



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



1858-33

**School on Physics, Technology and Applications of Accelerator Driven
Systems (ADS)**

19 - 30 November 2007

**Nuclear Reactions and Related Data Libraries at Low Energies.
Part I**

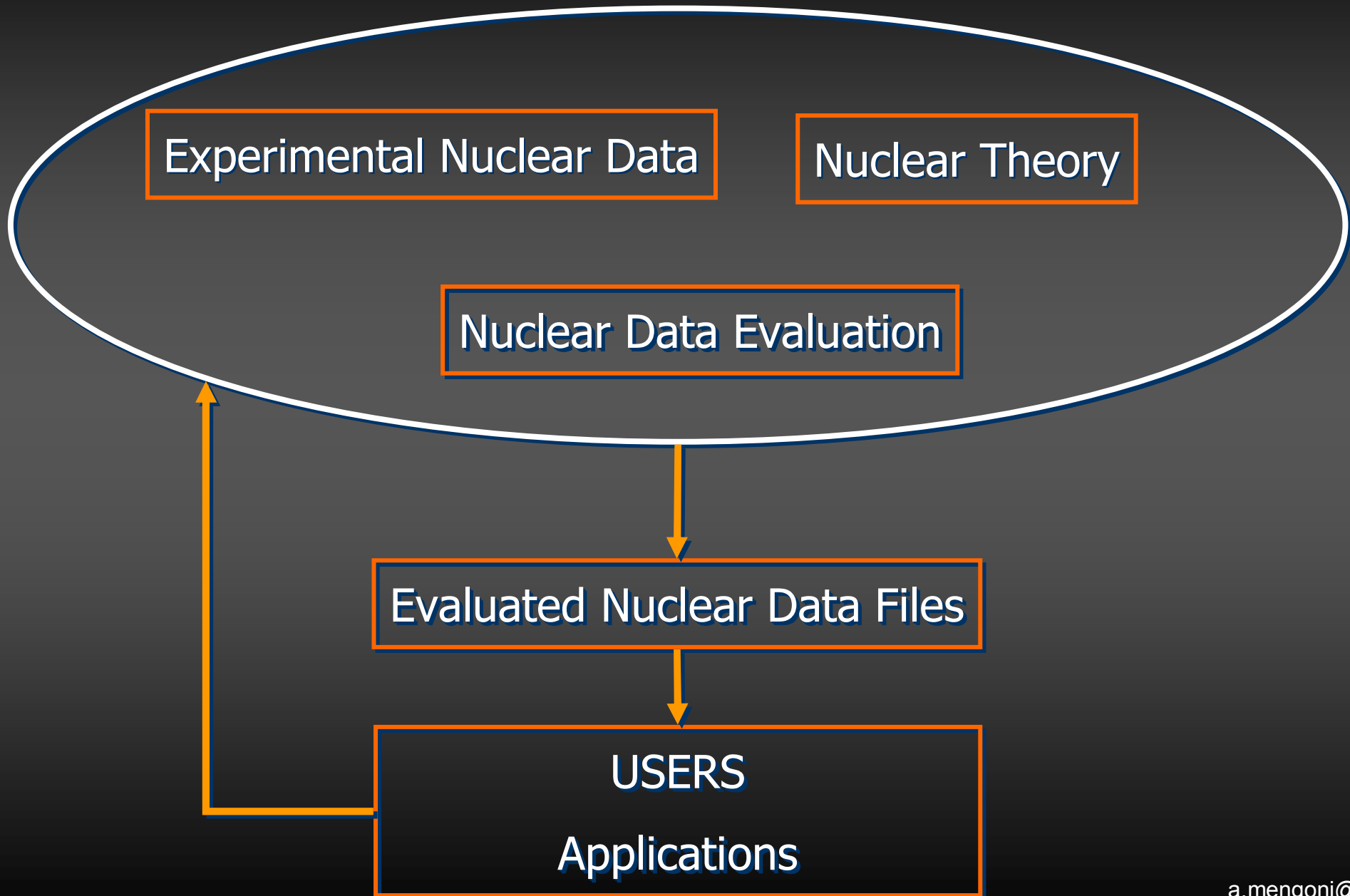
Alberto MENGONI
*ENEA, Bologna, Italy / IAEA Nuclear Data Section, Vienna
Austria*

Nuclear Reactions and Related Data Libraries at Low Energies

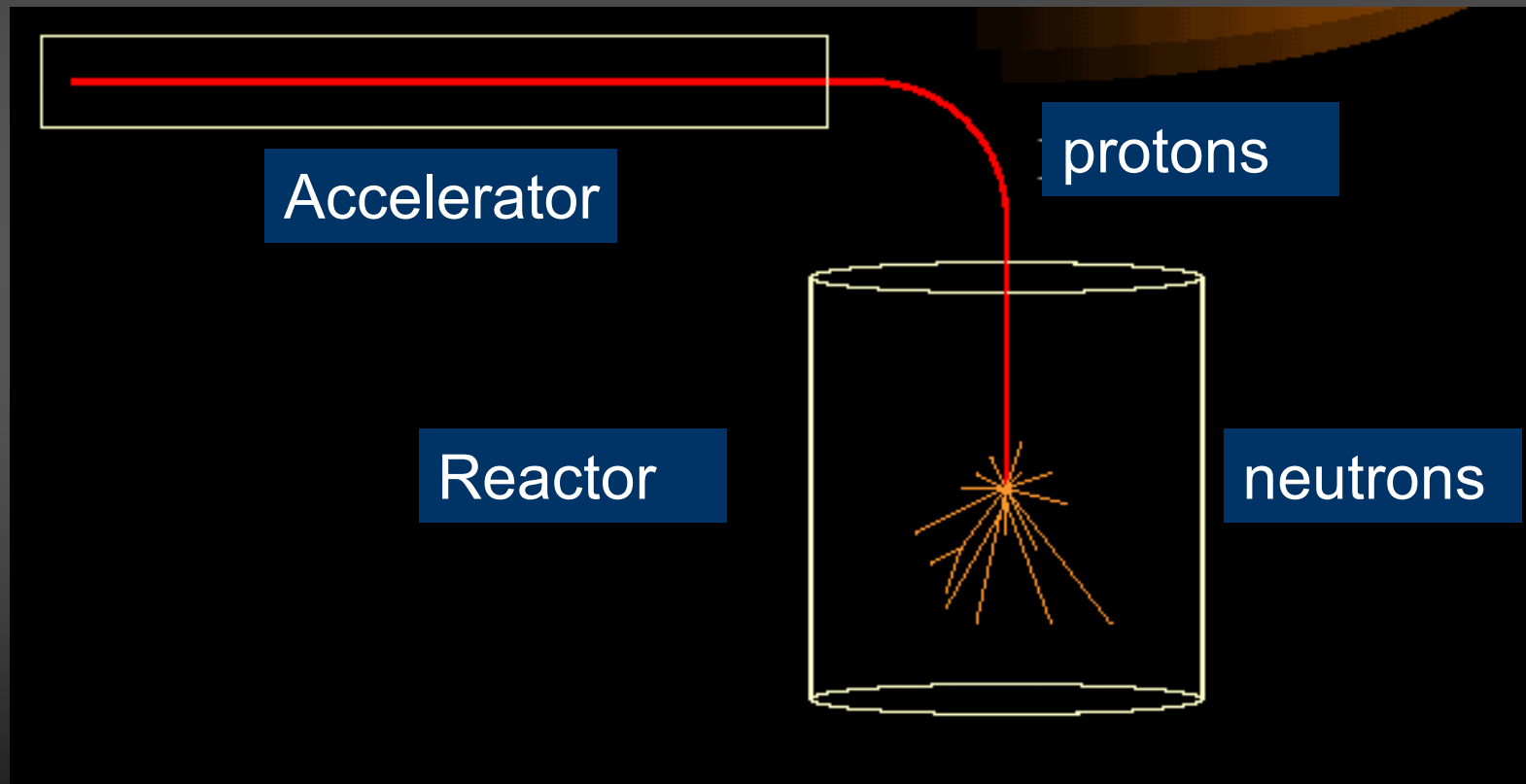
Alberto Mengoni
IAEA , Vienna

- Generalities
- Example of Nuclear Data experimental activity: The n_TOF facility at CERN
- From experimental data to evaluated libraries

Nuclear Reactions & Data Libraries



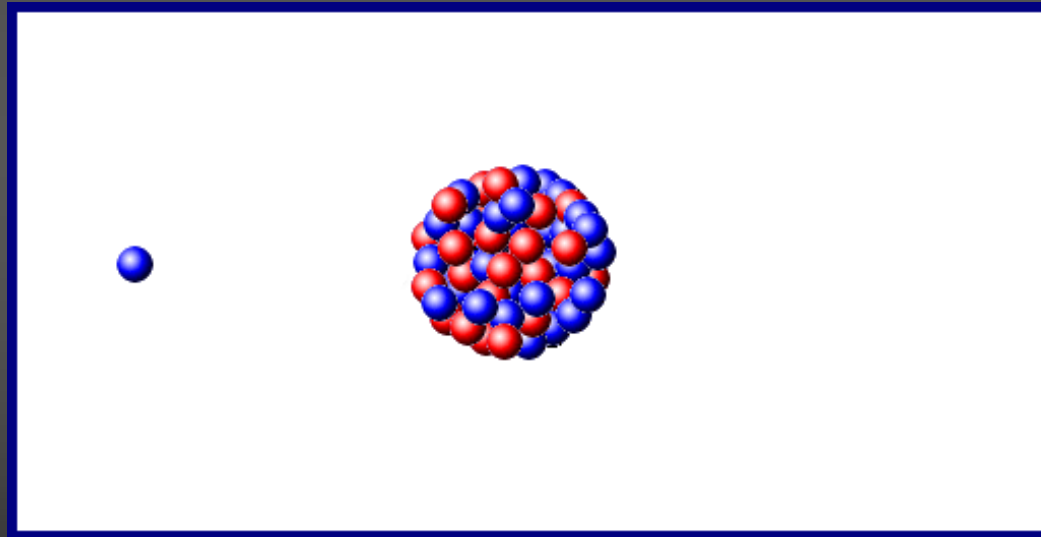
ADS (Accelerator Driven Systems)



Zen-ADS

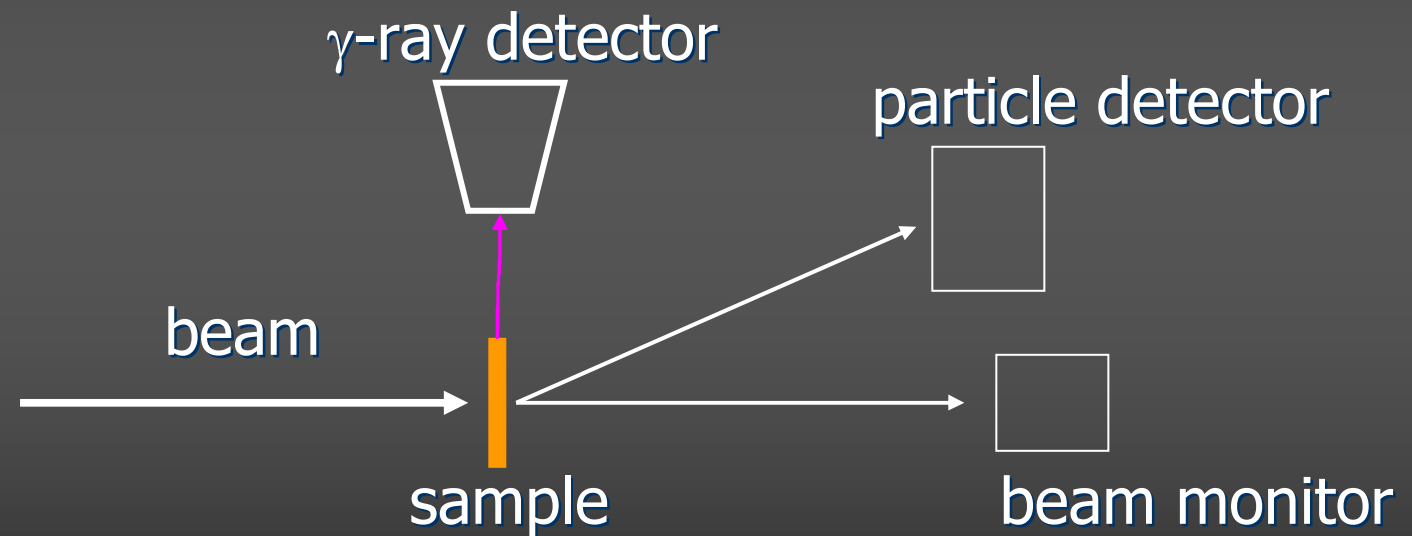
Nuclear Reaction Experiments

Nuclear Data Measurements



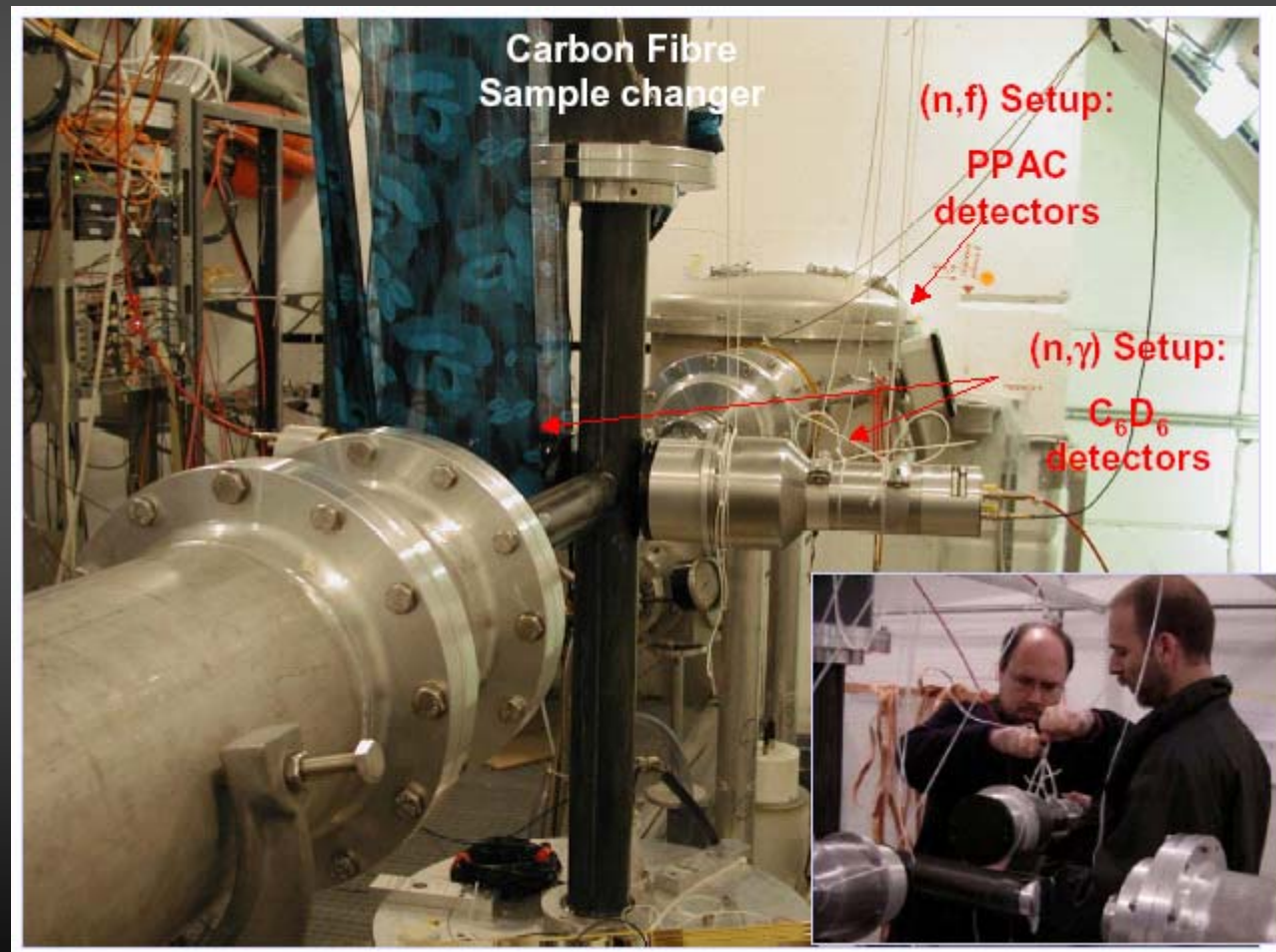
Nuclear Reaction Experiments

Nuclear Data Measurements



Nuclear Reaction Experiments

Nuclear Data Measurements



Nuclear Reaction Experiments



Say, here I am! A nuclear physicist.
And I need to measure neutron reaction
cross sections with the time-of-flight
technique...

World scene for tof measurements

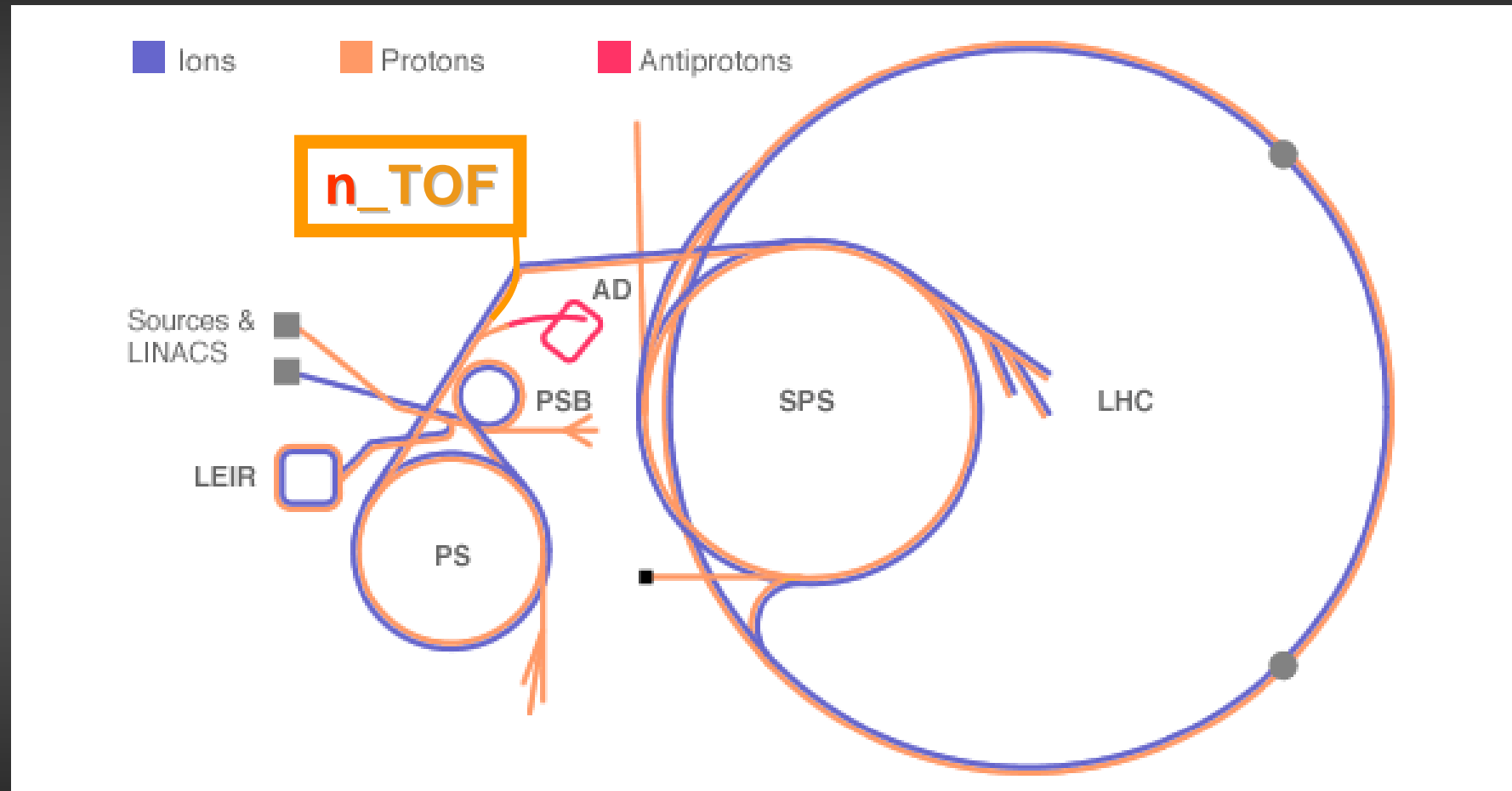
facility		driver and energy	repetition rate	n source	n energy range	flight path length
FZK	Karlsruhe	varii in the MeV range	MHz	$^7\text{Li}(p,n)$ & others	few keV up to 1 MeV monoE above	10s cm
TIT	Tokyo					
...	...					
GELINA	EC-JRC Geel	electron linac 150 MeV	800 Hz	photo-n photo-f	10 meV – 20 MeV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

The n_TOF facility at CERN



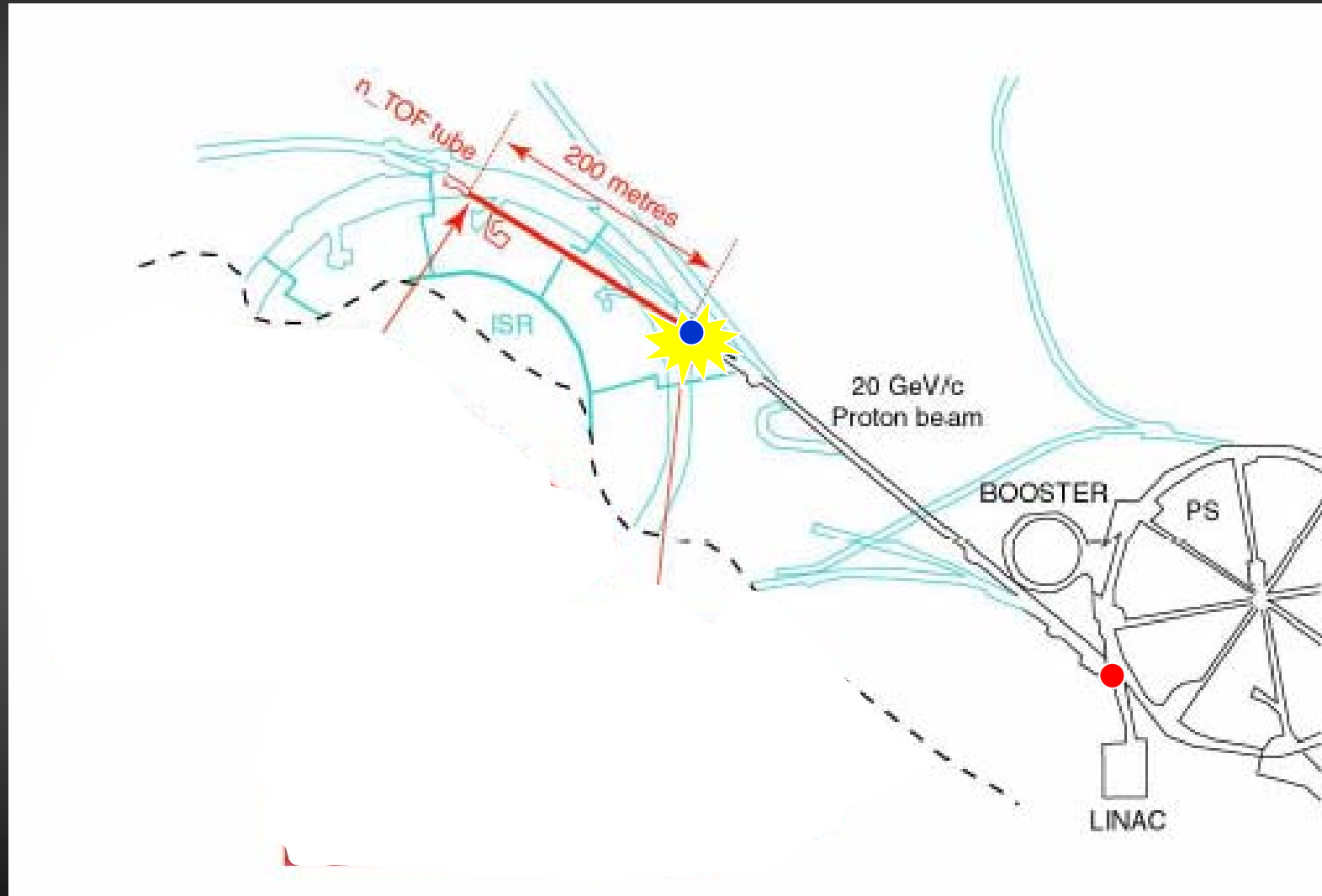
somewhere around here

CERN accelerator Complex



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

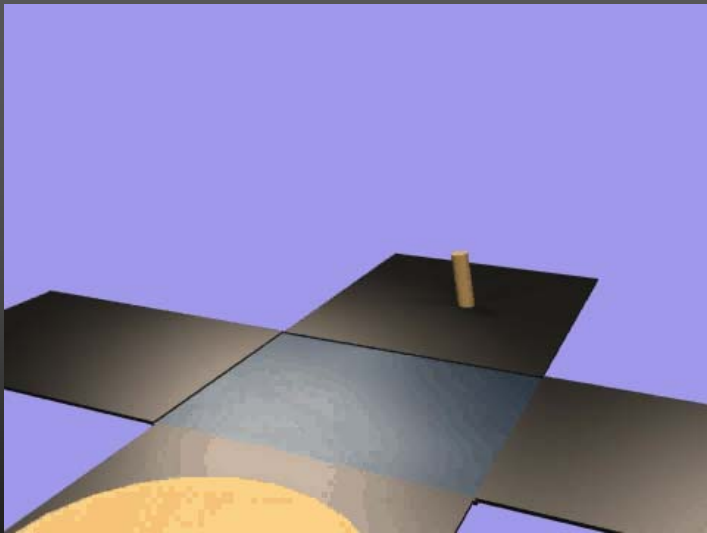
The n_TOF facility at CERN



The n_TOF facility at CERN

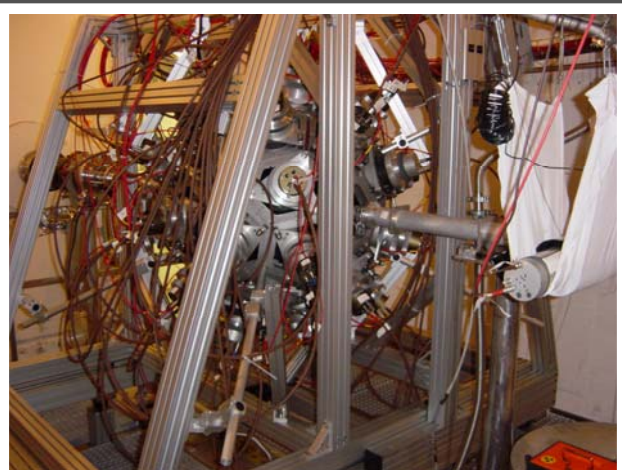
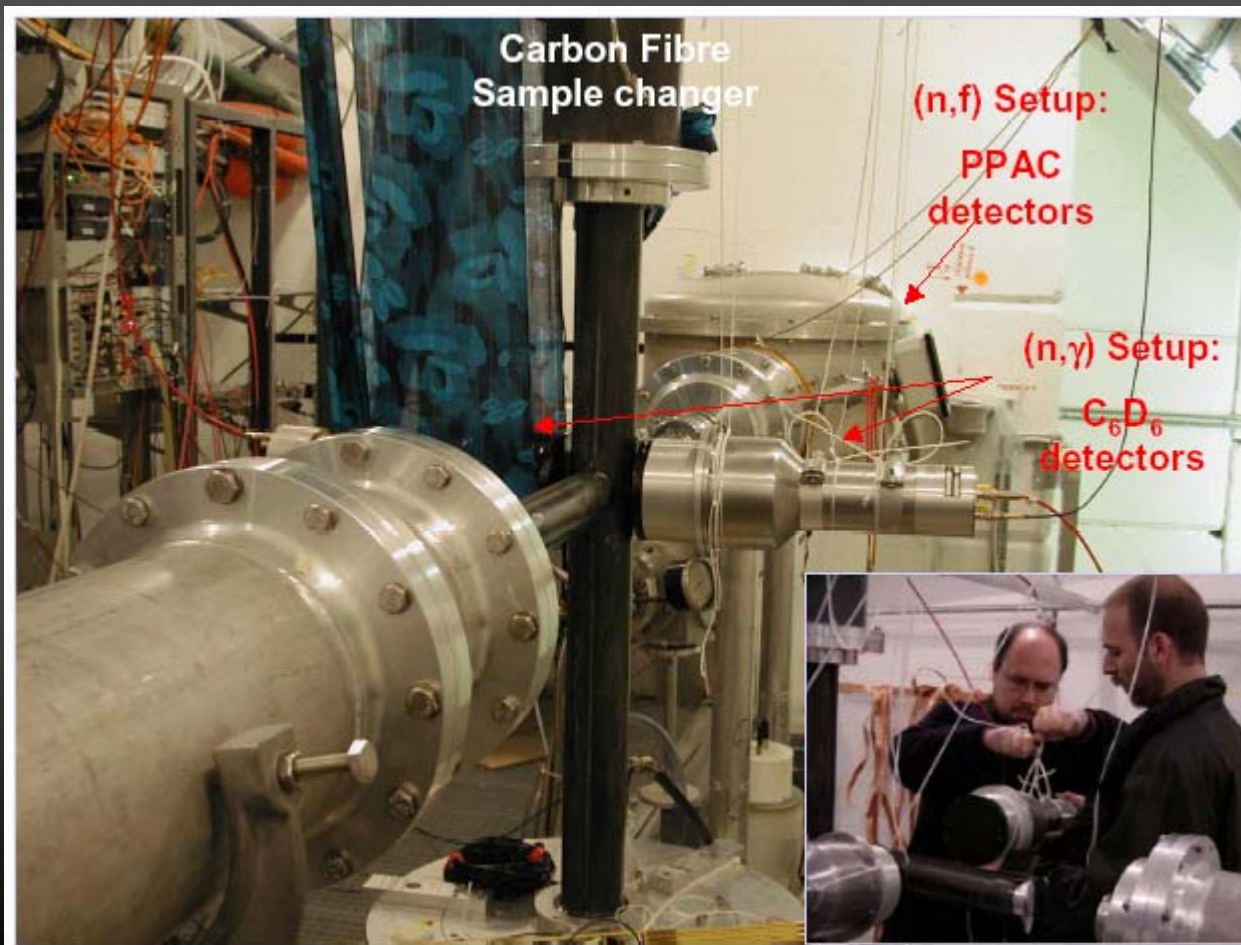
movie by V Vlachoudis (CERN)

- Design: the n_TOF tunnel



The real world

- **n_TOF** commissioned in 2001-2002



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)

n_TOF beam characteristics

■ the neutron flux

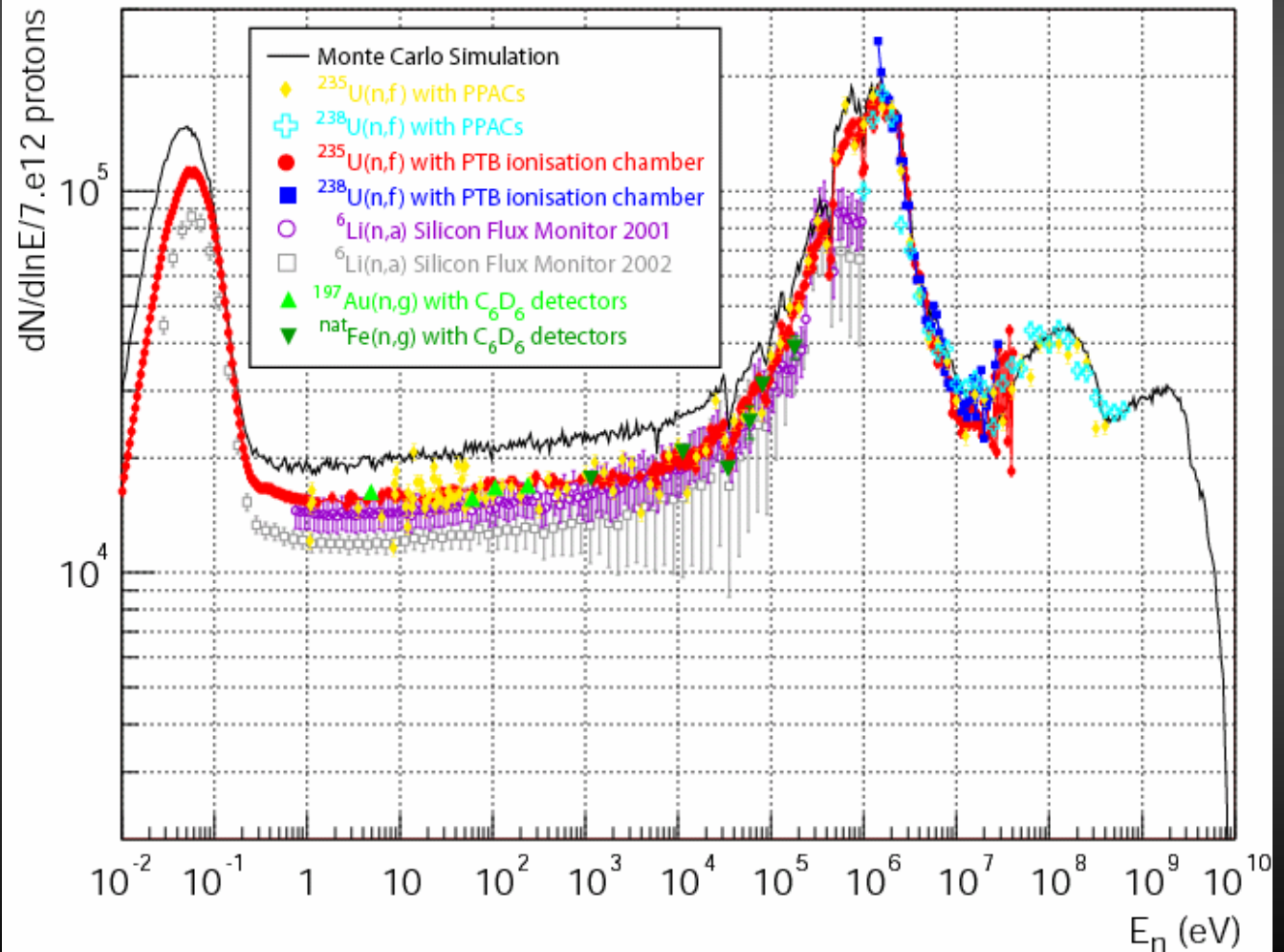
2nd collimator $\phi=1.8$ cm
(capture mode)

Performance Report
CERN-INTC-2002-037, January 2003
CERN-SL-2002-053 ECT

The neutron fluence in EAR-1

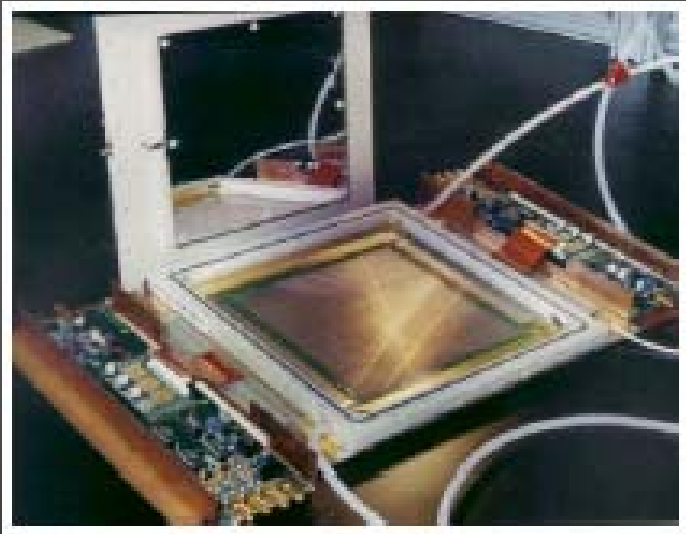
Energy range	Uncollimated [n/pulse/cm ²]	Capture mode [n/pulse]	Fission mode [n/pulse]
< 1 eV	2.0E+05	3.1E+05	2.0E+06
1 eV - 10 eV	2.7E+04	4.5E+04	2.9E+05
10 eV - 100 eV	2.9E+04	4.7E+04	3.1E+05
100 eV - 1000 eV	3.0E+04	5.1E+04	3.3E+05
1 eV - 1 keV	8.6E+04	1.4E+05	9.3E+05
1 keV - 10 keV	3.2E+04	5.4E+04	3.6E+05
10 keV - 100 keV	3.9E+04	7.1E+04	4.7E+05
100 keV - 1000 keV	1.1E+05	2.3E+05	1.5E+06
1 keV - 1 MeV	1.8E+05	3.5E+05	2.3E+06
1 MeV - 10 MeV	8.3E+04	2.4E+05	1.7E+06
10 MeV - 100 MeV	2.8E+04	7.2E+04	5.1E+05
> 100 MeV	4.4E+04	1.2E+05	5.6E+05
1 MeV - > 100 MeV	1.6E+05	4.4E+05	2.7E+06
Total	6.2E+05	1.2E+06	8.0E+06

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



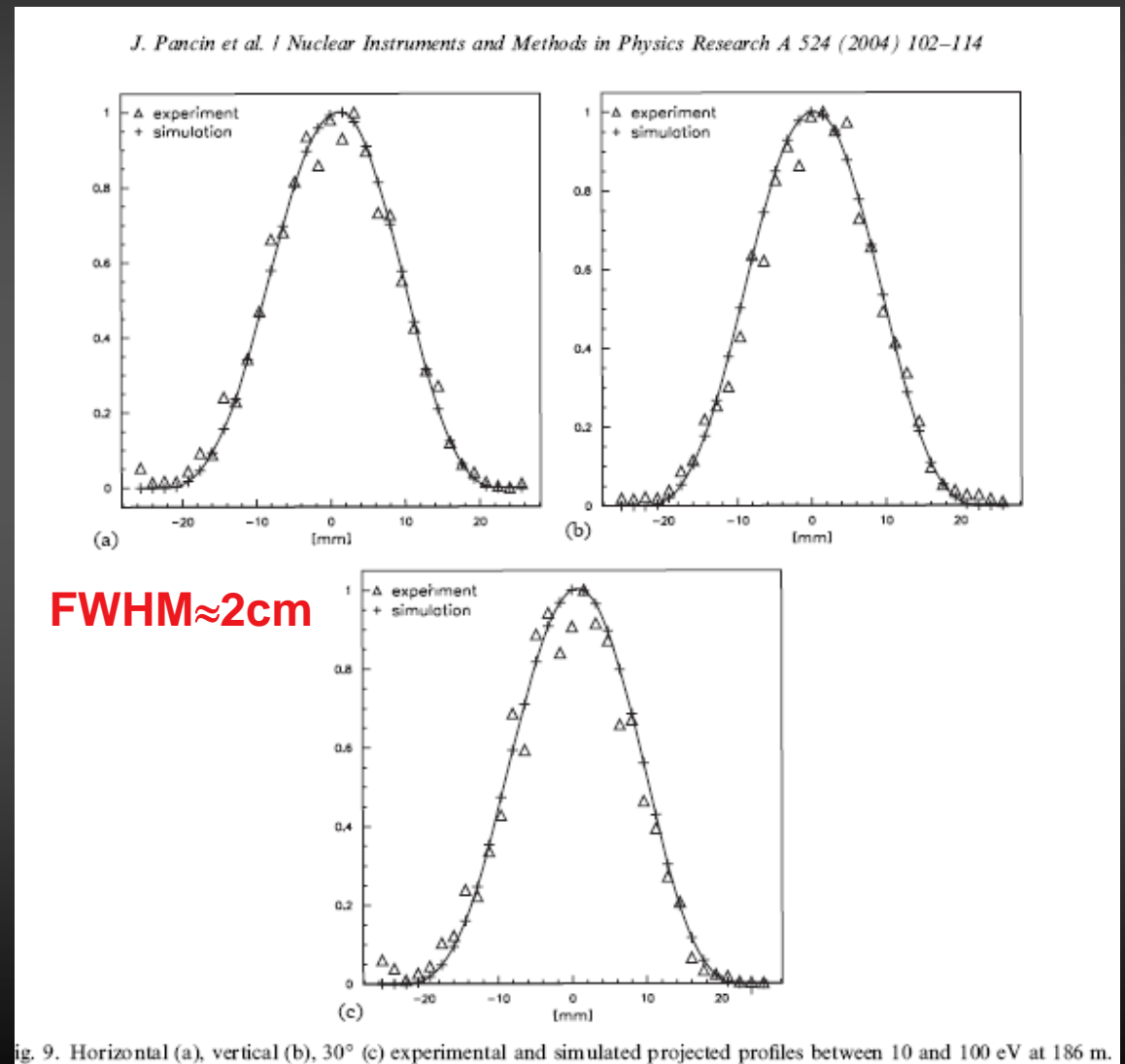
n_TOF beam characteristics

- Beam profile @ 187.5 m



MicroMegas detector

J Pancin, et al. (The n_TOF Collaboration)
NIMA 524 (2004) 102



n_TOF beam

energy resolution

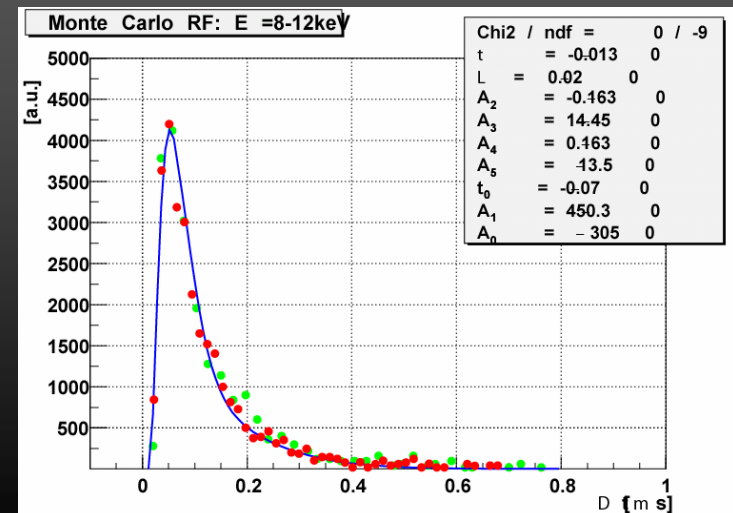
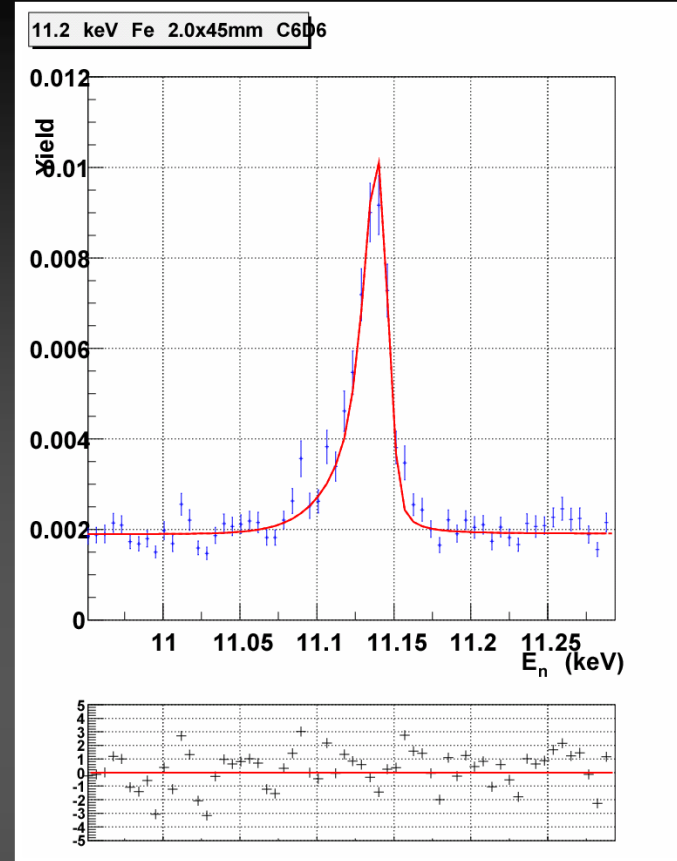
Performance Report
CERN-INTC-2002-037, January 2003
CERN-SL-2002-053 ECT

Energy resolution @ 187.5 m (collimator for capture mode)

Neutron Energy	p-beam pulse width FWHM [cm]	moderation FWHM [cm]	$\Delta E/E$
1 eV	0.0	3.0	3.0E-04
10 eV	0.1	3.0	3.2E-04
100 eV	0.2	3.3	3.5E-04
1 keV	0.6	5.1	5.5E-04
10 keV	2.0	7.9	8.7E-04
30 keV	3.4	10.2	1.1E-03
100 keV	6.2	18.0	2.0E-03
1 MeV	19.5	34.1	4.2E-03
10 MeV	61.7	16.9	6.8E-03
100 MeV	195.0	14.5	2.1E-02

$$\frac{\Delta E}{E} = \frac{2}{L} \sqrt{\Delta L^2 + 1.91 \cdot E \cdot \Delta T^2}$$

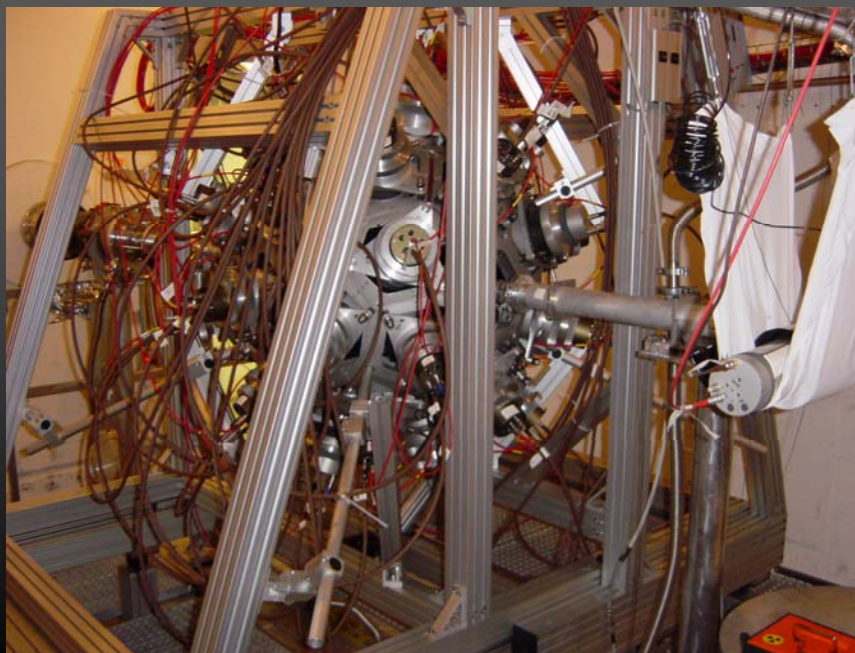
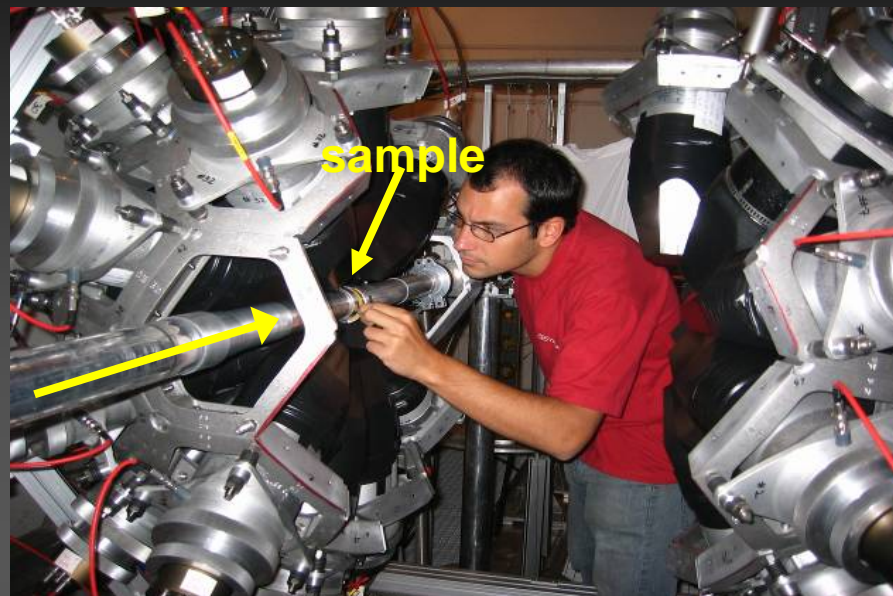
(for example: 6×10^{-4} @ 1 keV)



n_TOF TAC for (n,γ) measurements

- Structure mounted in April-04
- 4π geometry: end of May-04
- 1.5 month commissioning
- Au (n,γ) & other standards

First measurement with a radioactive sample started in August 2004
 $^{237}\text{Np}(n,\gamma)$



Why we do all this?



