Nuclear Physics Today

Rosa Vlastou

National Technical University of Athens (NTUA)
Department of Physics, Athens, Greece

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I will try to present an **overview** of activities and cover some of **the latest scientific achievements in Nuclear Physics, some of the new phenomena that have been discovered leading to unexpected insights into the nature of the nucleus.** **Applications** in medicine, materials, nuclear energy and associated environmental issues and **the new facilities that are currently constructed in Europe -** Participation of Greek teams

Fundamental Research

- **Nuclear Structure**
- **Nuclear Astrophysics**
- **Fission process**
- **Super Heavy Elements**

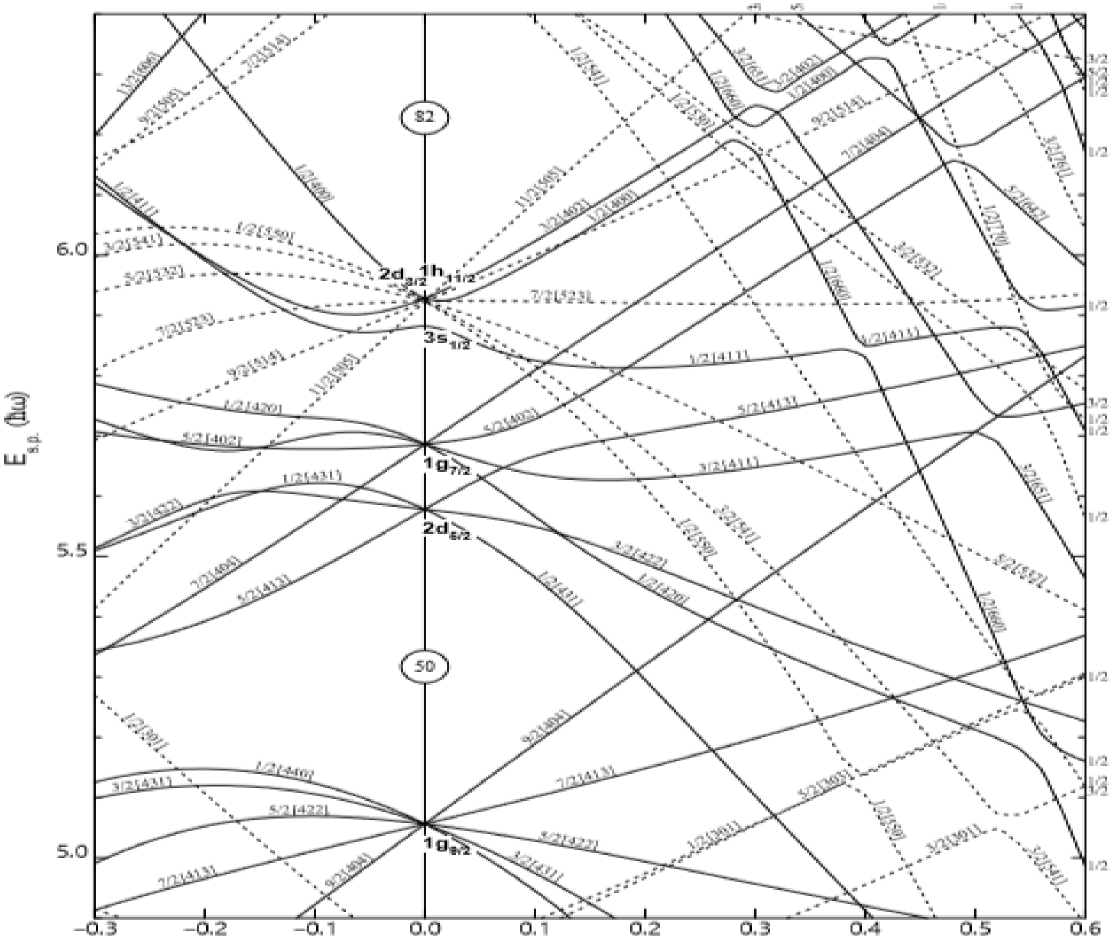
Applications

- **Development and application of Nuclear Analytical Techniques (IBA)**
- **Nuclear Medicine and Imaging**
- **Radioecology-Environmental Radioactivity**
- **Nuclear Technology (Fusion – Fission)**

New Facilities under construction in Europe

- **ITER and MYRRHA facilities**
- **European Spallation Source (ESS)**
- **Facility for Antiproton and Ion Research (FAIR)**
- **Neutrons For Science (NFS)**

Nuclear Structure : the advent of Heavy Ion Beams at High Energy and high-resolution gamma-ray detector arrays, led to the discovery of superdeformation, hyperdeformation, shape coexistence and new magic numbers in nuclei and more recently the Radioactive Ion Beams (RIBs) led to the investigation of more exotic shapes and exotic nuclei far from stability.



