The Abdus Salam
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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

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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

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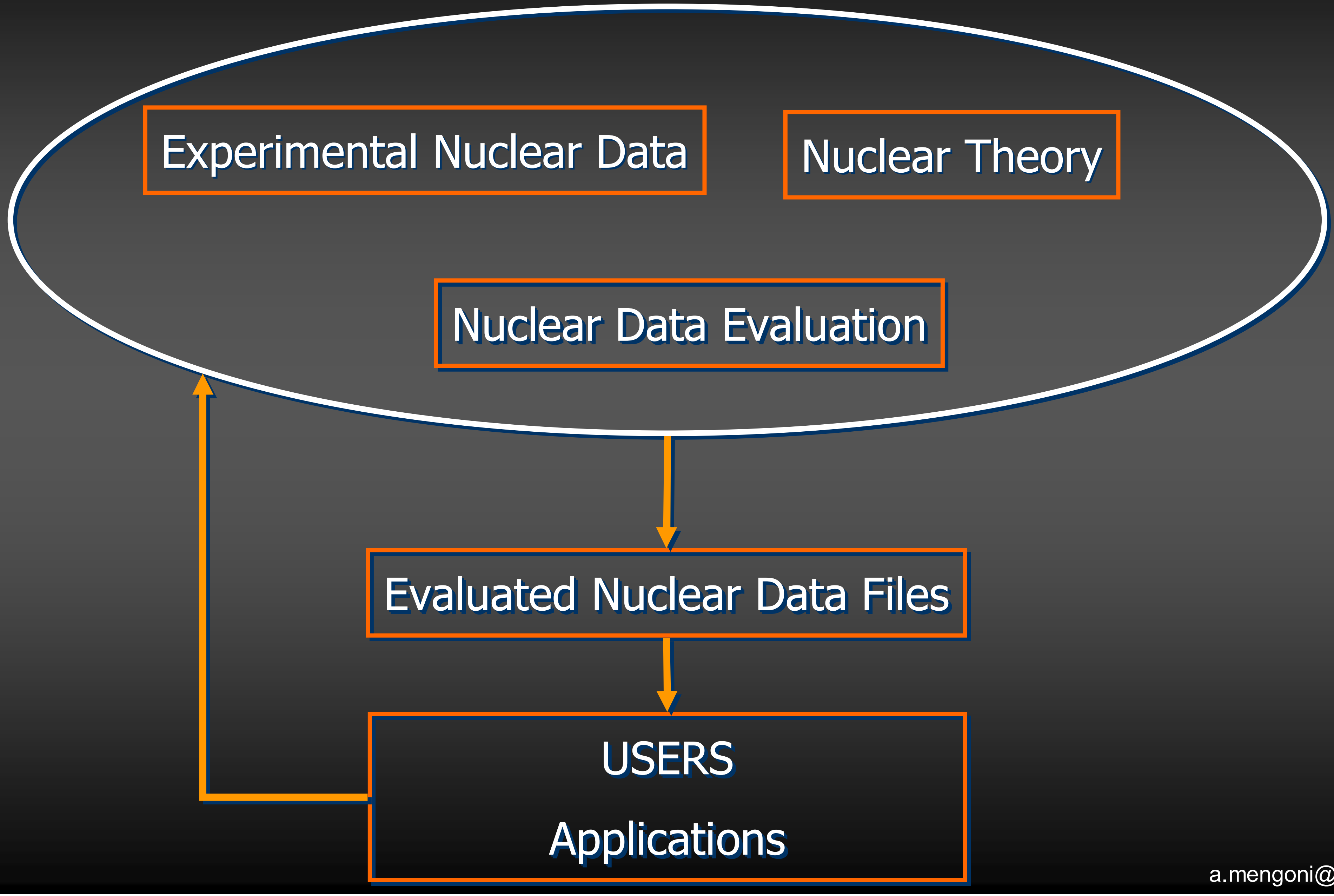
Nuclear Reactions & Data Libraries



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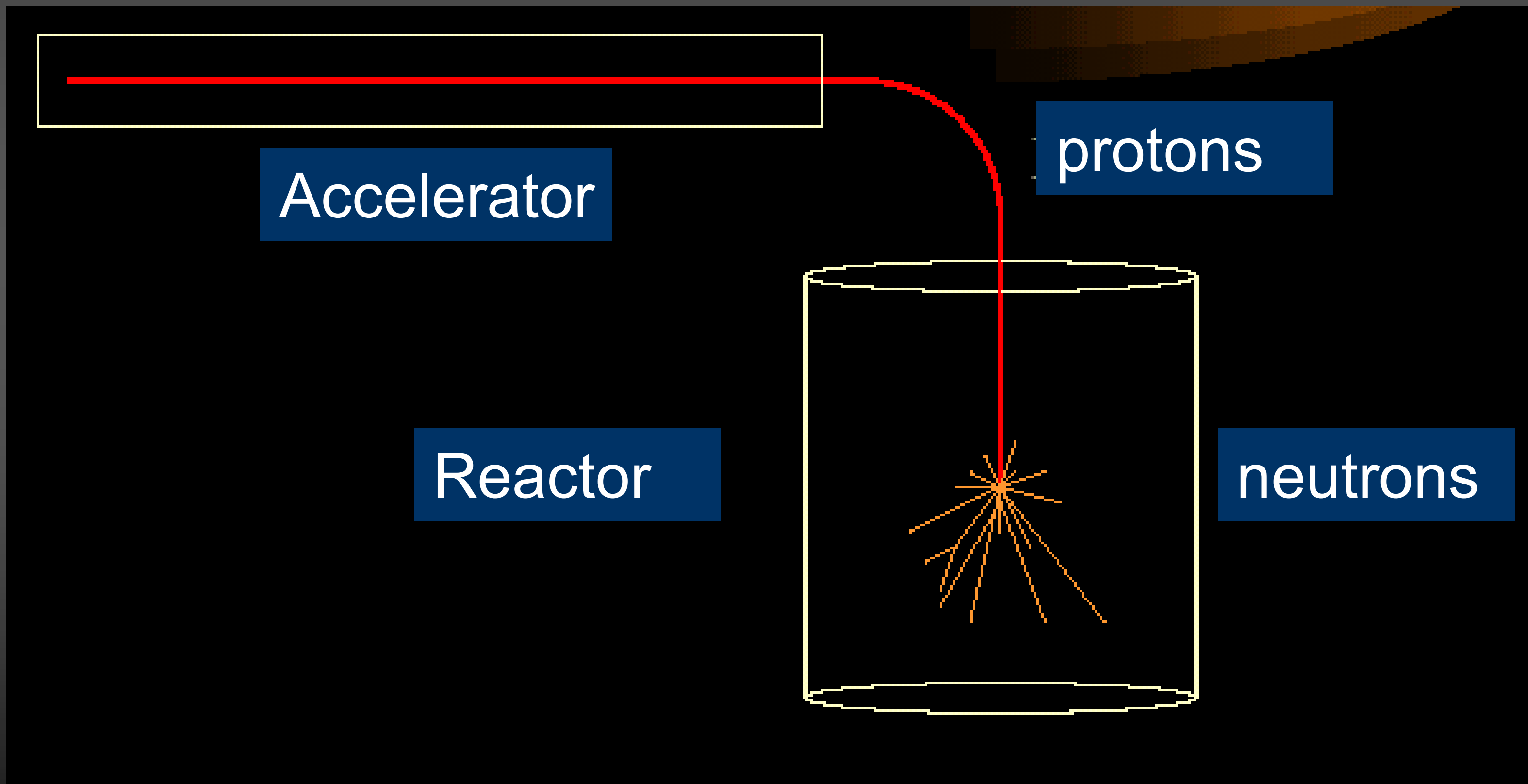
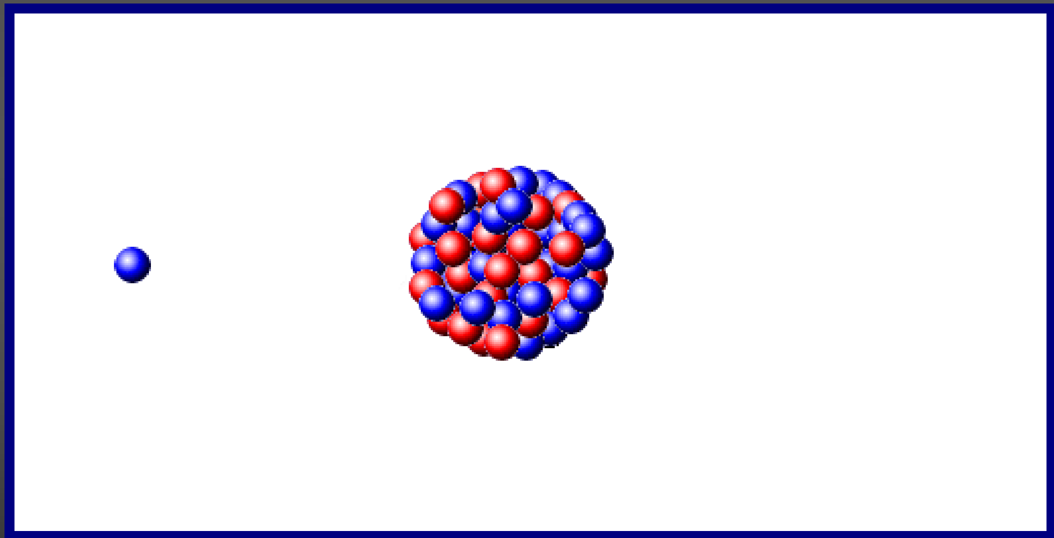
ADS (Accelerator Driven Systems)



