobi shape transition leads from an oblate nuclear shape, rotating along the symmetry axis, through a sequence of triaxial shapes to the elongated shape, rotating perpendicularly to the symmetry axis. At spins in the vicinity of the fission limit the Poincare transition may occur – here the nucleus undergoes a shape change from elongated prolate to elongated octupole.





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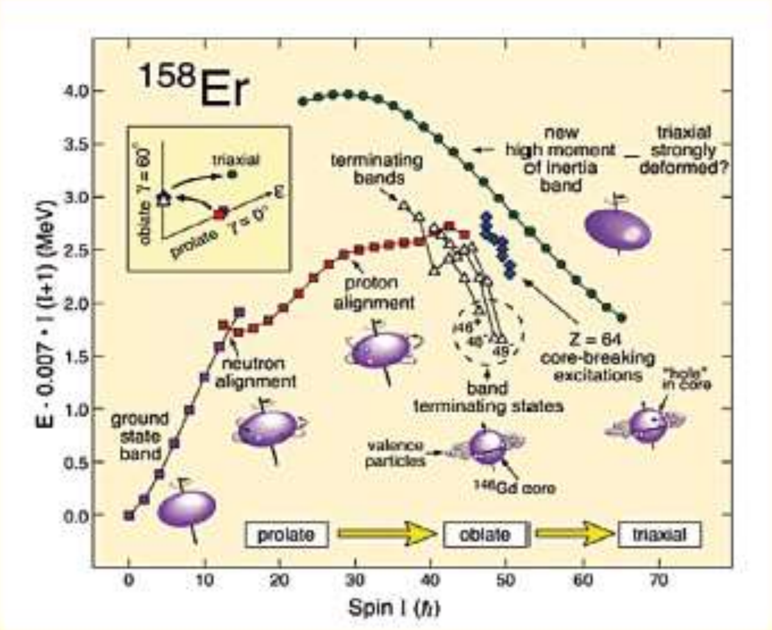

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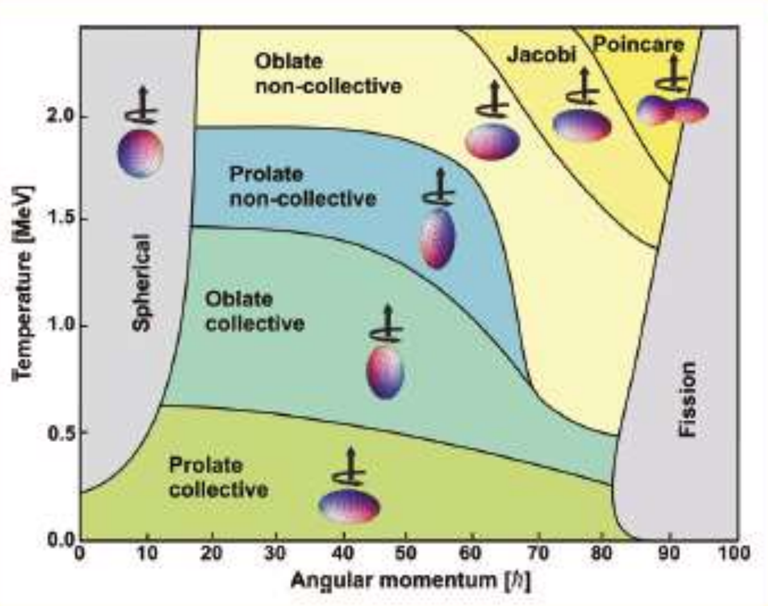
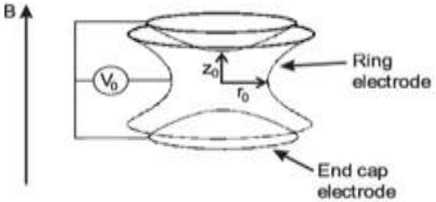


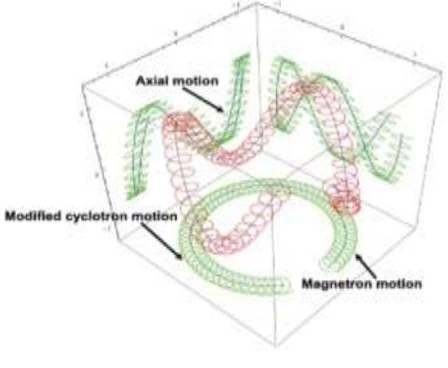
Ground-State Properties

- ***Charge and matter radii, nuclear moments and spins***
- ***The future with laser spectroscopy methods at ISOL facilities***
- ***The future with spin-oriented radioactive beams at in-flight facilities***
- ***Nuclear masses***

Instruments and future directions for direct mass measurements

The knowledge of nuclear masses has developed rapidly in recent years. Various methods have been implemented including ***ion traps, storage rings and time-of-flight spectrometers***. They are adapted to the various production and separation methods of exotic nuclei, including superheavy elements and reach highest sensitivity (single-ion detection), highest selectivity (isomer separation), subkeV precision and measurement times down to ~10 ms. ***Setups and programmes for direct mass measurements are important pillars of almost all existing RIB facilities in Europe, thus contribute to their efficient and full exploitation.***





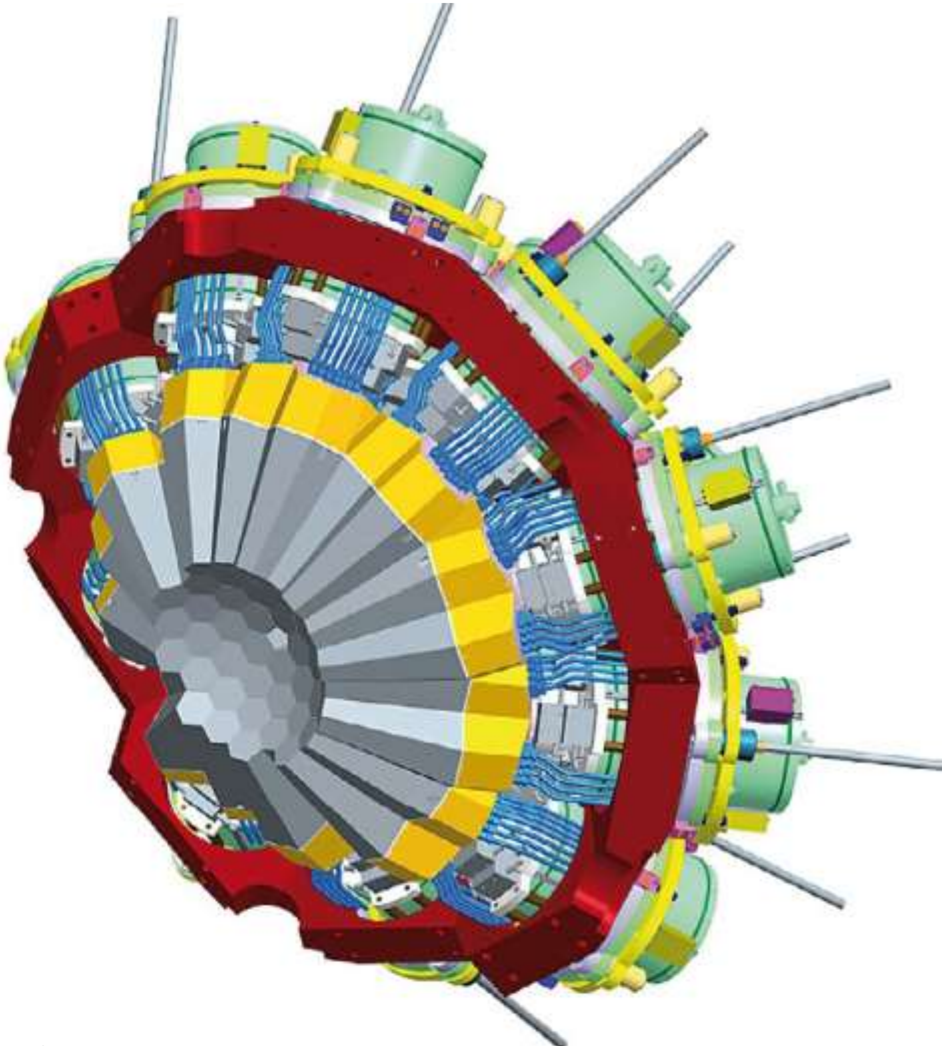
Instrumentation

Highly efficient and versatile instrumentation is a key feature in making the best possible use of the precious rare isotopes produced by the facilities. All large instrumentation projects in today's nuclear structure and reaction research are governed by co-operation in R&D work between groups, which often represent different subfields of the community.

