



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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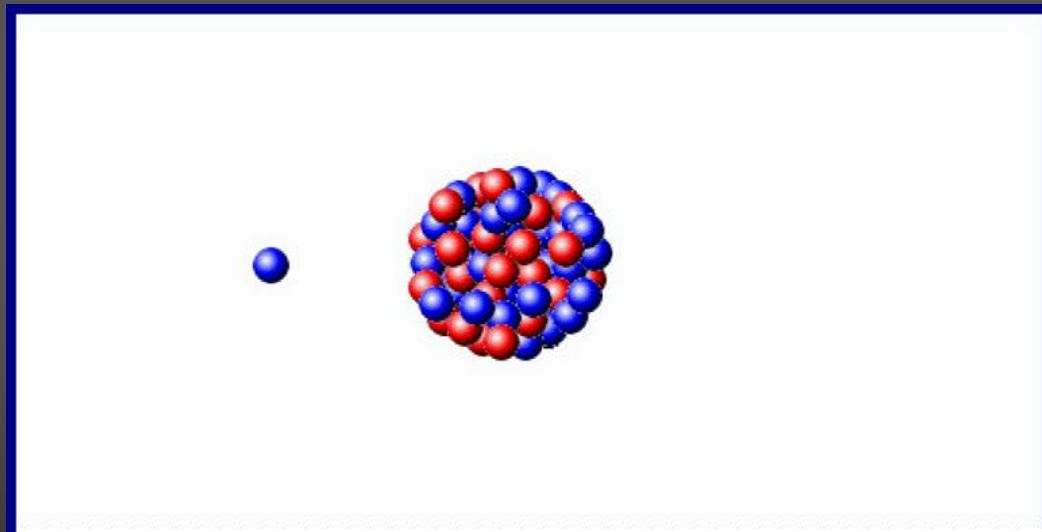
Nuclear Physics, Astrophysics, and Advanced Technologies with Neutrons

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

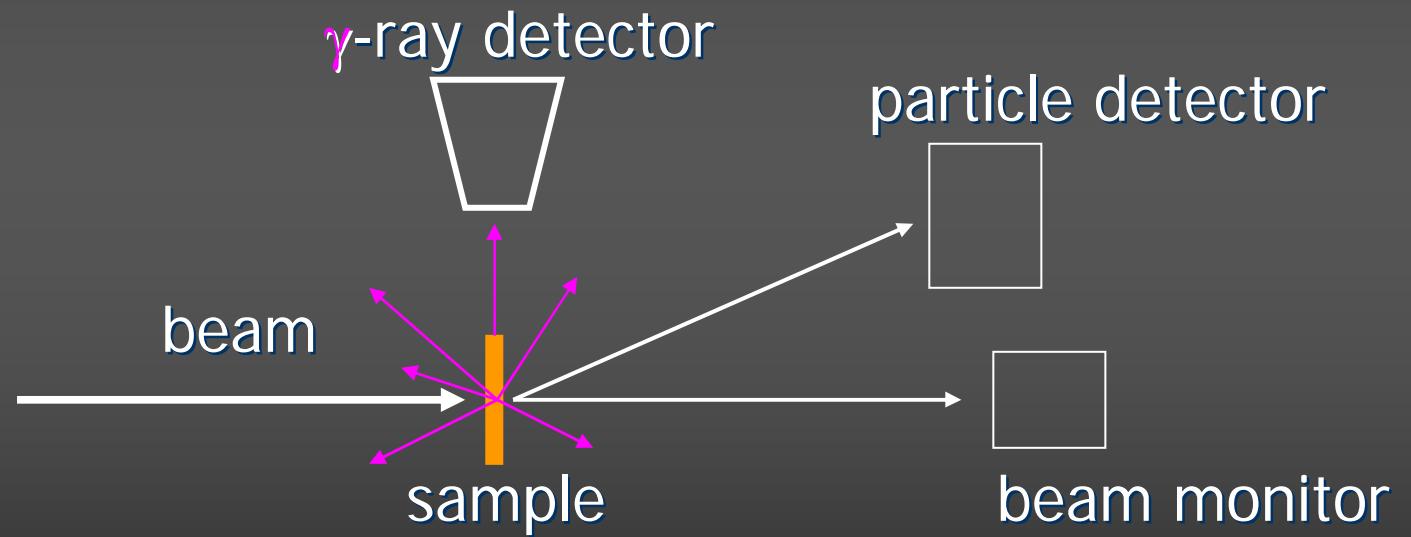


Source: the web

movie

Nuclear Reaction Experiments

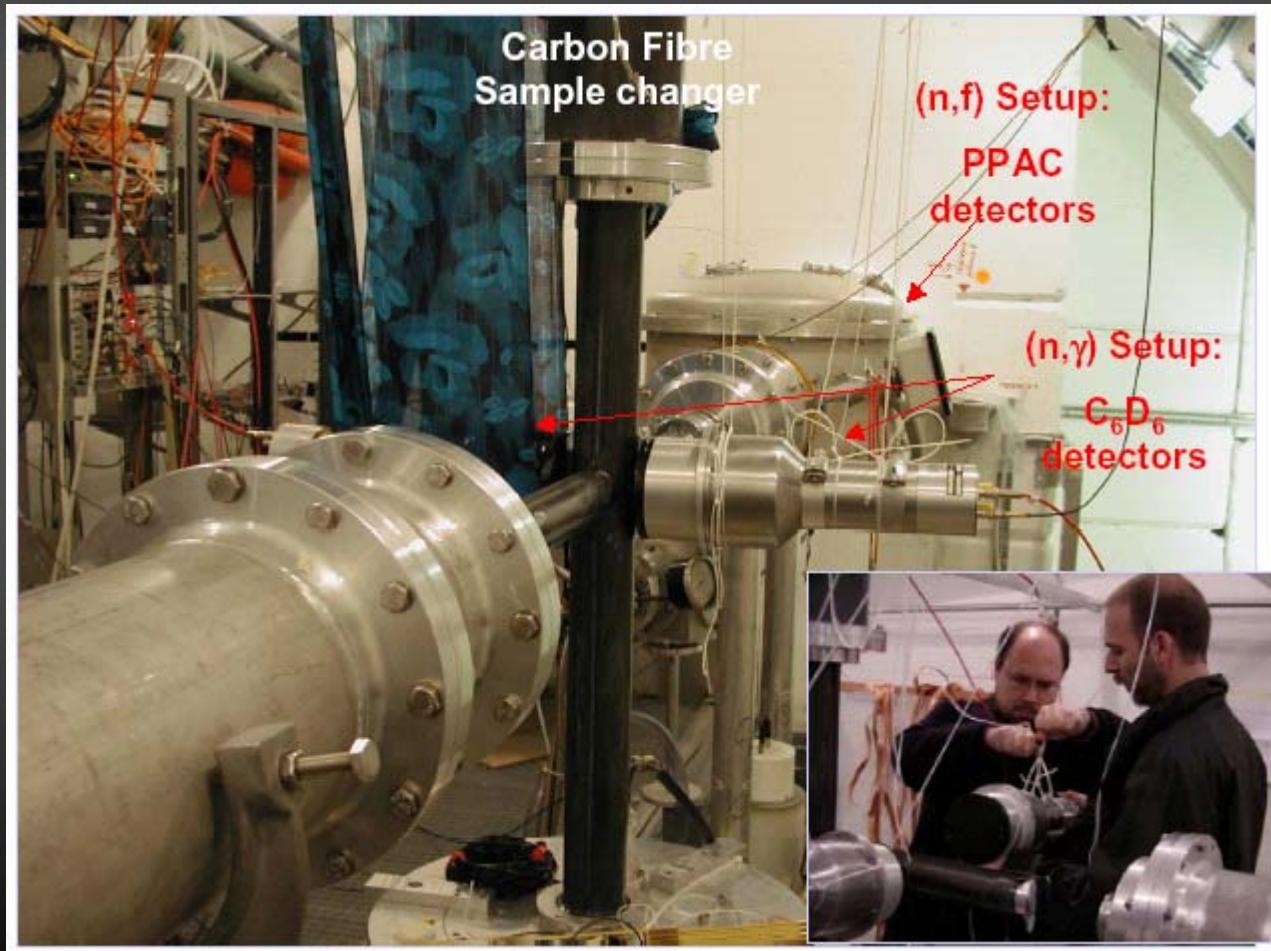
Neutron induced reactions



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

Nuclear Reaction Experiments

Neutron induced reactions



Objectives

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

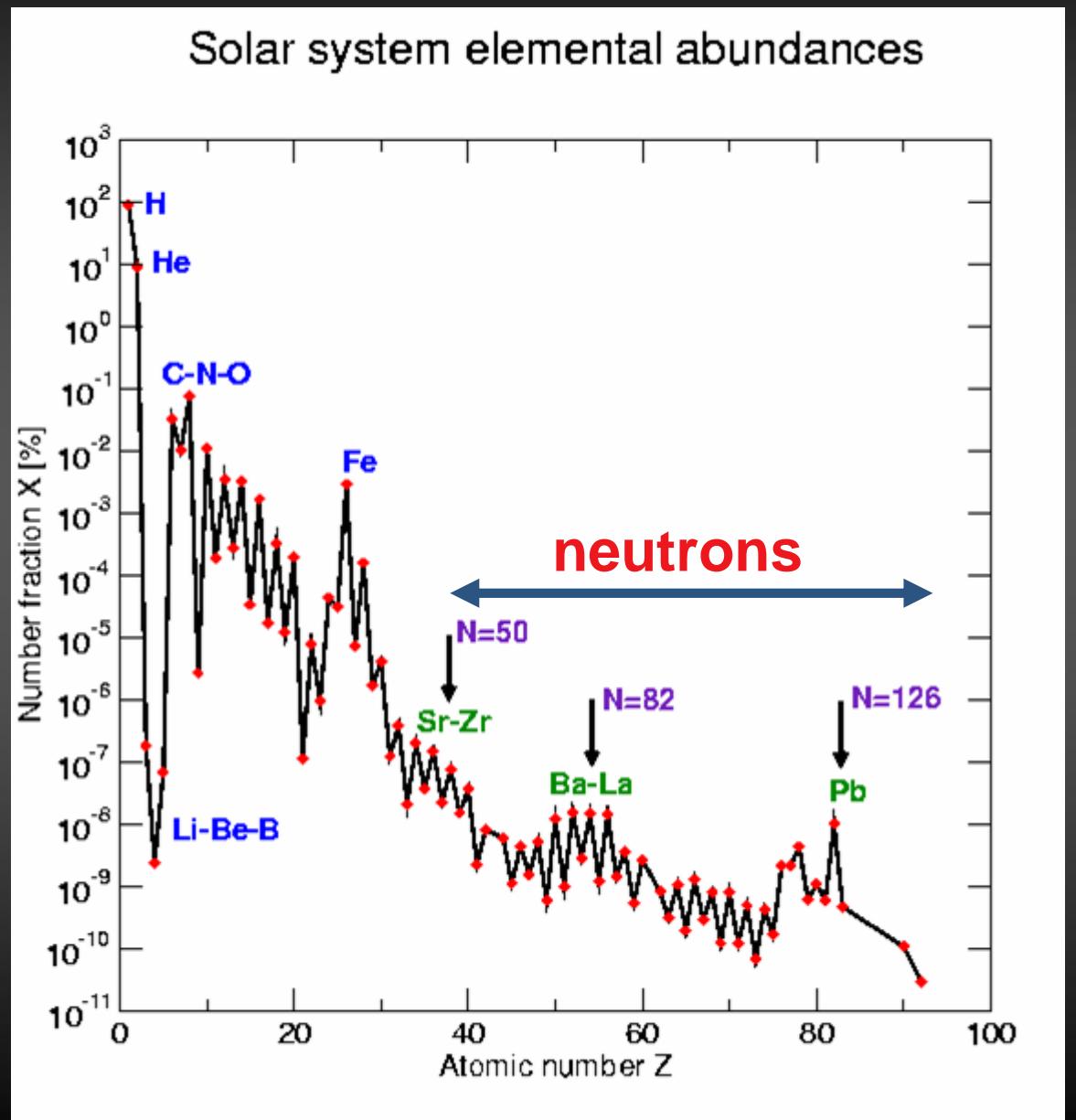
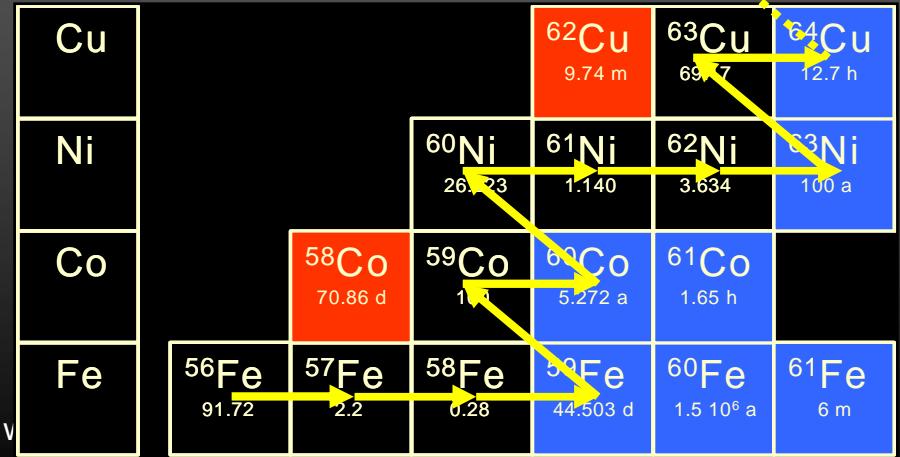
Nucleosynthesis: the s-process

direct correlation between neutron capture cross section and abundance:

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

>>

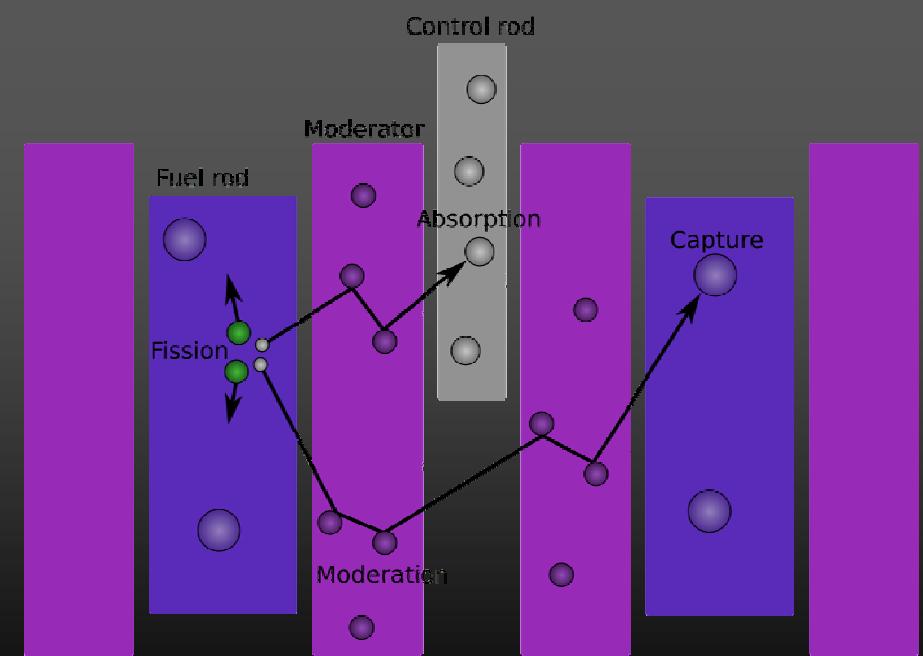
The canonical s-process



Energy generation and Nucleosynthesis: not only in stars!