Zen-ADS

Nuclear Reaction Experiments

Nuclear Data Measurements



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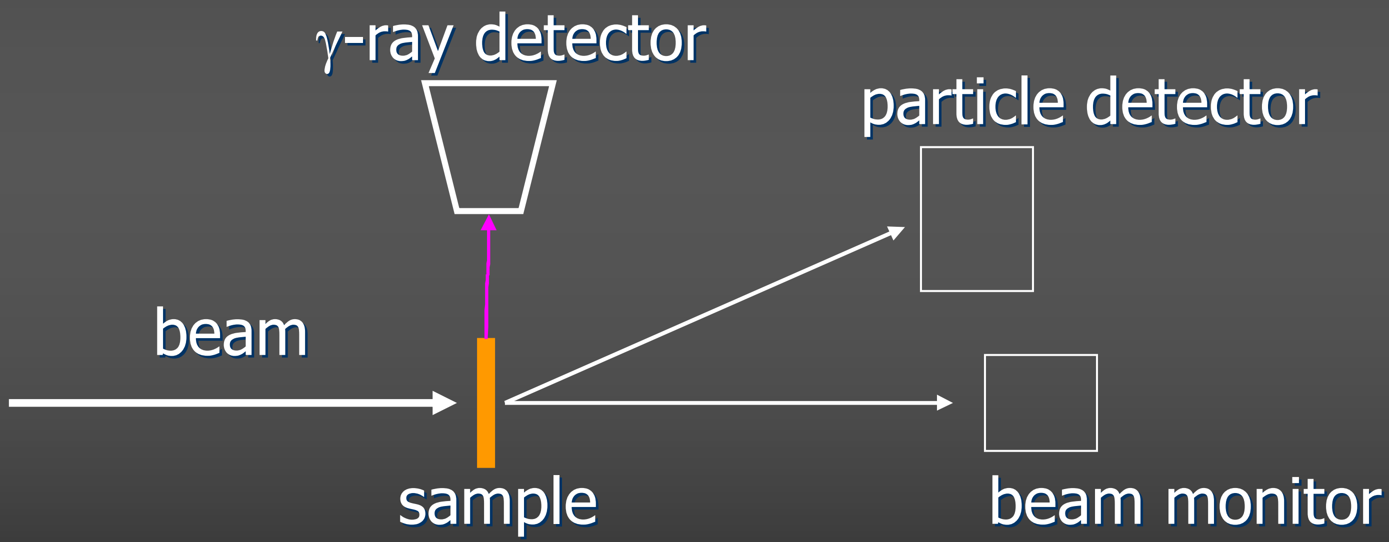
Nuclear Reaction Experiments

Nuclear Data Measurements



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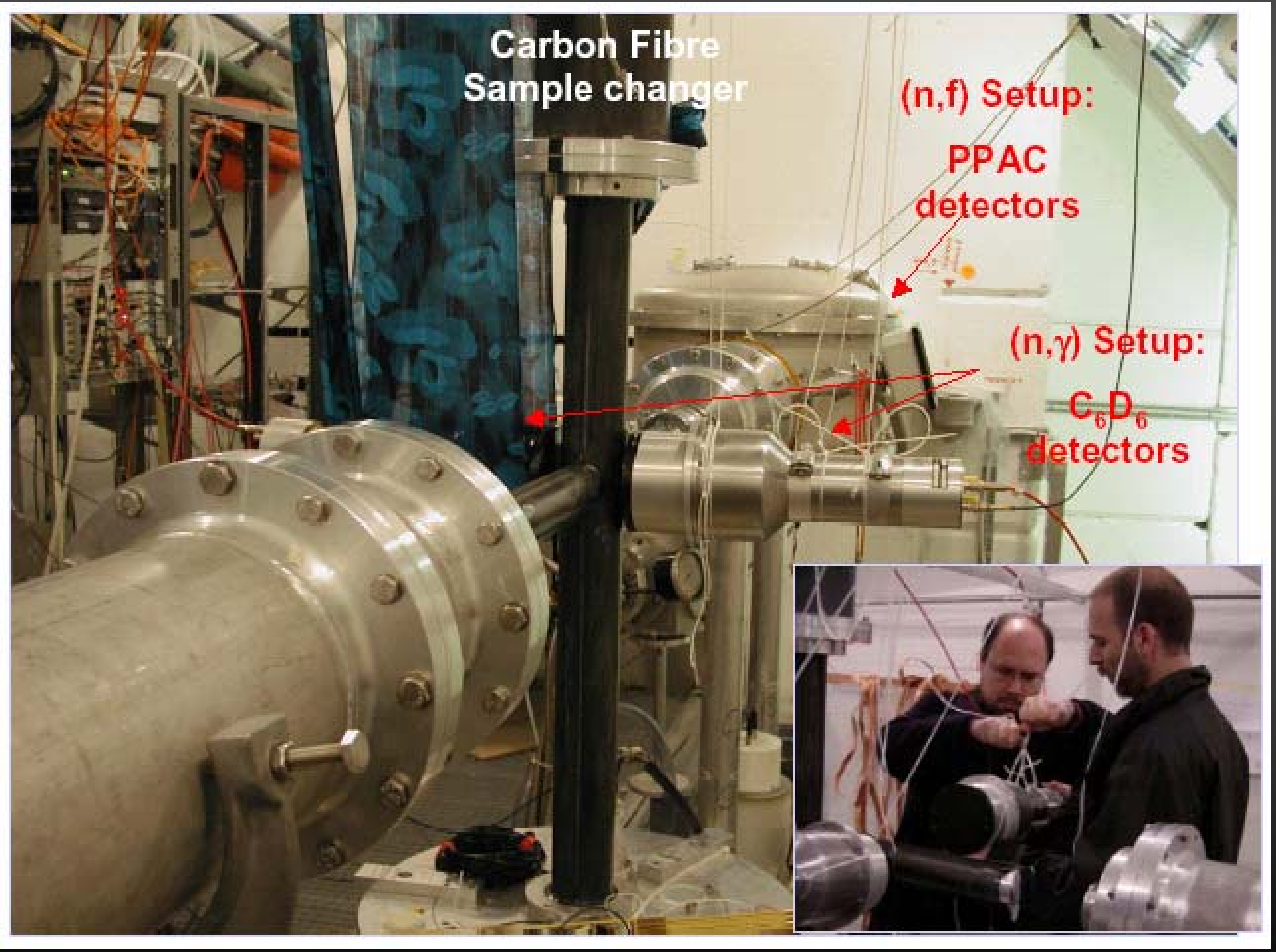
Nuclear Reaction Experiments

Nuclear Data Measurements



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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…

