



**The Abdus Salam  
International Centre for Theoretical Physics**



**1930-7**

**Joint ICTP-IAEA Advanced Workshop on Model Codes for Spallation  
Reactions**

*4 - 8 February 2008*

**Spallation Data and Applications**

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Austria*

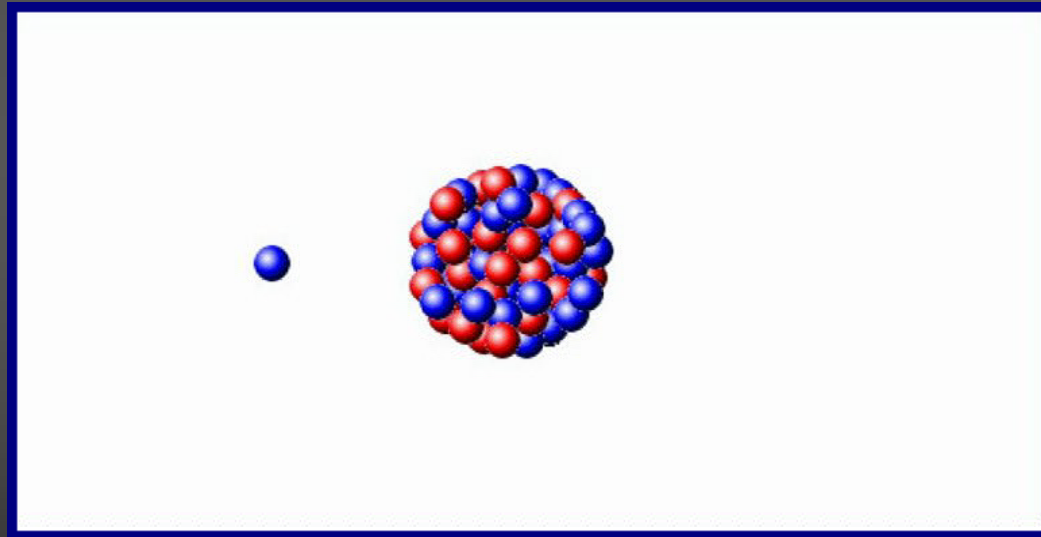
# Nuclear Physics, Astrophysics, and Advanced Technologies with Neutrons

Alberto Mengoni  
IAEA , Vienna

- Generalities
- Example of experimental activity: n\_TOF at CERN
- From experimental data to evaluated data libraries

# Nuclear Reaction Experiments

Neutron induced reactions

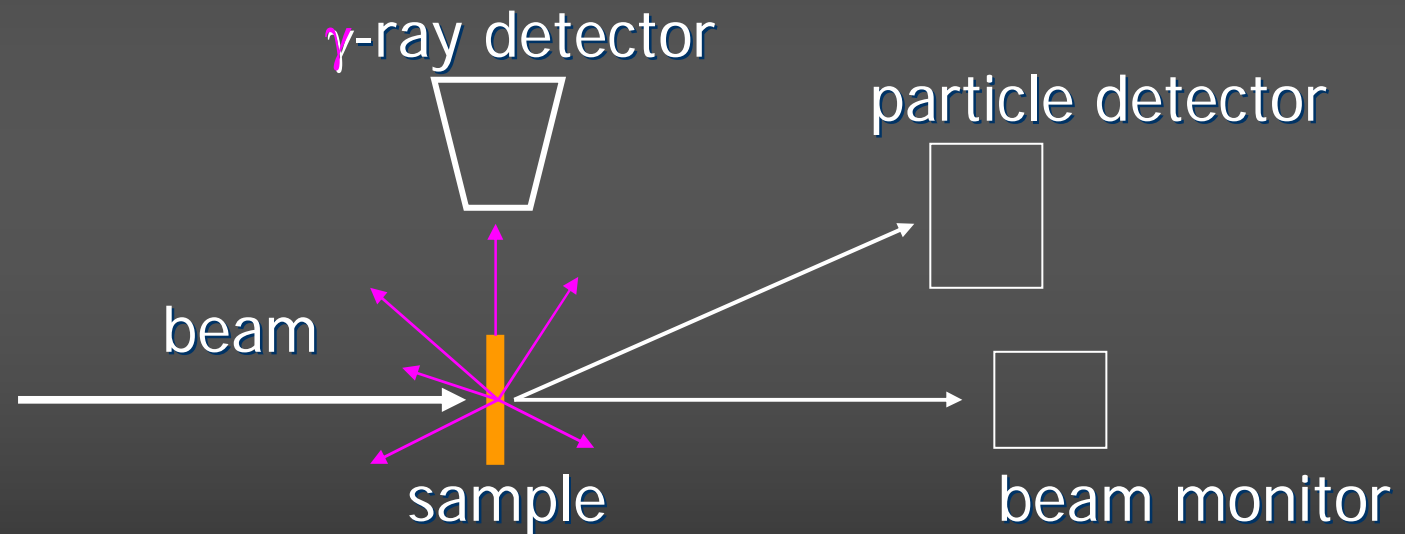


Source: the web

movie

# Nuclear Reaction Experiments

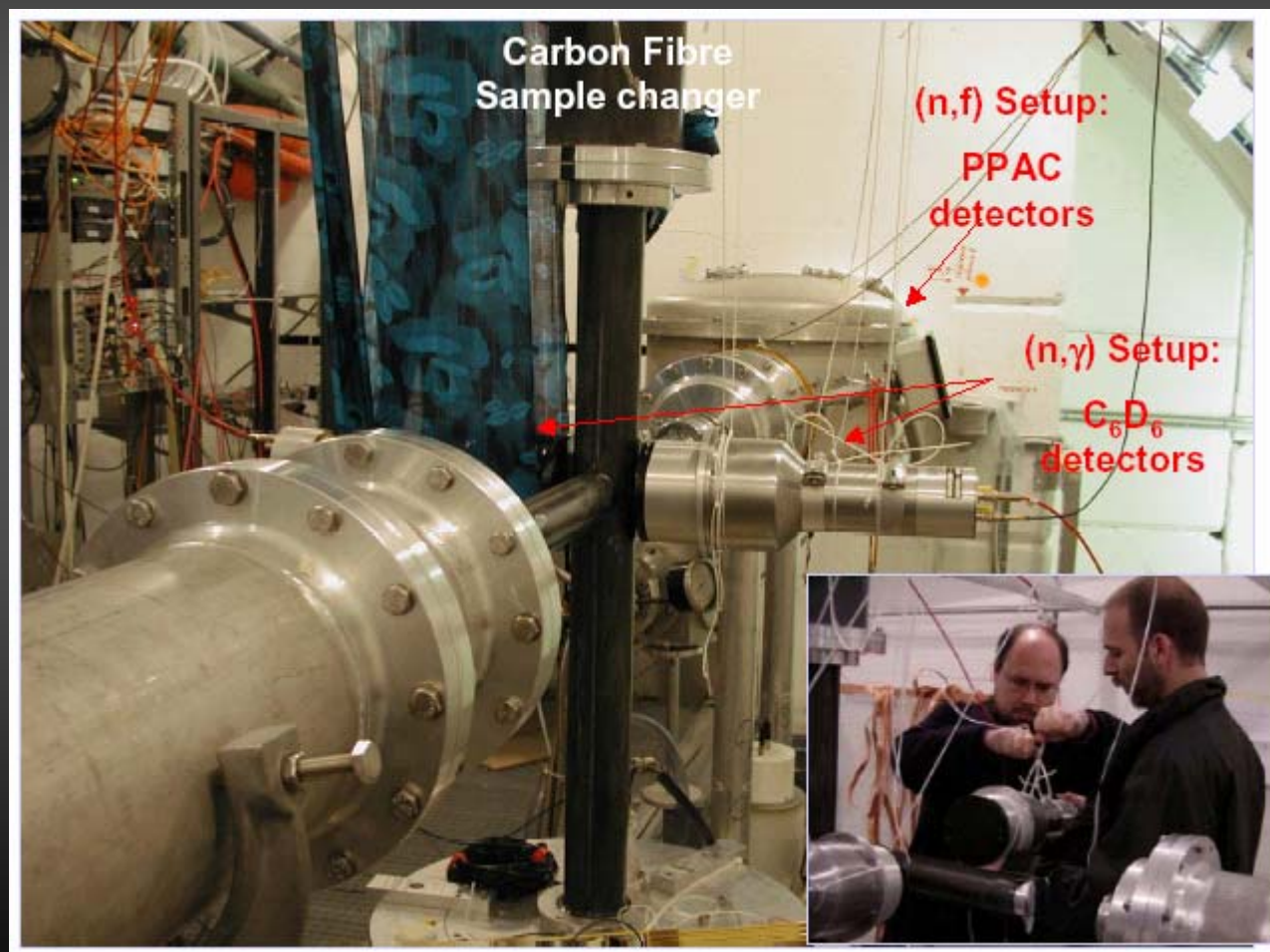
Neutron induced reactions



$$r = \Phi \sigma \rho_A$$

# Nuclear Reaction Experiments

Neutron induced reactions



# Objectives

- Nuclear Astrophysics
- Nuclear Technologies  
advanced reactors, nuclear waste transmutation, etc.
- Neutrons as probes for fundamental Nuclear Physics

# Nucleosynthesis: the s-process

direct correlation between  
neutron capture cross section  
and abundance:

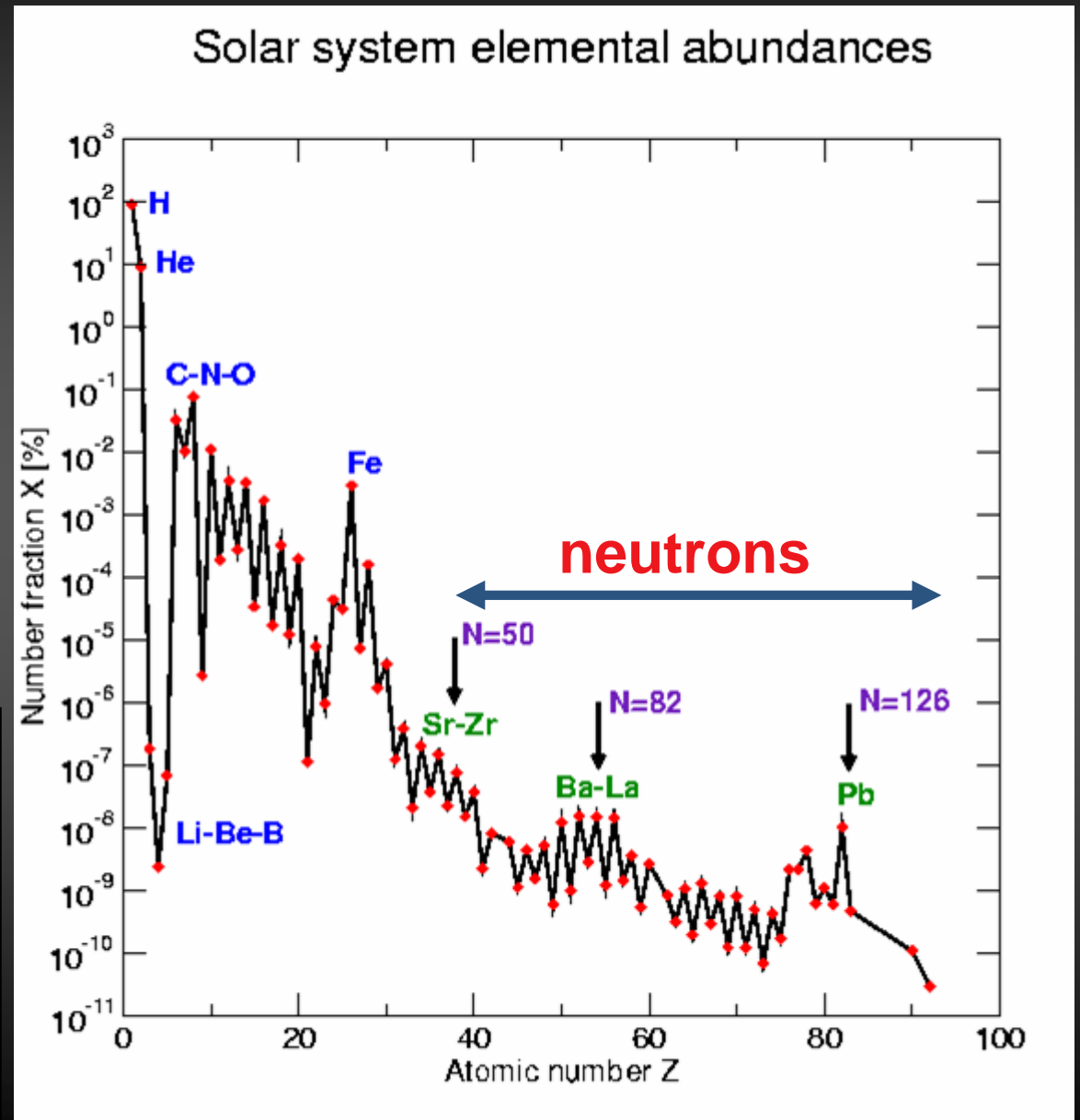
$$\sigma(n, \gamma) \cdot N = \text{const.}$$