Oblate deformation *Prolate deformation*

Nilsson diagram

p and *n* move in well defined orbits inside the nucleus as *e* do inside the atom. What happens to the Shell Model energy levels in a deformed nucleus ? Evolution of shell structure – splitting of levels rather than 2j+1 degeneracy – **new magic numbers**

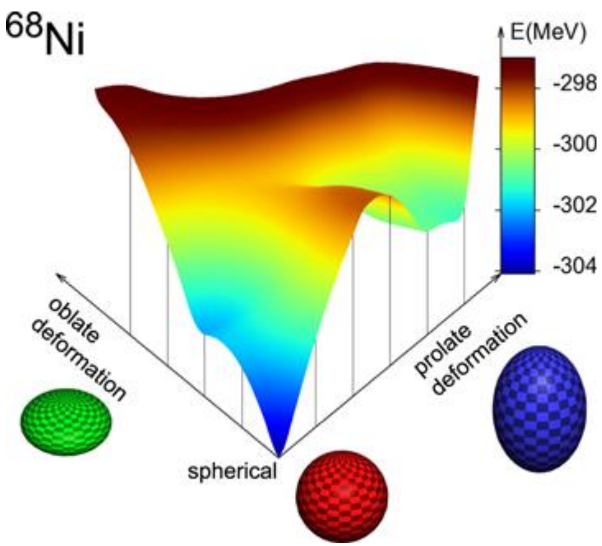
Experimental work at:
NTUA, Demokritos
Theoretical work at:
Demokritos, AUTH

Shapes of nuclei

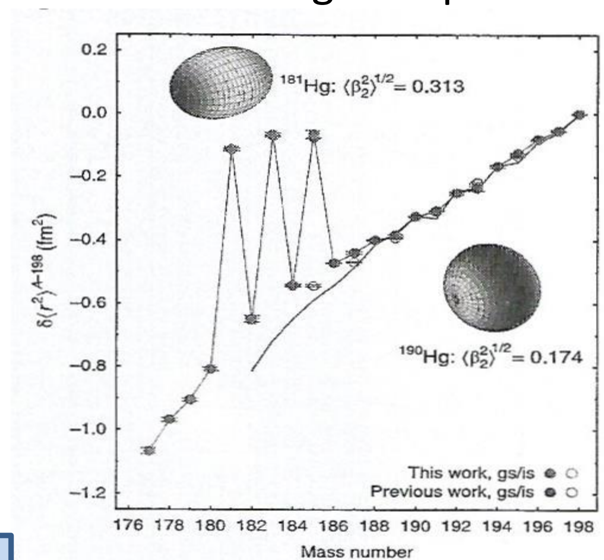
- **Exotic Shapes of nuclei - Rugby or football?**

Measurements of E/M properties of nuclei, quadrupole and dipole moments, g-factors etc. led to the conclusion that quantum correlations between the nucleons and excitation of coherent correlated pairs of nucleons between Nilsson states, drive the whole nucleus into more exotic shapes such as **pears or bananas (octupole and decaexapole deformations)**.

- **Shape coexistence** even in light nuclei and at low excitation energy



- Recent CERN press release from **ISOLDE** : **shape-staggering effect** between odd and even neutron deficient **Hg isotopes** : the removal of a single neutron in Hg isotopes 181-182-183-184-185-186

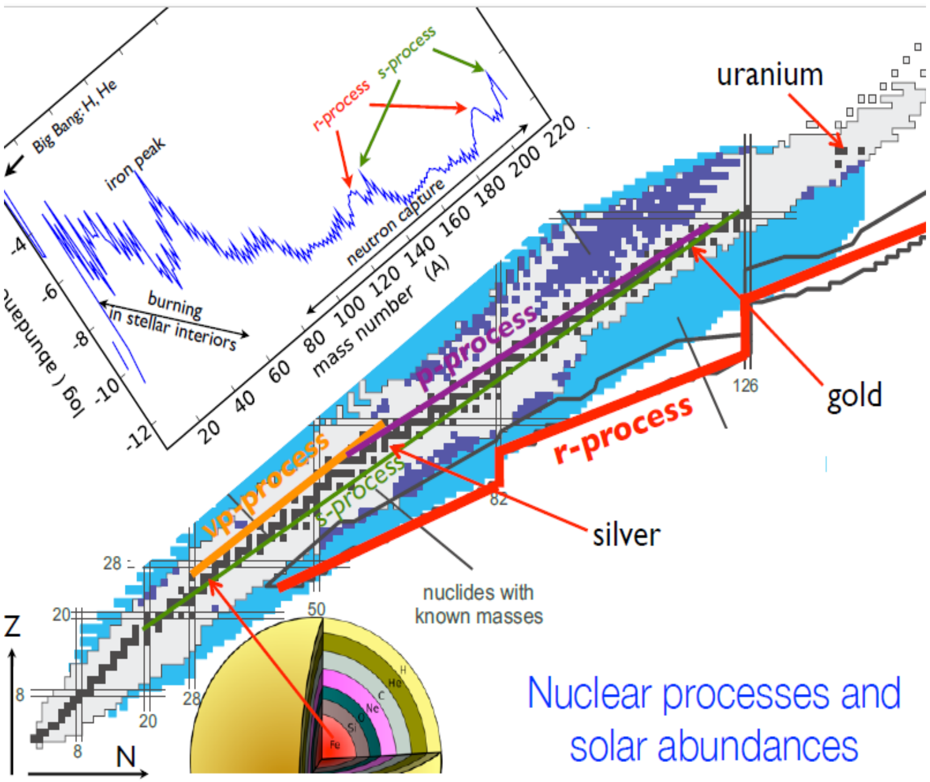


- Using the most advanced computational methods, **Monte Carlo Shell Model calculations** indicate an interplay between monopole and quadrupole interactions driving a quantum phase transition and identify specific participating orbitals for four p: $h_{11/2}$ and eight n: $i_{13/2}$ orbitals

Experimental work at UoI , NKUA, NCSR Demokritos
Theoretical work at NCSR Demokritos

Nuclear Reactions : Nuclear Astrophysics

Stars shine and evolve because nuclear reactions take place in their interiors. To understand stellar evolution and nucleosynthesis, cross section measurements are of major importance in nuclear astrophysics.