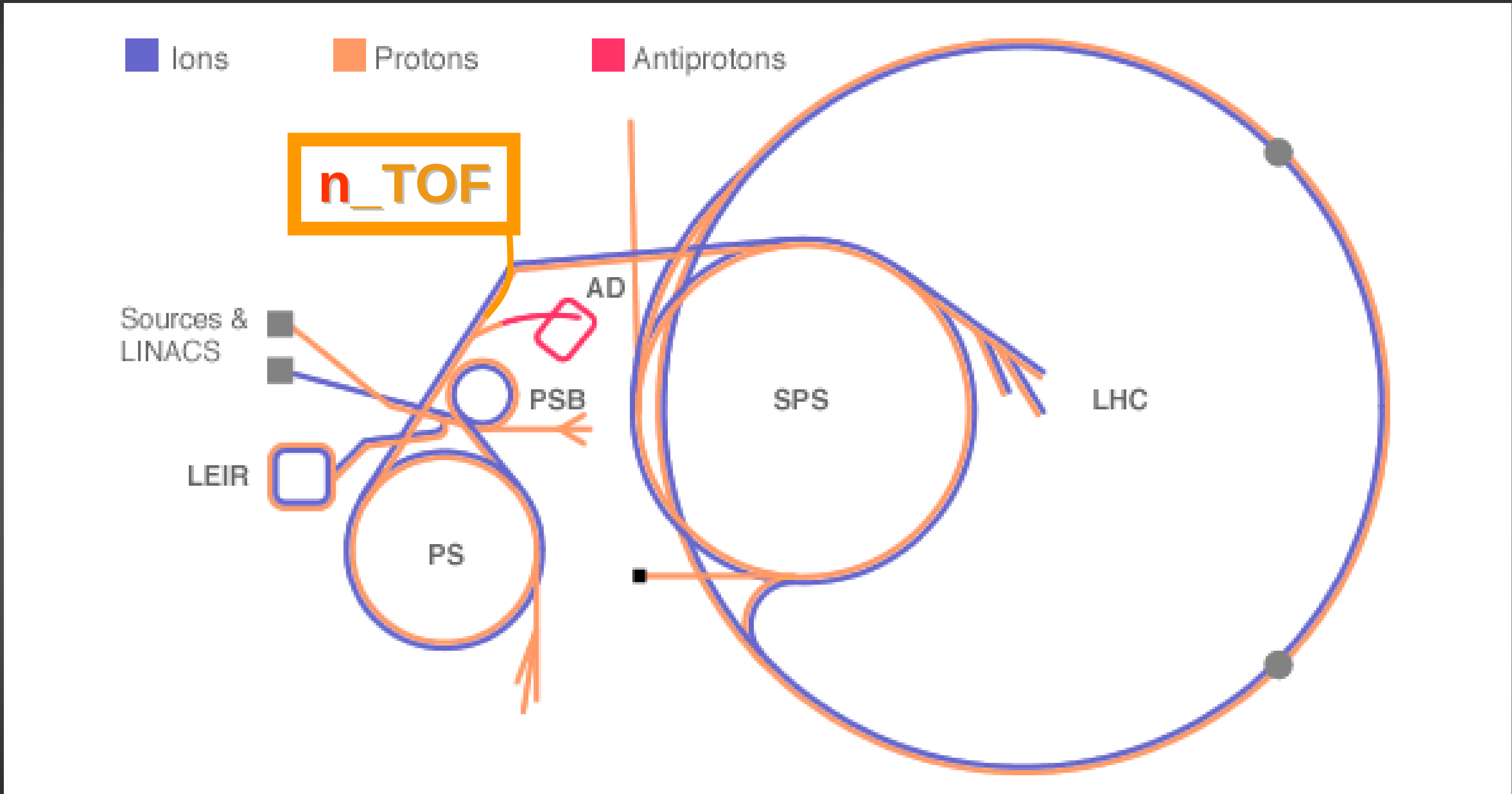
World scene for tof measurements

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

The n_TOF facility at CERN

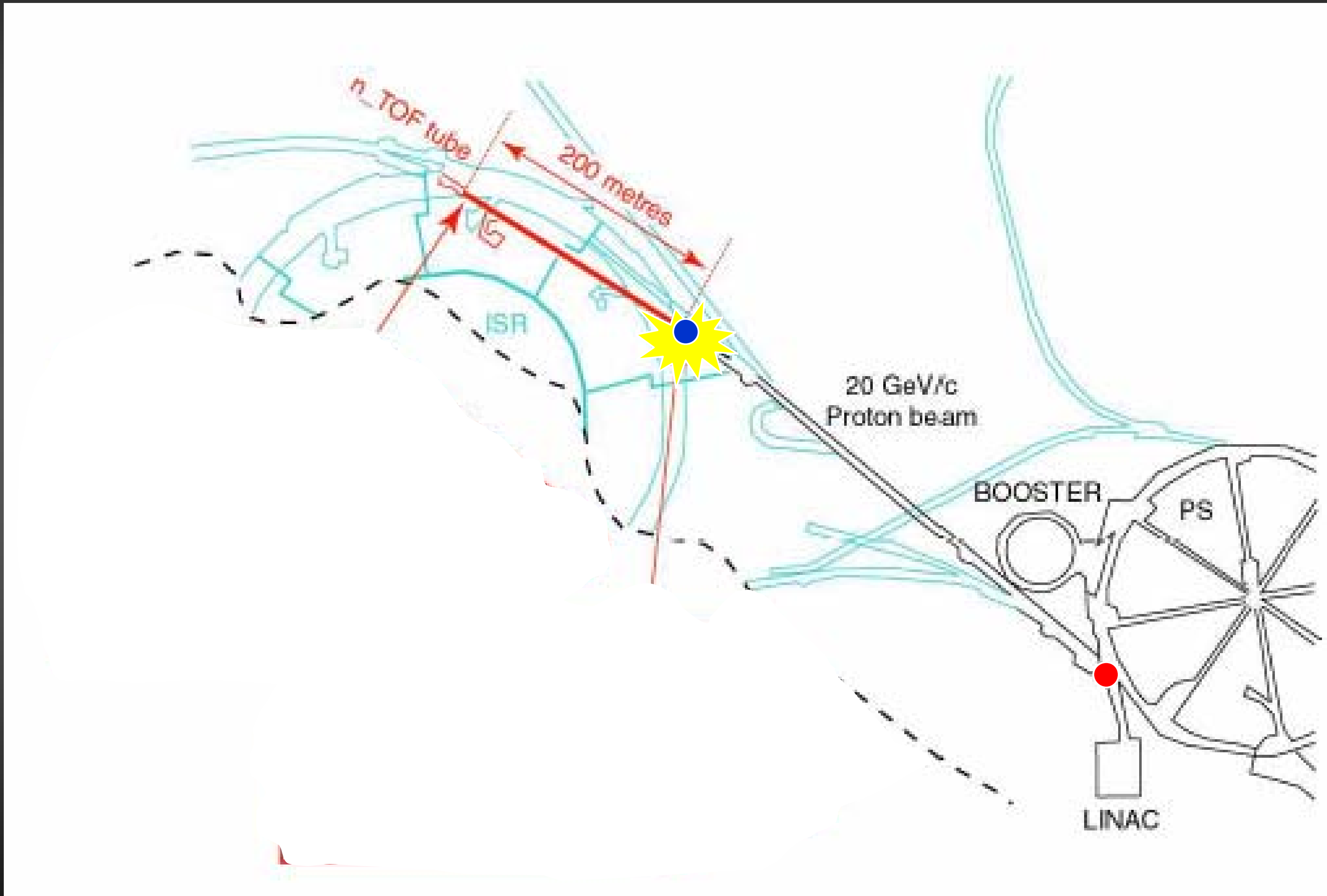
somewhere around here

CERN accelerator Complex



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

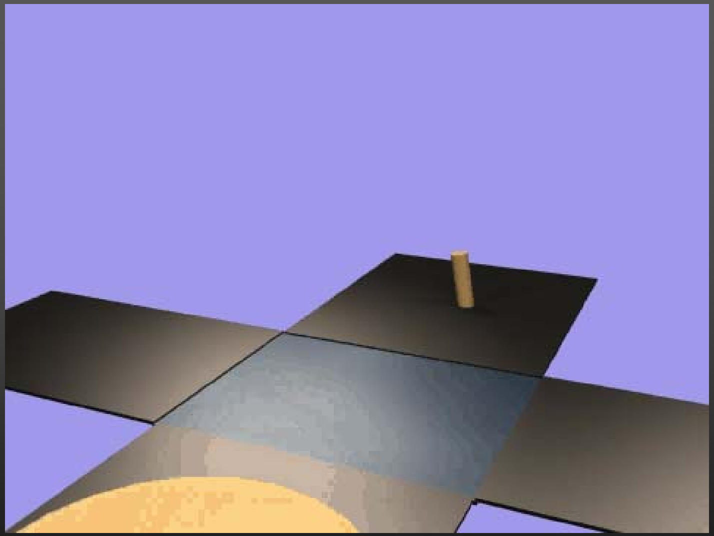
The n_TOF facility at CERN



The n_TOF facility at CERN

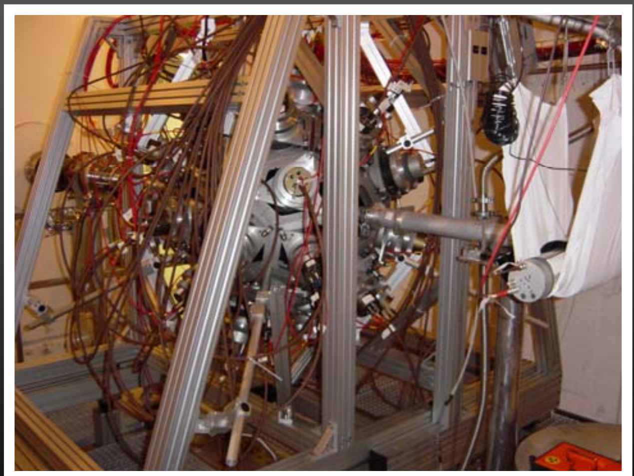
movie by V Vlachoudis (CERN)