$\gg$

## The canonical s-process

Cu			<b><math>^{62}\text{Cu}</math></b> 9.74 m	$^{63}\text{Cu}$ 69.17	$^{64}\text{Cu}$ 12.7 h	
Ni		$^{60}\text{Ni}$ 26.23	$^{61}\text{Ni}$ 1.140	$^{62}\text{Ni}$ 3.634	$^{64}\text{Ni}$ 100 a	
Co		<b><math>^{58}\text{Co}</math></b> 70.86 d	$^{59}\text{Co}$ 1.10	$^{60}\text{Co}$ 5.272 a	$^{61}\text{Co}$ 1.65 h	
Fe	$^{56}\text{Fe}$ 91.72	$^{57}\text{Fe}$ 2.2	$^{58}\text{Fe}$ 0.28	$^{59}\text{Fe}$ 44.503 d	$^{60}\text{Fe}$ $1.5 \cdot 10^9$ a	$^{61}\text{Fe}$ 6 m

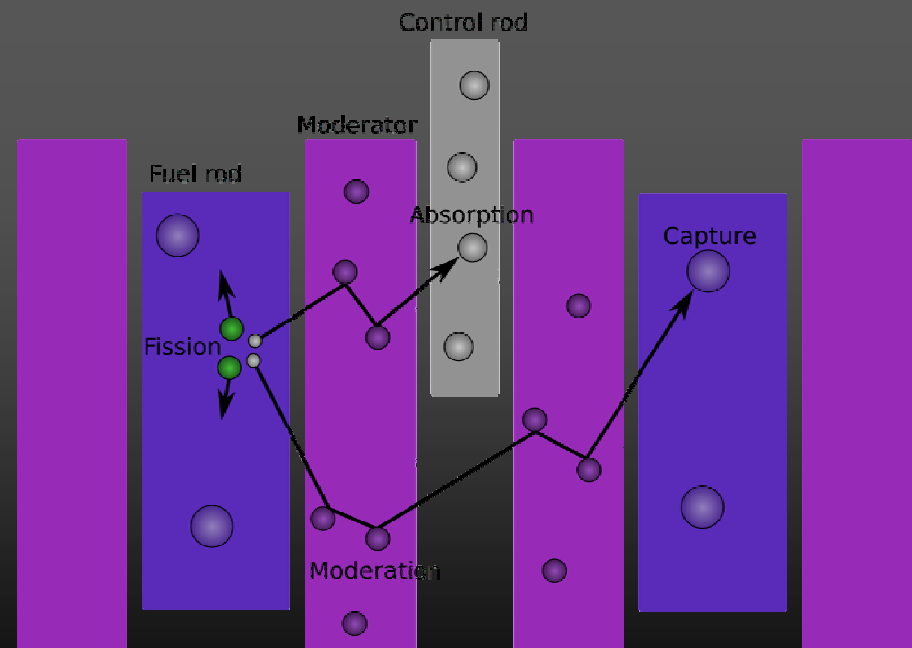
Yellow arrows indicate the s-process path from Fe to Cu. Red boxes highlight the branching points at  $^{58}\text{Co}$  and  $^{62}\text{Cu}$ .



# Energy generation and Nucleosynthesis: not only in stars!



The Candu Qinshan Nuclear Power Plant





# Nucleosynthesis: TRU (1000 MW<sub>e</sub> LWR)

	Cm 238 2,4 h	Cm 239 3 h	Cm 240 27 d	Cm 241 32,8 d	Cm 242 162,94 d	Cm 243 29,1 a	Cm 244 18,10 a	Cm 245 8500 a	Cm 246 4730 a
Am 236 ? 3,7 m	Am 237 73,0 m	Am 238 1,63 h	Am 239 11,9 h	Am 240 50,8 h	Am 241 432,2 a	Am 242 141 a	Am 243 7370 a	Am 244 26 m	Am 245 2,05 h
Pu 235 25,3 m	Pu 236 2,858 a	Pu 237 45,2 d	Pu 238 87,74 a	Pu 239 2,411 · 10 <sup>4</sup> a	Pu 240 6563 a	Pu 241 14,35 a	Pu 242 3,750 · 10 <sup>5</sup> a	Pu 243 4,956 h	Pu 244 8,00 · 10 <sup>7</sup> a
Np 234 4,4 d	Np 235 396,1 d	Np 236 22,5 h	Np 237 2,144 · 10 <sup>6</sup> a	Np 238 2,117 d	Np 239 2,355 d	Np 240 7,22 m	Np 241 13,9 m	Np 242 2,2 m	Np 243 1,85 m
U 233 1,592 · 10 <sup>5</sup> a	U 234 0,0055	U 235 0,7200	U 236 2,342 · 10 <sup>7</sup> a	U 237 6,75 d	U 238 99,2745	U 239 23,5 m	U 240 14,1 h		U 242 16,8 m
Pa 232 1,31 d	Pa 233 27,0 d	Pa 234 1,17 m	Pa 235 34,2 m	Pa 236 9,1 m	Pa 237 8,7 m	Pa 238 2,3 m			
Th 231 25,5 h	Th 232 100	Th 233 22,3 m	Th 234 24,10 d	Th 235 7,1 m	Th 236 37,5 m	Th 237 5,0 m			

244Cm  
1.5 Kg/yr

241Am: 11.6 Kg/yr  
243Am: 4.8 Kg/yr

239Pu: 125 Kg/yr

237Np: 16 Kg/yr

LLFP  
76.2 Kg/yr

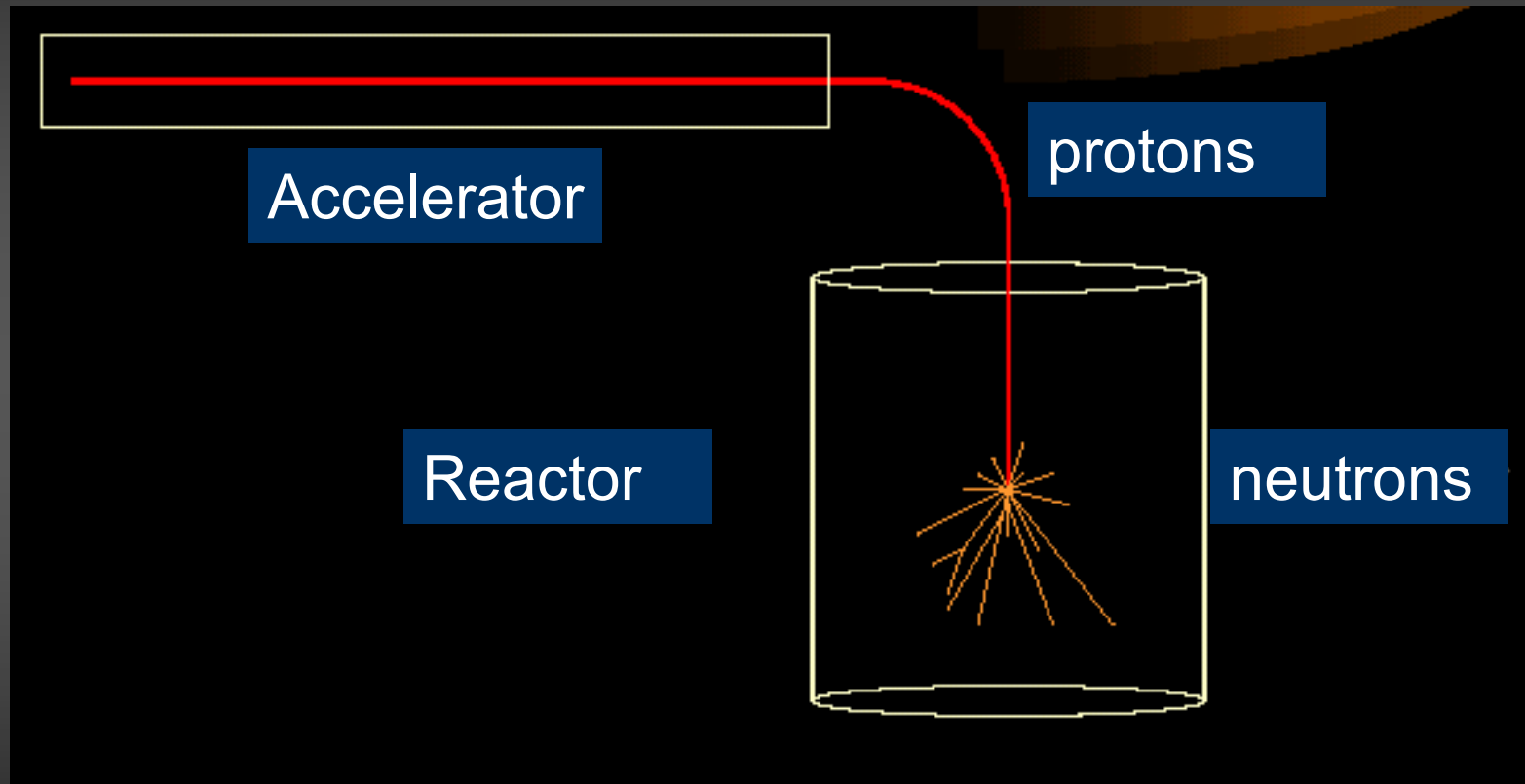
LLFP

source: Actinide and Fission Product Partitioning and Transmutation – NEA (1999)

# Th/U fuel cycle

	<b>Cm 238</b> 2,4 h	<b>Cm 239</b> 3 h	<b>Cm 240</b> 27 d	<b>Cm 241</b> 32,8 d	<b>Cm 242</b> 162,94 d	<b>Cm 243</b> 29,1 a	<b>Cm 244</b> 18,10 a	<b>Cm 245</b> 8500 a	<b>Cm 246</b> 4730 a	
<b>Am 236 ?</b> 3,7 m	<b>Am 237</b> 73,0 m	<b>Am 238</b> 1,63 h	<b>Am 239</b> 11,9 h	<b>Am 240</b> 50,8 h	<b>Am 241</b> 432,2 a	<b>Am 242</b> 141 a	<b>Am 243</b> 7370 a	<b>Am 244</b> 26 m	<b>Am 245</b> 2,05 h	
<b>Pu 235</b> 25,3 m	<b>Pu 236</b> 2,858 a	<b>Pu 237</b> 45,2 d	<b>Pu 238</b> 87,74 a	<b>Pu 239</b> $2,411 \cdot 10^4$ a	<b>Pu 240</b> 6563 a	<b>Pu 241</b> 14,35 a	<b>Pu 242</b> $3,750 \cdot 10^5$ a	<b>Pu 243</b> 4,956 h	<b>Pu 244</b> $8,00 \cdot 10^7$ a	
<b>Np 234</b> 4,4 d	<b>Np 235</b> 396,1 d	<b>Np 236</b> 22,5 h	<b>Np 237</b> $2,144 \cdot 10^6$ a	<b>Np 238</b> 2,117 d	<b>Np 239</b> 2,355 d	<b>Np 240</b> 7,22 m	<b>Np 241</b> 13,9 m	<b>Np 242</b> 2,2 m	<b>Np 243</b> 1,85 m	
<b>U 233</b> $1,592 \cdot 10^5$ a	<b>U 234</b> 0,0055	<b>U 235</b> 0,7200	<b>U 236</b> 120 ns	<b>U 237</b> 6,75 d	<b>U 238</b> 99,2745	<b>U 239</b> 23,5 m	<b>U 240</b> 14,1 h		<b>U 242</b> 16,8 m	
<b>Pa 232</b> 1,31 d	<b>Pa 233</b> 27,0 d	<b>Pa 234</b> 1,17 m	<b>Pa 235</b> 24,2 m	<b>Pa 236</b> 9,1 m	<b>Pa 237</b> 8,7 m	<b>Pa 238</b> 2,3 m	148		150	
<b>Th 231</b> 25,5 h	<b>Th 232</b> 100	<b>Th 233</b> 22,3 m	<b>Th 234</b> 24,10 d	<b>Th 235</b> 7,1 m	<b>Th 236</b> 37,5 m	<b>Th 237</b> 5,0 m				