In the future this approach is even more vital in order to construct the most versatile and powerful detection systems for probing exotic nuclei. They need to combine identification (in A and Z) of the outgoing reaction products together with detection of all emitted particles (gamma-rays, electrons, charged particles, neutrons etc.). ***The R&D projects are driven by physics ideas, but the introduction of new innovative experimental techniques and/or new materials often reveal unexpected phenomena.***

High-sensitivity gamma-ray detection

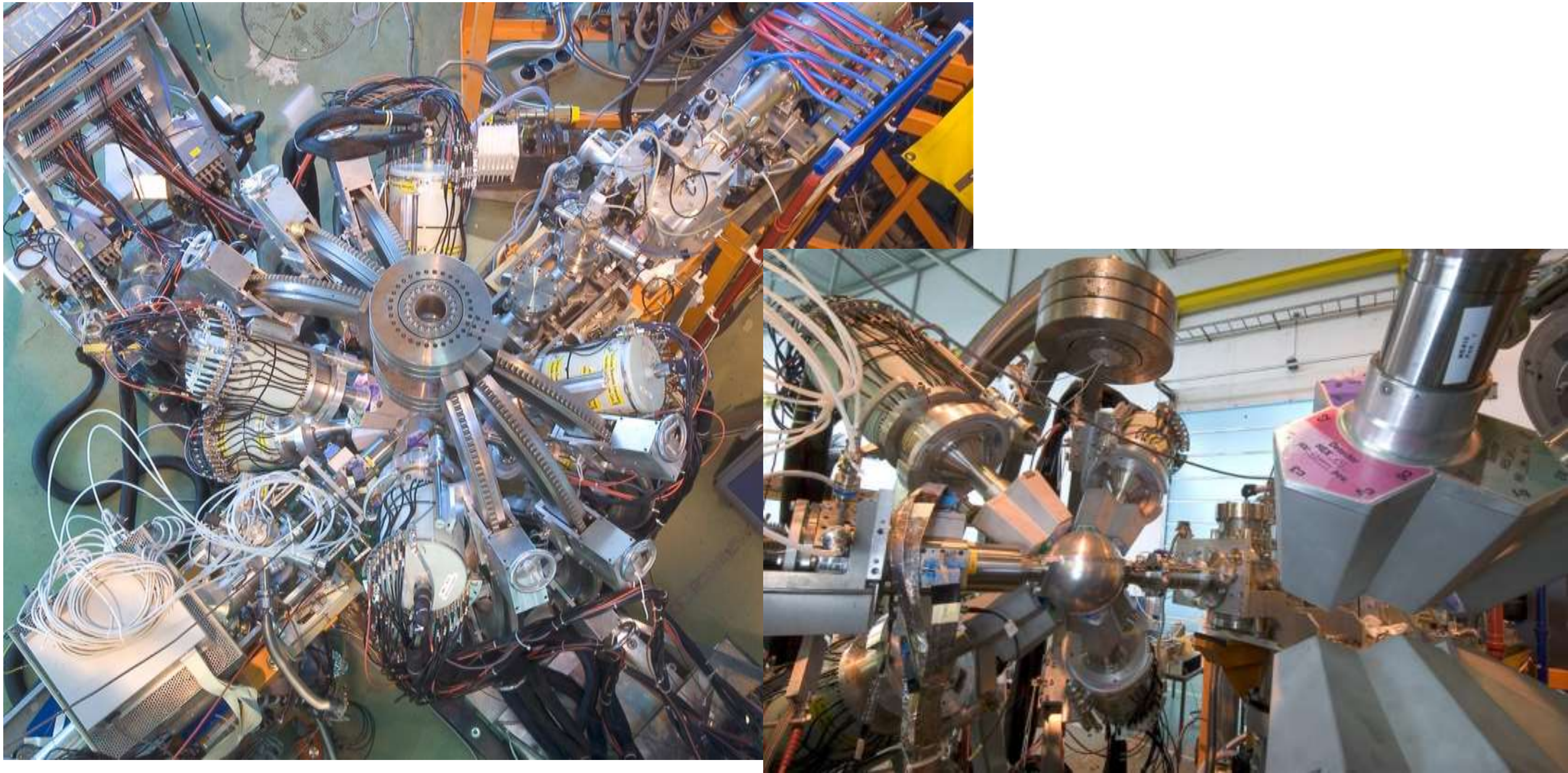
- High-granularity arrays consisting of Compton-suppressed Ge-detectors and various ancillary detection systems have recently resulted in an unprecedented sensitivity for spectroscopy and reaction studies.



1π section of the **AGATA** array comprising 45 encapsulated 36- fold segmented Ge- crystals in triple clusters.

ISOLDE

ISOLDE studies the properties of atomic nuclei, with further applications in fundamental studies, astrophysics, material and life sciences



The Isotope mass Separator On-Line facility (ISOLDE) is a unique source of low-energy beams of radioactive nuclides, those with too many or too few neutrons to be stable. The facility fulfils in fact the old alchemical dream of changing one element into another. It permits the study of the vast territory of atomic nuclei, including the most exotic species.

The high intensity proton beam from the Proton Synchrotron Booster (PSB) is directed into specially developed thick targets, yielding a large variety of atomic fragments. Different devices are used to ionize, extract and separate nuclei according to their mass, forming a low-energy beam that is delivered to various experimental stations. This beam can be further accelerated to 3 MeV/nucleon. The post acceleration of radioactive beams has opened new fields of research, allowing the study of nuclear reactions with light and medium-mass radioactive projectiles. Many of these experiments use Miniball, a gamma array of high purity germanium detectors. Presently an upgrade of the machine, HIE-ISOLDE, is underway that will improve the experimental capabilities of ISOLDE in many aspects. From the autumn of 2015 radioactive beams of 5.5 MeV/nucleon will be available.

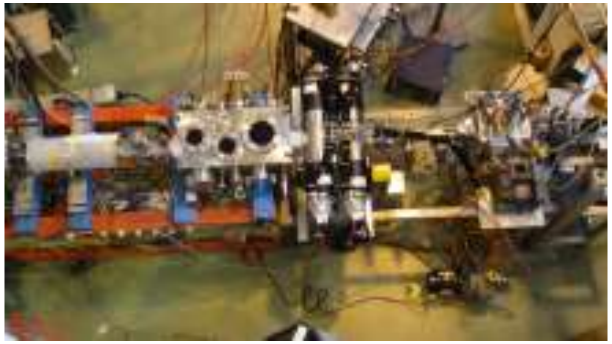
In the last 45 years the ISOLDE facility has gathered unique expertise in research with radioactive beams. Over 700 isotopes of more than 70 elements have been used in a wide range of research domains, from cutting edge nuclear structure studies, through atomic physics, nuclear astrophysics, fundamental interactions, to solid state and life sciences. Presently more than 450 researchers are active at ISOLDE, working on about 90 experiments. About 50 experiments take data every year.

Fixed experimental setups

ASPIC

Surfaces and interfaces are of crucial importance for the understanding of properties and processes in matter. Although most characteristics of surfaces differ drastically from the ones in the bulk, rarely more than five atomic layers are of relevance to describe the fundamentals of topics such as heterogeneous catalysis, corrosion or microelectronics. Despites this intense interest there are only very few techniques available to probe local properties with high sensitivity on surfaces and interfaces.

COLLAPS



COLLAPS (COLlinear LAser SPectroscopy) is a small experiment located at the “isotope factory” ISOLDE at CERN. ***Its aim is the investigation of ground state properties of exotic, short lived nuclei, such as spins, electro-magnetic moments and charge radii***. All these observables contribute widely to our understanding of the nuclear force – they give valuable information about the coupling between nucleons, about symmetry of the nuclear wave-functions and thus about the symmetry of the nuclear interaction itself."

