Nuclear data at n_TOF for fundamental science and technological applications

Enrique M. González Romero
CIEMAT, on behalf of the n_TOF Collaboration

New Opportunities in the Physics Landscape at CERN

CERN, Geneva
12-05-2009
n_TOF: Neutrons at CERN.

Nuclear data at n_TOF for fundamental science and technological applications

There is a wide range of Nuclear Data applications from:
- Medical treatment and diagnostics to
- search for oil or space exploration,
however the largest social impact is at:
- the electricity production by fission
- the reduction of nuclear wastes.

n_TOF@CERN was designed to provide data for the CERN concept of Energy Amplifier (an ADS) for energy production and Waste Transmutation.

Since then, n_TOF@CERN has become a world-leading facility for this type of measurements.
It is intrinsic to nuclear fission the large energy release per reaction and the production of short lived nuclear wastes (fission fragments)

However, the amount and nature of production of isotopes per activation (Pu and other actinides + structural materials) depends on the technological design.

New reactor concepts under evaluation might allow to reduce (1/100) the existing stock and production of the long lived high level waste (Transmutation).
One example: Nuclear waste minimization and P&T

**Partitioning & Transmutation**
*(providing new solutions to social request for nuclear wastes manag.)*

Heterogeneity of Spent nuclear fuel Components -> Separate and recycle materials dangerous for environment or valuable to produce energy.

P&T will:
- Reduce by 1/1000 the HLW mass
- Reduce by 1/100 the HLW radiotoxicity
- Reduce by 1/100 the Heat Load to repository
- Reduce by 1/1000 the time
- Reduce by 1/100 the proliferation in repository
- Increase by 5-30 the capacity of hard-rock repositories
- Increase by 30% to 3000% the energy from the fuel
Main reactions in a nuclear reactor or transmutation device

- \( n \)- induced fission (energy + wastes)
- neutron capture (activation + breeding)
- elastic and inelastic neutron scattering
- radioactive decay
- \((n,xn)\), \((n,\text{charged particle})\), …

E. Gonzalez: Nuclear data at n_TOF for fundamental science and industrial applications (CERN, 12-05-2009)
\[ \text{Rate} = \int n \sigma(E) \phi(E) dE \]

- n- induced fission
- neutron capture

- elastic and inelastic neutron scattering

Resonances (absorption, elastic, inelastic,…)

\( \sigma(E) \)

\( ^{238}\text{U Capture} \)

\( ^{235}\text{U Fission} \)

\( \phi(E) \)

Pressurized Water cooled Reactor

Thermalization, Moderation

Lead (Pb/Bi) cooled Fast ADS
Fast Spectrum Transmutation Scheme

Present in nuclear wastes
- Thermal and Fast Fission
- Medium Half-Life (<100 años)
- Short Half-Life (< 30 dias)
- High A actinides

Av. Flux Intensity (n/cm²/s)
3.00E+15

Second 1
Hour 3600 31570560
Day 86400
Year 3E+07

Pu239 and Pu239 Symbol & Mass
- Decay modes
- Half-Life
- Branching ratios
- Absorption-Half-Life

Cm242 and Cm243
- α / SF
- α / EC/SF

Am241 and Am242
- α / SF
- β− / SF

Am243 and Am244
- α / SF
- β− / SF

Pu238, Pu239, Pu240, Pu241, Pu242, Pu243
- α / SF

Np237, Np238, Np239
- α / SF
- β− / SF

Pu239 Symbol & Mass
- Decay modes
- Half-Life
- Branching ratios
- Absorption-Half-Life

TRU Transmutation Scheme
Fast Spectrum
Reactors: \((\Delta<0.5\%)\)

**Performance:** Reaction rates, Power distribution, Flux, Energy Spectrum

**Safety:** Criticality, Feedbacks, Reactivity coeffs, Damage, Shielding

**Waste:** Isotopic evolution, activation

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**Storage, Reprocessing and Fabrication plants:** \((\Delta<5\%-10\%)\)

**Isotopic composition !!!**
Radioactivity, Neutron emissions, Decay Heat, Proliferation interest

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**Storage, Reprocessing and Fabrication plants:** \((\Delta<5\%-10\%)\)

**Isotopic composition !!!**
Radioactivity, Neutron emissions, Decay Heat, Proliferation interest
Radiotoxicity and Dose to Public and Environment
Effective capacity
### Sensitivity analysis – ADS for Transmutation

