Neutron Physics at the CERN n_TOF facility

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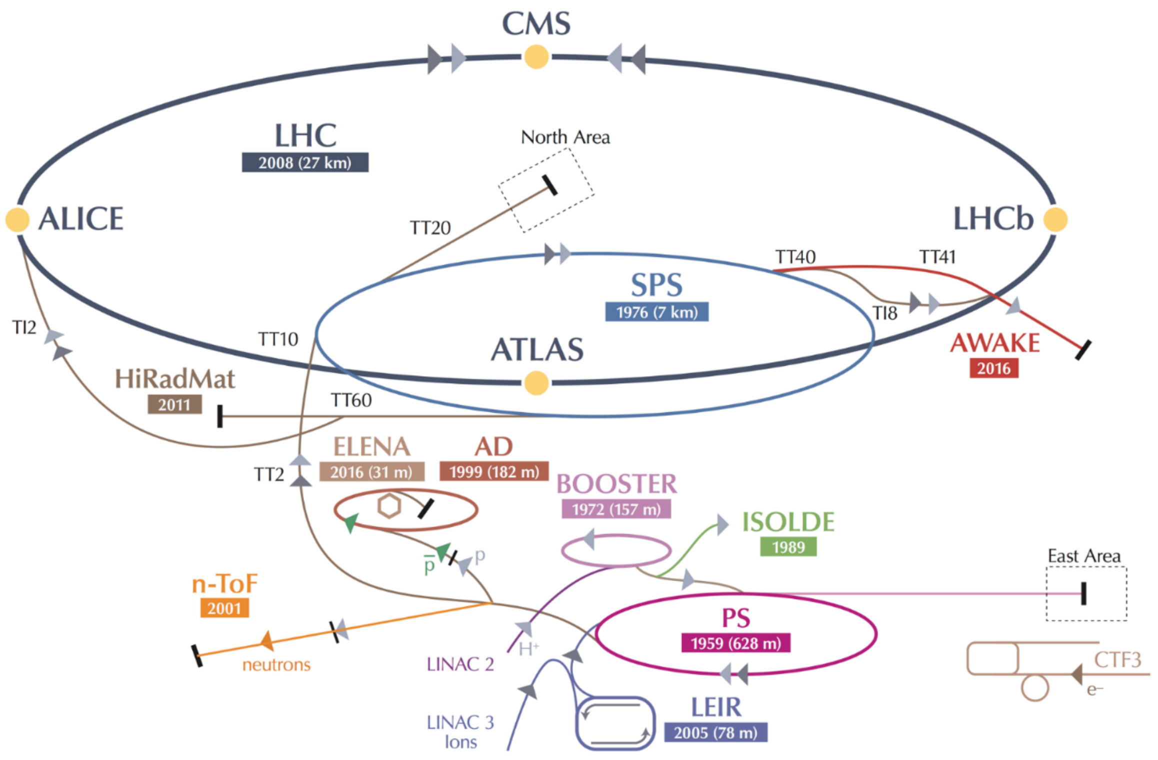
The n_TOF Collaboration

http://www.cern.ch/nTOF

The n_TOF Collaboration was founded in 2001

C. Rubbia et al., *A high resolution spallation driven facility at the CERN-PS to measure neutron cross sections in the interval from 1 eV to 250 MeV*, CERN/LHC/98-02(EET) 1998.



The n_TOF facility: A neutron spallation source using the PS 20 GeV/c proton beam
The neutron kinetic energy is determined by time-of-flight, hence the name n_TOF

46 Institutes - 140 participants - 3 experimental areas running in parallel

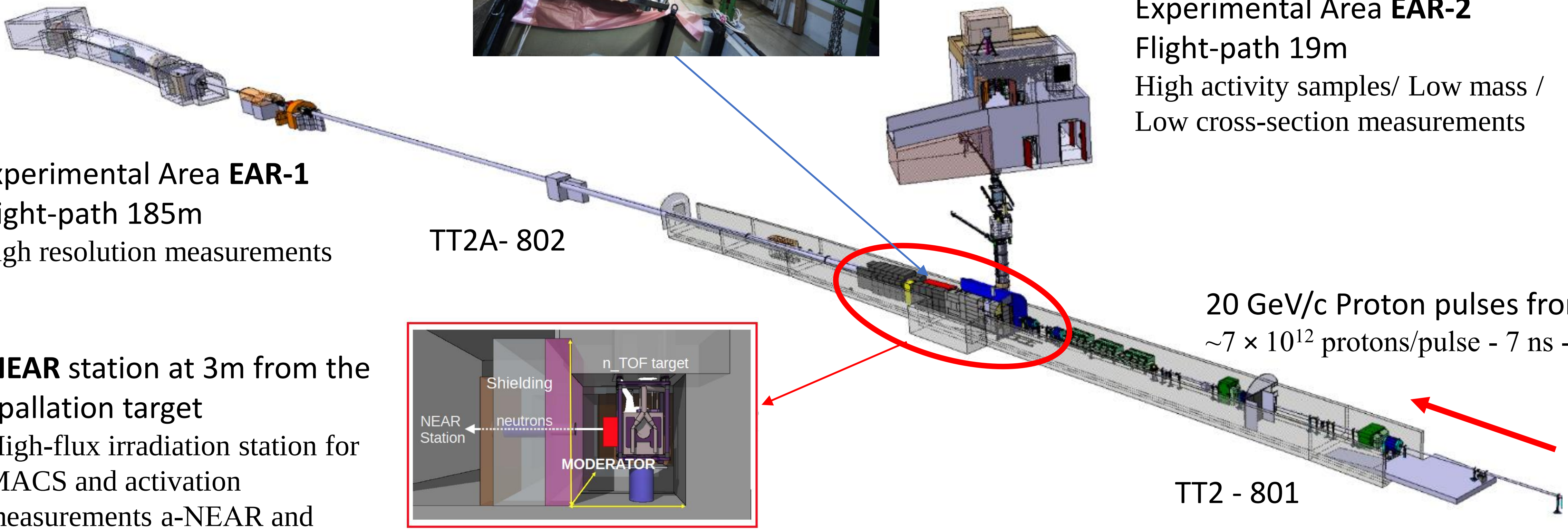
The n_TOF facility

Unique neutron facility

- **E_n from thermal to GeV**
- **Excellent energy resolution ($\Delta E/E = 10^{-4}$)**
- **high instantaneous neutron flux**
- **Low background**

New Pb spallation target installed and commissioned in 2021

Experimental Area **EAR-2**
Flight-path 19m
High activity samples/ Low mass / Low cross-section measurements



Experimental Area **EAR-1**
Flight-path 185m
High resolution measurements

20 GeV/c Proton pulses from the PS
$\sim 7 \times 10^{12}$ protons/pulse - 7 ns - every 1.2 s

NEAR station at 3m from the spallation target
High-flux irradiation station for MACS and activation measurements a-NEAR and irradiation i-NEAR