# ADS (Accelerator Driven Systems)

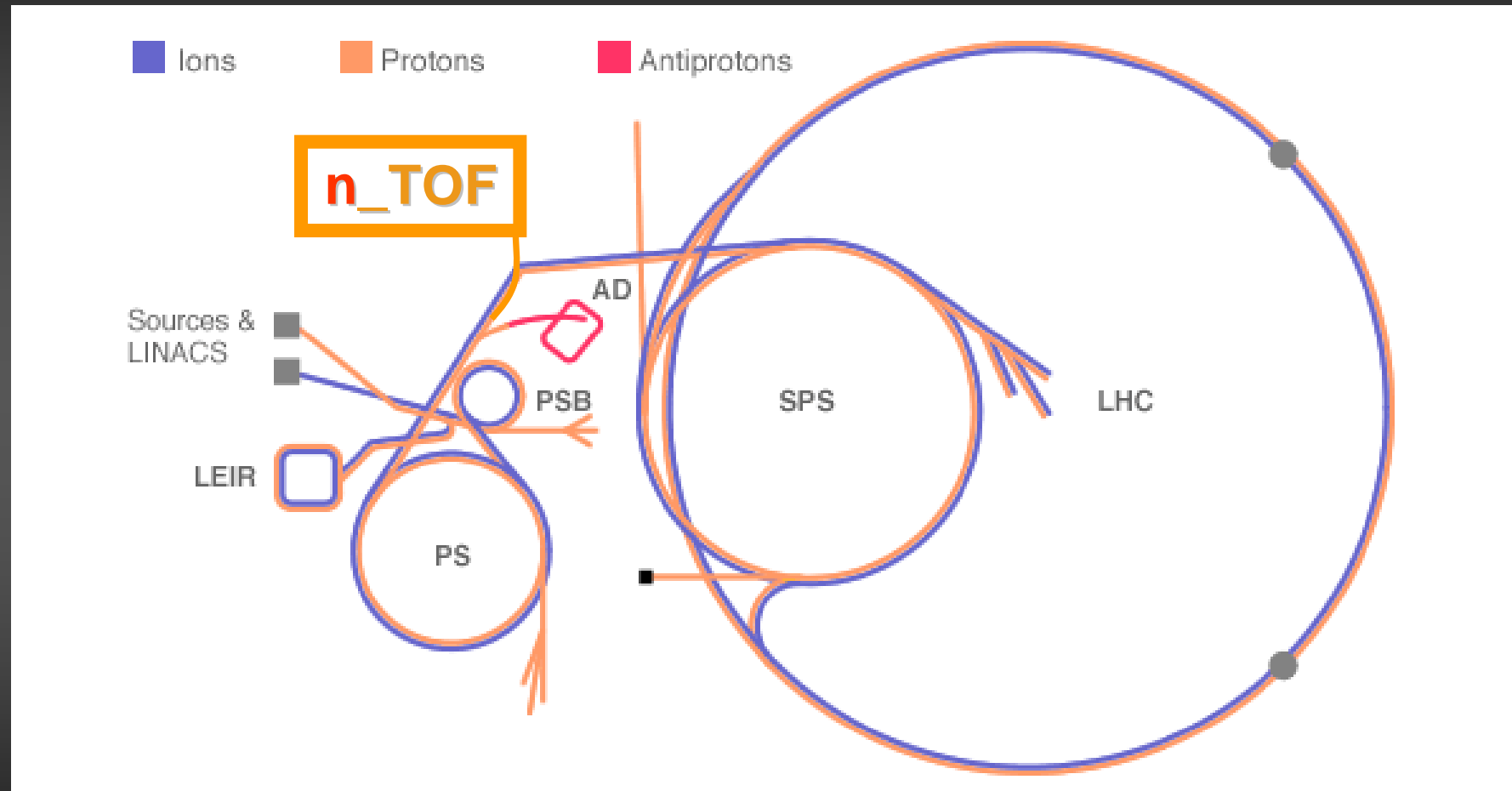


Zen-ADS

# World scene for tof measurements

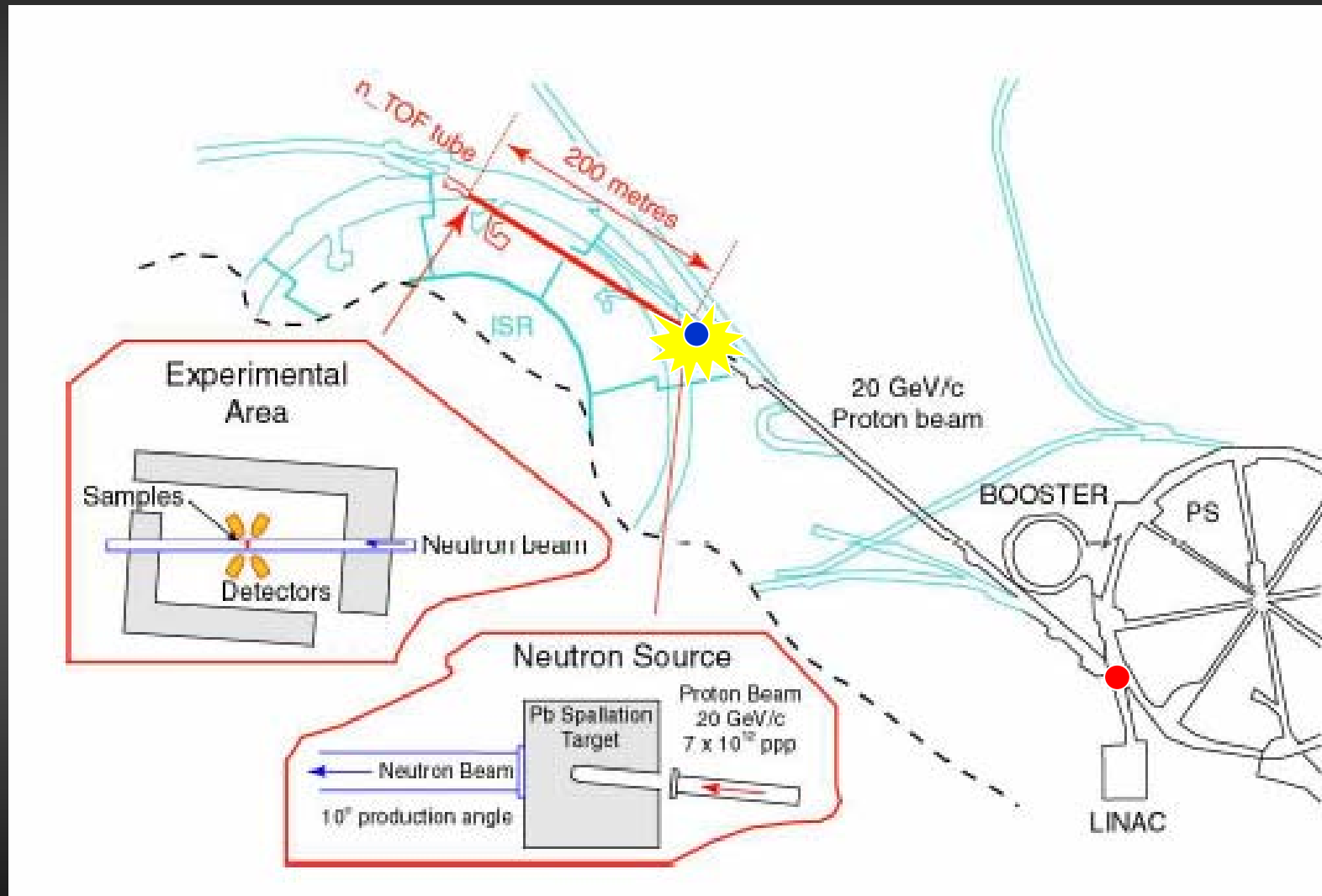
facility		driver and energy	repetition rate	n source	n energy range	flight path length
FZK	Karlsruhe	varii in the MeV range	MHz	$^7\text{Li}(p,n)$ & others	few keV up to 1 MeV monoE above	10s cm
TIT	Tokyo					
...	...					
GELINA	EC-JRC Geel	electron linac 150 MeV	800 Hz	photo-n photo-f	10 meV – 20 MeV	10m to 400m
LANSCCE	Los Alamos National Laboratory	proton linac 800 MeV	20 Hz	spallation	< 500 keV (DANCE)	20m
n_TOF	CERN	PS 20 GeV	0.4 Hz (average)	spallation	10 meV – 250 MeV (or wider)	200m

# CERN accelerator Complex



Linac(s): up to 50 MeV    PSB: up to 1 GeV    PS: up to 24 GeV

# The n\_TOF facility at CERN

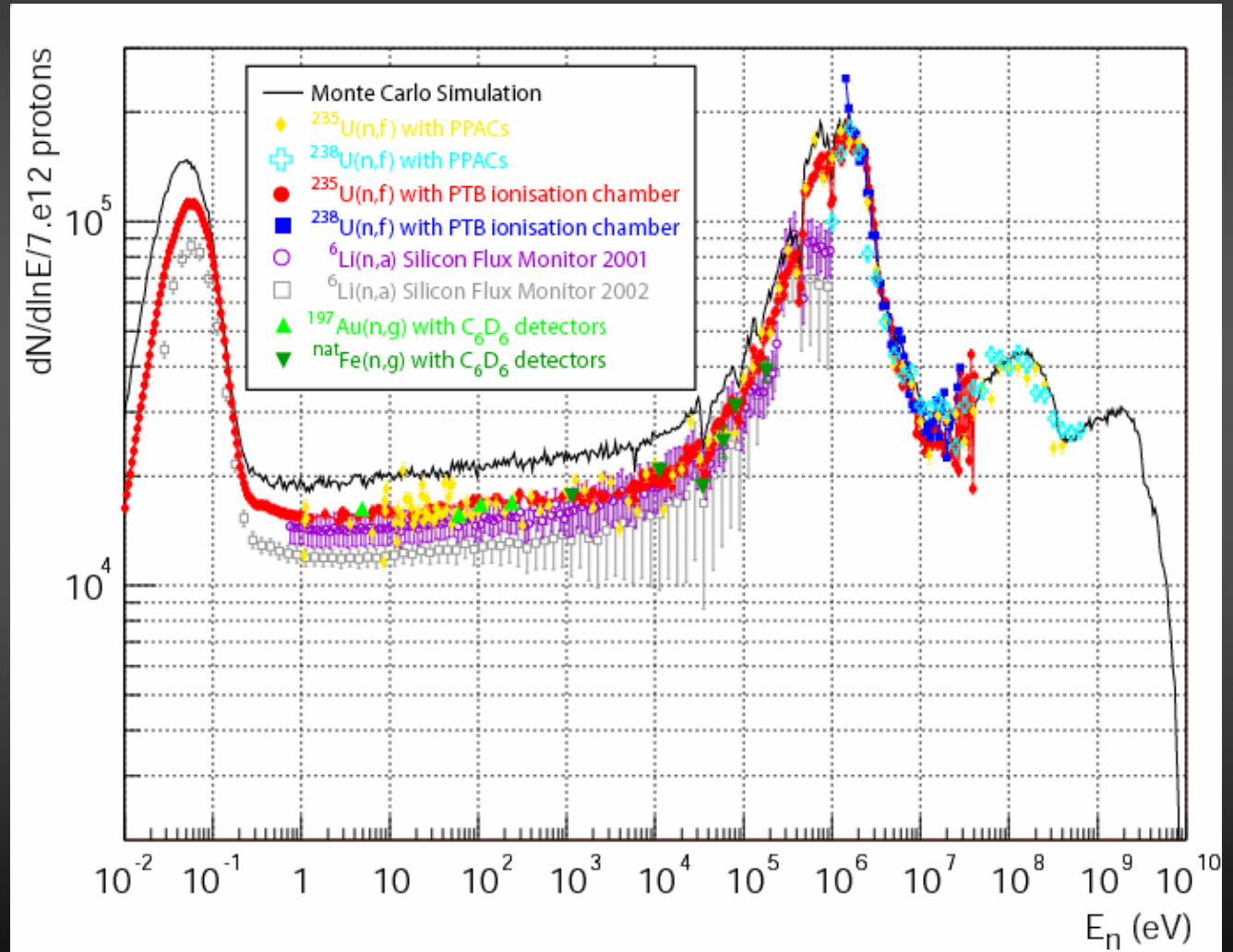


# n\_TOF basic parameters

proton beam momentum	20 GeV/c
intensity (dedicated mode)	$7 \times 10^{12}$ protons/pulse
repetition frequency	1 pulse/2.4s
pulse width	6 ns (rms)
n/p	300
lead target dimensions	80x80x60 cm <sup>3</sup>
cooling & moderation material	H <sub>2</sub> O
moderator thickness in the exit face	5 cm
neutron beam dimension in EAR-1 (capture mode)	2 cm (FWHM)

# Basic characteristics of experiments at n\_TOF

- wide energy range





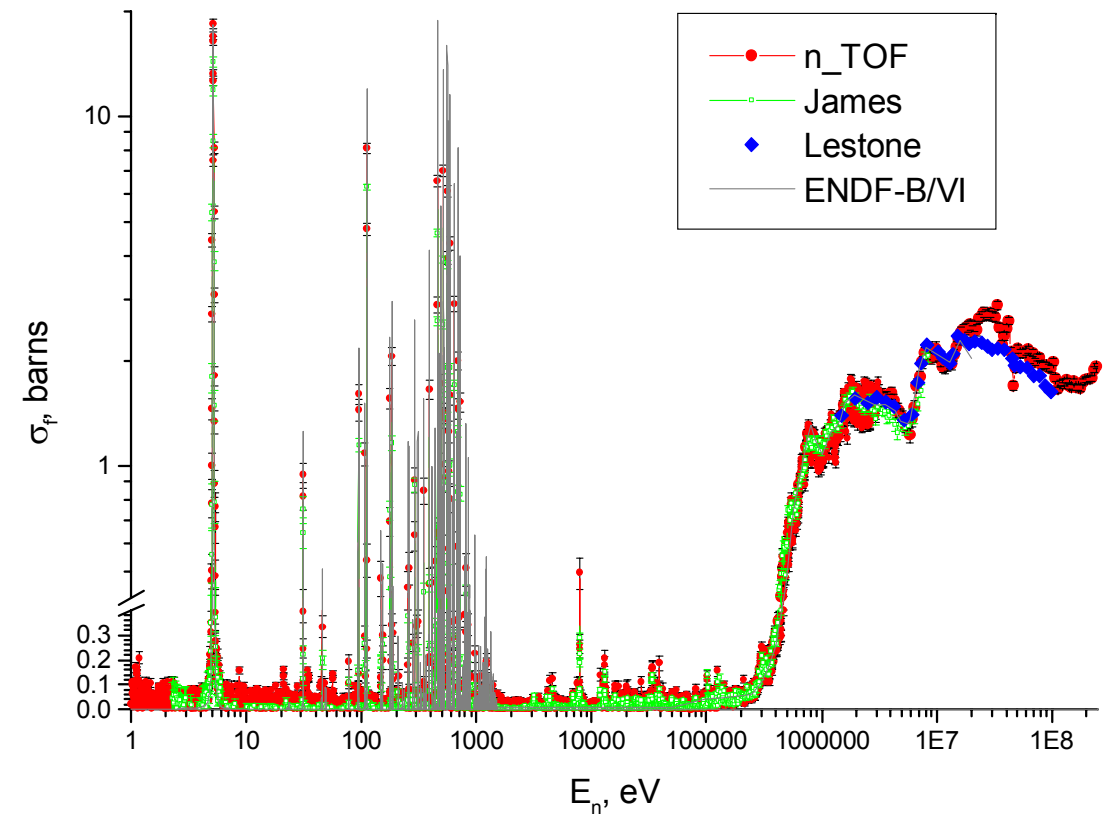
# Basic characteristics of experiments at n\_TOF