Objectives

- **M**easurements of **n**eutron cross sections relevant for Nuclear Waste Transmutation and related Nuclear Technologies
- **C**ross sections relevant for Nuclear Astrophysics
- **N**eutrons as probes for fundamental Nuclear Physics

Nuclear waste: TRU

(1000 MW_e 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 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
Np 234 4,4 d	Np 235 396,1 d	Np 236 22,5 h	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
U 233 1,592 · 10 ⁵ a	U 234 0,0055	U 235 0,7200	U 236 2,342 · 10 ⁷ 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)

Fast neutrons!

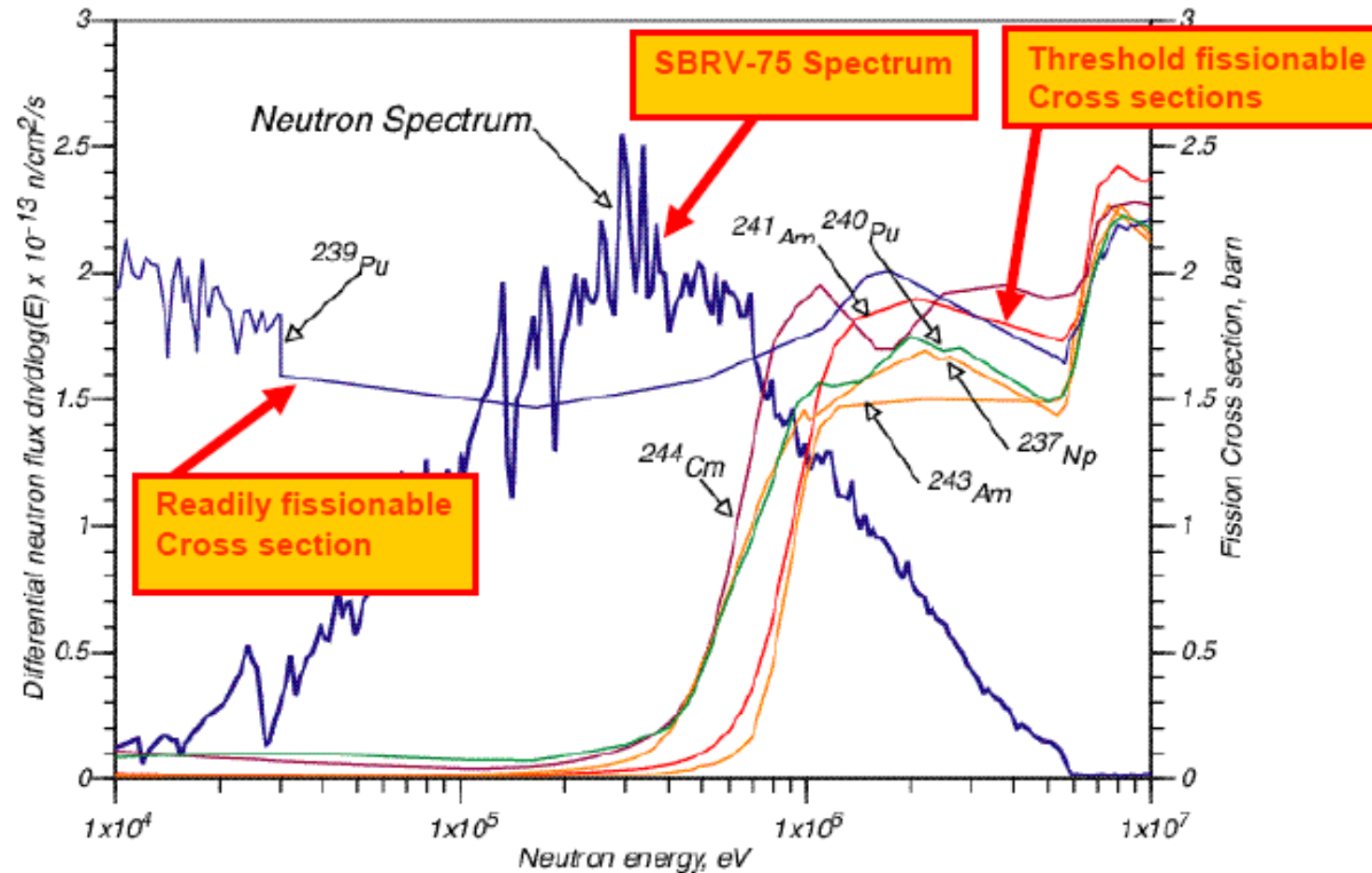
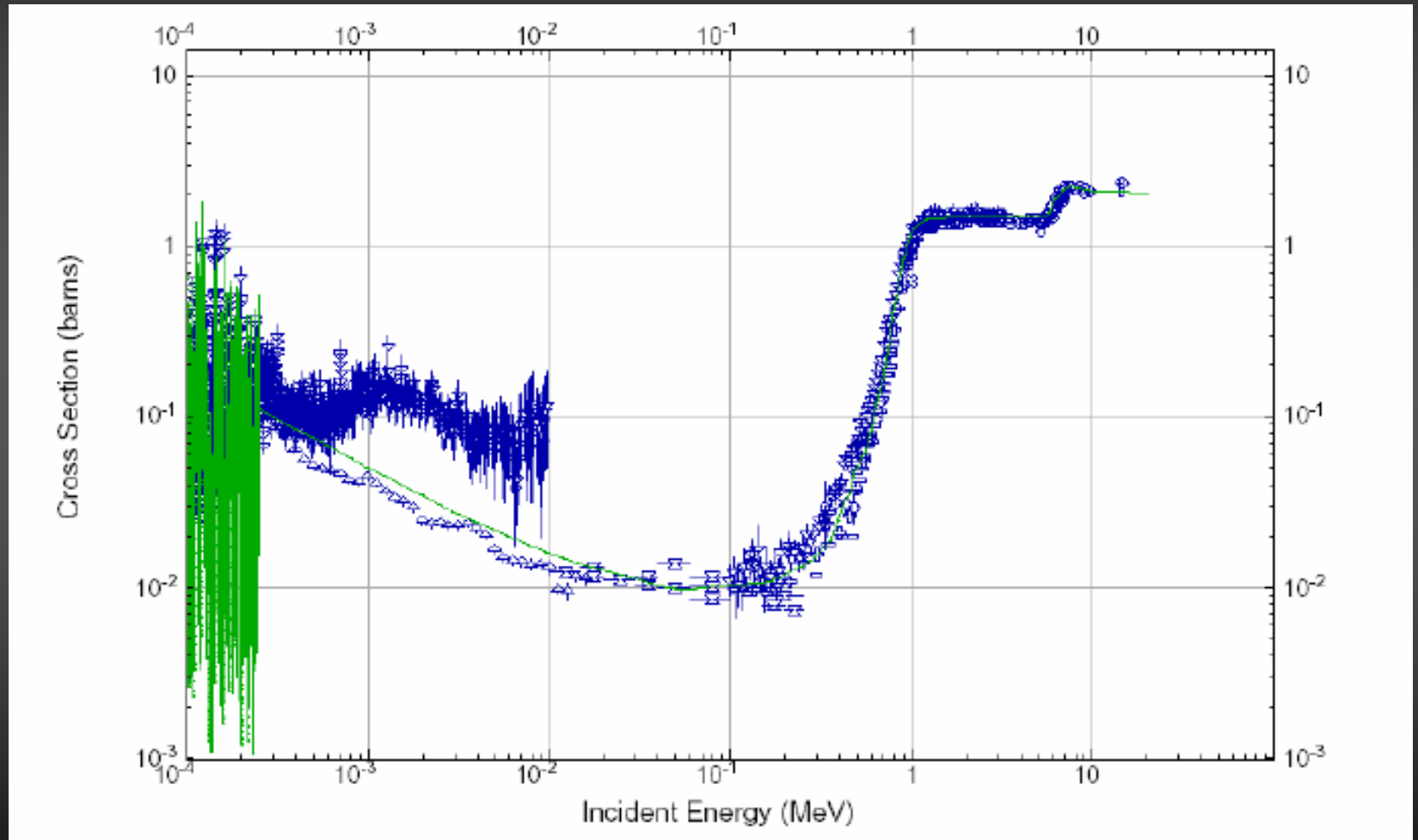


Figure 1: Simulation of the neutron spectrum in the SBRV-75 reactor [2], loaded with the Spiro MA fuel mixture (1/2 of ^{241}Am , 1/4 of ^{243}Am and 1/4 of equal amount of ^{244}Cm and ^{237}Np). The fission cross sections of several MA in consideration here are shown. The fission cross section of ^{239}Pu is also shown for a direct comparison with a non-threshold fission case.

Neutron cross sections data are needed!

$^{243}\text{Am}(n,f)$



source: n_TOF Collaboration
(fission proposal)

The n_TOF Collaboration

Neutron cross sections data are needed!

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

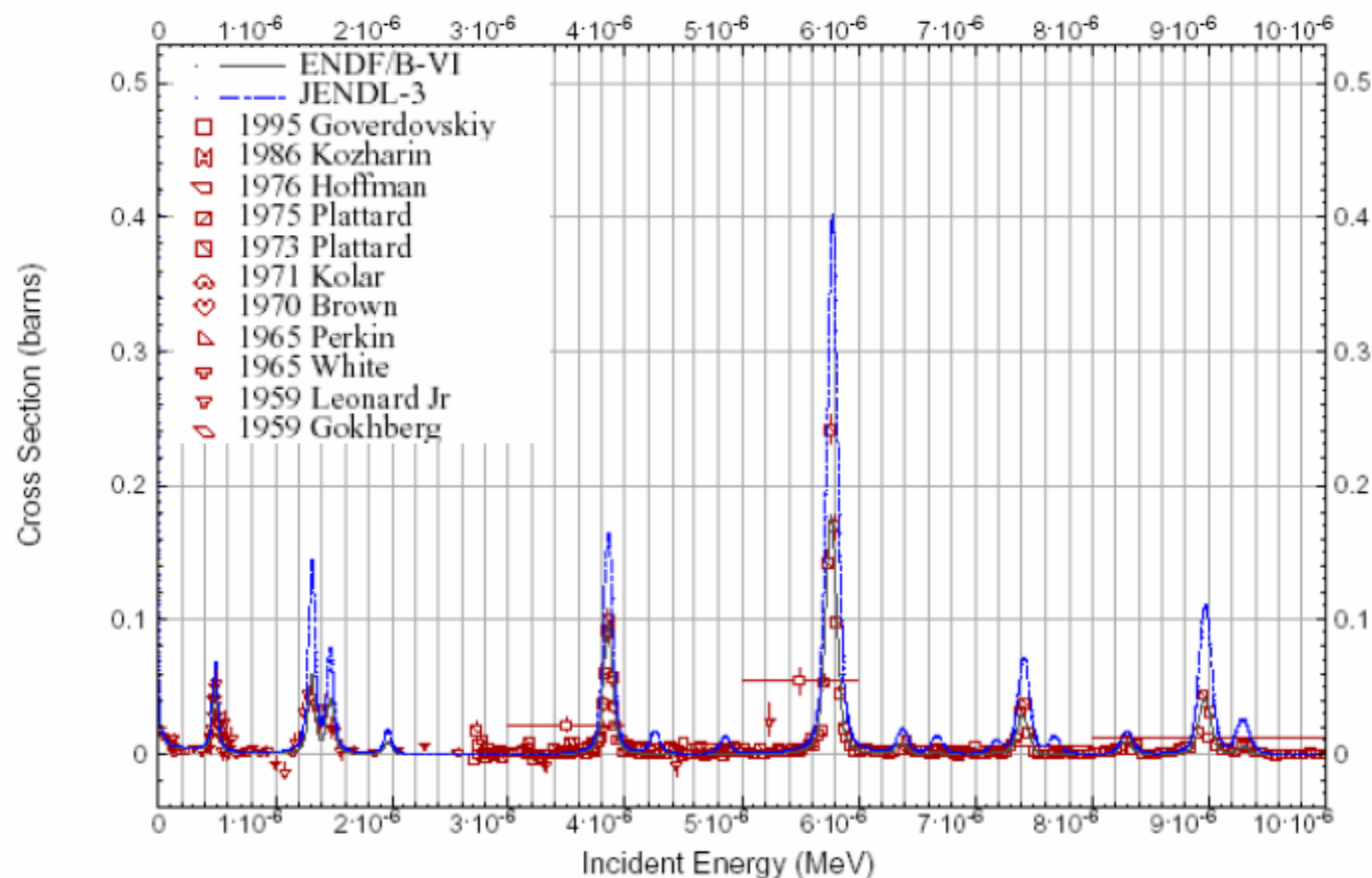
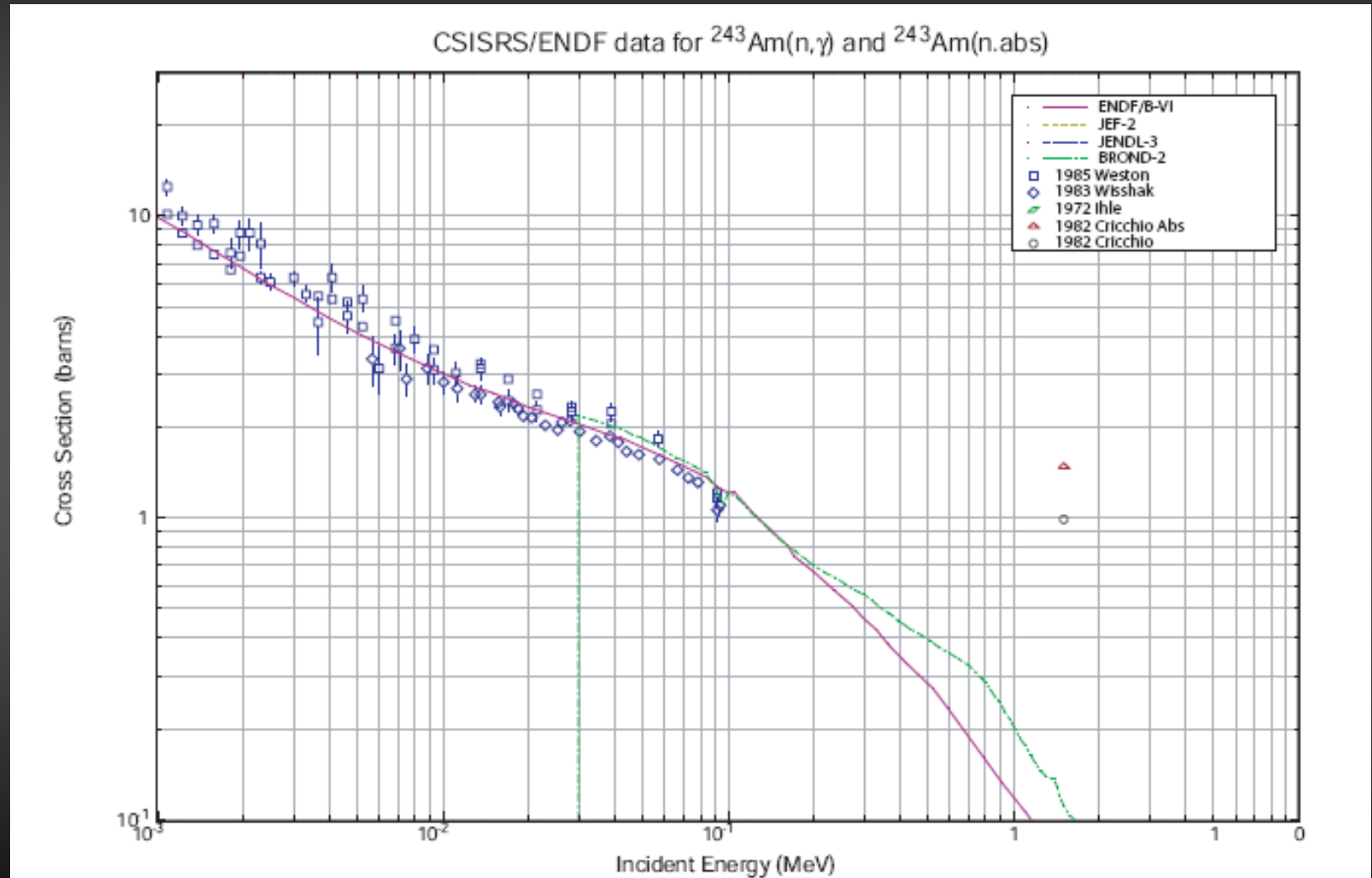


Figure A-1: fission cross section of ^{237}Np in the low energy region, $E_n \leq 10$ eV, well below the fission threshold.

Neutron cross sections data are needed!

$^{243}\text{Np}(n,\gamma)$

no data
in RRR



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	
	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 / 16 h	Am 243 7370 a	Am 244 26 m / 10,1 h	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 $2,411 \cdot 10^4$ a	Pu 240 6563 a	Pu 241 14,35 a	Pu 242 $3,750 \cdot 10^5$ a	Pu 243 4,956 h	Pu 244 $8,00 \cdot 10^7$ a
	Np 234 4,4 d	Np 235 396,1 d	Np 236 22,5 h / $1,54 \cdot 10^3$ a	Np 237 $2,144 \cdot 10^6$ a	Np 238 2,117 d	Np 239 2,355 d	Np 240 722 m / 65 m	Np 241 13,9 m	Np 242 2,2 m / 3,5 m	Np 243 1,85 m
	U 233 $1,592 \cdot 10^5$ a	U 234 0,0055	U 235 0,7200	U 236 120 ns / $2,342 \cdot 10^7$ 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 / 6,70 h	Pa 235 24,2 m	Pa 236 9,1 m	Pa 237 8,7 m	Pa 238 2,3 m		148	150
	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			

Objectives

- **M**easurements of **n**eutron cross sections relevant for Nuclear Waste Transmutation and related Nuclear Technologies
- **C**ross sections relevant for Nuclear Astrophysics
- **N**eutrons as probes for fundamental Nuclear Physics

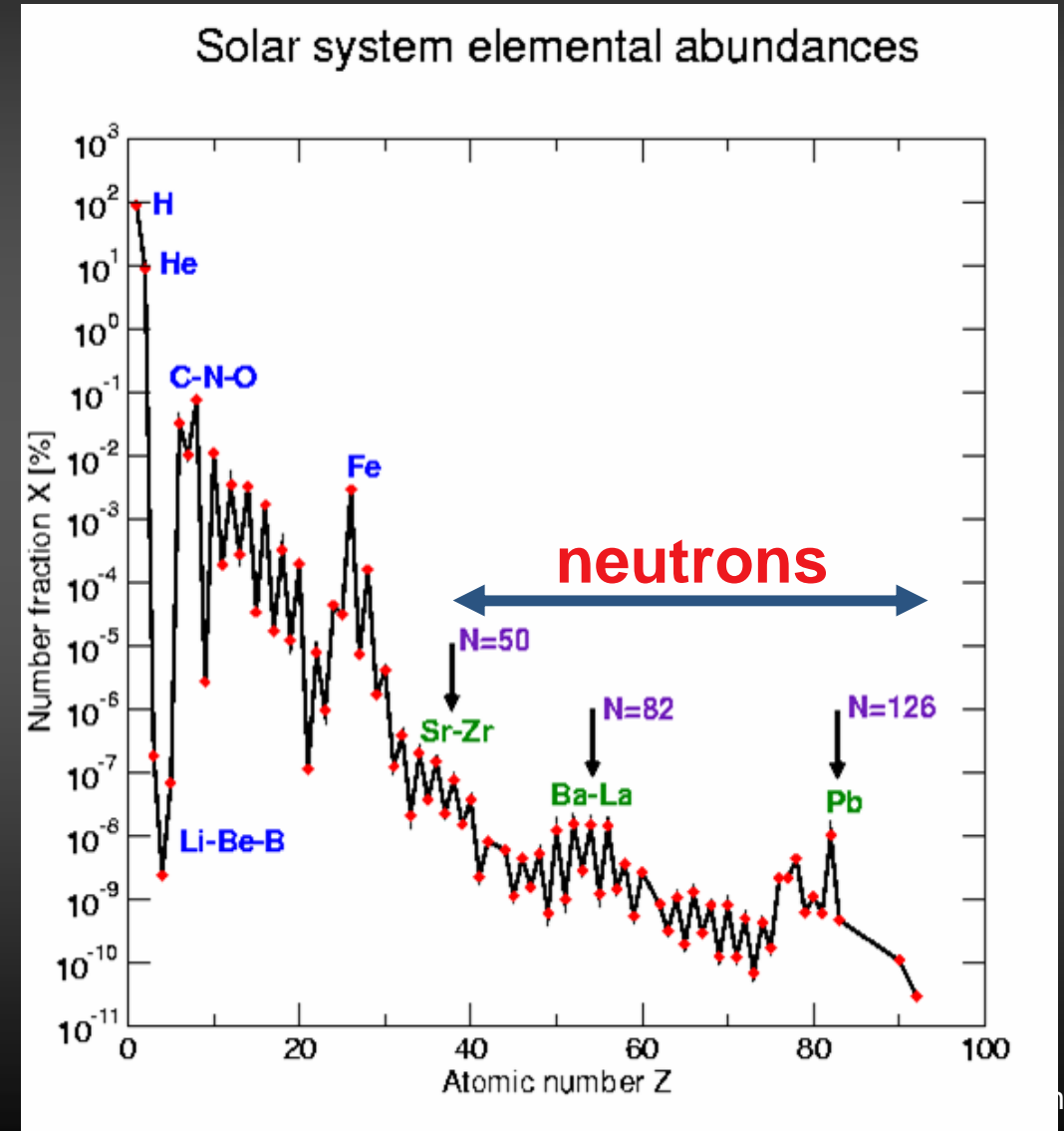
Nucleosynthesis: the s-process

- 1/2 of the elements above Fe are produced by the s-process
- The astrophysical sites of the s-process are:
 - He burning in intermediate/massive stars
 - Low-mass AGB's
- There exists a direct correlation between the neutron capture cross section and the abundance ($\sigma(n, \gamma) \cdot N = const.$)
- The neutron capture cross sections are key ingredients for s-process nucleosynthesis

The canonical s-process

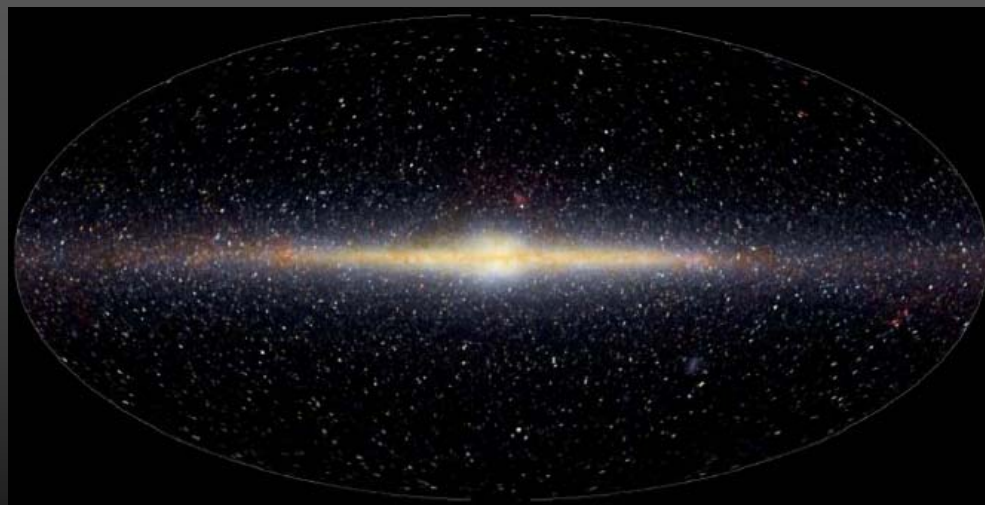
Cu			62Cu 9.74 m	63Cu 69.17	64Cu 12.7 h	
Ni		60Ni 26.123	61Ni 1.140	62Ni 3.634	63Ni 100 a	
Co		58Co 70.86 d	59Co 100	60Co 5.272 a	61Co 1.65 h	
Fe	56Fe 91.72	57Fe 2.2	58Fe 0.28	59Fe 44.503 d	60Fe 1.5 10 ⁶ a	61Fe 6 m

Yellow arrows indicate the s-process path: 56Fe → 57Fe → 58Fe → 59Fe → 60Fe → 61Fe → 60Co → 61Co → 60Ni → 61Ni → 62Ni → 63Ni → 62Cu → 63Cu → 64Cu.

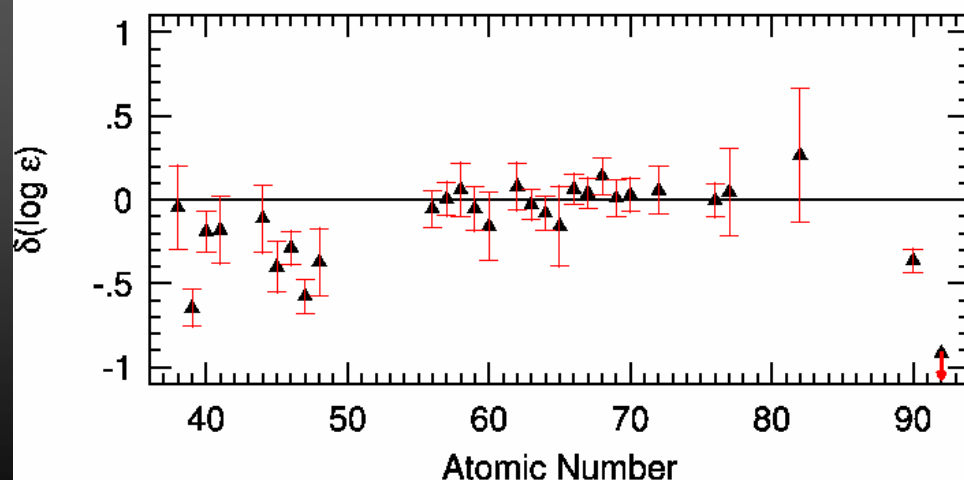
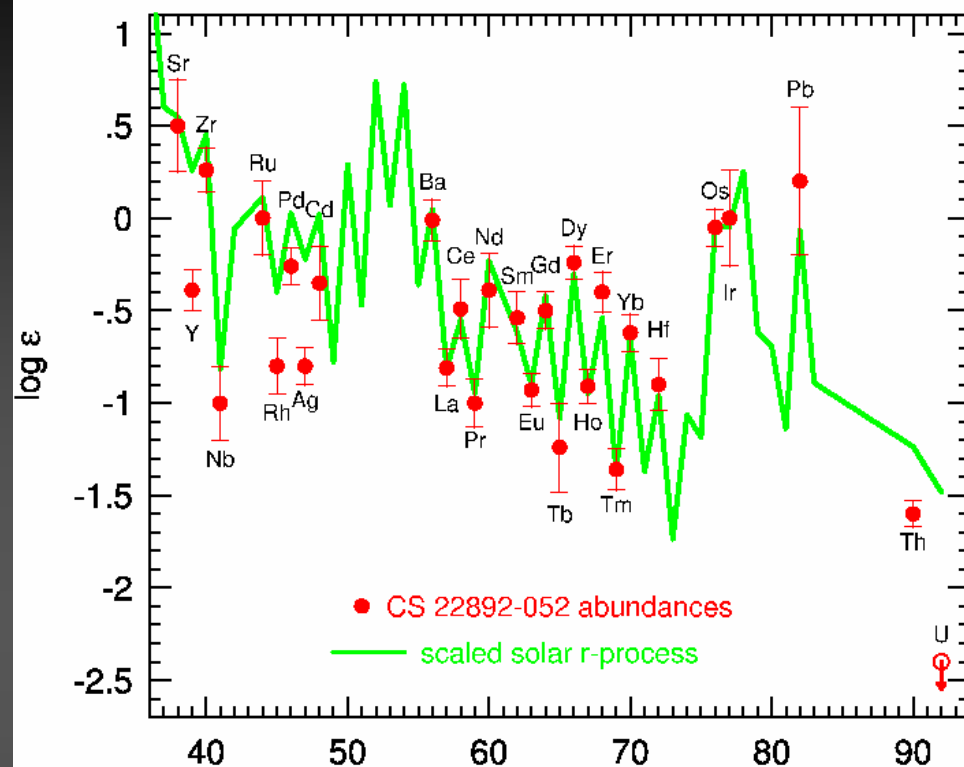


Nucleosynthesis: the s-process & the r-process residuals

$$N_r = N_{\text{solar}} - N_s$$



Neutron-Capture Abundances in CS 22892-052



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_TOF experiments 2002-4

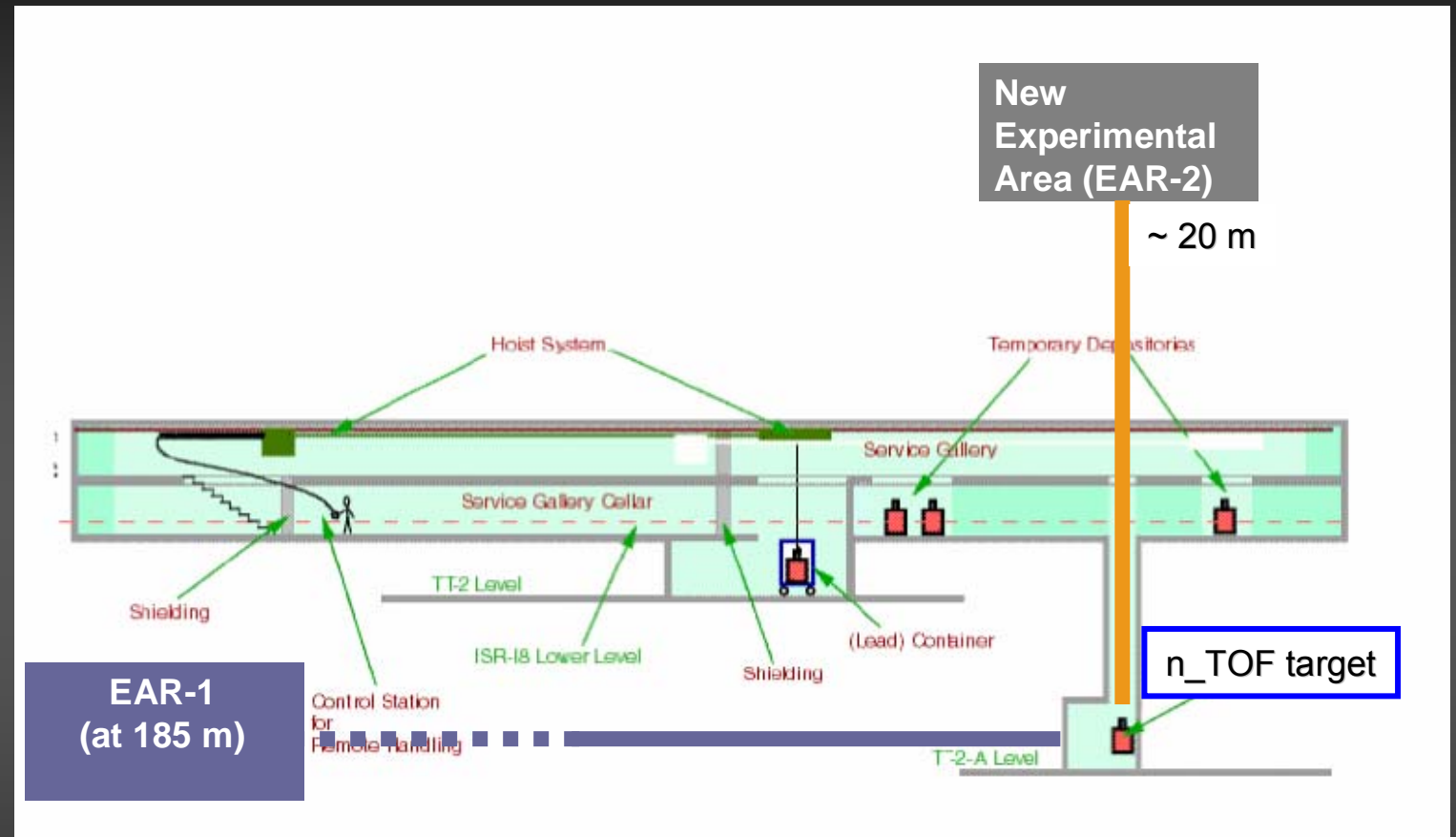
- **M**easurements of neutron cross sections relevant for Nuclear Waste Transmutation and related Nuclear Technologies
 - Th/U fuel cycle (capture & fission)
 - Transmutation of MA (capture & fission)
 - Transmutation of FP (capture)
- **C**ross sections relevant for Nuclear Astrophysics
 - s-process: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

The n_TOF Collaboration

U. Abbondanno¹⁴, G. Aerts⁷, H. Álvarez²⁴, F. Alvarez-Velarde²⁰, S. Andriamonje⁷, J. Andrzejewski³³, P. Assimakopoulos⁹, L. Audouin⁵, G. Badurek¹, P. Baumann⁶, F. Bečvář³¹, J. Benlliure²⁴, E. Berthoumieux⁷, F. Calviño²⁵, D. Cano-Ott²⁰, R. Capote²³, A. Carrillo de Albornoz³⁰, P. Cennini⁴, V. Chepell⁷, E. Chiaveri⁴, N. Colonna³, G. Cortes²⁵, D. Cortina²⁴, A. Couture²⁹, J. Cox²⁹, S. David⁵, R. Dolfini¹⁵, C. Domingo-Pardo²¹, W. Dridi⁷, I. Duran²⁴, M. Embid-Segura²⁰, L. Ferrant⁵, A. Ferrari⁴, R. Ferreira-Marques¹⁷, L. Fitzpatrick⁴, H. Fraiss-Koelbl³, K. Fujii¹³, W. Furman¹⁸, C. Guerrero²⁰, I. Goncalves³⁰, R. Gallino³⁶, E. Gonzalez-Romero²⁰, A. Goverdovski¹⁹, F. Gramegna¹², E. Griesmayer³, F. Gunsing⁷, B. Haas³², R. Haight²⁷, M. Heil⁸, A. Herrera-Martinez⁴, M. Igashira³⁷, S. Isaev⁵, E. Jericha¹, Y. Kadi⁴, F. Käppeler⁸, D. Karamanis⁹, D. Karadimos⁹, M. Kerveno⁶, V. Ketlerov¹⁹, P. Koehler²⁸, V. Konovalov¹⁸, E. Kossionides³⁹, M. Krtička³¹, C. Lamboudis¹⁰, H. Leeb¹, A. Lindote¹⁷, I. Lopes¹⁷, M. Lozano²³, S. Lukic⁶, J. Marganec³³, L. Marques³⁰, S. Marrone¹³, P. Mastinu¹², A. Mengoni⁴, P. M. Milazzo¹⁴, C. Moreau¹⁴, M. Mosconi⁸, F. Neves¹⁷, H. Oberhummer¹, S. O'Brien²⁹, M. Oshima³⁸, J. Pancin⁷, C. Papachristodoulou⁹, C. Papadopoulos⁴⁰, C. Paradela²⁴, N. Patronis⁹, A. Pavlik², P. Pavlopoulos³⁴, L. Perrot⁷, R. Plag⁸, A. Plompen¹⁶, A. Plukis⁷, A. Poch²⁵, C. Pretel²⁵, J. Quesada²³, T. Rauscher²⁶, R. Reifarh²⁷, M. Rosetti¹, C. Rubbia⁵, G. Rudolf⁶, P. Rullhusen¹⁶, J. Salgado³⁰, L. Sarchiapone⁴, C. Stephan⁵, G. Tagliente¹³, J. L. Tain²¹, L. Tassan-Got⁵, L. Tavora³⁰, R. Terlizzi¹³, G. Vannini³⁵, P. Vaz³⁰, A. Ventura¹¹, D. Villamarin²⁰, M. C. Vincente²⁰, V. Vlachoudis⁴, R. Vlastou⁴⁰, F. Voss⁸, H. Wendler⁴, M. Wiescher²⁹, K. Wisshak⁸

40 Research Institutions
120 researchers

The second n_TOF beam line & EAR-2



Flight-path length : ~20 m
at 90° respect to p-beam direction
expected neutron flux enhancement: ~ 100
drastic reduction of the t_0 flash

From measurements to data libraries

So, you see. That is how we usually do nuclear data experimental work.

Thank you. Now that we know how measurements are done, how can we produce evaluated data libraries?

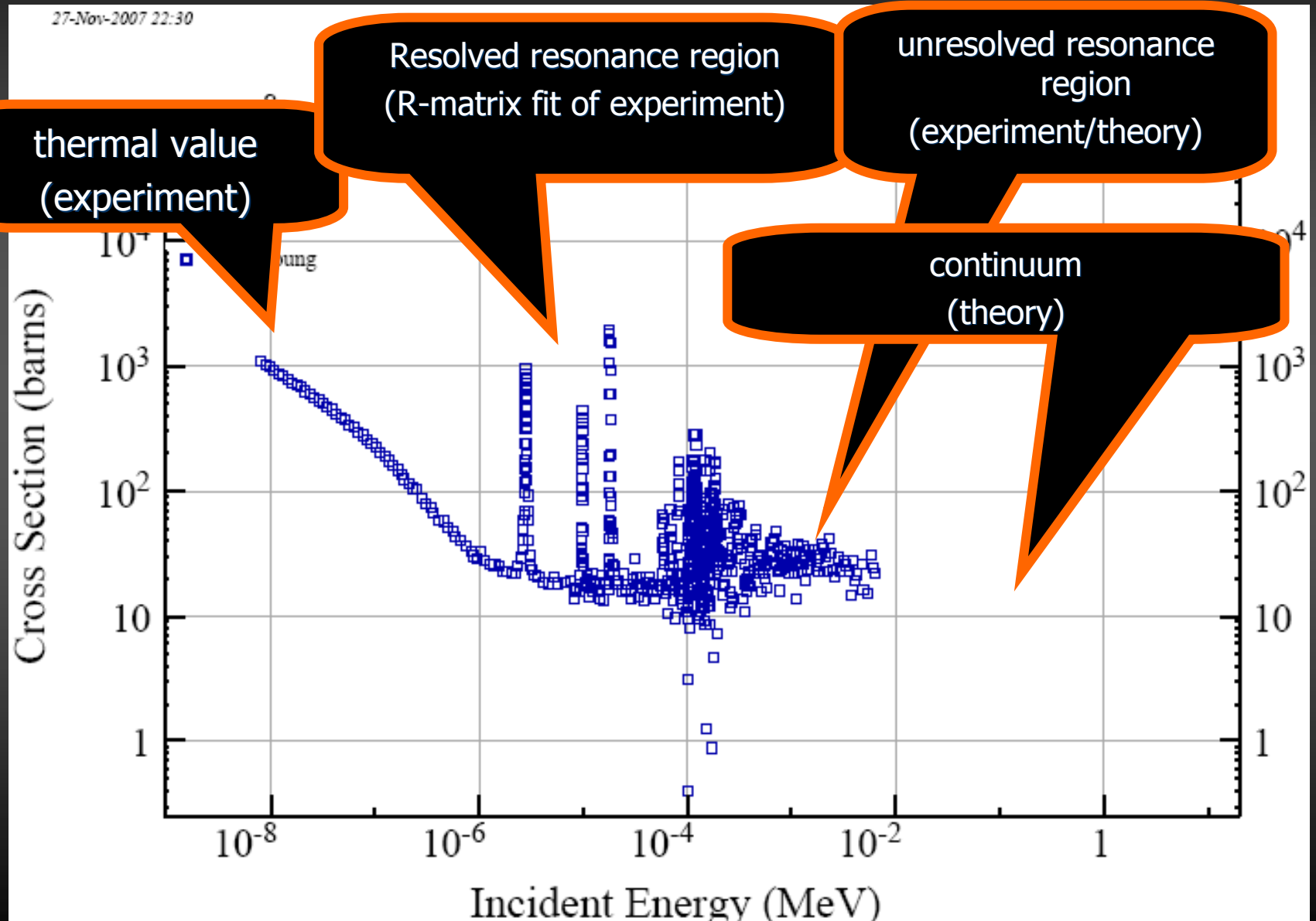


Evaluated Data Libraries

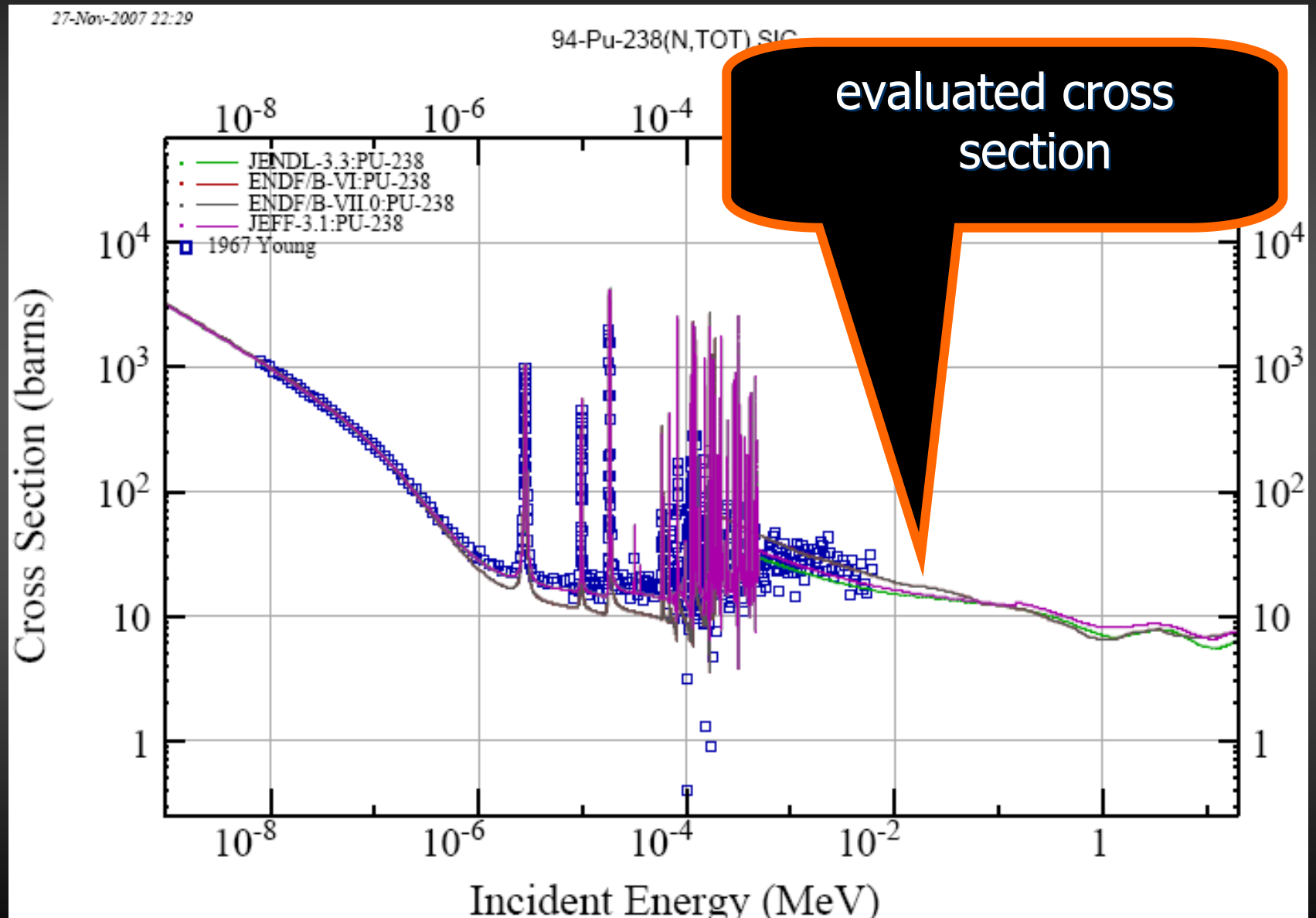
Evaluated data sets are produced through the process of critical comparison, selection renormalization and averaging of the available experimental data, normally complemented by nuclear model calculations.

