The n_TOF Collaboration, www.cern.ch/n_TOF

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Neutron Research at the n_TOF Facility (CERN)

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The n_TOF Collaboration
(~100 Researchers from 30 Institutes)

CERN
Technische Universitat Wien
IRMM EC-Joint Research Center, Geel
IN2P3-Orsay, CEA-Saclay, IN2P3-Strasbourg
KIT – Karlsruhe, Goethe University, Frankfurt
Univ. of Athens, Ioannina, Demokritos
INFN Bari, Bologna, LNL, Trieste, ENEA – Bologna
Tokyo Institute of Technology, JAEA
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IFIN – Bucarest
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Poland
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Spain
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n_TOF measurements at a glance

Nuclear Astrophysics (stellar nucleosynthesis)

Nuclear energy (fission products & Structural material)

Advanced nuclear reactors (actinides)

proton number Z

neutron number N

stable
β-
EC, β+
α
s-process nucleosynthesis: neutron captures and successive $\beta$-decays

The abundance of elements in the Universe depends on:

- **thermodinamic conditions** in stars (temperature and neutron density)
- neutron capture cross-sections

$s$-process

$\sigma(n,\gamma)$ is a key quantity

Along the $\beta$-stability valley

Need of new and accurate neutron capture cross-sections:

- **refine models** of stellar nucleosynthesis in the Universe;
- obtain information on the **stellar environment and evolution**
The nuclear waste problem

Quantities refer to yearly production in 1 GWₑ LW reactor

- $^{244, 245}$Cm: 1.5 Kg/yr
- $^{241}$Am: 11.6 Kg/yr
- $^{243}$Am: 4.8 Kg/yr
- $^{239}$Pu: 125 Kg/yr
- $^{237}$Np: 16 Kg/yr

LLFP: 76.2 Kg/yr
The n_TOF facility at CERN

n_TOF is a spallation neutron source based on 20 GeV/c protons from the CERN PS hitting a Pb block (~360 neutrons per proton). Experimental area at 200 m.
The advance of n_TOF are a direct consequence of the characteristics of the PS proton beam: high energy, high peak current, low duty cycle.

**Main feature:** very high instantaneous neutron flux \(10^5 \text{ n/cm}^2/\text{pulse}\):
- convenient for **radioactive isotopes** (maximizes signal-to-background ratio)
- ideal for **branching point isotopes** (Astrophysics) and **actinides** (nuclear technology)

**Other features**
- high **resolution in energy** \((\Delta E/E = 10^{-4})\)
  - **study resonances**
- wide **energy range** \((25 \text{ meV} < E_n < 1 \text{ GeV})\)
  - all data at once
- low **repetition rate** (< 0.8 HZ)
  - no wrap-around
The spallation target(s)

Phase 1: 2001 – 2004

Phase 2: 2008 – 2012
The capture reactions

Capture reactions are measured by detecting $\gamma$-rays emitted in the de-excitation process. At n_TOF, built two different systems, to minimize different types of background.

**C$_6$D$_6$ (deutered liquid scintillators)**
- low neutron sensitivity device

**Total Absorption Calorimeter (TAC)**
- High-efficiency $4\pi$ detector (40 BaF$_2$ scintillators with neutron shielding)
The fission reactions

- Micromegas chamber
  - low-noise, high-gain, radiation-hard detector

Parallel Plate Avalanche Counters (PPAC)
- Fission fragments detected in coincidence
- Very good rejection of α-background

Other detectors, for \((n, \alpha)\) reactions: sCVD diamonds and GEMs
The n_TOF activity

### Phase 1 (2001-2004)

**Capture**
- $^{24,25,26}\text{Mg}$
- $^{90,91,92,94,96}\text{Zr}$, $^{93}\text{Zr}$
- $^{186,187,188}\text{Os}$, $^{139}\text{La}$, $^{151}\text{Sm}$
- $^{204,206,207,208}\text{Pb}$, $^{209}\text{Bi}$
- $^{232}\text{Th}$, $^{233,234}\text{U}$
- $^{237}\text{Np}$, $^{240}\text{Pu}$, $^{243}\text{Am}$