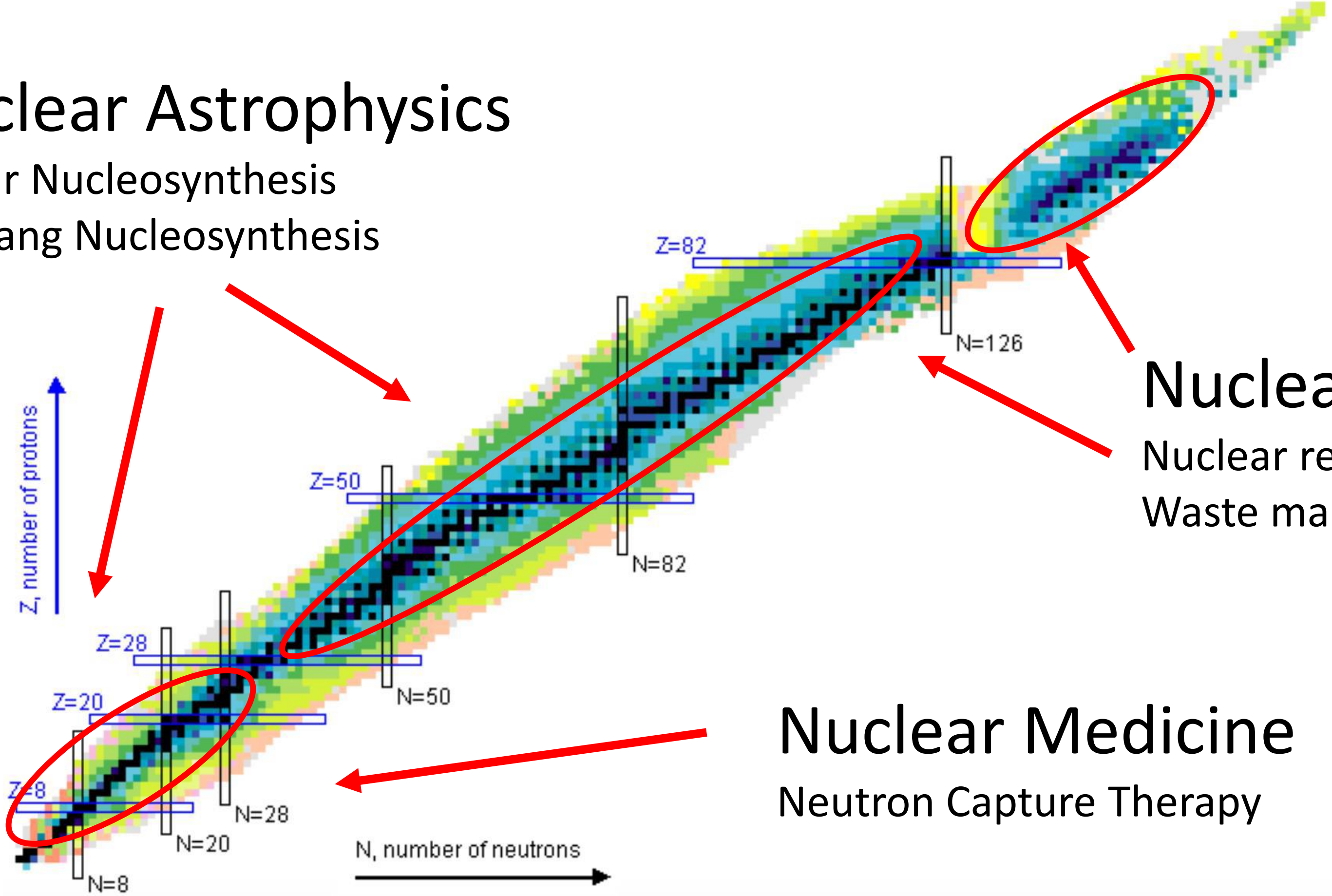
Neutron Physics at the CERN n_TOF facility

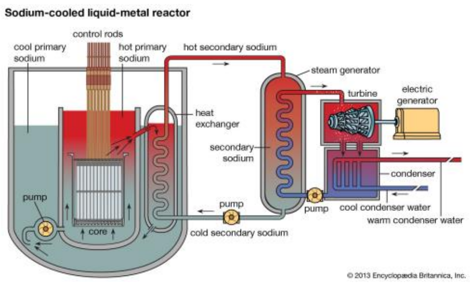
Nuclear Territory – Only 288 nuclei are stable – known to exist – Terra Incognita

Nuclear Astrophysics

Stellar Nucleosynthesis

Big Bang Nucleosynthesis





Nuclear Technologies

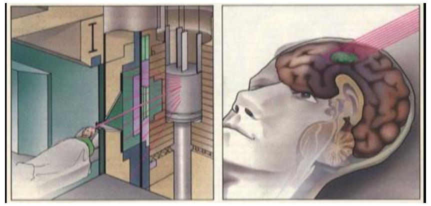
Nuclear reactors (energy production)

Waste management (transmutation)