The Candu Qinshan Nuclear Power Plant



Nucleosynthesis: TRU (1000 MW_e LWR)

244Cm
1.5 Kg/yr

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

239Pu: 125 Kg/yr

237Np: 16 Kg/yr

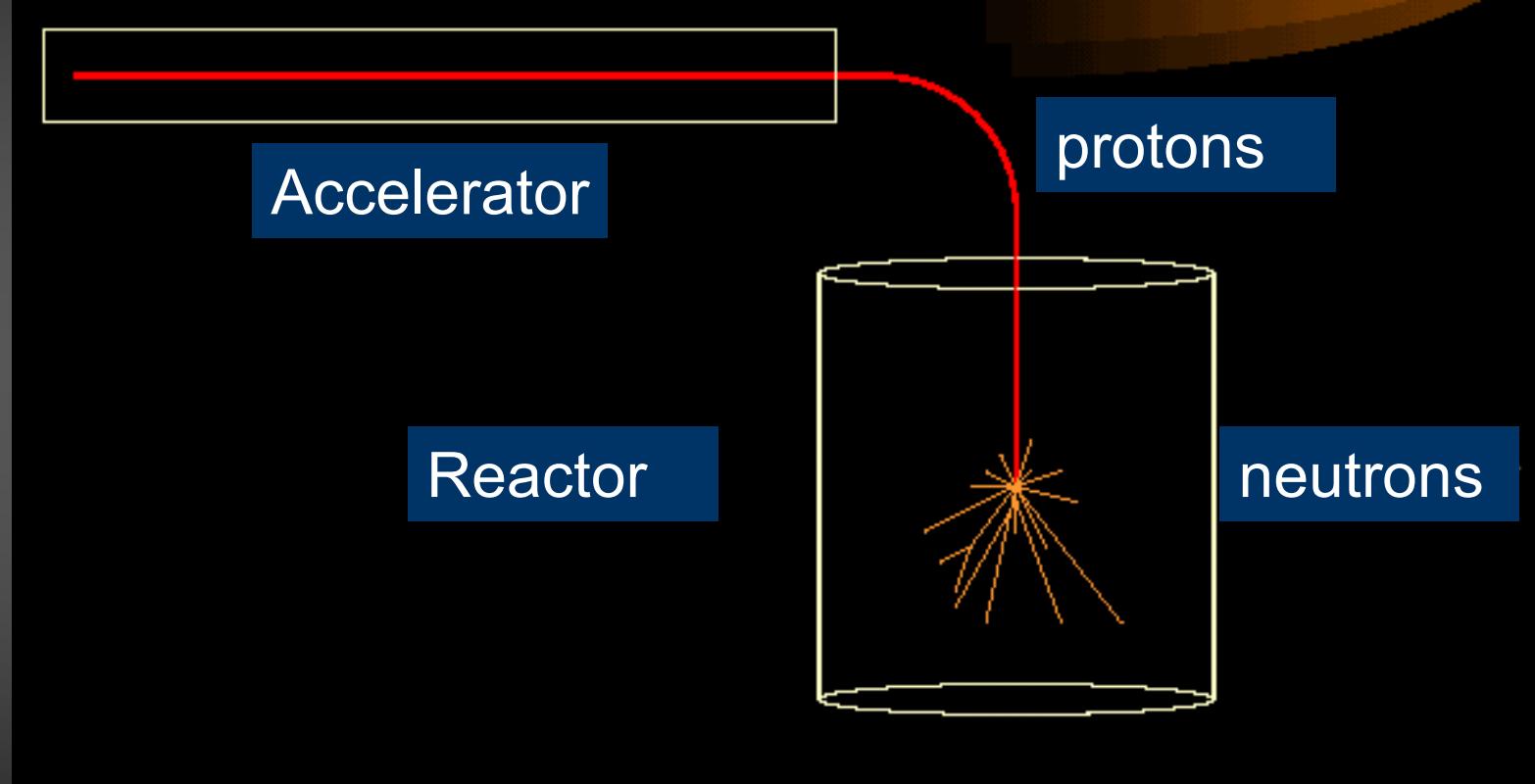
LLFP
76.2 Kg/yr

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

Th/U fuel cycle

	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
	α 6,52 γ 188...	α 5,94 γ 963; 919; 561; 608... β^-	α 6,291; 6,248... β^- γ 472; 431; 132... β^- θ^-	α 5,339... β^- γ 444...; θ^- α - 5	α 6,113; 6,059... β^- ; γ 278; 229; 210...; θ^- α - 20 η - 5	α 5,785; 5,748... β^- ; γ 143...; θ^- α 130; η 620	α 6,005; 6,702... β^- ; γ 175; 133... θ^- 15; η 1,1	α 5,361; 5,304... β^- ; γ 175; 133... θ^- 15; η 2100	α 5,388; 5,343 β^- ; γ 175; 133... θ^- 1,2; η 0,16
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 10,1 h
α 6,41	α 6,042 γ 280; 436; 474; 908... θ^-	α 5,94 γ 963; 919; 561; 608... β^-	α 5,774... β^- γ 278; 229... θ^-	α 5,378... β^- γ 968; 889... θ^-	α 5,409; 5,443... β^- ; γ 80; 28... θ^- ; 5 α 50 + 50; η 2,1	α 5,409; 5,443... β^- ; γ 80; 28... θ^- ; 5 α 50 + 50; η 2,1	α 5,275; 5,233... β^- ; γ 75; 44... θ^- ; 3 η 0,074	α 5,275; 5,233... β^- ; γ 75; 44... θ^- ; 3 η 0,074	α 5,275; 5,233... β^- ; γ 75; 44... θ^- ; 3 η 0,074
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 ⁴ a	Pu 240 6563 a	Pu 241 14,35 a	Pu 242 3,750 - 10 ⁵ a	Pu 243 4,956 h	Pu 244 8,00 - 10 ⁷ a
α 5,80 γ 49; (75); 34... θ^-	α 5,788; 5,721... β^- ; Mg 28 γ 140; 109...; θ^- η 180	α 5,534... γ 60...; θ^- η 2300	α 5,499; 5,468... β^- ; Si; Mg 28 γ (42; 100...); θ^- η 510; η 17	α 5,157; 5,144... β^- ; Si; Mg 28 γ (42; 100...); θ^- η 270; η 752	α 5,168; 5,124... β^- ; γ (45...) θ^- ; η α 290; η ~ 0,044	α 5,038; β^- γ (49)... θ^- ; 9 η 370; η 1010	α 4,901; 4,856... β^- ; γ (45...) θ^- ; 9 η 19; η ~ 0,2	α 4,901; 4,856... β^- ; γ (45...) θ^- ; 9 η 19; η ~ 0,2	α 4,988; 4,946 β^- ; γ θ^- ; 9 η 1,7
Np 234 4,4 d	Np 235 396,1 d	Np 236 22,5 m	Np 237 2,144 - 10 ⁶ 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
α ; β^+ γ 1559; 1528; 1602... η - 900	α ; β 5,025; 5,007... γ (26; 84...); θ^- η 160 + 7	α ; β 5,025; 5,007... γ (26; 84...); θ^- η 160 + 7	α ; β 5,025; 5,007... γ (26; 84...); θ^- η 160 + 7	α ; β 5,025; 5,007... γ (26; 84...); θ^- η 160 + 7	α ; β 5,025; 5,007... γ (26; 84...); θ^- η 160 + 7	α ; β 5,025; 5,007... γ (26; 84...); θ^- η 160 + 7	α ; β 5,025; 5,007... γ (26; 84...); θ^- η 160 + 7	α ; β 5,025; 5,007... γ (26; 84...); θ^- η 160 + 7	α ; β 5,025; 5,007... γ (26; 84...); θ^- η 160 + 7
U 233 1,592 - 10 ⁵ a	U 234 0,0055 2,455 - 10 ⁵ a	U 235 0,7200	U 236 120 ns	U 237 2,342 - 10 ⁷ a	U 238 6,75 d	U 239 99,2745	U 239 23,5 m	U 240 14,1 h	U 242 16,8 m
α 4,824; 4,783... γ 26; 97...; θ^- η 47; η 530	α 4,775; 4,729... β^- ; Mg 28 γ (42; 97...); θ^- η 530; η 0,006	α 4,735; 4,729... β^- ; Mg 28 γ (42; 97...); θ^- η 530; η 0,006	26 m	7,938 - 10 ⁴ a	α 4,494... β^- ; 4,448... γ 60; 208... θ^- ; 4,448... η 100; η < 0,35	α 4,456 - 10 ³ a	α 4,456 - 10 ³ a	α 4,456 - 10 ³ a	α 4,456 - 10 ³ a
Pa 232 1,31 d	Pa 233 27,0 d	Pa 234 1,17 m	Pa 235 24,2 m	Pa 236 9,1 m	Pa 237 8,7 m	Pa 238 2,3 m	Pa 239 14,1 h	Pa 240 14,1 h	Pa 242 16,8 m
β^- 0,3; 1,3...; γ η 969; 894; 150...; θ^- α 460; η 700	β^- 0,3; 0,4... γ 312; 300... 341...; θ^- α 20 + 18; η < 0	β^- 0,3; 0,4... γ 312; 300... 341...; θ^- α 20 + 18; η < 0	β^- 0,2... γ 131; 681... 787...; θ^- α 74; 2,4... η 500	β^- 1,4... γ 128 - 659... θ^-	β^- 2,0; 3,1... γ 842; 587; 1763...; θ^- α 77	β^- 1,4; 2,3... γ 854; 865; 529; 541... θ^-	β^- 1,7; 2,9... γ 1015; 635; 448; 680... θ^-	β^- 0,4... γ 44; (190...) θ^-	β^- 1,2; 1,3... γ 75; 44... θ^- 22; η 15
Th 231 25,5 h	Th 232 100 1,405 - 10 ¹⁹ a	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		148	150

ADS (Accelerator Driven Systems)