Elements up to Fe-Ni are produced by charged-particle reactions. The heavier elements, due to the Coulomb Barrier, are produced by neutron capture followed by β-decays.

- s-process (up to 10^{12} n/cm^3 – 10^8K)
- r-process (>10^{20} n/cm^3 – 10^9K)
- p-process (for 35 isotopes ^{74}Se-^{196}Hg)

Challenge

Cross sections for 20000 nuclear reactions are needed involving 2000 isotopes. **Radioactive Ion Beams (RIBs)**

Solution

Theoretical calculations using Hauser-Feshbach statistical model calculations

Experimental work at NCSR Demokritos and NKUA in the tandem accelerator and abroad
Theoretical work at NCSR Demokritos and AUTH

- **Re/Os cosmochronometer**

The long half-life of 41.2Gyr makes ^{187}Re an important potential cosmochronometer for the determination of the age of the galaxy via its β–decay.

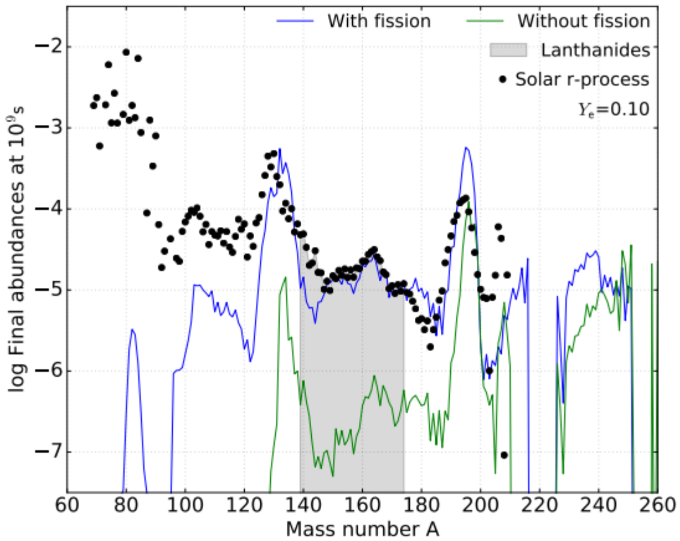
^{187}Re can be attributed to the r-process in supernova explosions and can be analyzed in terms of the daughter nucleus ^{187}Os, which can be determined by subtraction of the s-process component defined by the abundance of the s-only nucleus ^{186}Os via s-process systematics .

Neutron capture cross sections (n,γ) of ^{186}Os , ^{187}Os and ^{188}Os isotopes measured at the **CERN nTOF facility** led to independent results from the Re/Os clock, in agreement with other dating methods based on astronomical observations (Hubble age, globular cluster ages, U/Th abudances and cosmic microwave background).

- **Fission in r-process nucleosynthesis**

Neutron-induced, β-delayed and spontaneous fission reactions play a key role in the nucleosynthesis of heavy elements, that takes place in the Universe following explosive events like Supernovae or Neutron Star Mergers.

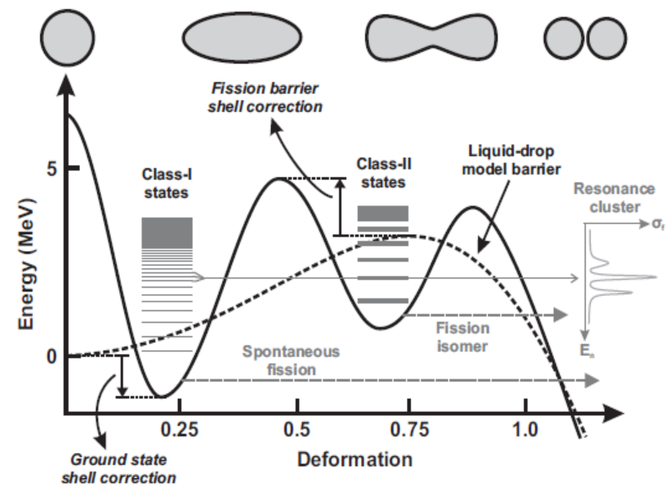
New project for the Phase-4 nTOF facility at CERN in 2022.