**Fission**
- $^{232}\text{Th}$, $^{209}\text{Bi}$
- $^{233,234,235,236}\text{U}$
- $^{237}\text{Np}$, $^{241,243}\text{Am}$, $^{245}\text{Cm}$

### Phase 2 (2008-2012)

**Capture**
- $^{25}\text{Mg}$, $^{54, 56, 57}\text{Fe}$
- $^{58, 60, 62}\text{Ni}$, $^{63}\text{Ni}$, $^{88}\text{Sr}$
- $^{236, 238}\text{U}$, $^{241}\text{Am}$

**Fission**
- $^{240, 242}\text{Pu}$
- $^{235}\text{U}(n,\gamma/f)$
- $^{232}\text{Th}$, $^{234}\text{U}$ $^{237}\text{Np}$
  ($\text{FF ang. distr.}$)
- ($n,\alpha$)
- $^{33}\text{S}$, $^{59}\text{Ni}$

**Capture**
- 37 isotopes (12 radioactive)

**Fission**
- 16 isotopes (15 radioactive)

**Papers:** $>$50

**Other publications:** $>$150

**Data available on EXFOR**

NB: for the applicative aspects, the INFN group in n_TOF receives since 2001, financial support from the European Commission.
Branching point isotopes: the $^{151}$Sm case

$^{151}$Sm ($T_{1/2} = 90$ y) is a branching point in the s-process nucleosynthesis

The branching ratio for $^{151}$Sm depends on:
- **Termodynamical condition** of the stellar site (temperature, neutron density, etc...)
- Cross-section of $^{151}$Sm(n,γ)

$^{151}$Sm used as **stellar thermometer** !!
The n_TOF results on $^{151}$Sm

n_TOF results provided strong evidence of thermal pulsing in AGB stars
The $^{63}$Ni(n,γ) branching point

$^{63}$Ni ($t_{1/2}=100$ y) represents the **first branching point** in the s-process reaction path:
- Highest uncertainty in $^{63,65}$Cu abundances comes from the $^{63}$Ni(n,γ) unknown cross section

- **$^{62}$Ni sample** irradiated in thermal reactor (in 1984 and 1992)
- total mass of 1 g, enriched $^{63}$Ni ~13%

Strong constraints on Cu, Ni, Zn production in massive stars and subsequent supernova (Almost) accepted on PRL

After chemical separation at PSI:
- NiO powder, (919 mg Ni)
- <0.01 mg $^{63}$Cu

First high-resolution measurement of $^{63}$Ni(n,γ) in the astrophysical energy range
First experimental observation of resonances in the keV region.
The age of the Universe: the Re/Os cosmochronometer
The Os/Re Cosmochronometer

Resolved resonance region

Unresolved resonance region

Maxwellian Average Cross Sections (MACS)

Age of the Universe from nuclear cosmochronometer: 14.9±0.8±2 Gyr

Reduced uncertainty due to nuclear data
Results relevant to nuclear technology

In the two campaigns, measured capture and fission cross sections for most long-lived actinides. We plan to measure in the near future also some short-lived actinides.

Data for the Th/U fuel cycle

At n_TOF measured the two main reactions of the cycle: the $^{232}\text{Th}(n,\gamma)$ and $^{233}\text{U}(n,F)$.

Data with high resolution, high accuracy (3 - 5 %) and wide energy range (from thermal to several MeV).

Important data for the development of the Th/U fuel cycle (large effort in India)
Data on actinides: the $^{237}$Np case

$^{237}$Np is the most abundant Minor Actinides produced in existing reactors. At n_TOF both capture and fission cross-sections determined with 4% accuracy.

For capture, large discrepancy between previous data (even from recent measurements) has been now settled.

Important results for the design of ADS and Gen IV fast reactors (closed fuel cycle)

50% Important results for the design of ADS and Gen IV fast reactors (closed fuel cycle)
Cross-sections for waste transmutation (and Gen. IV reactors)

$^{245}\text{Cm}(n,F)$

From **thermal energy to 30 eV** a evaluations need to be **revised**.

n_TOF results **confirm** previous data **above 30 eV** (nuclear explosion).