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').

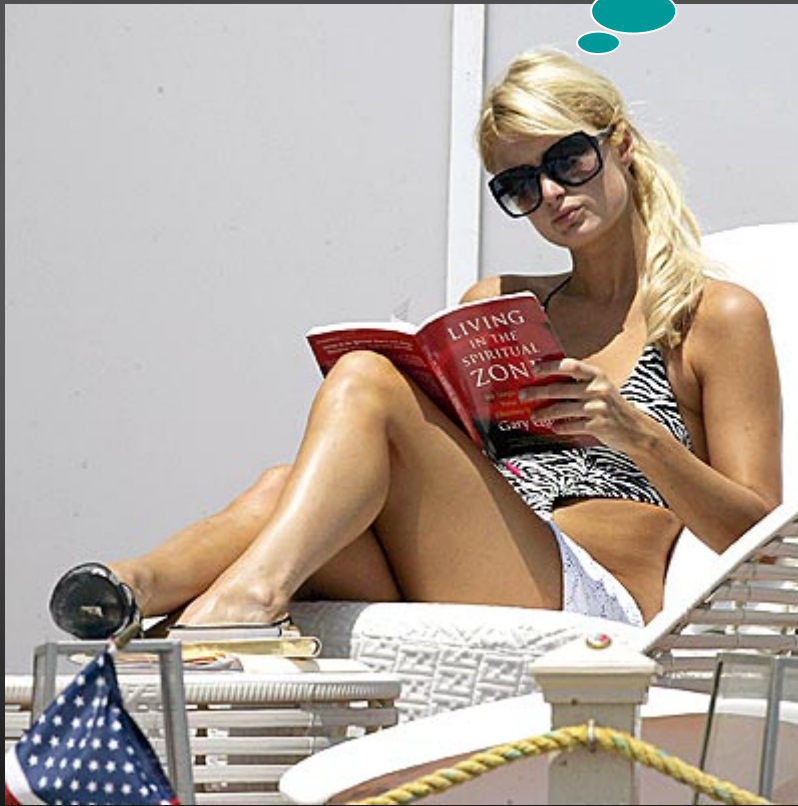
From experimental data...



... to evaluated Data Libraries



Uhhh... Interesting!
I wonder if I have to get
nuclear data from printed
stuff, or I ca get them
online...



Providing On-line Services: Retrieval and Display Tools

Example:

what is the capture cross section
of Zr-91 at $E_n = 30 \text{ keV}$?

Data Libraries

Mozilla Firefox

File Edit View History Bookmarks Tools Help

http://www-nds.iaea.org/

IAEA.org
International Atomic Energy Agency

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
- R1PL** - 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
- INDL/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 8 temperatures
- RNAL** - Reference Neutron Activation Library
- Standards** - Neutron Cross-section Standards 2006
- Th-U** - 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-0** - 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

Navigation

- Content Browser

Quick Links

- ADS-Lib
- AMDC
- CINDA
- DRÖSG-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
- R1PL
- RNAL
- Safeguards data
- SigmaCalc
- Standards
- Stopping Power Data
- Thermal Neutron Capture Gamma Rays
- Thorium-Uranium Fuel Cycle
- Wallet cards
- WIMS-D Library

NDS Mirror Sites

- India
- Brazil

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
- ICTP**
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

www-nds.iaea.org

Data Libraries

ENDF: Evaluated Nuclear Data File - Mozilla Firefox

File Edit View History Bookmarks Tools Help

http://www-nds.iaea.org/exfor/endf00.htm

Evaluated Nuclear Data File (ENDF)

Database Version of September 25, 2007

News

- 2007/04 New library: IBA-Eval
Differential charged-particle cross sections for ion beam analysis; [SigmaCalc] [IBANDL]
- 2007/03 Interactive Web plotting: zoom by mouse, actions by one click, more functions...
- 2007/02 New library:
1) IAEA-Standards, issued in 2006 [CRP-page]
- 2007/01 New library: ENDF/B-VII.0
ENDF/B-VII.0 US Evaluated Nuclear Data Library, released 2006/12 by NNDC [page]

[History]

Core nuclear reaction database contain recommended, evaluated cross sections, spectra, angular distributions, fission product yields, photo-atomic and thermal scattering law data, with emphasis on neutron induced reactions. The data were analyzed by experienced nuclear physicists to produce recommended libraries for one of the national nuclear data projects (USA, Europe, Japan, Russia and China). All data are stored in the internationally-adopted ENDF-B format maintained by CSEWG.

Standard Request (example); Go to: Advanced Request

Parameters:

Target

Reaction

Product

Quantity

[More Parameters...](#)

Libraries: All Selected Clean

Major Libraries Other Libraries

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

Options:

View: Basic Extended

Sort by: Reactions Evaluations

Clone Request:

Feedback:

Note:

- all criteria are optional (selected by checking)
- selected criteria are combined for search with logical AND
- criteria separated in a field by ";" are combined with logical OR
- wildcards and intervals are available
- pointwise libraries contain reconstructed resonances using parameters from MF=2 and applied Doppler broadening at a given temperature. They should be used for view and plot low energy cross sections.

Extensive temperature dependent pointwise libraries: [Point-2004 \(ENDFB-VI.8\)](#), [Point-2007 \(ENDFB-VII.0\)](#)

Database Manager: Viktor Zerkin, NDS, International Atomic Energy Agency (V.Zerkin@iaea.org)
Web and Database Programming: Viktor Zerkin, NDS, International Atomic Energy Agency (V.Zerkin@iaea.org)
Data Source: Nuclear Energy Agency International Working Party on Evaluation Cooperation (<http://www.nea.fr/html/science/wpec/>)
and Cross Section Evaluation Working Group (<http://www.nndc.bnl.gov/csewg/>)

Done

Data Libraries

ENDF: Evaluated Nuclear Data File - Mozilla Firefox

http://www-nds.iaea.org/exfor/endf00.htm

Evaluated Nuclear Data File (ENDF)

Database Version of September 25, 2007

News

- 2007/04 New library: IBA-Eval
Differential charged-particle cross sections for ion beam analysis; [SigmaCalc] [IBANDL]
- 2007/03 Interactive Web plotting: zoom by mouse, actions by one click, more functions...
- 2007/02 New library:
1) IAEA-Standards, issued in 2006 [CRP-page]
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ENDF/B-VII.0 US Evaluated Nuclear Data Library, released 2006/12 by NNDC [page]

[History]

Core nuclear reaction database contain recommended, evaluated cross sections, spectra, angular distributions, fission product yields, photo-atomic and thermal scattering law data, with emphasis on neutron induced reactions. The data were analyzed by experienced nuclear physicists to produce recommended libraries for one of the national nuclear data projects (USA, Europe, Japan, Russia and China). All data are stored in the internationally-adopted ENDF-B format maintained by CSEWG.

Standard Request (example); Go to: Advanced Request

Parameters:

Target Zr-91

Reaction N,G

Product

Quantity CS

[More Parameters...](#)

Libraries: All Selected Clean

Major Libraries Other Libraries

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

Options:

View: Basic Extended

Sort by: Reactions Evaluations

Clone Request:

Feedback:

Note:

- all criteria are optional (selected by checking)
- selected criteria are combined for search with logical AND
- criteria separated in a field by ";" are combined with logical OR
- wildcards and intervals are available
- pointwise libraries contain reconstructed resonances using parameters from MF=2 and applied Doppler broadening at a given temperature. They should be used for view and plot low energy cross sections.

Extensive temperature dependent pointwise libraries: [Point-2004 \(ENDFB-VI.8\)](#), [Point-2007 \(ENDFB-VII.0\)](#)

Database Manager: Viktor Zerkin, NDS, International Atomic Energy Agency (V.Zerkin@iaea.org)
Web and Database Programming: Viktor Zerkin, NDS, International Atomic Energy Agency (V.Zerkin@iaea.org)
Data Source: Nuclear Energy Agency International Working Party on Evaluation Cooperation (<http://www.nea.fr/html/science/wpec/>) and Cross Section Evaluation Working Group (<http://www.nndc.bnl.gov/csewg/>)

Done

Data Libraries

Request #806
ENDF Data Selection
Retrieve Retrieve+Plot Reset

Data Selection: Selected Unselected All
Plotting Mode: Sigma-Plot* (pointwise) MF3-Original Universal plot: DA,DE,DAE,SIG [test version]

Sorted by: [Reactions] Reorder by: [Libraries] View: basic extended

1) ZR-91 (N,G) ZR-92, SIG MT=102 MF=3 NSUB=10
MF3: [SIG] Cross sections MT102: [N,G] Radiative capture.

1	<input type="checkbox"/>	Sigma-tbl	Interpreted	Plot	JENDL-3.3	E=20MeV Lab=JNDC Date=20010810	JNDC FP NUCLEAR DATA W.G.
2	<input type="checkbox"/>	Sigma-tbl	Interpreted	Plot	JENDL-3.3	T=300K E=20MeV Lab=JNDC Date=20010810	JNDC FP NUCLEAR DATA W.G.
3	<input type="checkbox"/>	Sigma-tbl	Interpreted	Plot	ENDF/B-VI	E=20MeV Lab=SAI,BNL Date=20011108	M. DRAKE, D. SARGIS, T. MAUNG, P. ROSE
4	<input type="checkbox"/>	Sigma-tbl	Interpreted	Plot	ENDF/B-VI	T=300K E=20MeV Lab=SAI,BNL Date=20010826	M. DRAKE, D. SARGIS, T. MAUNG, P. ROSE
5	<input checked="" type="checkbox"/>	Sigma-tbl	Interpreted	Plot	ENDF/B-VII.0	E=20MeV Lab=JNDC,BNL Date=DIST-DEC06	JNDC FPND W.G., Mughabghab
6	<input type="checkbox"/>	Sigma-tbl	Interpreted	Plot	JEFF-2.2	Lab=NEA Date=920101	H. GRUPPELAAR, E. MENAPACK
7	<input type="checkbox"/>	Sigma-tbl	Interpreted	Plot	JEFF-3.0	E=20MeV Lab=JNDC Date=DIST-APR02	JNDC FP NUCLEAR DATA W.G.
8	<input type="checkbox"/>	Sigma-tbl	Interpreted	Plot	JEFF-3.1	E=20MeV Lab=JNDC Date=050504	JNDC FP NUCLEAR DATA W.G.
9	<input type="checkbox"/>	Sigma-tbl	Interpreted	Plot	JEFF-3.1/A	T=293K E=20MeV Lab=UKAEA Date=DIST-JUL03	Forrest, Kopecky, Sublet, Koning
10	<input type="checkbox"/>	Sigma-tbl	Interpreted	Plot	BROND-2.2	Lab=CJD+IATE Date=REV1-SEP9	GRUDZEVICH O.T. ET. AL.

[Glossary]: meaning of abbreviations and variables
[About]: a few words on ENDF-6 format

*Legend:
Plot-MF plotting the contents of the selected section of file 3. Quick, but not always correctly presents cross-sections in low energy region; use [Plot] option in order to compare data at the same conditions.
Plot cross section data (Sigma) with reconstructed resonances using parameters from MF=2 and applied Doppler broadening at the temperature =293°K (room temperature: 20°C)
UniPlot universal plot DA(MF4), DE(MF5), DAE(MF6), SIG(MF3+MF33) (room temperature: 20°C)

Page generated: 2007/10/09,13:05:16 by E4-Servlet on www.nds.iaea.org
Project: "Multi-platform EXFOR-CINDA-ENDF". V.Zeikin, IAEA, 1999-2007
Request from: pc32330.iaea.org (161.5.149.213)

Done

Data Libraries

E4/Servlet: Output - Mozilla Firefox

File Edit View History Bookmarks Tools Help

http://www-nds.iaea.org/exfor/servlet/E4sMakeE4

ENDF Request #806 (2)

Output Data

Format	Data (Size)
ENDF	Text (31Kb) ZIP (8Kb)

Cross Section

Note: The data shown on this plot were converted to the pointwise presentation (T=293K).

ENDF Request 806, 2007-Oct-09, 13:05:59

EXFOR Find and add to the plot experimental data

1) ENDF/B-VII.0: ZR-91(N,G)ZR-92

See: plotted data (556Kb)

Use My Data (example)

Columns: x y [dy [x]]

Type: Curve Points

Title: My Data

Multiply by: X: [1] Y: [1]

Log: XY X Y Lin: XY X Y Auto-range: XY X Y Page: >> << Zoom: <> >> Grid: YH 0 0 V H Pts: Txt Box PL Print

Reset Repaint Legend Authors Manual plotting options: [+]

Data for plotting: ZVD (536Kb), send to ZVView; download ZVView

Note: Zoom and other interactive plotting features were tested under Web-browsers: MS-Internet Explorer 5.5, Firefox 2.0, Safari, Opera 9.1, Netscape v-7.2

Page generated: 2007/10/09, 13:05:00 by E4-Servlet on www-nds.iaea.org
Project: "Multi-platform EXFOR-CINDA-ENDF", V.ZeKin, IAEA, 1999-2007
Request from: pc32330.iaea.org (161.5.149.213)

Done

Data Libraries

^{91}Zr capture cross section
at $E_n = 30$ keV:
61.8 mb

www-nds.iaea.org

E4/Servlet: getSectionSummary - Mozilla Firefox
http://www-nds.iaea.org/exfor/servlet/E4sGetTabSect?SectID=217401&req=806&PenSectID=20753

E4/Servlet: getSectionSummary X4/Servlet: Select

```
#LIBRARY      ENDF/B-VII.0
#REACTION    ZR-91 (N, G) ZR-92, SIG
#NUCLEUS     Zr-91
#MF          3
#MT          102
#EN-MIN      1e-05
#EN-MAX      2e+07
#E, eV       Sig, b      Interpolation
1E-05        41.8697      Lin-Lin
1.08624E-05  40.1732      Lin-Lin
1.17903E-05  38.56        Lin-Lin
1.28071E-05  36.9977      Lin-Lin
1.39012E-05  35.5119      Lin-Lin
1.51E-05     34.0731      Lin-Lin
1.639E-05    32.7048      Lin-Lin
1.78034E-05  31.3797      Lin-Lin
1.93243E-05  30.1195      Lin-Lin
2.09909E-05  28.8991      Lin-Lin
2.2784E-05   27.7386      Lin-Lin
2.47489E-05  26.6147      Lin-Lin
2.6863E-05   25.546       Lin-Lin
2.91798E-05  24.5109      Lin-Lin
3.16724E-05  23.5266      Lin-Lin
3.44039E-05  22.5733      Lin-Lin
3.73428E-05  21.6669      Lin-Lin
4.05633E-05  20.789       Lin-Lin
4.40284E-05  19.9542      Lin-Lin
4.78255E-05  19.1456      Lin-Lin
5.19109E-05  18.3768      Lin-Lin
5.63878E-05  17.6322      Lin-Lin
6.12047E-05  16.9242      Lin-Lin
6.64831E-05  16.2384      Lin-Lin
7.21623E-05  15.5864      Lin-Lin
7.83857E-05  14.9548      Lin-Lin
8.50817E-05  14.3543      Lin-Lin
9.24194E-05  13.7727      Lin-Lin
0.000100314  13.2196      Lin-Lin
0.000108965  12.684       Lin-Lin
0.000118274  12.1746      Lin-Lin
0.000128474  11.6813      Lin-Lin
0.000139449  11.2122      Lin-Lin
0.000151475  10.7579      Lin-Lin
0.000164414  10.3259      Lin-Lin
0.000178594  9.90755      Lin-Lin
0.00019385   9.50971      Lin-Lin
0.000210568  9.12438      Lin-Lin
0.000228555  8.75798      Lin-Lin
0.000248267  8.40312      Lin-Lin
0.000269474  8.06568      Lin-Lin
0.000292714  7.73888      Lin-Lin
0.000317719  7.4281       Lin-Lin
0.00034512   7.12713      Lin-Lin
0.000374601  6.84093      Lin-Lin
0.000406908  6.56375      Lin-Lin
0.000441667  6.30017      Lin-Lin
0.000479757  6.0449       Lin-Lin
0.00052074   5.80215      Lin-Lin
0.00056565   5.56706      Lin-Lin
0.00061397   5.3435       Lin-Lin
0.00066692   5.12699      Lin-Lin
```

Section: Summary Original data

Tabulated Data:

Points: 20285

Energy (eV)		
Min	Max	Reset
1e-05	2e+07	
From	To	Get data:
1e-05	2e+07	Submit

Calculation of Cross Section for a Single Energy:

Energy (eV) = 30e+3

Cross Section (b) = 0.0617753

Calculate!

Data Libraries

How about experimental data?

E4/Servlet: Output - Mozilla Firefox

http://www-nds.iaea.org/exfor/servlet/E4sMakeE4

ENDF Request #806 (2)

Output Data

Format	Data (Size)
ENDF	Text (31Kb) ZIP (8Kb)

Cross Section

Note: The data shown on this plot were converted to the pointwise presentation (T=293K).

ENDF Request 806, 2007-Oct-09, 13:05:59

EXFOR Find and add to the plot experimental data

1) ENDF/B-VII.0: ZR-91(N,G)ZR-92

See: plotted data (556Kb)

Use My Data [example]

Columns: x y [dx,j]

Type: Curve Points

Title: My Data

Multiply by: X: [1] Y: [1]

Log: XY X Y Lin: XY X Y Auto-range: XY X Y Page: >> << Zoom: <> >> Grid: YH 0 0 H Pts: Txt Box PL Print

Reset Repaint Legend Authors Manual plotting options: [+]

Data for plotting: ZVD (536Kb), send to ZVView; download ZVView

Note: Zoom and other interactive plotting features were tested under Web-browsers: MS-Internet Explorer 5.5, Firefox 2.0, Safari, Opera 9.1, Netscape v-7.2

Page generated: 2007/10/09, 13:05:00 by E4-Servlet on www-nds.iaea.org
Project: "Multi-platform EXFOR-CINDA-ENDF", V.ZeKin, IAEA, 1999-2007
Request from: pc32330.iaea.org (161.5.149.213)

Done

Data Libraries

X4/Servlet: Select - Mozilla Firefox

http://www-nds.iaea.org/exfor/Servlet/X4sMakeX4

E4/Servlet: Output X4/Servlet: Select

EXFOR Request #2459/1 (following ENDF Request #806)

Output Data

Format	Data (Size)
EXFOR	Text (32Kb) ZIP (8Kb)
Bibliography	html (7Kb) BibTeX (3Kb)

ENDF Request 806, 2007-Oct-09,13:05:59
EXFOR Request: 2459/1, 2007-Oct-09 13:07:39

Legend:

- ENDF/B-VII.0: ZR-91(N,G)ZR-92
- 2007 Nakamura
- 2005 Ohgama
- 1977 Del
- 1965 Kapchigashev
- 1963 Macklin

1) 40-ZR-91(N,G)40-ZR-92,,SIG
 2) ENDF/B-VII.0: ZR-91(N,G)ZR-92

See: plotted data (563Kb)

Use My Data [example]
Columns: x y [y [dx]]

Type: Curve Points
Title: My Data
Multiply by: X:1 Y:1

Log: XY | X | Y | Lin: XY | X | Y | Auto-range: XY | X | Y | Page: >> << Zoom: <> >> Grid: V|H | 0 | V | H | Pts: Txt | Box | PL | Print

Reset | Repaint | Legend | Authors Manual plotting options:[+]

Data for plotting: ZVD (544Kb), send to ZVView; download ZVView

Note. Zoom and other interactive plotting features were tested under Web-browsers:
MS-Internet Explorer 5.5, Firefox 2.0, Safari, Opera 9.1, Netscape v-7.2

Page generated: 2007/10/09,13:07:40 by X4-Servlet on www-nds.iaea.org
Project: "Multi-platform EXFOR-CINDA-ENDF", V.Zeklin, IAEA, 1999-2007
Request from: pc32330.iaea.org (161.5.149.213)

Done

Data Libraries

two experimental values:

59 ± 1 mb

67.6 ± 3.5 mb

weighted average:

$\sigma = 61.0 \pm 1.6$ mb

value from evaluated library:

$\sigma = 61.8$ mb

experimental data
from EXFOR

EXFOR/CSIRS: Experimental Nuclear ... X4/Servlet: Select http://www-nds.i..._x4.zvd.dat.txt

0.00041	0	0.6	0	# 1965, S. P. Kapchigashev	## 40034003
0.00045	0	0.475	0.07125	# 1965, S. P. Kapchigashev	## 40034003
0.0005	0	0.39	0.0585	# 1965, S. P. Kapchigashev	## 40034003
0.00057	0	0.38	0.057	# 1965, S. P. Kapchigashev	## 40034003
0.00061	0	0.49	0.0735	# 1965, S. P. Kapchigashev	## 40034003
0.0007	0	0.55	0.0825	# 1965, S. P. Kapchigashev	## 40034003
0.00078	0	0.55	0.0825	# 1965, S. P. Kapchigashev	## 40034003
0.0008	0	0.5	0.075	# 1965, S. P. Kapchigashev	## 40034003
0.0009	0	0.415	0.06225	# 1965, S. P. Kapchigashev	## 40034003
0.00095	0	0.33	0.0495	# 1965, S. P. Kapchigashev	## 40034003
0.00105	0	0.27	0.0405	# 1965, S. P. Kapchigashev	## 40034003
0.0011	0	0.235	0.03525	# 1965, S. P. Kapchigashev	## 40034003
0.00125	0	0.18	0.027	# 1965, S. P. Kapchigashev	## 40034003
0.0014	0	0.24	0.036	# 1965, S. P. Kapchigashev	## 40034003
0.0016	0	0.36	0.054	# 1965, S. P. Kapchigashev	## 40034003
0.0018	0	0.41	0.0615	# 1965, S. P. Kapchigashev	## 40034003
0.0019	0	0.47	0.0705	# 1965, S. P. Kapchigashev	## 40034003
0.00225	0	0.47	0.0705	# 1965, S. P. Kapchigashev	## 40034003
0.0026	0	0.405	0.06075	# 1965, S. P. Kapchigashev	## 40034003
0.003	0	0.38	0.057	# 1965, S. P. Kapchigashev	## 40034003
0.0034	0	0.35	0.0525	# 1965, S. P. Kapchigashev	## 40034003
0.0035	0.0005	0.287	0.014	# 1977, A. R. Del+	## 30423005
0.004	0	0.33	0.0495	# 1965, S. P. Kapchigashev	## 40034003
0.0045	0.0005	0.391	0.02	# 1977, A. R. Del+	## 30423005
0.0045	0	0.32	0.048	# 1965, S. P. Kapchigashev	## 40034003
0.0051	0	0.28	0.042	# 1965, S. P. Kapchigashev	## 40034003
0.0055	0.0005	0.137	0.007	# 1977, A. R. Del+	## 30423005
0.0062	0	0.252	0.0378	# 1965, S. P. Kapchigashev	## 40034003
0.007	0.001	0.218	0.011	# 1977, A. R. Del+	## 30423005
0.0074	0	0.25	0.0375	# 1965, S. P. Kapchigashev	## 40034003
0.0085	0	0.21	0.0315	# 1965, S. P. Kapchigashev	## 40034003
0.009	0.001	0.156	0.008	# 1977, A. R. Del+	## 30423005
0.01	0	0.165	0.033	# 1965, S. P. Kapchigashev	## 40034003
0.012	0	0.155	0.031	# 1965, S. P. Kapchigashev	## 40034003
0.0125	0.0025	0.14	0.01	# 1977, A. R. Del+	## 30423005
0.016	0	0.135	0.027	# 1965, S. P. Kapchigashev	## 40034003
0.0175	0.0025	0.072	0.005	# 1977, A. R. Del+	## 30423005
0.02	0.005	0.095	0.0053	# 1920, K. Ohgama+	## 22897002
0.02	0	0.105	0.021	# 1965, S. P. Kapchigashev	## 40034003
0.024	0	0.09	0.018	# 1965, S. P. Kapchigashev	## 40034003
0.025	0.005	0.064	0.005	# 1977, A. R. Del+	## 30423005
0.03	0	0.059	0.01	# 1963, R. L. Macklin+	## 11845003
0.03	0.005	0.0676	0.0035	# 1920, K. Ohgama+	## 22897002
0.031	0	0.087	0.011	# 1965, S. P. Kapchigashev	## 40034003
0.035	0.005	0.055	0.007	# 1977, A. R. Del+	## 30423005
0.039	0	0.055	0.011	# 1965, S. P. Kapchigashev	## 40034003
0.045	0.01	0.0437	0.0022	# 1920, K. Ohgama+	## 22897002
0.045	0.005	0.04	0.006	# 1977, A. R. Del+	## 30423005
0.045	0	0.053	0	# 1965, S. P. Kapchigashev	## 40034003
0.055	0.005	0.036	0.006	# 1977, A. R. Del+	## 30423005
0.056	0	0.033	0.0066	# 1965, S. P. Kapchigashev	## 40034003
0.07	0.01	0.028	0.005	# 1977, A. R. Del+	## 30423005
0.0775	0.0225	0.0323	0.0016	# 1920, K. Ohgama+	## 22897002
0.09	0.01	0.026	0.005	# 1977, A. R. Del+	## 30423005
0.125	0.025	0.022	0.005	# 1977, A. R. Del+	## 30423005
0.175	0.025	0.017	0.005	# 1977, A. R. Del+	## 30423005

//
#-----

#name: ENDF/B-VII.0: ZR-91 (N, G) ZR-92
#X.axis: Incident Energy
Done

Data Libraries



Uhhh...

$\sigma = 61.0 \pm 1.6 \text{ mb}$ at 30 keV

In perfect agreement with my
own evaluation!

Data Libraries

Other major 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}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



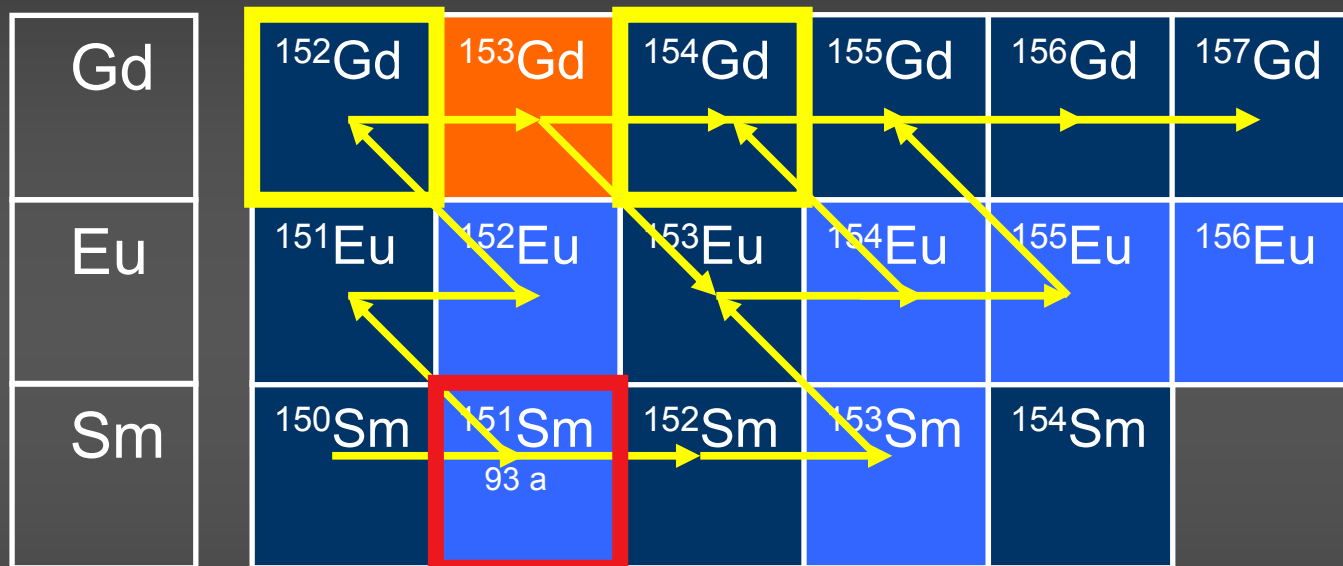
n_TOF experiments

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)



- $T_8 > 4$ using the “classical” s-process model
- from AGB modeling: 71% of ^{152}Gd

Present main uncertainty: $\lambda_\beta(T)$ of ^{151}Sm

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

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

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

Fission

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

^{232}Th

^{209}Bi

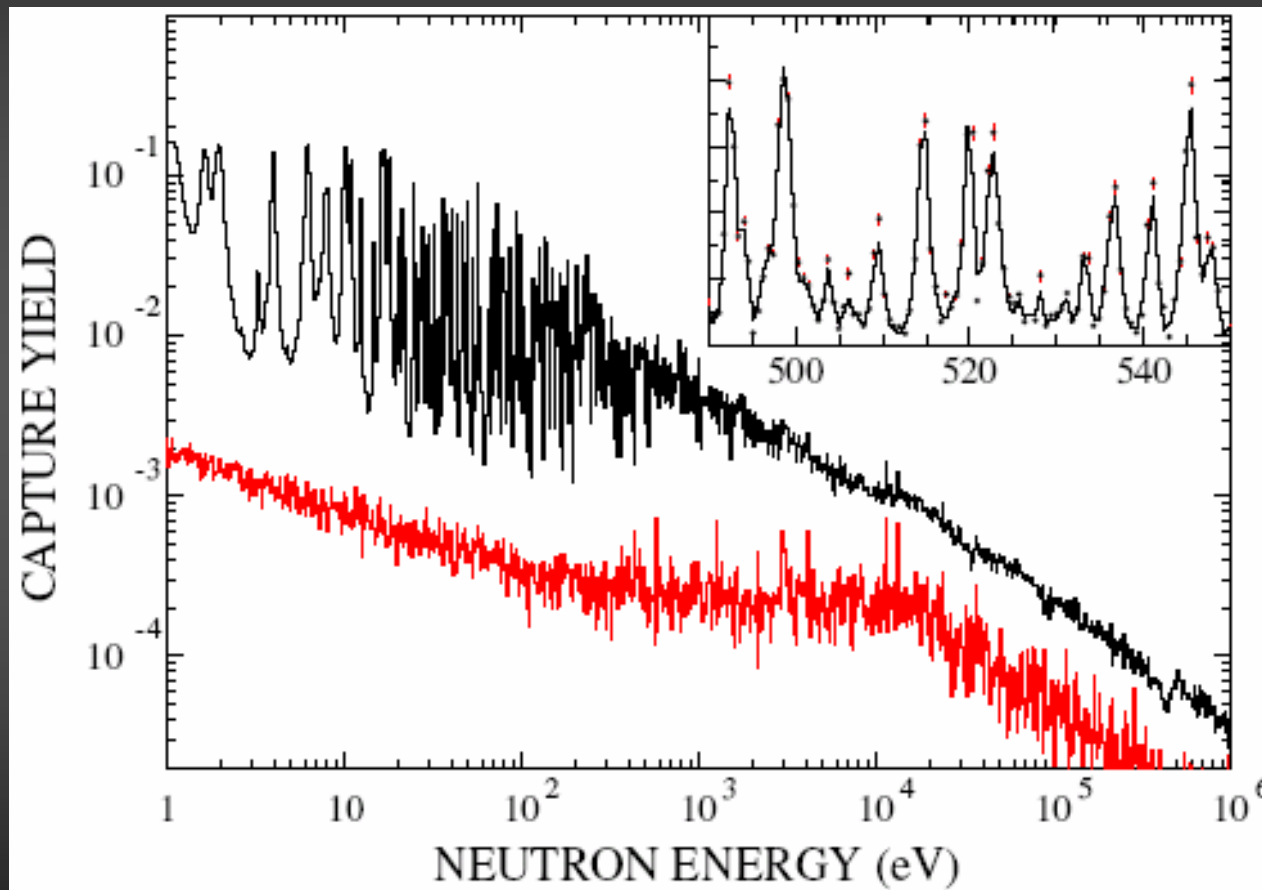
^{237}Np

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



n_TOF experiments

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



the 1st measurement at n_TOF

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

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^{232}Th

^{209}Bi

^{237}Np

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

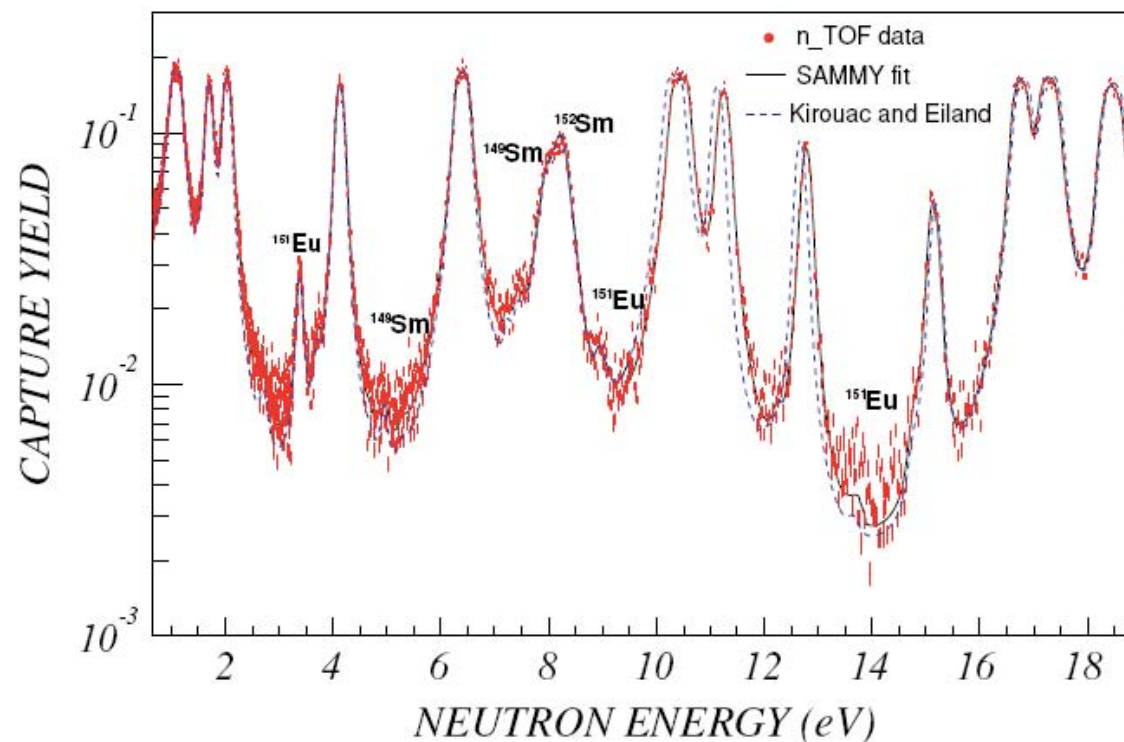


n_TOF experiments

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

&

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Phys. Rev. C **73** 03604 (2006)



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

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

Fission

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

^{232}Th

^{209}Bi

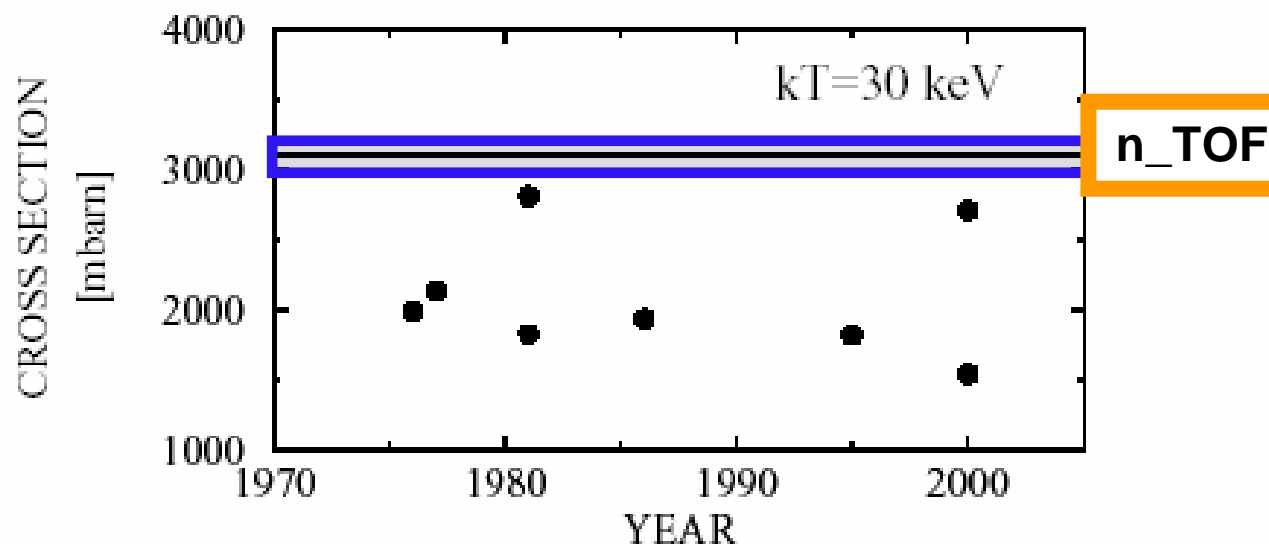
^{237}Np

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



n_TOF experiments

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)



$$\begin{aligned}\langle D_0 \rangle &= 1.49 \pm 0.07 \text{ eV} \\ S_0 &= (3.87 \pm 0.33) \times 10^{-4} \\ R_1 &= 3575 \pm 210 \text{ b}\end{aligned}$$

Capture

¹⁵¹Sm

^{204,206,207,208}Pb, ²⁰⁹Bi

²³²Th

^{24,25,26}Mg

^{90,91,92,94,96}Zr, ⁹³Zr

¹³⁹La

^{186,187,188}Os

^{233,234}U

²³⁷Np, ²⁴⁰Pu, ²⁴³Am

Fission

^{233,234,235,236,238}U

²³²Th

²⁰⁹Bi

²³⁷Np

^{241,243}Am, ²⁴⁵Cm



n_TOF experiments

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

for nuclear data
evaluators:
all infos available in
refereed journal
publications
&
on the n_TOF website
www.cern.ch/ntof

TABLE IX. The ¹⁵¹Sm(*n*, γ) cross section in the unresolved resonance region from 1 keV to 1 MeV.