NTUA and UoI

Nuclear Reactions : Understanding of fission process

Although significant progress has been made since the discovery of fission over 70 years ago, the complexity of the phenomenon, with **an interplay both of collective effects in the nucleus and single-particle interactions.** The liquid-drop estimate of the nuclear energy as a function of deformation and superposition of shell corrections and the pairing terms results in a **double-humped potential**



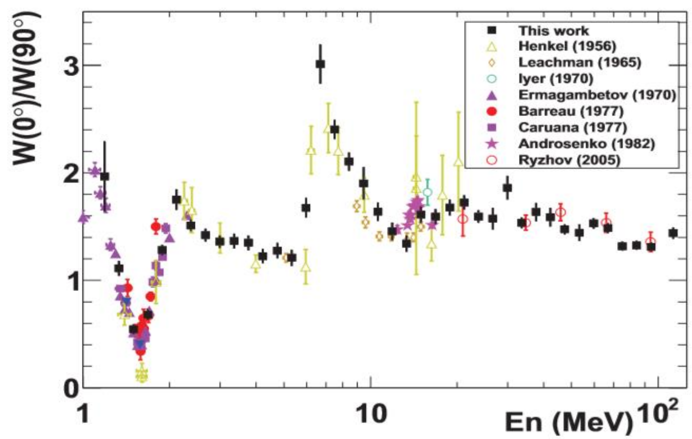


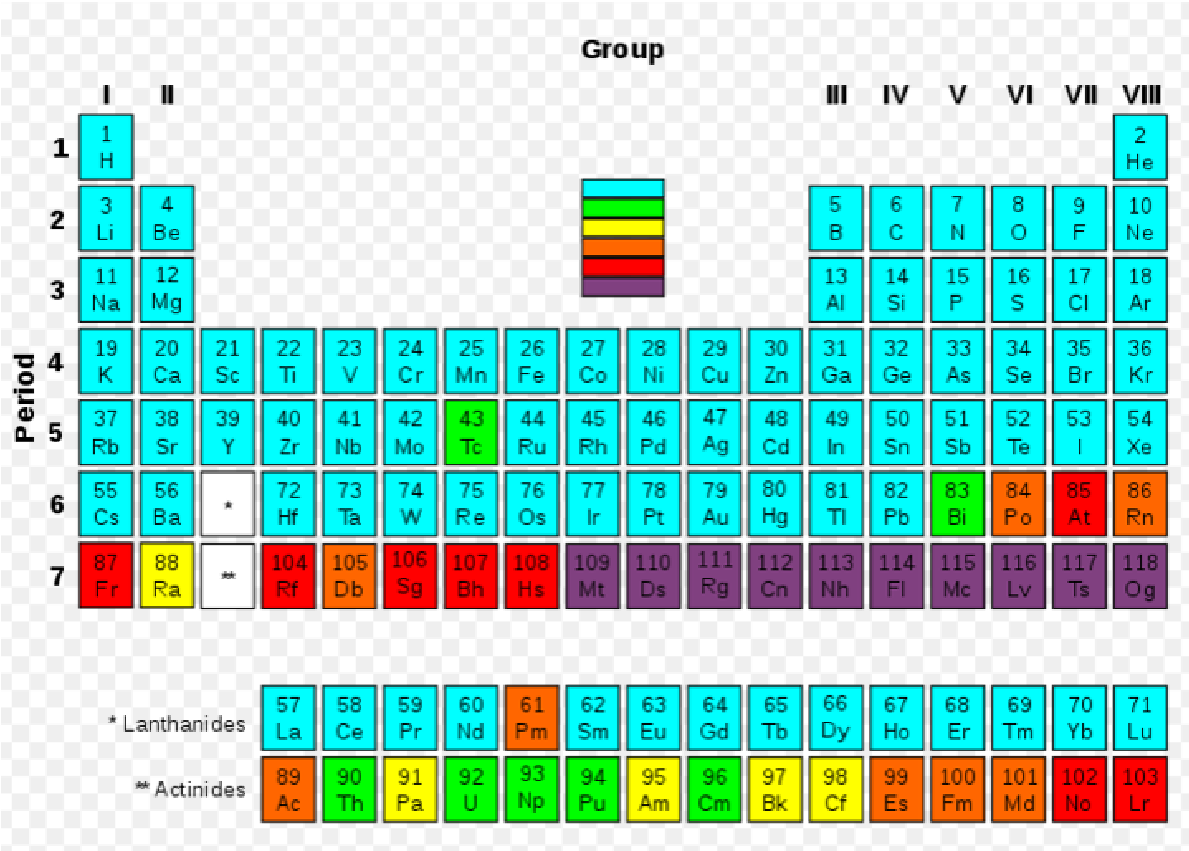
FIG. 4: Anisotropy parameter for the ^{232}Th(n,f) reaction.

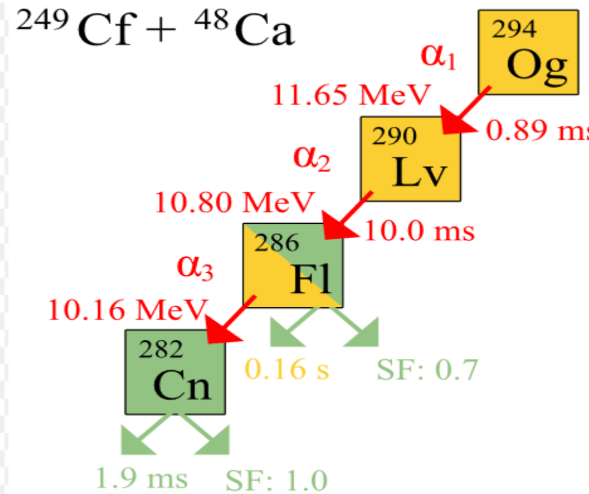
Measured at the CERN nTOF facility

- Coupling of class-I and class-II states
- Fission Isomers
- Although fission fragments are expected to be emitted isotropically, recently strong angular distribution effects have been observed.
- Importance of accurate high energy fission cross sections for nuclear energy, mainly in ADS and Generation_IV reactors