- wide energy range

PPACs & FIC-0 (2003)

$^{234}\text{U}(n,f)$



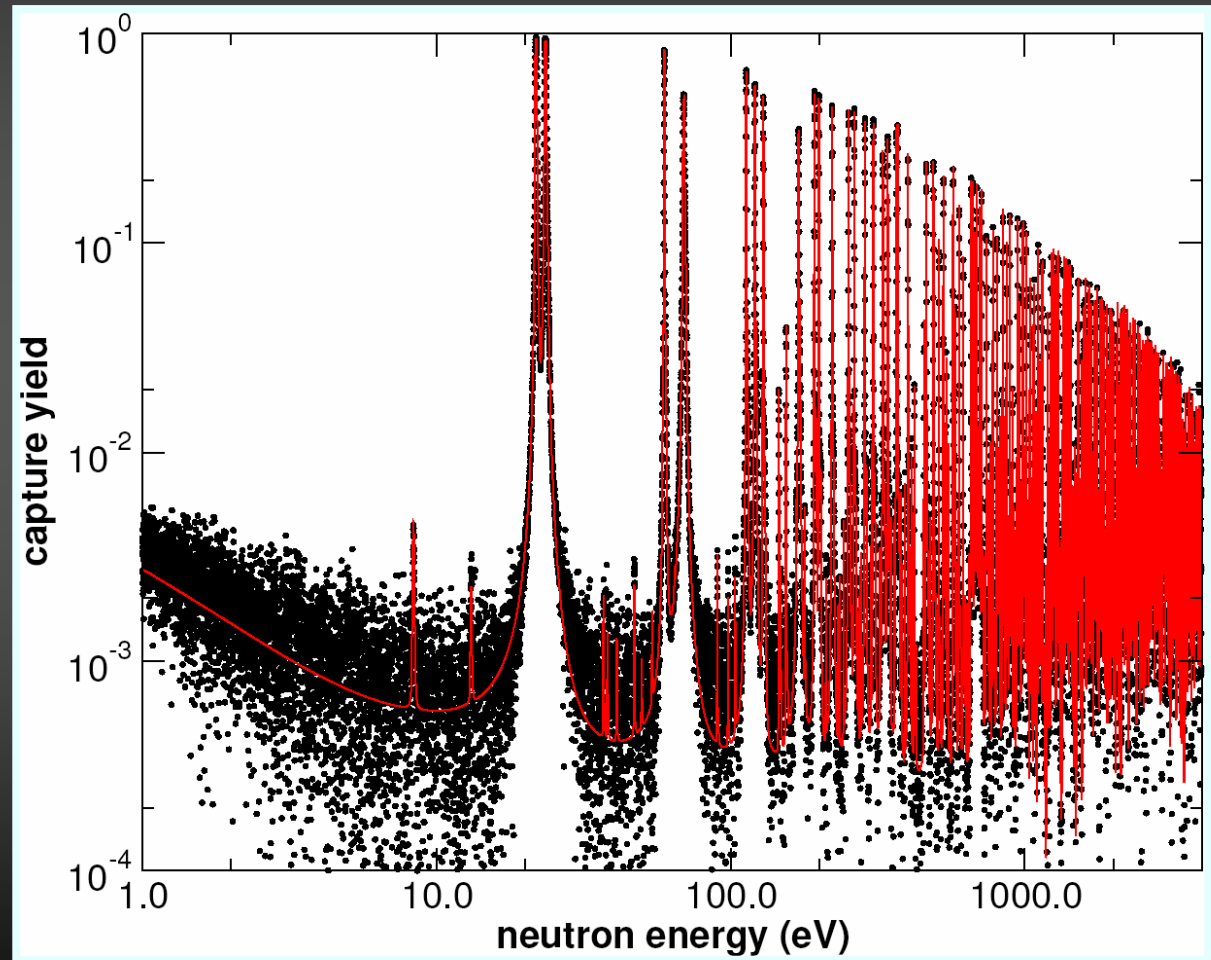
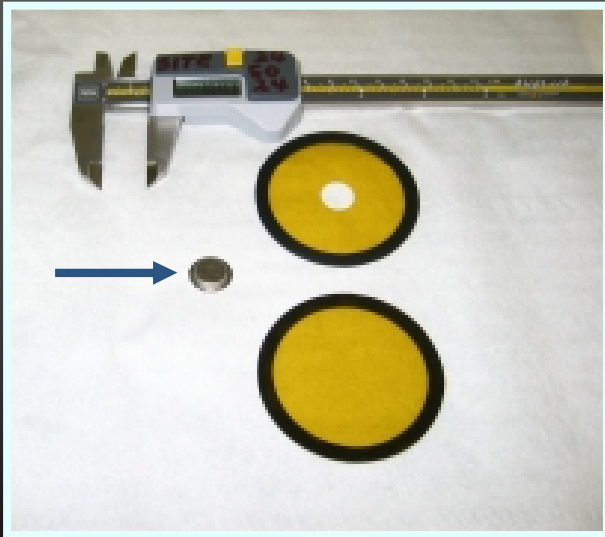
# Basic characteristics of experiments at n\_TOF