Energy bin (keV)	$\sigma_{(n,\gamma)}$ (b)	Uncertainty (%)		
		Stat.	Syst.	Tot.
1–1.2	24.52	0.8	4.4	4.5
1.2–1.5	23.68	0.8	4.3	4.4
1.5–1.75	21.94	1.0	4.2	4.3
1.75–2	19.76	1.2	4.2	4.3
2–2.5	15.43	1.1	4.1	4.3
2.5–3	15.36	1.3	4.1	4.3
3–4	12.78	1.2	4.1	4.3
4–5	10.04	1.4	4.1	4.3
5–7.5	8.91	2.1	2.9	3.6
7.5–10	5.85	3.0	3.1	4.3
10–12.5	5.38	3.9	2.9	4.8
12.5–15	4.26	4.9	3.2	5.8
15–20	3.82	3.8	3.2	4.9
20–25	3.52	4.6	3.5	5.8
25–30	3.13	4.5	3.1	5.5
30–40	2.69	4.4	3.2	5.5
40–50	2.17	4.8	3.4	5.9
50–60	1.90	5.2	3.3	6.2
60–80	1.66	4.1	3.6	5.5
80–100	1.30	5.1	4.6	6.9

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_TOF experiments

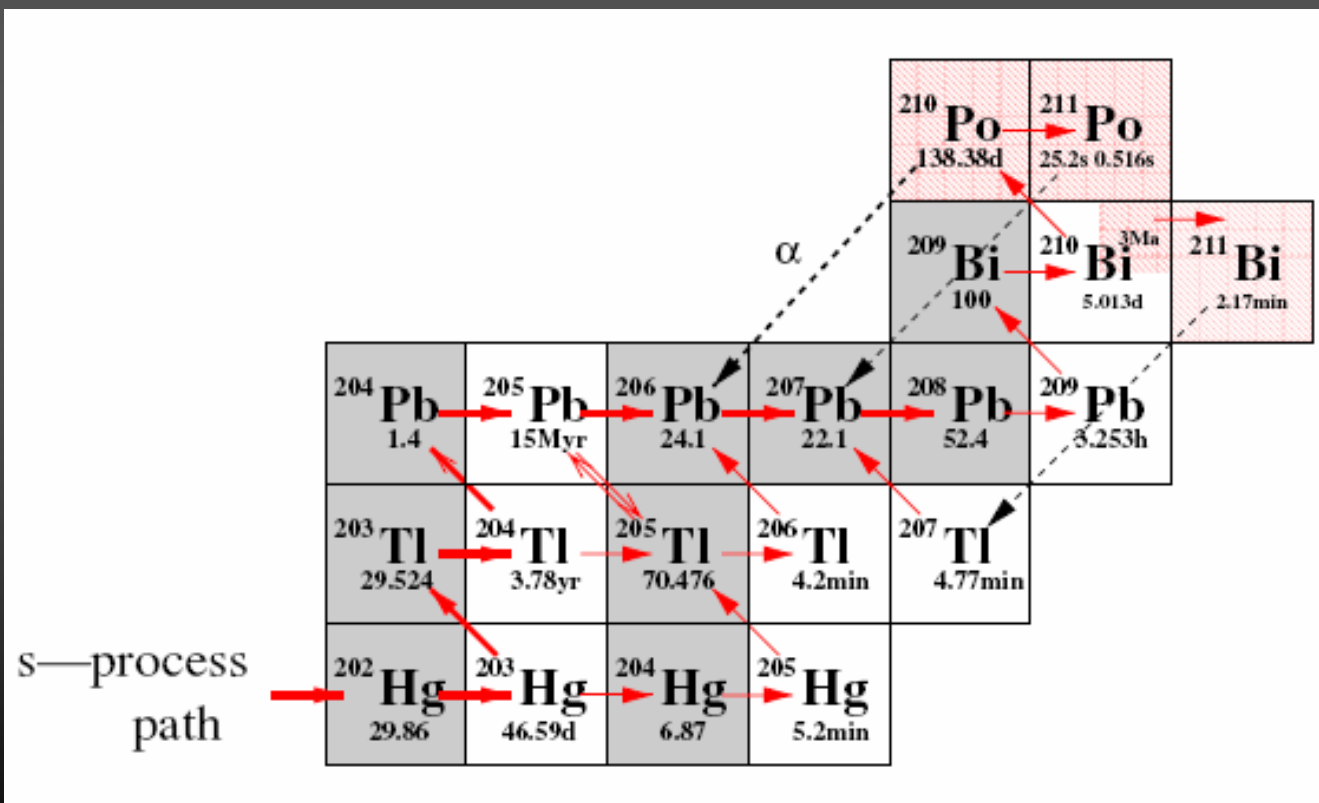
Pb & Bi

at the termination point of the s-process

Pb-204: s-only

Pb-206: s-, r-, and U-238 decay

Pb-207: s-, r-, and U-235 decay



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

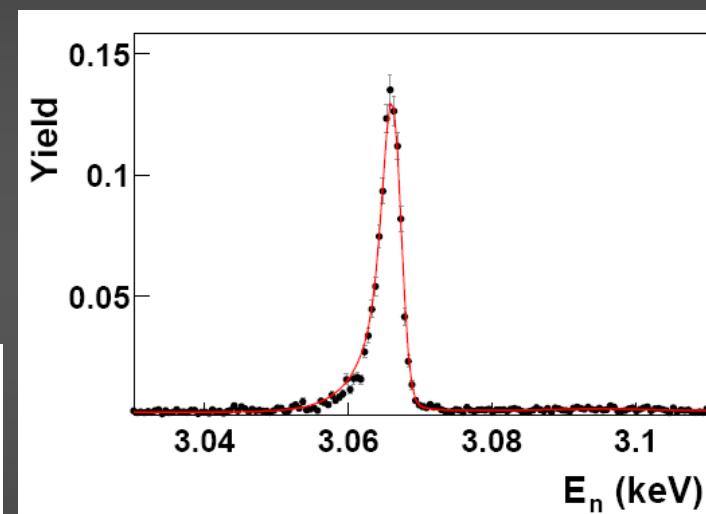
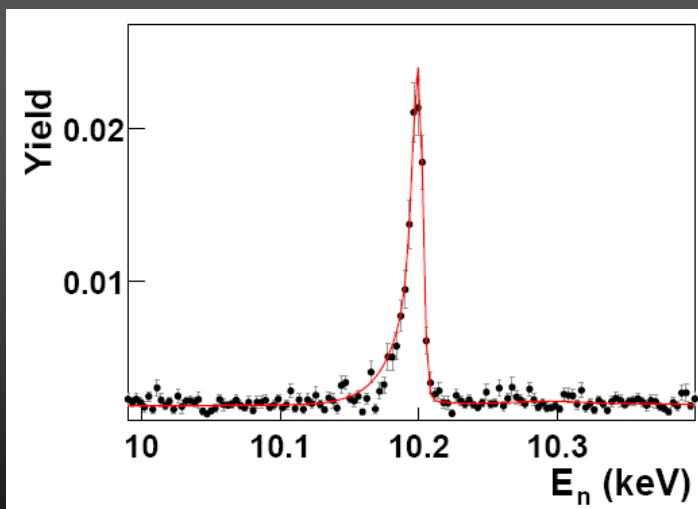
^{237}Np

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

n_TOF experiments

C Domingo-Pardo, et al. - The n_TOF Collaboration
ND2004 Conference, Santa Fe, NM – Sept. 2004
&
PRC 74 (2006) 055802

$^{207}\text{Pb}(n,\gamma)$



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

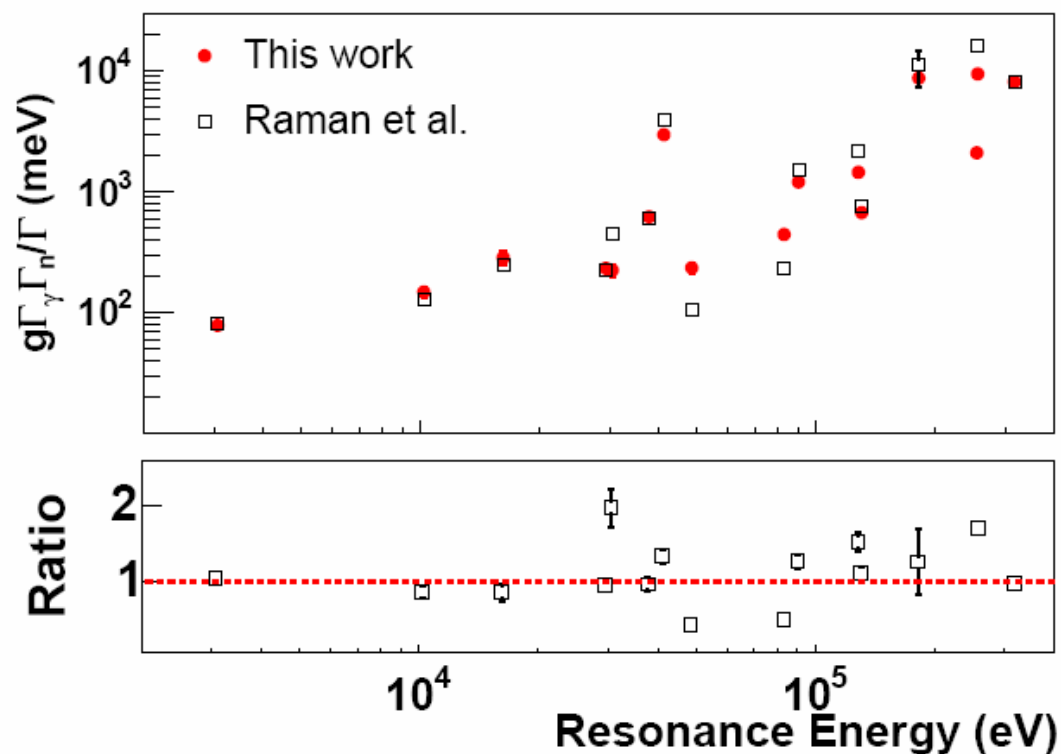
^{237}Np

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

n_TOF experiments

C Domingo-Pardo, et al. - The n_TOF Collaboration
ND2004 Conference, Santa Fe, NM – Sept. 2004
&
PRC 74 (2006) 055802

$^{207}\text{Pb}(n,\gamma)$



substantial disagreement for $E_n > 45$ keV

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

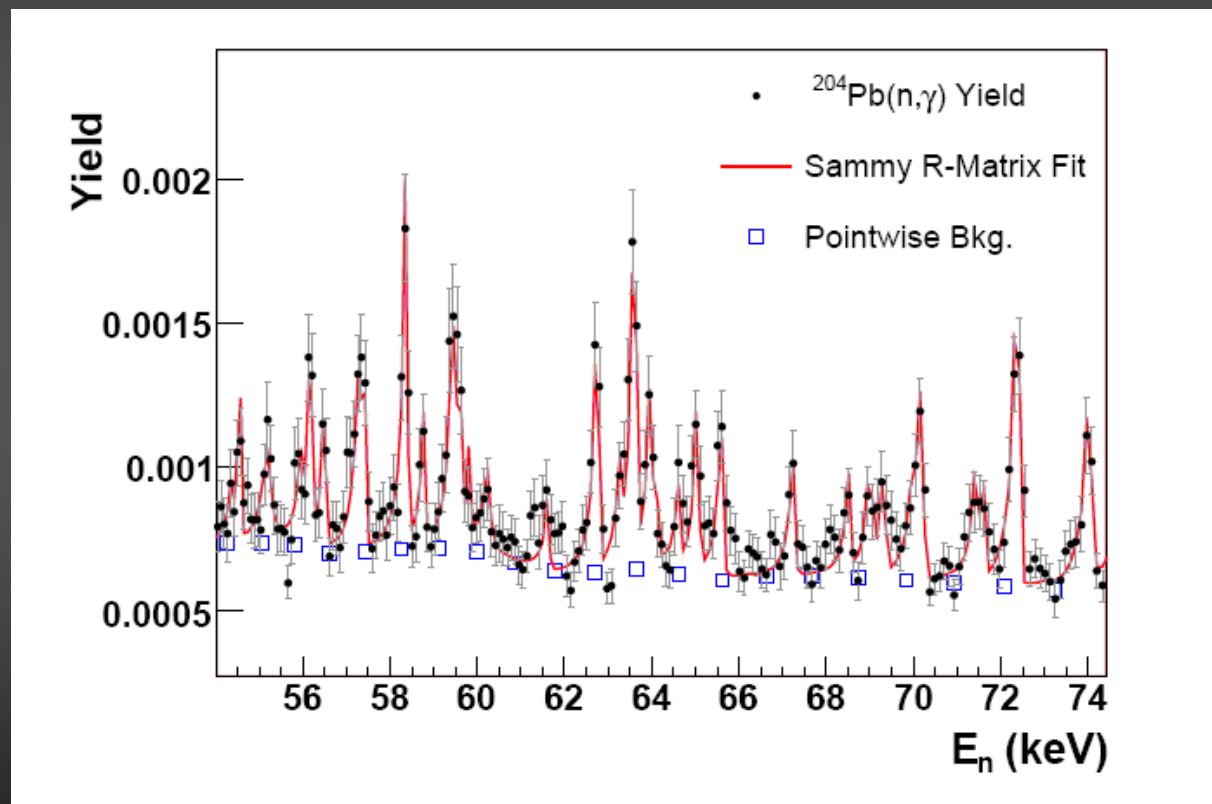
^{237}Np

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

n_TOF experiments

C Domingo-Pardo, et al. - The n_TOF Collaboration
ND2004 Conference, Santa Fe, NM – Sept. 2004
&
PRC 75 (2006) 015806

$^{204}\text{Pb}(n,\gamma)$



Very low neutron sensitivity of capture γ -ray
detection systems & high resolution

The n_TOF Collaboration

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

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

n_TOF experiments

C Domingo-Pardo, et al. - The n_TOF Collaboration
 ND2004 Conference, Santa Fe, NM – Sept. 2004
 &
 PRC 75 (2006) 015806

$^{204}\text{Pb}(n,\gamma)$

E_o (eV)	l	J	Γ_γ (meV)	$\Delta\Gamma_\gamma$ (%)	Γ_n (meV)	K_r (meV)	ΔK_r (%)
480.3	1	1/2	1.33	4	3.0	0.92 ^a	2.7
1333.8	1	1/2	105	4	46.3 ^b	32.1 ^a	1.3
1687.1	0	1/2	1029	0.7	3340	787 ^a	0.5
2481.0	0	1/2	514	1.1	5470	470 ^a	1.0
2600.0						8.35	6
2707.1	1	3/2	31.2	9	11.5	16.8	2
3187.9	0	1/2	316	10	1.7	1.69	0.1
3804.9	1	1/2	280	8	66.4	53.7	1.6
4284.1	1	3/2	111	9	24.0	39.4	1.7
4647.5						2.57	9
4719.4	1	3/2	41.2	5	95.0	57.5	3
5473.2	1	1/2				79.0	1.6
5561.4		(1/2)	1.03	10	1.9	0.67	6.4
6700.5	0	1/2	312	3	4540	292	3
7491.0						19.0	0.5
8357.4	0	1/2	1286	1.9	45000	1250	1.9
8422.9						11.3	7
8949.6						22.9	3
9101.0		(1/2)	193	8	150	84.4	4
9649.3	0	1/2	1076	2	7860	946	2
10254						37.0	8
11366	1	3/2	39.0	10	226	66.5	9
11722						22.8	9
12147						54.4	8

TABLE IV: Average neutron capture cross section for ^{204}Pb .

E_{low} (keV)	E_{high} (keV)	Cross section (barn)	Statistical uncertainty ^a (%)
88.210	92.404	0.059	9
92.404	96.748	0.059	5
96.748	101.406	0.058	11
101.406	106.408	0.057	8
106.408	111.790	0.057	7
111.790	117.591	0.056	8
117.591	123.855	0.056	7
123.855	130.634	0.055	7
130.634	137.985	0.054	6
137.985	145.974	0.054	6
145.974	154.678	0.053	6
154.678	164.185	0.053	7
164.185	174.596	0.052	7
174.596	186.030	0.051	6
186.030	198.625	0.051	5
198.625	212.544	0.050	5
212.544	227.981	0.049	5
227.981	245.162	0.049	5
245.162	264.363	0.048	4
264.363	285.911	0.047	4
285.911	310.207	0.046	4
310.207	337.739	0.046	4
337.739	369.107	0.045	4
369.107	405.060	0.044	4
405.060	443.512	0.043	3

^aThis value has to be added in quadrature with the overall systematic uncertainty of 10%.

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

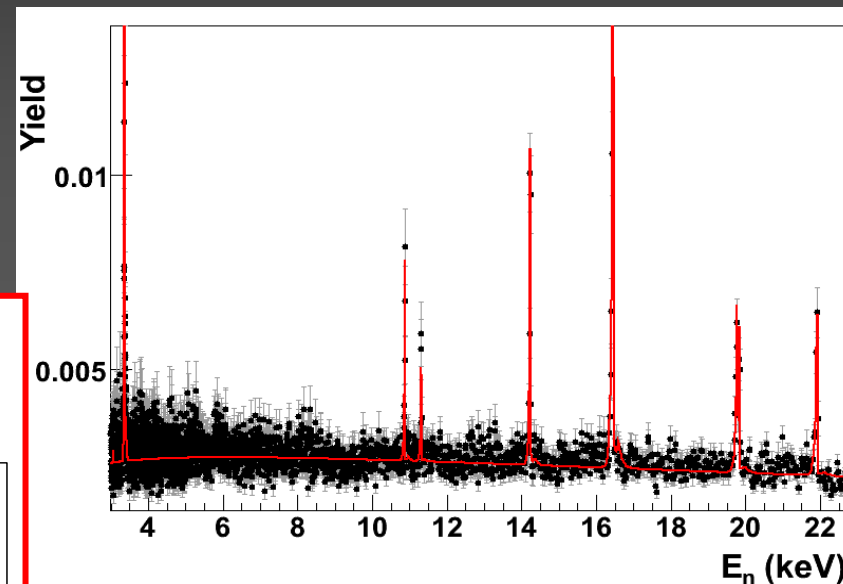
^{237}Np

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

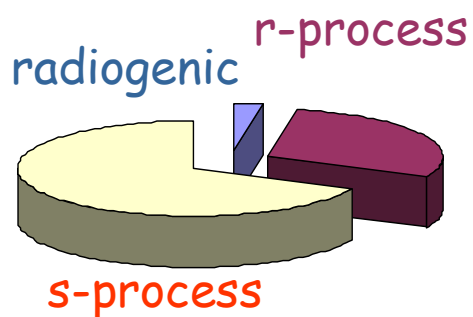
n_TOF experiments

C Domingo-Pardo, et al. - The n_TOF Collaboration
ND2004 Conference, Santa Fe, NM – Sept. 2004 &
Phys. Rev. C in press (2007)

$^{206}\text{Pb}(n,\gamma)$



^{206}Pb abundances



Very low neutron sensitivity of capture γ -ray
detection systems & high resolution

The n_TOF Collaboration

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

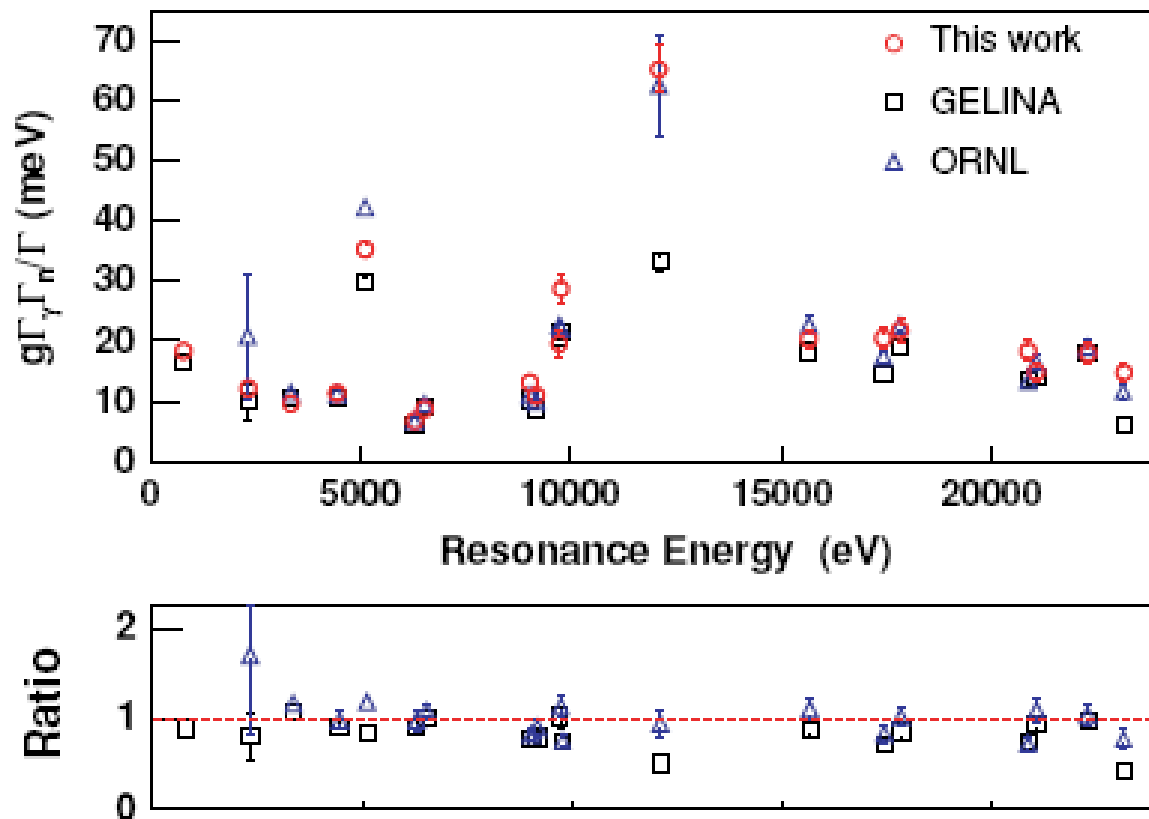
^{237}Np

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

n_TOF experiments

C Domingo-Pardo, et al. (The n_TOF Collaboration)
Phys. Rev. C **74**, 025807 (2006)

$^{209}\text{Bi}(n,\gamma)$



Very low neutron sensitivity of capture γ -ray detection systems & high resolution

The n_TOF Collaboration

Capture

^{151}Sm

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

^{232}Th

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

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

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

Fission

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

^{232}Th

^{209}Bi

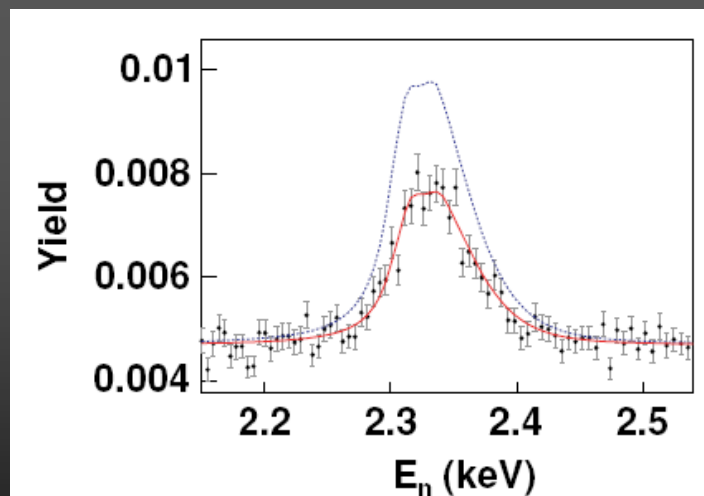
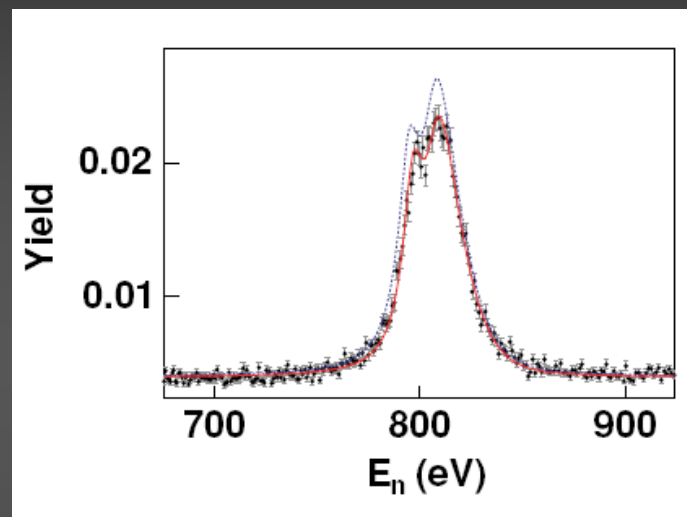
^{237}Np

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

n_TOF experiments

C Domingo-Pardo, et al. (The n_TOF Collaboration)
Phys. Rev. C **74**, 025807 (2006)

$^{209}\text{Bi}(n,\gamma)$



Very low neutron sensitivity of capture γ -ray
detection systems & high resolution

The n_TOF Collaboration

n_TOF experiments

Capture

¹⁵¹Sm

^{204,206,207,208}Pb, ²⁰⁹Bi

²³²Th

^{24,25,26}Mg

^{90,91,92,94,96}Zr, ⁹³Zr

¹³⁹La

^{186,187,188}Os

^{233,234}U

²³⁷Np, ²⁴⁰Pu, ²⁴³Am

Fission

^{233,234,235,236,238}U

²³²Th

²⁰⁹Bi

²³⁷Np

^{241,243}Am, ²⁴⁵Cm

	s-process [%]	Ref
Pb-204	~ 100	PRC 015806 (2007)
Pb-206	70 ± 4	PRC in press (2007)
Pb-207	77 ± 8	PRC 055802 (2006)
Bi-209	19 ± 3	PRC 025807 (2006)

- allows for accurate modeling of s-process in AGB stars
- allows for r-process abundance determination
- clocks & others

n_TOF experiments

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

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Fission

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^{232}Th

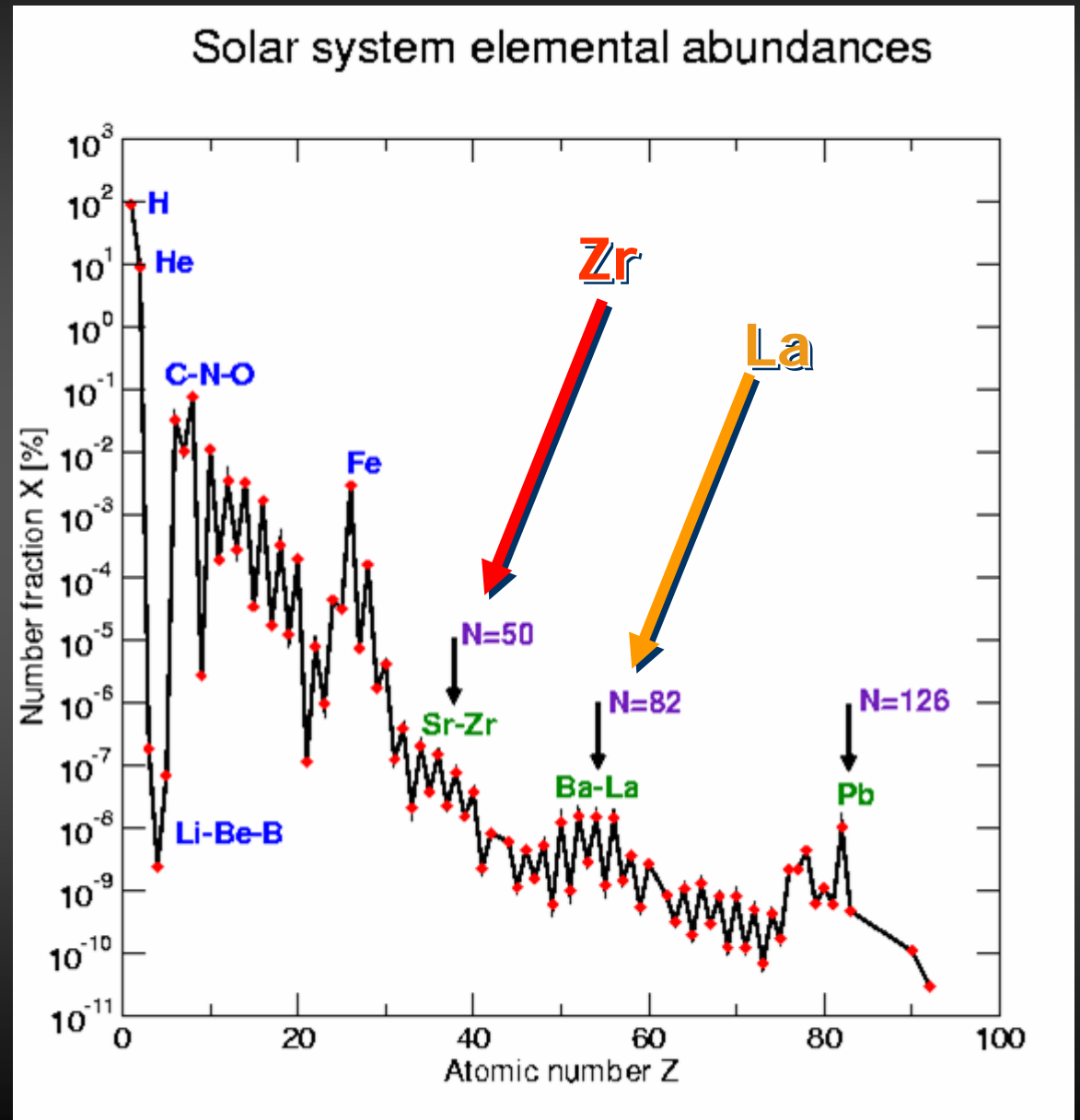
^{209}Bi

^{237}Np

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

canonical
s-process

>>



Capture

^{151}Sm

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

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

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^{209}Bi

^{237}Np

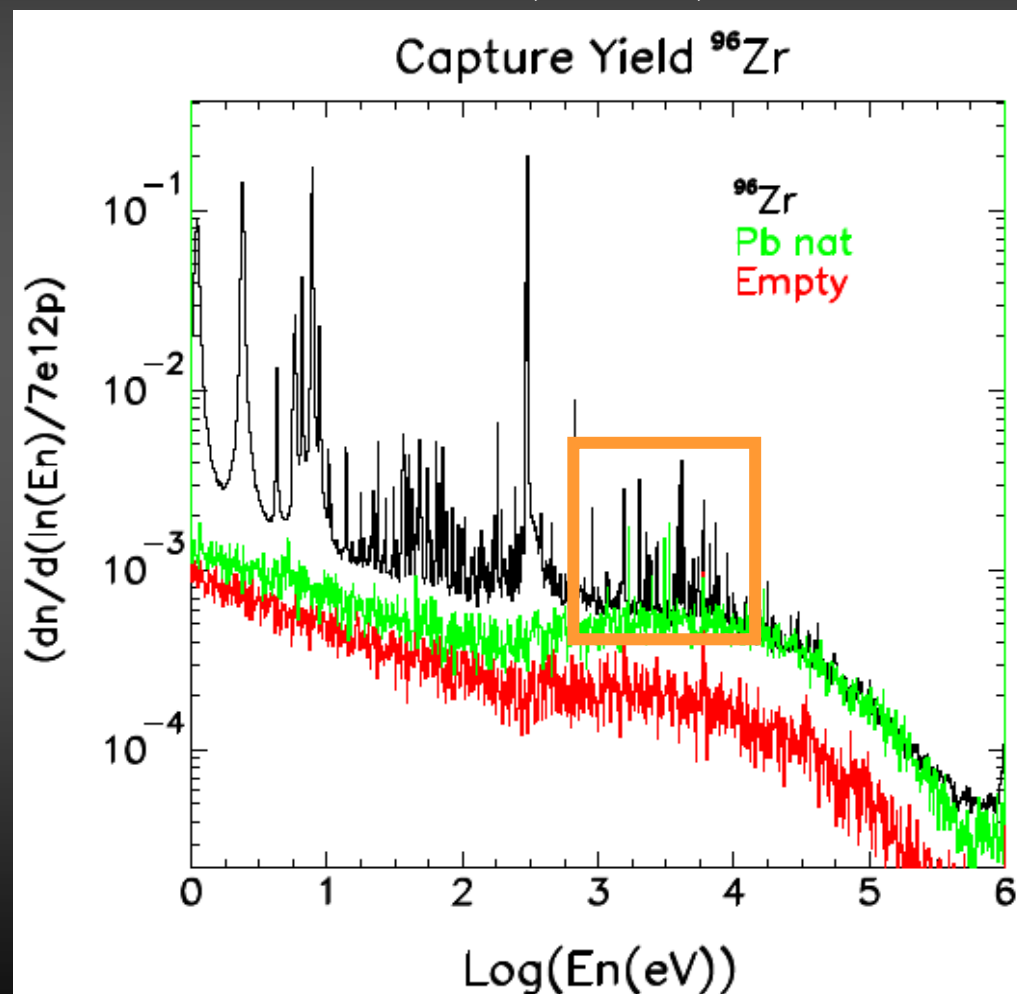
$^{241,243}\text{Am}$, ^{245}Cm

$^{96}\text{Zr}(n,\gamma)$

20% reduction
in the capture
strength
(average)

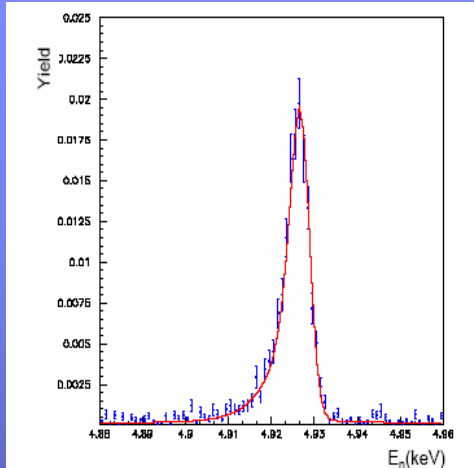
n_TOF experiments

C Moreau, et al. - The n_TOF Collaboration
ND2004 Conference, Santa Fe, NM – September 2004
G Tagliente et al. (The n_TOF Collaboration)
NIC-IX, CERN, June 2006

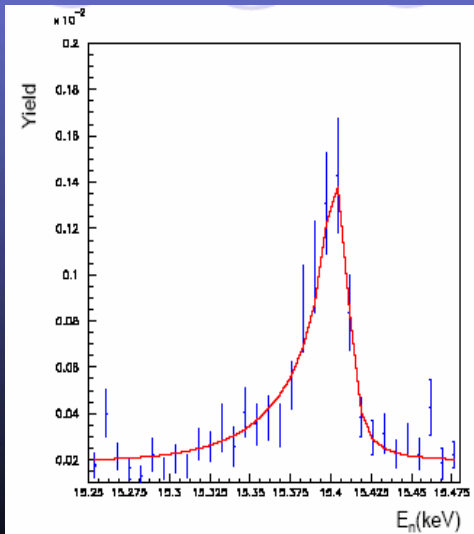


n_TOF experiments

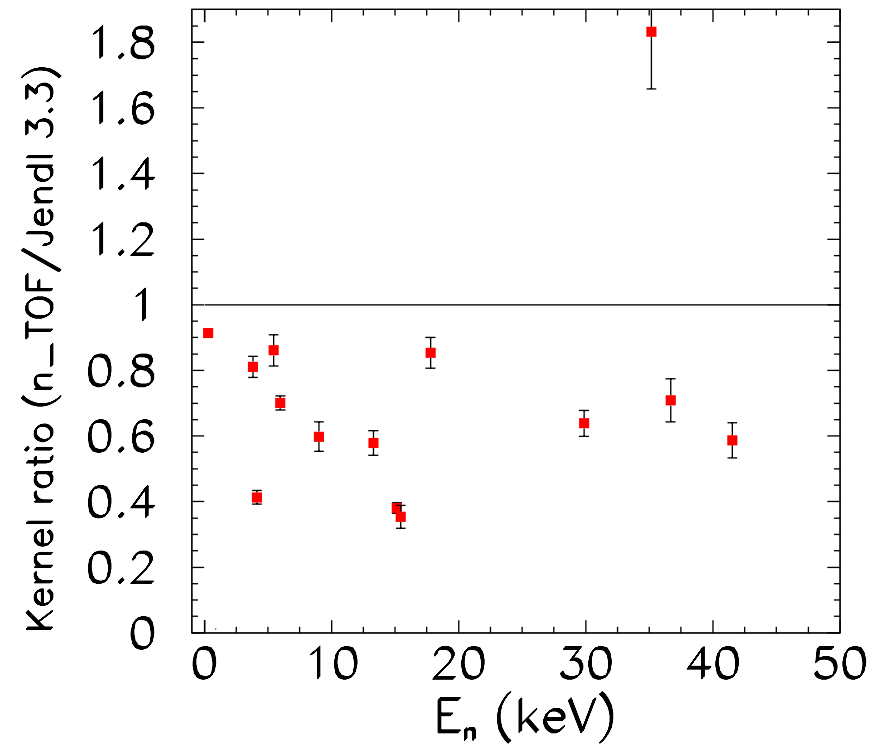
C Moreau, et al. - The n_TOF Collaboration
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NIC-IX, CERN, June 2006



$^{96}\text{Zr}(n,\gamma)$



20% reduction
in the capture
strength
(average)



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

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

Fission

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

^{232}Th

^{209}Bi

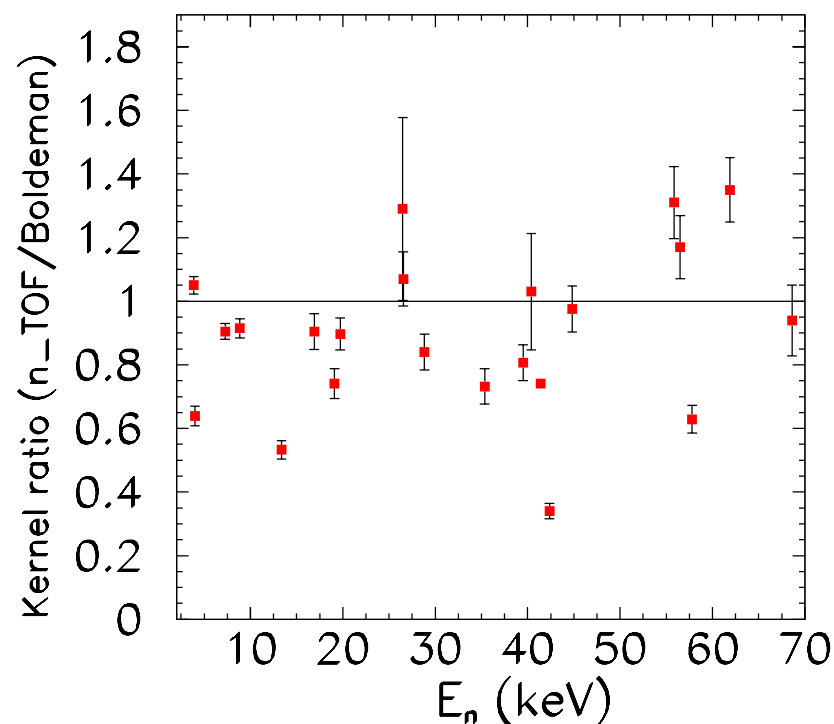
^{237}Np

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

$^{90}\text{Zr}(n,\gamma)$

n_TOF experiments

C Moreau, et al. - The n_TOF Collaboration
ND2004 Conference, Santa Fe, NM – September 2004
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Capture

^{151}Sm

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

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

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Fission

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

^{232}Th

^{209}Bi

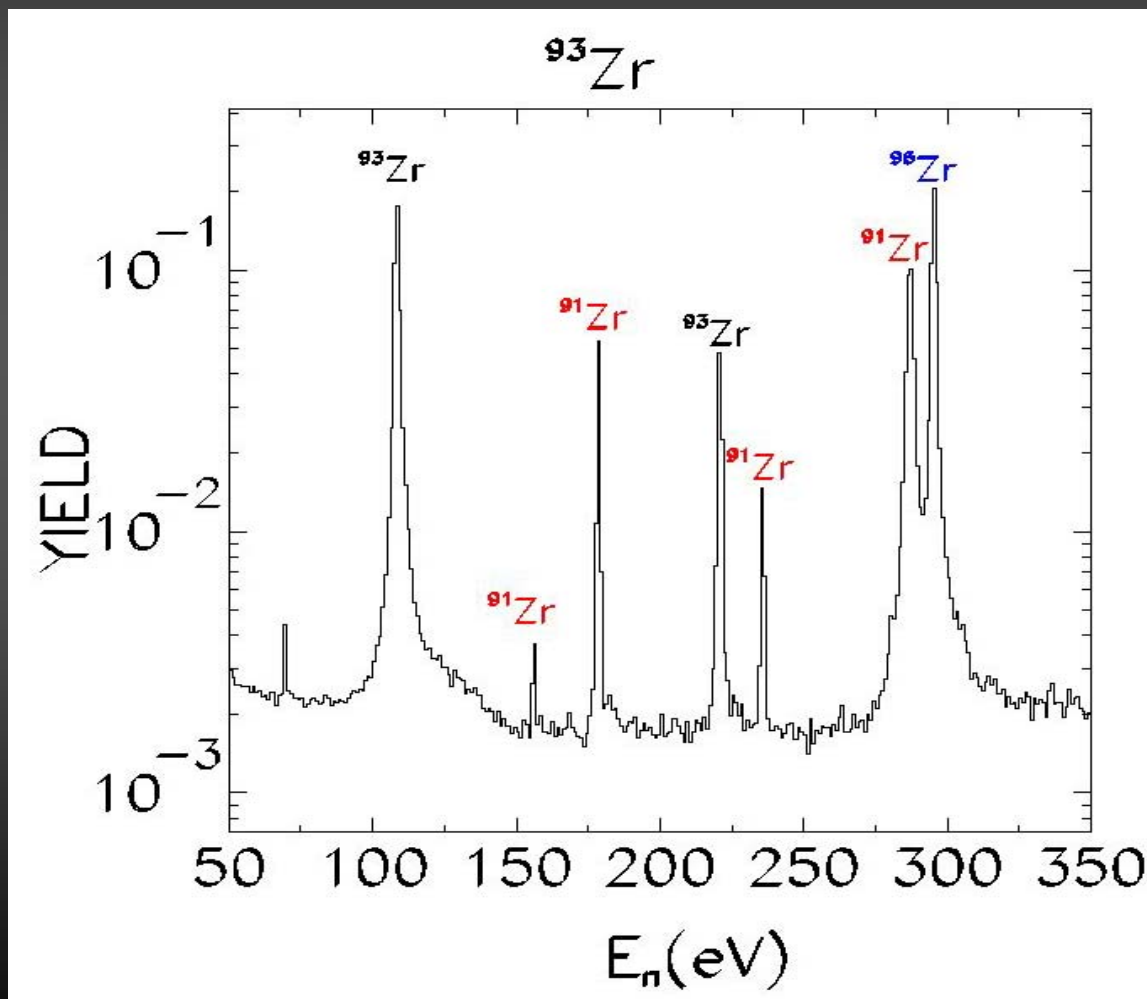
^{237}Np

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



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

n_TOF experiments



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

$^{139}\text{La}(n,\gamma)$

n_TOF experiments

R Terlizzi, et al. (The n_TOF Collaboration)

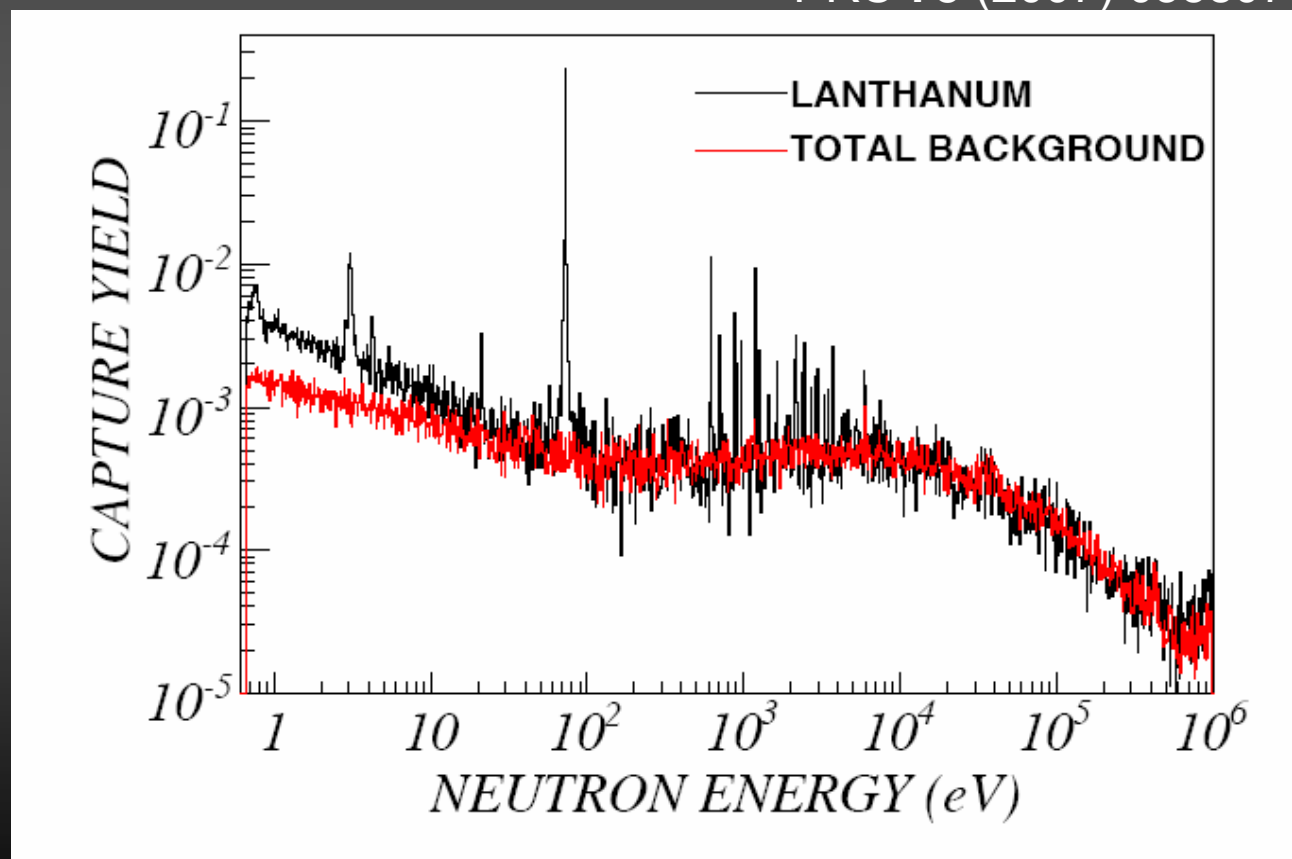
CGS12

Notre Dame, IN, USA

AIP Conference Proceedings 819

&

PRC 75 (2007) 035807



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_TOF experiments

$^{139}\text{La}(n,\gamma)$

R Terlizzi, et al. (The n_TOF Collaboration)

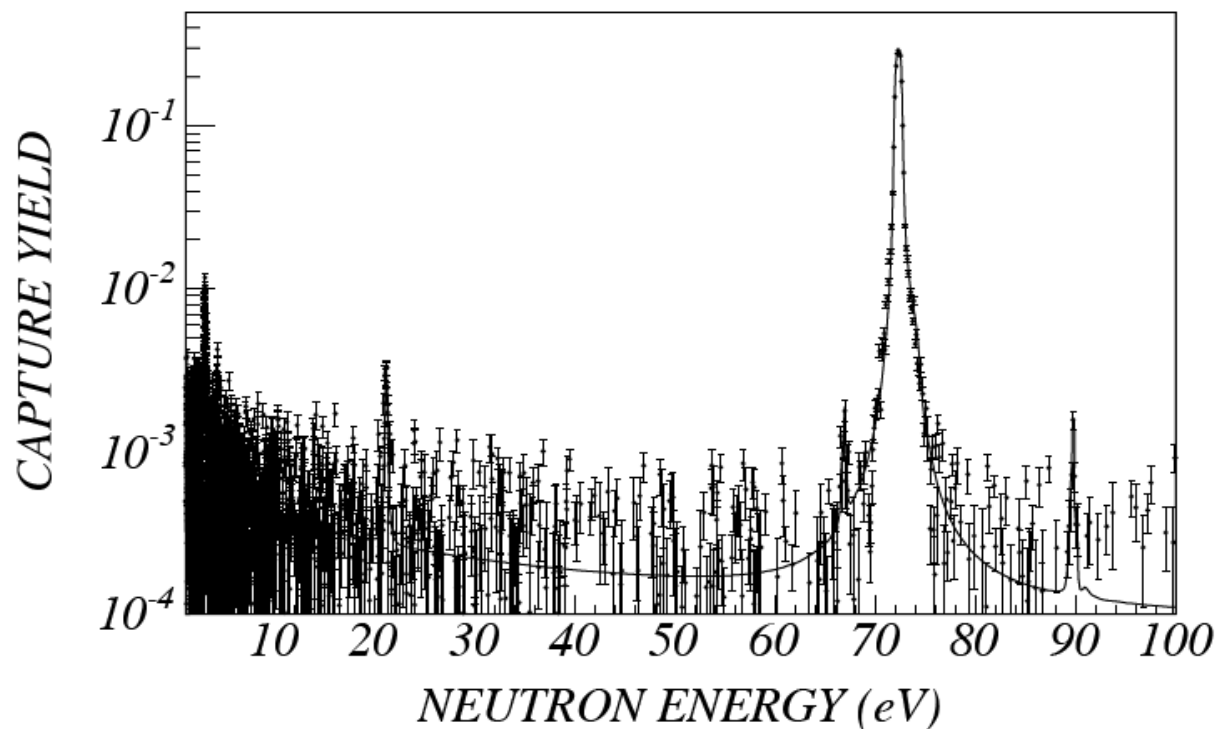
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PRC 75 (2007) 035807



n_TOF experiments

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

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

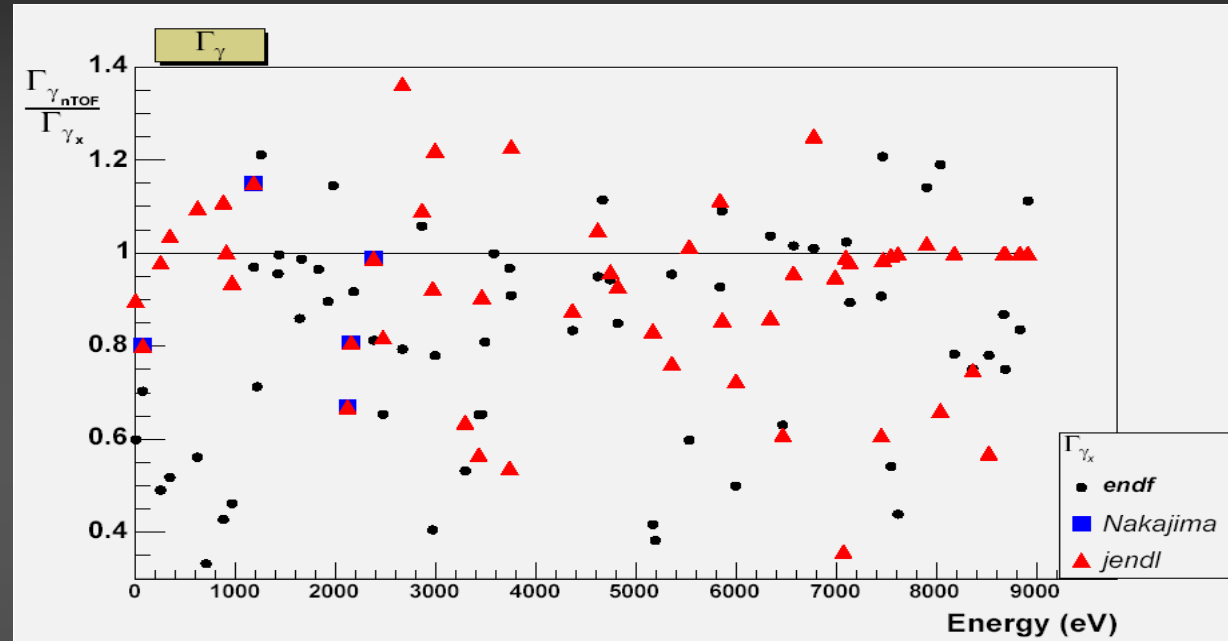
^{232}Th

^{209}Bi

^{237}Np

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

$^{139}\text{La}(n,\gamma)$



Remarkable energy resolution and background conditions have allowed to determine the resonance parameters up to 9 keV