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$\sigma_{cap}$</th>
<th>$\sigma_{fiss}$</th>
<th>$\nu$</th>
<th>$\sigma_{el}$</th>
<th>$\sigma_{inel}$</th>
<th>$\sigma_{n,2n}$</th>
<th>Total$^a$</th>
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<tbody>
<tr>
<td>$^{238}\text{Pu}$</td>
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<td>0.11</td>
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<td>—</td>
<td>—</td>
<td>0.11</td>
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<td>—</td>
<td>0.04</td>
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<td>0.01</td>
<td>—</td>
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<td>0.70</td>
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<td>0.01</td>
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<td>0.18</td>
<td>—</td>
<td>0.07</td>
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<td>1.11</td>
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<td>0.01</td>
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<td>—</td>
<td>—</td>
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<tr>
<td>$^{56}\text{Fe}$</td>
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<td>—</td>
<td>—</td>
<td>0.01</td>
<td>0.03</td>
<td>—</td>
<td>0.03</td>
</tr>
<tr>
<td>$^{58}\text{Ni}$</td>
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<td>—</td>
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<td>—</td>
<td>—</td>
<td>—</td>
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<td>$^{52}\text{Zr}$</td>
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<td>—</td>
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<td>0.07</td>
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<td>0.09</td>
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<td>$^{15}\text{N}$</td>
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<td>—</td>
<td>—</td>
<td>0.19</td>
<td>0.01</td>
<td>—</td>
<td>0.19</td>
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<td>$^{208}\text{Pb}$</td>
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<td>0.10</td>
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<td>0.02</td>
<td>0.43</td>
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<td>$^{209}\text{Bi}$</td>
<td>0.04</td>
<td>—</td>
<td>—</td>
<td>0.11</td>
<td>0.49</td>
<td>0.03</td>
<td>0.50</td>
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<tr>
<td><strong>Total$^a$</strong></td>
<td>1.54</td>
<td>1.97</td>
<td>0.54</td>
<td>0.25</td>
<td>1.05</td>
<td>0.04</td>
<td>2.77</td>
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</table>

a) Upper limit of the group

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$k_{eff}$
NEA/WPEC-26.

One possible optimization for target accuracy for innovative systems using recent covariance data evaluations (BOLNA).

Similar tables for each present or proposed future reactor

Still serious dependence on the reactor and fuel models and on the transmutation model (homogeneous) can slightly modify the target accuracy and details on the priority order

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Table 30. ADMAB: uncertainty reduction requirements needed to meet integral parameter target accuracies