NTUA and UoI at nTOF and at the Demokritos tandem accelerator
AUTH in Dubna, NKUA/UoI at Texas A&M

Super Heavy Elements (SHE)





118: Oganesson
117: Tennessine
116: Livermorium
115: Moscovium
114: Flerovium
113: Nihonium

The 7th row of the periodic table of the elements is now complete - RIBs

Nobelium isotopes are more robust than expected and survive against fission. ^{254}No has been studied via the ^{48}Ca +^{208}Pb reaction up to spin 20ħ and with a cross section of ~3μb

Laurence Berkeley Laboratory, Argonne, Jyvaskyla, Dubna, GSI, RIKEN

Applications

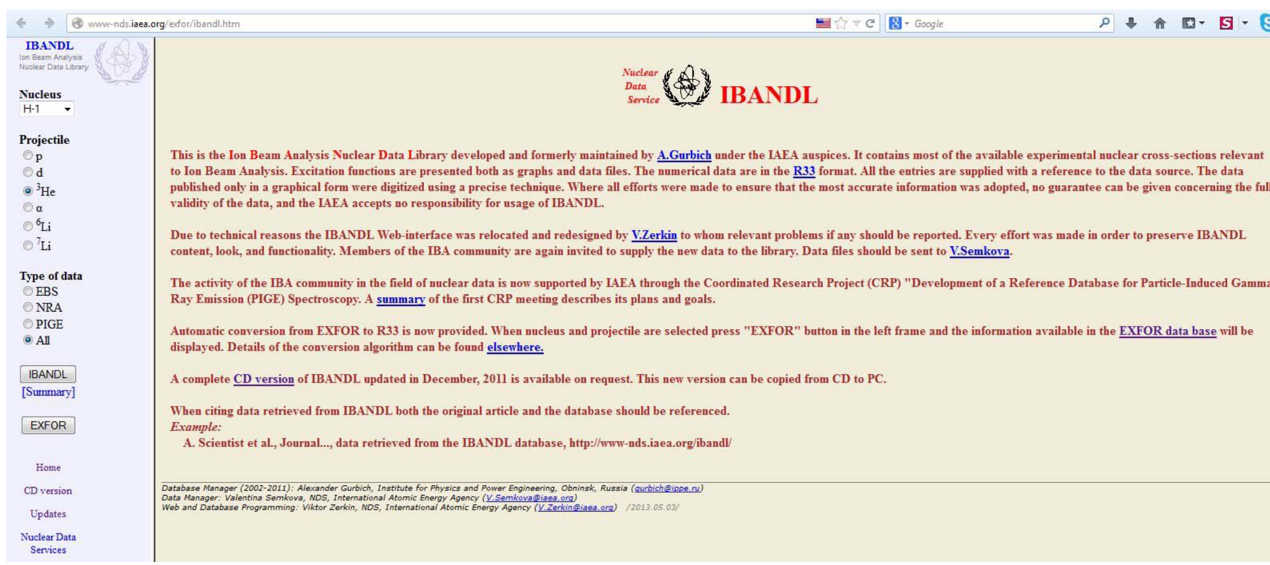
Development and application of Nuclear Analytical Techniques (IBA)
NAA, PIGE, PIXE, RBS, ERDA, NRA

NRA: Well–established nowadays as one of the principal IBA techniques for accurate stoichiometry and quantitative depth profiling of light elements in complex matrices – Cross sections of **Resonance reactions** are needed.

- **Deuteron induced reactions on light elements** (C, N, B, Li, F, S) relevant to materials analysis

- Development of an **IAEA reference data base** for ion beam analysis

Demokritos : INRASTES+INPP, NTUA, AUTH, UoI, Obninsc, Surrey, VINCA, IAEA



http://www-nds.iaea.org/exfor/ibandl.htm

Applications

Nuclear Medicine and Imaging

How nuclear research is improving human health

Diagnosis

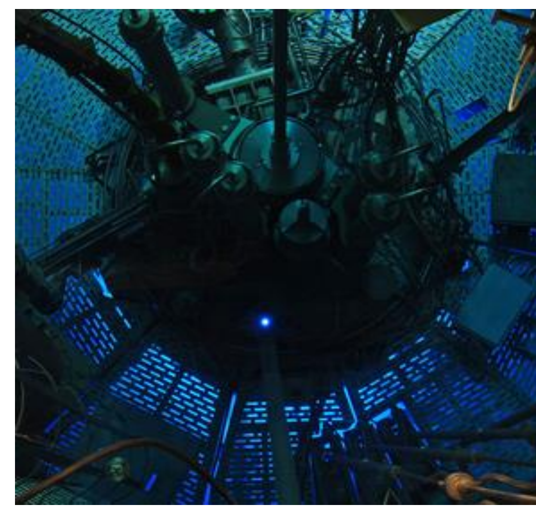
Medical imaging : Gamma-Camera , CT, MRI, SPECT, PET
need for higher resolution ~4mm