$RI = 10.8 \pm 1.0$ barn

average γ -widths:

s-waves = 50.7 ± 5.4 meV

p-waves = 33.6 ± 6.9 meV

$\langle D_0 \rangle = 252 \pm 22$ eV

$S_0 = (0.82 \pm 0.05) \times 10^{-4}$ $S_1 = (0.55 \pm 0.04) \times 10^{-4}$

n_TOF experiments

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

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

Fission

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

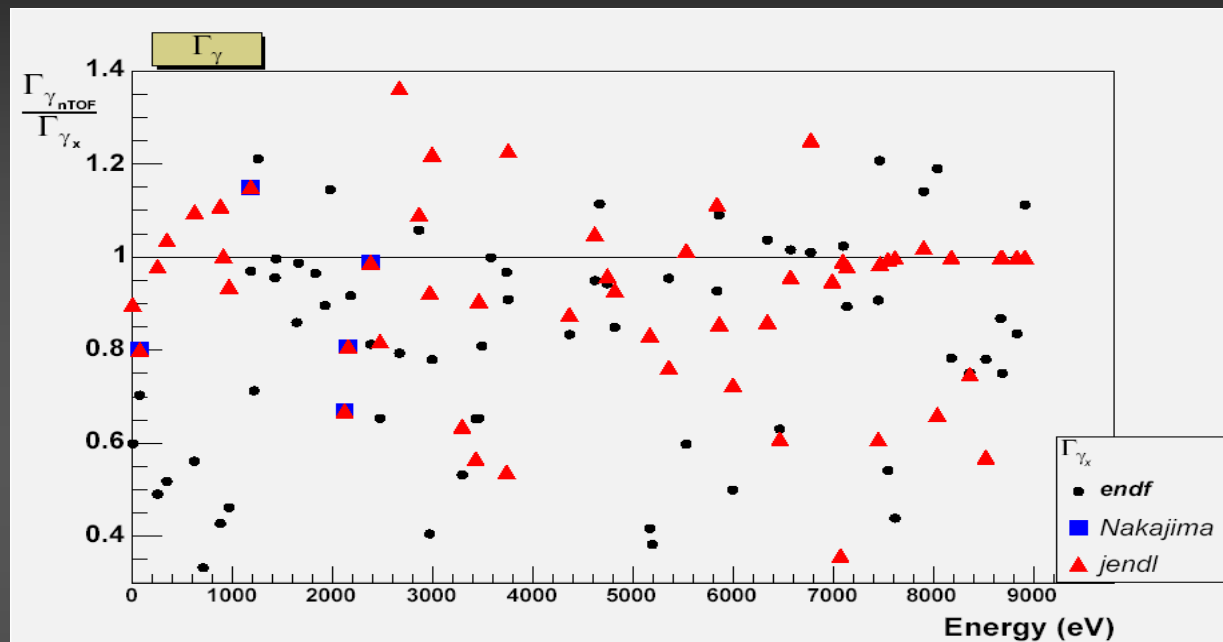
^{232}Th

^{209}Bi

^{237}Np

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

$^{139}\text{La}(n,\gamma)$



TP-AGB modeling leads to 74 ± 3 % of solar s- La

remember:

- MACS-8 determined from low-energy isolated resonances
- La is (almost) mono isotopic
- Good abundance determination from stellar spectra

n_TOF experiments

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

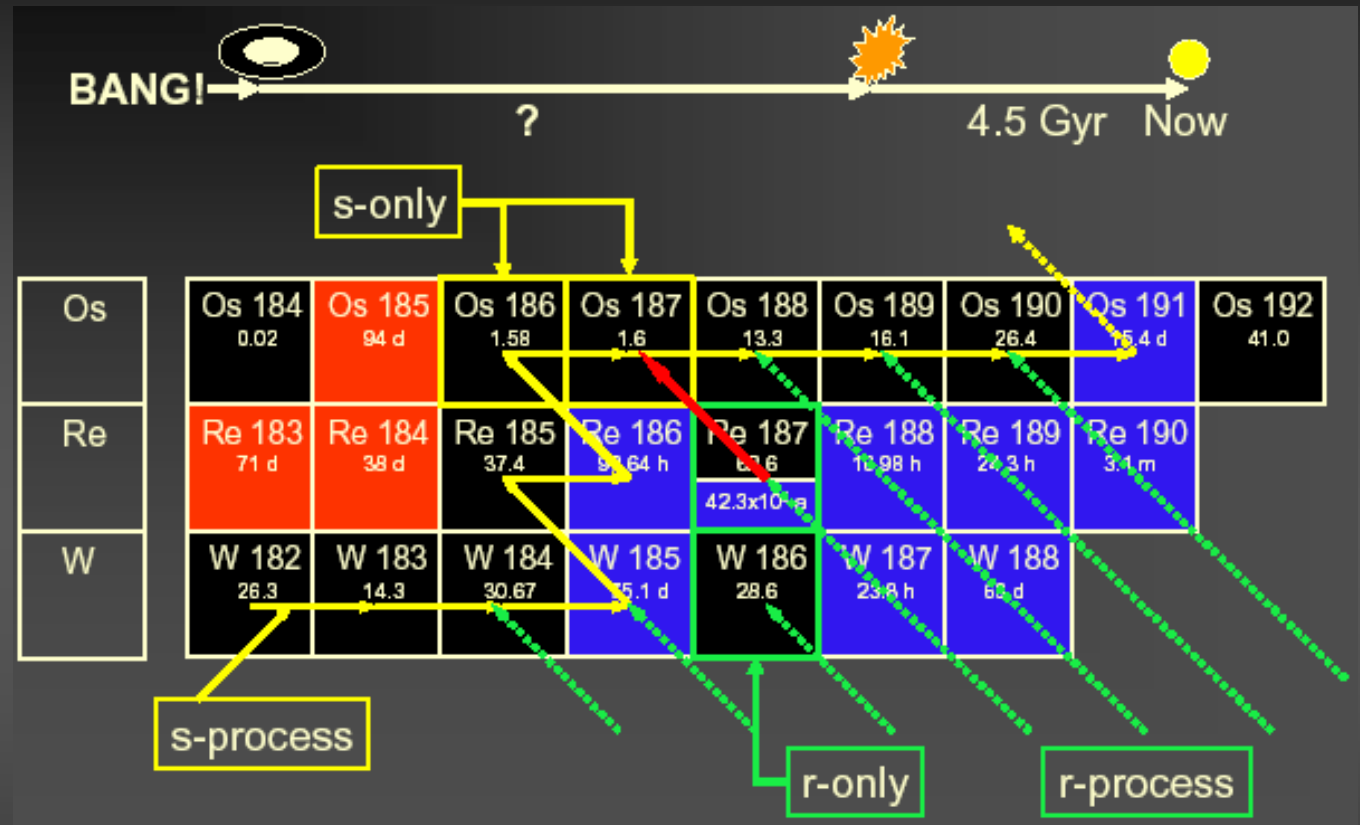
$^{233,234,235,236,238}\text{U}$

^{232}Th

^{209}Bi

^{237}Np

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



Re/Os clock

<< back

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

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

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

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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

Th/U nuclear 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
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 $2,411 \cdot 10^4$ a	Pu 240 6563 a	Pu 241 14,35 a	Pu 242 $3,750 \cdot 10^5$ a	Pu 243 4,956 h	Pu 244 $8,00 \cdot 10^7$ a
Np 234 4,4 d	Np 235 396,1 d	Np 236 22,5 h	Np 237 $2,144 \cdot 10^6$ 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
U 233 $1,592 \cdot 10^5$ a	U 234 0,0055 a	U 235 0,7200 a	U 236 $2,342 \cdot 10^7$ a	U 237 6,75 d	U 238 99,2745 a	U 239 23,5 m	U 240 14,1 h		U 242 16,8 m
Pa 232 1,31 d	Pa 233 2,0 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		148	150
Th 231 25,5 h	Th 232 100 a	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			

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

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

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

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

Fission

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

^{232}Th

^{209}Bi

^{237}Np

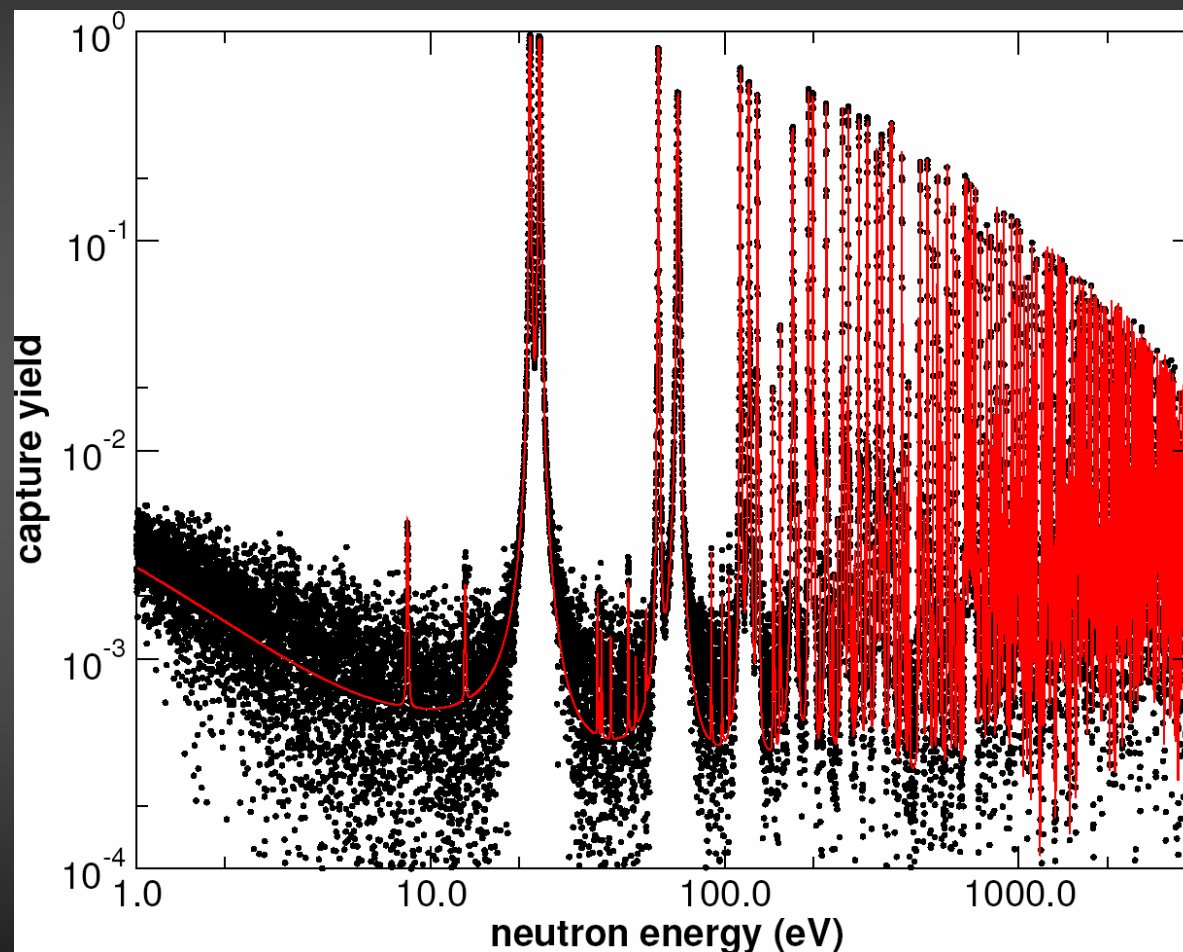
$^{241,243}\text{Am}$, ^{245}Cm



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

n_TOF experiments

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



extremely high-resolution data!

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

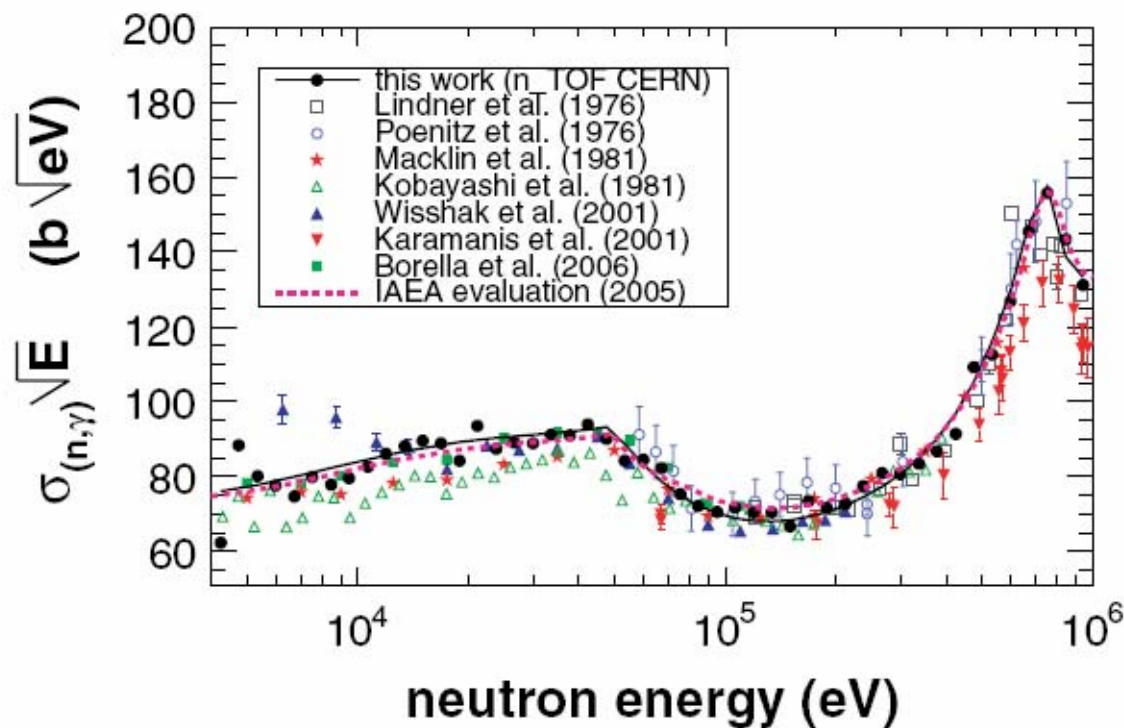


$^{232}\text{Th}(n,\gamma)$

n_TOF experiments

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

G Aerts et al. (The n_TOF Collaboration)
Phys. Rev. C 73, 054610 (2006)



Capture

^{151}Sm

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

^{232}Th

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

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$^{241,243}\text{Am}$, ^{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
&

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Phys. Rev. C 73, 054610 (2006)

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

Capture

^{151}Sm

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

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

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

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

Fission

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

^{232}Th

^{209}Bi

^{237}Np

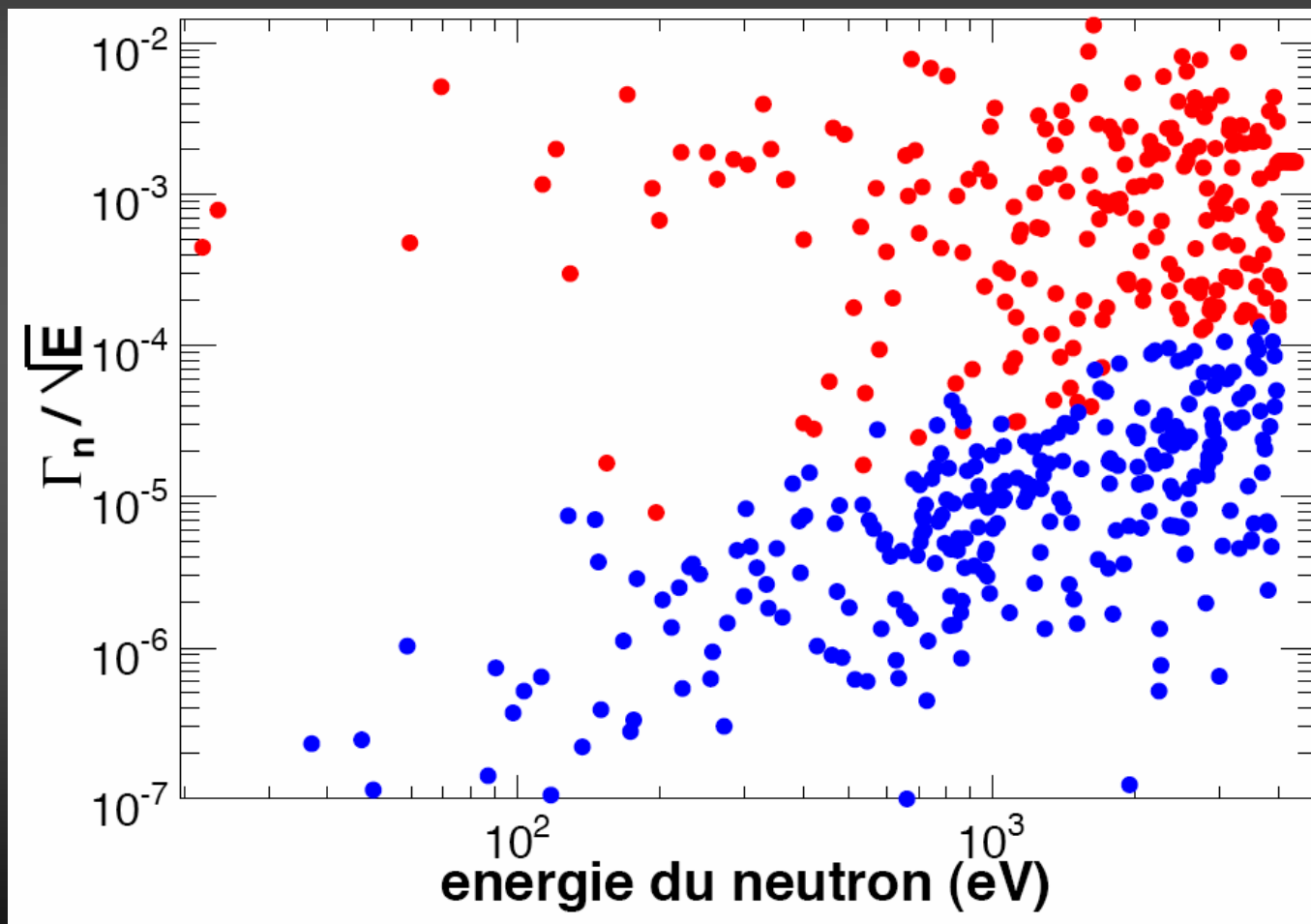
$^{241,243}\text{Am}$, ^{245}Cm



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

n_TOF experiments

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



Capture

^{151}Sm

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

^{232}Th

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

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

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

^{232}Th

^{209}Bi

^{237}Np

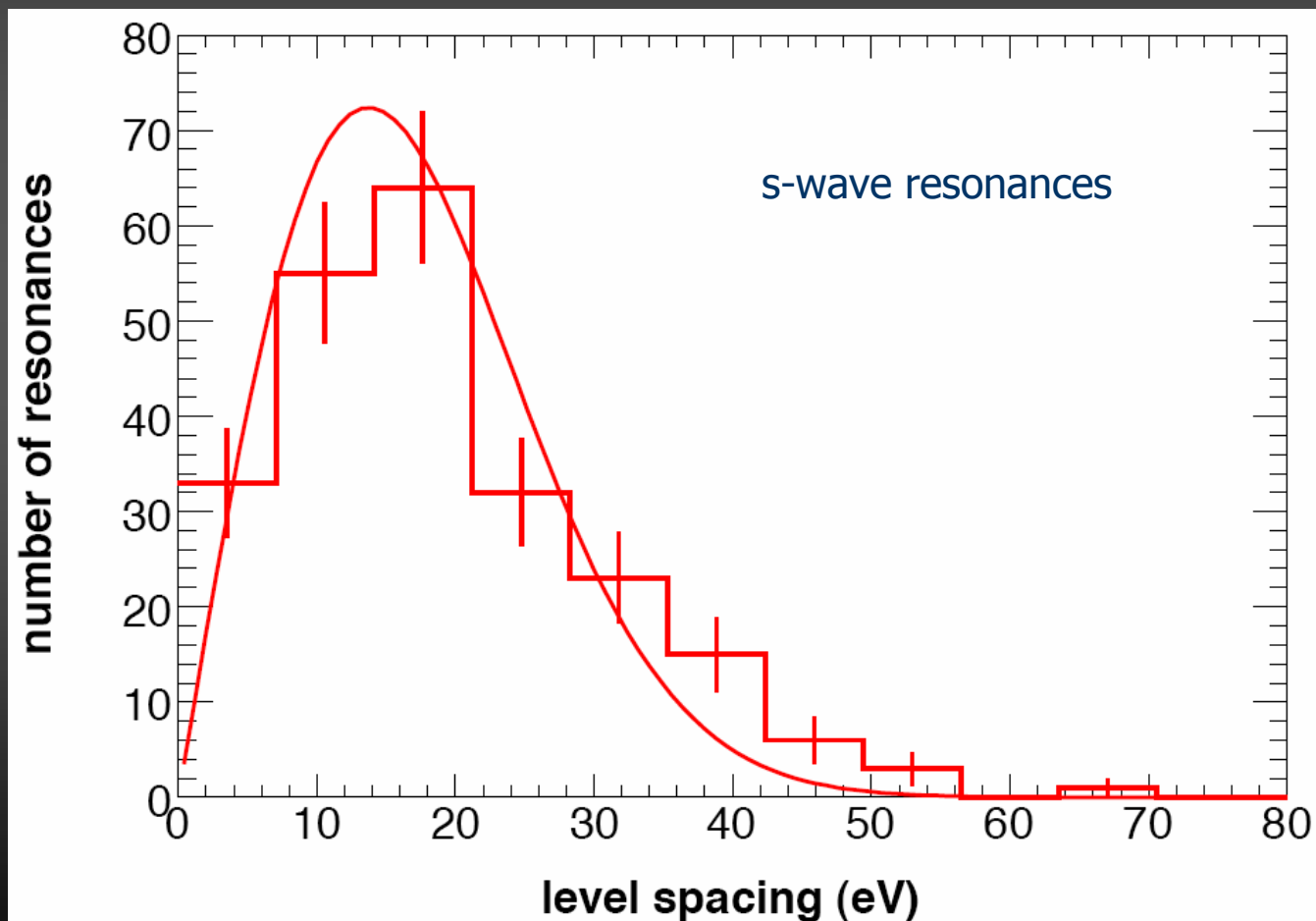
$^{241,243}\text{Am}$, ^{245}Cm



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

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F Gunsing, et al. - The n_TOF Collaboration
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^{237}Np , ^{240}Pu , ^{243}Am

Fission

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

^{232}Th

^{209}Bi

^{237}Np

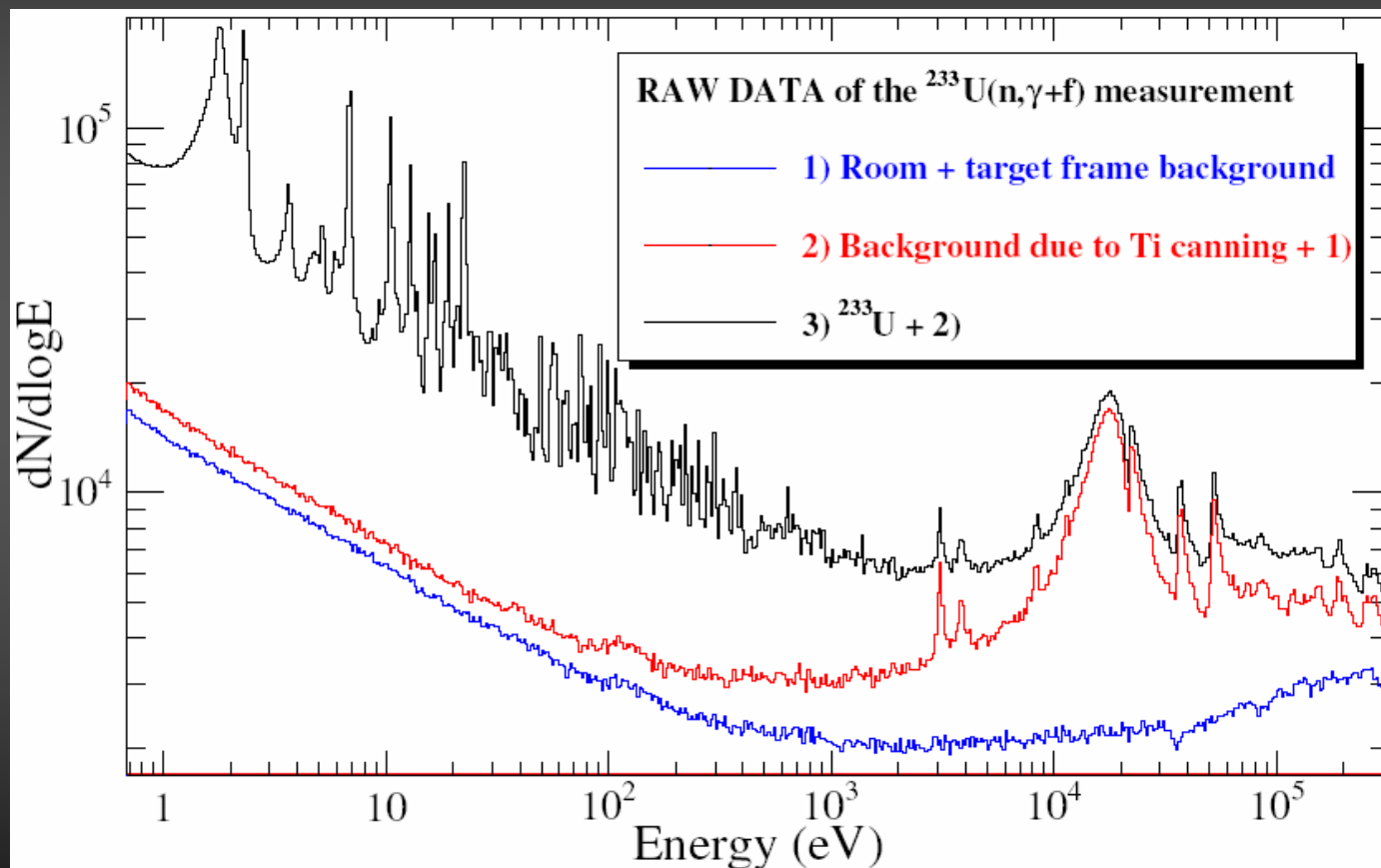
$^{241,243}\text{Am}$, ^{245}Cm



n_TOF experiments

$^{233}\text{U}(n,\gamma)$

W Dridi, E Berthoumieux, *et al.*, (Dec. 2004)



n_TOF TAC in operation

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

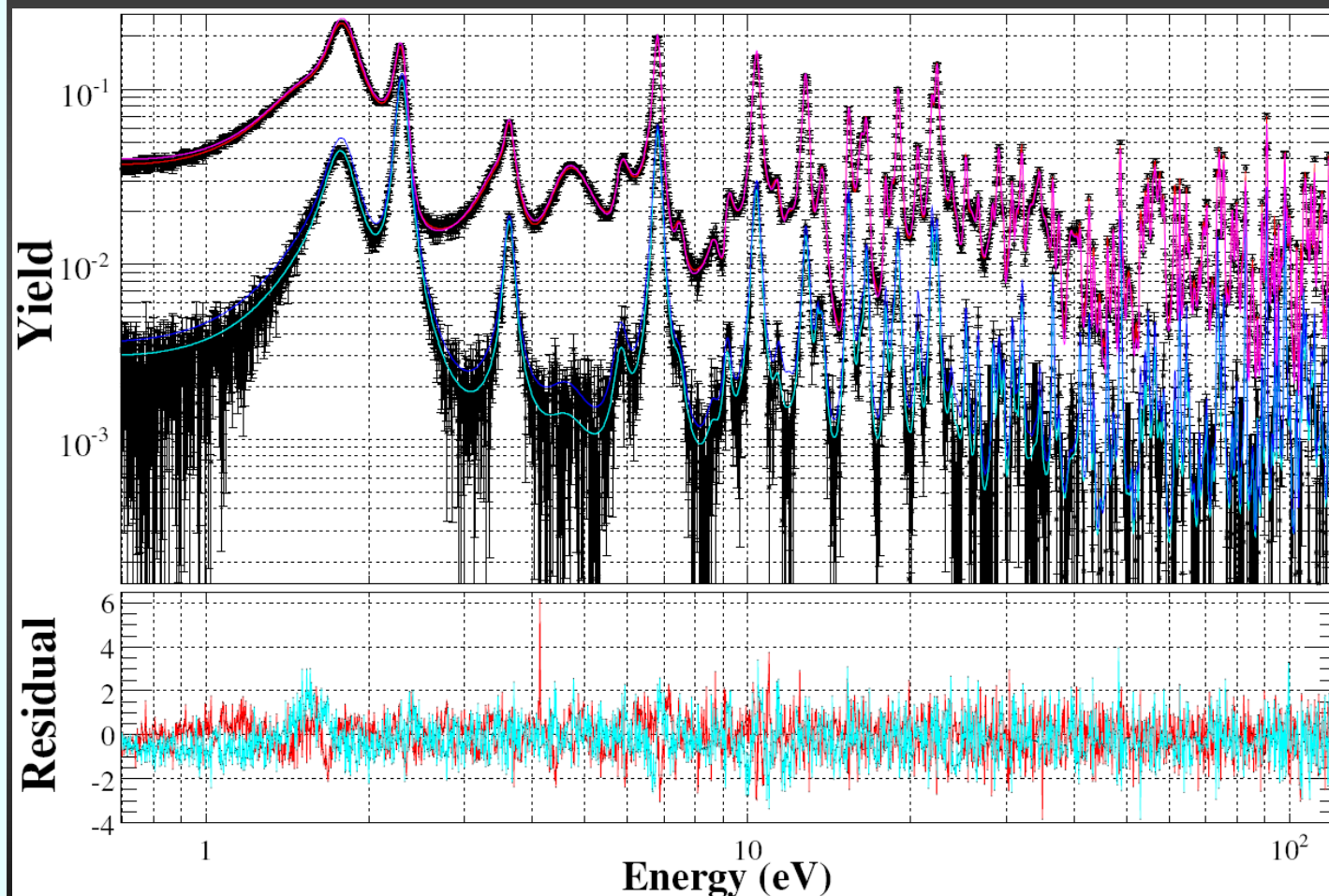
$^{241,243}\text{Am}$, ^{245}Cm



$^{233}\text{U}(n,\gamma)$

n_TOF experiments

W Dridi, E Berthoumieux, *et al.*, CEA/Saclay
Paper in preparation (October 2006)



n_TOF TAC in operation: capture & fission discrimination

The n_TOF Collaboration

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

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

^{232}Th

^{209}Bi

^{237}Np

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

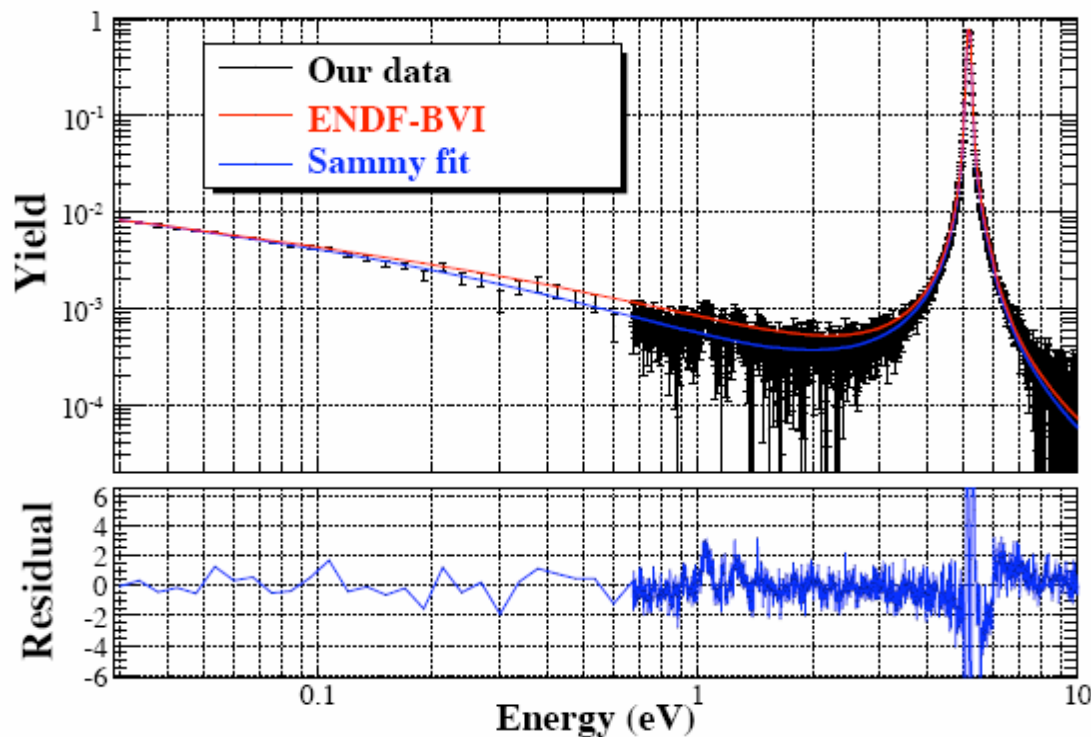


n_TOF experiments

W Dridi, E Berthoumieux, et al. (The n_TOF Collaboration)
PHYSOR-2006, Vancouver, September 2006
full paper in preparation

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

Figure 3: Neutron capture on ^{234}U yield in the thermal region and for the first resonance obtained in the present experiment.



n_TOF TAC in operation

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

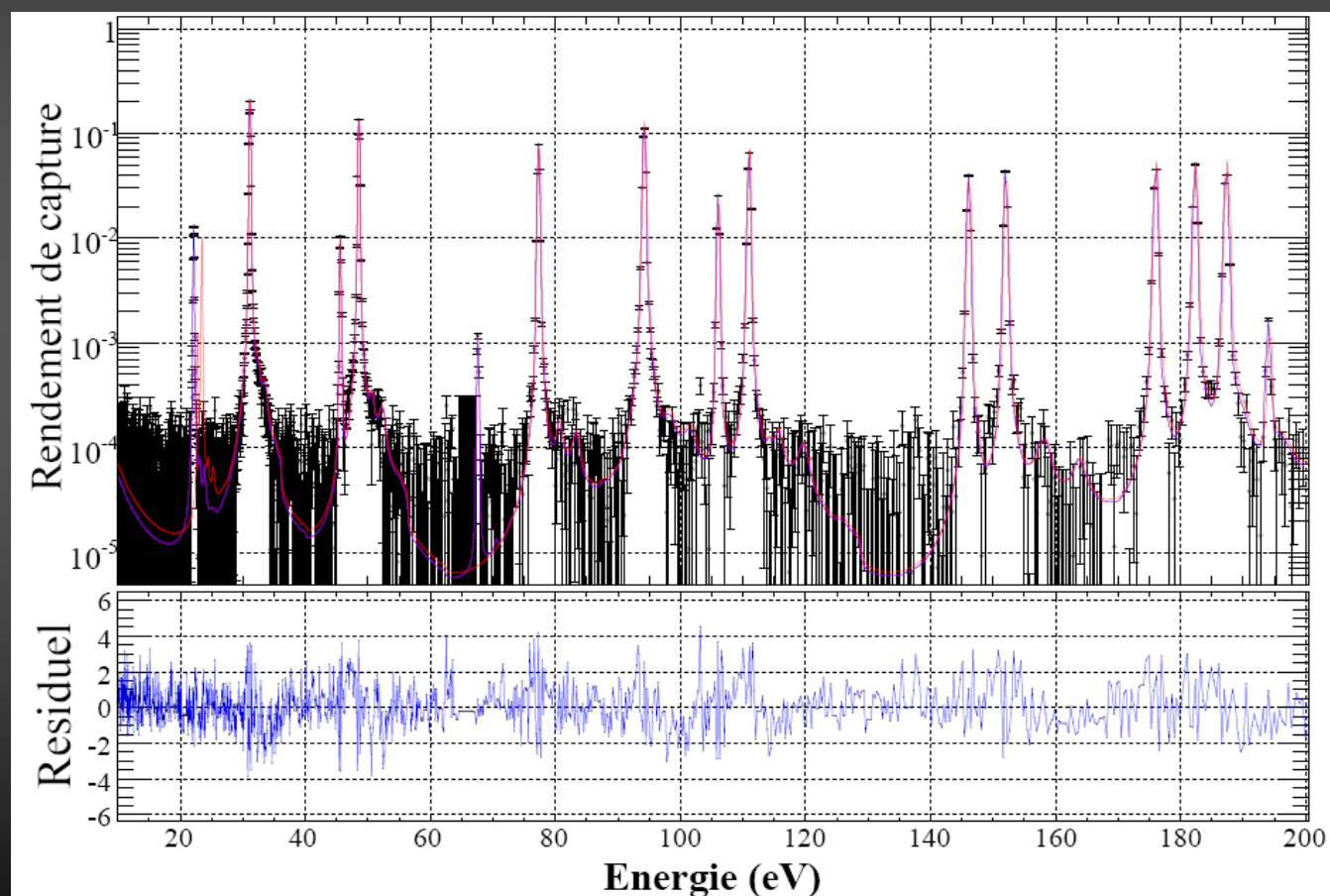
$^{241,243}\text{Am}$, ^{245}Cm



n_TOF experiments

W Dridi, E Berthoumieux, et al. (The n_TOF Collaboration)
PHYSOR-2006, Vancouver, September 2006
full paper in preparation

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



n_TOF TAC in operation

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

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

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

Fission

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

^{232}Th

^{209}Bi

^{237}Np

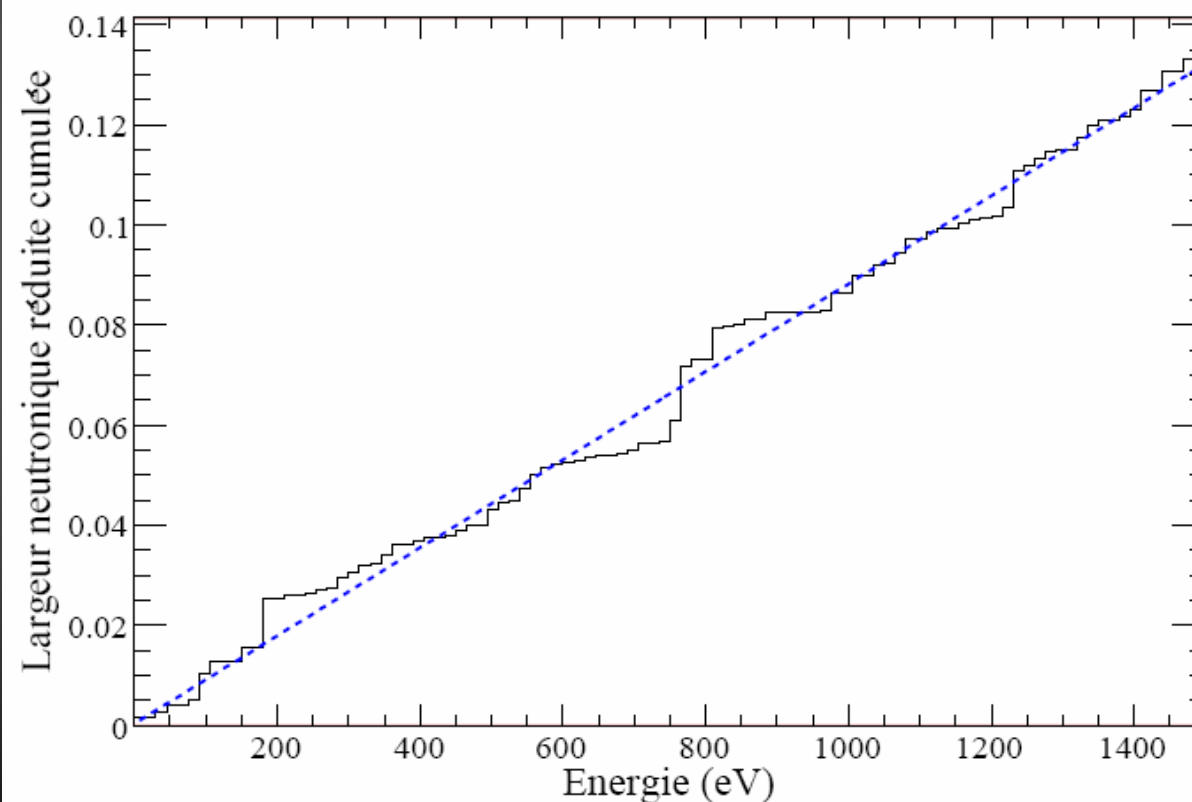
$^{241,243}\text{Am}$, ^{245}Cm



n_TOF experiments

W Dridi, E Berthoumieux, et al. (The n_TOF Collaboration)
PHYSOR-2006, Vancouver, September 2006
full paper in preparation

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



n_TOF TAC in operation

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

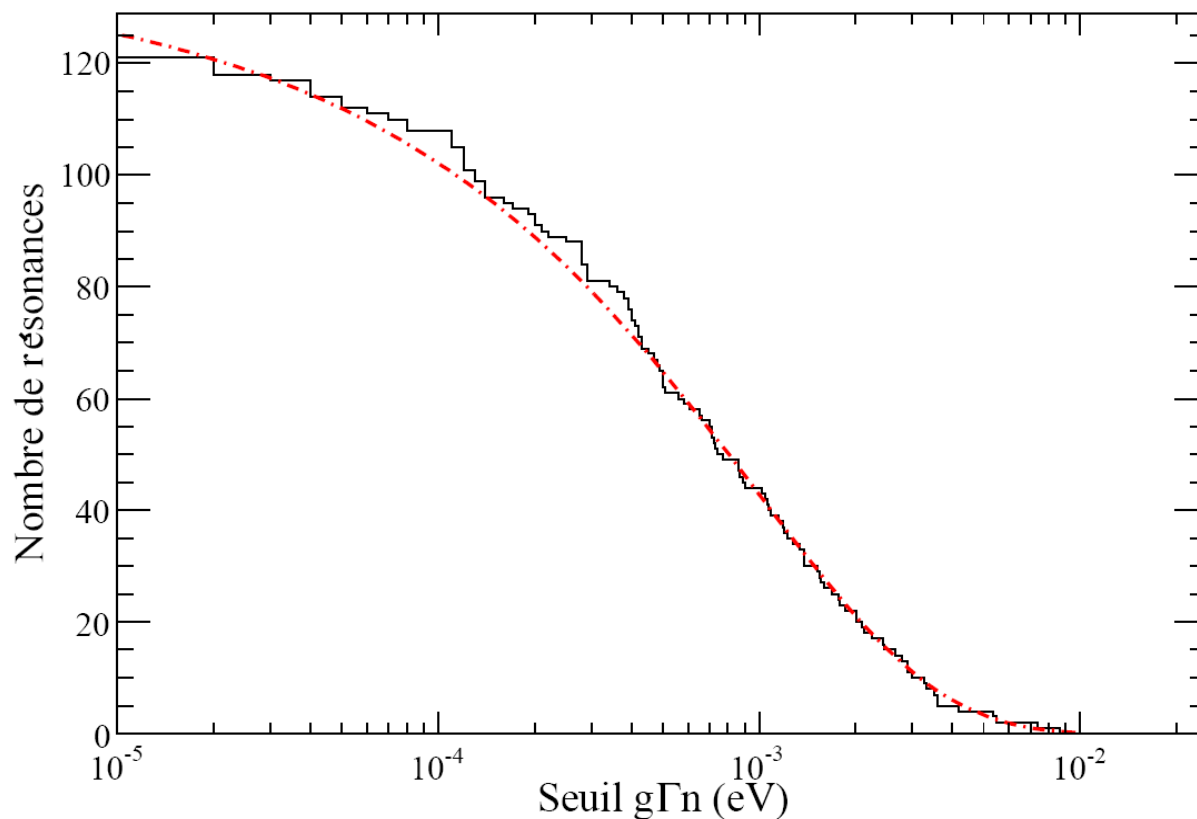
$^{241,243}\text{Am}$, ^{245}Cm



n_TOF experiments

W Dridi, E Berthoumieux, et al. (The n_TOF Collaboration)
PHYSOR-2006, Vancouver, September 2006
full paper in preparation