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Cross-Section</th>
<th>Energy range</th>
<th>Uncertainty (%)</th>
</tr>
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<tr>
<td></td>
<td></td>
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<td>Initial</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>Required λ=1</td>
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<tr>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>Pu238</td>
<td>$\sigma_{\text{fiss}}$</td>
<td>6.07 - 0.498 MeV</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>$\sigma_{\text{cap}}$</td>
<td>1.35 - 0.183 MeV</td>
<td>7</td>
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<tr>
<td>Pu239</td>
<td>$\sigma_{\text{fiss}}$</td>
<td>4.98 - 2.03 keV</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>$\sigma_{\text{cap}}$</td>
<td>6.07 - 0.498 MeV</td>
<td>25</td>
</tr>
<tr>
<td>Pu240</td>
<td>$\sigma_{\text{fiss}}$</td>
<td>183 - 67.4 keV</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>$\sigma_{\text{cap}}$</td>
<td>2.23 - 0.498 MeV</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>$\sigma_{\text{neq}}$</td>
<td>1.35 - 0.498 MeV</td>
<td>4</td>
</tr>
<tr>
<td>Pu241</td>
<td>$\sigma_{\text{fiss}}$</td>
<td>6.07 MeV - 22.6 eV</td>
<td>15</td>
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<tr>
<td></td>
<td>$\sigma_{\text{cap}}$</td>
<td>24.8 - 9.12 keV</td>
<td>35</td>
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<td>Np237</td>
<td>$\sigma_{\text{fiss}}$</td>
<td>6.07 - 0.498 MeV</td>
<td>8</td>
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<tr>
<td></td>
<td>$\sigma_{\text{cap}}$</td>
<td>4.98 - 0.454 keV</td>
<td>6</td>
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<tr>
<td>Am241</td>
<td>$\sigma_{\text{fiss}}$</td>
<td>1.35 MeV - 0.454 keV</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>$\sigma_{\text{cap}}$</td>
<td>6.07 - 0.183 MeV</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>$\sigma_{\text{neq}}$</td>
<td>6.07 - 1.35 MeV</td>
<td>2</td>
</tr>
<tr>
<td>Am242m</td>
<td>$\sigma_{\text{fiss}}$</td>
<td>1.35 MeV - 9.12 keV</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>$\sigma_{\text{cap}}$</td>
<td>1.35 MeV - 0.454 keV</td>
<td>10</td>
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<tr>
<td>Am243</td>
<td>$\sigma_{\text{fiss}}$</td>
<td>6.07 - 0.498 MeV</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>$\sigma_{\text{cap}}$</td>
<td>6.07 MeV - 24.8 keV</td>
<td>40</td>
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<td>Cm242</td>
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<td>6.07 MeV - 67.4 keV</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>$\sigma_{\text{cap}}$</td>
<td>1.35 MeV - 67.4 keV</td>
<td>50</td>
</tr>
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<td>Cm243</td>
<td>$\sigma_{\text{fiss}}$</td>
<td>4.98 - 9.12 keV</td>
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</tr>
<tr>
<td></td>
<td>$\sigma_{\text{cap}}$</td>
<td>6.07 MeV - 67.4 keV</td>
<td>45</td>
</tr>
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<td>$\sigma_{\text{neq}}$</td>
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<td>10</td>
</tr>
<tr>
<td>Cm245</td>
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<td>6.07 MeV - 0.454 keV</td>
<td>45</td>
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<tr>
<td></td>
<td>$\sigma_{\text{cap}}$</td>
<td>183 - 0.454 keV</td>
<td>12</td>
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<td>Fe56</td>
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<td>Zr90</td>
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<td>N15</td>
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<td>2.23 MeV - 67.4 keV</td>
<td>5</td>
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<td>Pb</td>
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<td>Bi209</td>
<td>$\sigma_{\text{fiss}}$</td>
<td>2.23 - 0.498 MeV</td>
<td>34</td>
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</table>

\(^{(*)}\) See Table 24 for λ ≠ 1, case A
### Important isotopes for Transmutation Fuel Cycles: The multi-recycling point of view

Report of the Numerical results from the Evaluation of the nuclear data sensitivities, Priority list and table of required accuracies for nuclear data. E. Gonzalez-Romero (Ed), NUDATRA Deliverable D5.11 from IP-Eurotrans

<table>
<thead>
<tr>
<th>Isotopes</th>
<th>Uncertainty in the abundance %</th>
<th>Burnup (GWd/t)</th>
<th>Important for:</th>
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<td></td>
<td></td>
<td>150</td>
<td>500</td>
</tr>
<tr>
<td>234U</td>
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<td>4.6</td>
<td>16.1</td>
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<td>14.7</td>
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<td>7.9</td>
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<td>28.6</td>
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<td>6.4</td>
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<td>52.4</td>
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</table>

T= Transmutation efficiency  
DH= Decay Heat load  
N = Neutron emission  
R = Radiotoxicity
Identifying and setting priorities of Nuclear data for applications: An international endeavor

- Applications set the problems to be analyzed and the required accuracies for the simulation.
- Detailed uncertainty and covariance propagation to evaluate the accuracy.
- Sensitivity analysis identify the relevance of each data for each isotope/reaction/energy on the most significant parameters
- Linear Optimization with expert assessment of “cost” (experimental difficulties) to set priorities

Efforts coordinated by dedicated expert groups of NEA/OECD, IAEA, and dedicated EU framework programs

EU support and demand for nuclear data measurements:

- Clear and repeated demand from the Nuclear Waste community, Sustainability of Nuclear Energy (Resources, Safety, Waste) by EU Framework Program calls:
  - FP5: nTOF_ND_ADS (start of n_TOF facility at CERN)
  - FP6: NUDATRA (inside EUROTRANS),
  - FP6: EFNUDAT (Transnat. Access) + CANDIDE (Roadmap for ND)
  - FP7: ANDES proposal to WP2009
- Collaboration with other measurements at USA, Japan, Russia.

One EU call on Nuclear Data for each FP (FP5-FP7), n_TOF measurements in all of them
n_TOF beam characteristics

- Wide energy range
- High instantaneous n-flux
- High resolution
- Low ambient background
- Low repetition frequency
- Favorable duty cycle for radioactive samples.