Basic Nuclear Physics

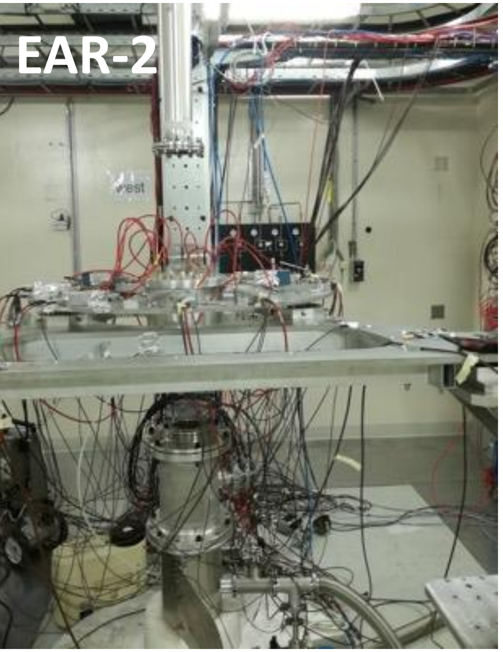
Nuclear Medicine

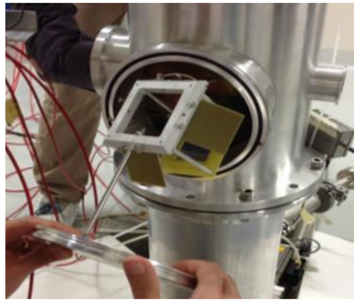
Neutron Capture Therapy

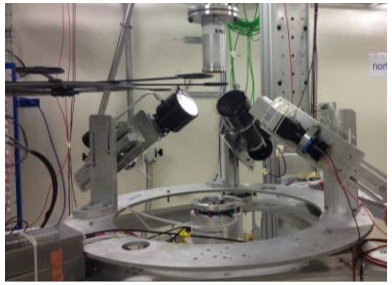


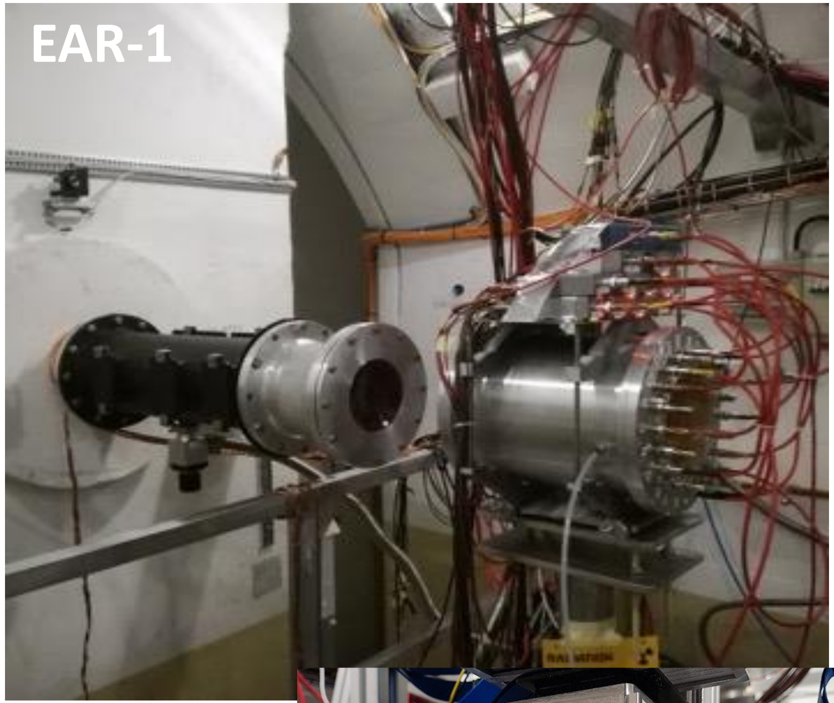
Detection Systems at n_TOF

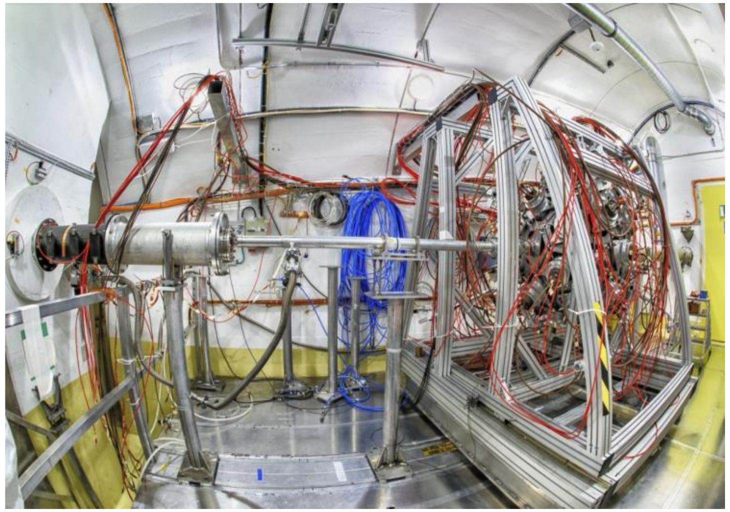
for (n, f), (n,γ) and (n,cp) reaction cross section measurements