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



n_TOF TAC in operation

Capture

^{151}Sm

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

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

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

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

^{232}Th

^{209}Bi

^{237}Np

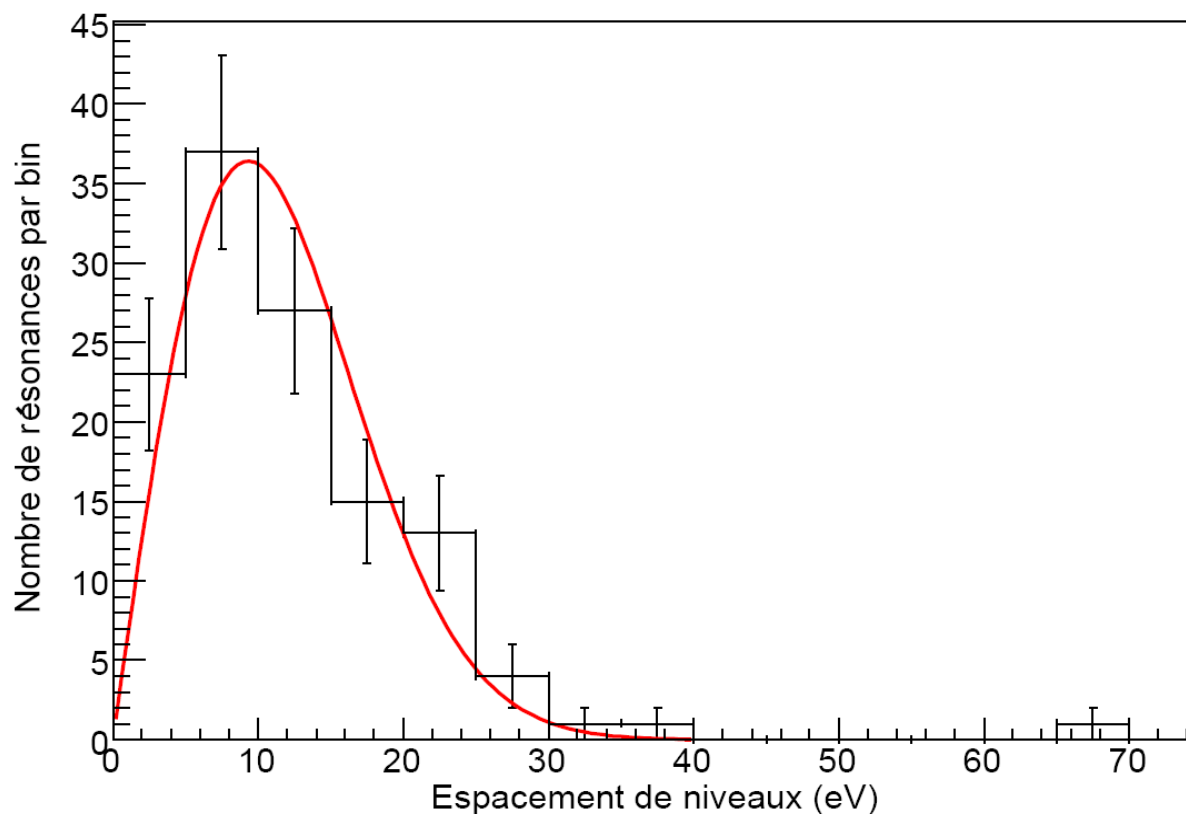
$^{241,243}\text{Am}$, ^{245}Cm



n_TOF experiments

W Dridi, E Berthoumieux, et al. (The n_TOF Collaboration)
PHYSOR-2006, Vancouver, September 2006
full paper in preparation

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



n_TOF TAC in operation

Capture

^{151}Sm

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

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^{232}Th

^{209}Bi

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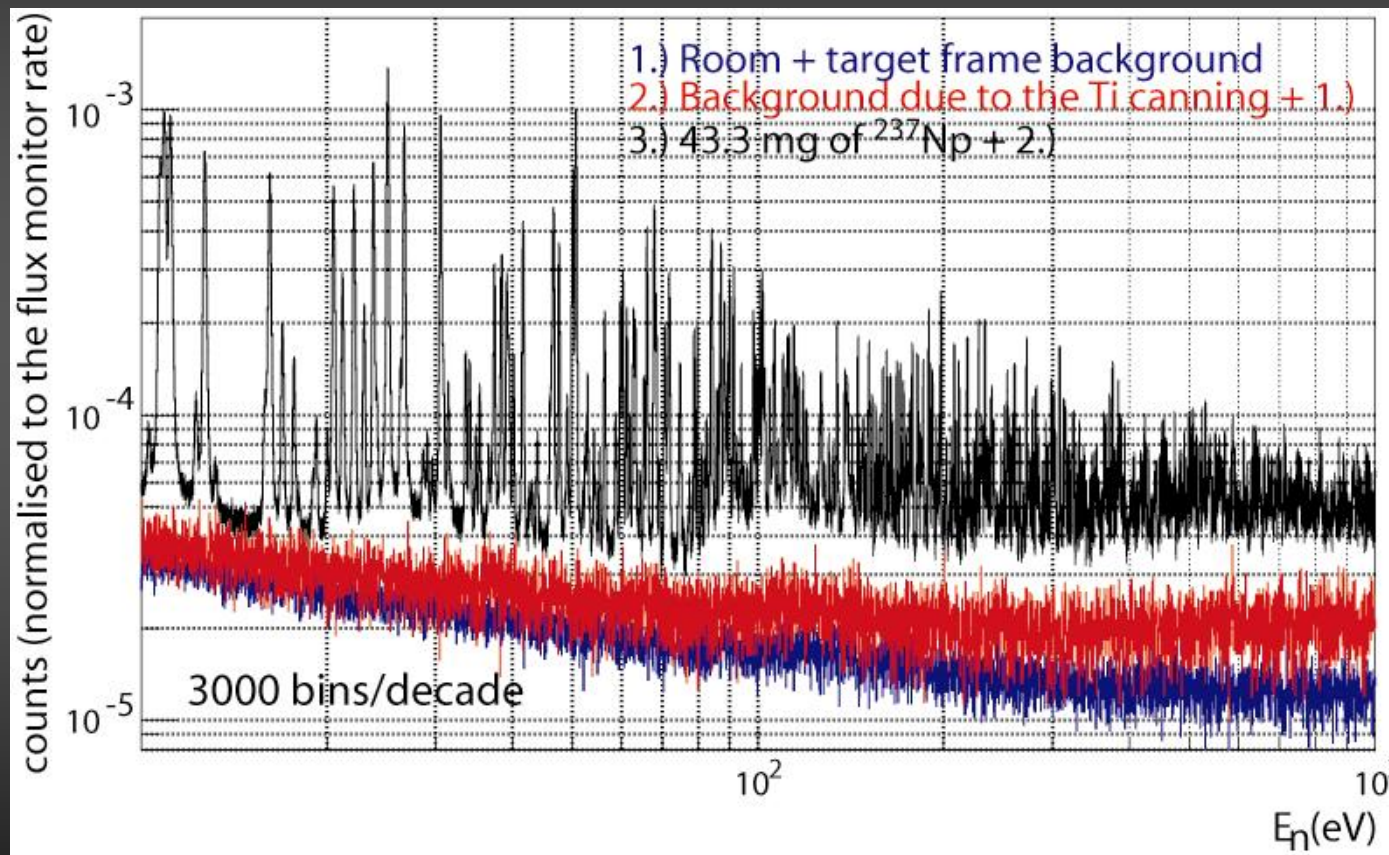
$^{241,243}\text{Am}$, ^{245}Cm



n_TOF experiments

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

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



n_TOF TAC in operation

The n_TOF Collaboration

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

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

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

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

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

^{232}Th

^{209}Bi

^{237}Np

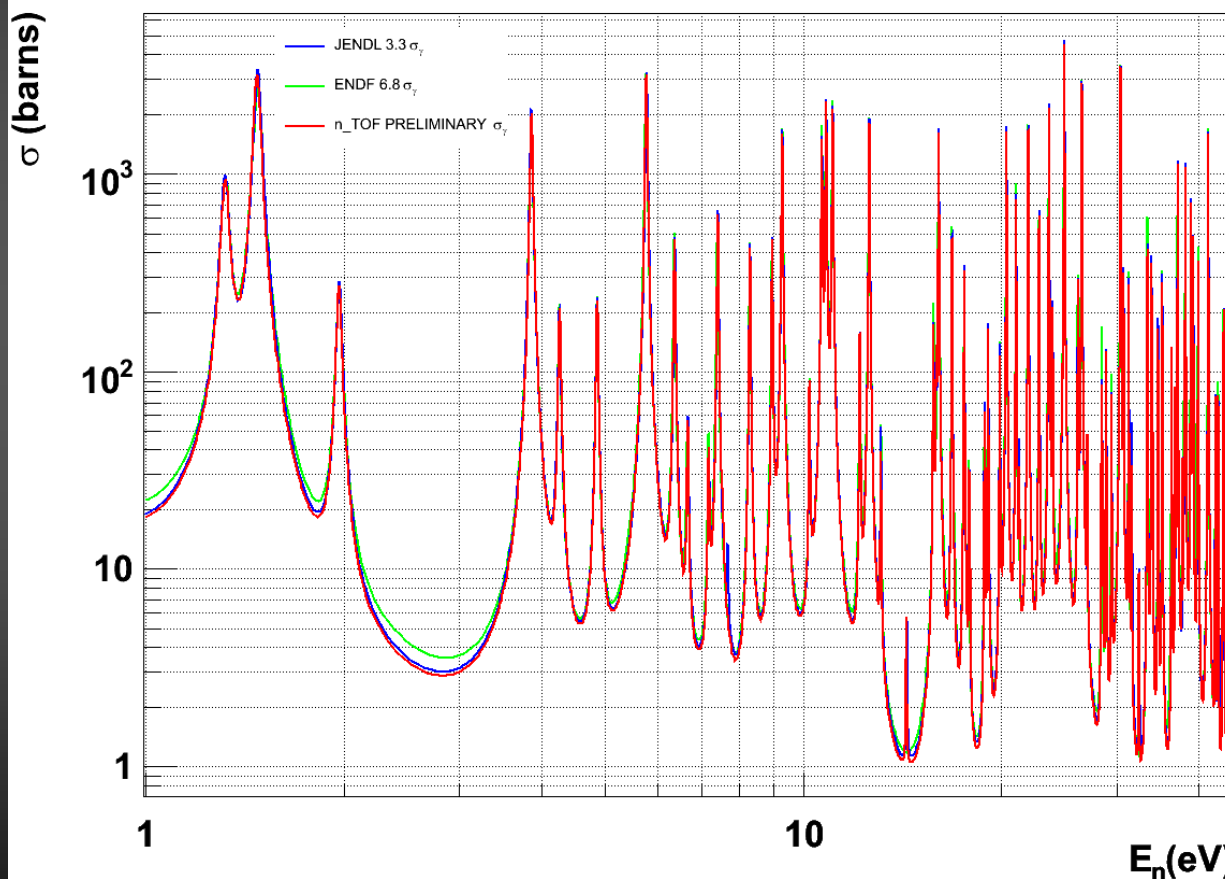
$^{241,243}\text{Am}$, ^{245}Cm



n_TOF experiments

C Guerero, D Cano-Ott, et al. - The n_TOF Collaboration
PHYSOR 2006, Vancouver, September 2006

n_TOF ^{237}Np $\sigma(n,\gamma)$ compared to Evaluated Data Libraries



n_TOF TAC in operation

The n_TOF Collaboration

Capture

^{151}Sm

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

^{232}Th

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

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^{209}Bi

^{237}Np

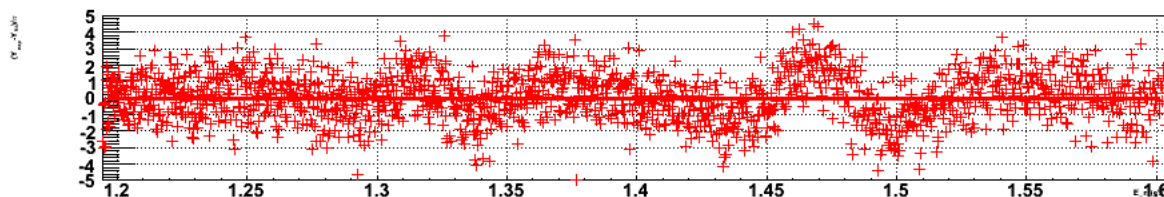
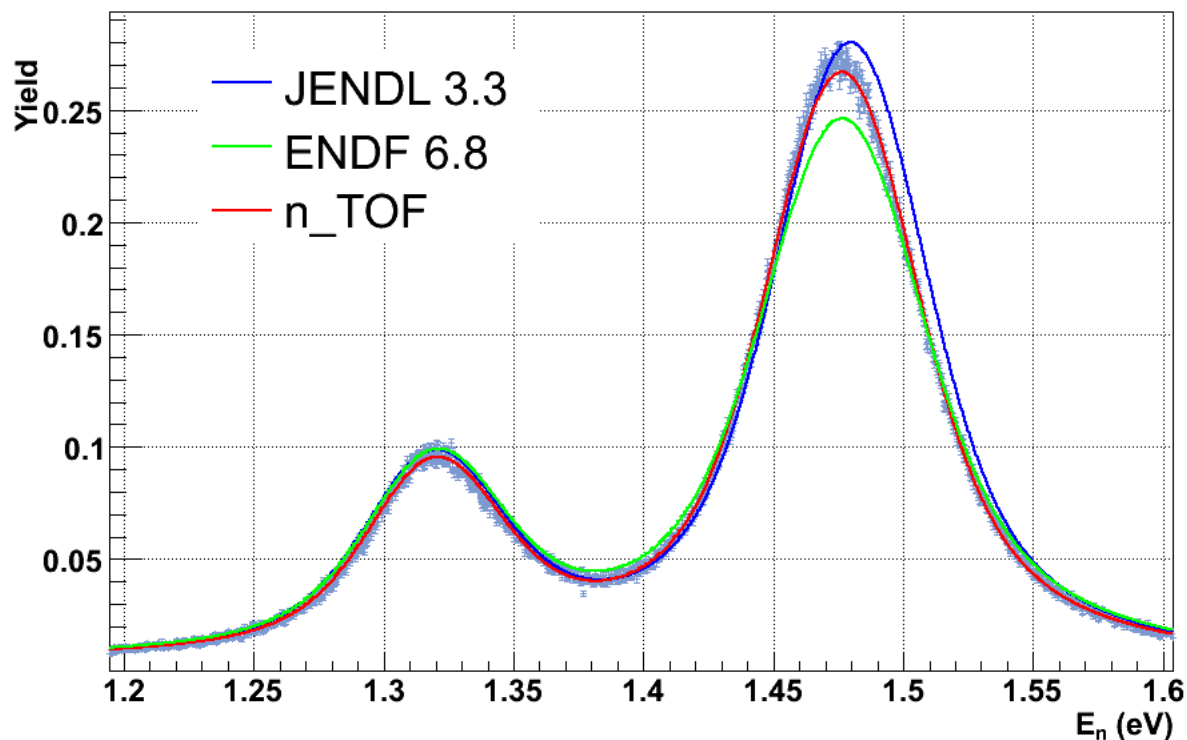
$^{241,243}\text{Am}$, ^{245}Cm



n_TOF experiments

C Guerero, D Cano-Ott, et al. - The n_TOF Collaboration
PHYSOR 2006, Vancouver, September 2006

^{237}Np experimental Yield fitted with SAMMY



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

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

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

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

^{232}Th

^{209}Bi

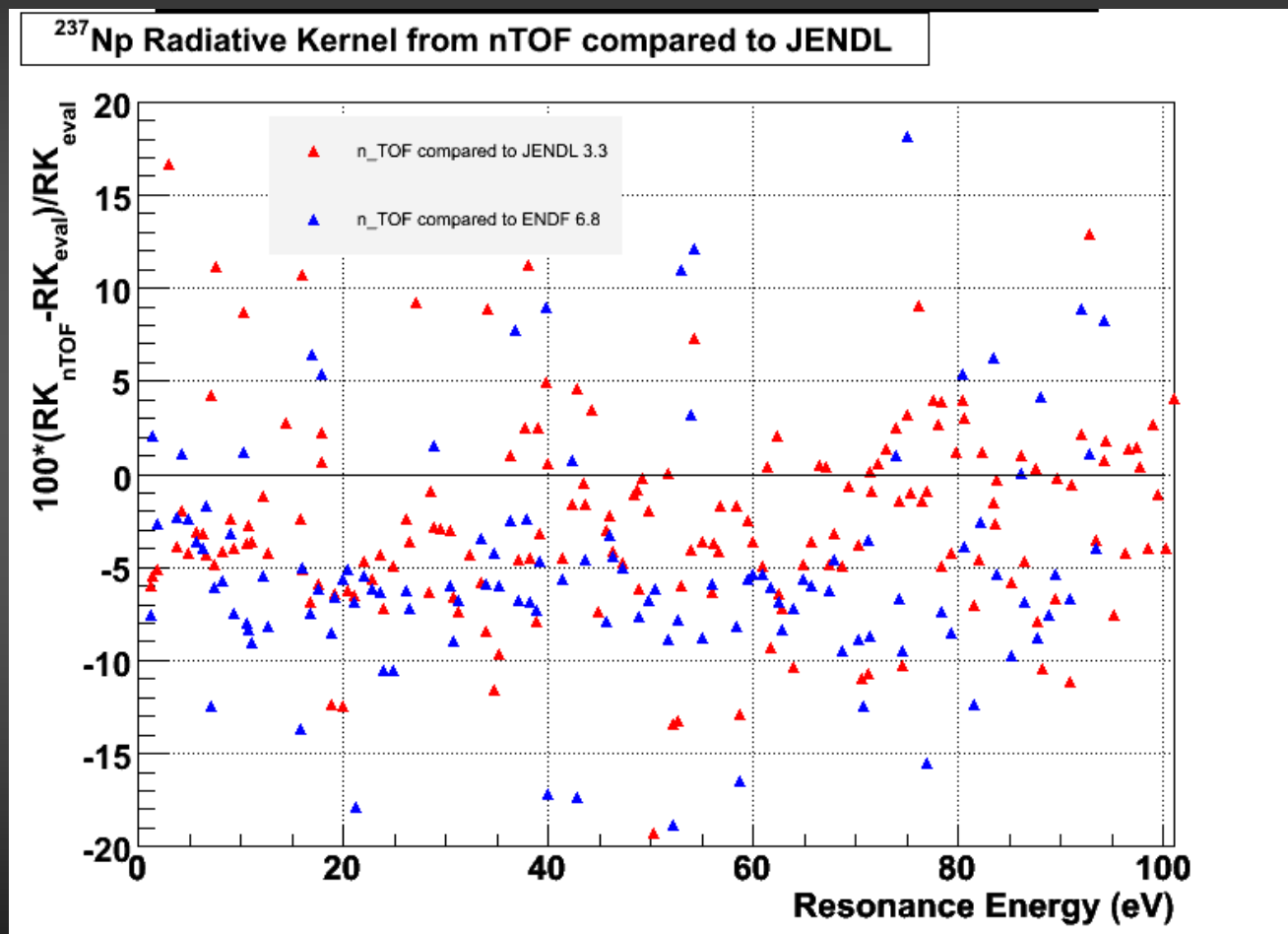
^{237}Np

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



n_TOF experiments

C Guerero, D Cano-Ott, et al. - The n_TOF Collaboration
PHYSOR 2006, Vancouver, September 2006



$\text{RK}_{\text{n_TOF}}$ on average 3% below the RK_{JENDL} and 6% below the RK_{ENDF}

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

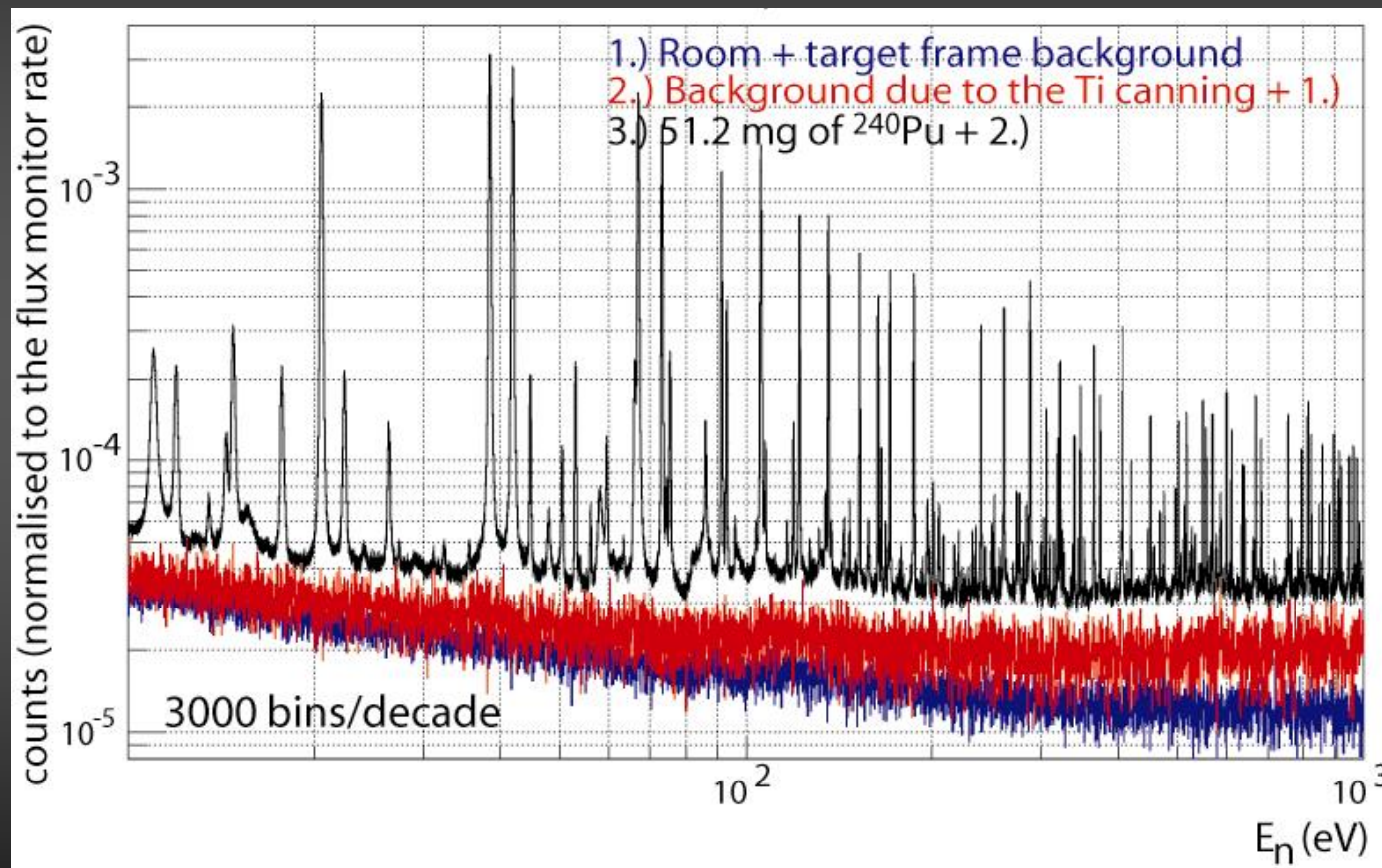
$^{241,243}\text{Am}$, ^{245}Cm



n_TOF experiments

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

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



n_TOF TAC in operation

The n_TOF Collaboration

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

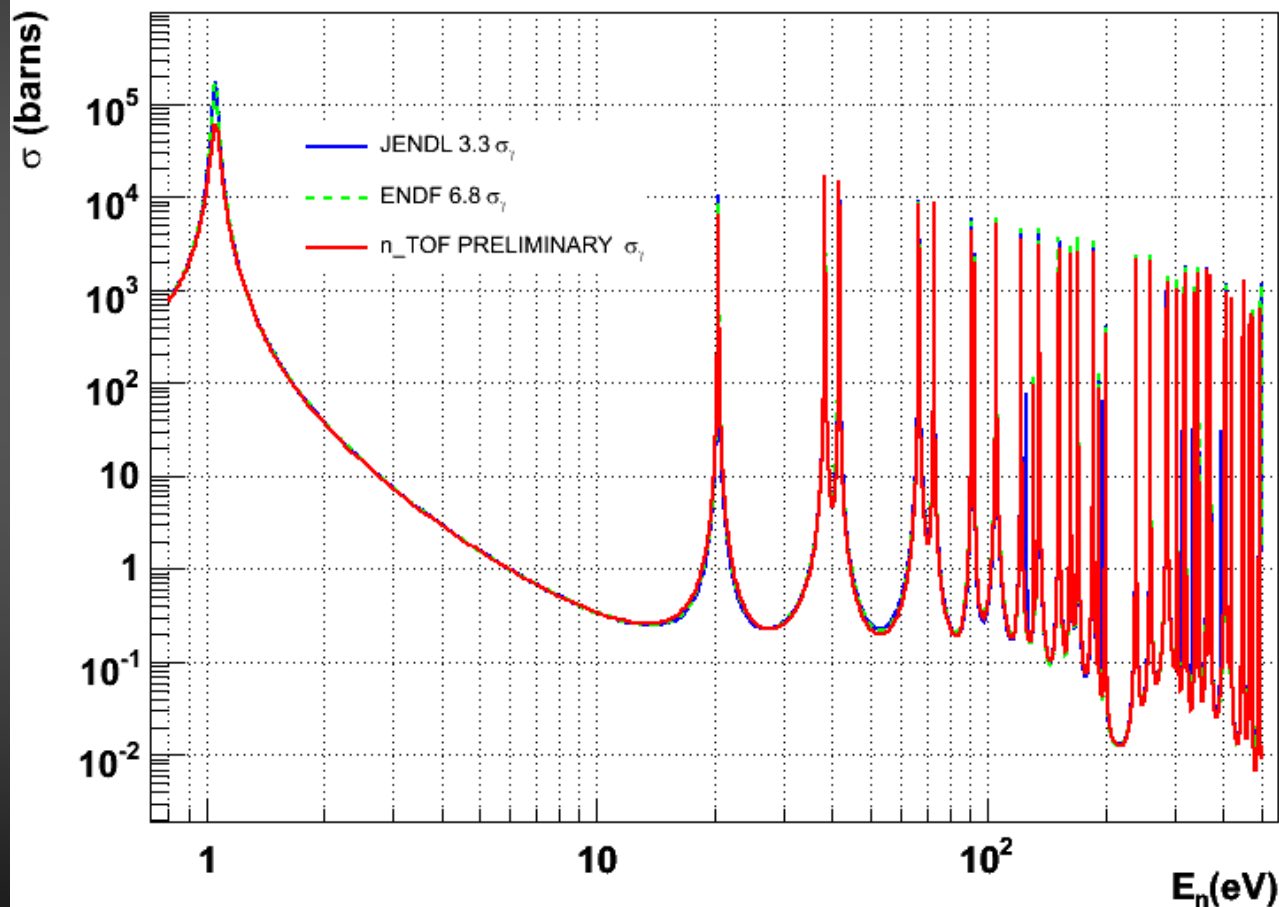
$^{241,243}\text{Am}$, ^{245}Cm



n_TOF experiments

C Guerero, D Cano-Ott, et al. - The n_TOF Collaboration
PHYSOR 2006, Vancouver, September 2006

n_TOF ^{240}Pu $\sigma(n,\gamma)$ compared to Evaluated Data Libraries



n_TOF TAC in operation

The n_TOF Collaboration

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

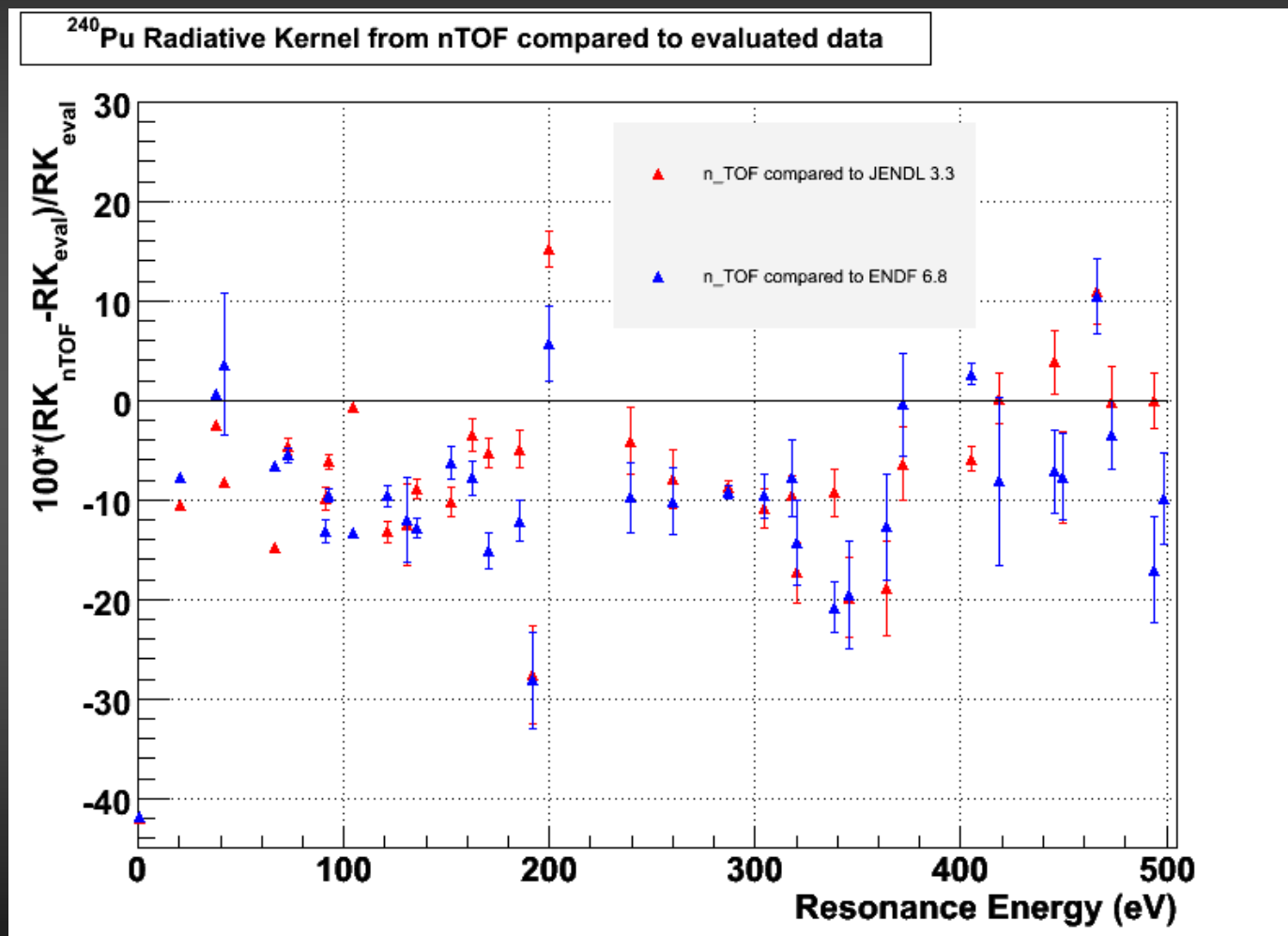
^{237}Np

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



n_TOF experiments

C Guerero, D Cano-Ott, et al. - The n_TOF Collaboration
PHYSOR 2006, Vancouver, September 2006



$\text{RK}_{\text{n_TOF}}$ is on average 9% smaller than RK_{JENDL} and 7% smaller than RK_{ENDF} .

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

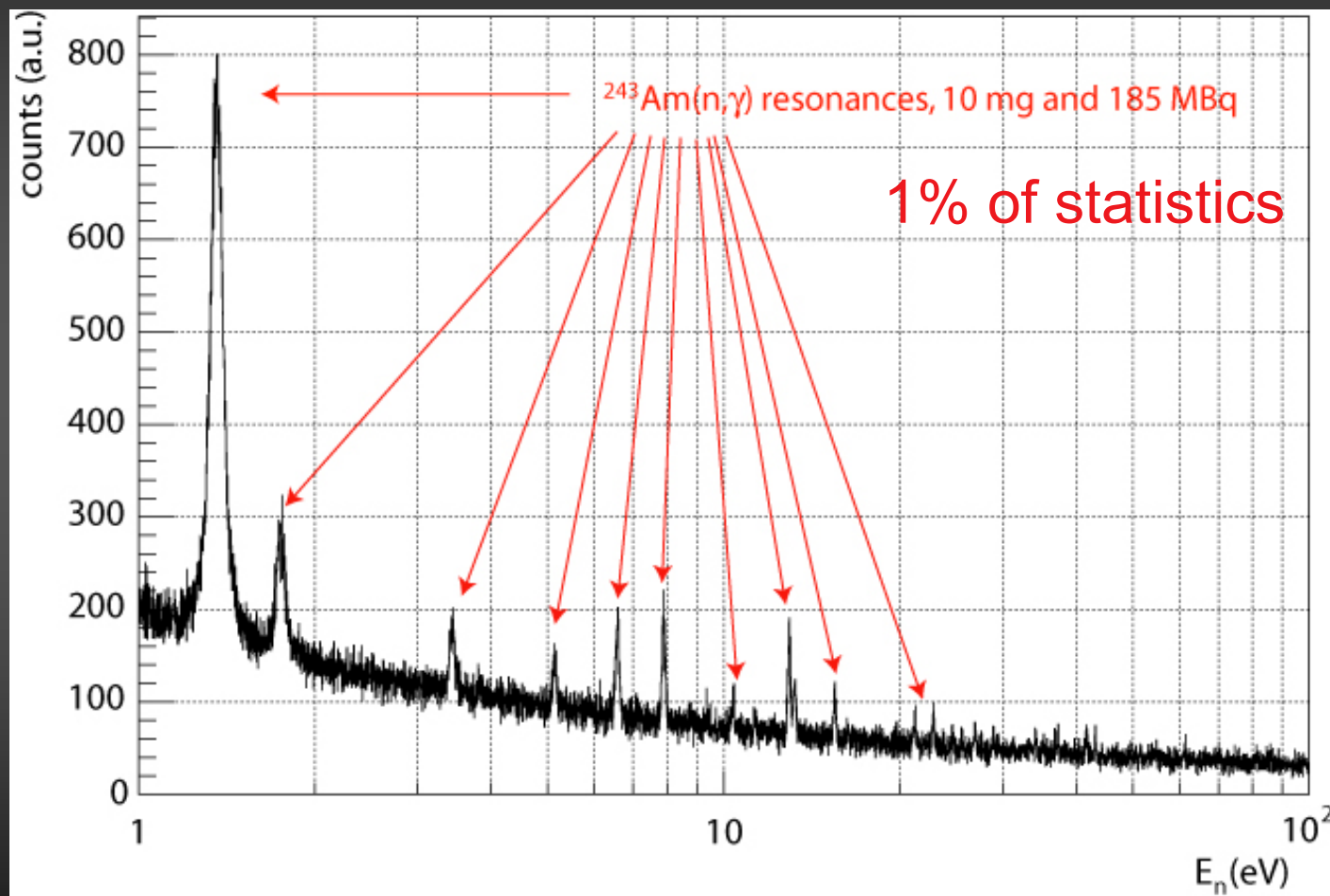
^{237}Np

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



n_TOF experiments

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



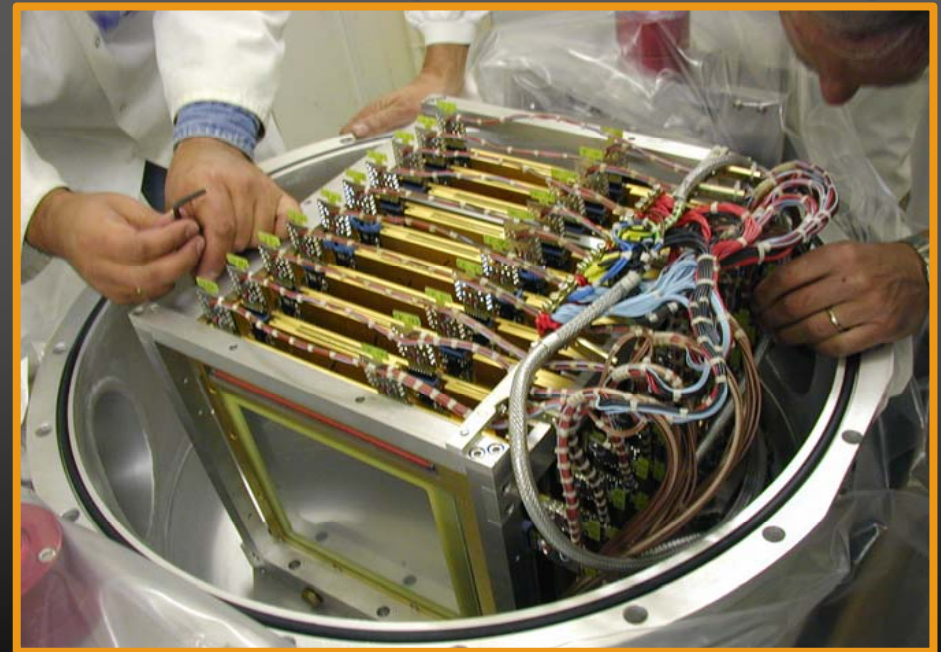
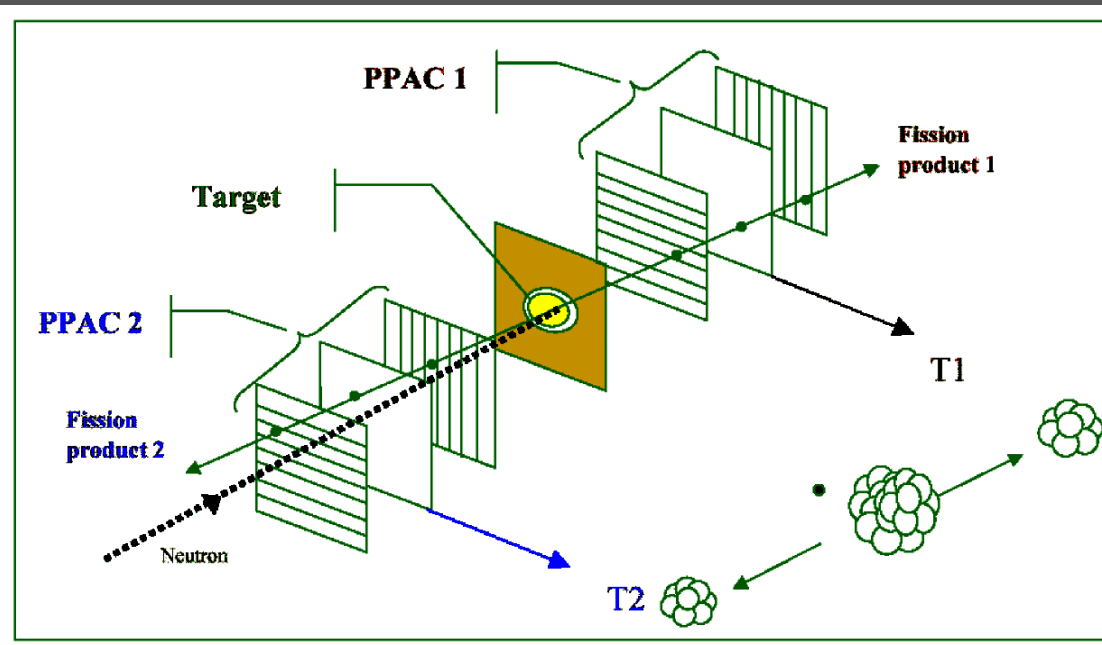
n_TOF TAC in operation

n_TOF experiments: fission measurements

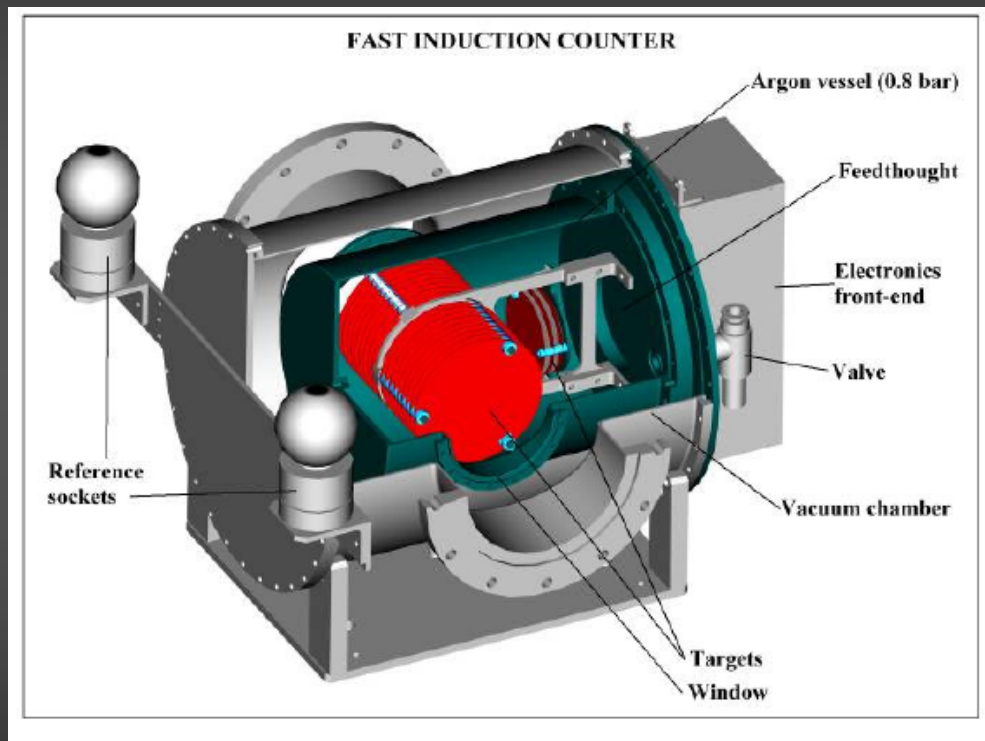
n_TOF experiments: fission measurements

- 20x20 cm²
- Isobutane gas 7 mbar
- HV 500-600 V
- 3 mm between electrodes
- 1 anode (a few ns signal width)
- Electrode thickness: 1.5 μm (Mylar+Al)
- Deposit thickness : 100-300 μg/cm²
- Backing thickness : 0.1 μm (Al)
- : 1.5 μm (Mylar)
- Fission event identification: T2 in coincidence with T1

developed at IPN Orsay



n_TOF experiments: fission measurements



- Gas: Ar (90%) CF_4 (10%)
- Gas pressure : 720 mbar
- Electric field : 600 V/cm
- Gap pitch : 5 mm
- Electrode diameter : 12 cm
- Electrode thickness: 15 μm (Al)
- Deposit thickness : 125 $\mu\text{m}/\text{cm}^2$
- Backing thickness : 100 μm (Al)
- Window thickness : 125 μm

developed by a CERN/Obninsk/Dubna team

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

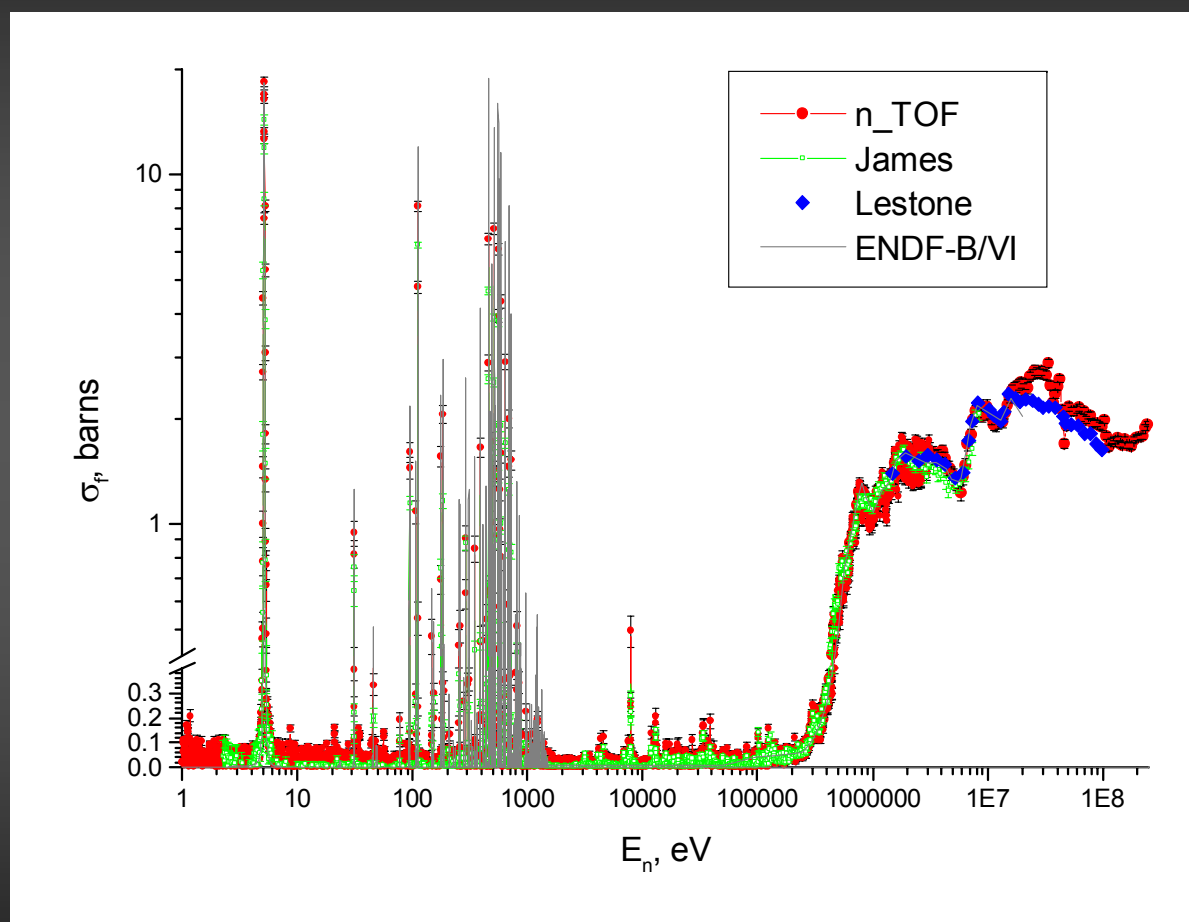
$^{241,243}\text{Am}$, ^{245}Cm



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

n_TOF experiments

PPACs & FIC-0 (2003)