$^{232}\text{Th}(n,\gamma)$

- wide energy range
- high neutron flux & high energy resolution

small samples

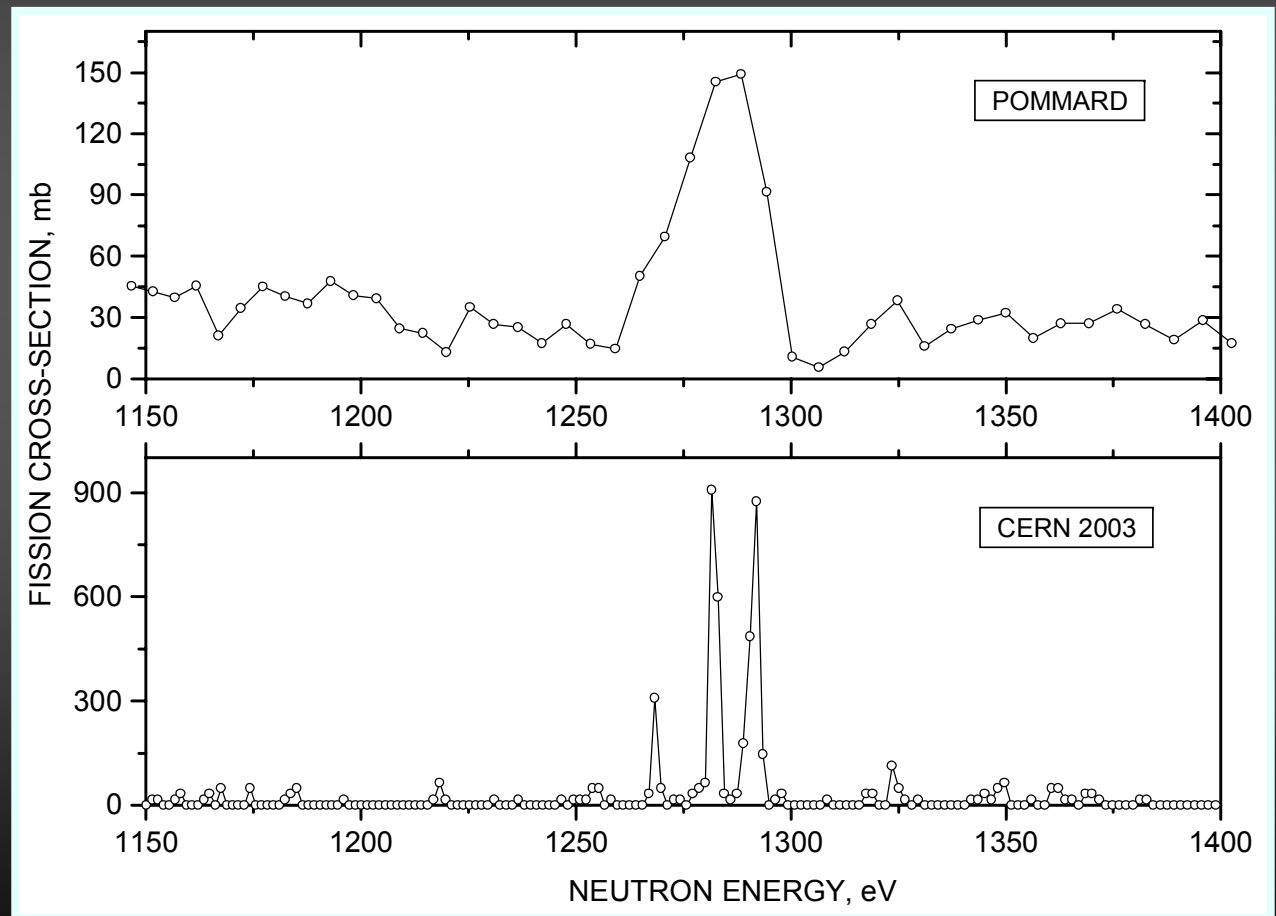


# Basic characteristics of experiments at n\_TOF



$^{236}\text{U}(n,f)$

- wide energy range
- high neutron flux & high energy resolution

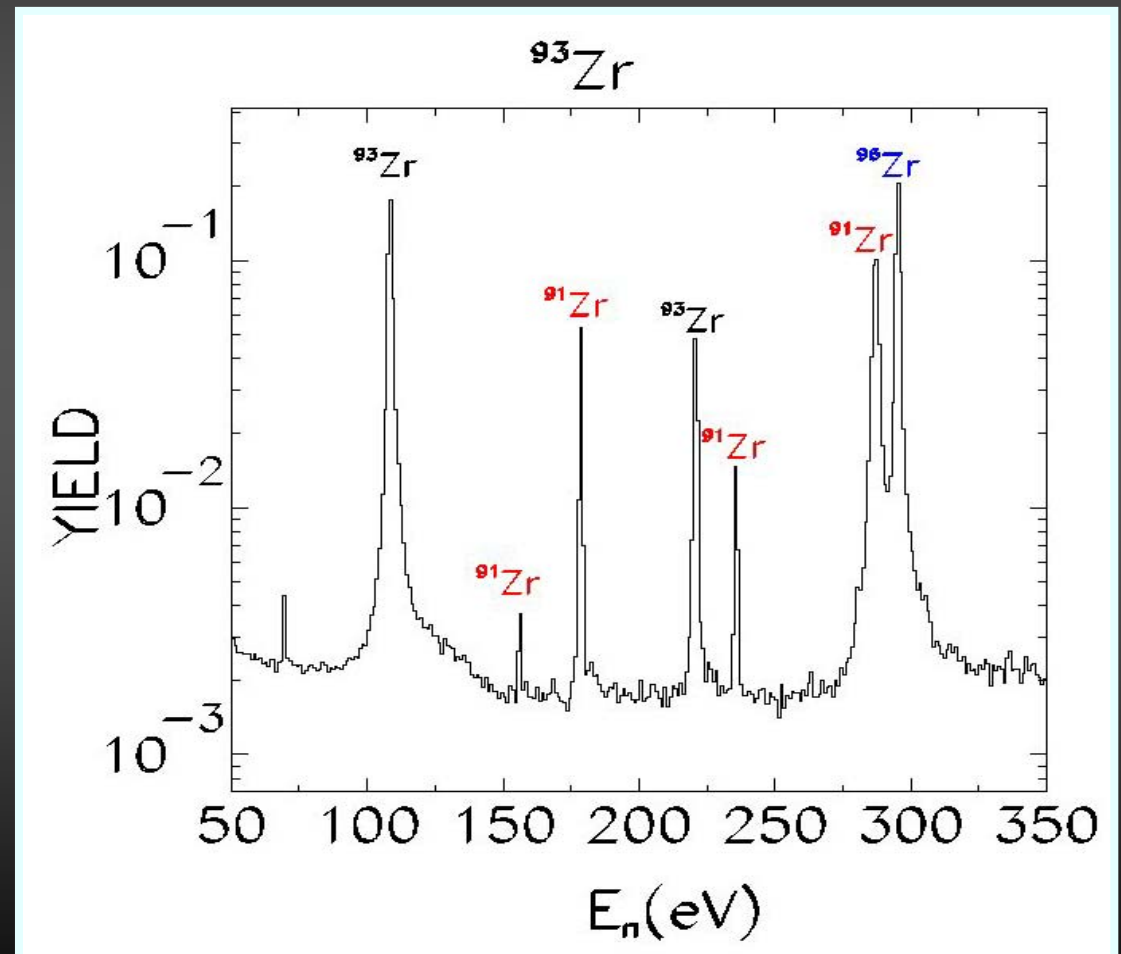


# Basic characteristics of experiments at n\_TOF



$^{93}\text{Zr}(n,\gamma)$

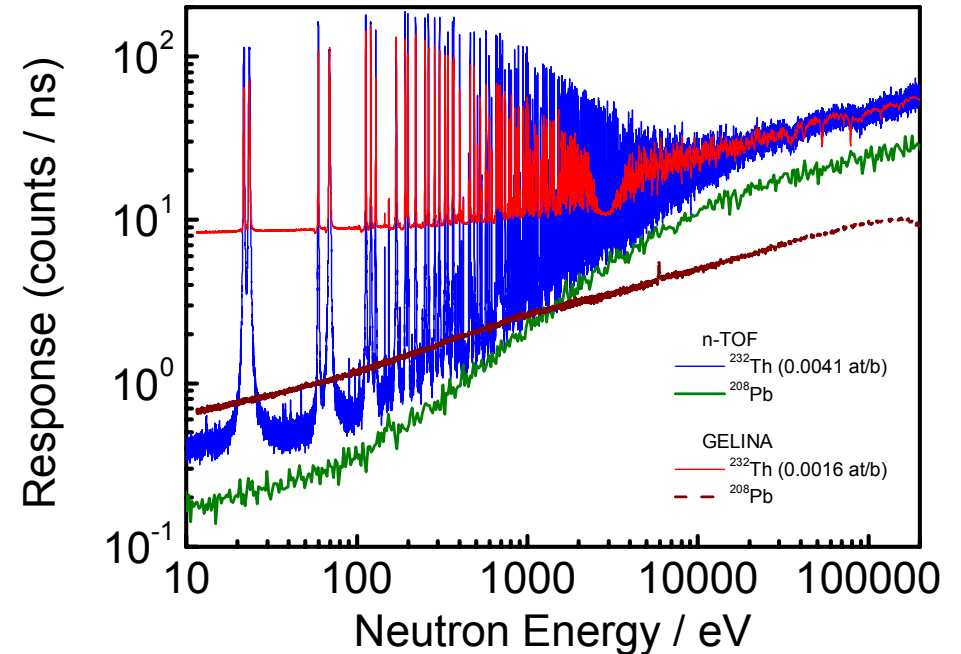
- wide energy range
- high neutron flux & high energy resolution



# Basic characteristics of experiments at n\_TOF

$^{232}\text{Th}(n,\gamma)$

- wide energy range
- high neutron flux & high energy resolution
- low repetition rate of the proton driver



$$\frac{f_1}{f_2} \times \frac{L_1}{L_2} = \frac{0.28 [1/s]}{800 [1/s]} \times \frac{187.5 [m]}{30 [m]} = \frac{1}{457}$$

source: P Rullhusen (GELINA)

comparison with GELINA (~ same average flux at 30m)

# Basic characteristics of experiments at n\_TOF

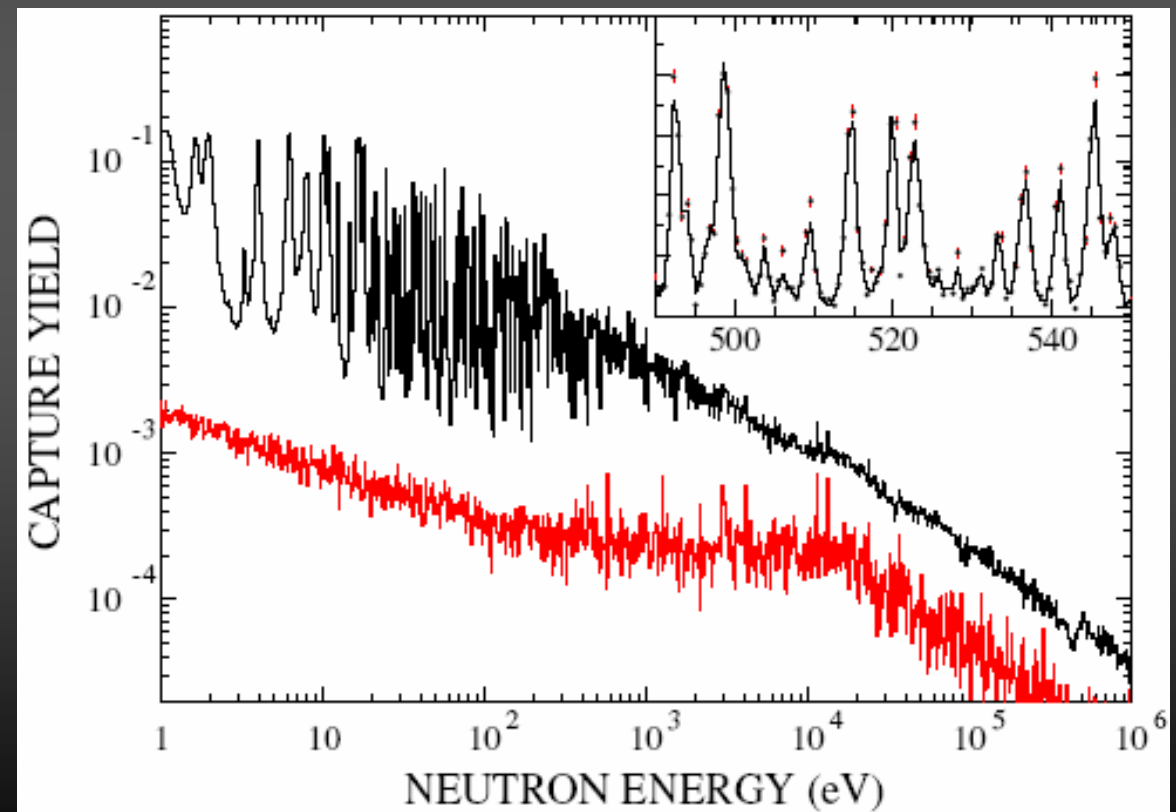


- wide energy range
- high neutron flux & high energy resolution
- low repetition rate of the proton driver
- low background conditions

U Abbondanno et al. (The n\_TOF Collaboration)  
Phys. Rev. Lett. **93** (2004), 161103  
&

S Marrone et al. (The n\_TOF Collaboration)  
Phys. Rev. C **73** 03604 (2006)

$^{151}\text{Sm}(n,\gamma)$



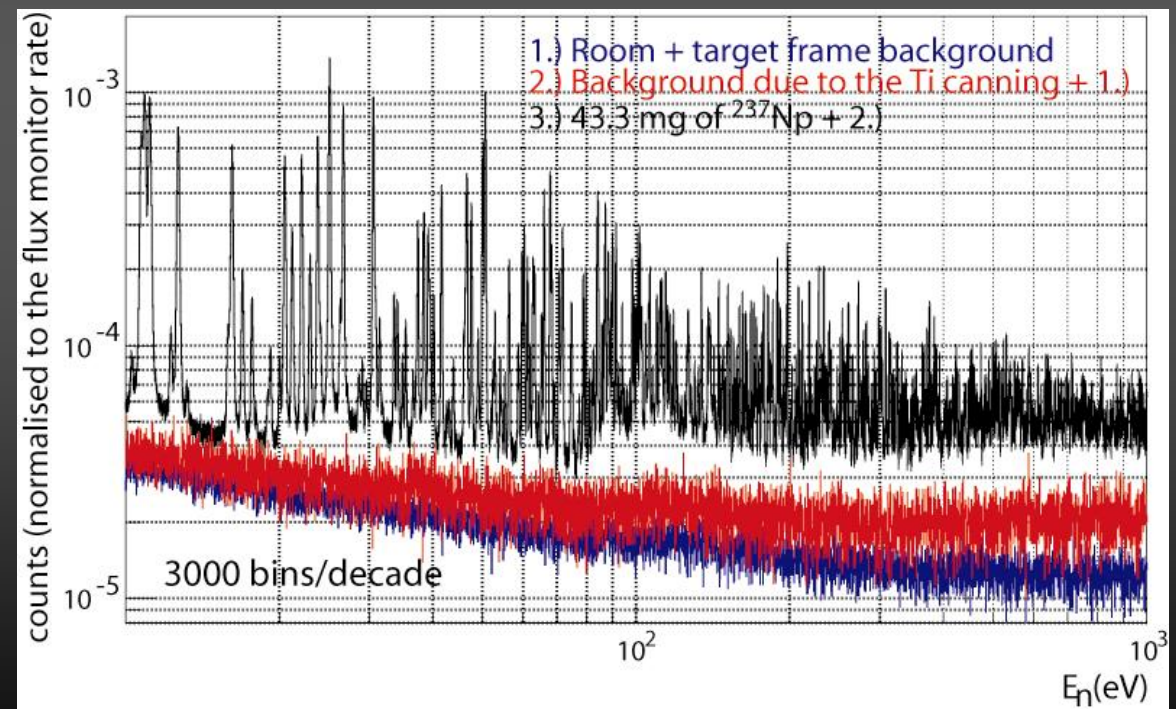
# Basic characteristics of experiments at n\_TOF



- wide energy range
- high neutron flux & high energy resolution
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- low background conditions

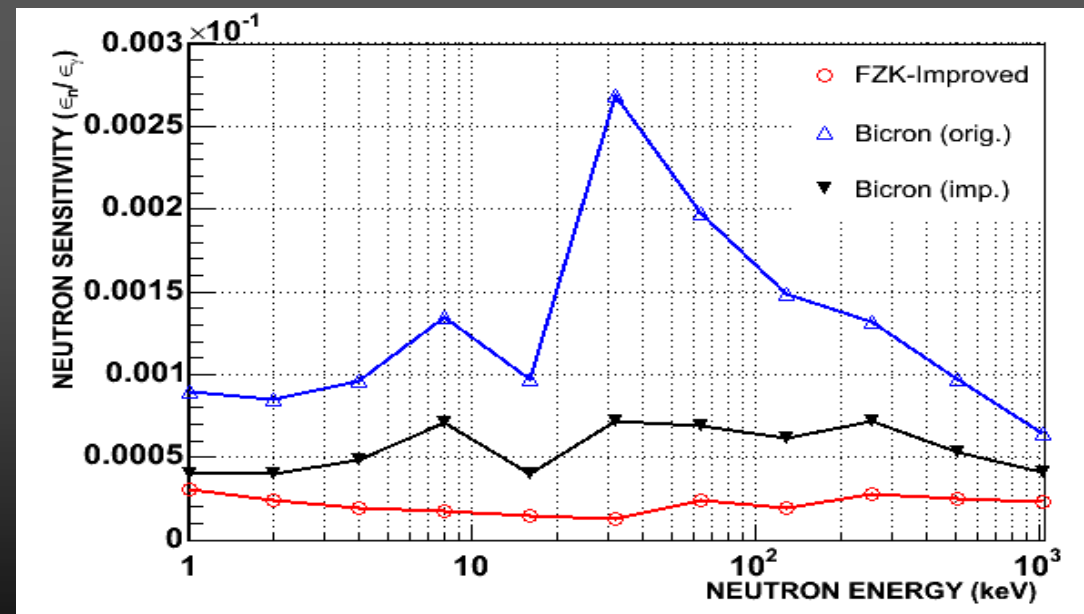
$^{237}\text{Np}(n,\gamma)$

D Cano-Ott, *et al.* (The n\_TOF Collaboration)  
ND2004 Conference, Santa Fe, NM – Sept. 2004



# Basic characteristics of experiments at n\_TOF

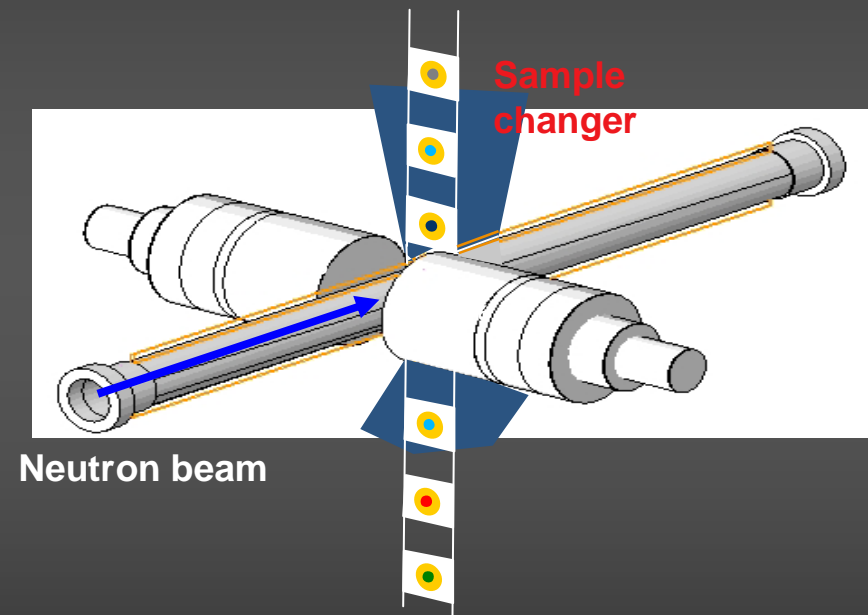
- wide energy range
- high neutron flux & high energy resolution
- low repetition rate of the proton driver
- low background conditions
- detectors with extremely low neutron sensitivity