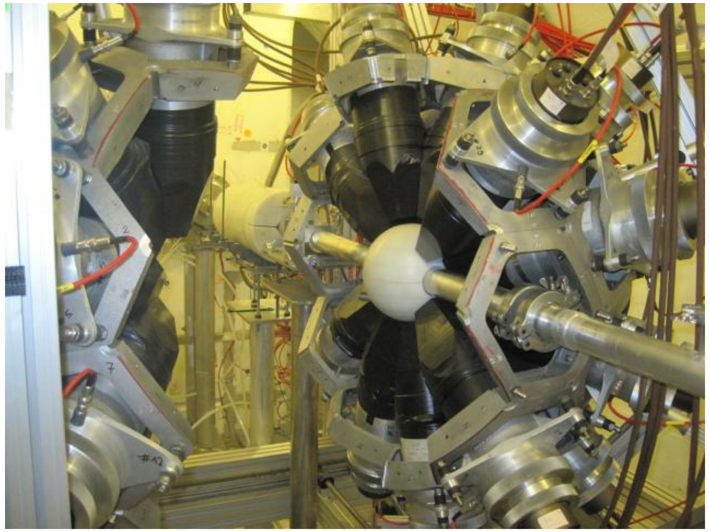


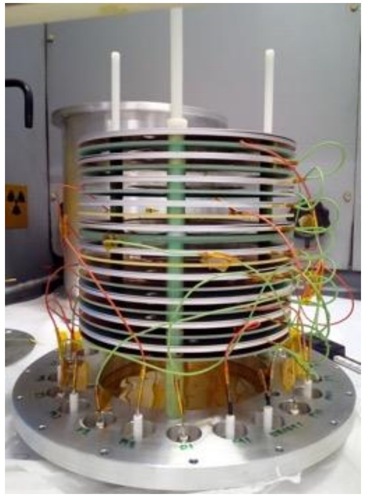


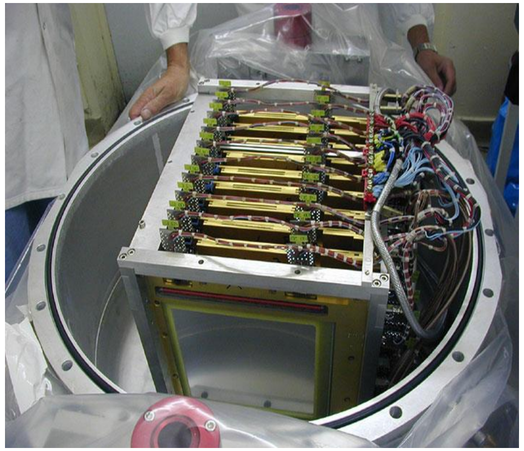


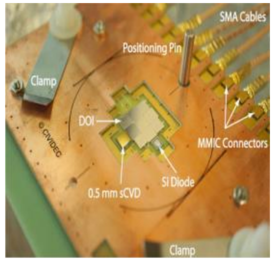


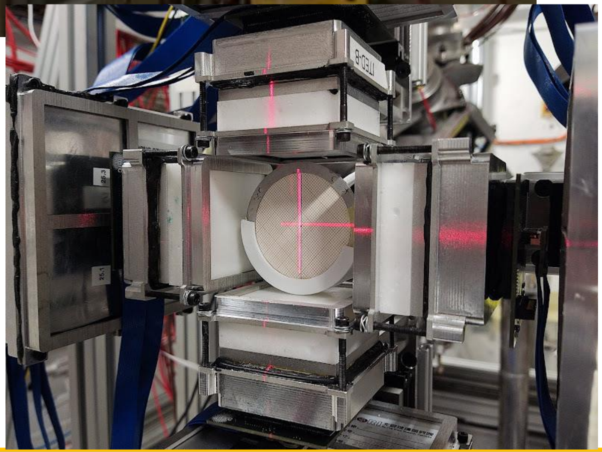












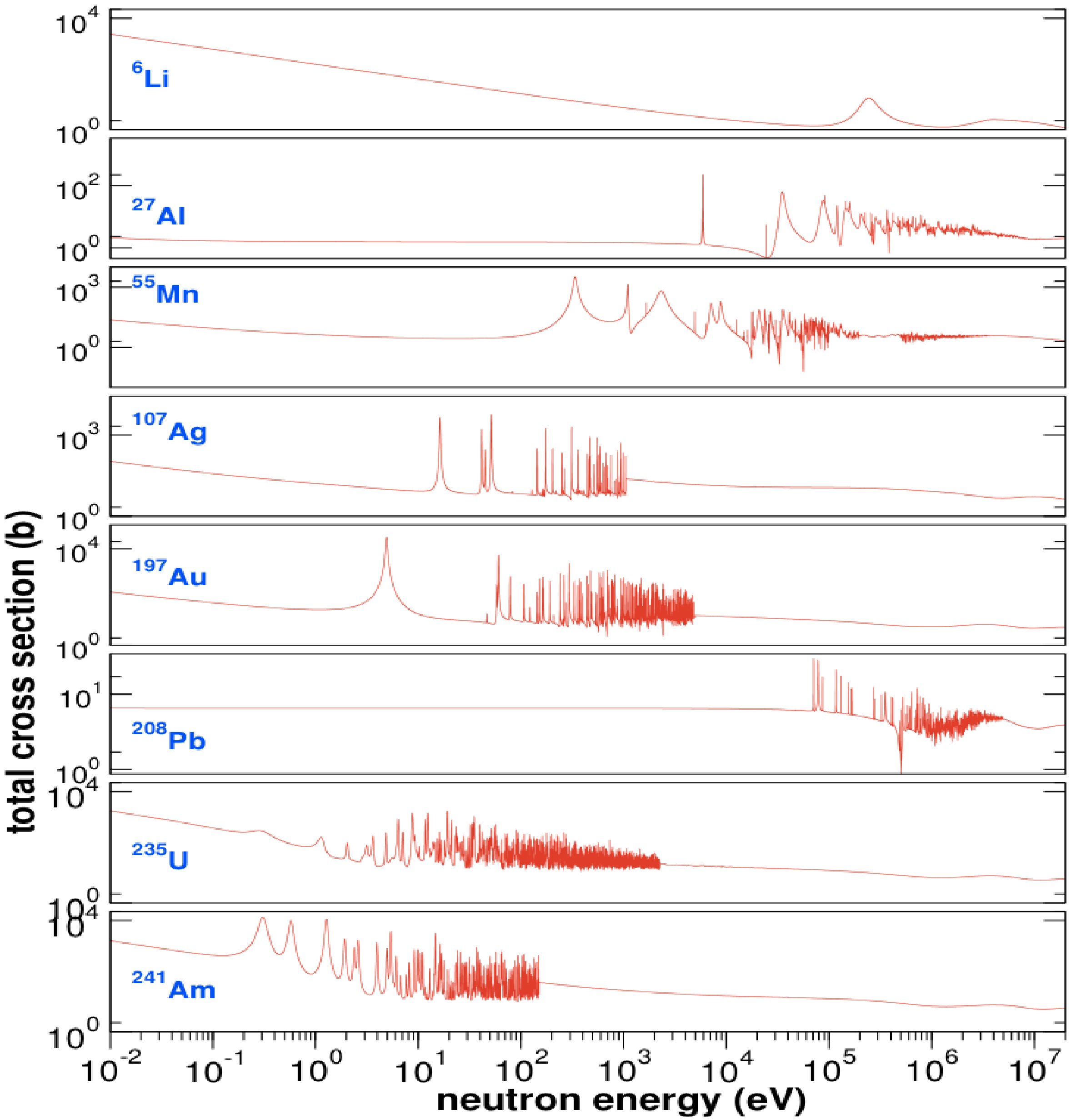
Basic Nuclear Physics

Neutron resonance spectroscopy is used to obtain crucial information on level densities in the vicinity of the neutron binding energy, i.e. at several MeV above the ground state.

Level densities are an important part in the calculation of nuclear reaction rates, having applications in astrophysical processes and in nuclear reactor devices based on fission or fusion reactions. A large number of level density models exist which are all calibrated by the level density observed with neutron resonances.

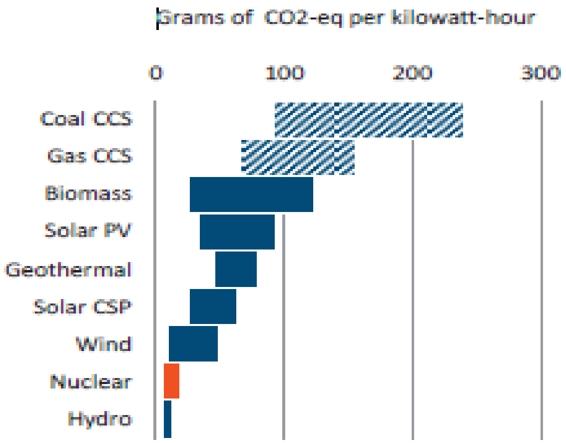
Cross-section as a function of neutron energy for several nuclei with increasing mass ranging from ^{6}Li to ^{241}Am. The resonance structure present in the cross-sections corresponds to nuclear levels in the compound nucleus. One can observe the decrease of the spacing between two levels, or the increase of the level density, when the mass of the nucleus increases. The significant shell effects are illustrated by the case of ^{208}Pb, a nucleus with closed neutron and proton shells, where a decrease in the level density can be observed.

n_TOF Home Page



Nuclear Technology at n_TOF

Nuclear reactors for energy production and waste management



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**.

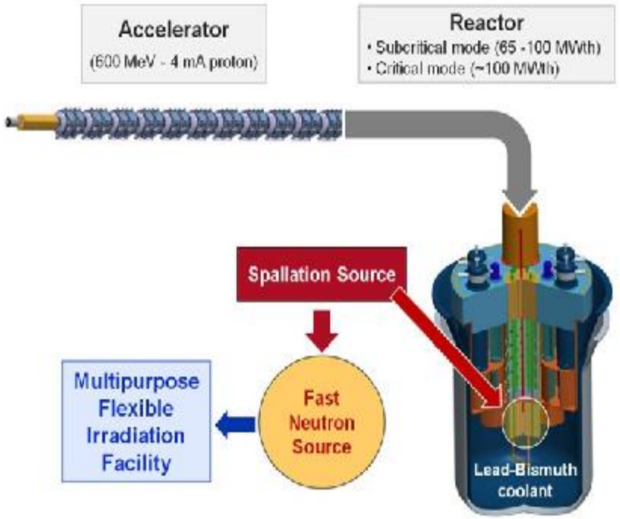
Nuclear Energy with disadvantages : safety, radioactive waste

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

- **ADS** (Accelerator Driven Systems) proposed by Carlo Rubbia - Reactor using energetic neutrons coming from an accelerator, not from chain reactions and ^{232}Th as a fuel

$$^{232}\mathrm{Th}(n,\gamma)^{233}\mathrm{Th} \xrightarrow{\beta^-,\ t_{1/2}=22.3\ \mathrm{m}} {}^{233}\mathrm{Pa} \xrightarrow{\beta^-,\ t_{1/2}=27\ \mathrm{d}} {}^{233}\mathrm{U}$$