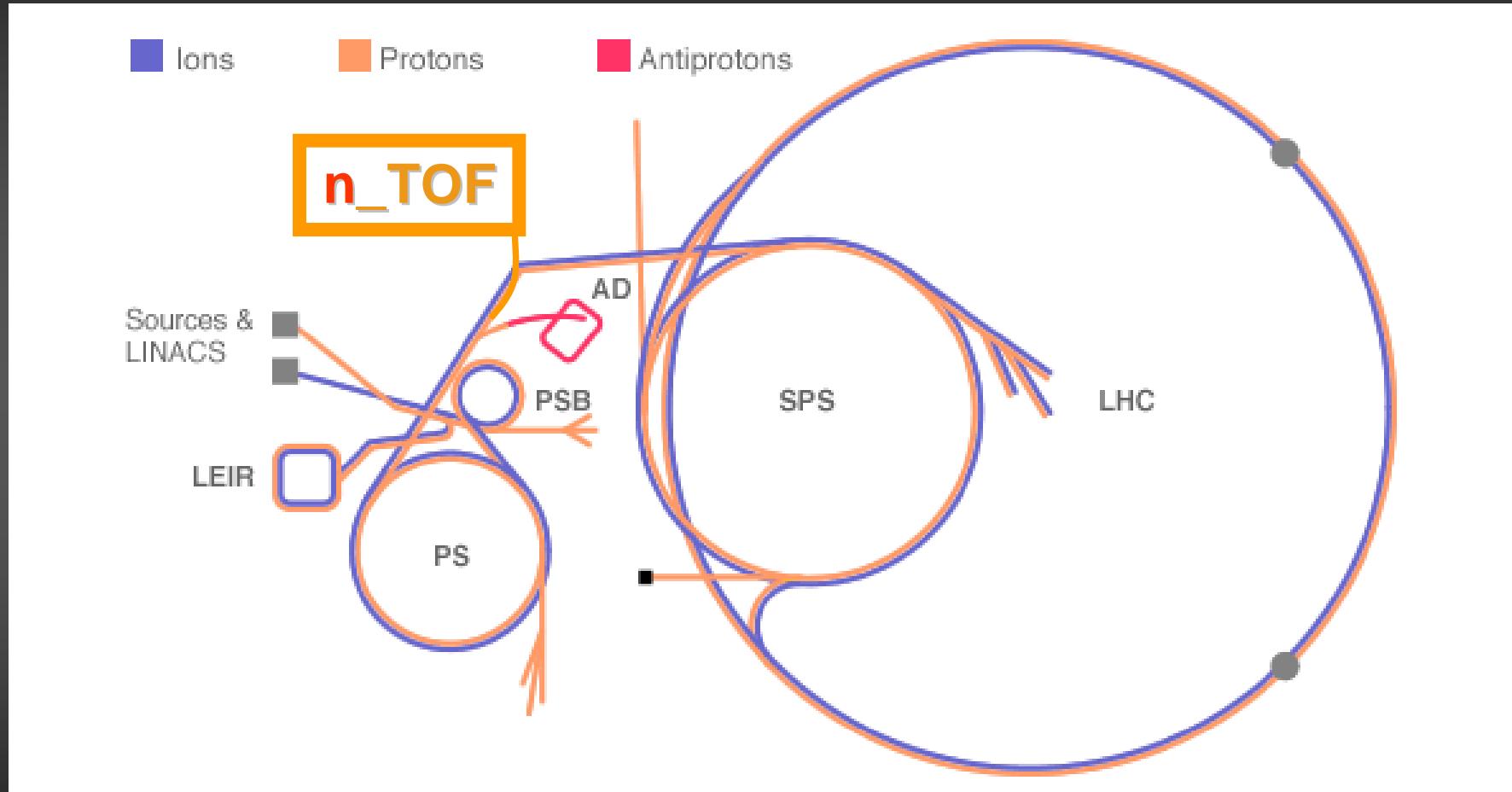


Zen-ADS

World scene for tof measurements

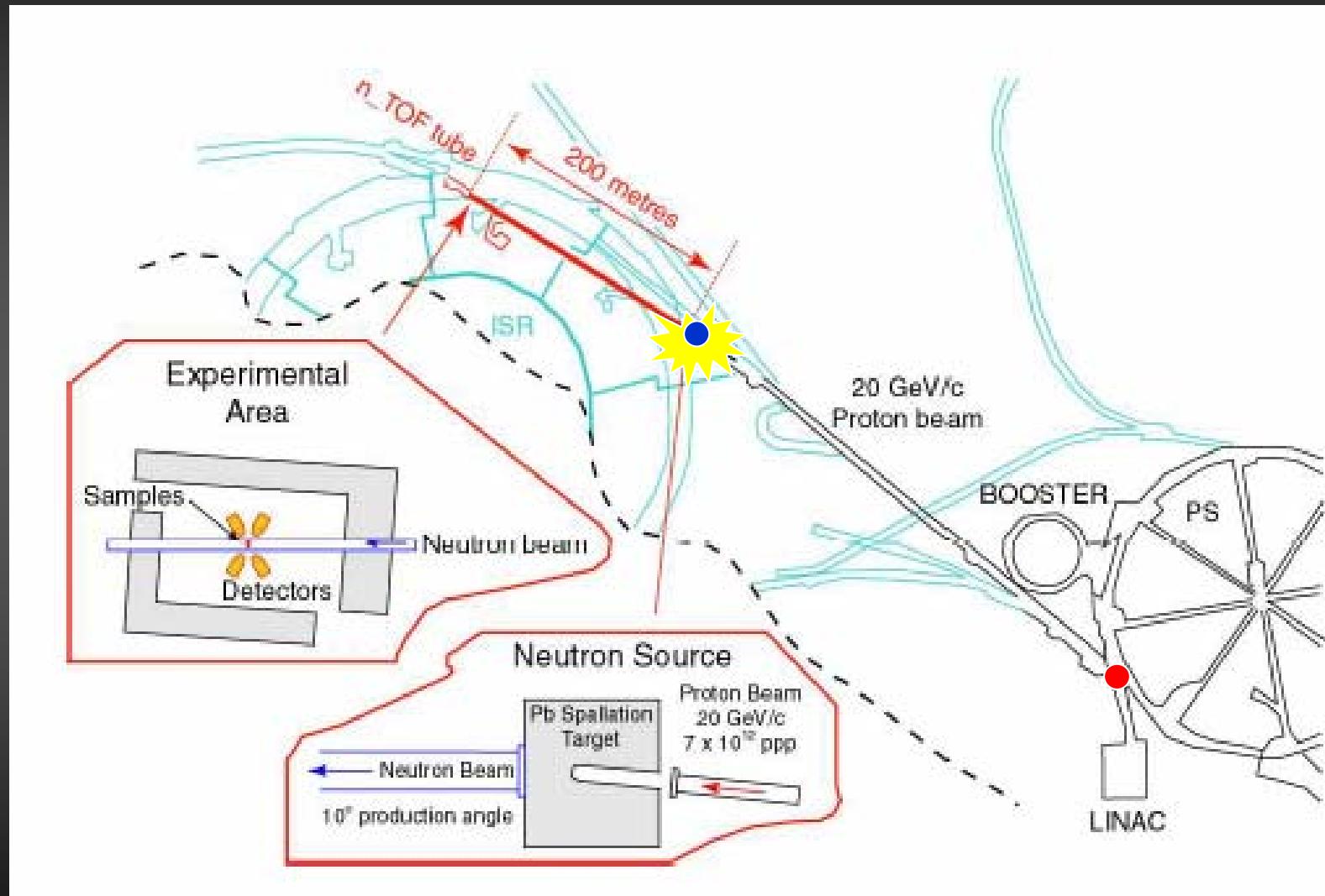
facility		driver and energy	repetition rate	n source	n energy range	flight path length
FZK TIT ...	Karlsruhe Tokyo ...	varii in the MeV range	MHz	⁷ Li(p,n) & others	few keV up to 1 MeV monoE above	10s cm
GELINA	EC-JRC Geel	electron linac 150 MeV	800 Hz	photo-n photo-f	10 meV – 20 MeV	10m to 400m
LANSCE	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

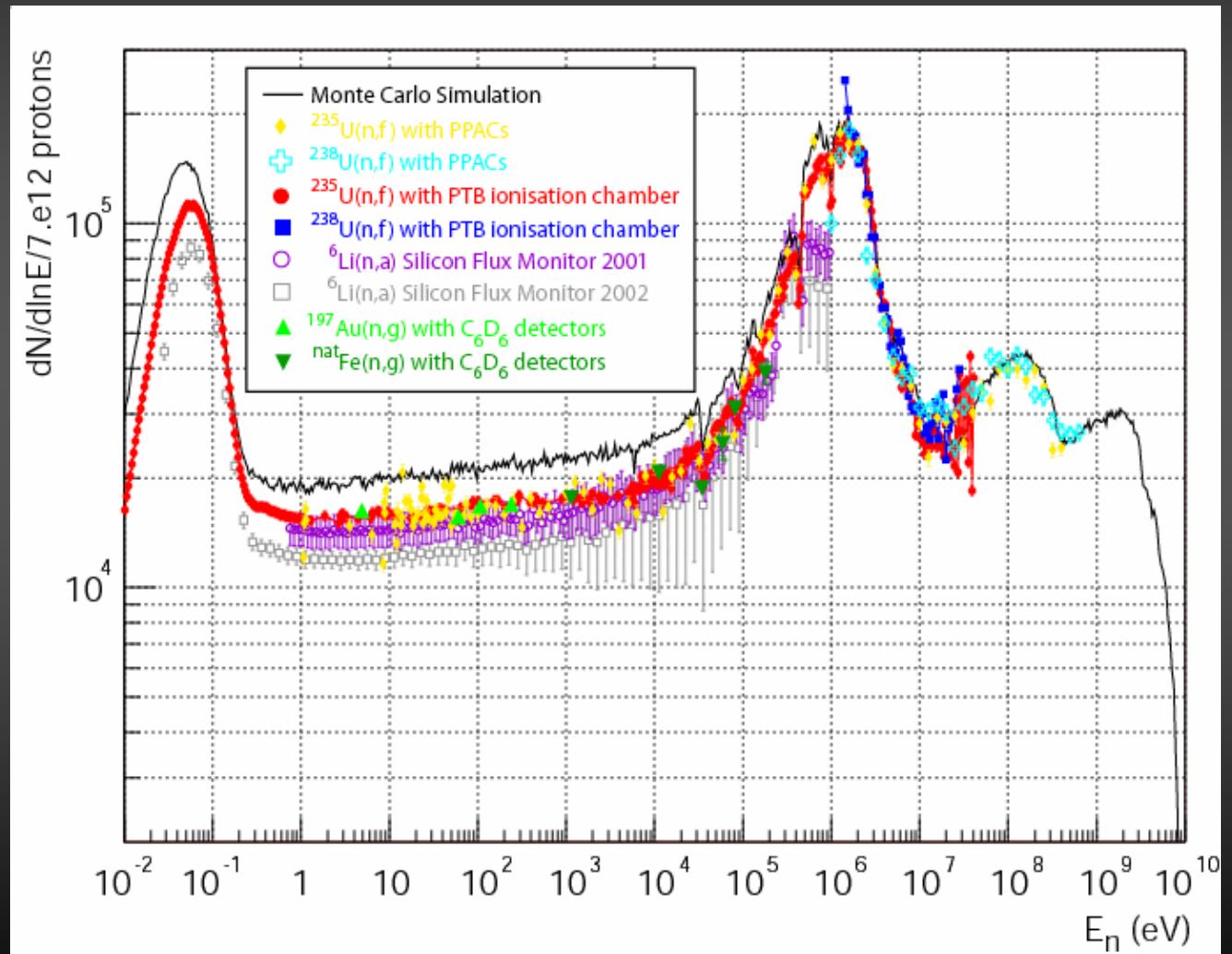


n_TOF basic parameters

proton beam momentum	20 GeV/c
intensity (dedicated mode)	7×10^{12} protons/pulse
repetition frequency	1 pulse/2.4s
pulse width	6 ns (rms)
n/p	300
lead target dimensions	80x80x60 cm ³
cooling & moderation material	H ₂ 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



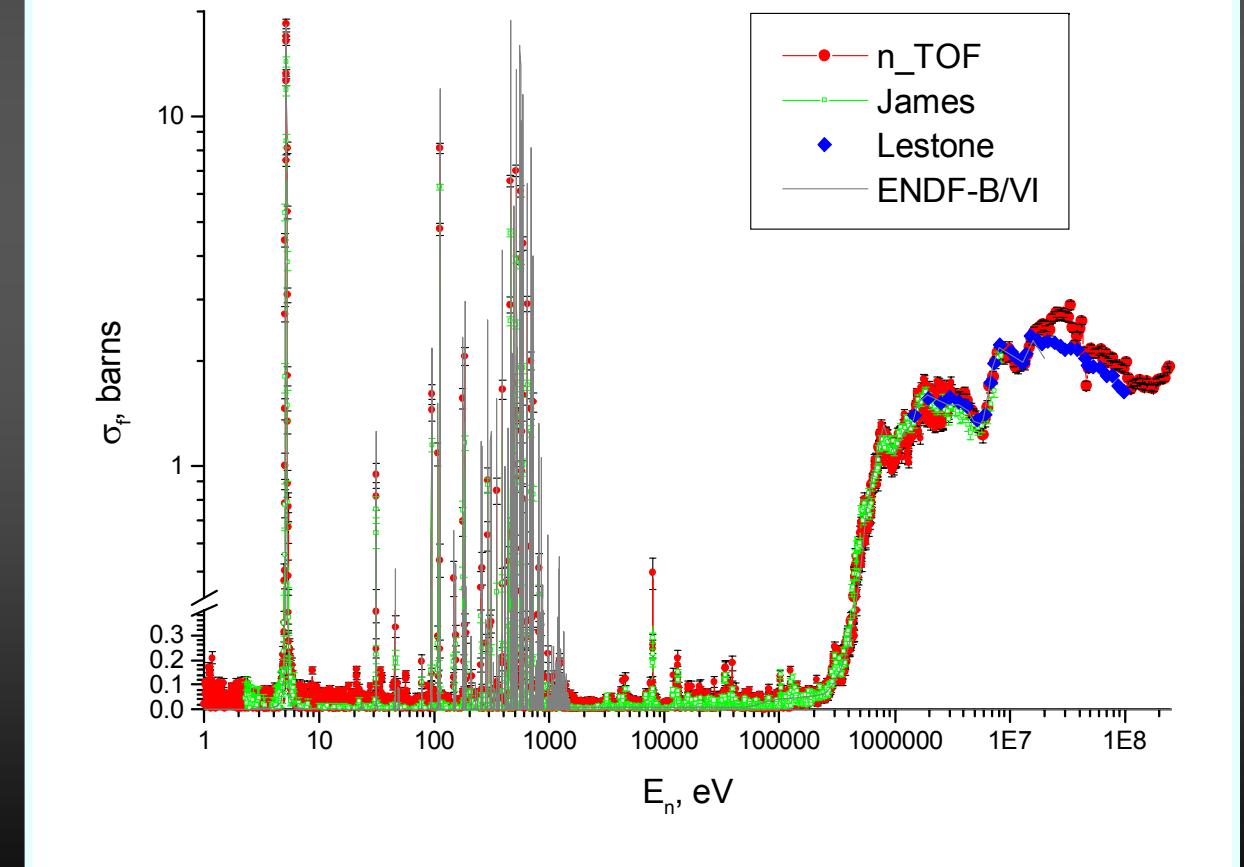
Basic characteristics of experiments at n_TOF



- wide energy range

PPACs & FIC-0 (2003)