An unprecedented wide energy range can be explored at n_TOF in a single experiment

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

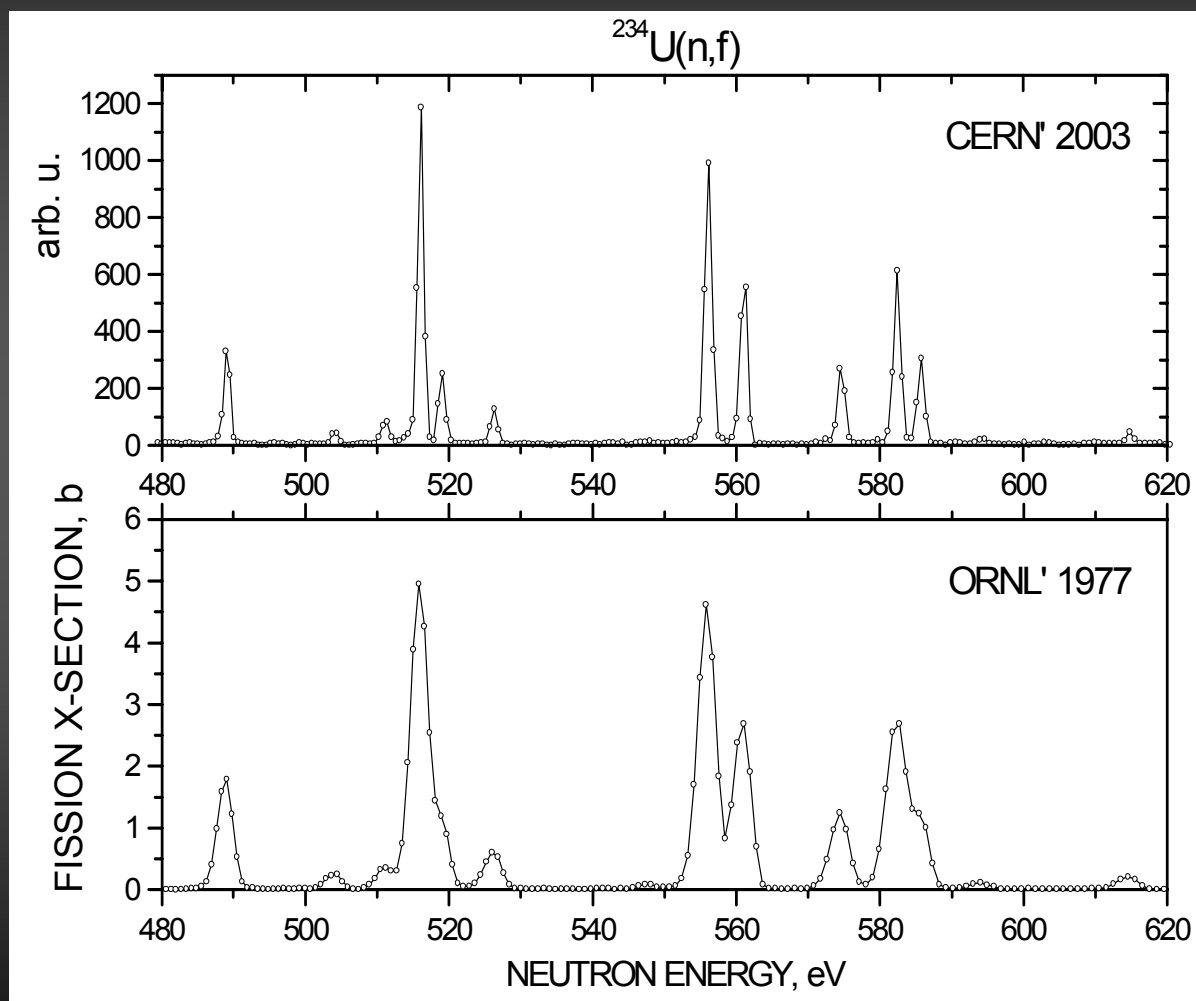
$^{241,243}\text{Am}$, ^{245}Cm



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

n_TOF experiments

PPACs & FIC-0 (2003)



High-resolution data up to high(er) energies

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

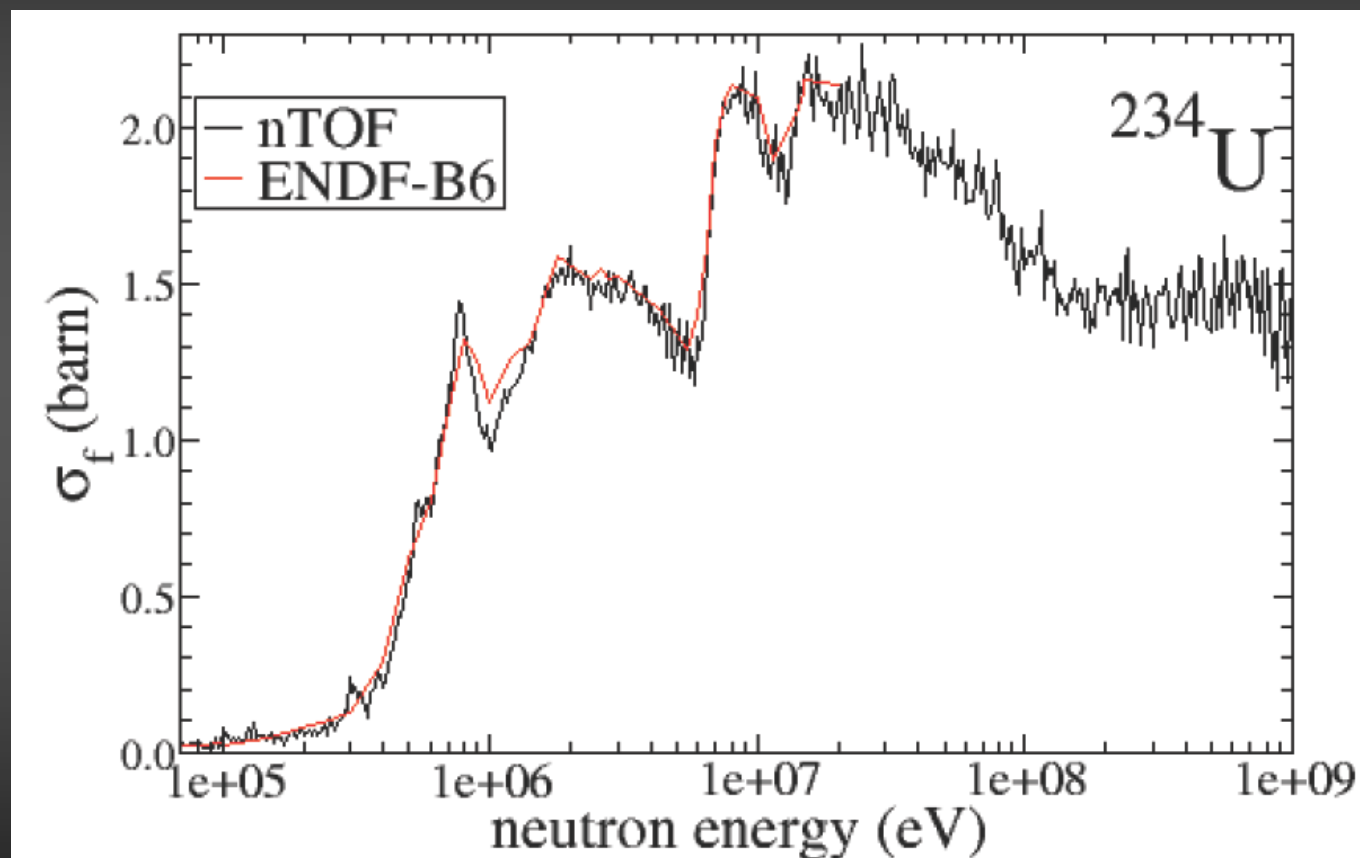
$^{241,243}\text{Am}$, ^{245}Cm



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

n_TOF experiments

PPACs & FIC-0 (2003)



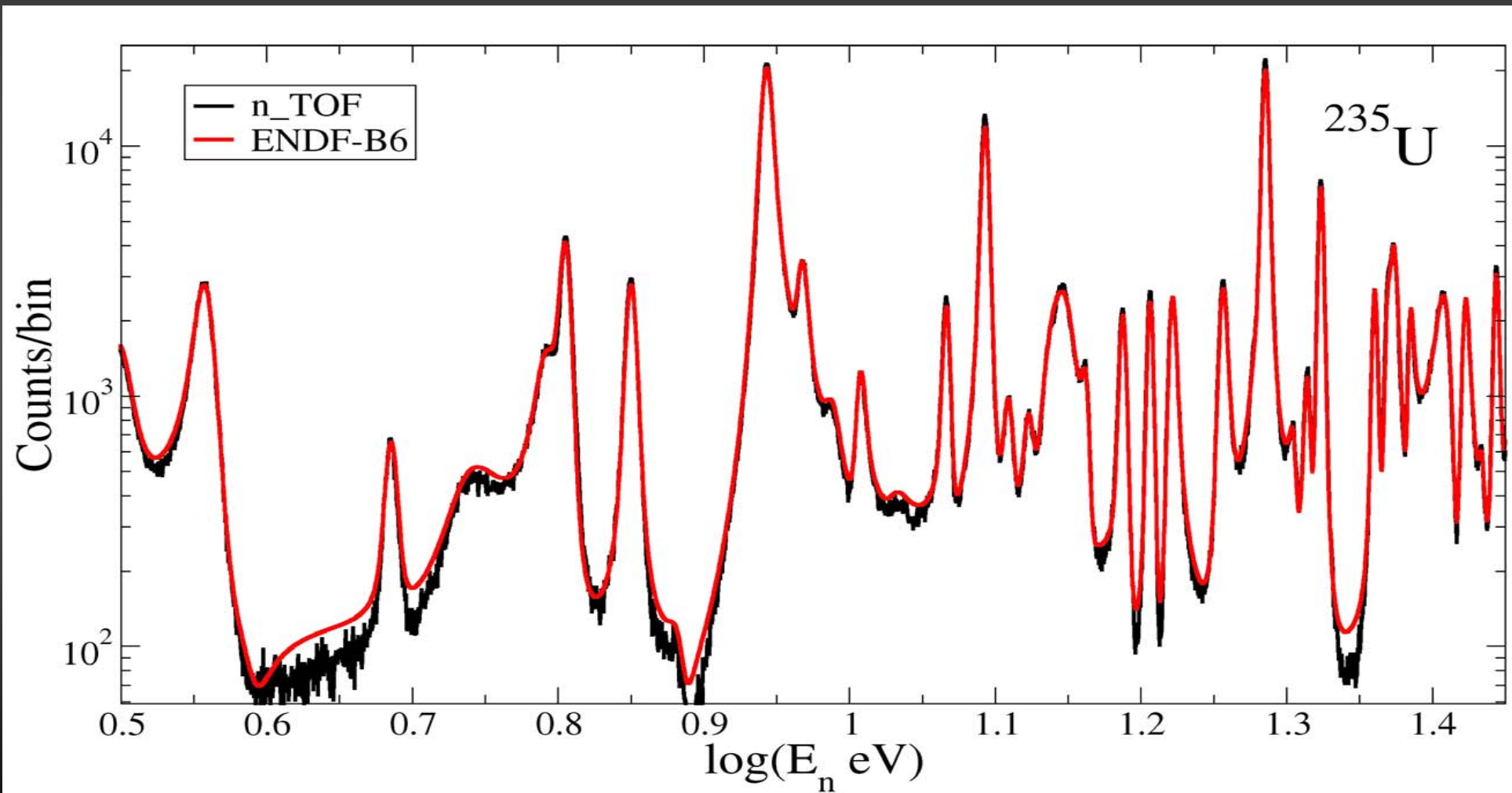
High-resolution data up to high(er) energies



n_TOF experiments

$^{235}\text{U}(n,f)$

PPACs (2002 & 2003)



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

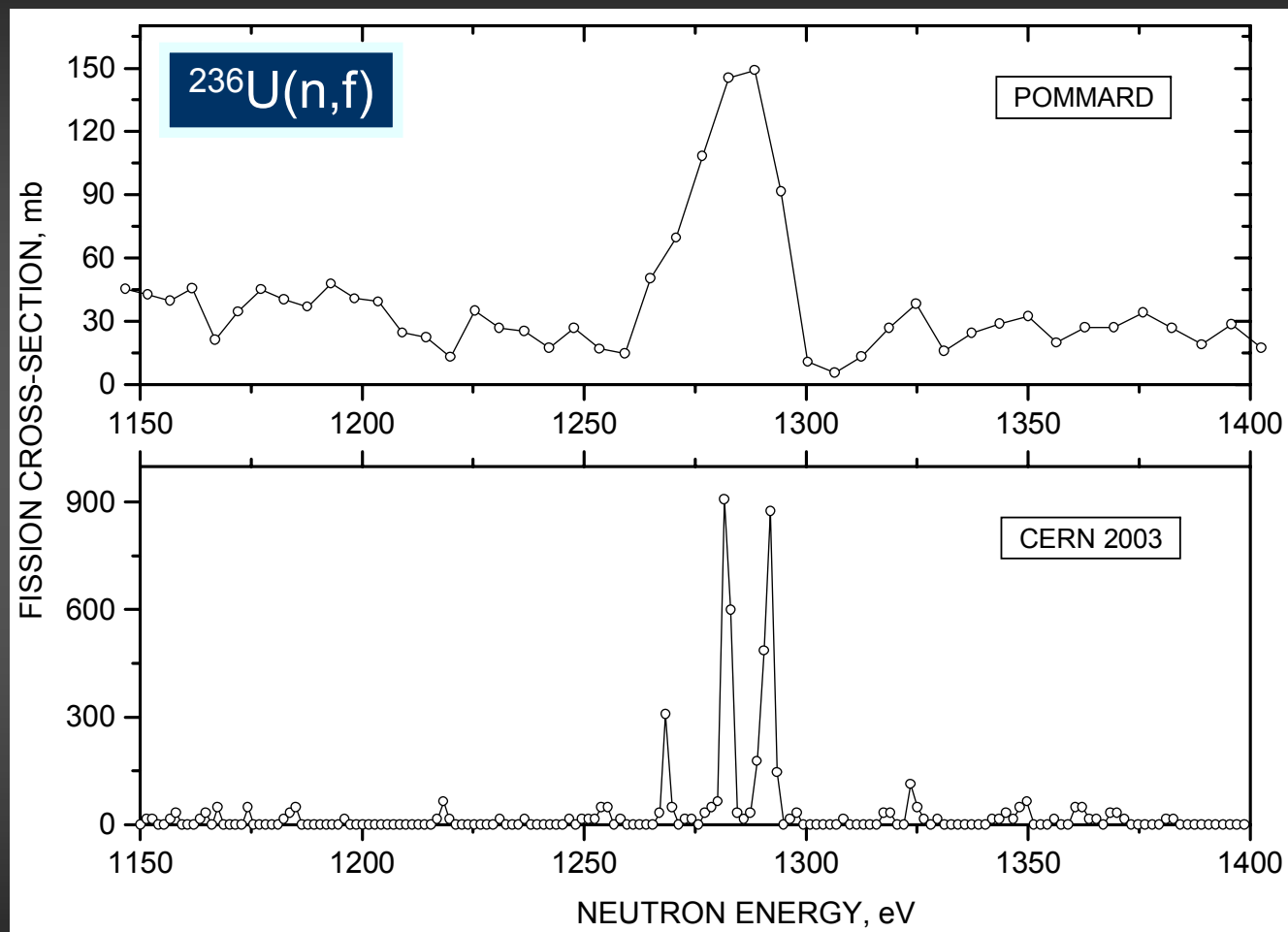
^{237}Np

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



n_TOF experiments

FIC-1 (2003)



An unprecedented wide energy range can be explored at n_TOF in a single experiment

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

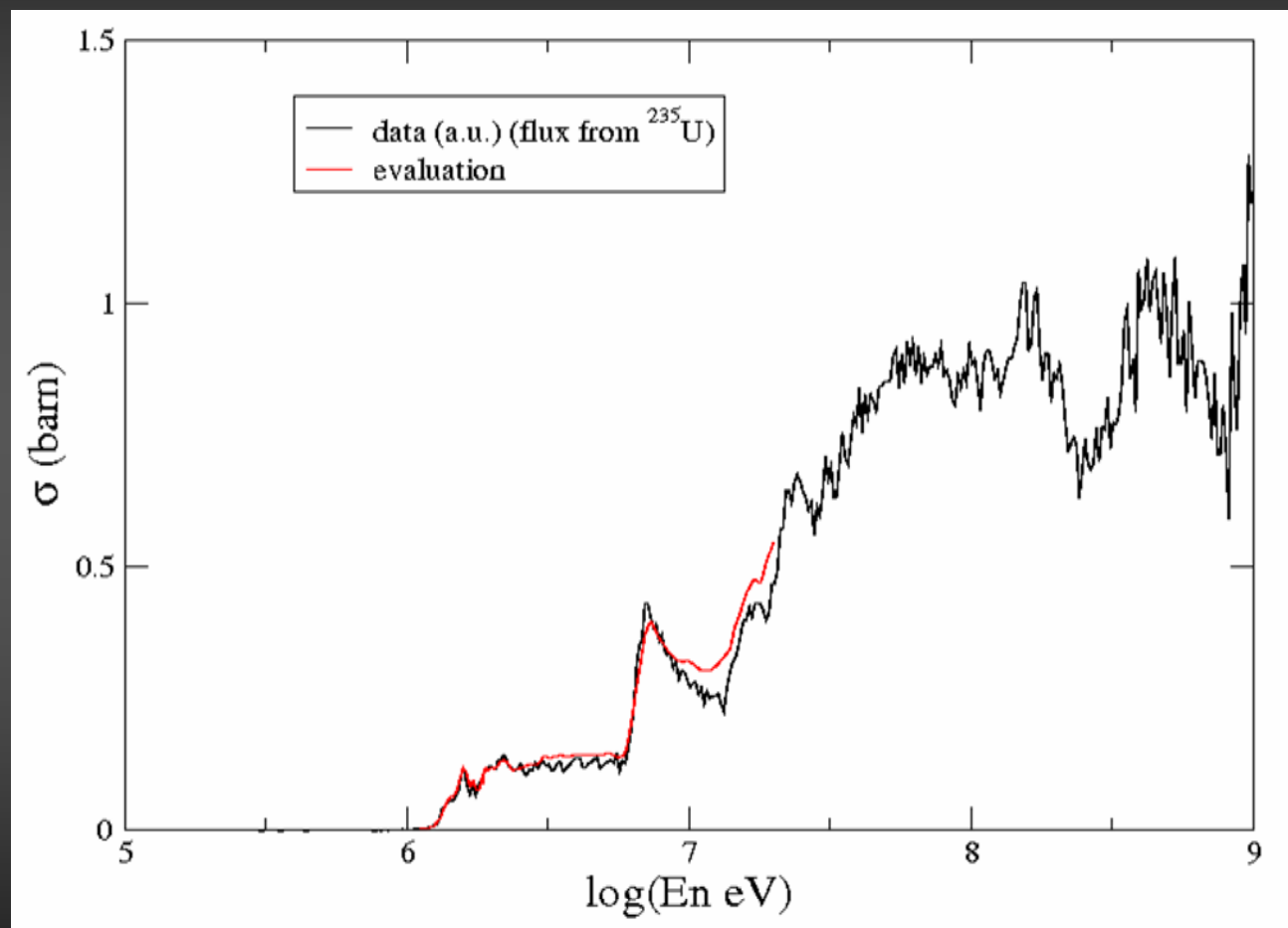
$^{241,243}\text{Am}$, ^{245}Cm



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

n_TOF experiments

PPAC detectors



An unprecedented wide energy range can be explored at n_TOF in a single experiment

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

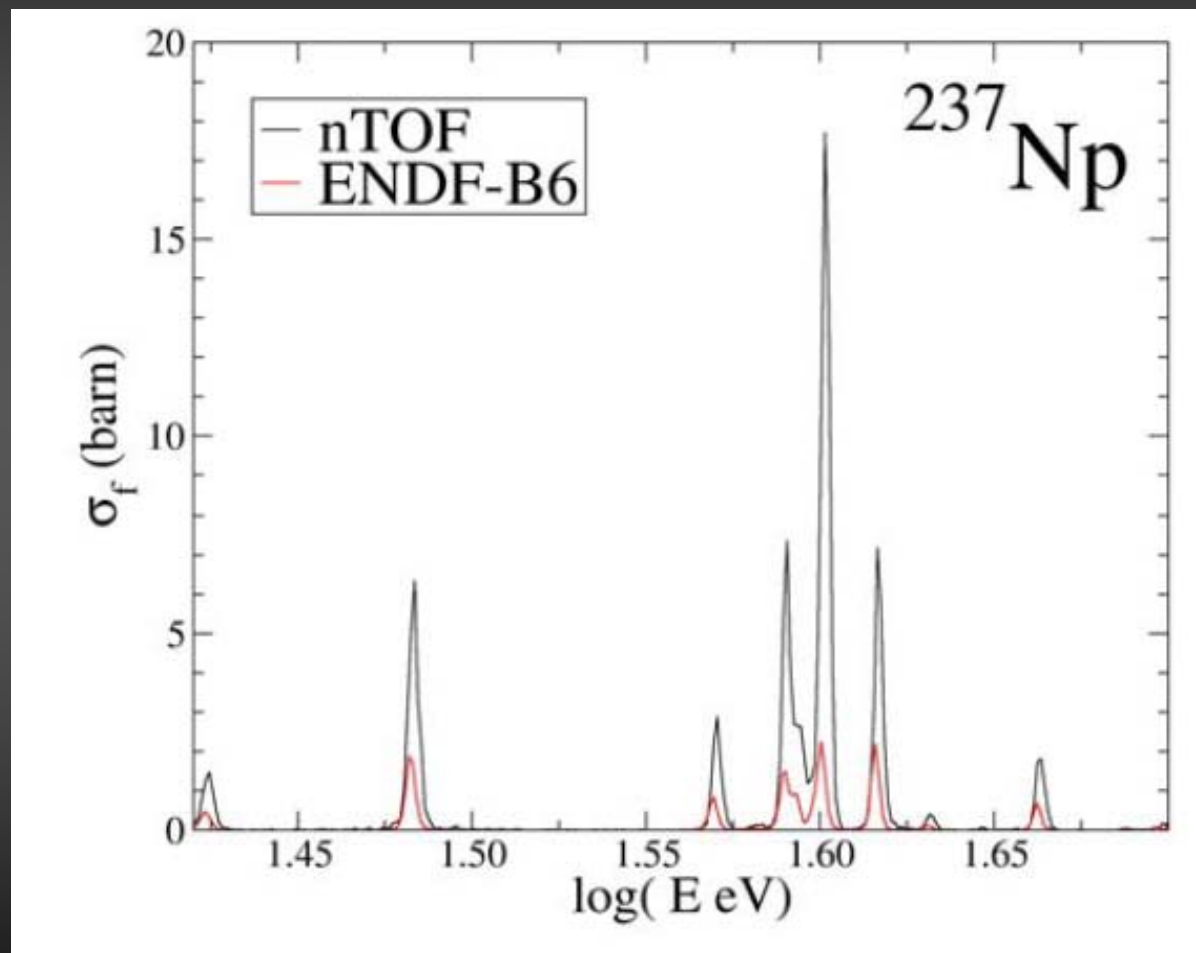
$^{241,243}\text{Am}$, ^{245}Cm



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

n_TOF experiments

FIC-0 (2003)



Higher fission x-section in the sub-threshold region

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

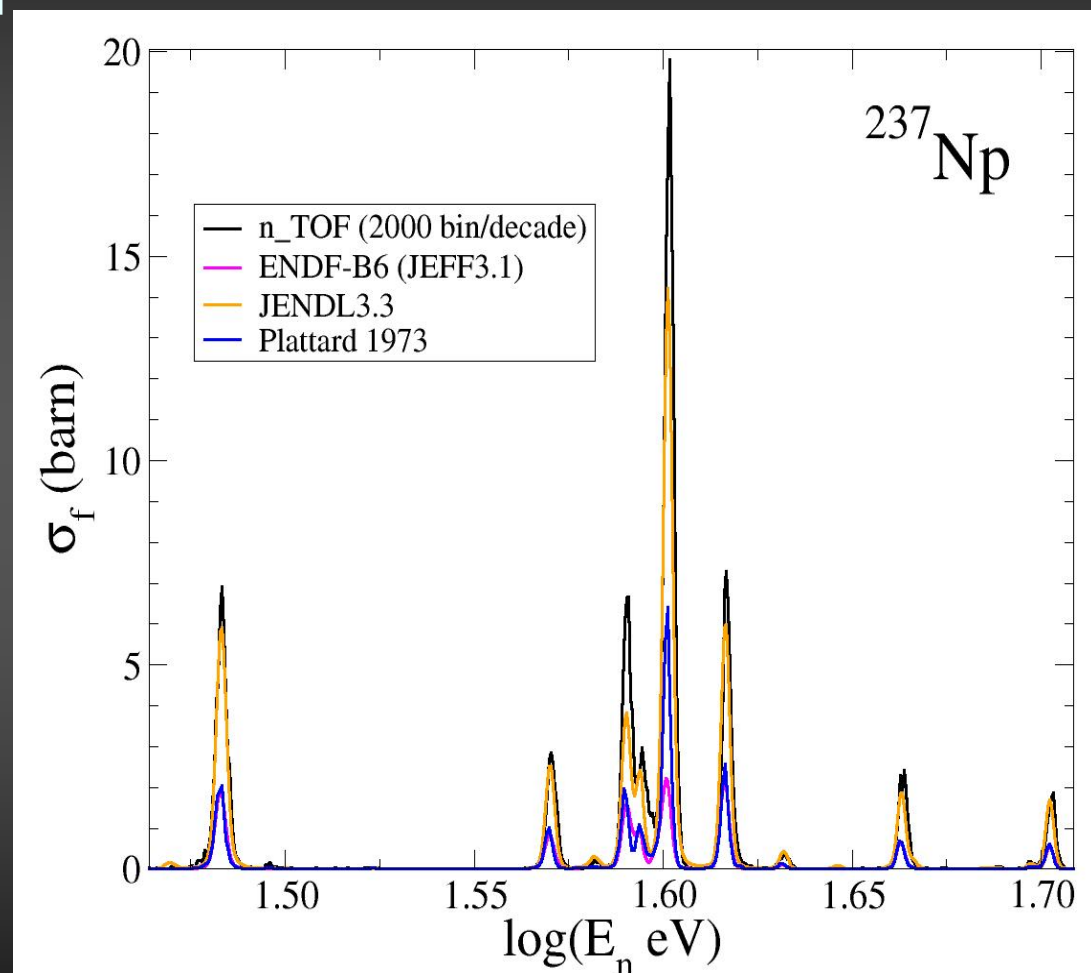
$^{241,243}\text{Am}$, ^{245}Cm



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

n_TOF experiments

PPACs (2003)



Higher fission x-section in the sub-threshold region

The n_TOF Collaboration

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

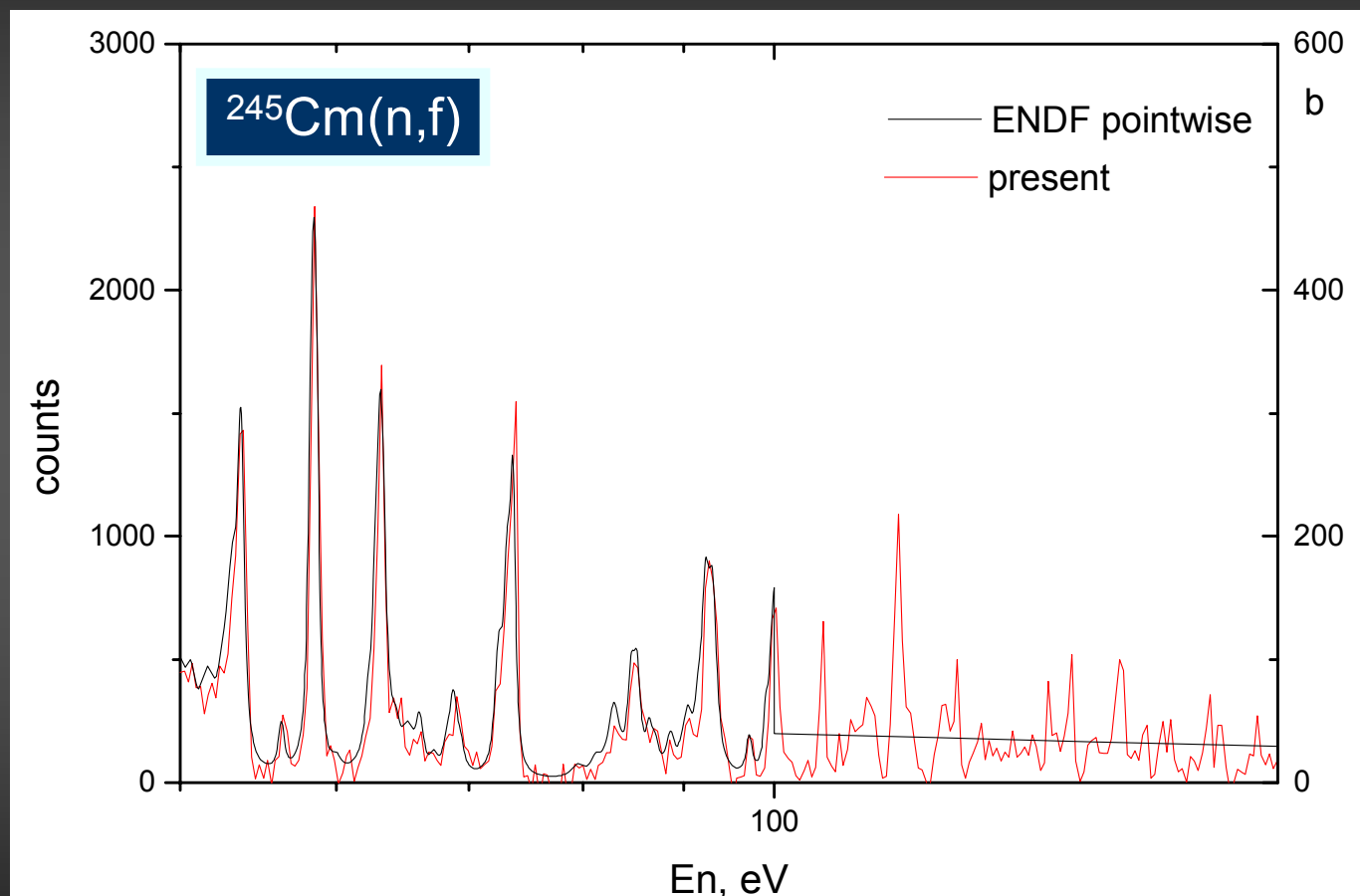
^{237}Np

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



n_TOF experiments

FIC-1 (2003)



High-resolution data up to high(er) energies

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

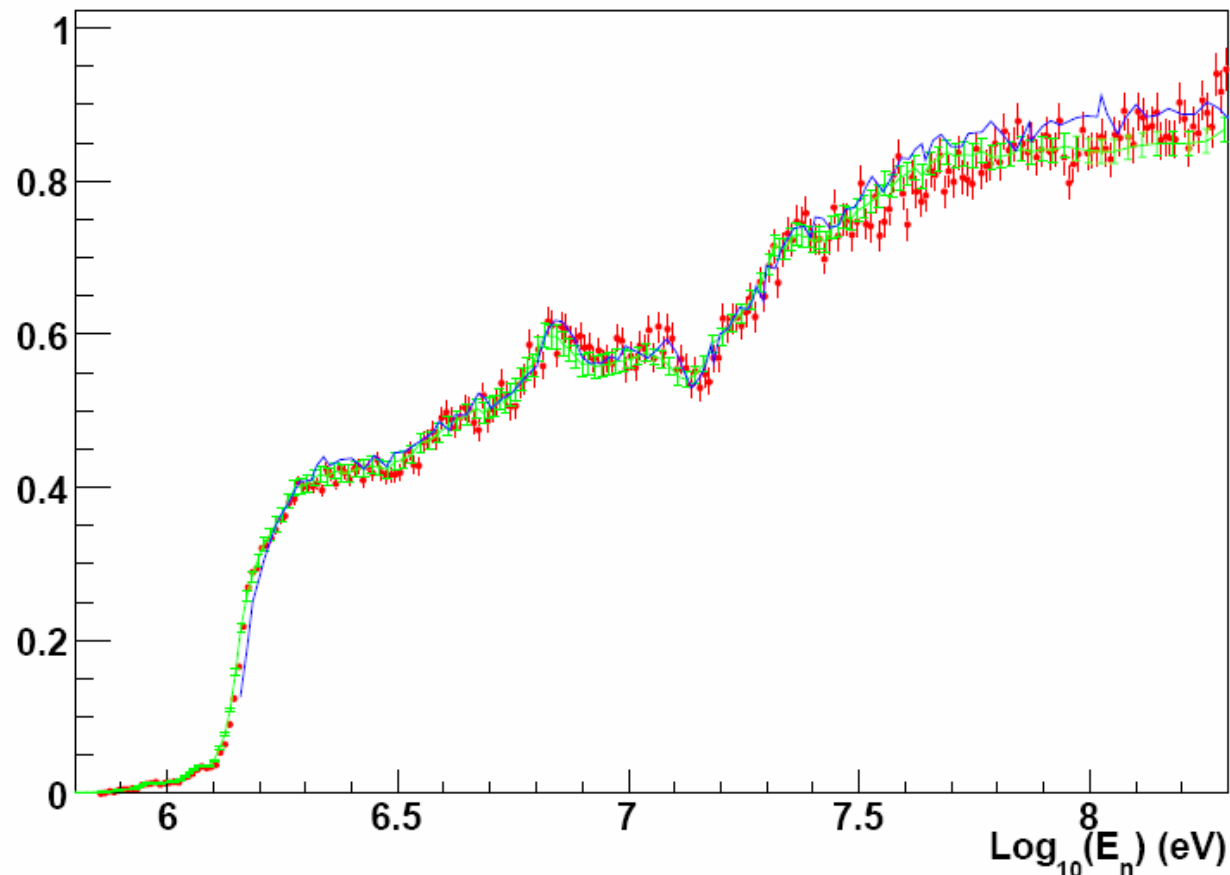


$^{238}\text{U}(n,f)/^{238}\text{U}(n,f)$

n_TOF experiments

FIC1 data
source: M Calviani et al. (INFN)

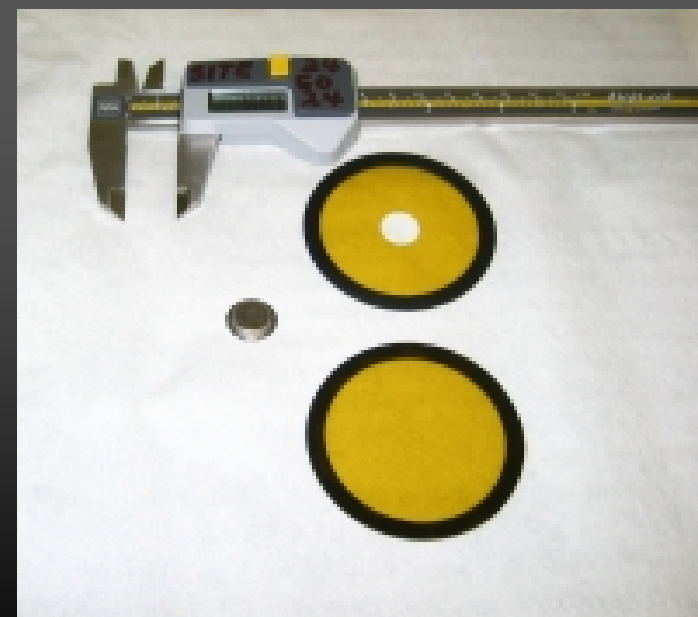
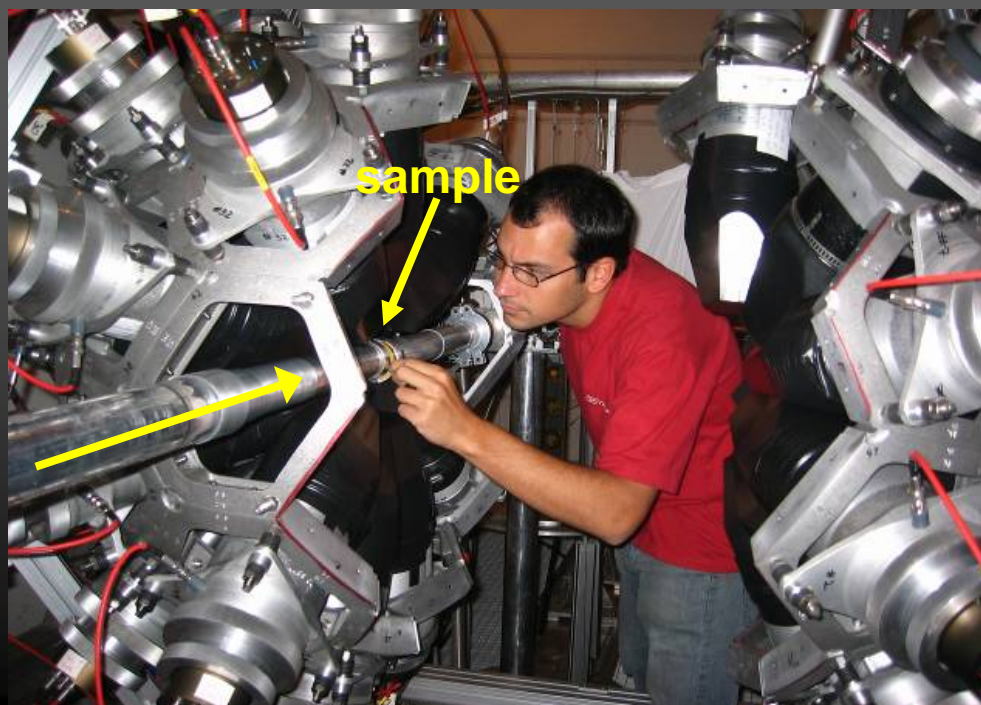
$^{238}\text{U}(n,f)/^{235}\text{U}(n,f)$ ratio



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Capture samples

Sample	A	half-life	half-life	Lambda	Mass	N	Activity		LA	# of LA
		yr	s				Bq	Ci		
Sm-151	151	9.30E+01	2.9E+09	2.36E-10	160	6.36E+20	1.5E+11	4.1E+00	-	-
U-233	233	1.59E+05	5.0E+12	1.38E-13	100	2.58E+20	3.6E+07	9.6E-04	700	50,755
U-234	234	2.46E+05	7.7E+12	8.95E-14	37	9.49E+19	8.5E+06	2.3E-04	700	12,126
U-236	236	2.34E+07	7.4E+14	9.38E-16	400	1.02E+21	9.5E+05	2.6E-05	800	1,192
Np-237	237	2.10E+06	6.6E+13	1.05E-14	50	1.27E+20	1.3E+06	3.6E-05	300	4,413
Pu-240	240	6564	2.1E+11	3.35E-12	50	1.25E+20	4.2E+08	1.1E-02	200	2,091,380
Pu-242	242	3.73E+05	1.2E+13	5.88E-14	20	4.96E+19	2.9E+06	7.9E-05	200	14,588
Am-241	241	432	1.4E+10	5.08E-11	400	9.96E+20	5.1E+10	1.4E+00	200	253,164,001
Am-243	243	7370	2.3E+11	2.98E-12	25	6.17E+19	1.8E+08	5.0E-03	200	919,833



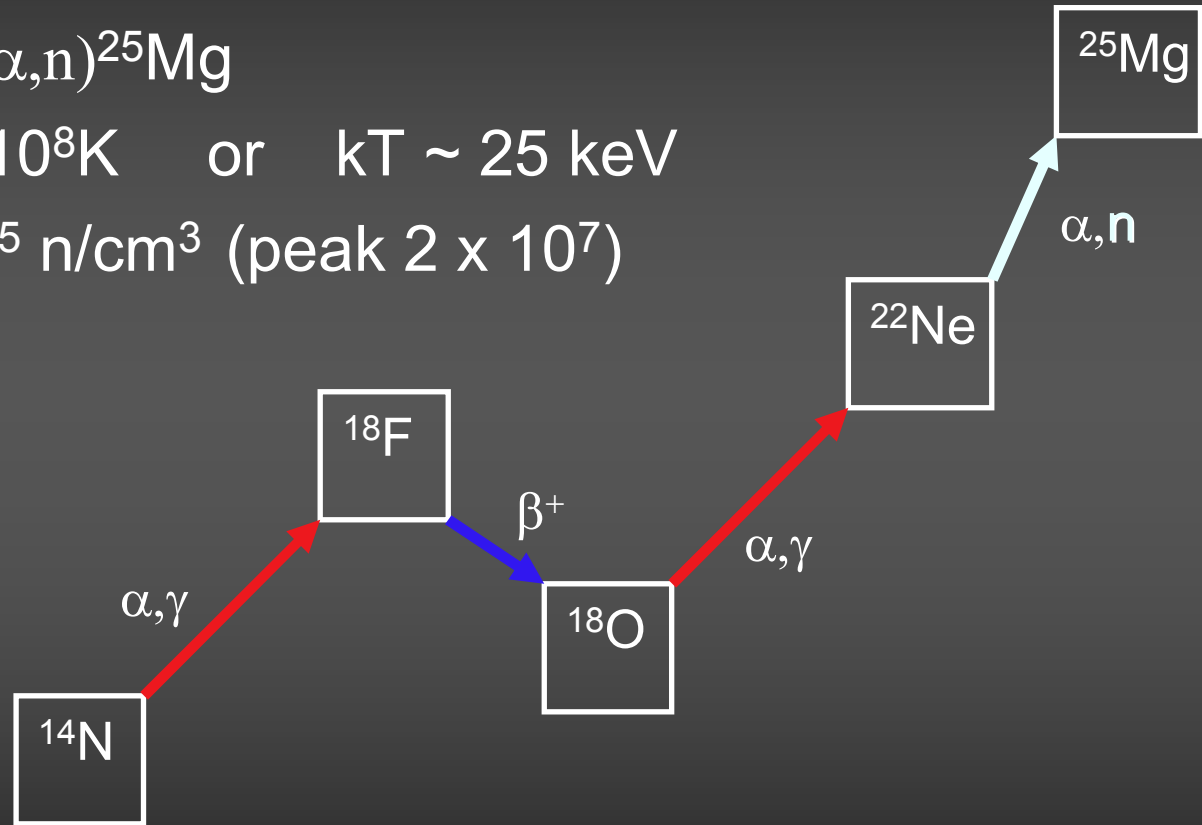
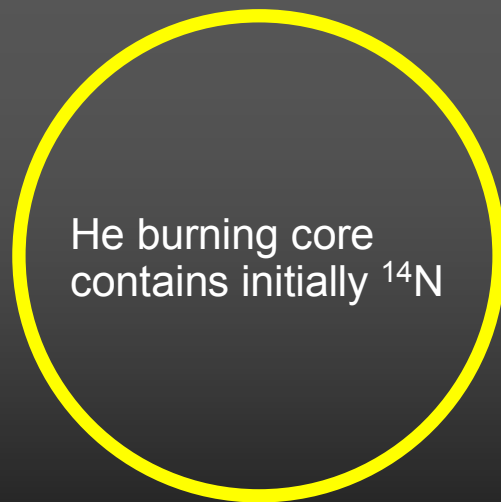
Fission samples (FIC detectors)