CRIS

The CRIS (Collinear Resonant Ionization Spectroscopy) experiment at CERN ISOLDE is joining together the high resolution of collinear laser spectroscopy with the high efficiency and selectivity of resonant ionization. ***It is used to study the ground-state properties of exotic nuclei, such as spins, nuclear moments and shapes, and to produce beams of high isomeric purity for dedicated decay studies.***

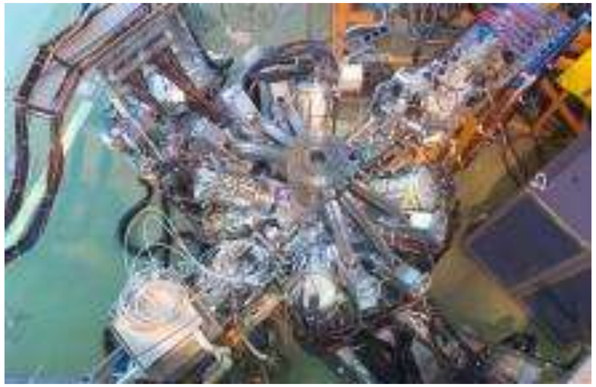
ISOLTRAP

Precision mass measurements are performed at the mass spectrometer ISOLTRAP with a relative mass uncertainty routinely reaching to 1*10^-8. The time-of-flight detection technique is employed to determine the frequency of an ion stored in a Penning trap, from which the mass can be extracted. The system has studied nuclides with half-lives below 100ms and production yields of less than 1000 ions per second, supplied by the isotope separator ISOLDE at CERN.

LUCRECIA

Lucrecia is a Total Absorption gamma Spectrometer (TAS) located at the ISOLDE hall. ***It has been designed to measure feeding in beta decay through the detection of the gamma cascades following the decay.*** The β-feeding is one of the main ingredients in the calculation of the β-strength function, and is thus an essential element in the proper estimation of the B(GT) or B(F).

MINIBALL



The high-resolution Miniball germanium detector array has been operational at REX-ISOLDE at CERN for over 10 years. This array consists of 24 six-fold segmented, tapered, encapsulated high-purity germanium crystals and was specially designed for low multiplicity experiments with low-intensity radioactive ion beams (RIB). For work with rare-isotope beams, the multiplicities are low (often only a few states are excited) and the yields of such beams are usually much lower than for conventional experiments, so efficiency is paramount.

NICOLE

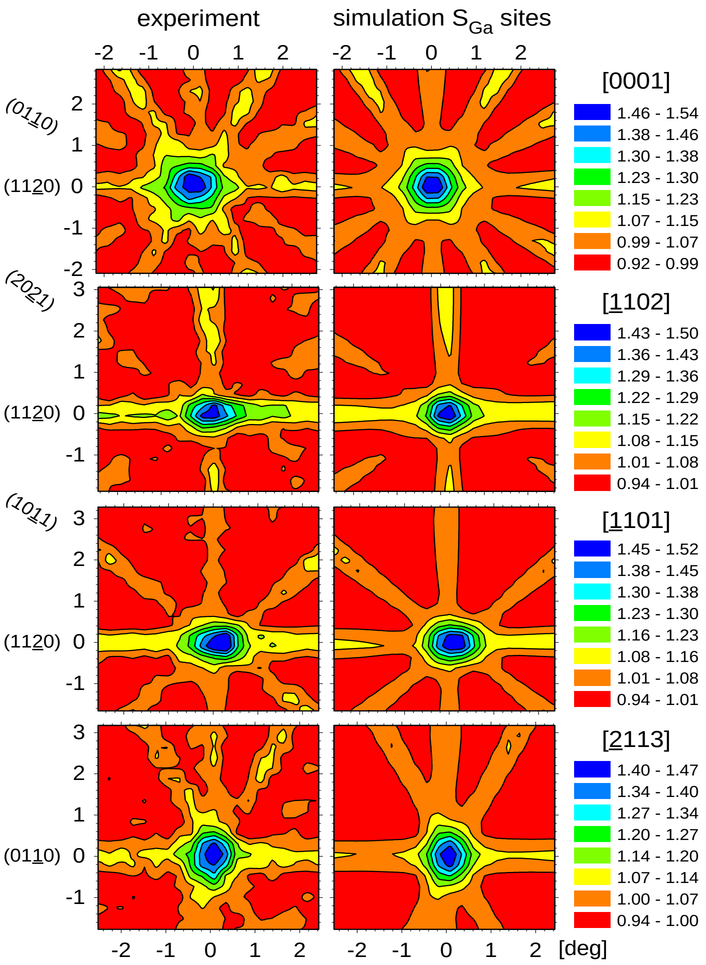
The Nicole On-Line Nuclear Orientation facility comprises a large 3He/4He refrigerator with room temperature side access through which an ion beam from ISOLDE can be introduced to impinge upon a suitable metallic foil maintained at temperatures down to below 10 millkelvin. Using ferromagnetic foils, the implanted nuclei experience hyperfine magnetic fields of order 20 – 200 T, sufficient to produce large degrees of nuclear polarization subject to a spin-lattice relaxation time which can vary between hours and milliseconds.

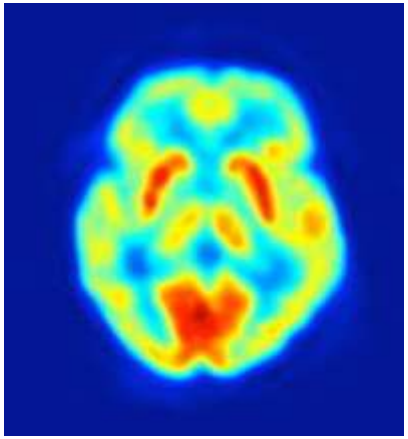
WITCH

The WITCH experiment has been set up for investigation of the weak interaction focussing on the β-ν angular correlation coefficient . This is determined by measuring the recoil energy distribution of daughter nuclei after β decay. A precision experiment with e.g. 35Ar will set new limits for a scalar contribution to weak interaction.