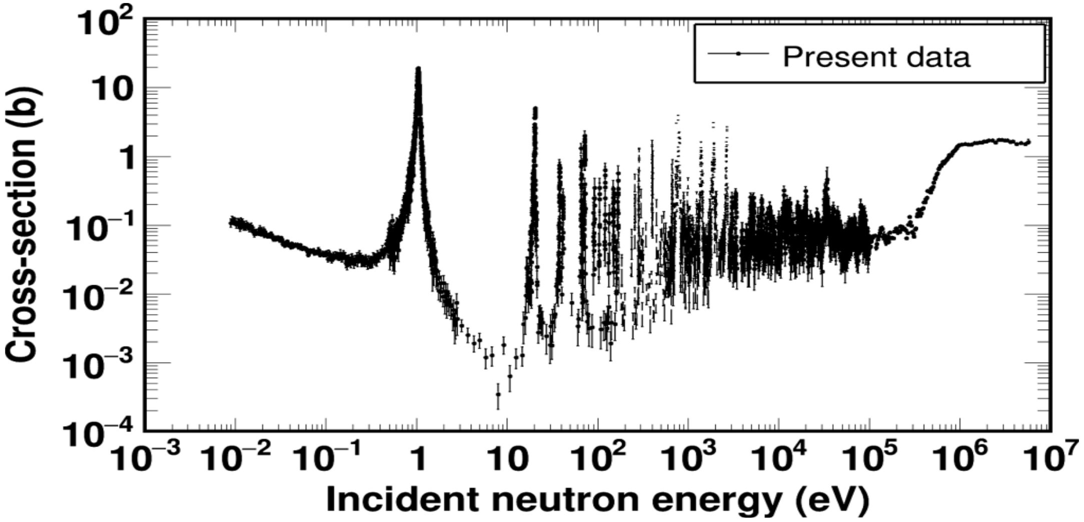
- **Fast neutron Generation IV reactors** : enhanced safety, minimal radioactive waste, transmutation of minor actinides (Pu, Np, Am, Cm) to FFs have much shorter half lives



Accurate cross section data for neutron induced (n,f) and (n,γ) reactions over a wide energy range are needed for the development of this new generation of reactors

Many (n,f) and (n,γ) reaction cross sections relevant to nuclear energy applications have been measured at the CERN n_TOF facility

As an example the ^{240}Pu(n,f) cross section was obtained in a broad energy range that spanned from 9 meV up to 6MeV!!!



Basic nuclear physics : Understanding of fission process

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

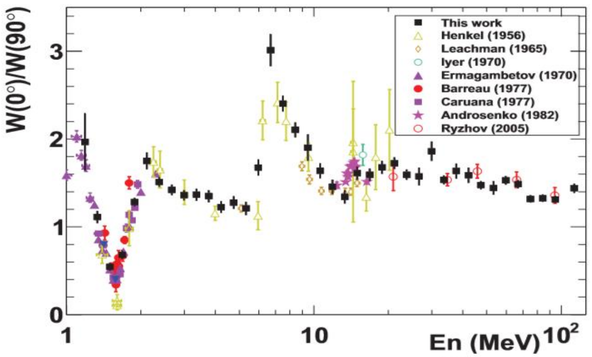
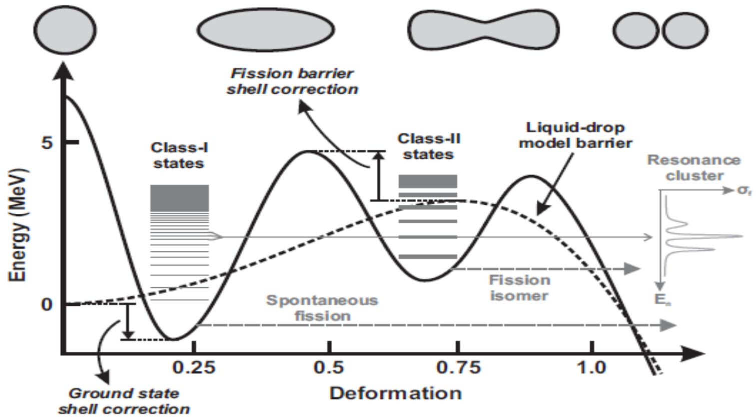


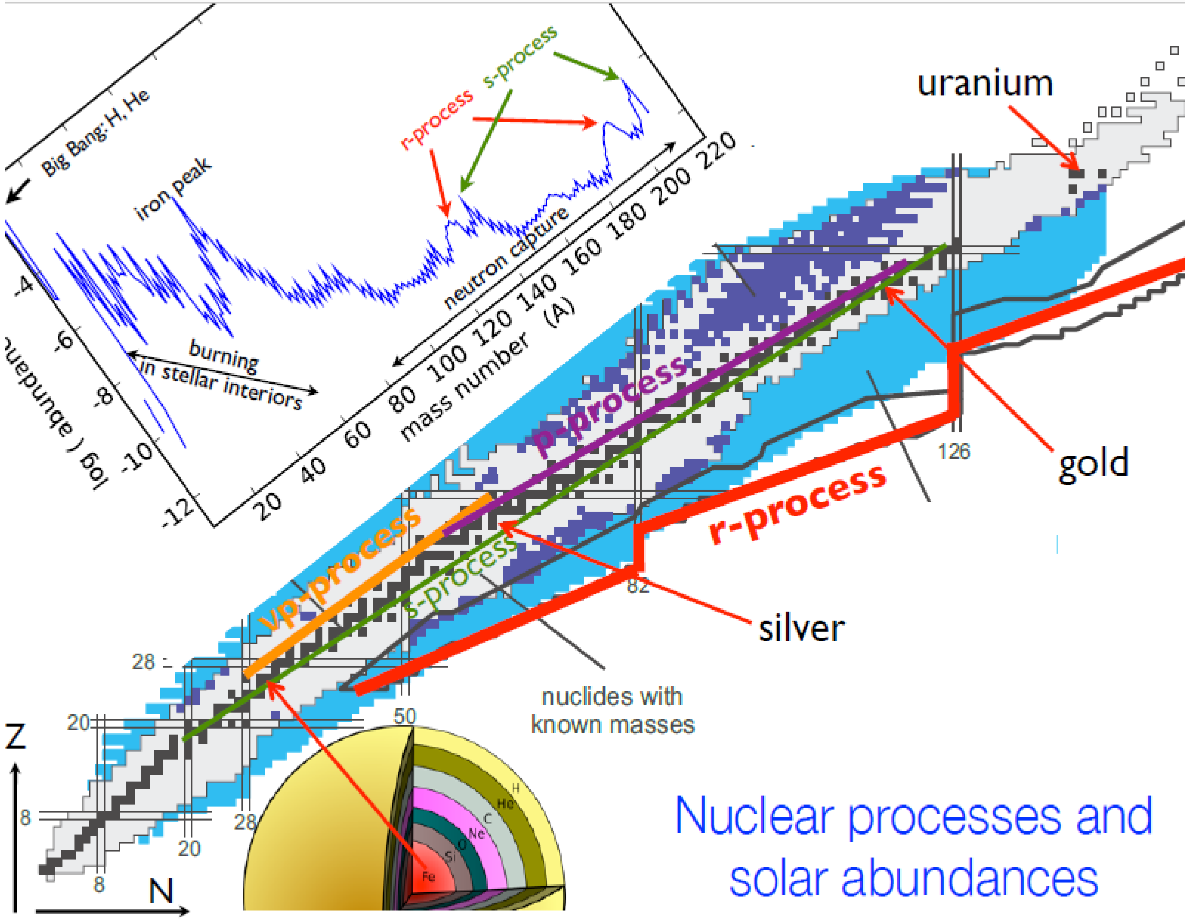
FIG. 4: Anisotropy parameter for the ^{232}Th(n,f) reaction.