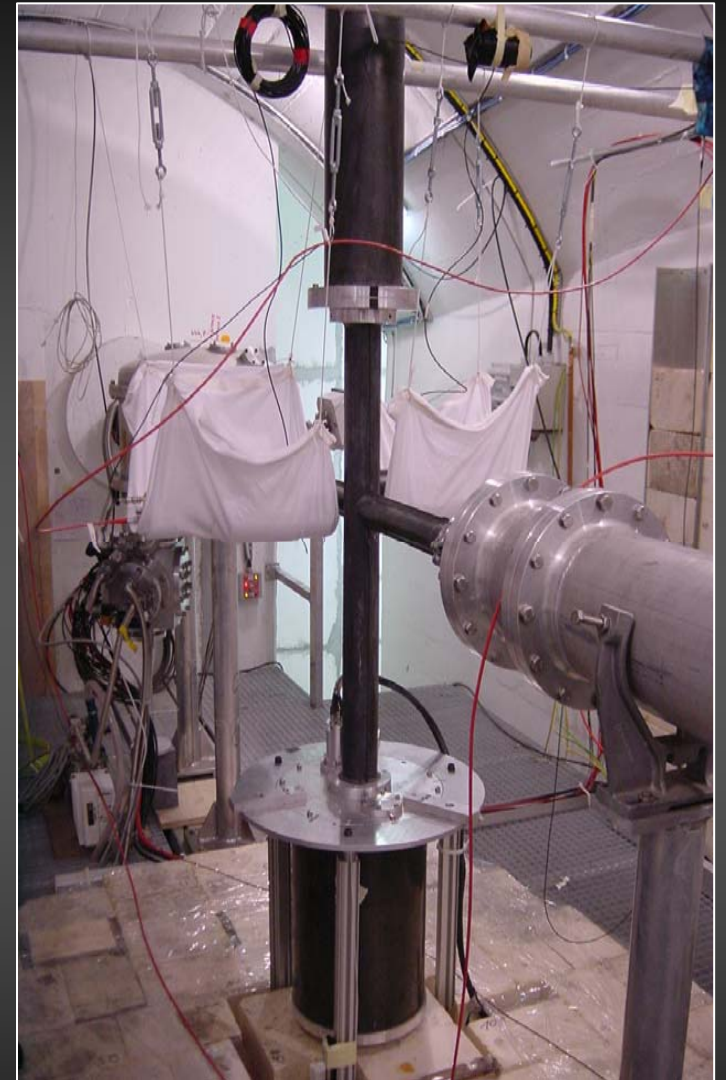
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- low background conditions
  
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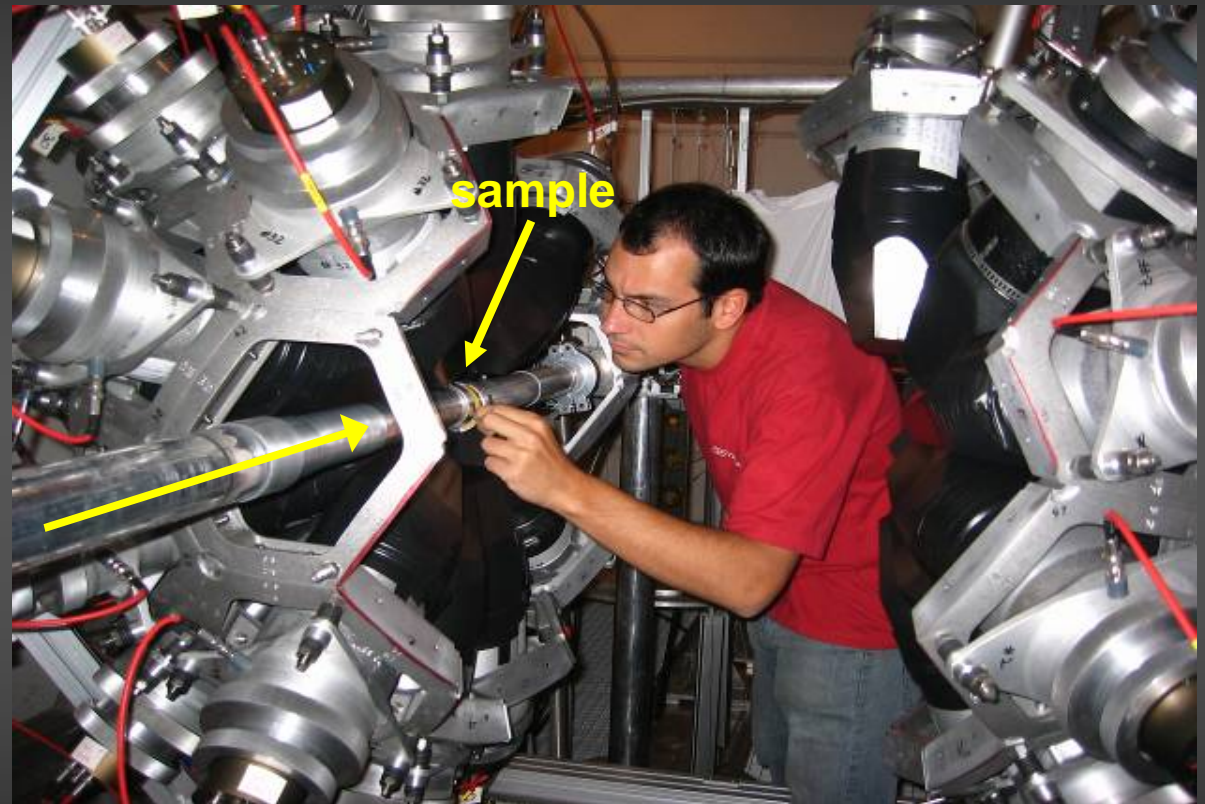


sample changer and beam pipe  
made out of carbon fiber

# Basic characteristics of experiments at n\_TOF

- 40 BaF<sub>2</sub> crystals
- high detection efficiency ≈100%
- good energy resolution

- wide energy range
- high neutron flux & high energy resolution
- low repetition rate of the proton driver
- low background conditions
- detectors with extremely low neutron sensitivity
- high-efficiency detectors (TAC)



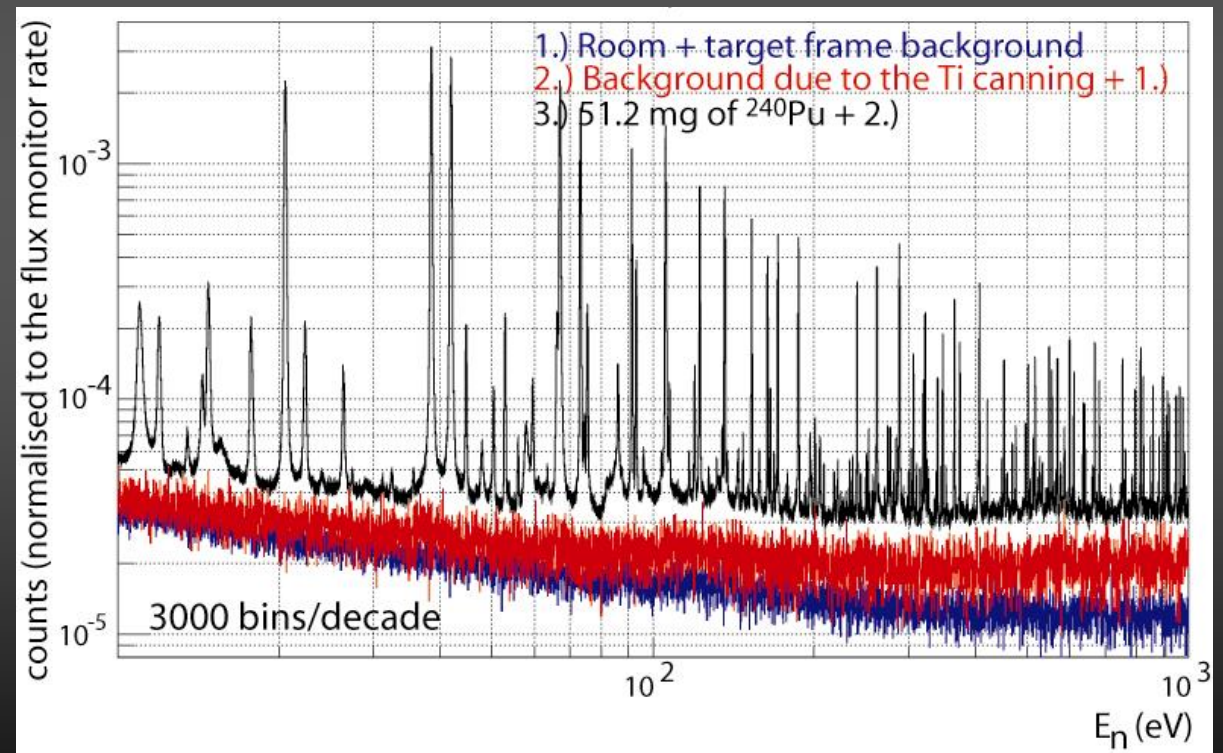
[more >>](#)

# Basic characteristics of experiments at n\_TOF

- wide energy range
- high neutron flux & high energy resolution
- low repetition rate of the proton driver
- low background conditions
  
- detectors with extremely low neutron sensitivity
- high-efficiency detectors (TAC)

$^{240}\text{Pu}(n,\gamma)$

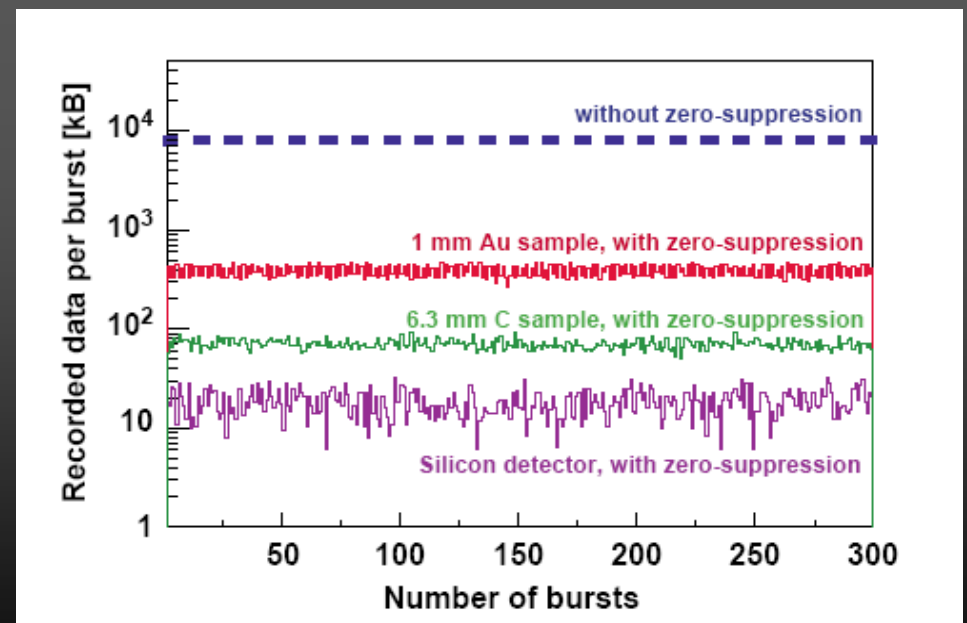
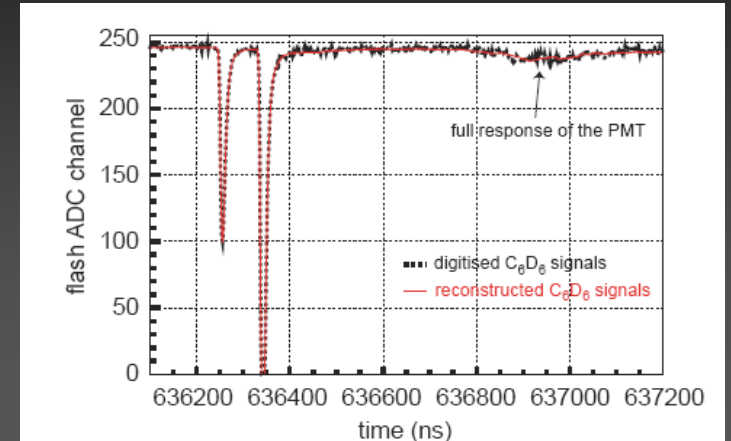
C Guerrero *et al.* (The n\_TOF Collaboration)  
ND2007 Conference, Nice, France, April 2007



# Basic characteristics of experiments at n\_TOF

R Plag et al. (The n\_TOF Collaboration)  
NIMA 538 (2005) 693

- wide energy range
- high neutron flux & high energy resolution
- low repetition rate of the proton driver
- low background conditions
  
- detectors with extremely low neutron sensitivity
- high-efficiency detectors (TAC)
- advanced daq system