Societal Applications and Benefits

Nuclear Physics Tools and Applications

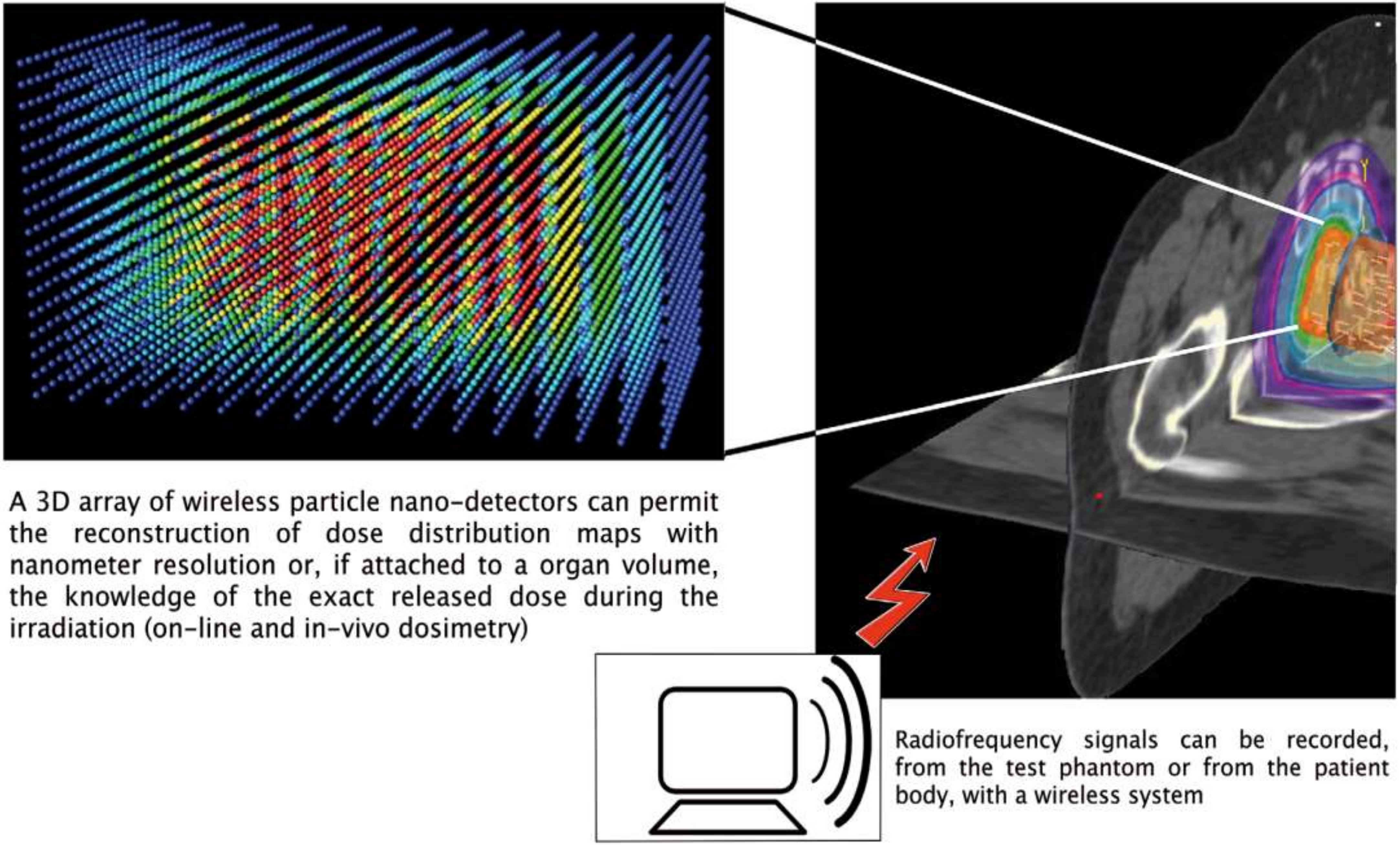




Life Sciences

- ***Key Questions***
- What can Nuclear Physics bring in therapeutic applications?
- How can nuclear physics techniques improve diagnostics methods?
- What are the risks of low-level radioactivity?

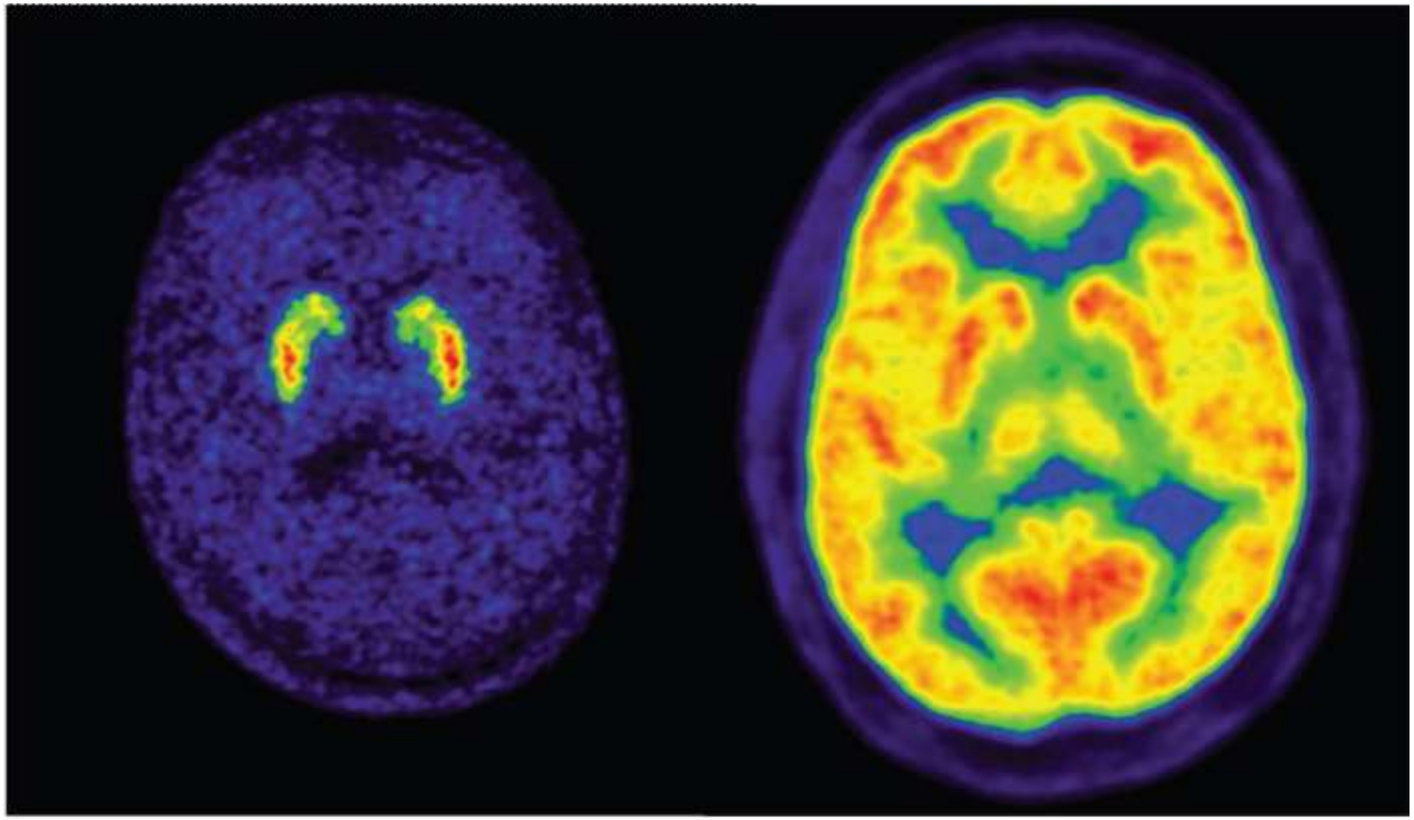
- ***Key Issues***
- New methods for producing radioisotopes for medicine, new isotopes
- Assessment of the benefits of hadron-therapy
- Improvement of the quality of imaging technologies decreasing the dose to the patient
- Development of radiobiology studies



A 3D array of wireless particle nano-detectors can permit the reconstruction of dose distribution maps with nanometer resolution or, if attached to a organ volume, the knowledge of the exact released dose during the irradiation (on-line and in-vivo dosimetry)