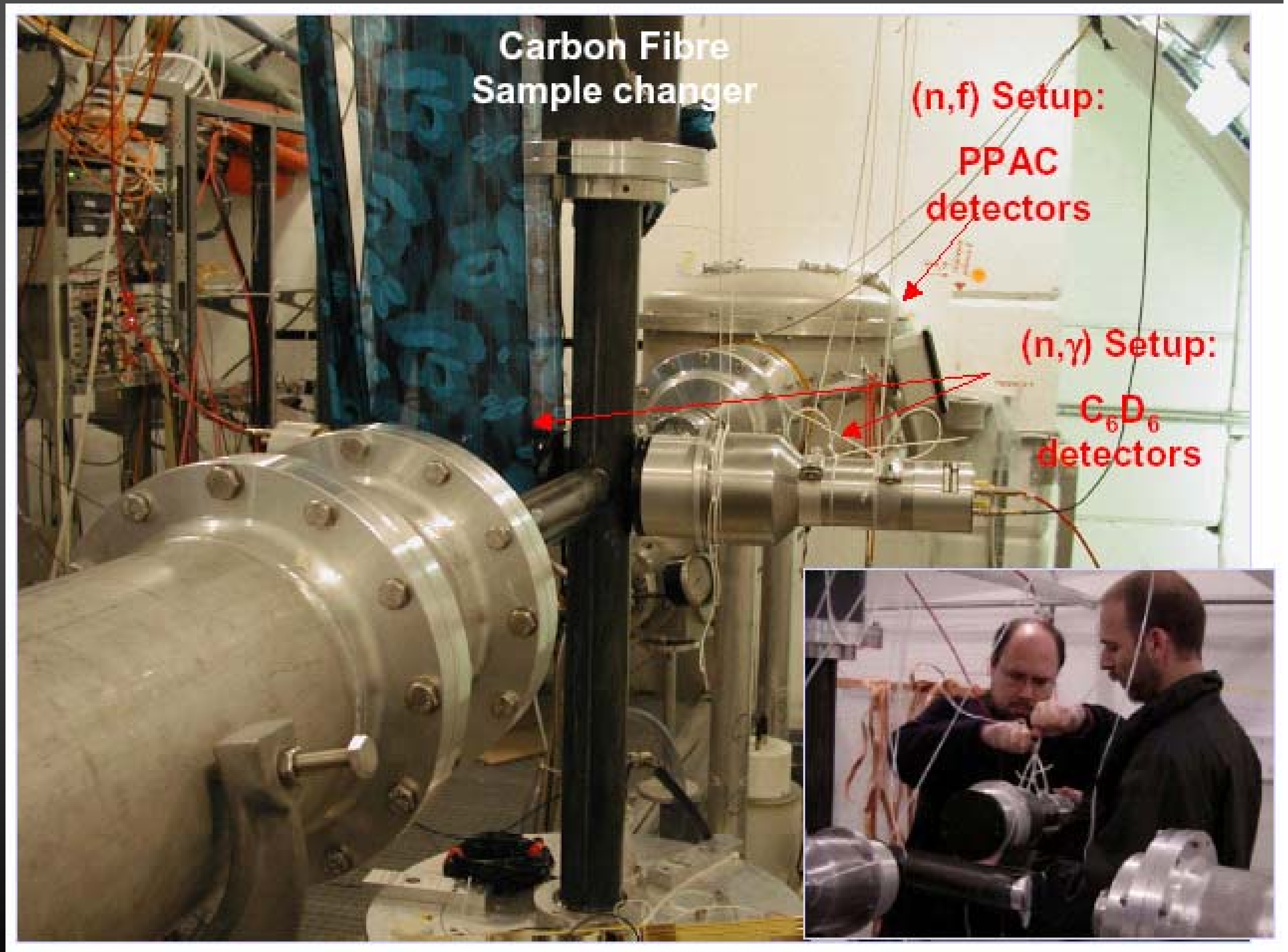
- Design: the n_TOF tunnel



The real world

- n_TOF commissioned in 2001-2002





n_TOF basic parameters

proton beam momentum	20 GeV/c
intensity (dedicated mode)	7 x 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_2O
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

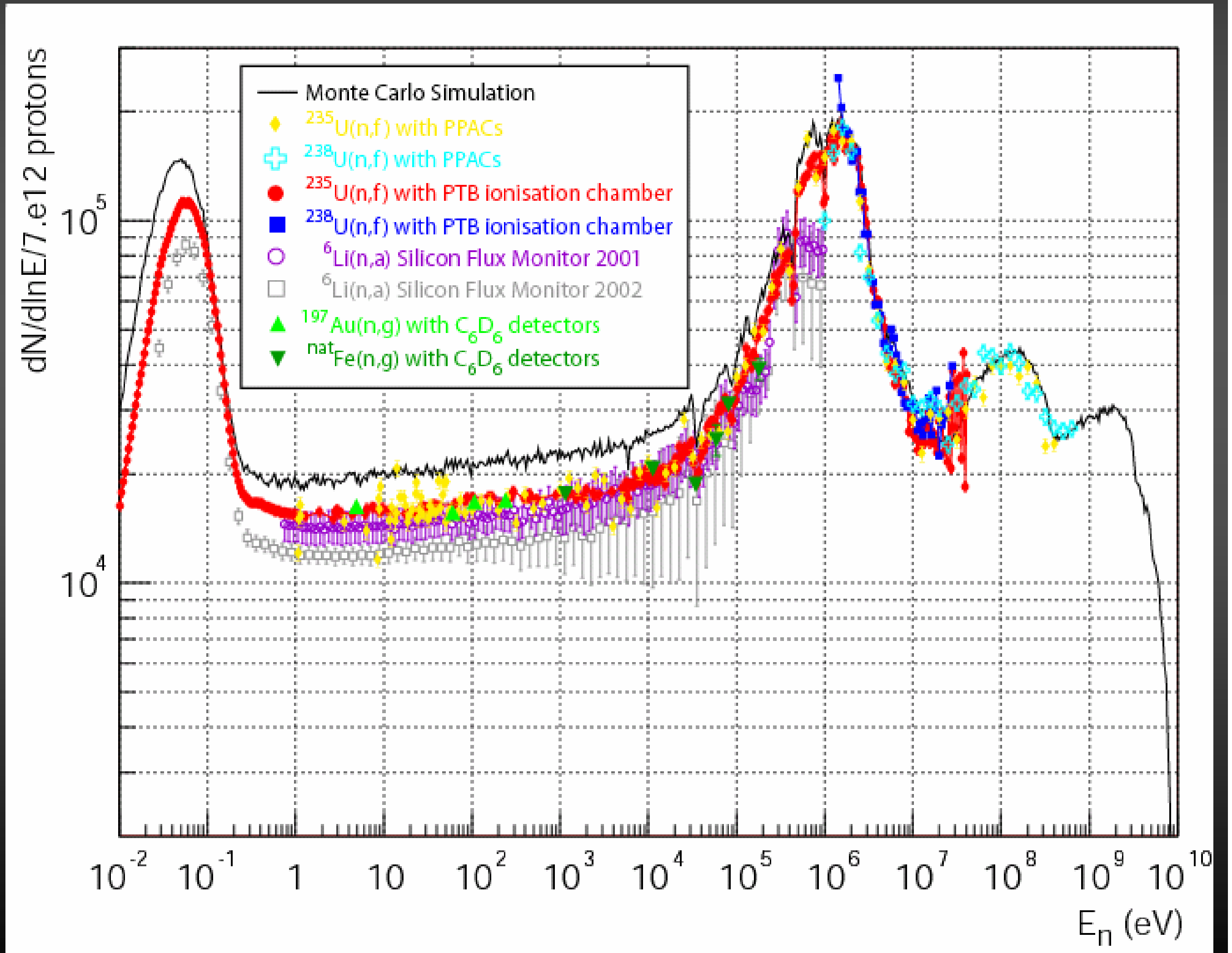
2nd collimator ϕ=1.8 cm
(capture mode)

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

The neutron fluence in EAR-1

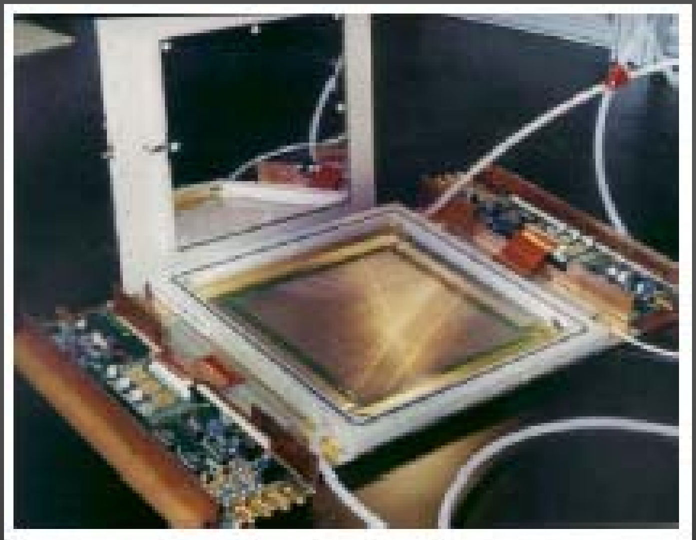
Energy range	Uncollimated [n/pulse/cm2]	Capture mode [n/pulse]	Fission mode [n/pulse]
< 1 eV	**2.0E+05**	**3.1E+05**	**2.0E+06**
1 eV - 10 eV	2.7E+04	4.5E+04	2.9E+05
10 eV - 100 eV	2.9E+04	4.7E+04	3.1E+05
100 eV - 1000 eV	3.0E+04	5.1E+04	3.3E+05
1 eV - 1 keV	**8.6E+04**	**1.4E+05**	**9.3E+05**
1 keV - 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