# Basic characteristics of experiments at n\_TOF

- wide energy range
- high neutron flux & high energy resolution
- low repetition rate of the proton driver
- low background conditions
  
- detectors with extremely low neutron sensitivity
- high-efficiency detectors (TAC)
- advanced daq system

**n\_TOF beam characteristics and experimental setup proved to be a unique combination for high accuracy measurements**

# n\_TOF experiments

## 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

$^{233,234,235,236,238}\text{U}$

$^{232}\text{Th}$

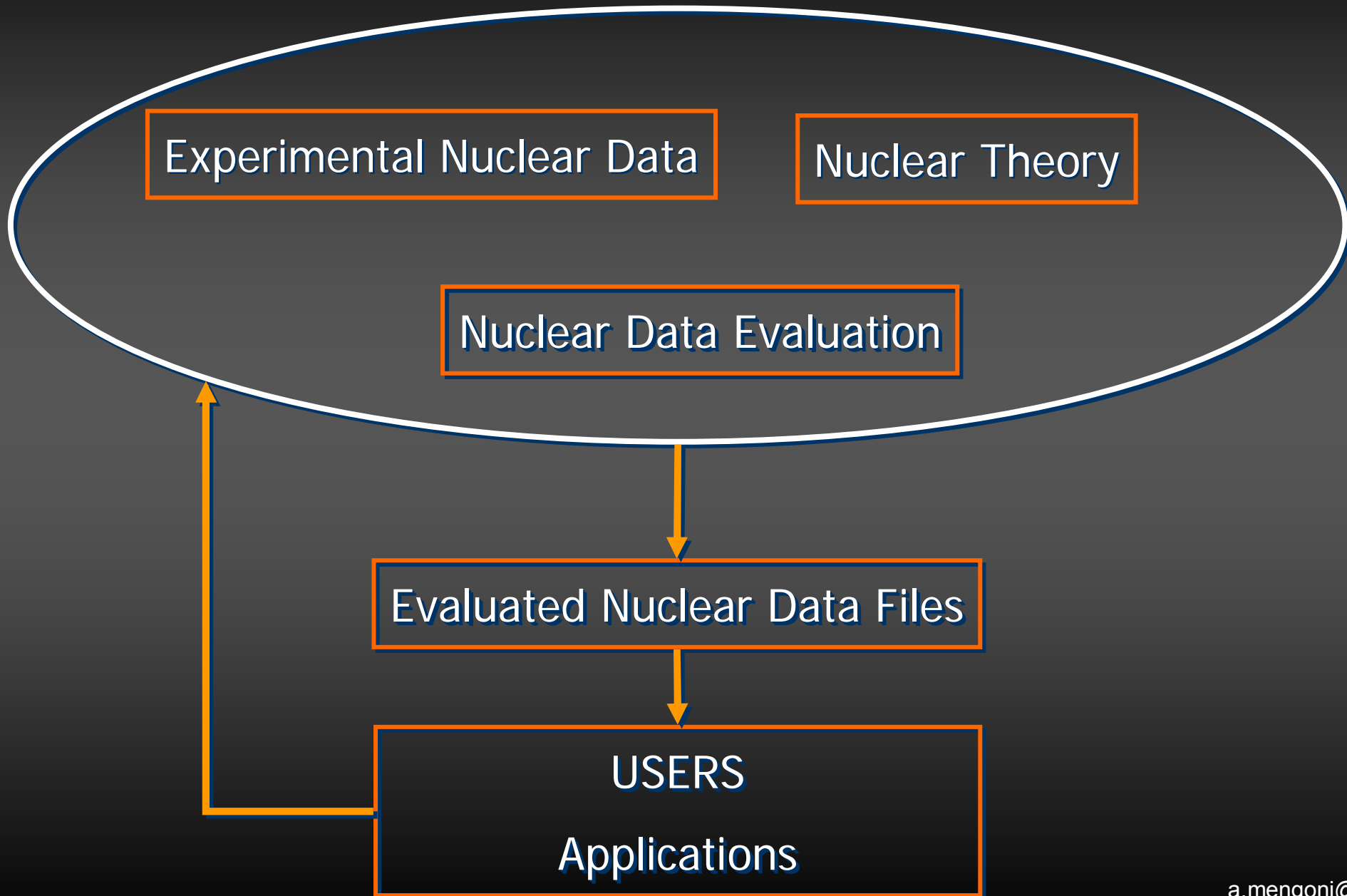
$^{209}\text{Bi}$

$^{237}\text{Np}$

$^{241,243}\text{Am}$ ,  $^{245}\text{Cm}$

- **M**easurements of neutron cross sections relevant for Nuclear Waste Transmutation and related Nuclear Technologies
  - Th/U fuel cycle (capture & fission)
  - Transmutation of MA (capture & fission)
  - Transmutation of FP (capture)
- **C**ross sections relevant for Nuclear Astrophysics
  - s-process: branchings
  - s-process: presolar grains
- **N**eutrons as probes for fundamental Nuclear Physics
  - Nuclear level density & n-nucleus interaction

# Nuclear Reactions & Data Libraries





# Evaluated Data Libraries

Evaluated data sets are produced through the process of critical comparison, selection renormalization and averaging of the available experimental data, normally complemented by nuclear model calculations.

Evaluated Libraries are computer files of evaluated data which, appropriately processed, form the input data to computations for a wide variety of nuclear science and technology applications. Each of these evaluated libraries may consist of individual evaluated data sets for several hundred isotopes or elements (commonly referred to as 'materials').

# Data Libraries

The screenshot shows a Mozilla Firefox browser window displaying the IAEA Nuclear Data Services website. The browser's address bar shows the URL <http://www-nds.iaea.org/>. The website header features the IAEA logo and the text "IAEA.org International Atomic Energy Agency".

The main content area is titled "Welcome to the IAEA Nuclear Data Centre" and "Nuclear Data Services". It includes a search bar with the text "Search NDS" and a "Go" button. Below the search bar, there are several sections:

- NDS Mirror Sites:** Includes links for India and Brazil.
- Navigation:** A list of navigation options including Content Browser, Quick Links, ADS-Lib, AMDC, CINDA, DROSG-2000, ENDF, ENSDF, ENSDF ASCII Files, EXFOR, FENDL-2.1, IBANDL, INDL/TSL, IRDF-2002, Masses 2003, Medical Radioisotopes Production, MIRD, Minsk Actinides, NGATLAS, NuDat 2.1, NSR, PGAA-IAEA, Photonuclear, Photon+Electron Interaction, POINT2007, POINT2004, Q-values, Thresholds, RIPL, RNAL, Safeguards data, SigmaCalc, Standards, Stopping Power Data, Thermal Neutron Capture Gamma Rays, Thorium-Uranium Fuel Cycle, Wallet cards, and WIMS-D Library.
- Major Databases:** Lists CINDA (neutron reaction data bibliography), ENDF (evaluated nuclear reaction cross section libraries), EXFOR (experimental nuclear reaction data), ENSDF (evaluated nuclear structure and decay data), NSR (Nuclear Science References), and NuDat 2.2 (selected evaluated nuclear data).
- Nuclear Databases and Files:** Includes a General section with links to Atomic Mass Data Center, Q-values, Thresholds, RIPL, Thermal neutron capture gamma rays, and Wallet cards. It also lists other evaluated data libraries in ENDF format, such as IAEA Photonuclear Data Library, INDL/TSL, IRDF-2002, Minsk Actinides Library, NGATLAS, POINT2007, POINT2004, RNAL, Standards, and Th-U.
- Evaluated libraries in different formats:** Lists ADS-Lib, Charged-particle cross section database, FENDL-2.1, IAEA-NDS-0, IBANDL, MIRD, Nuclear Data for Safeguards, PGAA-IAEA, Photon and Electron Interaction Data, SigmaCalc, Stopping Power Data for Light Ions, X and Gamma-rays standards, WIMS-D-IAEA Library, and Various Specialized Evaluated Data Libraries.
- Electronic Documents:** Includes Citation Guidelines and ENDF Format Manual.

On the right side of the page, there is a "NDS Events" section featuring a "Meetings & Workshops" link, a photo of a person working with a device, and information about the "NEMEA-4" 4th Workshop on Neutron Measurements, Evaluations and Applications - Nuclear data needs for Generation IV and accelerator driven systems, held in Prague, Czech Republic, from October 16-18, 2007. Below this, there is a link to a "Workshop on Nuclear Data for Science and Technology: Medical Applications" held in Miramare, Trieste, Italy, from November 12-23, 2007. At the bottom right, there is a link to a "Joint ICTP-IAEA Workshop on Nuclear Structure and Decay Data: Theory and Evaluation".

[www-nds.iaea.org](http://www-nds.iaea.org)

# Data Libraries

Major Evaluated Nuclear Data libraries available for display & retrieval:

**Libraries:**  All  Selected  Clean

<input type="radio"/> Major Libraries	<input type="radio"/> Other Libraries
<input type="checkbox"/> ENDF/B-VII.0 (USA, 2006)	<input type="checkbox"/> IAEA-Standards, 2006
<input type="checkbox"/> JEFF-3.1 (Europe, 2005)	<input type="checkbox"/> IAEA-Medical (for radioisotope prod.)
<input type="checkbox"/> JENDL-3.3 (Japan, 2002)	<input type="checkbox"/> IRDF-2002 (Dosimetry)
<input type="checkbox"/> ENDF/B-VI.8 (USA, 2001)	<input type="checkbox"/> JEFF-3.1/A (Activation)
<input type="checkbox"/> BROND-2.2 (Russia, 1992)	<input type="checkbox"/> Special Purpose Libraries
<input type="checkbox"/> CENDL-2 (China, 1991)	<input type="checkbox"/> Archival Libraries

The End

# Capture

$^{151}\text{Sm}$

$^{204,206,207,208}\text{Pb}$ ,  $^{209}\text{Bi}$

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$^{232}\text{Th}(n,\gamma)$

# n\_TOF experiments

Th/U nuclear fuel cycle

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Th 231 25,5 h	Th 232 100	Th 233 2,3 m	Th 234 24,10 d	Th 235 7,1 m	Th 236 37,5 m	Th 237 5,0 m			

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$^{233,234}\text{U}$

$^{237}\text{Np}$ ,  $^{240}\text{Pu}$ ,  $^{243}\text{Am}$

## Fission

$^{233,234,235,236,238}\text{U}$

$^{232}\text{Th}$

$^{209}\text{Bi}$

$^{237}\text{Np}$

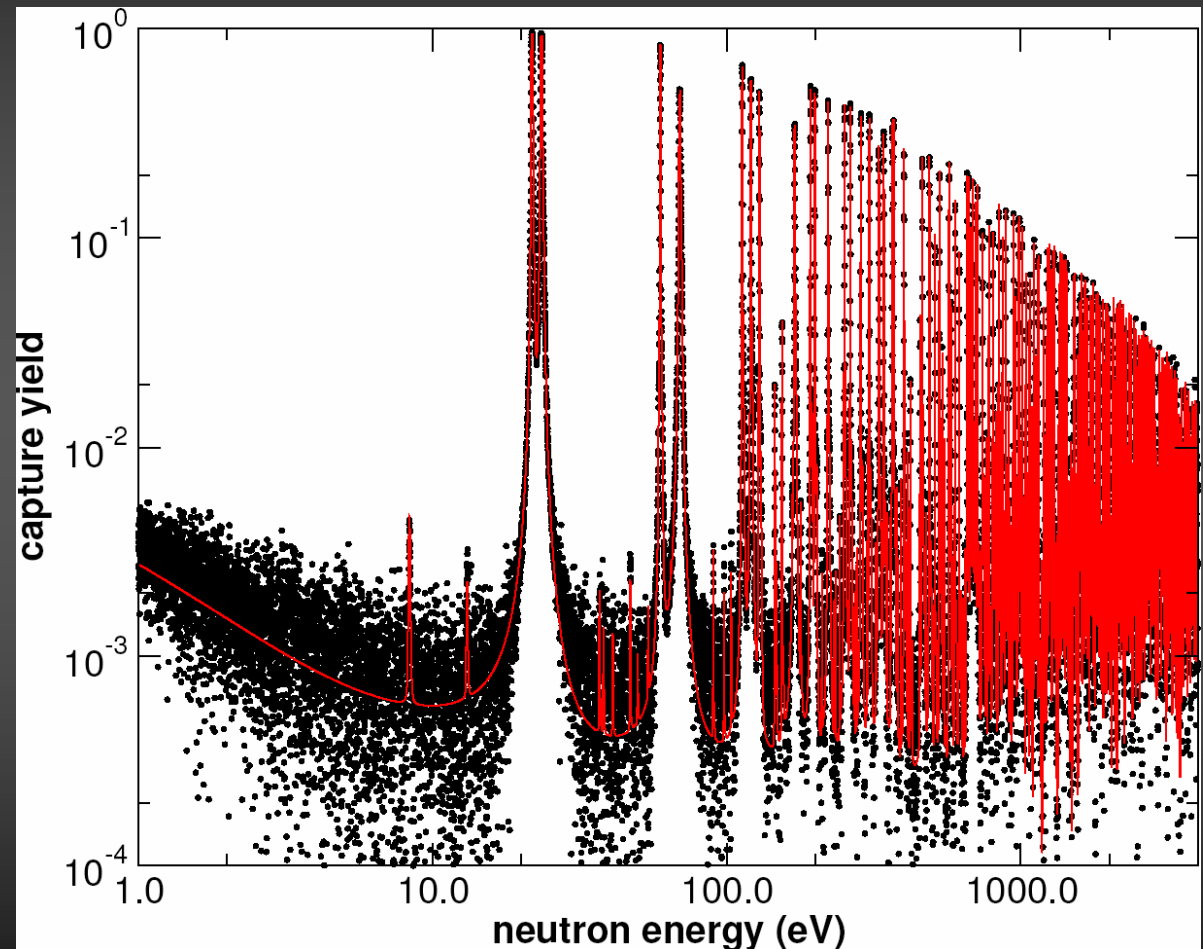
$^{241,243}\text{Am}$ ,  $^{245}\text{Cm}$



$^{232}\text{Th}(n,\gamma)$

# n\_TOF experiments

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ND2004 Conference, Santa Fe, NM – Sept. 2004



extremely high-resolution data!