- 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 at n_TOF



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.



Nuclear processes and solar abundances

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.

Solution

Theoretical calculations using Hauser-Feshbach statistical model calculations

Examples of n_TOF measurements relevant to Astrophysics

- **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.

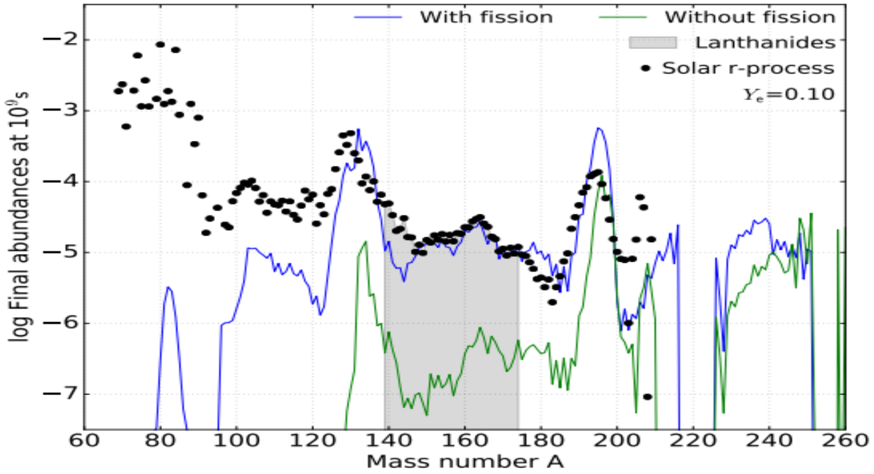
^{187}Re can be attributed to the r-process in supernova explosions and can be analyzed in terms of the daughter nucleus ^{187}Os, which can be determined by subtraction of the s-process component defined by the abundance of the s-only nucleus ^{186}Os via s-process systematics.

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 for 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 future experiments at n_TOF



J. Lippuner, L.F. Roberts, Astrophys. J. Suppl. S. 233, 18 (2017)

Nuclear Medicine

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 → ^{4}He + ^{7}Li)**

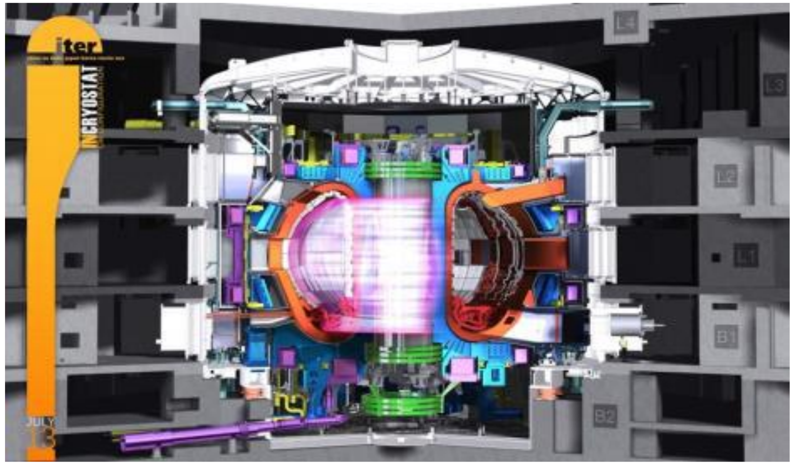
Research
- **Carriers** to deliver radionuclide to a tumor
- **Radiochemistry :** Radiolabeled nanoparticles, antibodies, biomolecules with ^{99m}Tc, $^{186/188}$Re, $^{74/77}$As, $^{90/95}$Nb etc.
- **Radiopharmacy** : development and evaluation of radioactive drugs
- **New radioisotopes** with clinical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

At n_TOF :

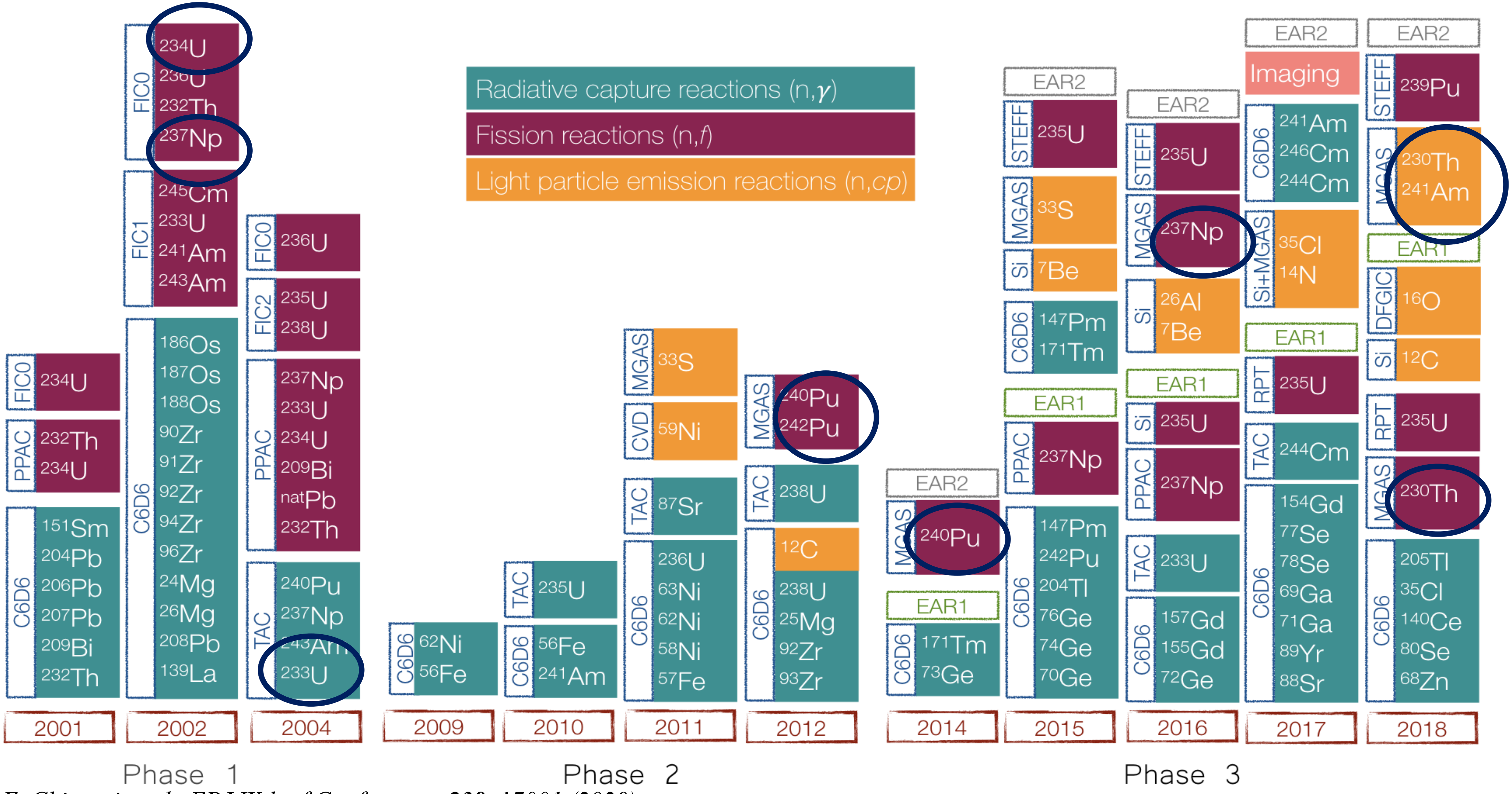
Studies of innovative therapeutic modalities
Enhanced BNCT - **^{33}S(n,α)^{30}Si, ^{14}N(n,p)^{14}C and ^{35}Cl(n,p)^{35}S** reactions have been measured at n_TOF