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

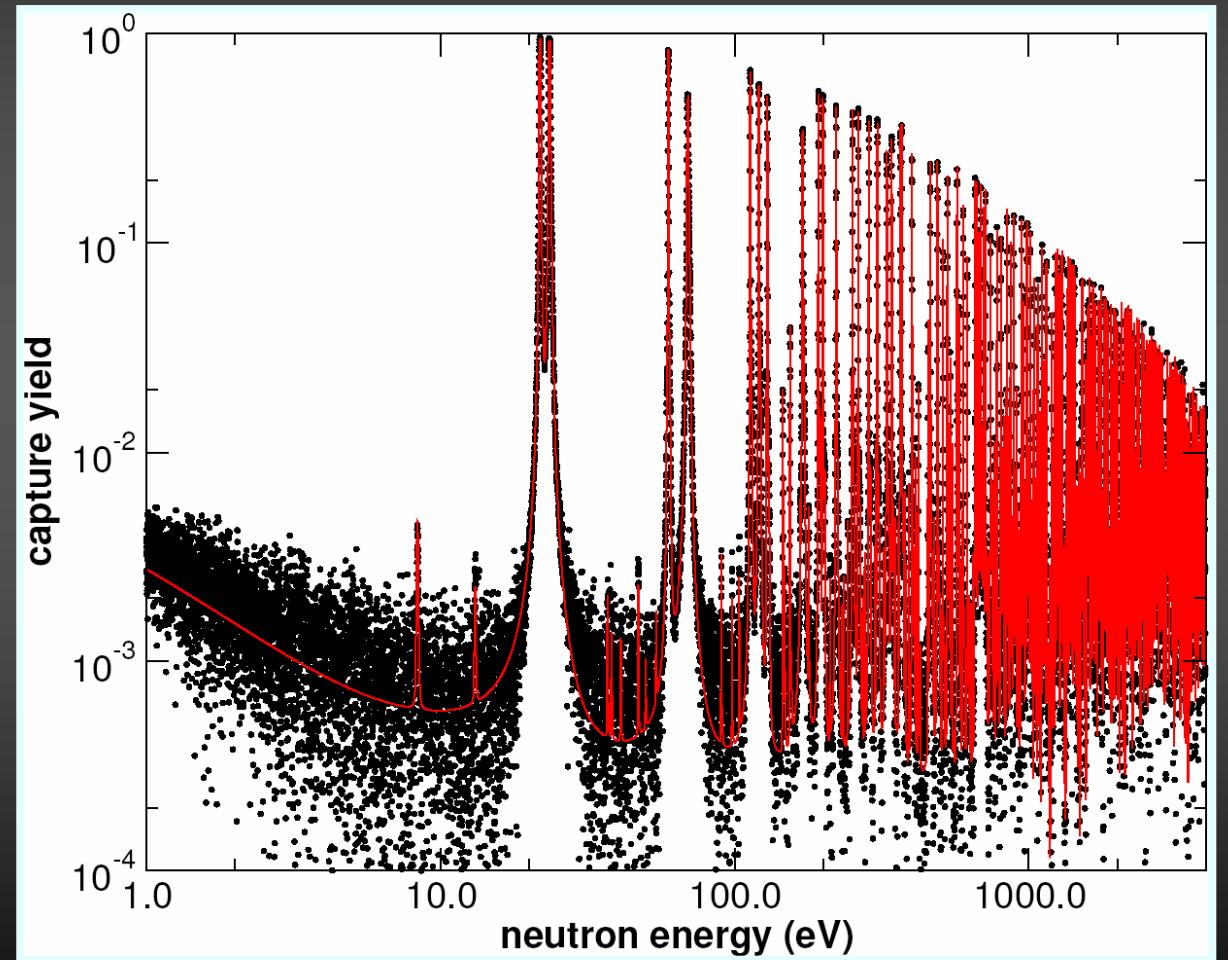
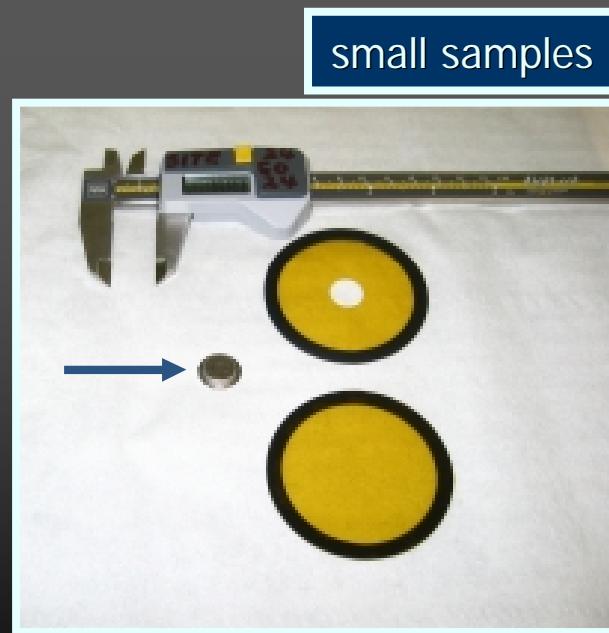


Basic characteristics of experiments at n_TOF



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

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

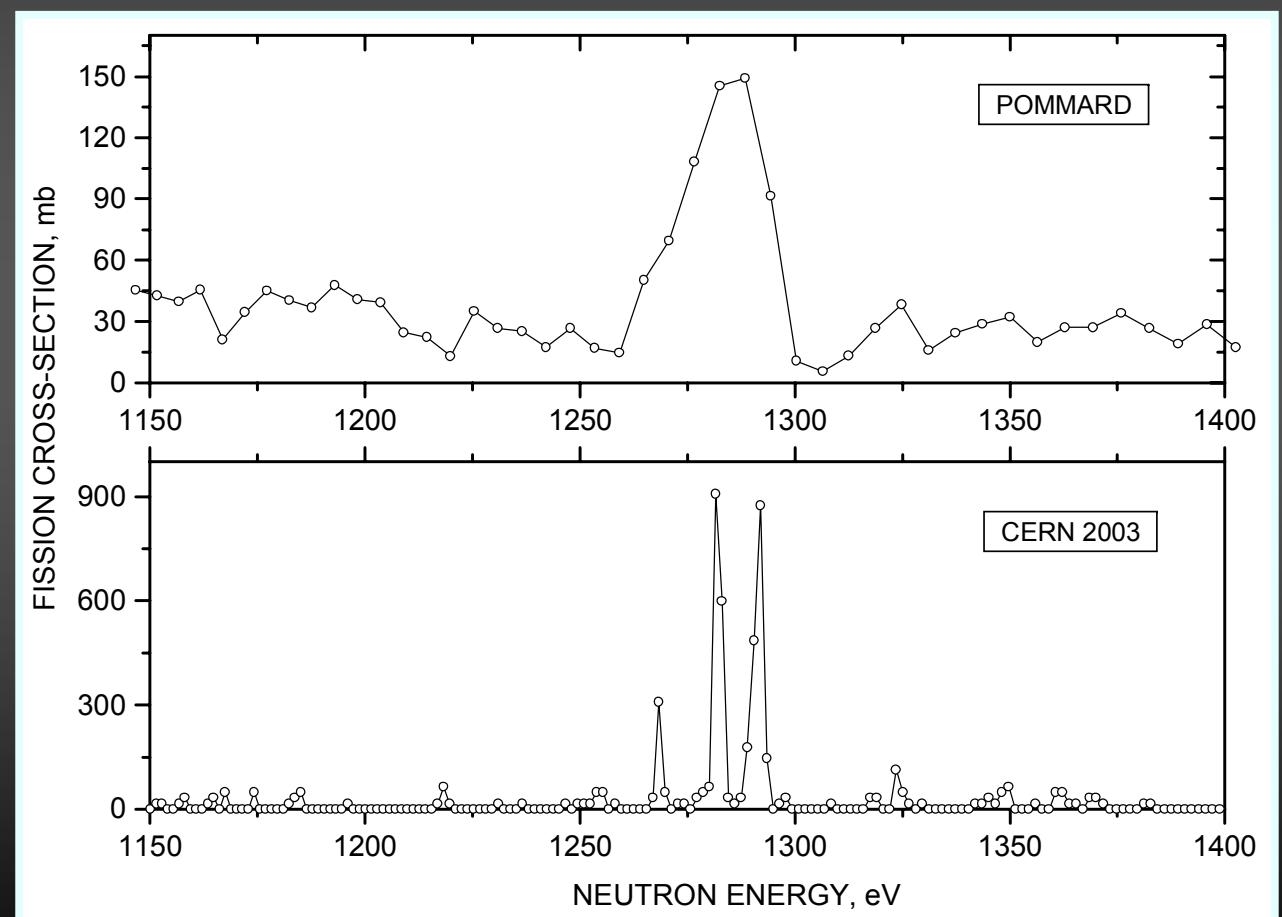


Basic characteristics of experiments at n_TOF



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

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

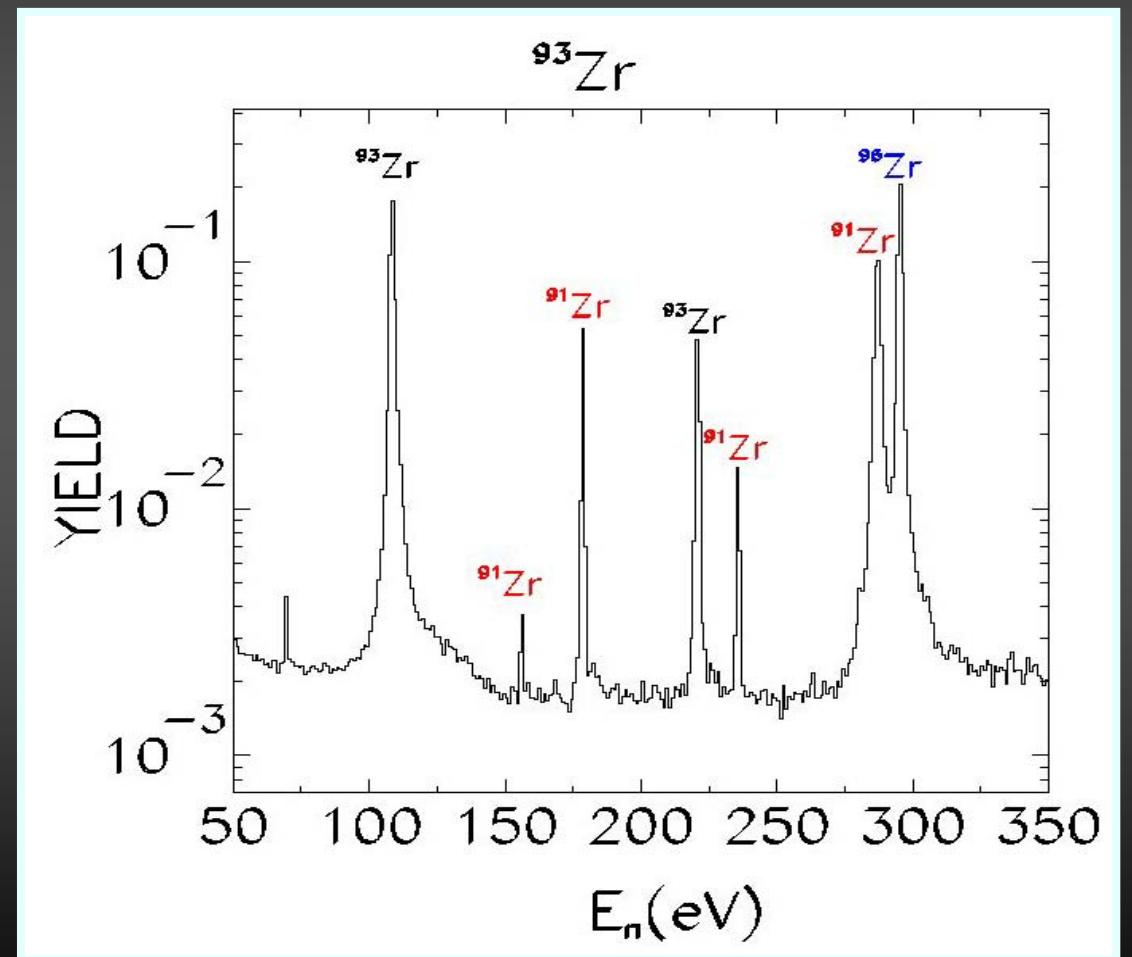


Basic characteristics of experiments at n_TOF



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

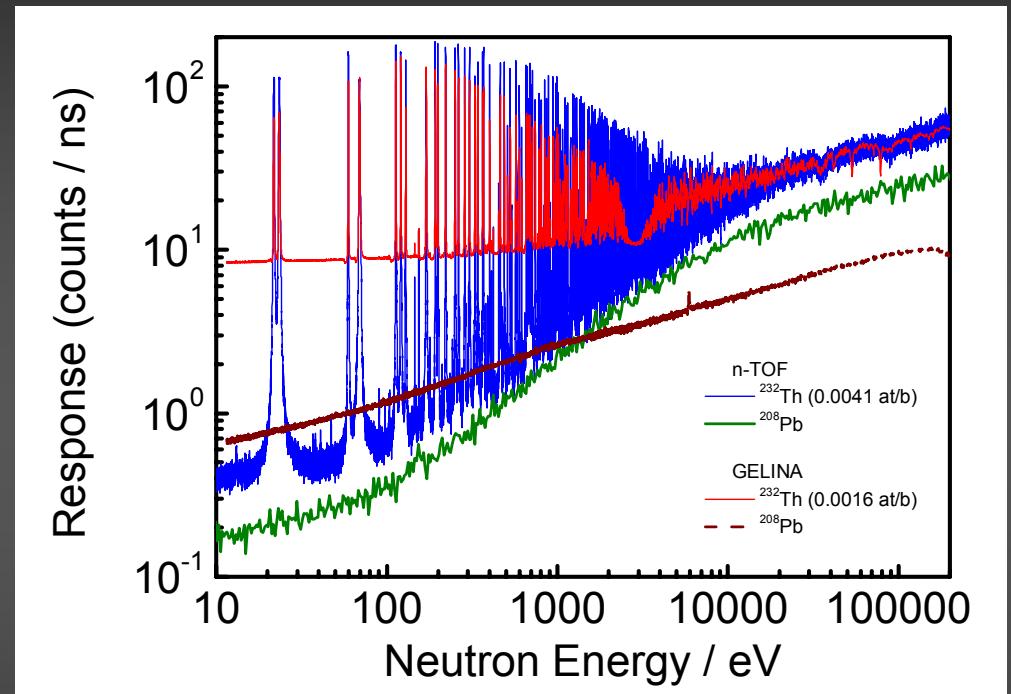
- wide energy range
- high neutron flux & high energy resolution



Basic characteristics of experiments at n_TOF

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

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



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

source: P Rullhusen (GELINA)

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



Basic characteristics of experiments at n_TOF

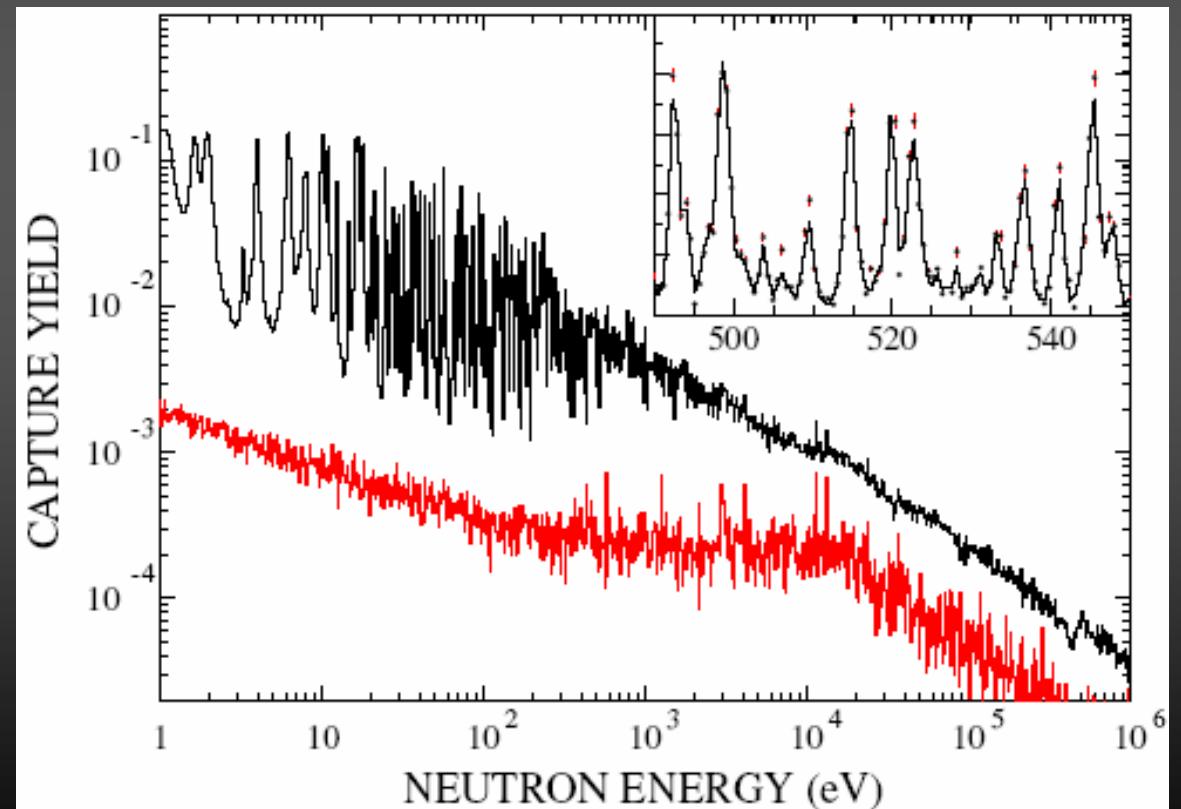
U Abbondanno et al. (The n_TOF Collaboration)
Phys. Rev. Lett. **93** (2004), 161103