The neutron fluence in EAR-1

<table>
<thead>
<tr>
<th>Energy range</th>
<th>Uncollimated</th>
<th>Capture mode</th>
<th>Fission mode</th>
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<tbody>
<tr>
<td>&lt; 1 eV</td>
<td>2.8E+05</td>
<td>3.1E+05</td>
<td>2.0E+06</td>
</tr>
<tr>
<td>1 eV - 10 eV</td>
<td>2.7E+04</td>
<td>4.5E+04</td>
<td>2.6E+05</td>
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<tr>
<td>10 eV - 100 eV</td>
<td>2.3E+04</td>
<td>4.7E+04</td>
<td>3.1E+05</td>
</tr>
<tr>
<td>100 eV - 1000 eV</td>
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<td>5.1E+04</td>
<td>3.3E+05</td>
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<td>1 eV - 1 keV</td>
<td>8.6E+04</td>
<td>1.4E+05</td>
<td>2.9E+05</td>
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<tr>
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<td>5.4E+04</td>
<td>3.6E+05</td>
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<tr>
<td>10 keV - 100 keV</td>
<td>3.9E+04</td>
<td>7.1E+04</td>
<td>4.7E+05</td>
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<tr>
<td>1 keV - 1 MeV</td>
<td>1.8E+05</td>
<td>3.3E+05</td>
<td>2.3E+06</td>
</tr>
<tr>
<td>1 MeV - 10 MeV</td>
<td>8.3E+04</td>
<td>2.4E+05</td>
<td>1.7E+06</td>
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<tr>
<td>10 MeV - 100 MeV</td>
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<td>7.2E+04</td>
<td>5.1E+05</td>
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<tr>
<td>&gt; 100 MeV</td>
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</tr>
<tr>
<td>1 MeV - &gt; 100 MeV</td>
<td>1.6E+05</td>
<td>4.4E+04</td>
<td>2.7E+06</td>
</tr>
<tr>
<td>Total</td>
<td>6.2E+05</td>
<td>1.2E+06</td>
<td>8.0E+06</td>
</tr>
</tbody>
</table>

Note: 1 pulse is 7E+12 protons. Collimated fluence (fission and capture modes) is integrated over the beam surface.

One of the best worldwide facilities for radioactive samples:
Complementary to GELINA (EU JRC-IRMM@Geel, Belgium)
In good position respect to competitors at LANSCE/ORELA(USA) at JPARK (Japan)
n_TOF: Advanced DAQ and detectors

+ Precision simulations (Geant4, MCNPX, Fluka): Utilization and Validation

Low n-sensitivity capture detectors

Total Absorption Segmented Calorimeter

First FADC DAQ for T.o.F facilities

Fission detector reconstructing F.F. trajectories
**Capture**

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

**Fission**

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

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**n_TOF experiments**

2000-2004 measurements

**Sensitivity analysis**

- NEA/WPEC-26 (2008)
- NUDATRA Deliverable D5.11 of IP-Eurotrans (2009)

**Other types of reactor & cycles (Th-U, PWR)**

---

**Challenge for the first n_TOF campaign:**

- To improve the quality of previous measurements
- Demonstrate feasibility of challenging isotopes

**All data first published then stored in the EXFOR database**

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The n_TOF Collaboration
n_TOF measurements are designed to obtain the maximum information for basic nuclear physics

• **Nuclear structure models**
  - Improving the accuracy and statistical information from resolved resonances (RR)
    - Extending the RR region
    - Level densities and criteria for the estimation of missed resonances
  - Photon Strength functions from the TAC
  - Direct vs. compound nuclei mechanism
  - Measurements in closed-shell nuclei and light nuclei (Pb, Mg,…)

• **Fission: towards a better understanding of the process**
  - High resolution measurements over large energy ranges in the same setup
  - FF kinetic energy and angular distributions determination
  - Fissile ($^{233}$U, $^{235}$U, $^{245}$Cm) and Fissionable isotopes ($^{234}$U, $^{232}$Th, …)
  - Sub-threshold, direct and multiple chance fission
  - Fine structures in the fission barriers (outer fission barrier and hyper-deformation of the fission potential)

• **Basic reactions**
  - n-n scattering by $^2$H(n,np)n
  - (n, l.c.p.) reactions (l.c.p. = light charged particles like p, $\alpha$, $^3$H, Li,…)
High resolution low backgr. of radioactive samples: $^{232}$Th by $\text{C}_6\text{D}_6$

High peak n flux intensity reduce the radioactive background + high resolution -> larger RRR + Small resonances
High resolution low backgr. of radioactive samples: $^{237}\text{Np TAC}$

$n_{\text{TOF}}$ capture + GELINA transmission = One of the best measur. made at Europe.