N. Colonna – INFN Bari
Simultaneous measurement of capture and fission cross section

**Graphs:**
- **Graph a:** Measured and ENDF/B-VII data for capture cross section as a function of neutron energy.
- **Graph b:** Measured and ENDF/B-VII data for fission cross section as a function of neutron energy.
- **Graph c:** Measured/ENDF/B-VII ratio of resonance integral ratios for capture reactions.
- **Graph d:** Measured/ENDF/B-VII ratio of alpha ratios for fission reactions.

**Image:**
- The image shows experimental setup with a BaF$_2$ module and MGAS with 3 $^{235}$U samples.

**References:**
- DOI 10.1140/epja/i2012-12029-2

**HIGHLIGHTED PAPERS**
- Simultaneous measurement of neutron-induced capture and fission reactions at CERN

**Tools for Experiment and Theory**

**April 2012**
- EPJ A - A new technique for simultaneous measurement of neutron-induced capture and fission reactions

**Abstract:**
- The accurate knowledge of (n, gamma) neutron-capture cross-sections for fissile isotopes is highly relevant for next-generation applications of nuclear technology. However, accurate measurements are difficult due to the gamma-ray background generated in competing (n, fission) reactions. Scientists at the n_TOF facility at CERN have developed a new experimental setup that is capable of simultaneously measuring and identifying the capture and fission reactions. The setup combines the existing 4p1 BaF$_2$ Total Absorption Calorimeter (TAC) with a set of three MicroLasos detectors.
The main features of EAR 2

**Comparison of the Neutron Fluence in EAR1 and EAR2**

Flux in EAR2 25 times larger than in EAR1. The shorter flight path implies a factor of 10 smaller time-of-flight.

Global gain relative to EAR1: 250 times in neutron rate (thus in signal/background ratio for radioactive isotopes!)

The huge **signal-to-background** ratio in EAR2 will allow to measure **radioactive isotopes** with half lives as low as a few years.
The experimental program in EAR2

The EAR2 will allow to:

- measure samples of very small mass (<1 mg)
- measure short-lived radioisotopes (down to a few years)
- collect data on a much shorter time scale
- measure \((n,\text{charged particle})\) reactions with thin samples

Letter of intent for measurements in EAR2:

- \((n,p)\) and \((n,\alpha)\) cross sections on \(^7\text{Be}, \, ^{25}\text{Mg}, \, ^{26}\text{Al}\)
- Fission cross sections of the short lived actinides \(^{232}\text{U}, \, ^{238,241}\text{Pu}\) and \(^{244}\text{Cm}\)
- Capture cross section of \(^{79}\text{Se}, \, ^{245}\text{Cm}\)
- Cross section and angular distribution of fragments from \(^{232}\text{U}(n,f)\)

Status of the EAR2:

- Approved by CERN, final design phase
- Start construction in 2013
- Beam ready in mid-2014
- Physics start after commissioning in 2015
• There is need of **accurate new data** on neutron cross-section both for astrophysics and advanced nuclear technology.

• Since 2001, **n_TOF@CERN** has provided an important contribution to the field, with an intense activity on **capture and fission measurements**.

• Several results of interest for **stellar nucleosynthesis** (Sm, Os, Zr, Ni, Fe, etc...).

• Important data on actinides, of interest for **nuclear waste transmutation**.

• A second **experimental area at 20 m** has been proposed and accepted by CERN for high flux measurements.

• The EAR2 (starting in 2015) will open **new perspectives** for frontier measurements on short-lived radionuclides.
WORK IN PROGRESS

Thank you
n_TOF history

1997

- Concept by C. Rubbia
- Note 97-19

1999

- Construction started

2000

- Commissioning

2001-2004

- 2nd Exp. area

2008

- New Target installed

2009

- Phase I Measurement campaign

2009-2012

- Phase II Measurement campaign

2010

- Upgrades 10B-water
- Class-A area

2012

- 2nd Exp. area

2014
$^{241}\text{Am}(n,\gamma)$

- 32.2 mg of $^{241}\text{Am}$ oxide, embedded in a 305 mg $\text{Al}_2\text{O}_3$ matrix and encapsulated in a 0.5 mm thick Al canning
- Sample diameter 12.2 mm
- Very high activity sample

- First time that complete region is covered from thermal to MeV in a single measurement
- Combined $\text{C}_6\text{D}_6$/TAC measurement for improved accuracy
- Unprecedented resolution and statistics, to extend RRR beyond 150 eV