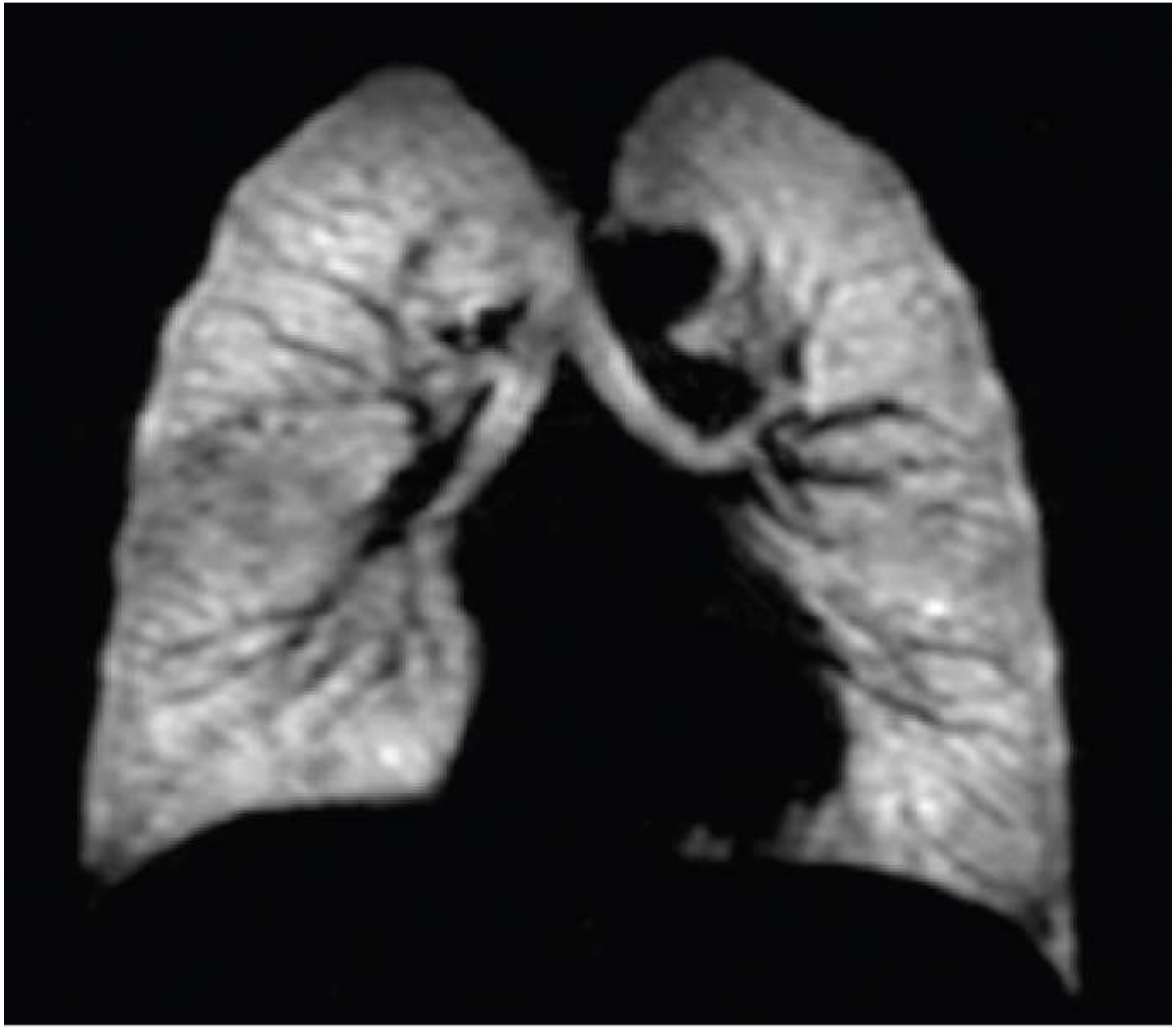
Radiofrequency signals can be recorded, from the test phantom or from the patient body, with a wireless system

DIAGNOSING AND CURING MEDICAL CONDITIONS



PET is a powerful tool to probe the functions of the brain. In these images of the brain, the radionuclide is fluorine-18 while the molecules for each image obviously have different biodistributions. The left-hand figure shows fluorodopa (to probe dopamine integrity) while the right-hand figure shows fluorodeoxyglucose (to probe sugar metabolism).

SOURCE: Courtesy of Don Wilson, British Columbia Cancer Agency



The use of polarized helium-3 has also led to a new MRI technique for imaging the gas space of the lungs: ***noble gas imaging***. This is a good illustration of the spin-off applications of fundamental research.

SOURCE: Courtesy of Gordon Cates, University of Virginia.

New Radioisotopes for Targeted Radioimmunotherapy

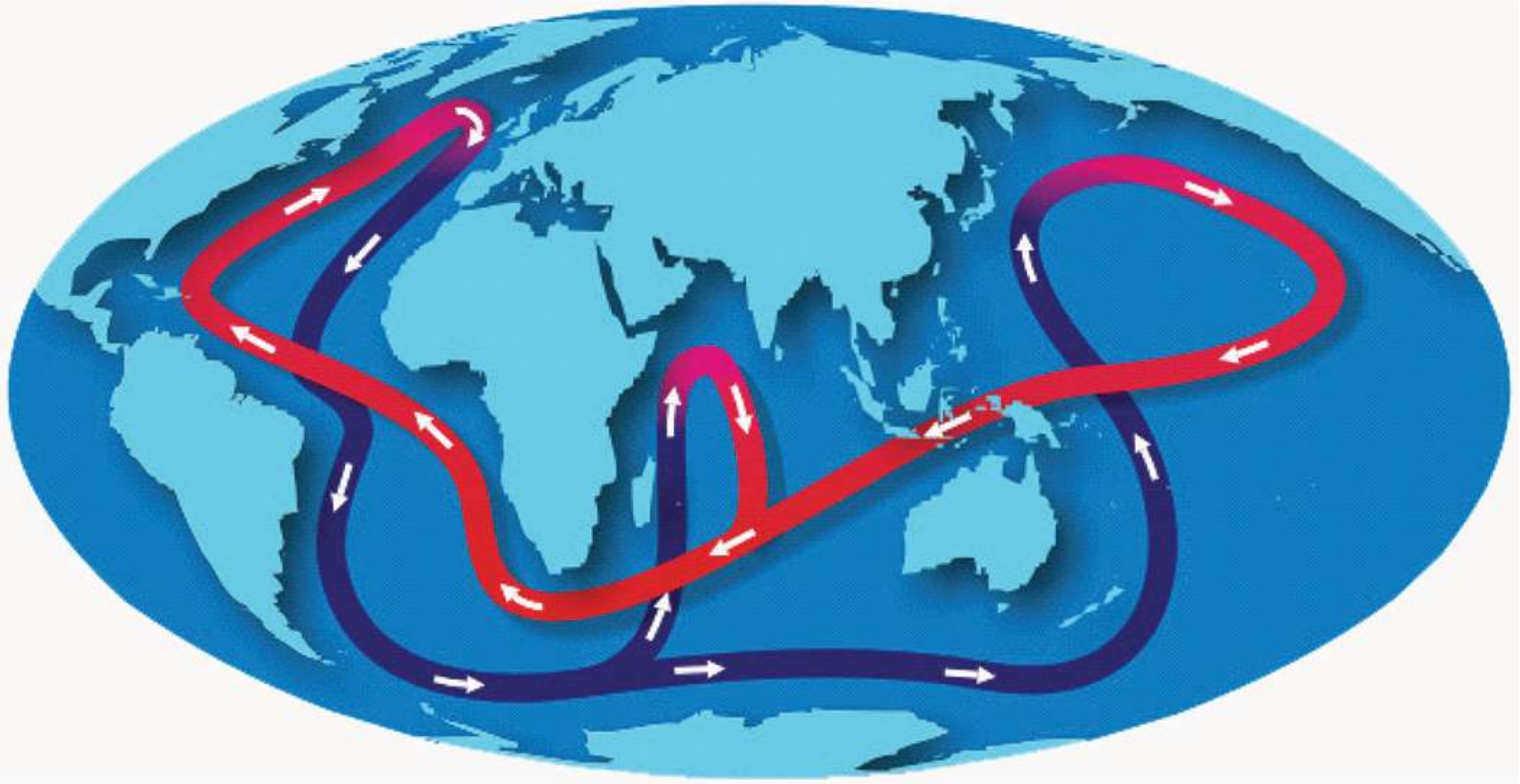
- Radiopharmaceuticals have been developed that can be targeted directly at the organ being treated. These therapy radiopharmaceuticals rely on the destructive power of ionizing radiation at short ranges, which minimizes damage to neighboring organs. A frontier direction is ***targeted radiopharmaceuticals***. This involves attaching a relatively short-lived radioactive isotope that decays via high-energy transfer radiation (alpha-particle emission, for example) to a biologically active molecule, like a monoclonal antibody that has a high affinity for binding to receptors on cancer tumors.

- Many research efforts are focused on the production of alternative isotopes with superior cytotoxicity for use in therapy. A promising class of isotopes is those that decay by alpha emission, since alpha particles have a very short range in tissue, resulting in an enhanced cytotoxicity. The radionuclide ***actinium-225*** combines several favorable properties, including a half-life of 10 days, high alpha-particle energy, versatile coordination chemistry, and several alpha-emitting daughter isotopes.