&

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

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

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



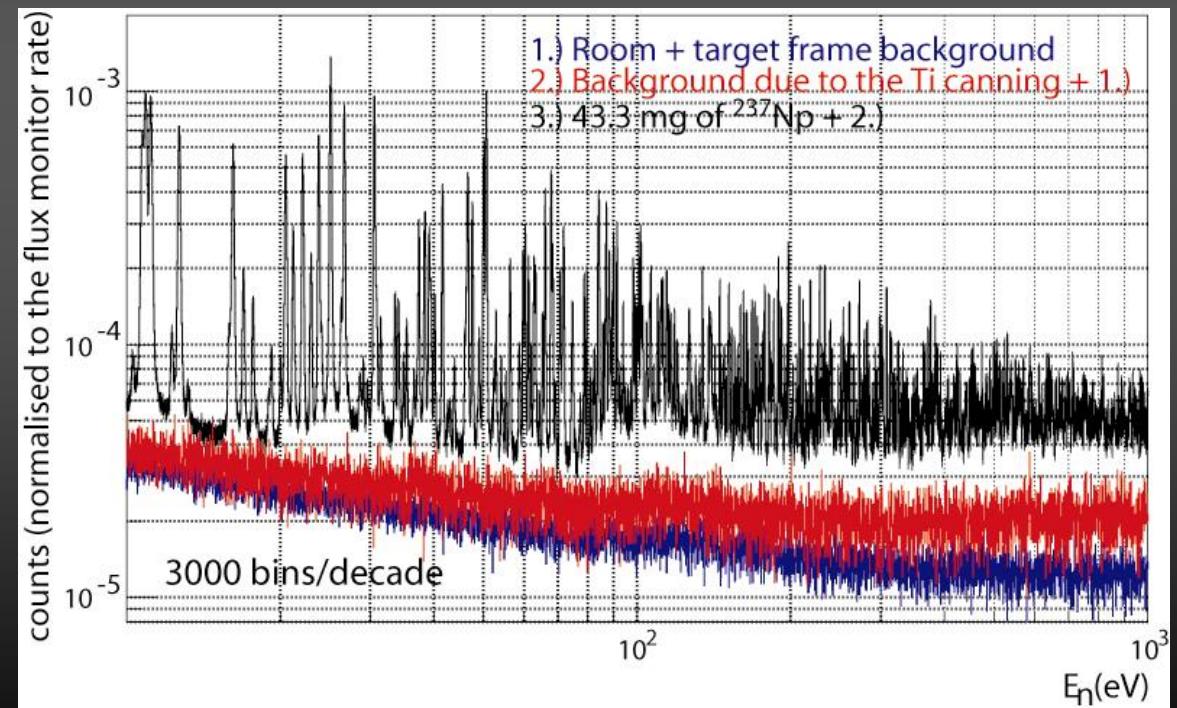


Basic characteristics of experiments at n_TOF

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

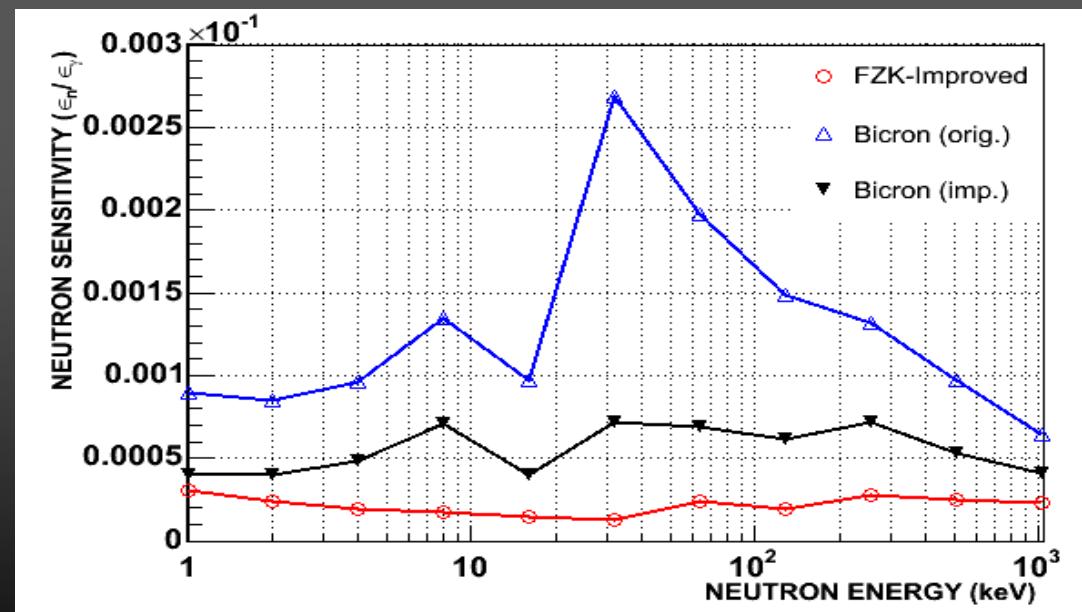
$^{237}\text{Np}(\text{n},\gamma)$

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



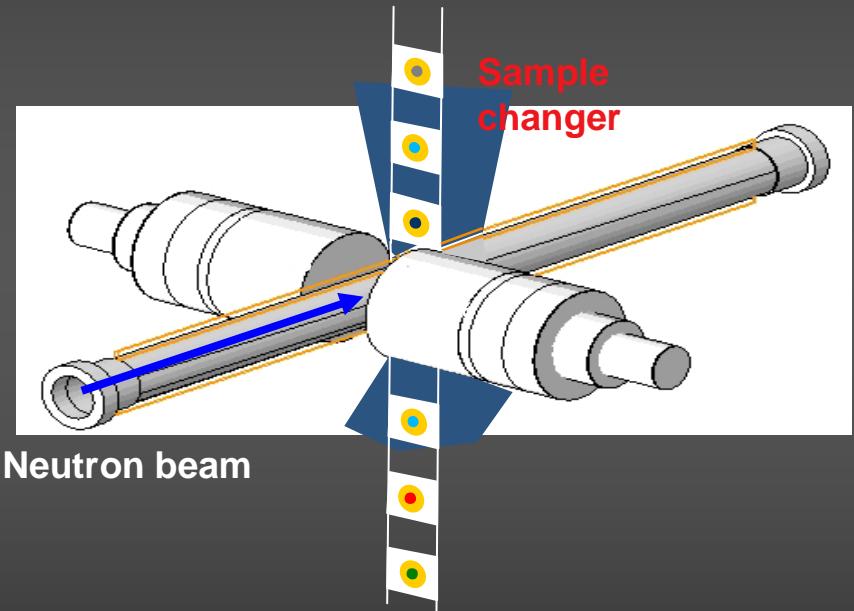
Basic characteristics of experiments at n_TOF

- 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



Basic characteristics of experiments at n_TOF

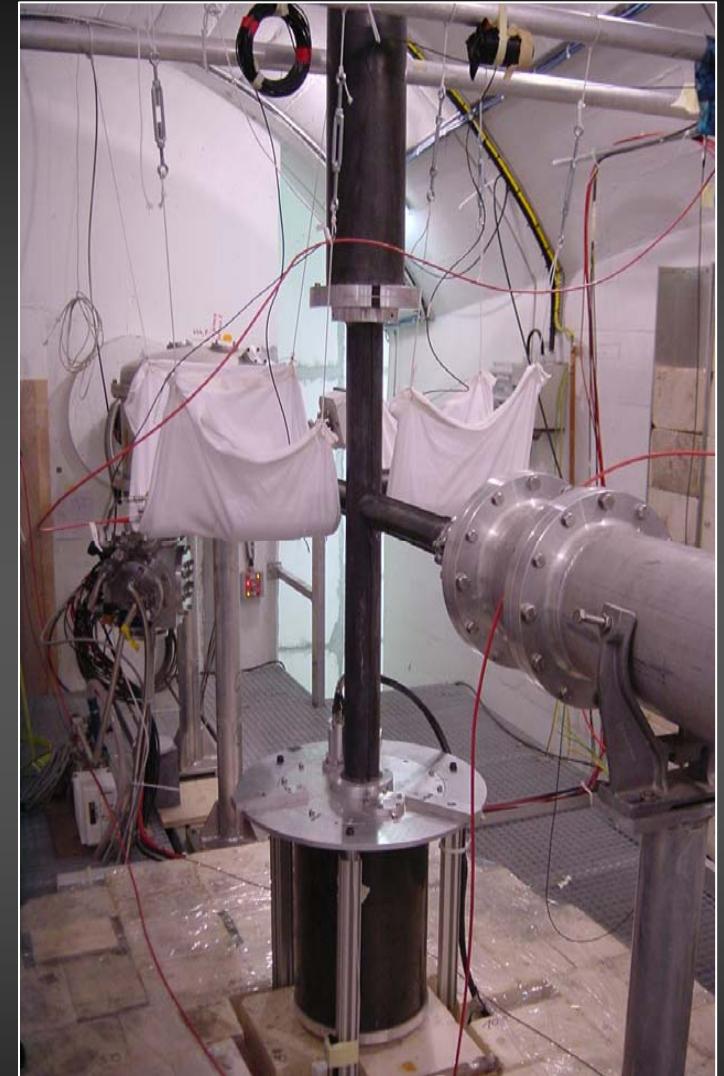
- wide energy range
- high neutron flux & high energy resolution
- low repetition rate of the proton driver
- low background conditions
- detectors with extremely low neutron sensitivity



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



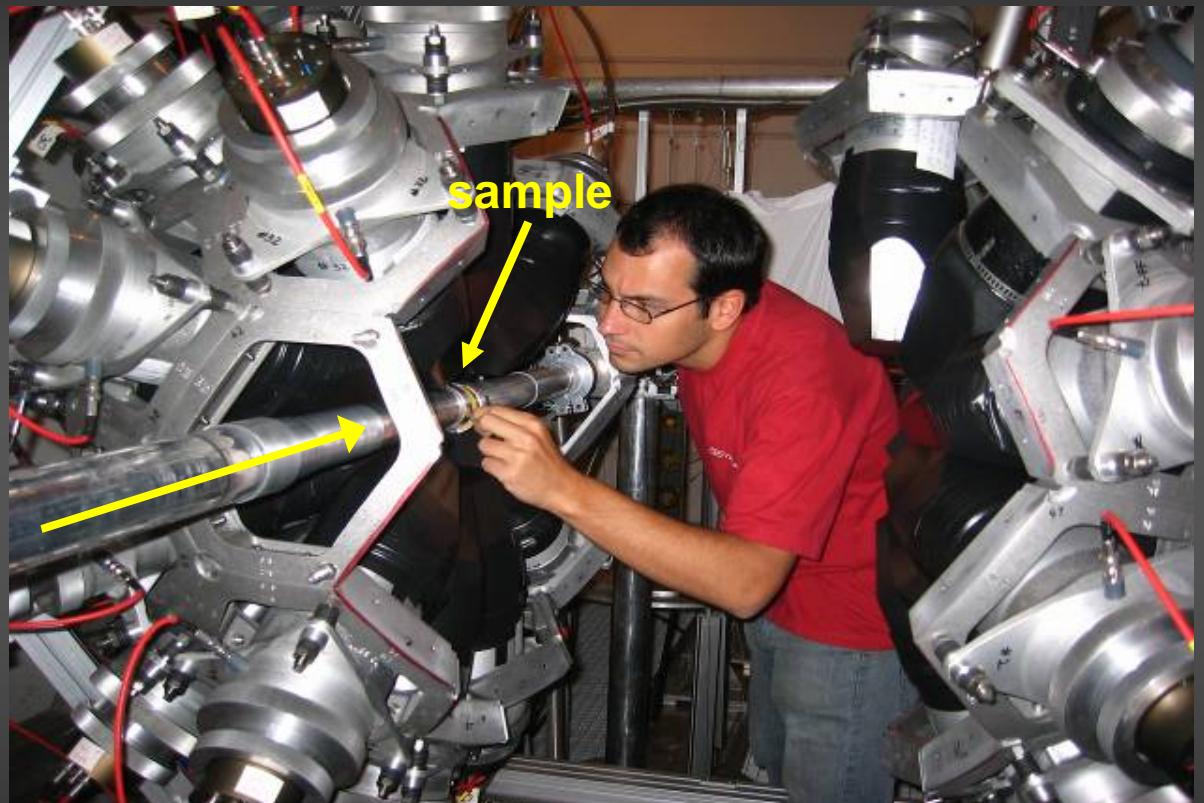
sample changer and beam pipe
made out of carbon fiber

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)