Therapy

- Proton therapy (42 centers worldwide)
- Carbon therapy
- BNCT **($n + {}^{10}B \rightarrow {}^{4}He + {}^{7}Li$)**

Research

- **Carriers** to deliver radionuclide to a tumor
- **Radiochemistry :** Radiolabeled nanoparticles, antibodies, biomolecules with ${}^{99m}Tc$, ${}^{186/188}Re$, ${}^{74/77}As$, ${}^{90/95}Nb$ etc.
- **Radiopharmacy** : development and evaluation of radioactive drugs
- **New radioisotopes** with clinical potential (${}^{177}Lu$)



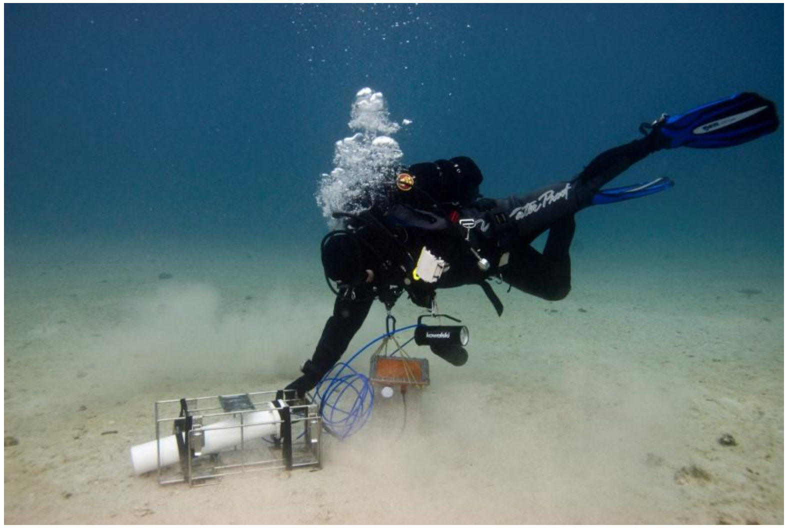
NKUA, UoI, UWA, NTUA (S.El.Eng.), “Demokritos”(INRASTES),

Applications

Radioecology-Environmental Radioactivity

- Levels of environmental radioactivity, natural and athropogenic, in the atmosphere, ground, marine/aquatic environment – monitoring
- Radioactivity in the marine sediments – Monte Carlo simulations
- Estimation of internal and external dose in pelagic fishes - Monte Carlo simulations
- Investigation of atmospheric dispersion of radionuclides, influence of meteorology and pollutant sources distribution in urban pollution
- Study and dispersion of radionuclides in the marine environment
- Influence of active and past mining activities in the ground, marine and costal areas
- Radon concentration and seismology
- Management of radioactive materials and waste
- Development of detection systems for environmental radioactivity

NCSR Demokritos (INRASTES), *NTUA (S.Mec.Eng. & Physics), AUTH, HCMR, UoI, NKUA, Greek AEC in collaboration with IAEA*



Other Applications with impact to the Society

- **Archaeometry – Radiodating (^{14}C, ^{40}K, ^{87}Rb)**
- **NAA in archeomerty and cultural heritage**
- **Accelerator Mass Spectrometry (AMS)**

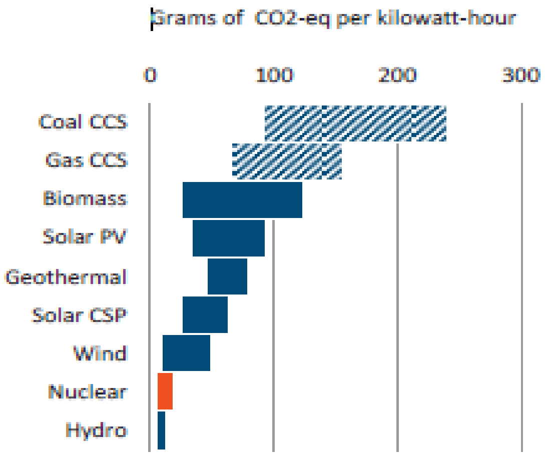
- **Dosimetry**
- **Radiation Protection and Safety**
- **Nuclear Decommissioning and Waste Management**

Demokritos : INRASTES, Greek AEC, AUTH, NKUA, UoI

Applications

Nuclear Technology (Fusion – Fission)

The continuous growth of the human population and the increase in energy consumption, are leading to a rapid increase in global energy demands. The combustion of fossil fuels, which is the main source of energy production, has two main disadvantages: the **greenhouse effect**, as a result of the emission of CO_2 in the atmosphere, and the foreseen **exhaustion of the fuel reserves**.