CARBON-EMISSION-FREE ENERGY FOR THE FUTURE

- Nuclear Fission Energy : Next generation fission reactors; Accelerator-driven systems for nuclear waste transmutation
- Nuclear Fusion Energy: Fusion reactors (ITER)

- ***Key Question:***
- How can Nuclear Physics contribute to the sustainability and acceptability of nuclear energy generation?
- ***Key Issues***
- Accurate nuclear data for the design of new generation reactors
- Study and modeling of nuclear reactions involved in transmutation processes or new fuel cycles
- Modern Nuclear Physics tools (accelerators, detectors, modeling techniques,..) applied to the design and construction of next generation fission/fusion reactors and incineration factories



Thermohaline circulation, commonly referred to as the ocean “conveyor belt,” is made up of ocean currents that transport heat from the tropics to the polar regions. AMS of the radioactive isotope argon-39 will be used to explore this conveyor belt and its impact on climate.

SOURCE: National Oceanic and Atmospheric Administration.

Security

- ***Key Questions:***

• Which new, or modifications of existing Nuclear Physics tools are needed to cope with new requirements regarding homeland security?

• Can neutrinos be used as a probe for non-proliferation control?

- ***Key issues:***

• Portable highly sensitive detector systems for ionizing radiation

• An improved high intensity neutron generator

• Requirement for β-emitter decay data for non-proliferation control

• Smaller and improved Accelerator Mass Spectrometry (AMS) systems

Applications in Material Science and Other Fundamental Domains

- ***Key Questions:***
- How do materials behave under extreme conditions?
- Can we understand interatomic interactions (e.g. bond formation) at extremely short time scales?
- Can nuclear physics help to visualize dynamics of ion-beam processes where other techniques fail?

- ***Key Issues:***
- Understanding and characterization of material properties
- Controlled modification and nanostructuring of materials

Cultural Heritage, Arts and Archaeology

- ***Key Question:***

- How to improve non-destructive in-depth elemental analysis?
- How to improve dating techniques?

- ***Key Issues:***

- New developments in IBA techniques
- Portable devices
- Higher precision radiocarbon measurements using AMS
- Improved communication between the different disciplines

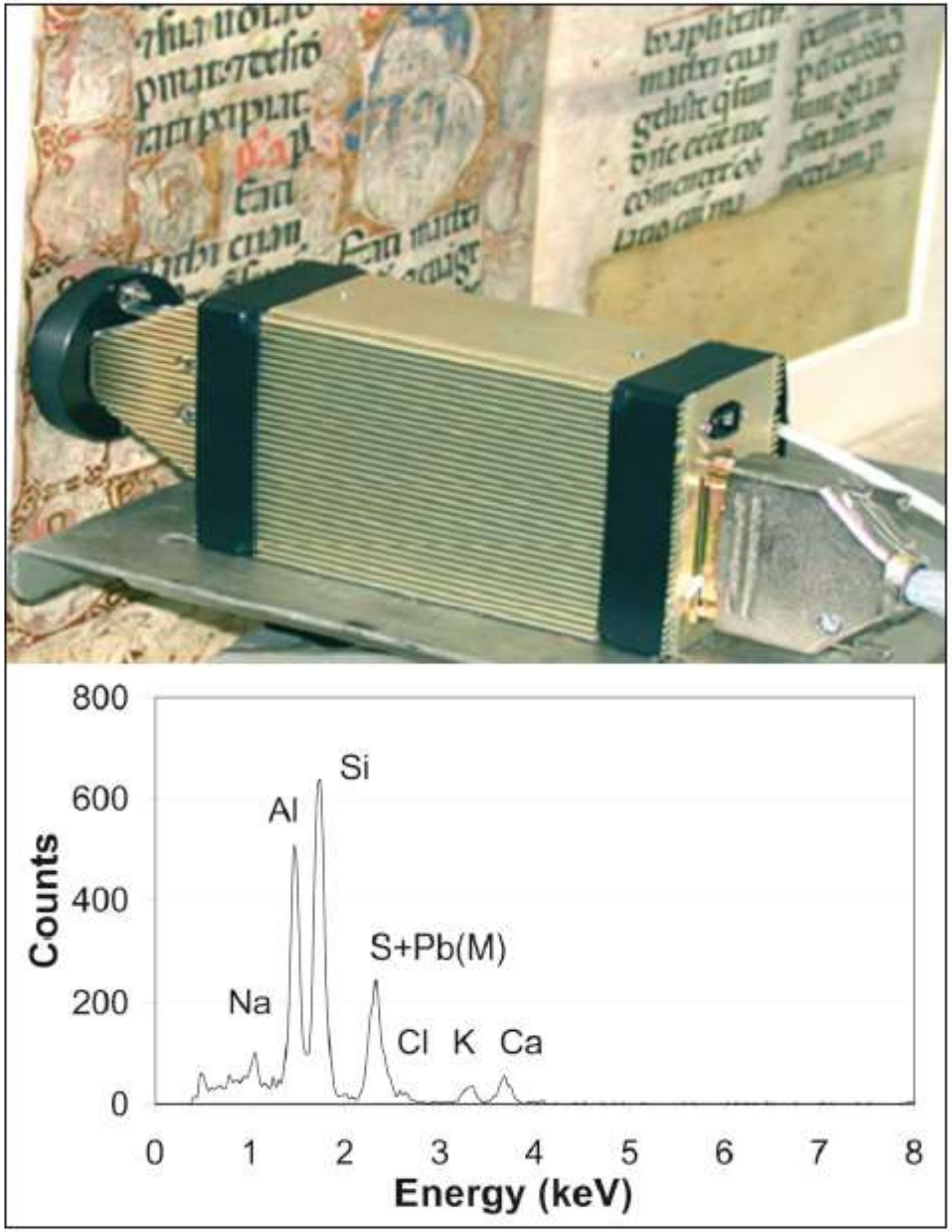


Figure 6. PIXE-α system (^{210}Po) measuring a gold preparation in a Pontificale from Salerno; the x-ray spectrum features an efficient excitation of light elements.