Isotope	Diam. [mm]	Density [$\mu\text{g}/\text{cm}^2$]	# of targets	Mass [mg]	T1/2 [yr]	A [Bq]	A[Ci]	N
U-234	50	150	6	35.3	2.46E+05	8.1E+06	2.2E-04	9.1E+19
U-235	50	200	2	15.7	7.04E+08	1.3E+03	3.4E-08	4.0E+19
U-236	80	100	2	20.1	2.34E+07	4.8E+04	1.3E-06	5.1E+19
U-238	80	300	2	60.3	4.47E+09	7.5E+02	2.0E-08	1.5E+20
Th-232	80	400	2	80.4	1.41E+10	3.2E+02	8.8E-09	2.1E+20
Np-237	80	150	1	15.1	2.10E+06	4.0E+05	1.1E-05	3.8E+19
Am-241	80	5	4	2.0	432.2	2.5E+08	6.9E-03	5.0E+18
Am-243	80	25	4	10.0	7370	7.4E+07	2.0E-03	2.5E+19
Cm-245	80	10	2	2.0	8500	1.3E+07	3.4E-04	4.9E+18

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s-process site-s & conditions: weak

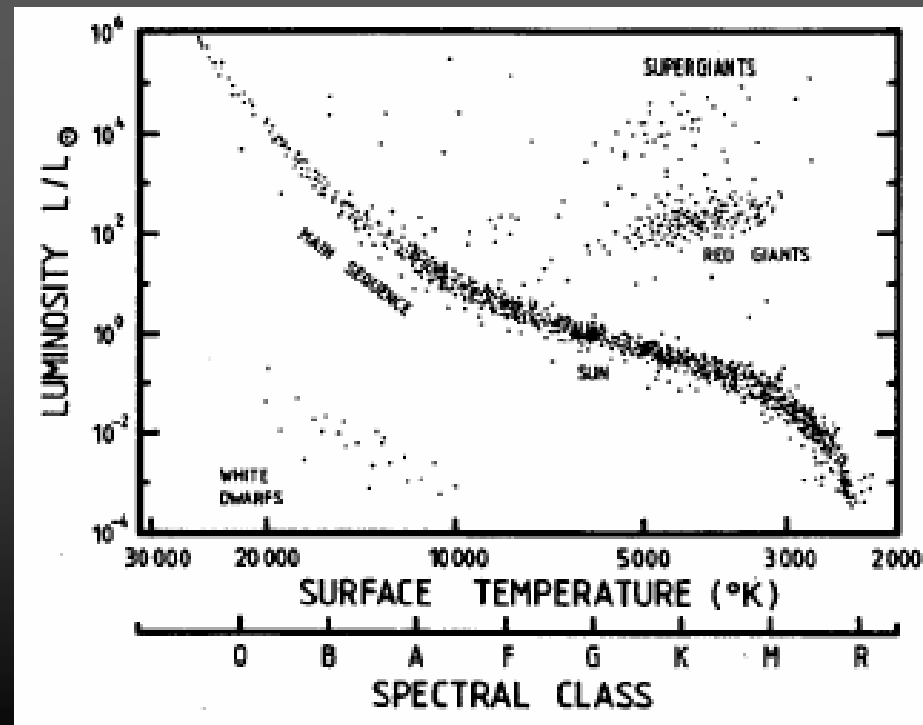
Site	He-burning phase of intermediate/massive stars
Neutron sources	$^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$
Temperature	$\sim 3 \times 10^8 \text{K}$ or $kT \sim 25 \text{keV}$
Neutron density	$7 \times 10^5 \text{ n/cm}^3$ (peak 2×10^7)



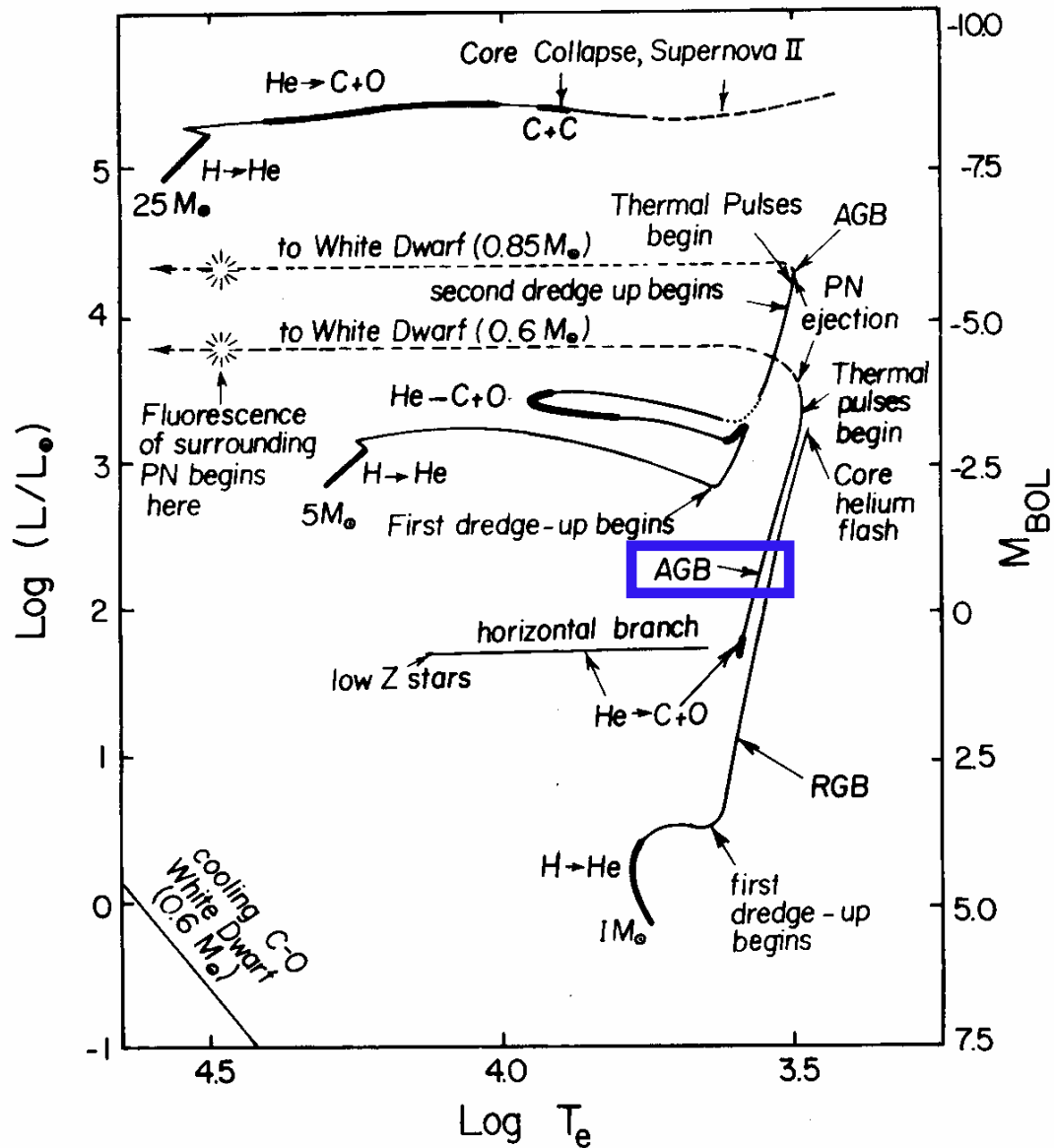
at the end of the He burning $T \approx 3 \times 10^8$: $^{22}\text{Ne}(\alpha, n)$ provides a neutron source
preexisting Fe and other “metals” serve as seed for the s-process synthesis

s-process site-s & conditions: main

Site	Thermal pulses of AGB stars (He-burning shell)	
Neutron sources	$^{13}\text{C}(\alpha,n)^{16}\text{O}$	$^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$
Temperature	10^8K	$kT \sim 8 \text{ keV}$
Neutron density	$7 \times 10^7 \text{ n/cm}^3$	10^{10} n/cm^3



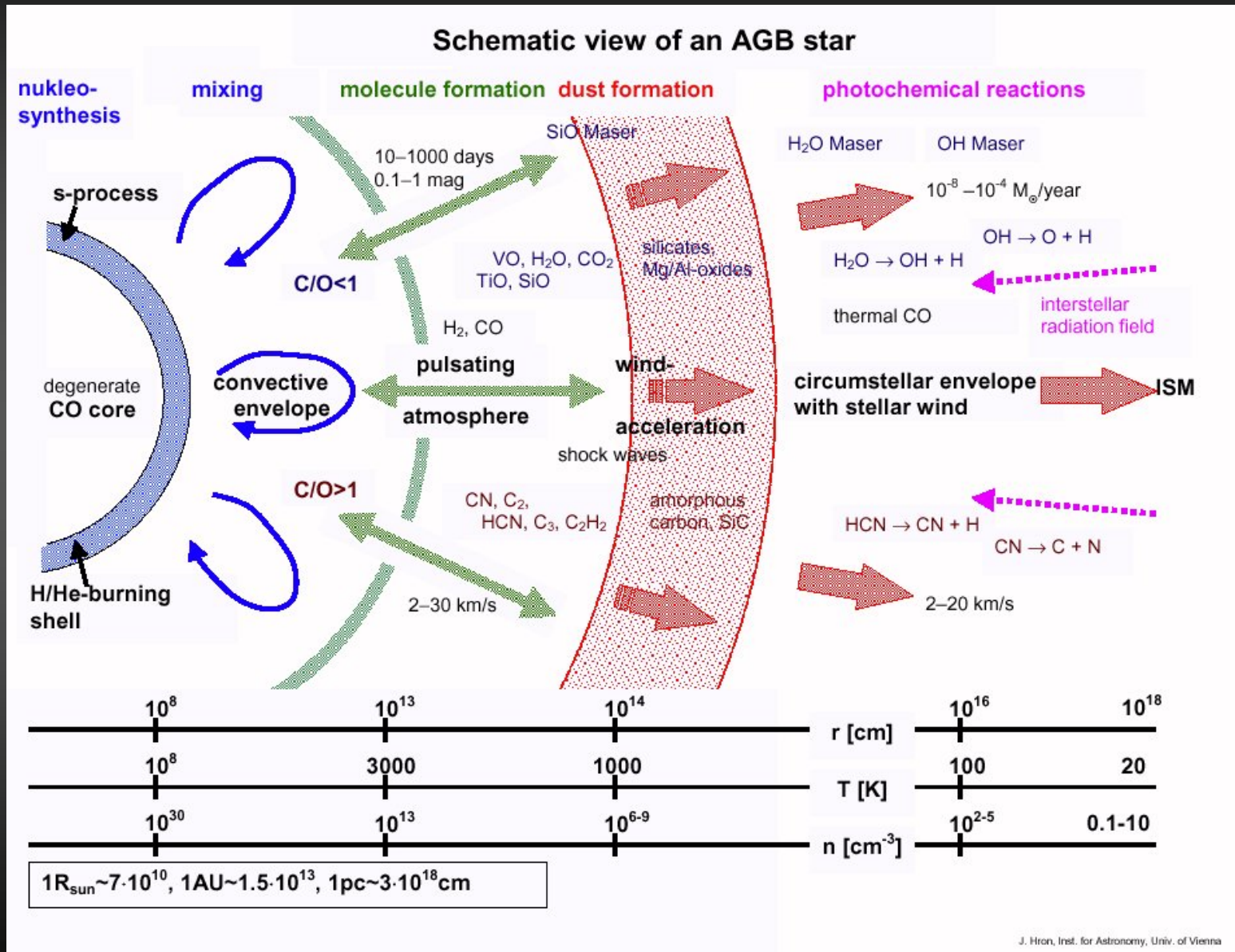
s-process site-s & conditions: main



Thermal pulses
of AGB stars (He-burning shell)

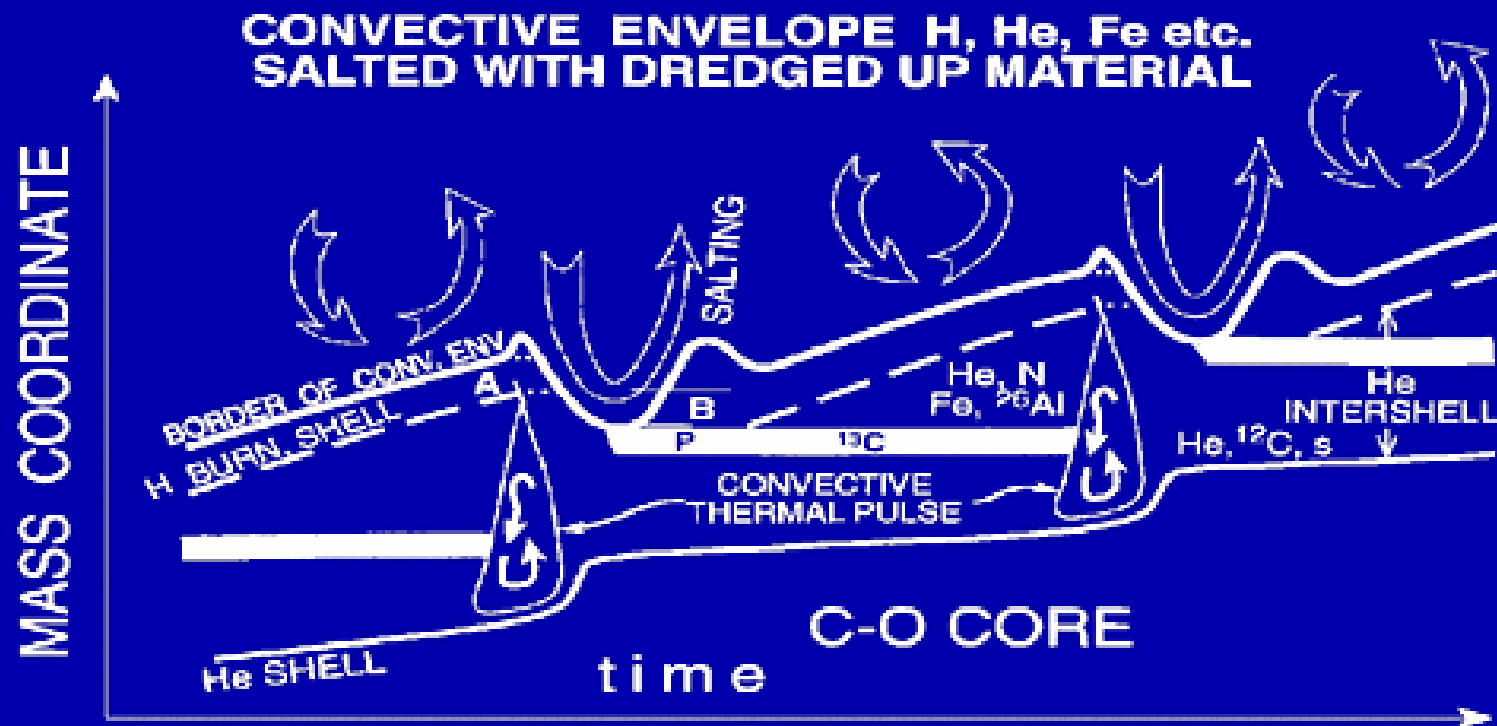
AGB stars

Source: F Erwig



AGB stars: s-processing

THE THERMAL PULSES: TIME EVOLUTION OF CONVECTION ZONES AND THE S-PROCESS



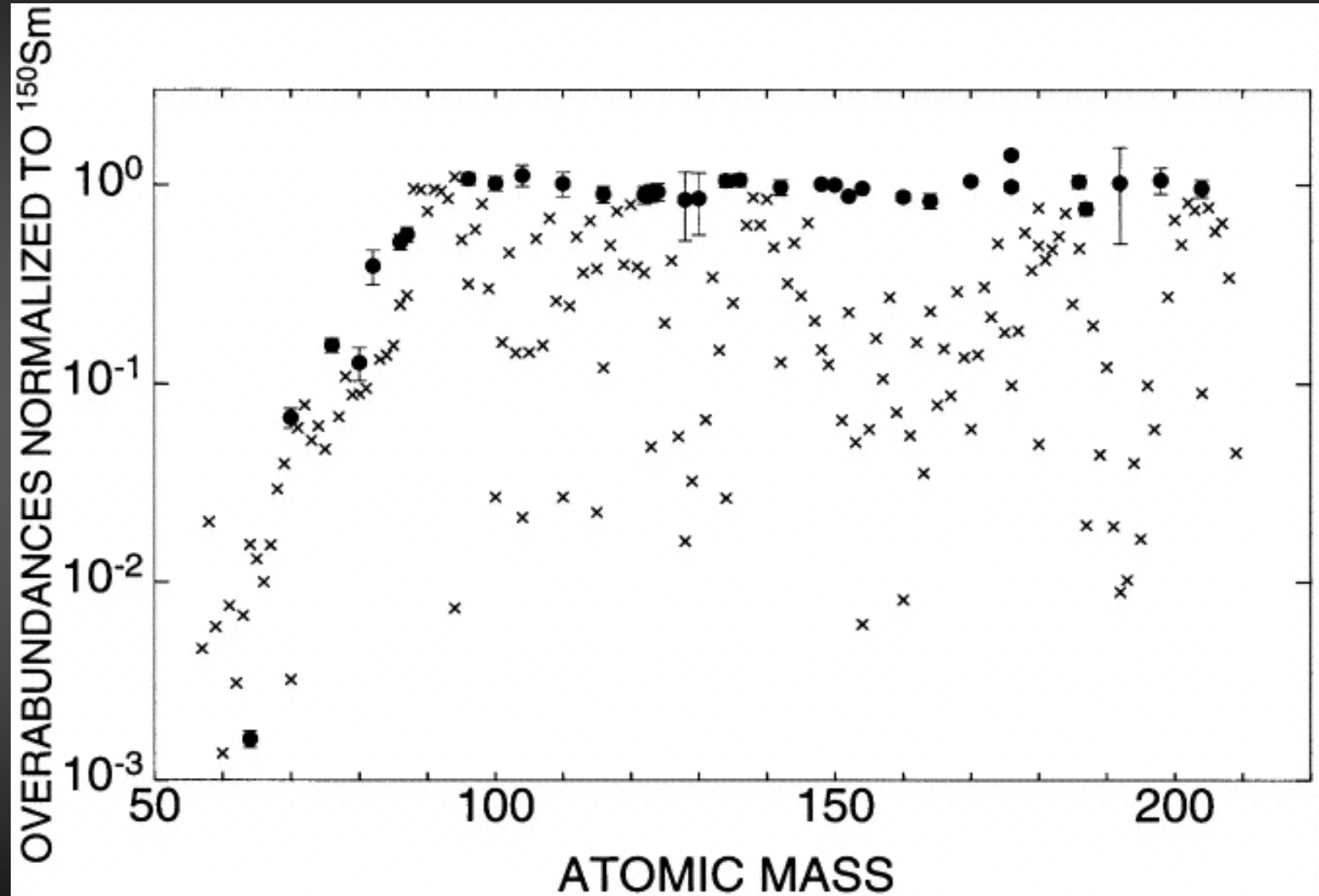
from Busso, Gallino & Wasserburg (1999)

Falk Herwig: »The s-process in rotating AGB stars«, 29 March 2002, Seattle.

alberto.mengoni@cern.ch

AGB stars: s-processing

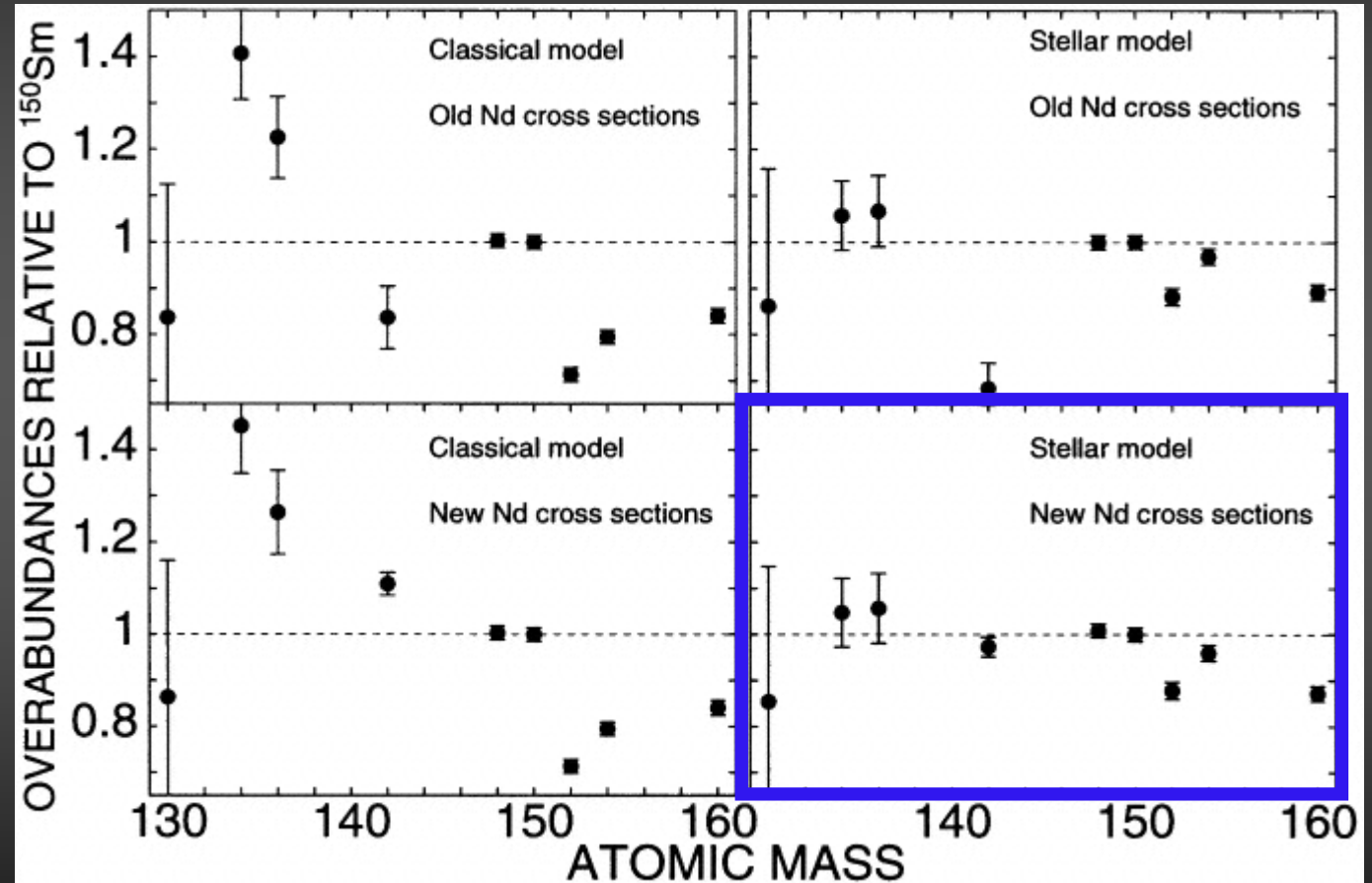
- $M = 2 M_{\odot}$
- $Z = 0.5 Z_{\odot}$



C Arlandini, *et al.*: ApJ 525 (1999) 886

AGB stars: s-processing

- $M = 2 M_{\odot}$
- $Z = 0.5 Z_{\odot}$



C Arlandini, *et al.*: ApJ 525 (1999) 886

The canonical s-process

The time dependence of the abundances, N_A , is given by:

$$\frac{dN_A}{dt} = N_n(t)N_{A-1}(t)\langle\sigma_{n,\gamma}v\rangle_{A-1} - N_n(t)N_A(t)\langle\sigma_{n,\gamma}v\rangle_A - \lambda_\beta N_A(t)$$

We can define a time-integrated neutron flux (neutron exposure)

$$\tau = \int_0^t \phi_n(t')dt' = v_T \int_0^t N_n(t)dt$$

Assuming: *i) $T \approx const.$*

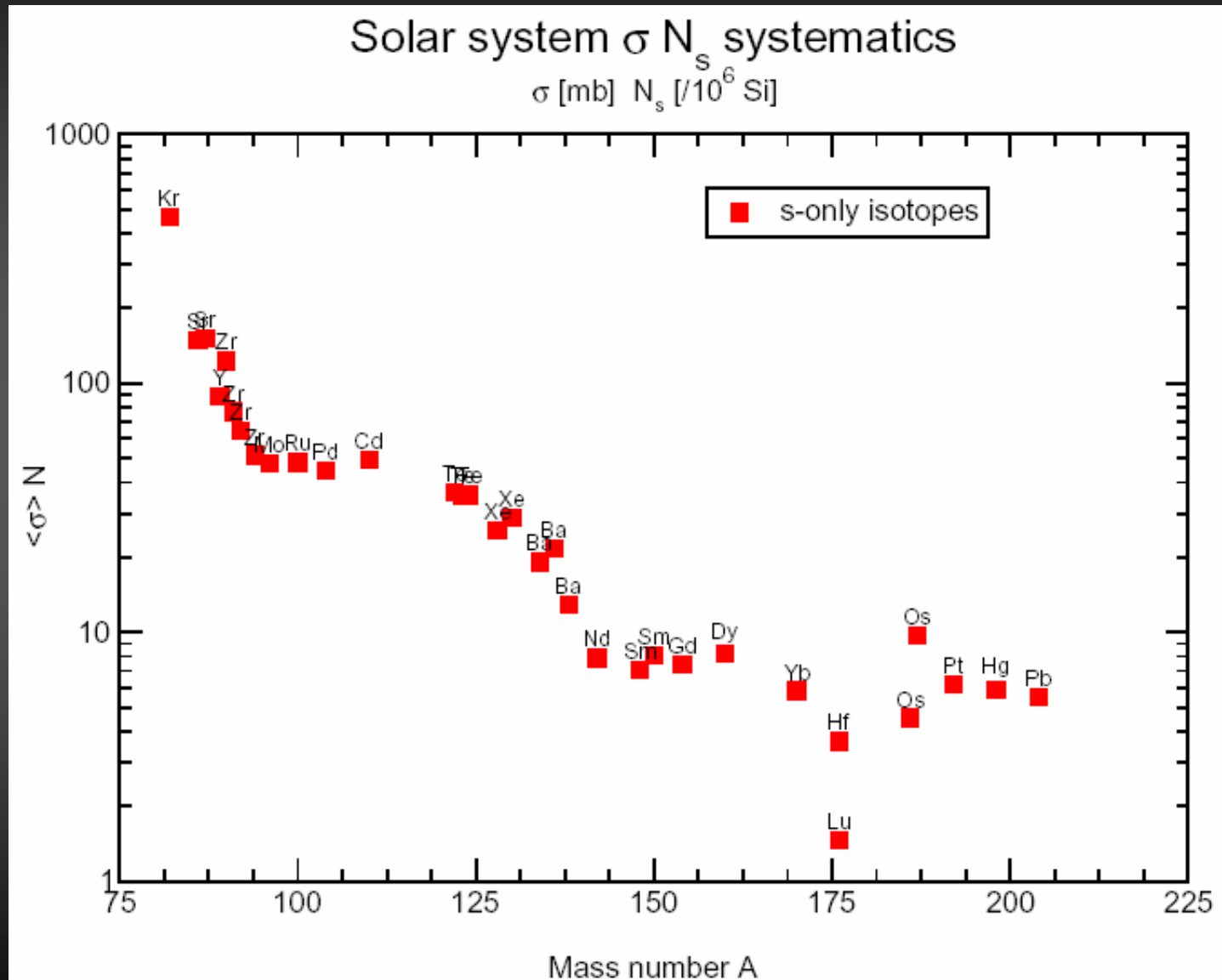
ii) $\lambda_\beta \ll \lambda_{n,\gamma}$ (neutron capture dominates over β -decay)

$$\frac{dN_A}{d\tau} = \langle\sigma_{n,\gamma}\rangle_{A-1} N_{A-1} - \langle\sigma_{n,\gamma}\rangle_A N_A$$

It follows that along the s-process path:

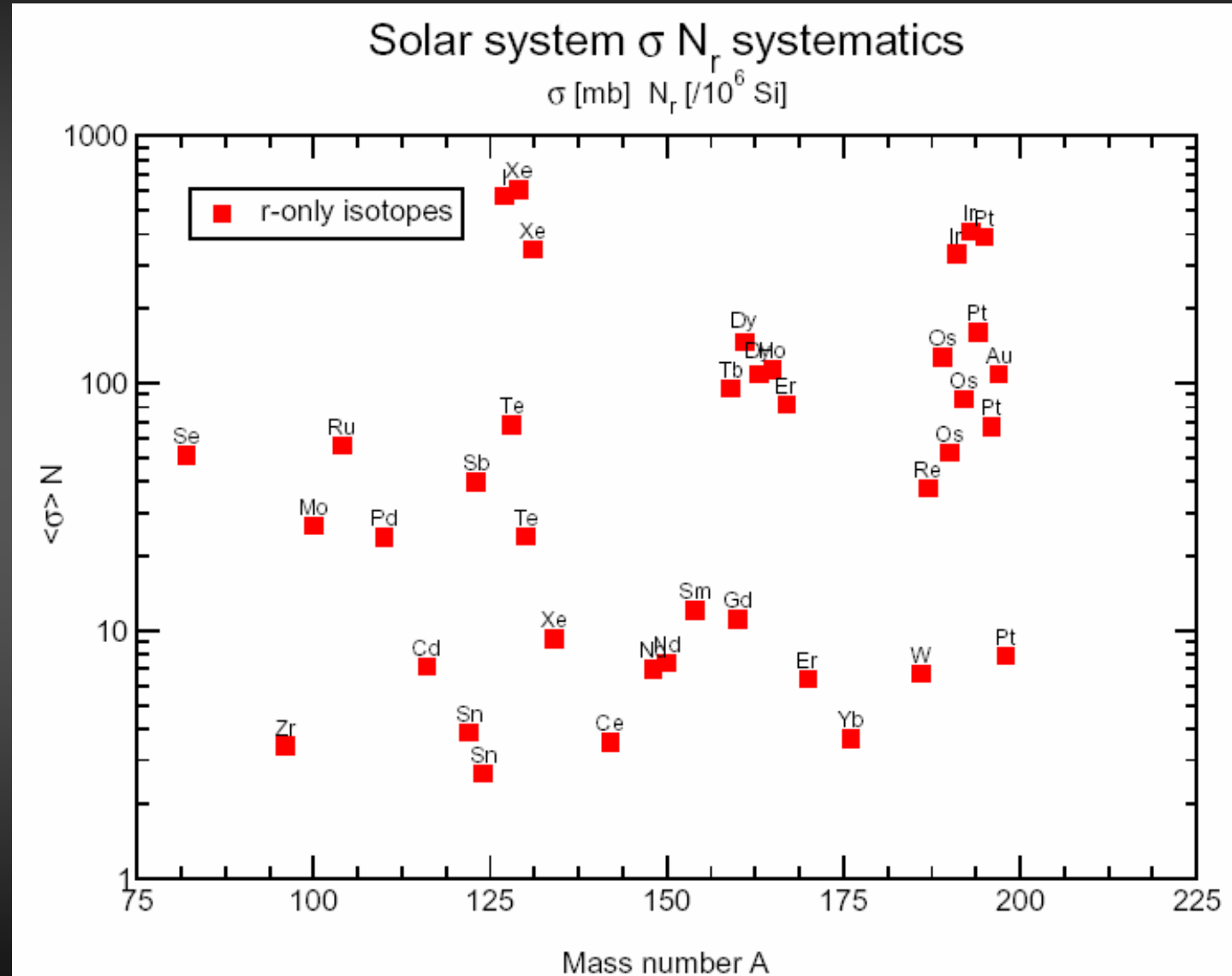
$$\boxed{\langle\sigma_{n,\gamma}\rangle_{A-1} N_{A-1} = \langle\sigma_{n,\gamma}\rangle_A N_A = const.}$$

The canonical s-process



The canonical s-process

No $\langle \sigma \rangle N$ correlation
observed for
nuclei **not** in the
s-process path



The canonical s-process

Assuming an exponential distribution of neutron exposures:

$$\rho(\tau) = \frac{f N_{56}}{\tau_0} e^{-\tau/\tau_0}$$

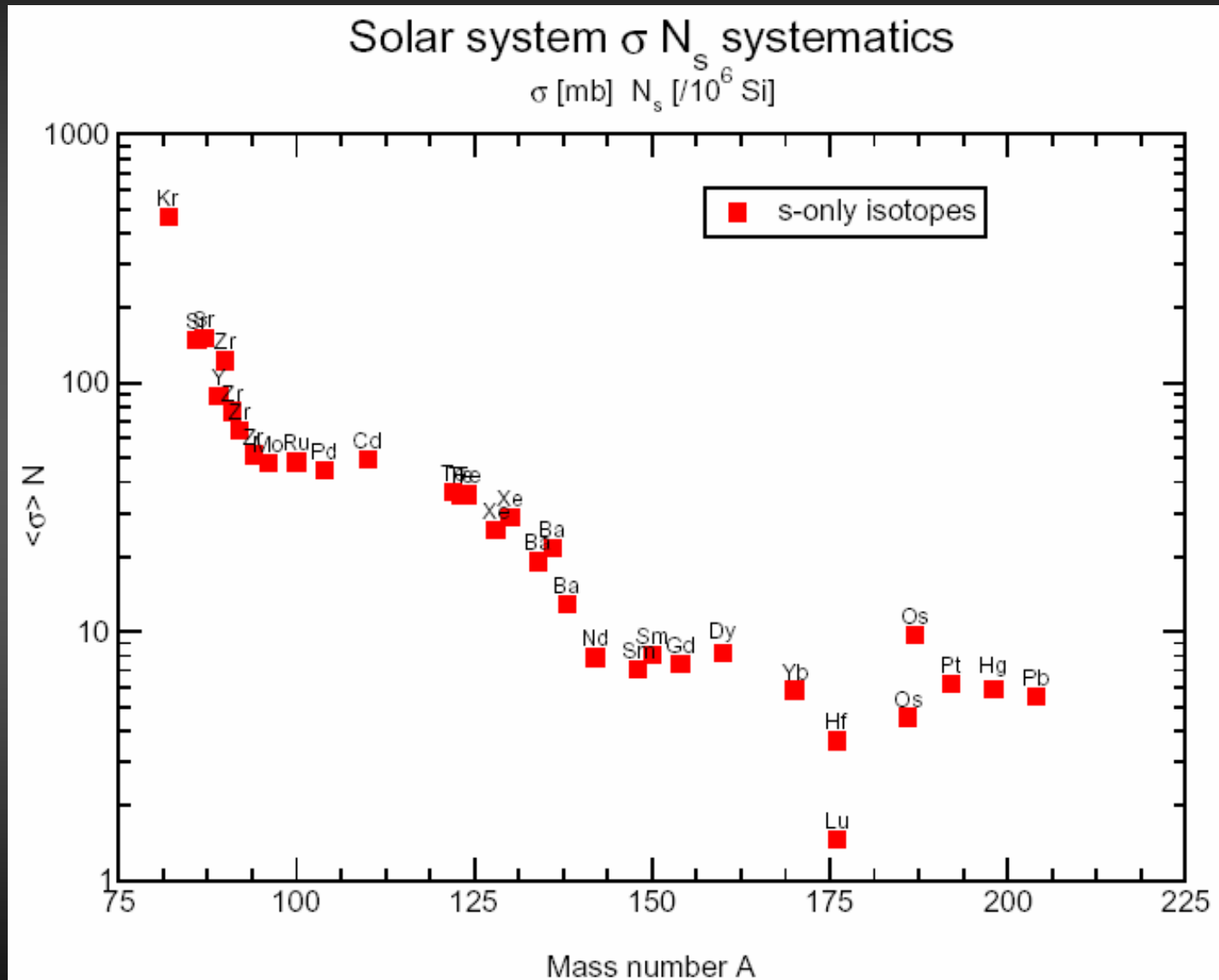
the solution of the coupled system of equations

$$\frac{dN_A}{d\tau} = \langle \sigma_{n,\gamma} \rangle_{A-1} N_{A-1} - \langle \sigma_{n,\gamma} \rangle_A N_A$$

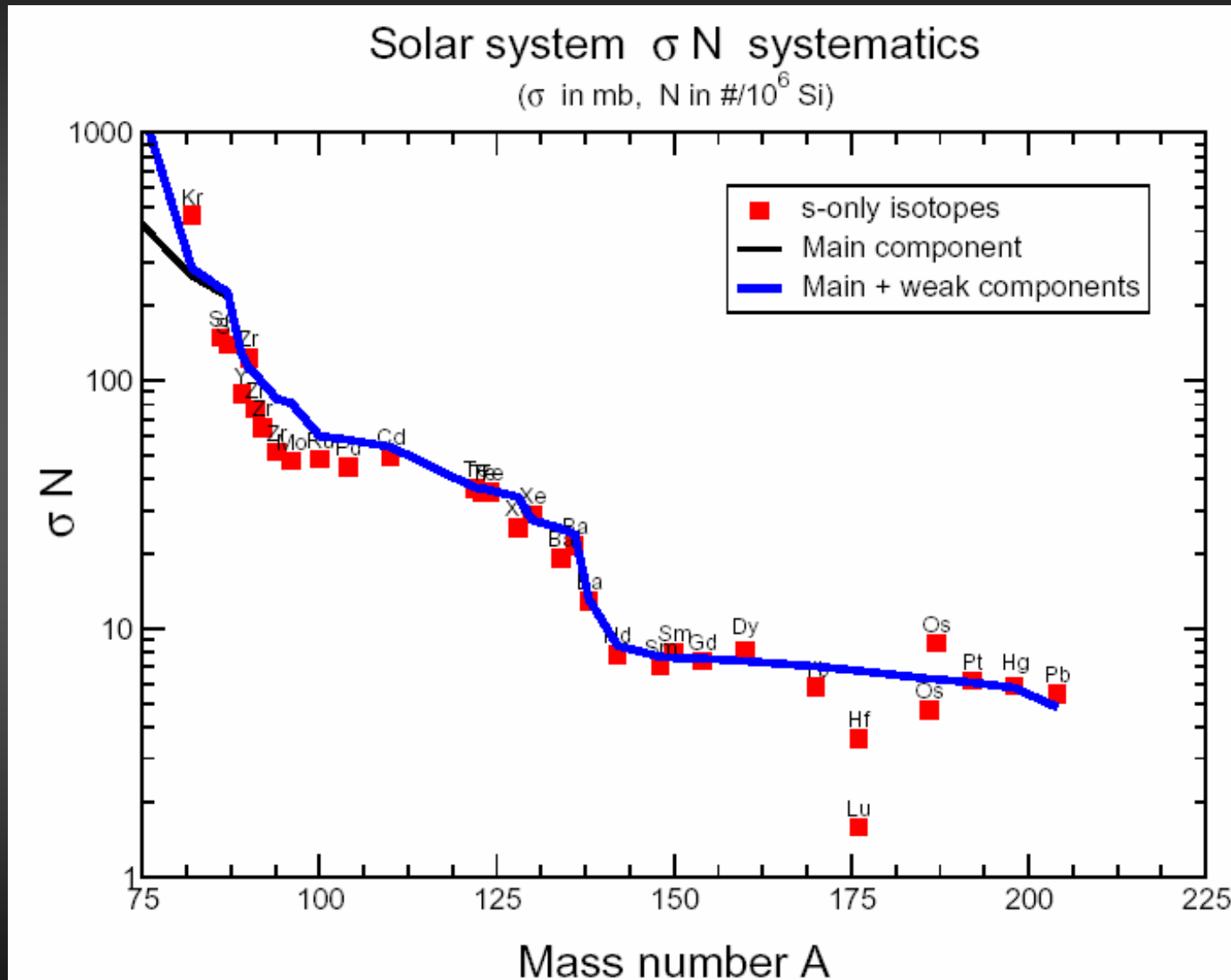
is

$$\langle \sigma \rangle_A N_A = \frac{\langle \sigma \rangle_{A-1} N_{A-1}}{1 + 1/\tau_0 \langle \sigma \rangle_A} = \frac{f N_{56}}{\tau_0} \prod_{i=1}^A \left(1 + \frac{1}{\tau_0 \langle \sigma \rangle_i} \right)^{-1}$$

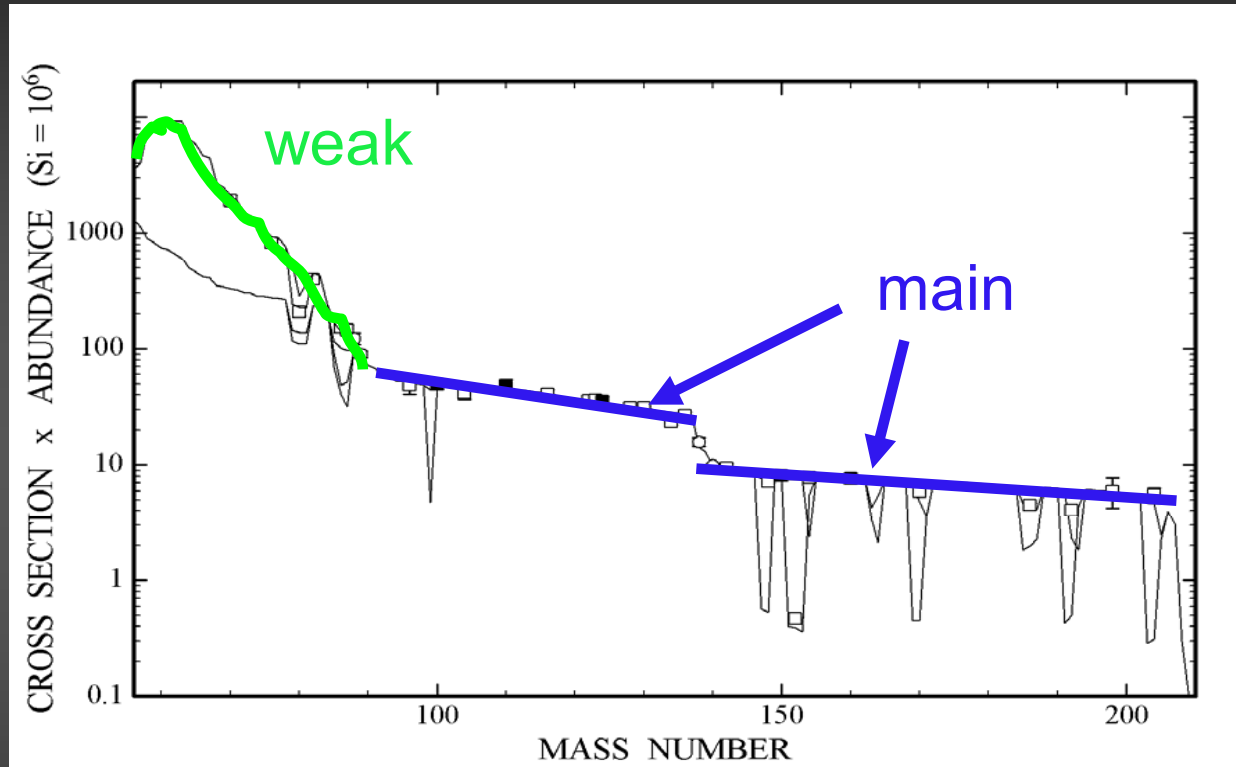
The canonical s-process



The canonical s-process



The canonical s-process



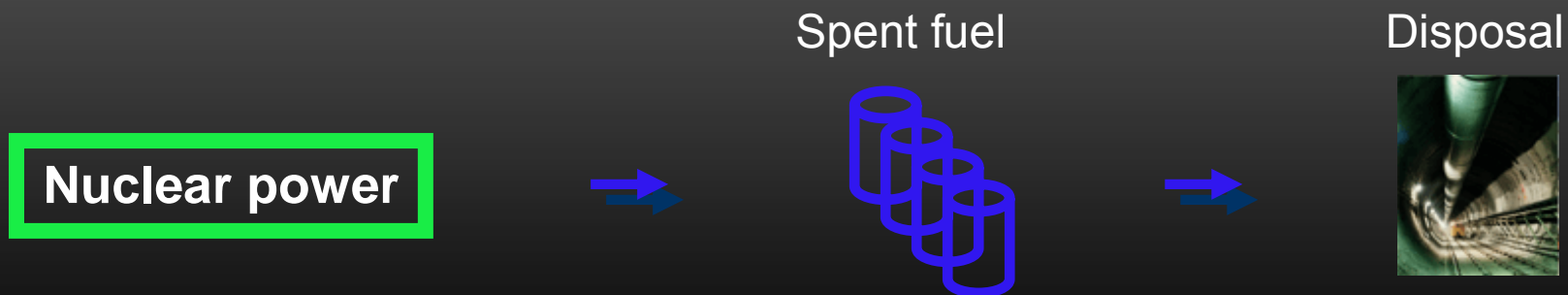
F Käppeler (Prog. Part. Nucl. Phys. 43, 1999)

weak: core He burning in massive stars (e.g. 25 solar masses)

main: He shell flashes in low mass TP-AGB stars

The problem

- Nuclear power now accounts for 4.5% of total world's energy production. Already at this level the accumulated spent fuel inventory, at the yearly production rate of 8,000 ton, will reach by 2020 about 200,000 ton
- NB: the Yucca Mountain deep underground repository in the US has a capacity of 70,000 ton and a cost of 15 G\$
- Assuming by 2050 a substantial classic nuclear contribution to heal the greenhouse effect ($\approx 30\%$ of the projected, increased world's power consumption or $+2.3\%/yr$), the yearly waste production would be of 100,000 ton/y: fill a Yucca Mountain type of repository every 8 months!



Partitioning and Transmutation (P&T)