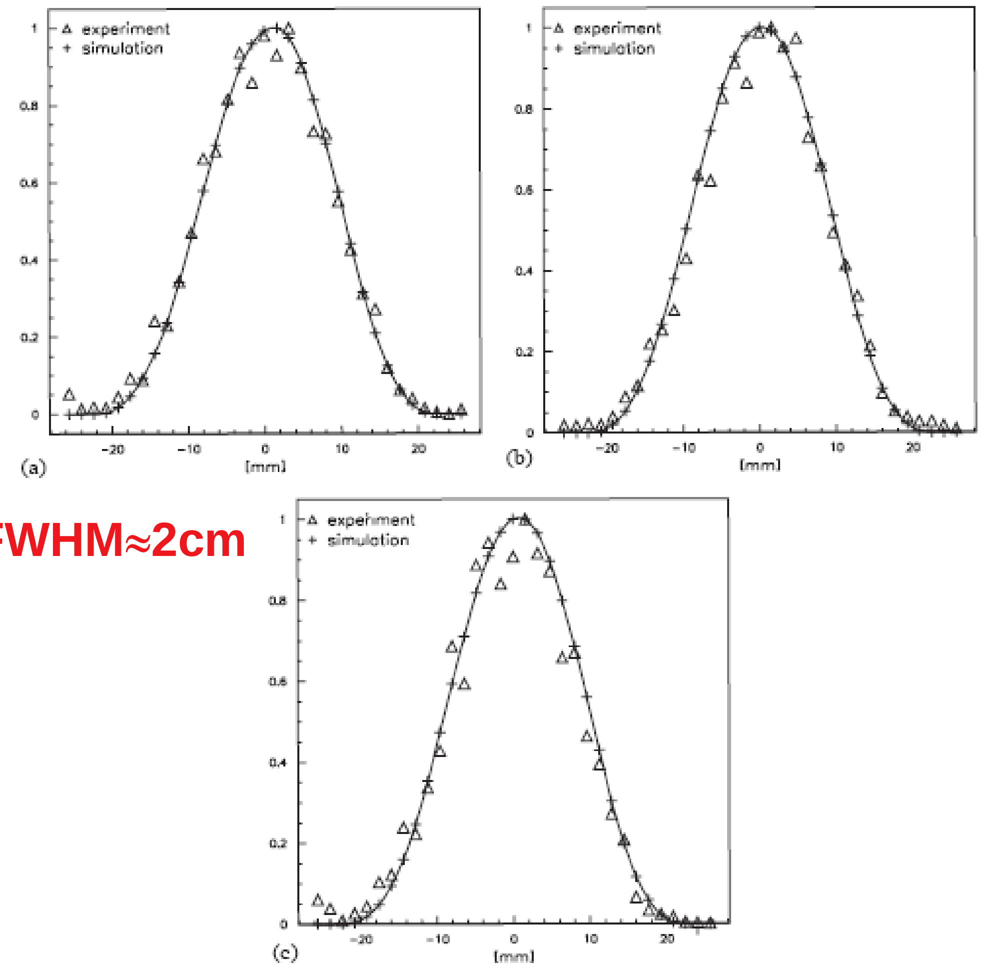
- Beam profile @ 187.5 m



MicroMegas detector

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

J. Pancin et al. / Nuclear Instruments and Methods in Physics Research A 524 (2004) 102–114



FWHM≈2cm

ig. 9. Horizontal (a), vertical (b), 30° (c) experimental and simulated projected profiles between 10 and 100 eV at 186 m.

n_TOF beam

- energy resolution

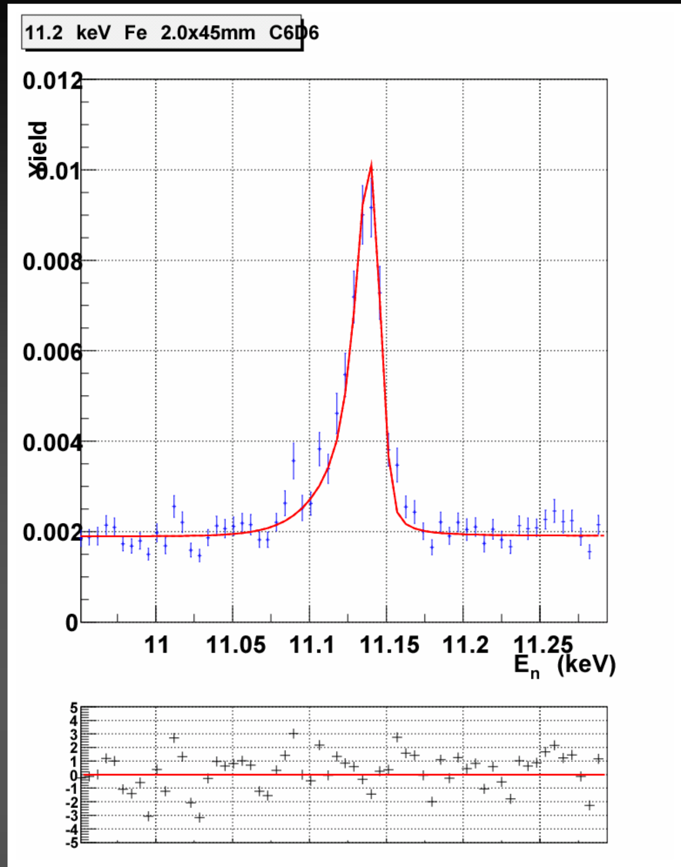
Performance Report
CERN-INTC-2002-037, January 2003
CERN-SL-2002-053 ECT

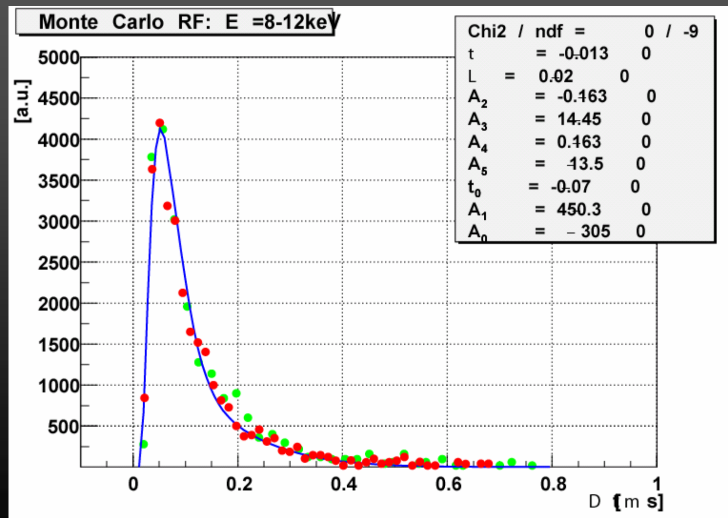
Energy resolution @ 187.5 m
(collimator for capture mode)

Neutron Energy	p-beam pulse width FWHM [cm]	moderation FWHM [cm]	ΔE/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)

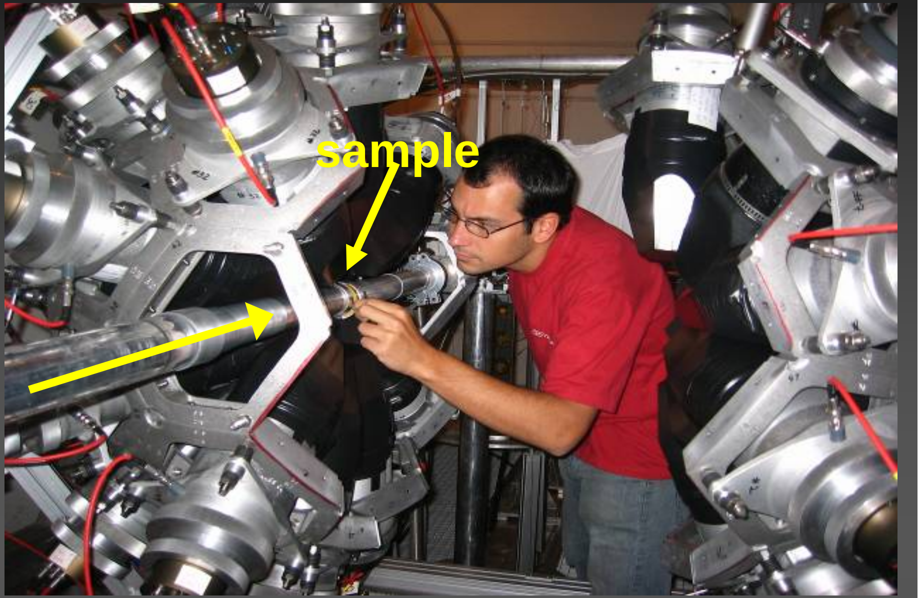


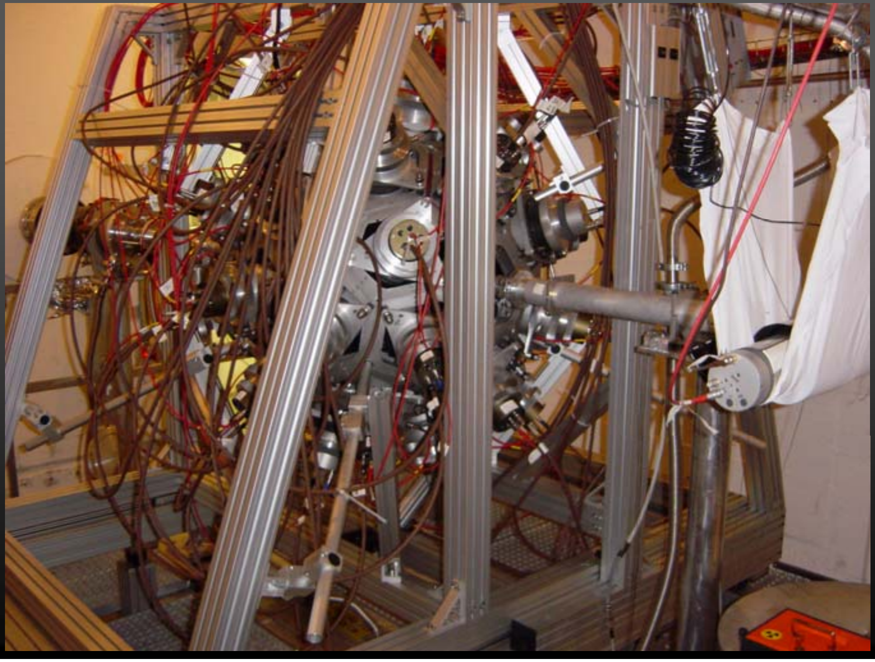


n_TOF TAC for (n,γ) measurements

- 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}Np(n,γ)





Why we do all this?