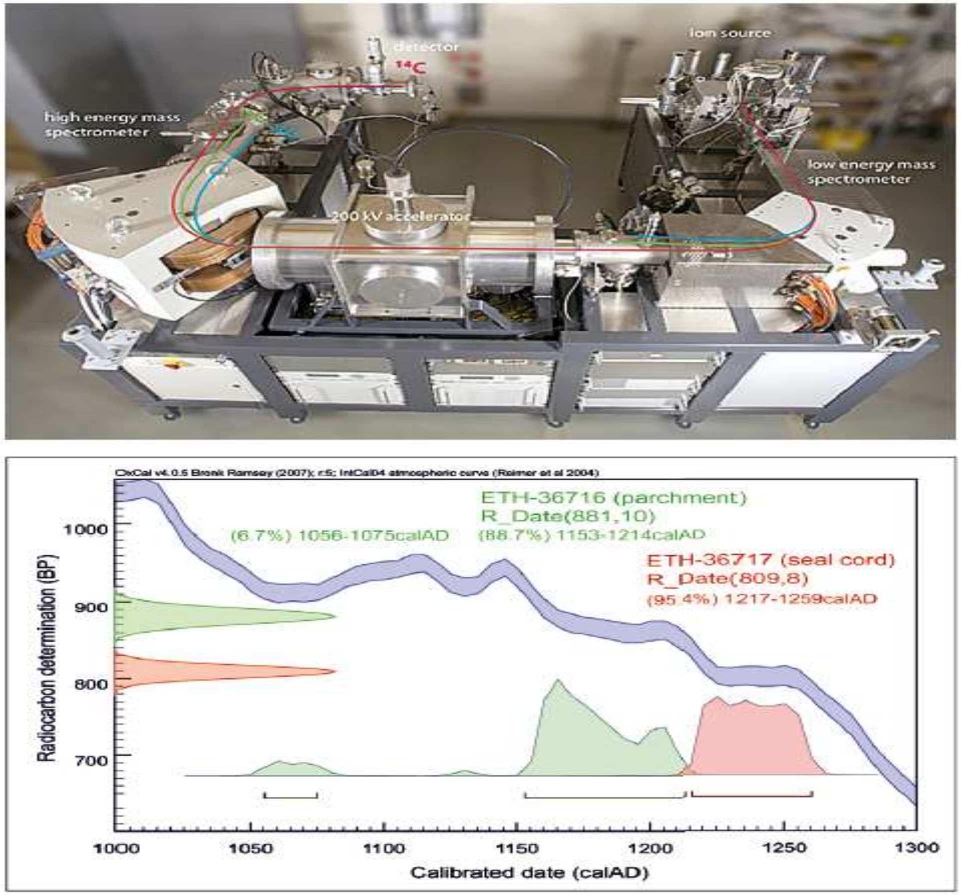


Figure 7. The new generation Accelerator Mass Spectrometry (AMS) system MICADAS developed at ETH Zurich is based on a 200 kV accelerator and allows routine measurements of ^{14}C at a very compact facility. This concept of a compact and easy-to-tune AMS system is attractive to many areas where ^{14}C measurements play a role ranging from routing ^{14}C dating to biomedical and environmental applications. The excellent stability of the system allows also highest-precision ^{14}C measurements as it is demonstrated by the dating the parchment and the seal cord of the "Goldene Handfeste" of Berne, Switzerland. This document established the town privileges making it an Imperial Free City and, effectively, an independent state. Highest-precision ^{14}C measurements can help to solve the ongoing controversy among scholars that the document might be a Bernese forgery from the middle of the 13th century.

New Frontiers in Nuclear Physics Tools

- ***Key Question:***

- What is needed for major advances in particle accelerator and radiation detectors technology?

- ***Key Issues:***

- High-intensity accelerators for Accelerator Driven Subcritical Reactors (ADSRs), ISOL based facilities, and the European Spallation Sources (ESS)
- Laser acceleration techniques
- Radiation hard, fast detectors with low material budget

Nuclear Physics in Serbia

- ***Present status in Serbia***
- Was the most developed scientific field until 1970ties
- From the '90ties sharp drop due to the moratorium on nuclear power plants
- Permanent decrease in the budgeting, equipping and public interest
- Serious ageing of the manpower
- Lack of nuclear related scientific machines (reactors, accelerators)
- Developed observational techniques
- International collaboration

- Research activities in four institutions
- Vinca Institute - Belgrade,
- UNSPMF – Novi Sad,
- Institute of Physics – Belgrade,
- Fac. of Sci. – University of Kragujevac
- Master education (embedded in general physics) at four universities:
- Belgrade, Novi Sad, Nis, Kragujevac
- PhD studies : Novi Sad, Belgrade
- Total number of researchers in the field – about 150

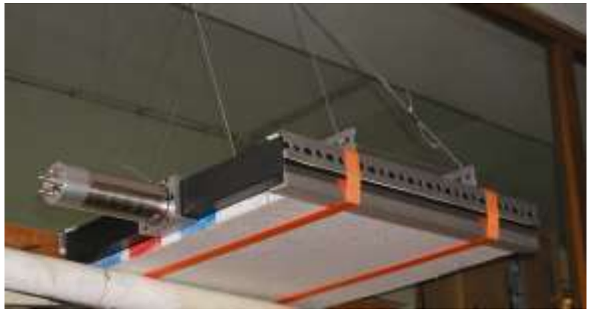
The Nuclear Physics Group in Novi Sad

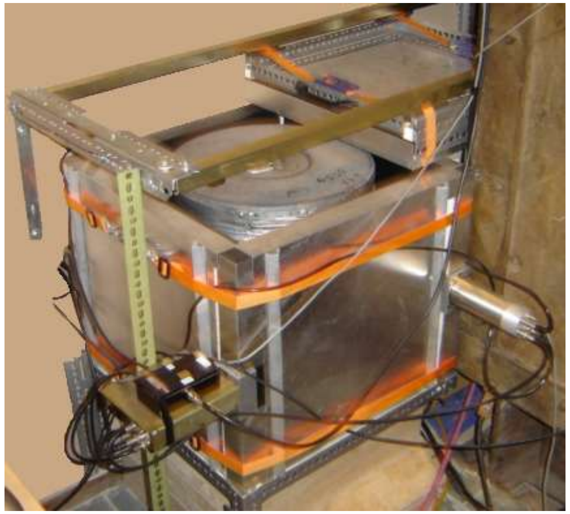
Background :

nuclear structure studies by γ,β spectroscopy ;

γ-γ,γ-β coincidences ,

γ-γ, γ-β directional angular correlations, nuclear orientations





Present:

- University based research group (***rare nuclear events, double beta decay, cosmic ray physics, muon induced nuclear reactions***)
- Public services in radiation protection (gamma spectrometry, field alpha, beta, gamma, neutron dosimetry, non-ionising radiation, radon)
- Expertise in low-level gamma spectroscopy (common high sensitivity direct, coincidence, anticoincidence methods for fundamental and applied research)

Nuclear Science

*N*uclear Science is the study of the structure, properties, and interactions of the atomic nuclei. Nuclear scientists calculate and measure the masses, shapes, sizes, and decays of nuclei at rest and in collisions. They ask questions, such as: Why do nucleons stay in the nucleus? What combinations of protons and neutrons are possible? What happens when nuclei are compressed or rapidly rotated? What is the origin of the nuclei found on Earth?

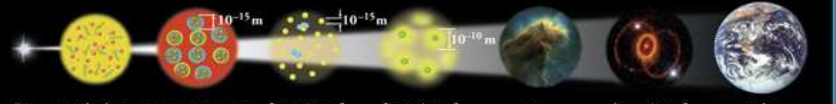
Legend
- *proton*
- *neutron*
- *electron (e^-)*
- *positron (e^+)*
- *neutrino (ν)*
- *antineutrino ($\bar{\nu}$)*
- *quark*
- *gluon field*
- *gluon*
- *photon (γ)*

$A_{\text{number}}^{\text{mass}}$ $Z_{\text{number}}^{\text{atomic}}$ $^{14}_{6}C$

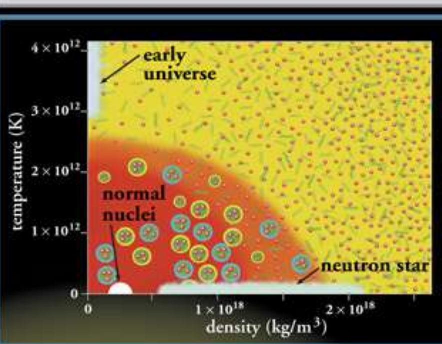
$N_{\text{number}}^{\text{neutron}} = A - Z$

Expansion of the Universe

*A*fter the Big Bang, the universe expanded and cooled. At about 10^{-6} second, the universe consisted of a soup of quarks, gluons, electrons, and neutrinos. When the temperature of the Universe, T_{universe}, cooled to about 10^{12} K, this soup coalesced into protons, neutrons, and electrons. As time progressed, some of the protons and neutrons formed deuterium, helium, and lithium nuclei. Still later, electrons combined with protons and these low-mass nuclei to form neutral atoms. Due to gravity, clouds of atoms contracted into stars, where hydrogen and helium fused into more massive chemical elements. Exploding stars (supernovae) form the most massive elements and disperse them into space. Our earth was formed from supernova debris.



	Big Bang	quark-gluon plasma	proton & neutron formation	formation of low-mass nuclei	formation of neutral atoms	star formation	dispersion of massive elements	today
T_{universe}		$>10^{12}$ K	10^{12} K	10^{9} K	4,000 K	50 K–3 K	<50 K–3 K	3 K
time		10^{-6} s	10^{-4} s	3 min	400,000 yr	3×10^{8} yr	$>3 \times 10^{8}$ yr	14×10^{9} yr

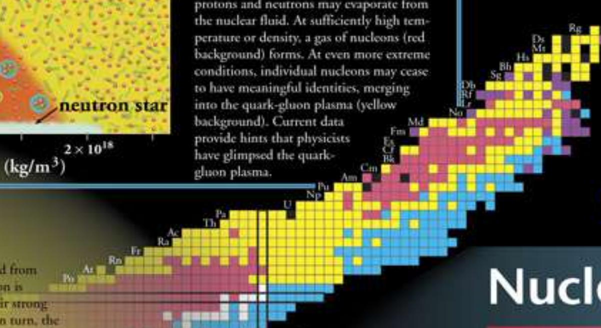


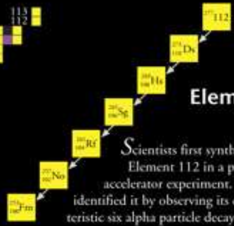
Phases of Nuclear Matter

*N*uclear matter can exist in several phases. When collisions excite nuclei, individual protons and neutrons may evaporate from the nuclear fluid. At sufficiently high temperature or density, a gas of nucleons (red background) forms. At even more extreme conditions, individual nucleons may cease to have meaningful identities, merging into the quark-gluon plasma (yellow background). Current data provide hints that physicists have glimpsed the quark-gluon plasma.