E. Gonzalez: Nuclear data at n_TOF for fundamental science and industrial applications (CERN, 12-05-2009)
High resolution low capture cross section samples: C$_6$D$_6$ + TAC

M. Heil (FZK), Nuclei in the Cosmos IX, Geneva 2005

C. Domingo-Pardo et al. (n_TOF Collaboration), Phys. Rev. C 74/75, 2006/7

E. Gonzalez: Nuclear data at n_TOF for fundamental science and industrial applications (CERN, 12-05-2009)
High resolution and large energy range accurate fission data

\[ \sigma_f (\text{barn}) \]

\( E_n \) (eV)

235U: High accuracy differences

245Cm: poor previous experimental results

233U: High accuracy

238U/235U: both isotopes are fission standards up to 200 MeV.
High resolution and large energy range accurate fission data

Fine structures in the fission barriers (outer fission barrier and hyper-deformation of the fission potential)
**n_TOF_ph2 experiments**

**Current program**

**Capture**

Stable Isotopes:

- **Mo, Bi**: Materials for fuel matrix (Mo) and coolant (Bi)
- **Fe, Ni, Zn, 79Se**: Structural materials
- **234, 236, 238U, 231Pa**: Th/U fuel cycle
- **239, 240, 242Pu, 241, 243Am, 245Cm**: transmutation of minor actinides

**Fission**

- **231Pa, 234, 235, 236, 238U**: Safety and sustainability of nuclear energy
- **241Pu, 241, 243Am, 244Cm, 245Cm**: transmutation of minor actinides
- **234U**: study of vibrational resonances below the barrier

**Other**

- **n-n scattering by 2H(n,np)n**
- (n, lcp) (lcp = light charged particles like p, α, 3H, Li,…)

**Sensitivity analysis**

- **NEA/WPEC-26 (2008)**
- **NUDATRA Deliverable D5.11 of IP-Eurotrans (2009)**
- **Other types of reactor & cycles (Th-U, PWR)**

Reaching required accuracy indicated by the sensitivity analysis: (5-10%) M.A. and (2%-5%) for main isotopes.
n_TOF_ph2 experiments

Main upgrades from n_TOF

- New target, target cooling station and ventilation system (improving safety and reliability)
- New fission detectors to measure more physical magnitudes (angle, kinetic energy)
- New capture samples design for the calorimeter with lower beam scattered background
- The possibility to have independent moderator and cooling circuits:
  - Moderation by borated water to reduce in-beam $\gamma$ background.

Further upgrades ahead:
- convert EAR1 to Class A/B Rad. Laboratory
- Building a new short flight path and the associated experimental area EAR2 (also expected to be Class A Rad. Laboratory)

Most measurements proposed before can be done with the facility as it is (3 first upgrades), however some fission targets are conditioned by R.P. rules and will require to upgrade the Experimental Area to a Class A/B Rad. Laboratory.
The next frontier: n_TOF @ EAR2

Actinides with very short half life (10-200 yr): $^{238,241}Pu$, $^{242m}Am$, $^{243,244}Cm$

- These isotopes are key steps for the nuclear waste breeding, but their radioactivity makes their measurement very difficult.
- **Very low mass samples** ($<<1$ mg): to reduce the radioactivity induced background and to be compatible with R.P. rules.
- Same conditions allow very rare materials (even deposits from rad beams ISOLDE?), and materials of very low cross section: $^{90}Sr$, $^{79}Se$, $^{126}Sn$, $^{147}Pm$, $^{135}Cs$: long lived FF
The next frontier: n_TOF @ EAR2 and SPL/PS2

Improving the Signal to noise ratio for very small samples:

(1) Radioactivity background
   - High brightness (peak flux intensity) and low duty cycle
   - Shorter flight path 1/10 -> 100 times larger flux (EAR2)
   - Higher pulse intensity (SPL/PS2)

(2) Scattered beam background
   - Very thin sample support no encapsulation
     Class A laboratory (EAR2)
   - Distance from samples to walls (EAR2)

(3) Background vs. Detectors
   - Low neutron sensitivity of detectors
   - Improved background rejection by detectors