Fusion energy applications

Fusion - the energy source of the sun and stars:
^{2}H + ^{3}H → ^{4}He + n + 17.6 MeV
T~10^{8}K, plasma density ~ 10^{8} nuclei/m^{3},
pressure ~3-10bar (**JET, ITER, DEMO**)



Estimate lifetime of **structural materials**
Embrittlement due to gas (hydrogen and helium) production.
Need to study **(n,p) and (n,α) reactions on various stable isotopes at n_TOF**



E. Chiaveri et al., EPJ Web of Conferences ***239****, 17001 (2020)*

This year : ^{243}Am(n,f), ^{nat}Er(n,γ), ^{30}Si(n,γ), ^{64}Ni(n,γ), ^{12}C(n,cp), ^{26}Al(n,α)+Detector tests (Si-strip detectors, Diamond detectors etc)

Conclusions and perspectives

n_TOF is one of the world leading neutron facilities producing nuclear data for fundamental science, energy, astrophysics, health and other applications.
Powerful neutron source with unique characteristics :

- very high energy resolution
- white energy spectrum
- very high instantaneous flux
- 3 experimental areas combined with flexible and innovative detection systems

Driven by the **world largest scientific collaboration** (about 140 scientists) doing neutron induced reaction studies
One of the **main contributors** to the international **nuclear databases**
Young European scientists in neutron research and nuclear data measurements **get trained**.

In the near future:

- Construction of **new off-beam counting station** for activation analyses and **rabbit system** connecting with NEAR station .
- Construction of new **high-performance γ-ray detector array for (n,γ) and (n,n'γ)** cross section measurements
- Construction of **moderation system**, (^{10}B-based Filter + AlF_3 moderator) needed to suppress the low and high-energy component at NEAR station **for MACS capture measurements**
- Fast cycling-activation station at NEAR called **CYCLING**, for performing a rapid series of irradiation and activation measurements of short-lived nuclei.
- Cryogenic sample measurements with gaseous targets, γ-ray spectrometry with Ge detector-array for (n,n') and fission isomer measurements, position sensitive scintillators for (n,γ) measurements etc.

A bright future for neutron physics at the CERN n_TOF facility

Thank you for your attention

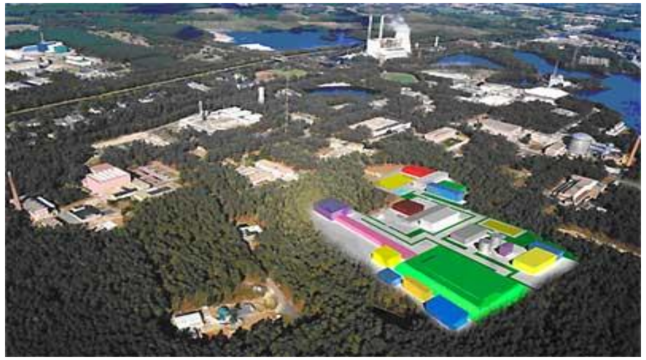
Back-up slides

New Facilities under construction in Europe

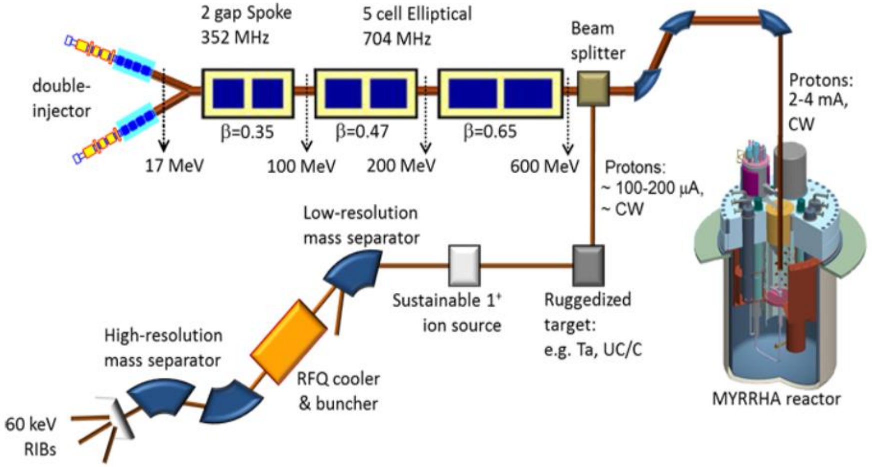
MYRRHA (Multi-purpose hYbrid Research Reactor for High-tech Applications), Belgium

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

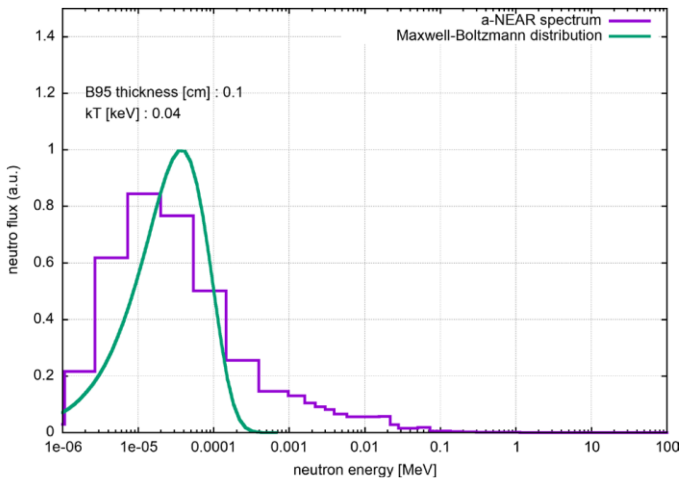
ITER ("The Way" in Latin) in southern France