- 40 BaF₂ crystals
- high detection efficiency ≈100%
- good energy resolution



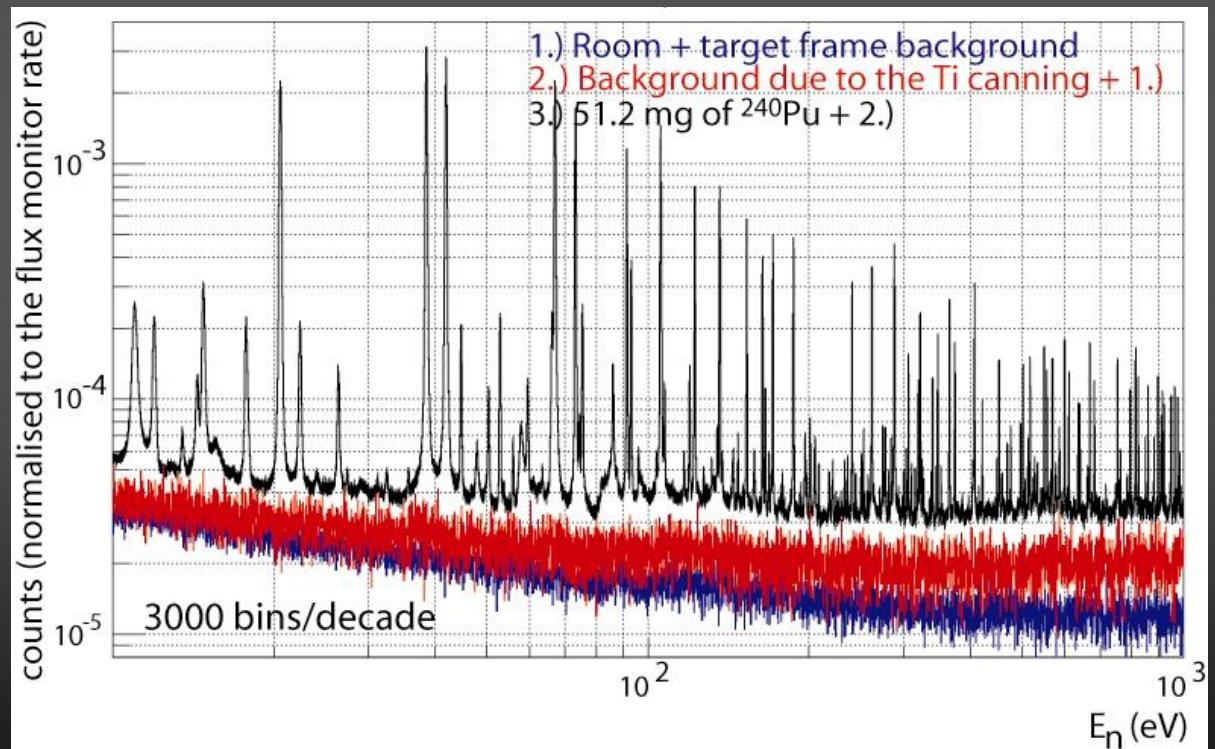
[more >>](#)

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

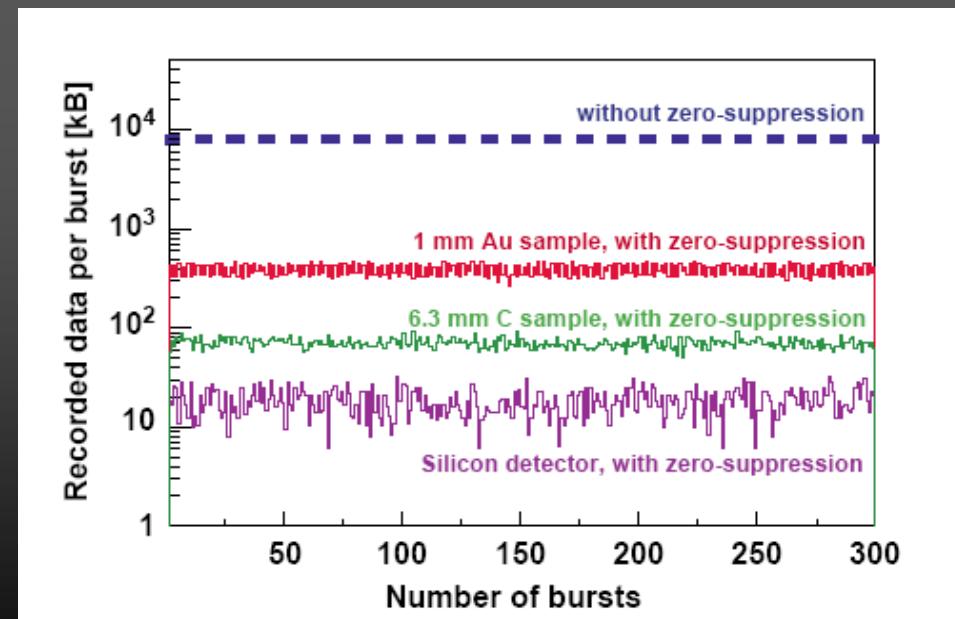
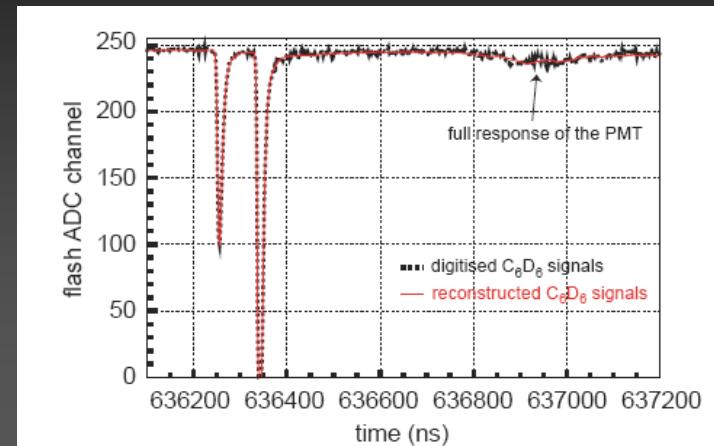


Basic characteristics of experiments at n_TOF

- 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

R Plag et al. (The n_TOF Collaboration)
NIMA 538 (2005) 693



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

Capture

^{151}Sm

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

^{232}Th

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

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

^{139}La

$^{186,187,188}\text{Os}$

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

^{237}Np , ^{240}Pu , ^{243}Am

Fission

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

^{232}Th

^{209}Bi

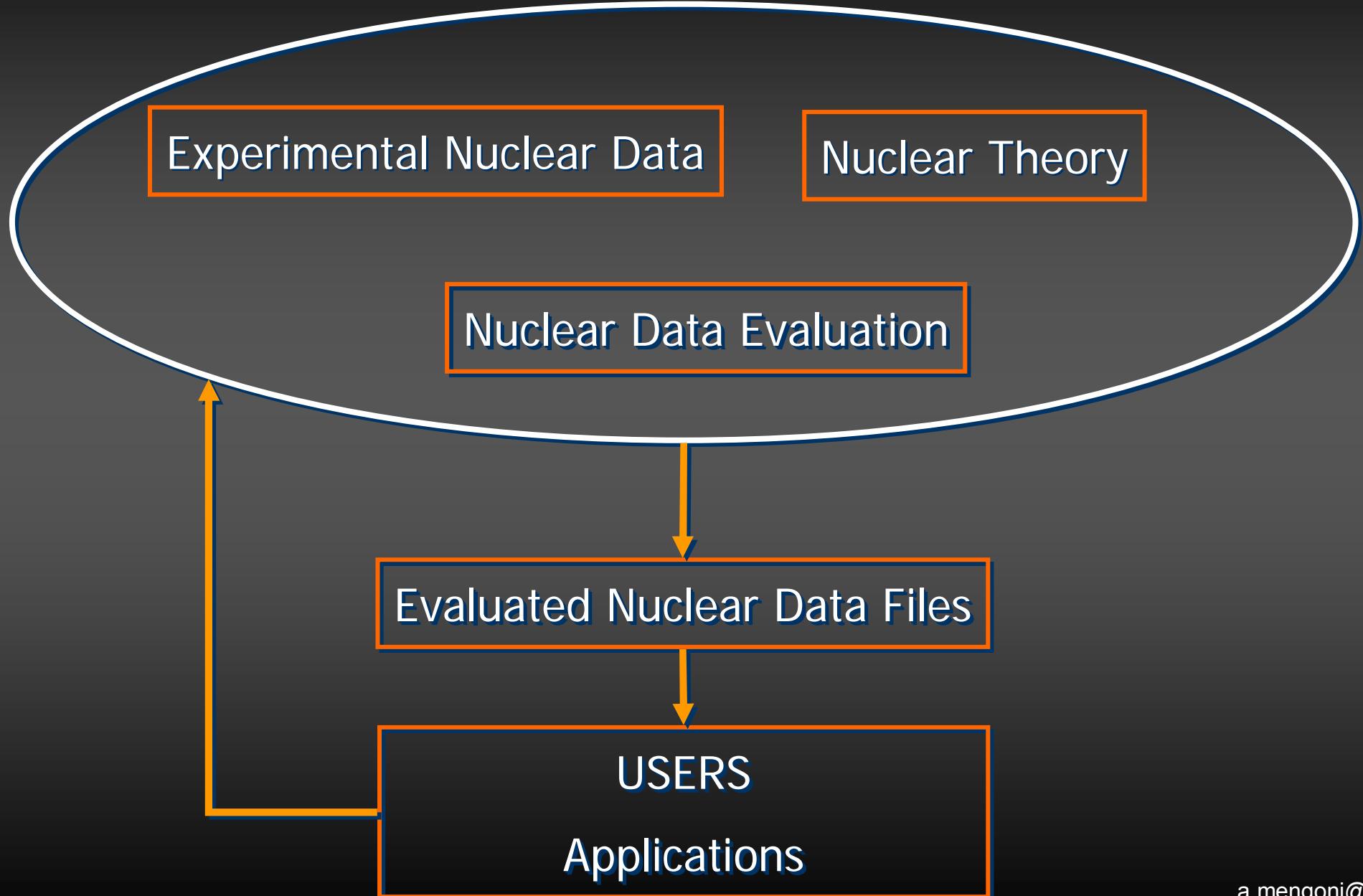
^{237}Np

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

$n_{_}\text{TOF}$ experiments

- Measurements 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)
- Cross sections relevant for Nuclear Astrophysics
 - s-process: branchings
 - s-process: presolar grains
- Neutrons 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

Mozilla Firefox
File Edit View History Bookmarks Tools Help
<http://www-nds.iaea.org/> Google

Welcome to the IAEA Nuclear Data Centre

Nuclear Data Services

Search NDS Go

Major Databases

- CINDA - neutron reaction data bibliography
- ENDF - evaluated nuclear reaction cross section libraries
- EXFOR - experimental nuclear reaction data
- ENSDF - evaluated nuclear structure and decay data (includes XUNDL)
- NSR - Nuclear Science References
- NuDat 2.2 - selected evaluated nuclear data

Nuclear Databases and Files

General

- Atomic Mass Data Center - 2003 atomic mass evaluation, NUBASE, PC-NUCLEUS, etc.
- Q-values, Thresholds - atomic masses, Q-values and threshold energies
- RPL - reference parameters for nuclear model calculations
- Thermal neutron capture gamma rays - by target and by energy
- Wallet cards - ground and metastable state properties

Other evaluated data libraries in ENDF format

- IAEA Photonuclear Data Library - cross sections and spectra up to 140MeV
- IND/TSL - IAEA Evaluated Nuclear Data Library / Thermal Scattering Law
- IRDF-2002 - International Reactor Dosimetry File
- Minsk Actinides Library - evaluated neutron reaction data (Maslov et al.)
- NGATLAS - atlas of neutron capture cross sections ([old-version](#) is here)
- POINT2007 - Pointwise data of ENDF/B-VII.0 processed into temperature dependent form
- POINT2004 - Pointwise data of ENDF/B-VI Release 8 at B temperatures
- RNAL - Reference Neutron Activation Library
- Standards - Neutron Cross-section Standards 2006
- ThU - Evaluated nuclear data for the Thorium-Uranium fuel cycle

Evaluated libraries in different formats

- ADS-Lib Application test library in ACE and MATXS format for ADS neutronics design
- Charged-particle cross section database for medical radioisotope production
- FENDL-2.1 - Fusion Evaluated Nuclear Data Library, Version 2.1
- IAEA-NDS-Q - index to IAEA NDS documentation series
- IBANDL - Ion Beam Analysis Nuclear Data Library
- MIRD - medical internal radiation dose tables
- Nuclear Data for Safeguards - recommendations, 2007
- PGAA-IAEA - database of prompt gamma rays from slow neutron capture
- Photon and Electron Interaction Data - EPDL, EADL, EEDL, EXDL and ASF
- SigmaCalc - Evaluated (recommended) differential cross sections for Ion Beam Analysis
- Stopping Power Data for Light Ions - Graphs, data, programs, compiled by H. Paul
- X and Gamma-rays standards - Decay data standards for detector calibration
- WIMSD-IAEA Library - multigroup data library for the WIMS-D code
- Various Specialized Evaluated Data Libraries in ENDF and other formats

Electronic Documents

- Citation Guidelines - online data service manual and citation guidelines
- ENDF Format Manual - ENDF-102 June 2005 version

> NDS Mirror Sites

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- Brazil

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> Quick Links

- ADS-Lib
- AMDC
- CINDA
- DROSG-2000
- ENDF
- ENSDF
- ENSDF ASCII Files
- EXFOR
- FENDL-2.1
- IBANDL
- IND/TSL
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- Medical Radioisotopes Production
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- Minsk Actinides
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- NuDat 2.1
- NSR
- PGAA-IAEA
- Photoneuclear
- Photon+Electron Interaction
- POINT2007
- POINT2004
- Q-values, Thresholds
- RPL
- RNAL
- Safeguards data
- SigmaCalc
- Standards
- Stopping Power Data
- Thermal Neutron Capture Gamma Rays
- Thorium-Uranium Fuel Cycle
- Wallet cards
- WIMSD Library

> NDS Events

Meetings & Workshops

- NEMEA-4**
4th Workshop on Neutron Measurements, Evaluations and Applications - Nuclear data needs for Generation IV and accelerator driven systems
October 16-18, 2007
Prague, Czech Republic
- Workshop on Nuclear Data for Science and Technology: Medical Applications**
12 - 23 November, 2007
Miramare, Trieste, Italy
- Joint ICTP-IAEA Workshop on Nuclear Structure and Decay Data: Theory and Evaluation**

Done

Data Libraries

Major Evaluated Nuclear Data libraries available for display & retrieval:



The End

Capture

^{151}Sm

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

^{232}Th

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

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

^{139}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}Th

^{209}Bi

^{237}Np

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



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

n_TOF experiments

Th/U nuclear fuel cycle

	$\text{Cm } 238$ 2,4 h	$\text{Cm } 239$ 3 h	$\text{Cm } 240$ 27 d	$\text{Cm } 241$ 32,8 d	$\text{Cm } 242$ 162,94 d	$\text{Cm } 243$ 29,1 a	$\text{Cm } 244$ 18,10 a	$\text{Cm } 245$ 8500 a	$\text{Cm } 246$ 4730 a	
	ϵ $\alpha, 6.52$	ϵ $\gamma, 169, \dots$ g	ϵ $\alpha, 6.291; 6.246, \dots$ sf g	ϵ $\gamma, 5.95, \dots$ sf g	ϵ $\alpha, 113; 9.05, \dots$ sf g $\gamma, 472; 431; 132, \dots$ g	ϵ $\alpha, 5.795, 5.740, \dots$ sf g $\gamma, 275; 258, \dots$ $210, \dots$ $\alpha, 132; \alpha, 620$	ϵ $\alpha, 5.405; 6.752, \dots$ sf g $\gamma, 143, \dots$ $\alpha, 15, \alpha, 1.1$	ϵ $\alpha, 5.261; 5.204, \dots$ sf g $\gamma, 175, 193, \dots$ $\alpha, 360; \alpha, 2100$	ϵ $\alpha, 5.368, 5.343, \dots$ sf g $\gamma, 455, \dots$ $\alpha, 1.2, \alpha, 0.16$	
$\text{Am } 236 ?$ 3,7 m	$\text{Am } 237$ 73,0 m	$\text{Am } 238$ 1,63 h	$\text{Am } 239$ 11,9 h	$\text{Am } 240$ 50,8 h	$\text{Am } 241$ 432,2 a	$\text{Am } 242$ 141 a	$\text{Am } 243$ 7370 a	$\text{Am } 244$ 26 m	$\text{Am } 245$ 2,05 h	
ϵ $\alpha, 6.41$	ϵ $\alpha, 6.042$ $\gamma, 200; 438; 474, \dots$ g	ϵ $\alpha, 5.94$ $\gamma, 563; 819; 561, \dots$ g	ϵ $\alpha, 5.774, \dots$ $\gamma, 276; 268, \dots$ g	ϵ $\alpha, 5.378, \dots$ $\gamma, 988; 889, \dots$ g	ϵ $\alpha, 5.489; 5.443, \dots$ sf g $\gamma, 50; 26; \alpha, 311$	ϵ $\alpha, 5.489; 5.443, \dots$ sf g $\gamma, 5.208, \dots$ $\alpha, 7; \alpha, 1.1$	ϵ $\alpha, 5.275; 5.233, \dots$ sf g $\gamma, 175, 44, \dots$ $\alpha, 75 + 5, \alpha, 0.074$	ϵ $\alpha, 5.275; 5.233, \dots$ sf g $\gamma, 166, \dots$ $\alpha, 154, \dots$ $\alpha, 2200$	ϵ $\alpha, 5.275; 5.233, \dots$ sf g $\gamma, 250, \dots$ $(241; 296, \dots)$ $\alpha, 1.7$	
$\text{Pu } 235$ 25,3 m	$\text{Pu } 236$ 2,858 a	$\text{Pu } 237$ 45,2 d	$\text{Pu } 238$ 87,74 a	$\text{Pu } 239$ 2,411 - 10^4 a	$\text{Pu } 240$ 6563 a	$\text{Pu } 241$ 14,35 a	$\text{Pu } 242$ 3,750 - 10^5 a	$\text{Pu } 243$ 4,956 h	$\text{Pu } 244$ 8,00 - 10^7 a	
ϵ $\alpha, 5.83$ $\gamma, 48; (156; 34, \dots)$ g	ϵ $\alpha, 5.768; 5.721, \dots$ $\gamma, Mg, 28$ $\gamma, 148; 109, \dots$ $\alpha, 160$	ϵ $\alpha, 5.334, \dots$ $\gamma, 62, \dots$ $\alpha, 230$	ϵ $\alpha, 5,490; 5,458, \dots$ $\gamma, Mg, 28$ $\gamma, 42; 100, \dots$ $\alpha, 17$	ϵ $\alpha, 5,157; 5,144, \dots$ $\gamma, Mg, 28$ $\gamma, 152, \dots$ $\alpha, 270, \alpha, 752$	ϵ $\alpha, 5,168; 5,124, \dots$ $\gamma, Mg, 28$ $\gamma, 45, \dots$ $\alpha, 280, \alpha, 0.044$	ϵ $\alpha, 5,02, \dots$ $\gamma, 486, \dots$ $\gamma, 148, \dots$ $\alpha, 370, \alpha, 1010$	ϵ $\alpha, 4,901; 4,856, \dots$ $\gamma, 145, \dots$ $\alpha, 19, \alpha, 0.2$	ϵ $\alpha, 4,856; 4,806, \dots$ $\gamma, 145, \dots$ $\alpha, 100, \alpha, 200$	ϵ $\alpha, 4,588; 4,546, \dots$ $\gamma, 174, \dots$ $\alpha, 1.7$	
$\text{Np } 234$ 4,4 d	$\text{Np } 235$ 396,1 d	$\text{Np } 236$ 22,5 h	$\text{Np } 237$ 1,54 - 10^3 a	$\text{Np } 238$ 2,144 - 10^6 a	$\text{Np } 239$ 2,117 d	$\text{Np } 240$ 2,355 d	$\text{Np } 240$ 7,22 m	$\text{Np } 241$ 13,9 m	$\text{Np } 242$ 2,2 m	
ϵ β^+, \dots $\gamma, 1559; 1528, \dots$ $1602, \dots$ $\alpha, 900$	ϵ $\alpha, 5,025, \dots$ $\gamma, 1642, \dots$ $\gamma, 160, \dots$ $\alpha, 270, \alpha, 2610$	ϵ $\alpha, 5,025, \dots$ $\gamma, 1642, \dots$ $\gamma, 160, \dots$ $\alpha, 270, \alpha, 2610$	ϵ $\alpha, 4,790; 4,774, \dots$ $\gamma, 29; 87, \dots$ $\alpha, 180, \alpha, 0.020$	ϵ $\alpha, 4,794; 4,774, \dots$ $\gamma, 1029, \dots$ $\gamma, 1026, 924, \dots$ $\alpha, 32 + 19, \alpha, < 1$	ϵ $\alpha, 4,04; 0,7, \dots$ $\gamma, 106, 278, \dots$ $\gamma, 226, \dots$ $\alpha, 32 + 19, \alpha, < 1$	ϵ $\alpha, 3,9, \dots$ $\gamma, 588, \dots$ $\alpha, 607, \dots$ $\alpha, 601, \dots$ $\alpha, 498, \dots$	ϵ $\alpha, 1,3, \dots$ $\gamma, 175, (133, \dots)$ g	ϵ $\alpha, 1,3, \dots$ $\gamma, 175, (133, \dots)$ g	ϵ $\alpha, 2,7, \dots$ $\gamma, 738, \dots$ $\gamma, 788, \dots$ $\alpha, 645, \dots$ $\alpha, 598, \dots$ $\alpha, 1673, \dots$ $\alpha, 173, \dots$ $\alpha, 158, \dots$ $\alpha, 147, \dots$ $\alpha, 146, \dots$ $\alpha, 145, \dots$ $\alpha, 144, \dots$ $\alpha, 143, \dots$ $\alpha, 142, \dots$ $\alpha, 141, \dots$ $\alpha, 140, \dots$ $\alpha, 139, \dots$ $\alpha, 138, \dots$ $\alpha, 137, \dots$ $\alpha, 136, \dots$ $\alpha, 135, \dots$ $\alpha, 134, \dots$ $\alpha, 133, \dots$ $\alpha, 132, \dots$ $\alpha, 131, \dots$ $\alpha, 130, \dots$ $\alpha, 129, \dots$ $\alpha, 128, \dots$ $\alpha, 127, \dots$ $\alpha, 126, \dots$ $\alpha, 125, \dots$ $\alpha, 124, \dots$ $\alpha, 123, \dots$ $\alpha, 122, \dots$ $\alpha, 121, \dots$ $\alpha, 120, \dots$ $\alpha, 119, \dots$ $\alpha, 118, \dots$ $\alpha, 117, \dots$ $\alpha, 116, \dots$ $\alpha, 115, \dots$ $\alpha, 114, \dots$ $\alpha, 113, \dots$ $\alpha, 112, \dots$ $\alpha, 111, \dots$ $\alpha, 110, \dots$ $\alpha, 109, \dots$ $\alpha, 108, \dots$ $\alpha, 107, \dots$ $\alpha, 106, \dots$ $\alpha, 105, \dots$ $\alpha, 104, \dots$ $\alpha, 103, \dots$ $\alpha, 102, \dots$ $\alpha, 101, \dots$ $\alpha, 100, \dots$ $\alpha, 99, \dots$ $\alpha, 98, \dots$ $\alpha, 97, \dots$ $\alpha, 96, \dots$ $\alpha, 95, \dots$ $\alpha, 94, \dots$ $\alpha, 93, \dots$ $\alpha, 92, \dots$ $\alpha, 91, \dots$ $\alpha, 90, \dots$ $\alpha, 89, \dots$ $\alpha, 88, \dots$ $\alpha, 87, \dots$ $\alpha, 86, \dots$ $\alpha, 85, \dots$ $\alpha, 84, \dots$ $\alpha, 83, \dots$ $\alpha, 82, \dots$ $\alpha, 81, \dots$ $\alpha, 80, \dots$ $\alpha, 79, \dots$ $\alpha, 78, \dots$ $\alpha, 77, \dots$ $\alpha, 76, \dots$ $\alpha, 75, \dots$ $\alpha, 74, \dots$ $\alpha, 73, \dots$ $\alpha, 72, \dots$ $\alpha, 71, \dots$ $\alpha, 70, \dots$ $\alpha, 69, \dots$ $\alpha, 68, \dots$ $\alpha, 67, \dots$ $\alpha, 66, \dots$ $\alpha, 65, \dots$ $\alpha, 64, \dots$ $\alpha, 63, \dots$ $\alpha, 62, \dots$ $\alpha, 61, \dots$ $\alpha, 60, \dots$ $\alpha, 59, \dots$ $\alpha, 58, \dots$ $\alpha, 57, \dots$ $\alpha, 56, \dots$ $\alpha, 55, \dots$ $\alpha, 54, \dots$ $\alpha, 53, \dots$ $\alpha, 52, \dots$ $\alpha, 51, \dots$ $\alpha, 50, \dots$ $\alpha, 49, \dots$ $\alpha, 48, \dots$ $\alpha, 47, \dots$ $\alpha, 46, \dots$ $\alpha, 45, \dots$ $\alpha, 44, \dots$ $\alpha, 43, \dots$ $\alpha, 42, \dots$ $\alpha, 41, \dots$ $\alpha, 40, \dots$ $\alpha, 39, \dots$ $\alpha, 38, \dots$ $\alpha, 37, \dots$ $\alpha, 36, \dots$ $\alpha, 35, \dots$ $\alpha, 34, \dots$ $\alpha, 33, \dots$ $\alpha, 32, \dots$ $\alpha, 31, \dots$ $\alpha, 30, \dots$ $\alpha, 29, \dots$ $\alpha, 28, \dots$ $\alpha, 27, \dots$ $\alpha, 26, \dots$ $\alpha, 25, \dots$ $\alpha, 24, \dots$ $\alpha, 23, \dots$ $\alpha, 22, \dots$ $\alpha, 21, \dots$ $\alpha, 20, \dots$ $\alpha, 19, \dots$ $\alpha, 18, \dots$ $\alpha, 17, \dots$ $\alpha, 16, \dots$ $\alpha, 15, \dots$ $\alpha, 14, \dots$ $\alpha, 13, \dots$ $\alpha, 12, \dots$ $\alpha, 11, \dots$ $\alpha, 10, \dots$ $\alpha, 9, \dots$ $\alpha, 8, \dots$ $\alpha, 7, \dots$ $\alpha, 6, \dots$ $\alpha, 5, \dots$ $\alpha, 4, \dots$ $\alpha, 3, \dots$ $\alpha, 2, \dots$ $\alpha, 1, \dots$ $\alpha, 0, \dots$	ϵ $\alpha, 1,2, \dots$ $\gamma, 111, (647, \dots)$ $\gamma, 196, \dots$
$\text{Th } 231$ 25,5 h	$\text{Th } 232$ 1,100	$\text{Th } 233$ 1,23 m	$\text{Th } 234$ 24,10 d	$\text{Th } 235$ 7,1 m	$\text{Th } 236$ 37,5 m	$\text{Th } 237$ 5,0 m				
ϵ $\beta^-, 0,3, 0,4, \dots$ $\gamma, 29; 84, \dots$ e^-	ϵ $\alpha, 4,013; 3,950, \dots$ $\gamma, (84, \dots)$ $\gamma, 7,37; \alpha, 0.000003$	ϵ $\alpha, 1,2, \dots$ $\gamma, 87, 29, \dots$ $\gamma, 459, \dots$ $\alpha, 150, \alpha, 15$	ϵ $\beta^-, 0,2, \dots$ $\gamma, 63, 92; 93, \dots$ $\gamma, 1, \dots$ $\alpha, 1,5; \alpha, < 0,01$	ϵ $\beta^-, 1,4, \dots$ $\gamma, 417; 727, \dots$ $\gamma, 696, \dots$	ϵ $\beta^-, 1,0, \dots$ $\gamma, 111, (647, \dots)$ $\gamma, 196, \dots$	ϵ $\beta^-, 1,7, \dots$				