Unstable Nuclei

*S*table nuclides form a narrow white band on the Chart of the Nuclides. Scientists produce unstable nuclides far from this band and study their decays, thereby learning about the extremes of nuclear conditions. In its present form, this chart contains about 2500 different nuclides. Nuclear theory predicts that there are at least 4000 more to be discovered with Z ≤ 113.

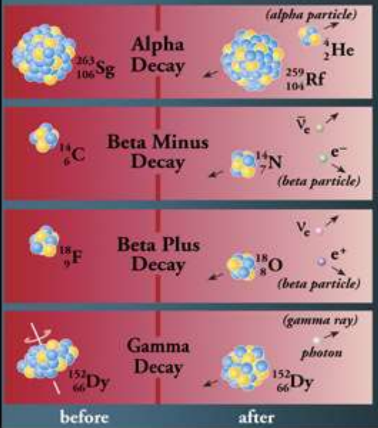




Element 112

*S*cientists first synthesized Element 112 in a particle accelerator experiment. They identified it by observing its characteristic six alpha particle decay chain.

Radioactivity

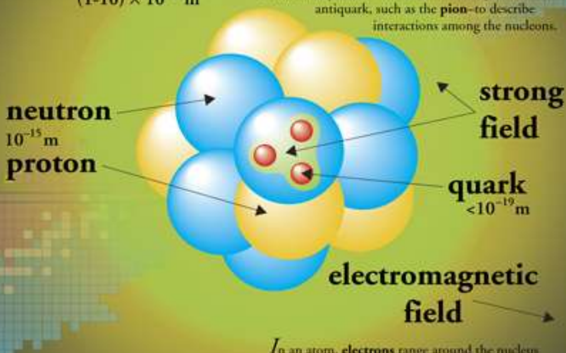


*R*adioactive decay transforms a nucleus by emitting different particles. In **alpha** decay, the nucleus releases a $^{4}_{2}$He nucleus –an alpha particle. In **beta** decay, the nucleus either emits an electron and antineutrino (or a positron and neutrino) or captures an atomic electron and emits a neutrino. A positron is the name for the antiparticle of the electron. Antimatter is composed of antiparticles. Both alpha and beta decays change the original nucleus into a nucleus of a different chemical element. In **gamma** decay, the nucleus lowers its internal energy by emitting a photon–a gamma ray. This decay does not modify the chemical properties of the atom.

The Nucleus

(1-10) × 10^{-15} m

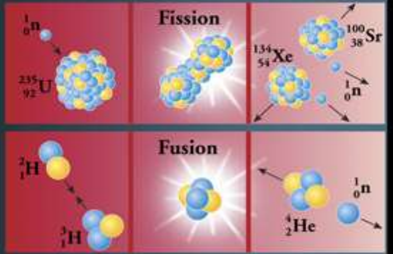
*A*t the center of the atom is a nucleus formed from **nucleons**–protons and neutrons. Each nucleon is made from three **quarks** held together by their strong interactions, which are mediated by gluons. In turn, the nucleus is held together by the **strong** interactions between the gluon and quark constituents of neighboring nucleons. Nuclear physicists often use the exchange of mesons–particles which consist of a quark and an antiquark, such as the **pion**–to describe interactions among the nucleons.



*I*n an atom, **electrons** range around the nucleus at distances typically up to 10,000 times the nuclear diameter. If the electron cloud were shown to scale, this chart would cover a small town.

Nuclear Energy

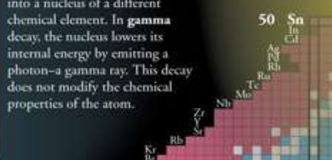
*N*uclear reactions release energy when the total mass of the products is less than the sum of the masses of the initial nuclei. The "lost mass" appears as kinetic energy of the products ($E = mc^2$). In fission, a massive nucleus splits into two major fragments that usually eject one or more neutrons. In fusion, low mass nuclei combine to form a more massive nucleus plus one or more ejected particles—neutrons, protons, photons, or alpha particles.

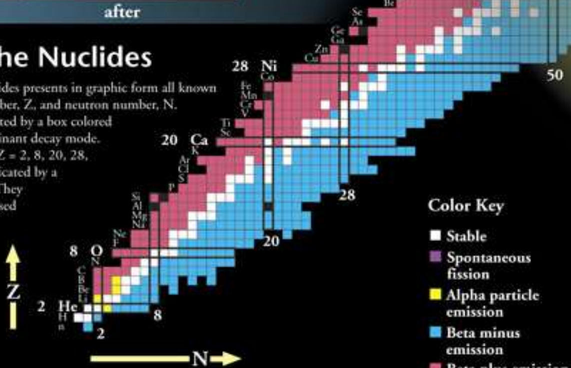


*I*n the early stages of stellar evolution of our sun and other stars, hydrogen fuses to form helium, releasing energy in the form of photons (light) and neutrinos. During the later stages of stellar evolution, more massive nuclei up to and beyond uranium are synthesized by fusion. By measuring the number of neutrinos that come from the Sun, scientists recently have demonstrated that neutrinos must have a mass greater than zero.

Chart of the Nuclides

*T*he Chart of the Nuclides presents in graphic form all known nuclei with atomic number, Z, and neutron number, N. Each nuclide is represented by a box colored according to its predominant decay mode. **Magic numbers** (N or Z = 2, 8, 20, 28, 50, 82 and 126) are indicated by a rectangle on the chart. They correspond to major closed shells and show regions of greater nuclear binding energy.





Color Key
- ⬜ **Stable**
- 🟪 **Spontaneous fission**
- 🟨 **Alpha particle emission**
- 🟦 **Beta minus emission**
- 🟥 **Beta plus emission or electron capture**

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Applications

Radioactive Dating

*N*aturally occurring radioactive isotopes such as $^{14}_{6}C$ are used to date objects that were once living, such as wood. For example, from a study of artifacts found at the site, scientists determined that Stonehenge was built nearly 4,000 years ago.

Space Exploration

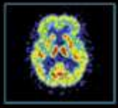
*S*ojourner used alpha particles to identify chemical elements present in Martian rocks. On Earth, nuclear reactions are used in many areas from criminal investigations to art authentication.

Nuclear Reactors

*N*uclear reactors use the fission of $^{235}_{92}U$ or $^{239}_{94}Pu$ nuclei to produce electric power. Reactors and most other nuclear applications generate radioactive waste; disposal of this waste is a subject of current research.

Smoke Detectors

*M*any smoke detectors use a small amount of the alpha emitter $^{241}_{95}Am$ to ionize the air. Smoke entering the detector reduces the current and sets off the alarm.



Nuclear Medicine

*R*adioactive isotopes, such as $^{99m}_{43}Tc$, $^{60}_{27}Co$ and $^{131}_{53}I$, are commonly used in the diagnosis and treatment of disease. Positron emitters such as $^{18}_{9}F$ are used in Positron Emission Tomography (PET) to generate images of brain activity.

Magnetic Resonance Imaging

*M*agnetic Resonance Imaging (MRI) makes use of atomic transitions involving the magnetic field of a nucleus to study the local chemical environment. This technique accurately maps the density of hydrogen to produce three-dimensional images of the human body.

Astrophysical pictures courtesy NASA/JPL/Caltech and AURA/STScI.

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Thank you!