(4) In beam background
   - Large angle of neutron and proton lines (EAR2)
   - Lower proton energies (SPL/PS2)
   - Optimized moderator

(5) Ambient background
   - Walls distance and detector background rejection
The second n_TOF experimental area (EAR2)

- Flight-path length: ~20 m: 100 time brighter!
- at 90° respect to p-beam direction
- Class A laboratory for minimum encapsulation
- reduced beam induced background
- Wide area for lower ambient background

- Reducing the mass by 100 from 1mg -> 10µg
- Acceptable half-life from 500y -> 10y
- Improve accuracy and efficiency for larger samples

n_TOF @ SPL/PS2:
- Further increase of brightness
- Lower background 20 -> 4 GeV protons

Dedicated capture and fission areas
Possible combination with HI_E_ISOLDE
Summary and conclusions

- n_TOF @ CERN is a first class neutron Time Of Flight facility
- It is specially well suited for radioactive materials, samples of rare materials or low cross section.
- Excellent facility for measuring neutron capture and fission cross sections and the most needed cross sections identified for nuclear applications (nuclear waste minimization). Sustained support from the EU framework programs.
- The measurements provide very relevant parameters to improve the understanding and physics models of nuclides and reactions.
- Combined with high performance detectors and DAQ allows to perform high accuracy cross section measurements.
- The n_TOF potentiality was proved by successful operation from 2000 to 2004
- The current campaign, with improved setup, will allow to fully exploit its possibilities to fulfill the request of the highest priority nuclear data needs
- The collaboration proposes to enhance the performance with an additional short flight path and EAR2 that will allow to open a new frontier of sample masses, short lived isotopes and accurate measurements
- We also propose the exploration of the possibilities of the future SPL/PS2 for further improvements by reaching higher neutron source brightness.
<table>
<thead>
<tr>
<th>Production</th>
<th>Flight path [m]</th>
<th>E range [eV]</th>
<th>Repetition rate [Hz]</th>
<th>Pulse width [ns]</th>
<th>$\Phi_n$ [cm$^{-2}$ dec$^{-1}$ s$^{-1}$]</th>
<th>$\Phi_n$ [cm$^{-2}$ dec$^{-1}$ pulse$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>n_TOF Spallation</td>
<td>185</td>
<td>10$^{-1}$-10$^{8}$</td>
<td>&lt;0.4&gt;</td>
<td>6</td>
<td>10$^5$</td>
<td>2.5$\cdot 10^5$</td>
</tr>
<tr>
<td>LANSCE Spallation</td>
<td>20</td>
<td>1-10$^{8}$</td>
<td>20</td>
<td>250</td>
<td>5$\cdot 10^5$</td>
<td>2.5$\cdot 10^5$</td>
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<tr>
<td>ORELA ($\gamma,f$)</td>
<td>40</td>
<td>th-5$\cdot 10^6$</td>
<td>525</td>
<td>8</td>
<td>2$\cdot 10^4$</td>
<td>20</td>
</tr>
<tr>
<td>GELINA ($\gamma,f$)</td>
<td>30</td>
<td>th-4$\cdot 10^6$</td>
<td>800</td>
<td>1</td>
<td>5$\cdot 10^4$</td>
<td>50</td>
</tr>
<tr>
<td>n_TOF (EAR2) Spallation</td>
<td>20</td>
<td>10$^{-1}$-10$^{8}$</td>
<td>&lt;0.4&gt;</td>
<td>6</td>
<td>3$\cdot 10^6$</td>
<td>8$\cdot 10^6$</td>
</tr>
</tbody>
</table>
New isotopic composition of transmutation and future reactor fuels
New coolants and fuel matrices
New requirements for structural materials
New neutron spectra
High energy neutrons from the Spallation Source
Nuclear structure: TAC response $^{197}$Au(n,γ): $E_{\text{sum}}$ and $m_\gamma$

Validation of Adjusted Photon Strength Functions models with $^{197}$Au(n,γ) TAC data for deposited energy (with and without conditions in $m_\gamma$) but also for $m_\gamma$ ($E_{\text{sum}}>1.5$ MeV).

Similar studies for several isotopes.
High resolution low backgr. of radioactive samples: $^{232}$Th by $C_6D_6$

Resolved Resonance Region

Unresolved Resonance Region

mass ($^{232}$Th) = 2.8037 g

diameter = 1.5 cm

purity = 99.5%