Nuclear Energy with disadvantages : safety, radioactive waste

Proposed solutions for future **clean and safe nuclear energy**, which are in the R&D phase :

- **Fusion** - the energy source of the sun and stars: $\mathbf{{}^2H + {}^3H \rightarrow {}^4He + n + 17.6\ MeV}$
  T~10^8K, plasma density ~ 10^8 nuclei/m^3, pressure ~3-10bar (**JET, ITER, DEMO**)
- **Fission : ADS** (Accelerator Driven Systems) Reactor using energetic n coming from accelerator, not from chain reactions and ^{232}Th as a fuel **(MYRRHA)** $^{232}Th(n,\gamma)^{233}Th \xrightarrow{\beta^-,\ t_{1/2}=22.3\ m} {}^{233}Pa \xrightarrow{\beta^-,\ t_{1/2}=27\ d} {}^{233}U$
- **Fast neutron Generation IV reactors** : enhanced safety, minimal radioactive waste, transmutation of minor actinides (Pu, Np, Am, Cm) to FFs have much shorter half lives

NCSR Demokritos (INRASTES), *NTUA (S.Mec.Eng. & S.El.Eng.), AUTH, DUTH*

New Facilities under construction in Europe

ITER ("The Way" in Latin) in southern France

ITER is one of the most ambitious energy projects in the world today – bring fusion to the point where a demonstration fusion **D + T reactor** **($^{2}H + {}^{3}H \rightarrow {}^{4}He + n$)** can be designed .

- ITER is the first fusion device to produce **net energy** and **maintain fusion** for long periods of time. In 1997, **JET (Joint European Torus) in Oxfordshire,UK,** produced 16 MW of fusion power from a total input heating power of 24MW (Q=0.67). ITER is designed to produce **500 MW** of fusion power from 50 MW of input heating power **(Q=10)** .
- **ITER** will contribute to the design of the next-generation machine **DEMO** **t**hat will bring fusion research to the threshold of a prototype fusion reactor (after 2040) with **Q=30-50**.
- ITER is the first fusion device to **test** the integrated **technologies, materials, and physics** regimes necessary for the commercial production of fusion-based electricity.
- Test **tritium breeding :** feasibility of producing tritium within the vacuum vessel **($n + {}^{6}Li \rightarrow {}^{3}H + {}^{4}He$) .**

EU, USA, Russia, China, India, Japan, S.Korea
Euratom, IAEA, ANSTO, CERN

ITER's First Plasma is scheduled for December 2026
Deuterium-Tritium Operation begins in 2035

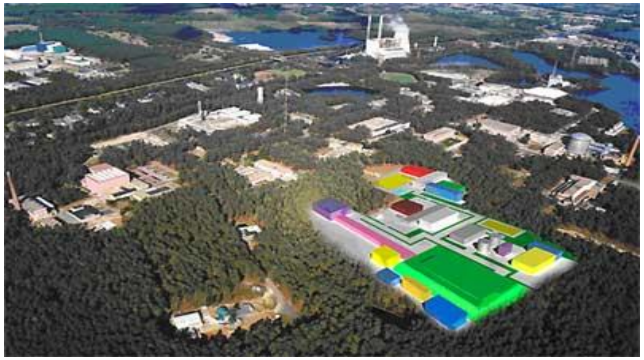
NCSR Demokritos (INRASTES), NTUA (S.El.Engeneering)

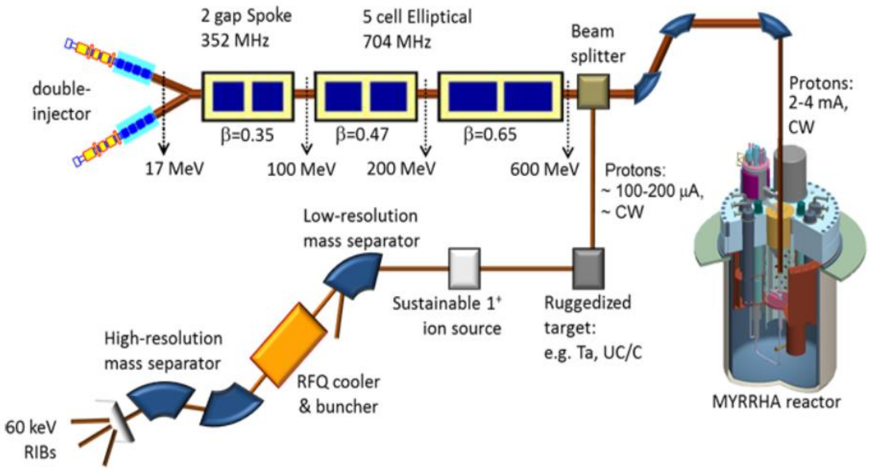
New Facilities under construction in Europe

MYRRHA (Multi-purpose hYbrid Research Reactor for High-tech Applications), Belgium

A multifunctional research facility for innovative applications

- world's first prototype of **ADS** - subcritical lead-bismuth cooled reactor driven by a particle accelerator (4 mA beam of 600 MeV protons). The **particle accelerator** is used as an external neutron source to create the chain reaction.
- **safe and highly controllable** nuclear technology
- **Nuclear waste transmutation**
- **Isotope Separation On-Line (ISOL) infrastructure** that will make a whole new category of experiments possible: ISOL@MYRRHA.
- '**Radioactive Ion Beams**' or RIBs focused on experiments which require **long beam times without interruption**.





Fully operational by 2033

Cost : 6.5 billion euros only for the construction

New Facilities under construction in Europe

European Spallation Source (ESS) in Lund, Sweden

The future facility is composed of a linear accelerator in which protons are accelerated and collide with a rotating, helium-cooled tungsten target – cold neutrons

ESS will provide **neutron beams up to 30 times brighter** than any current neutron source enabling scientific breakthroughs in research related to materials, energy, health and the environment. It will be operational in 2023.