## Capture

$^{151}\text{Sm}$

$^{204,206,207,208}\text{Pb}$ ,  $^{209}\text{Bi}$

$^{232}\text{Th}$

$^{24,25,26}\text{Mg}$

$^{90,91,92,94,96}\text{Zr}$ ,  $^{93}\text{Zr}$

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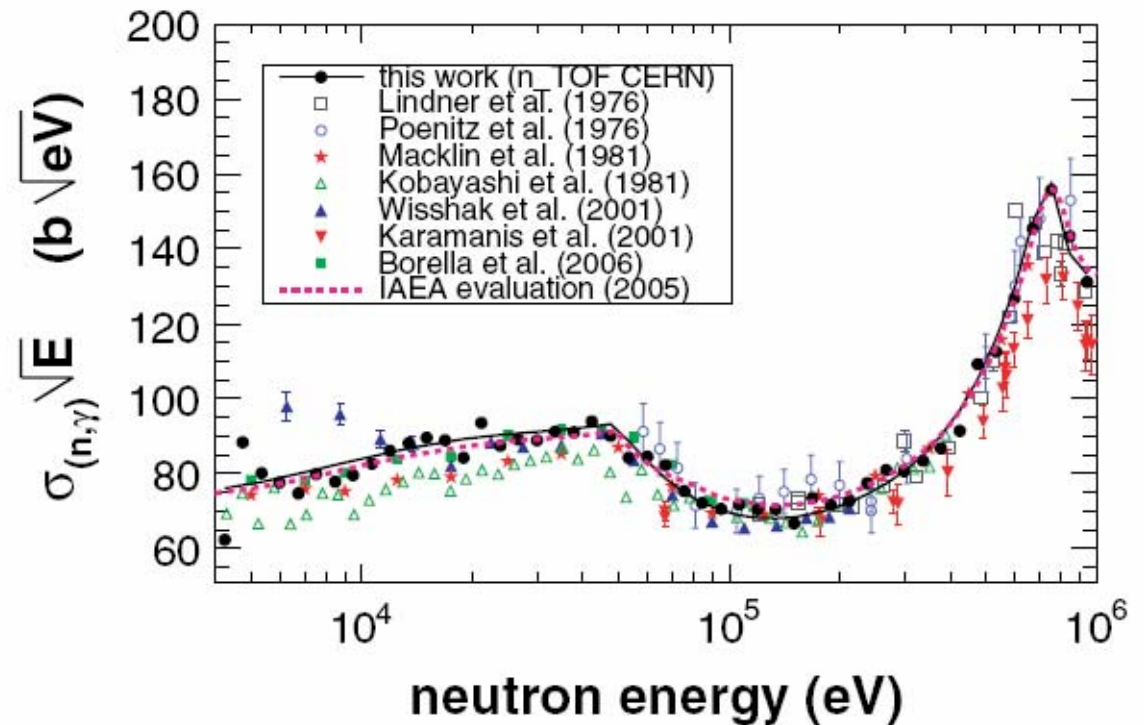


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Phys. Rev. C 73, 054610 (2006)



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TABLE II. Different components of estimated systematic or correlated uncertainty in the measured cross section.

Component	Uncertainty (%)
PHWT	0.5
Normalization	0.5
Background	2.5
Flux shape	2.0
Total	3.3

For  $E_n = 4$  keV up to 1 MeV full dataset is available on the PRC publication

$E_{\text{low}}$ (keV)	$E_{\text{high}}$ (keV)	Cross section (b)	Uncertainty (b)
3.994	4.482	0.958	0.020
4.482	5.028	1.281	0.021
5.028	5.642	1.097	0.016
5.642	6.331	1.004	0.014
6.331	7.103	0.912	0.013
7.103	7.970	0.919	0.013
7.970	8.942	0.848	0.013
8.942	10.033	0.817	0.012
10.033	11.257	0.800	0.012
11.257	12.631	0.787	0.012
12.631	14.172	0.761	0.012
14.172	15.902	0.729	0.011
15.902	17.842	0.685	0.011
17.842	20.019	0.613	0.010
20.019	22.461	0.641	0.010
22.461	25.202	0.566	0.009
25.202	28.277	0.545	0.009
28.277	31.728	0.513	0.008
31.728	35.599	0.497	0.009
35.599	39.943	0.468	0.009
39.943	44.816	0.456	0.008
44.816	50.285	0.413	0.007
50.285	56.421	0.365	0.006
56.421	63.305	0.346	0.006
63.305	71.029	0.318	0.006
71.029	79.696	0.275	0.005
79.696	89.421	0.248	0.005
89.421	100.332	0.229	0.005
100.332	112.574	0.220	0.004
112.574	126.310	0.204	0.004
126.310	141.722	0.192	0.004



## Capture

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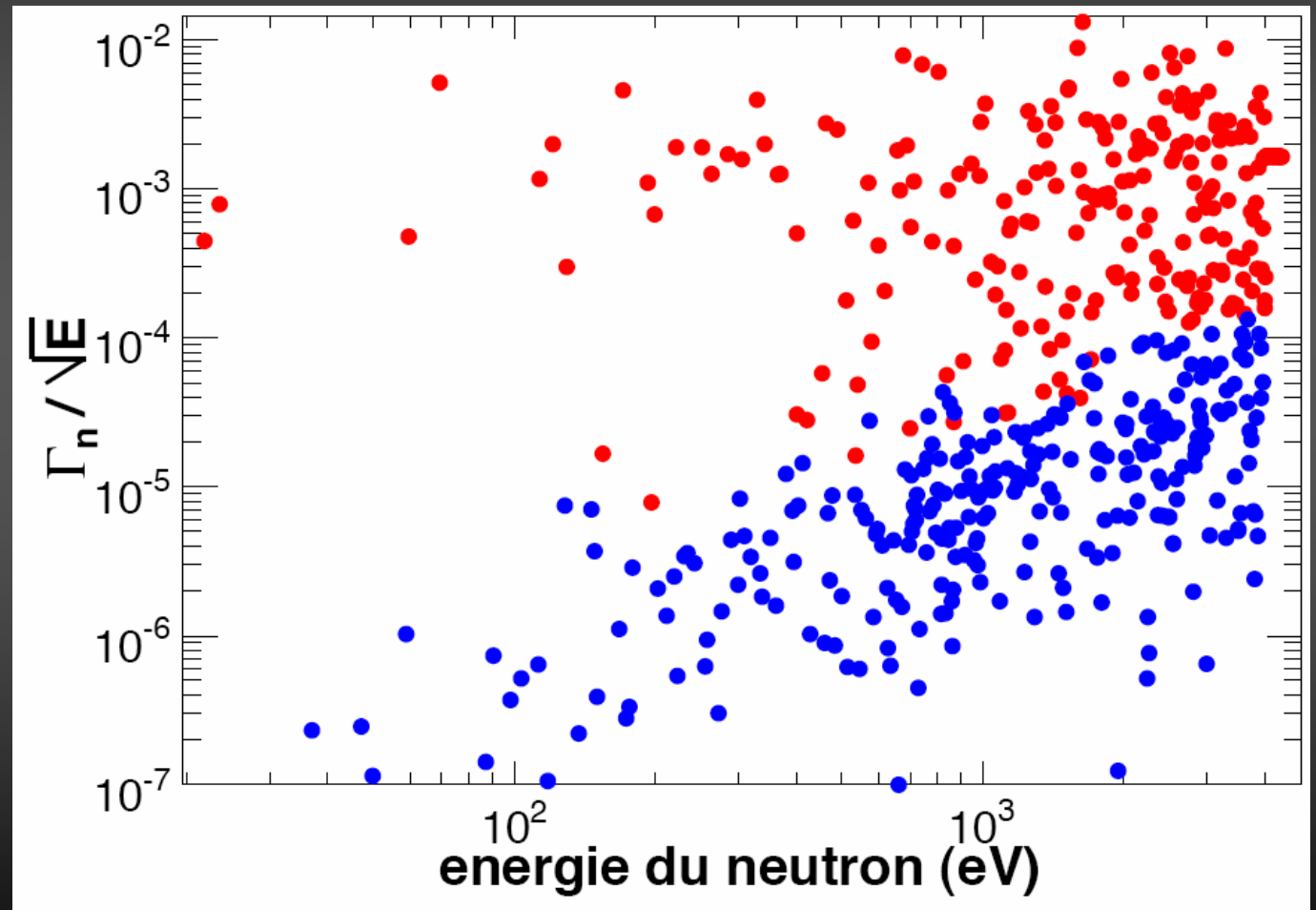
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$^{232}\text{Th}(n,\gamma)$

# n\_TOF experiments

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analysis in progress



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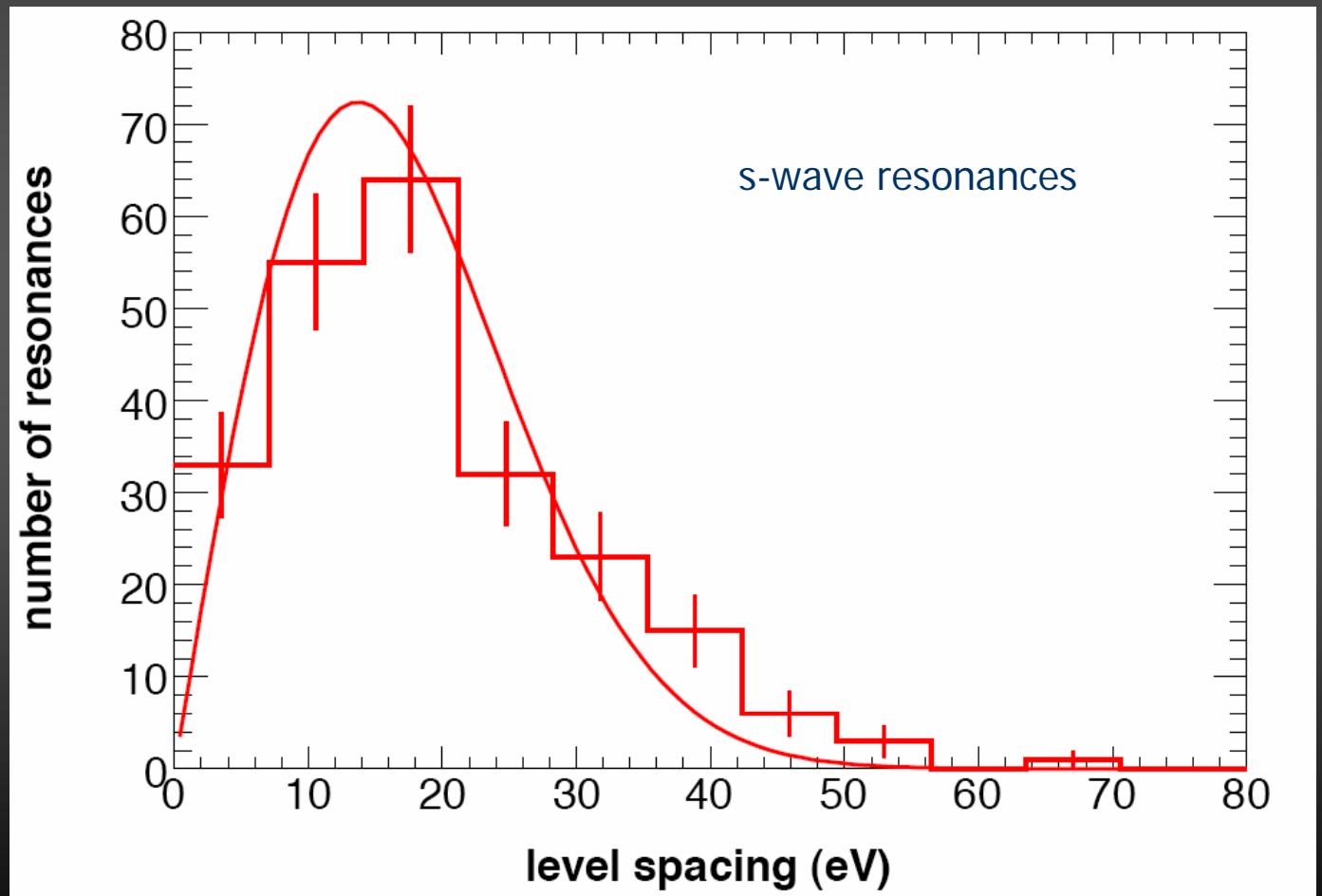
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# n\_TOF experiments

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