Capture

^{151}Sm

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

^{232}Th

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

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

^{139}La

$^{186,187,188}\text{Os}$

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

^{237}Np , ^{240}Pu , ^{243}Am

Fission

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

^{232}Th

^{209}Bi

^{237}Np

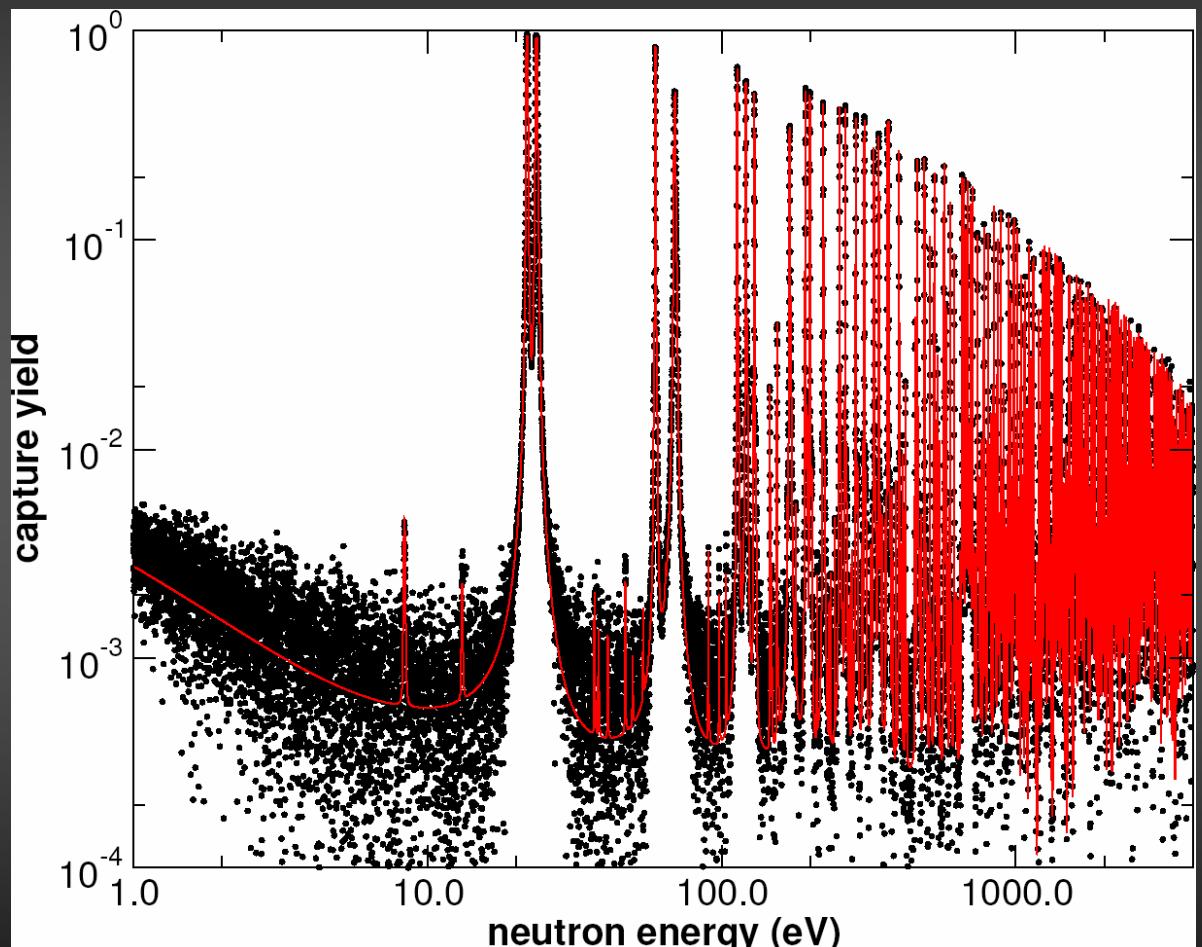
$^{241,243}\text{Am}$, ^{245}Cm



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

n_TOF experiments

F Gunsing, et al. - The n_TOF Collaboration
ND2004 Conference, Santa Fe, NM – Sept. 2004



extremely high-resolution data!

The n_TOF Collaboration

Capture

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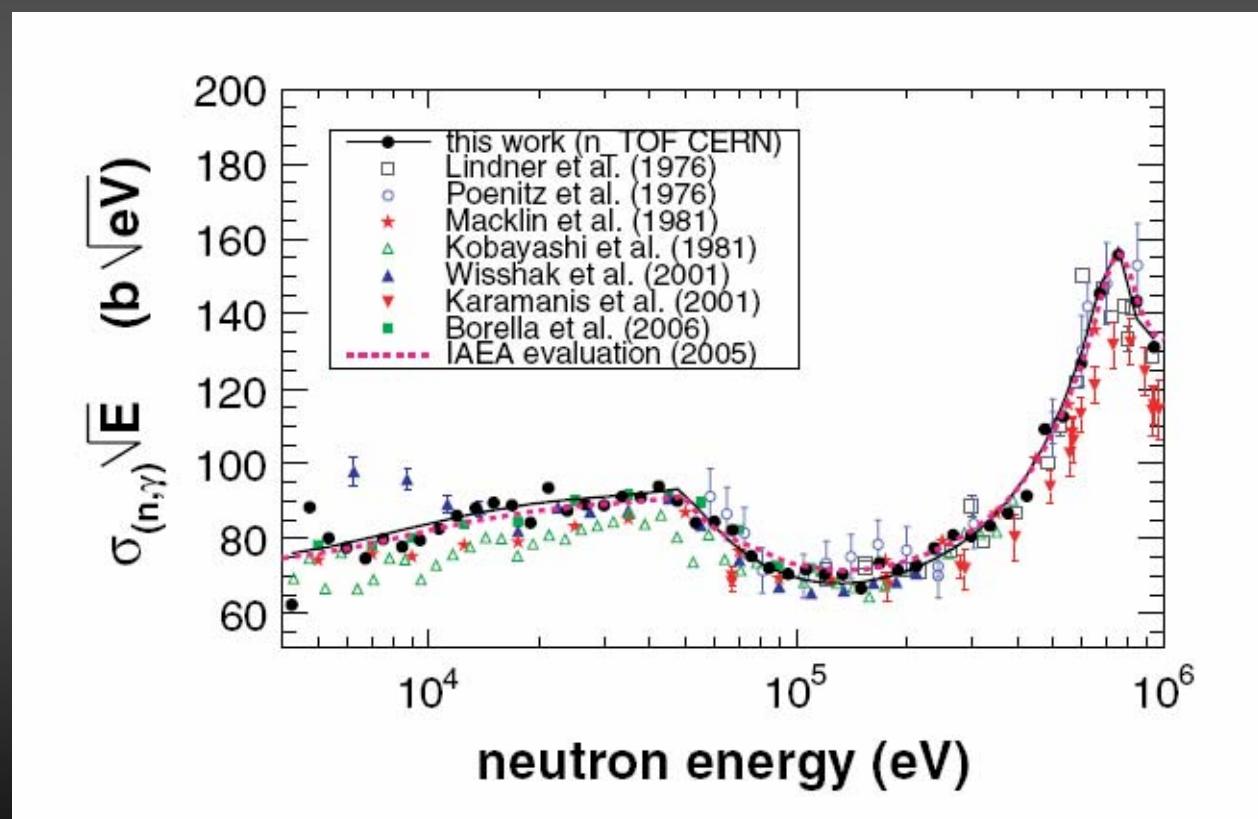


$^{232}\text{Th}(n,\gamma)$

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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_{low} (keV)	E_{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

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Capture

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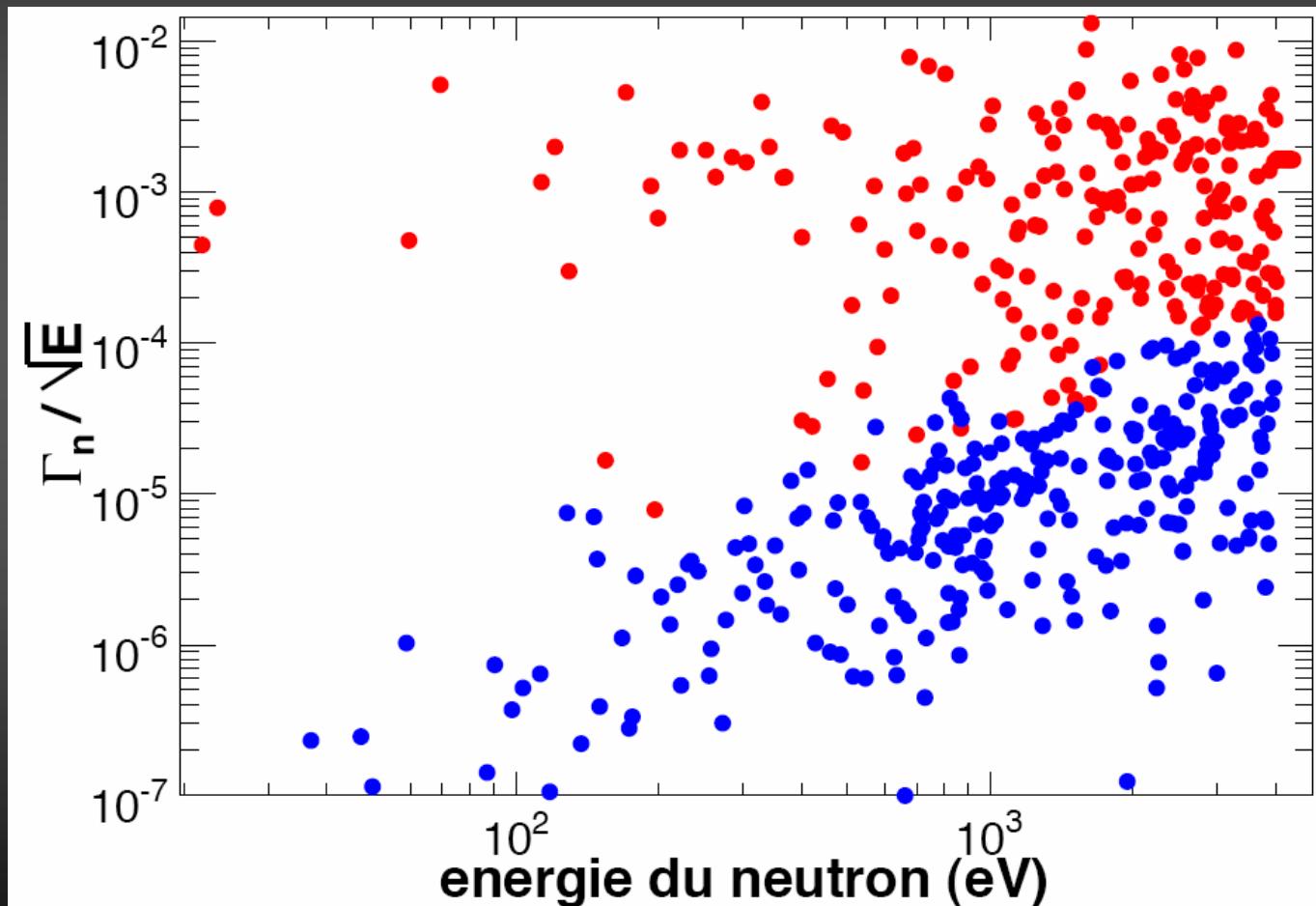
$^{241,243}\text{Am}, \ ^{245}\text{Cm}$



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

n_TOF experiments

F Gunsing, et al. - The n_TOF Collaboration
analysis in progress



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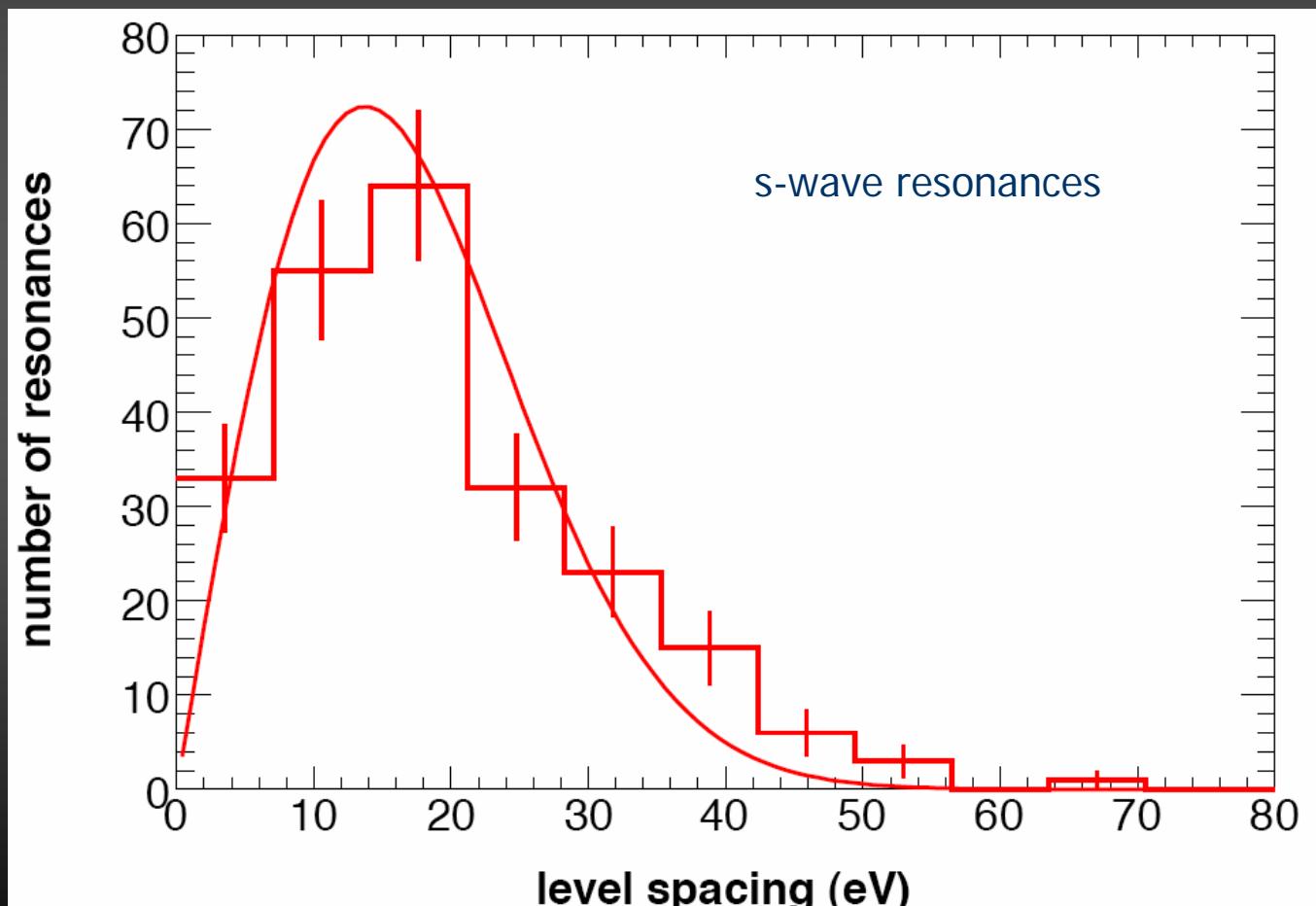
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