13 European countries , 120 Institutions, ~ 2 billion euros : construction cost

New Facilities under construction in Europe

FAIR (Facility for Antiproton and Ion Research) in Darmstadt, Germany

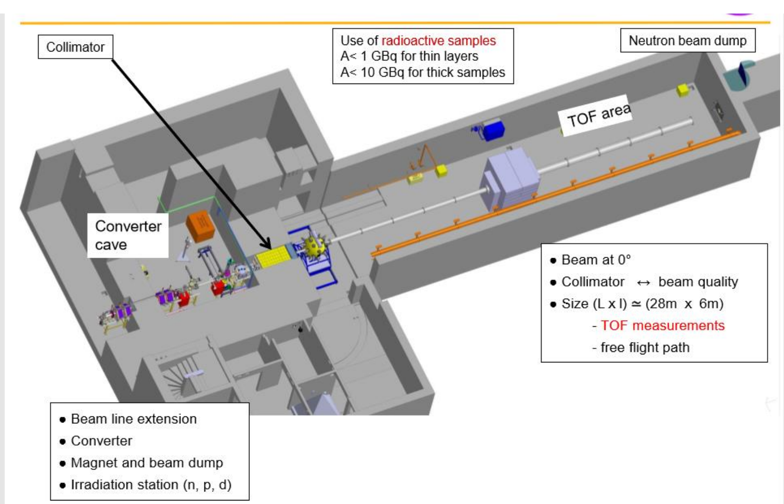
The key components of FAIR is a ring accelerator with a circumference of 1,100 m. and a complex system of storage rings and experimental stations. The existing **GSI accelerators** will serve as the first acceleration stage. **Ions of all the natural elements** in the periodic table, as well as **antiprotons,** will be accelerated. One of the main research projects of N.P. is the NUSTAR for Nuclear Structure Astrophysics and Reactions.

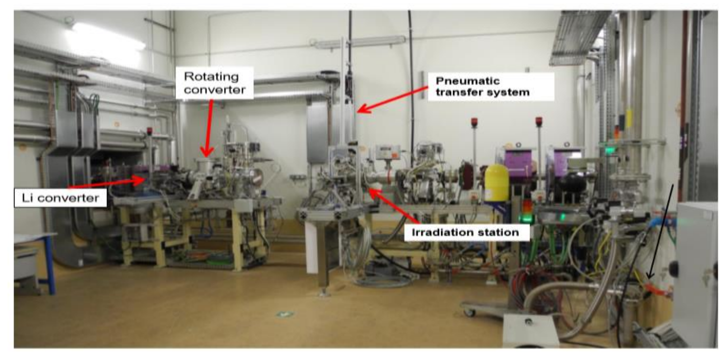
The commission is planned for 2025. Participation of 3000 researchers from 50 countries
Cost ~ 1.5 billion euros

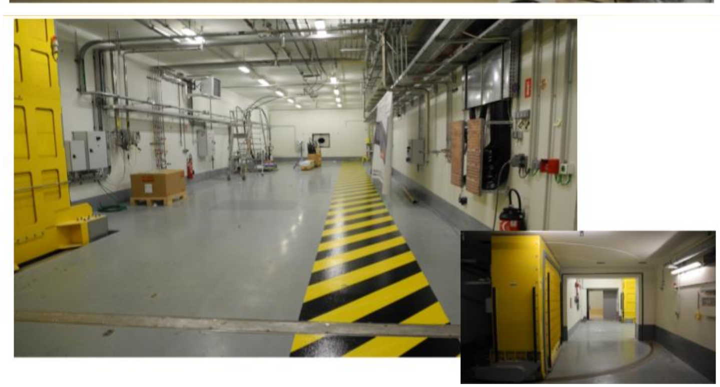
New Facilities under construction in Europe

Neutrons For Science (NFS) at GANIL in Caen, France

The Neutrons For Science (NFS) facility is a component of SPIRAL-2, the new superconducting linear accelerator built at GANIL. Continuous and quasi-mono-kinetic energy spectra will be available at NFS, produced by the interaction of a deuteron beam on a thick Be converter and by the $^{7}Li(p,n)$ reaction on thin converter. The pulsed neutron beam **flux of up to two orders of magnitude higher** than those of other existing time-of-flight facilities, will open new opportunities of experiments in fundamental research as well as in nuclear data measurements for applications like the transmutation of nuclear waste, design of future fission and fusion reactors, nuclear medicine etc.







NFS has been already installed - waiting for the license to start the commissioning

Hellenic Nuclear Physics Society

- Very **active Nuclear Physics community** with many collaborations with the European facilities and institutes, large scale facilities, small scale facilities, IAEA , ESA etc.
- Scientific output of many **publications and announcements in local and international conference proceedings**
- **Organization of international conferences (FINUSTAR, ECAART, ENVIRA etc.)** and annual **national conference** + proceedings since 1990
- **Financial support** only by bilateral agreements, grants from abroad, european programs and Trans-national access programs - **The national support is very limited**

Thank you
For your attention