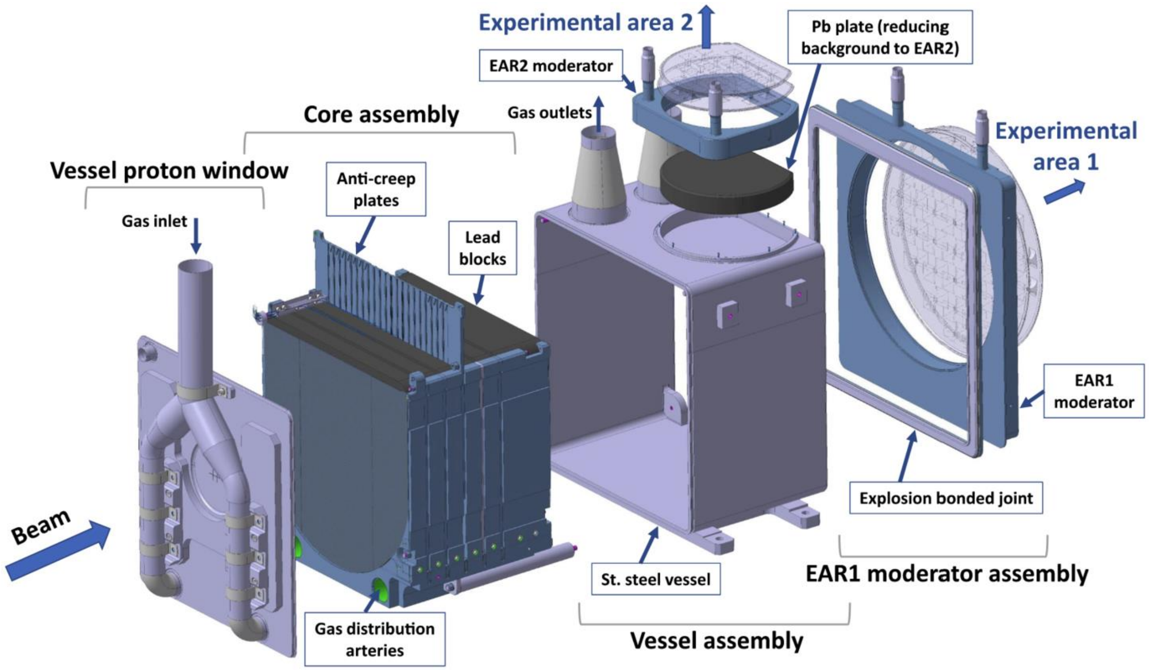
ITER is one of the most ambitious energy projects in the world today – bring fusion to the point where a demonstration fusion **D + T reactor** **($^2H + ^3H \rightarrow ^4He + n$)** can be designed .

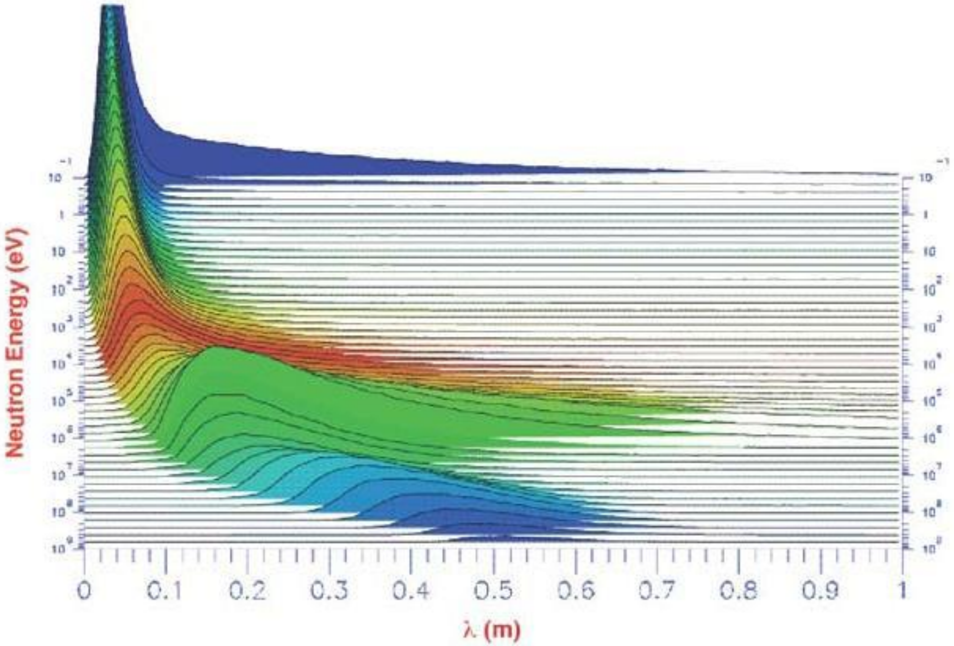
- ITER is the first fusion device to produce **net energy** and **maintain fusion** for long periods of time. In 1997, **JET (Joint European Torus) in Oxfordshire,UK,** produced 16 MW of fusion power from a total input heating power of 24MW (Q=0.67). ITER is designed to produce **500 MW** of fusion power 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 **($n + ^6Li \rightarrow ^3H + ^4He$) .**

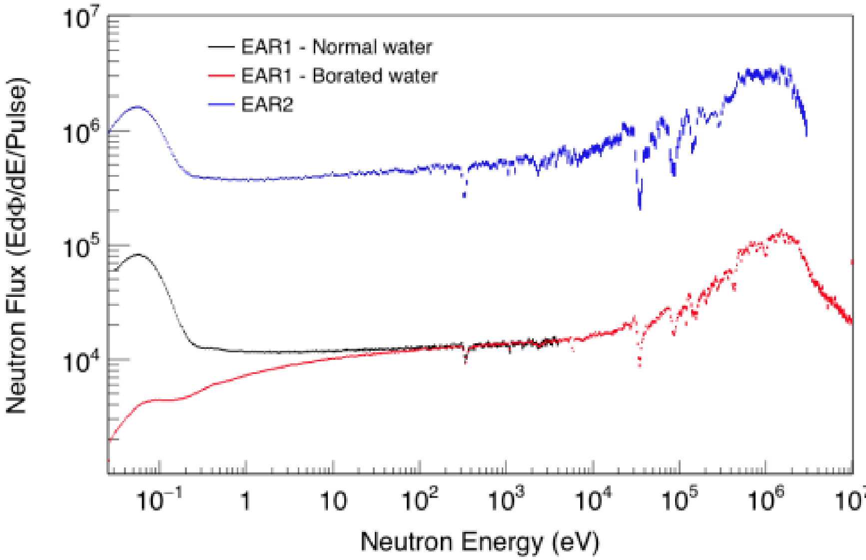
EU, USA, Russia, China, India, Japan, S.Korea
Euratom, IAEA, ANSTO, CERN

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


a-NEAR spectrum
Maxwell-Boltzmann distribution
B95 thickness [cm] : 0.1
kT [keV] : 0.04
neutro flux (a.u.)
neutron energy [MeV]
1e-06
1e-05
0.0001
0.001
0.01
0.1
1
10
100
1.4
1.2
1
0.8
0.6
0.4
0.2
0


Experimental area 2
Pb plate (reducing background to EAR2)
EAR2 moderator
Core assembly
Gas outlets
Experimental area 1
Vessel proton window
Anti-creep plates
Gas inlet
Lead blocks
EAR1 moderator
Explosion bonded joint
Beam
St. steel vessel
EAR1 moderator assembly
Gas distribution arteries
Vessel assembly


Neutron Energy (eV)
λ (m)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1


EAR1 - Normal water
EAR1 - Borated water
EAR2
Neutron Flux (EdΦ/dE/Pulse)
Neutron Energy (eV)
10^7
10^6
10^5
10^4
10^{-1}
1
10
10^2
10^3
10^4
10^5
10^6
10^7