Objectives

- Measurements of neutron cross sections relevant for Nuclear Waste Transmutation and related Nuclear Technologies

- Cross sections relevant for Nuclear Astrophysics

- Neutrons as probes for fundamental Nuclear Physics

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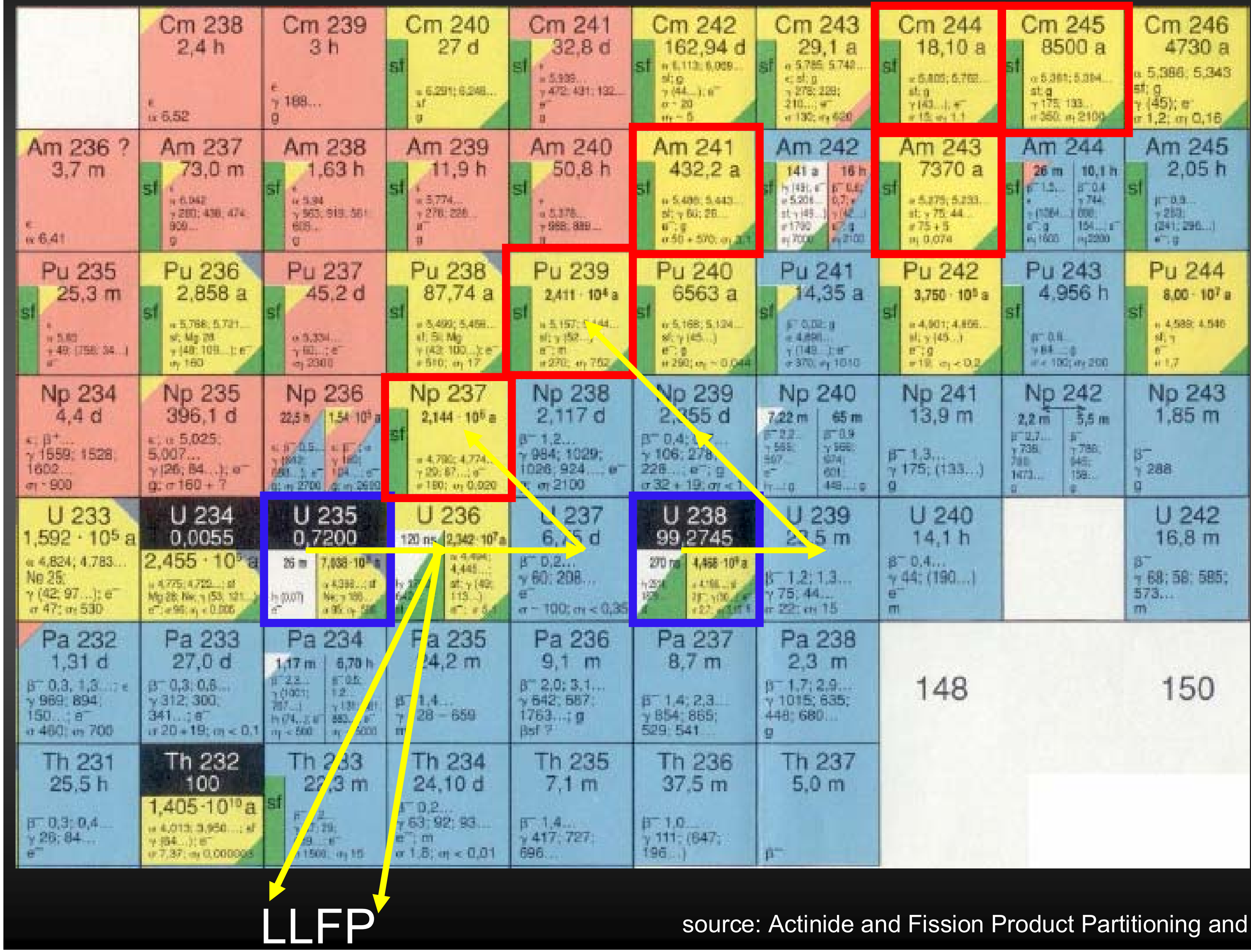
Nuclear waste: TRU

(1000 MW_e LWR)



^{244}Cm
1.5 Kg/yr

^{241}Am: 11.6 Kg/yr
^{243}Am: 4.8 Kg/yr

^{239}Pu: 125 Kg/yr

^{237}Np: 16 Kg/yr

LLFP
76.2 Kg/yr

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

Fast neutrons!

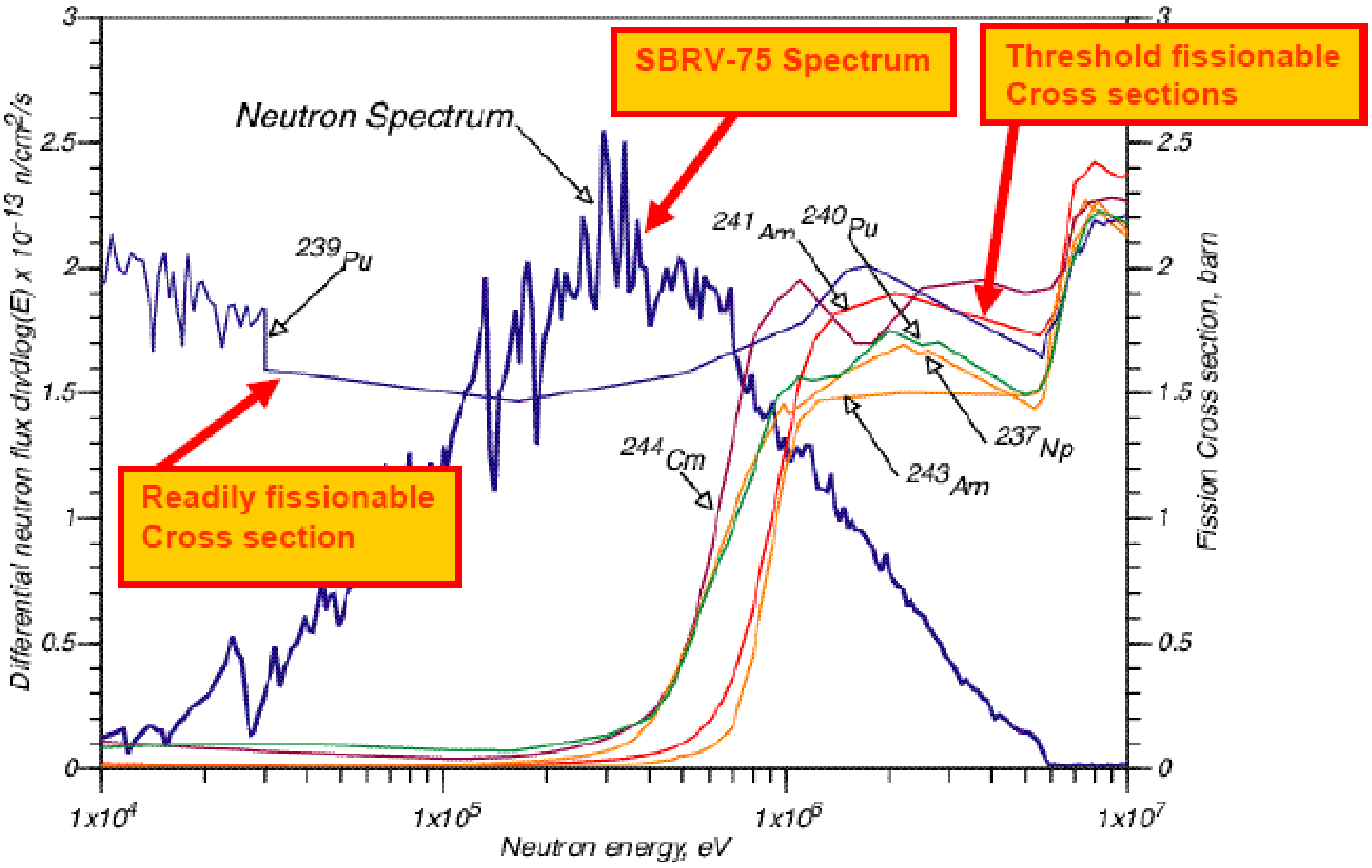
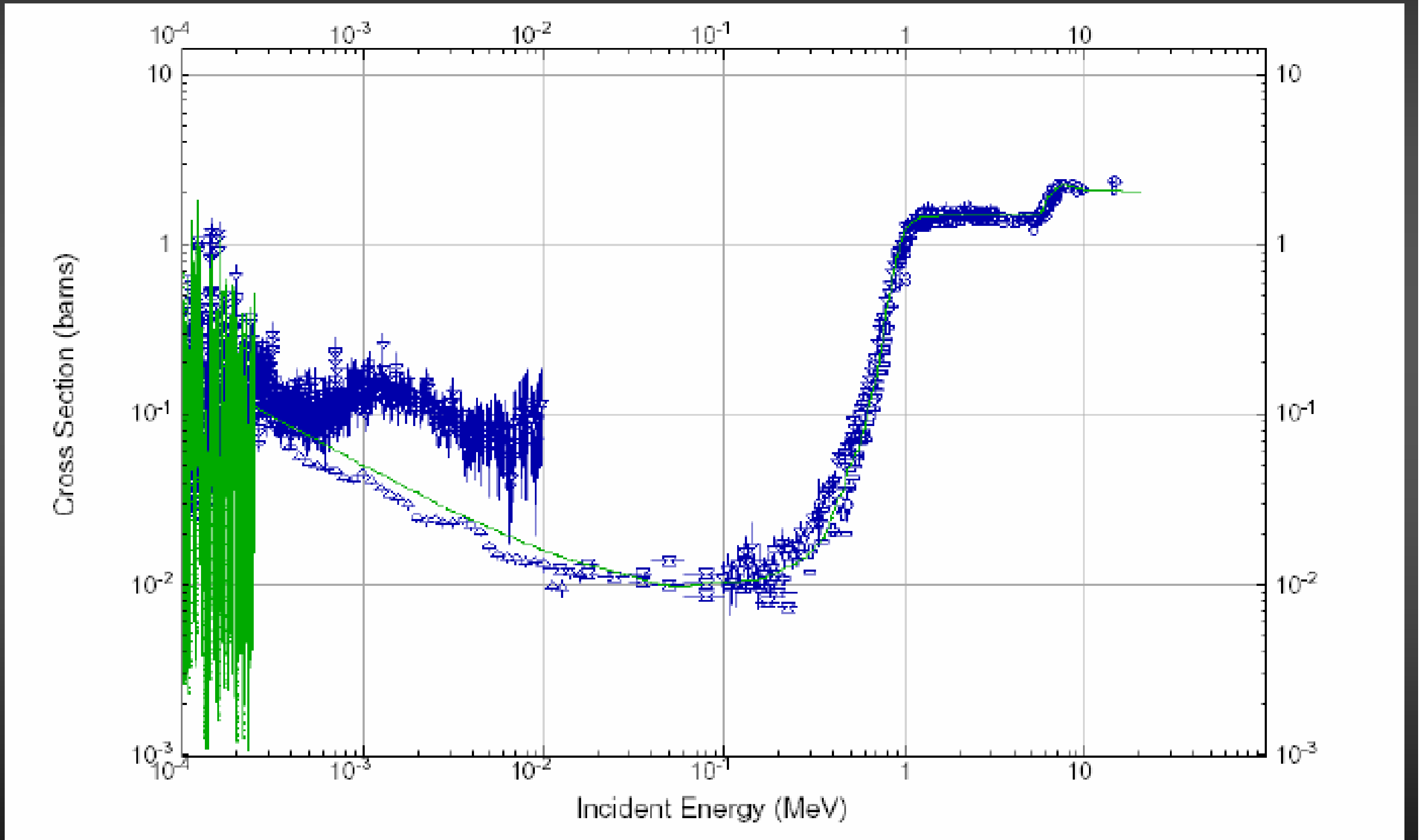


Figure 1: Simulation of the neutron spectrum in the SBRV-75 reactor [2], loaded with the Spiro MA fuel mixture (1/2 of ^{241}Am, 1/4 of ^{243}Am and 1/4 of equal amount of ^{244}Cm and ^{237}Np). The fission cross sections of several MA in consideration here are shown. The fission cross section of ^{239}Pu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

source: C Rubbia

Neutron cross sections data are needed!

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



source: n_TOF Collaboration
(fission proposal)

Neutron cross sections data are needed!

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

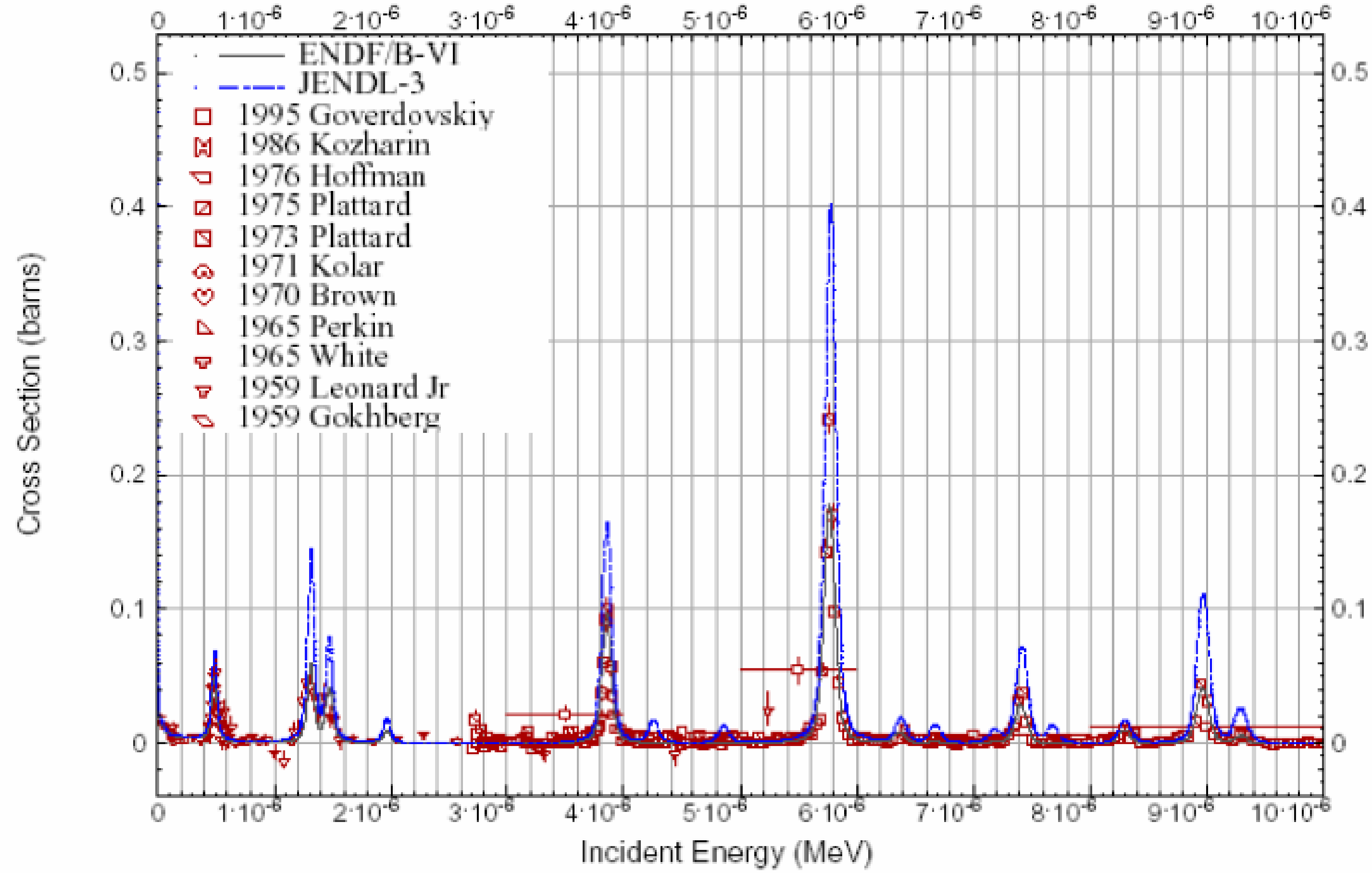


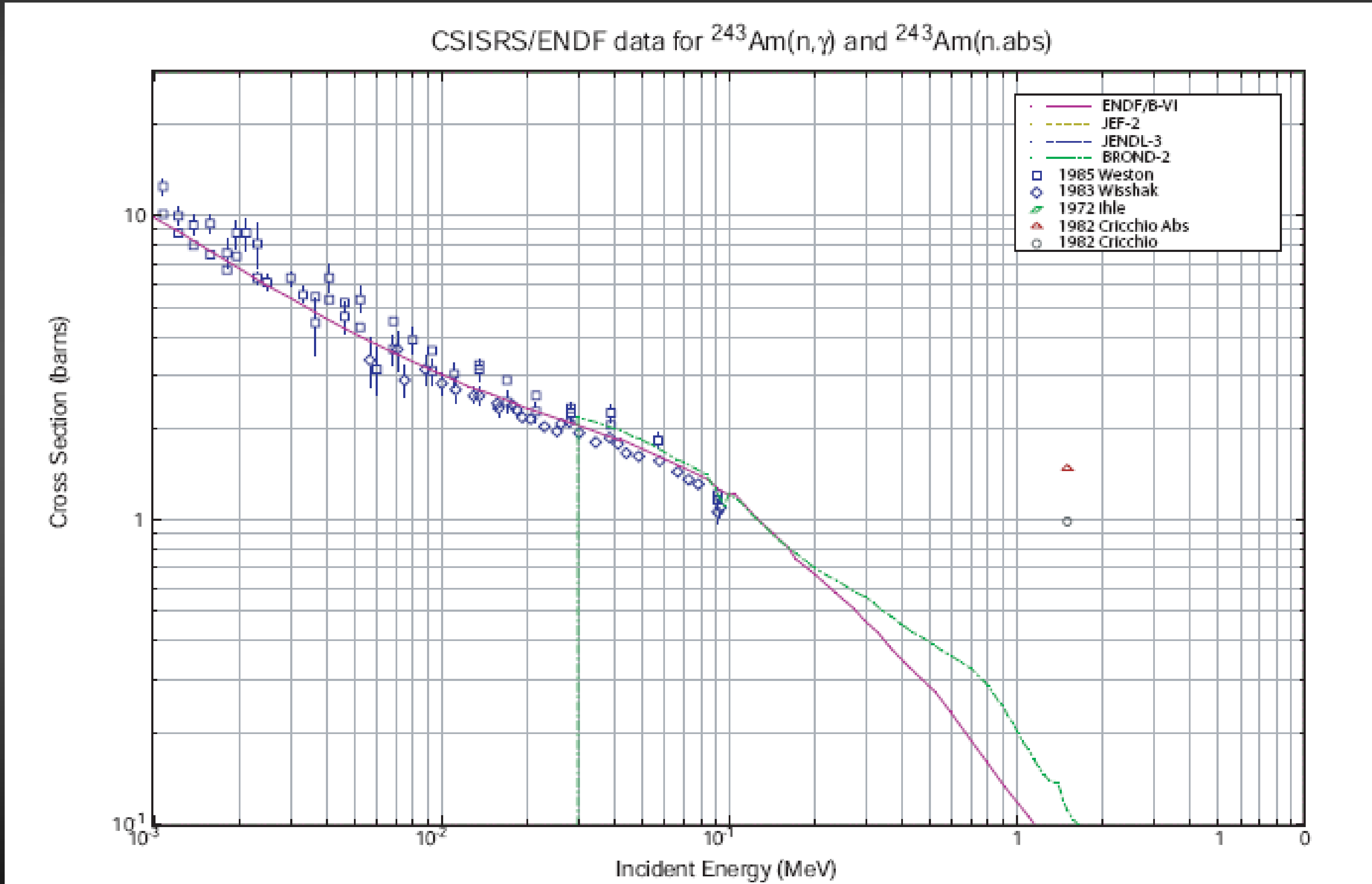
Figure A-1: fission cross section of ^{237}Np in the low energy region, $E_n \leq 10$ eV, well below the fission threshold.

source: n_TOF Collaboration (fission proposal)

Neutron cross sections data are needed!

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

no data
in RRR



source: n_TOF Collaboration
(MA capture proposal)

Th/U fuel cycle

Objectives

- Measurements of neutron cross sections relevant for Nuclear Waste Transmutation and related Nuclear Technologies
- Cross sections relevant for Nuclear Astrophysics
- Neutrons as probes for fundamental Nuclear Physics

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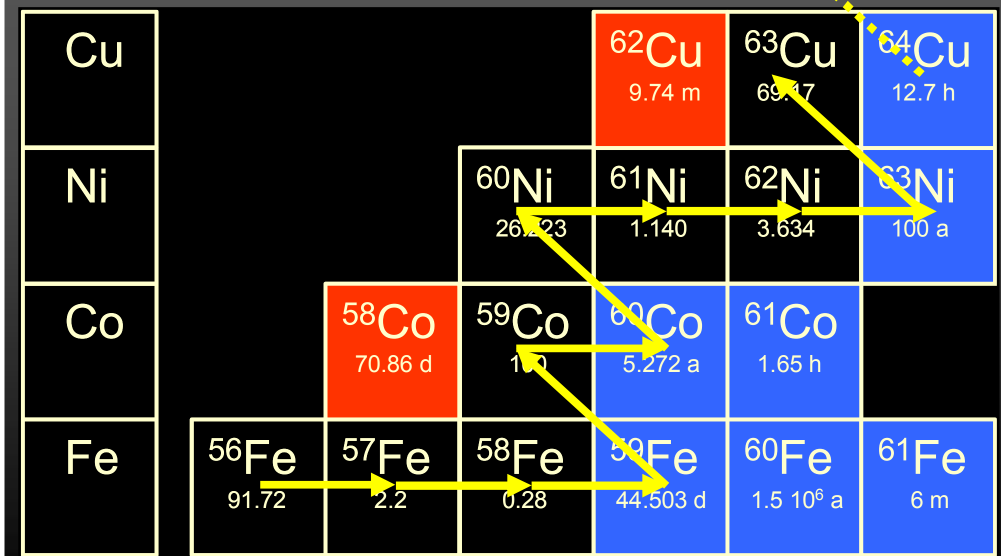
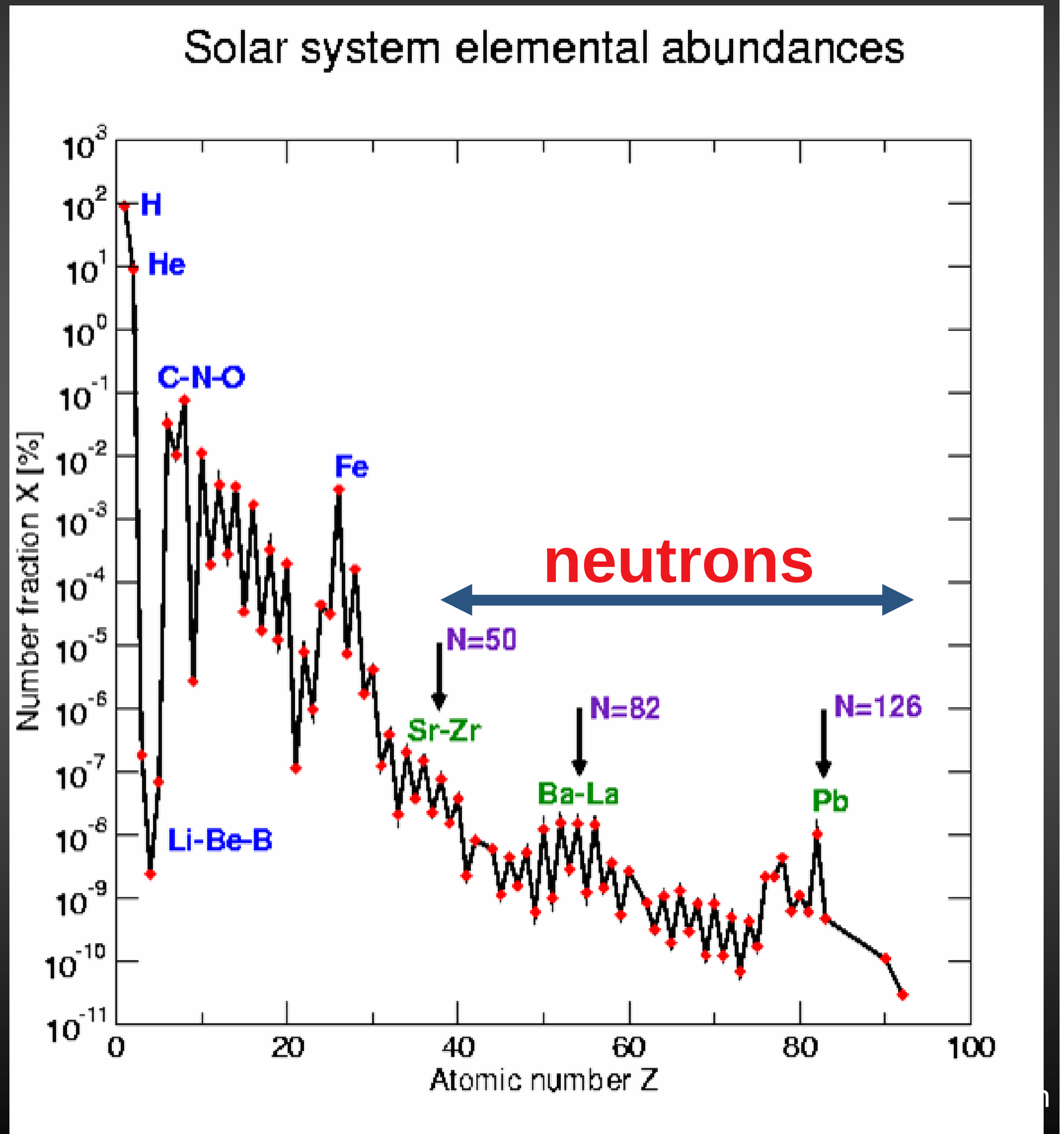
Nucleosynthesis: the s-process

- ½ 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

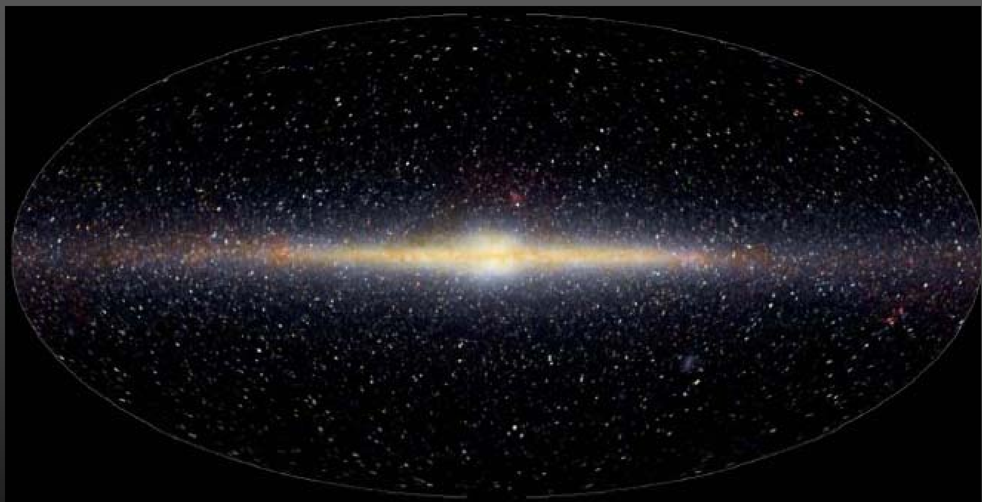
The canonical s-process

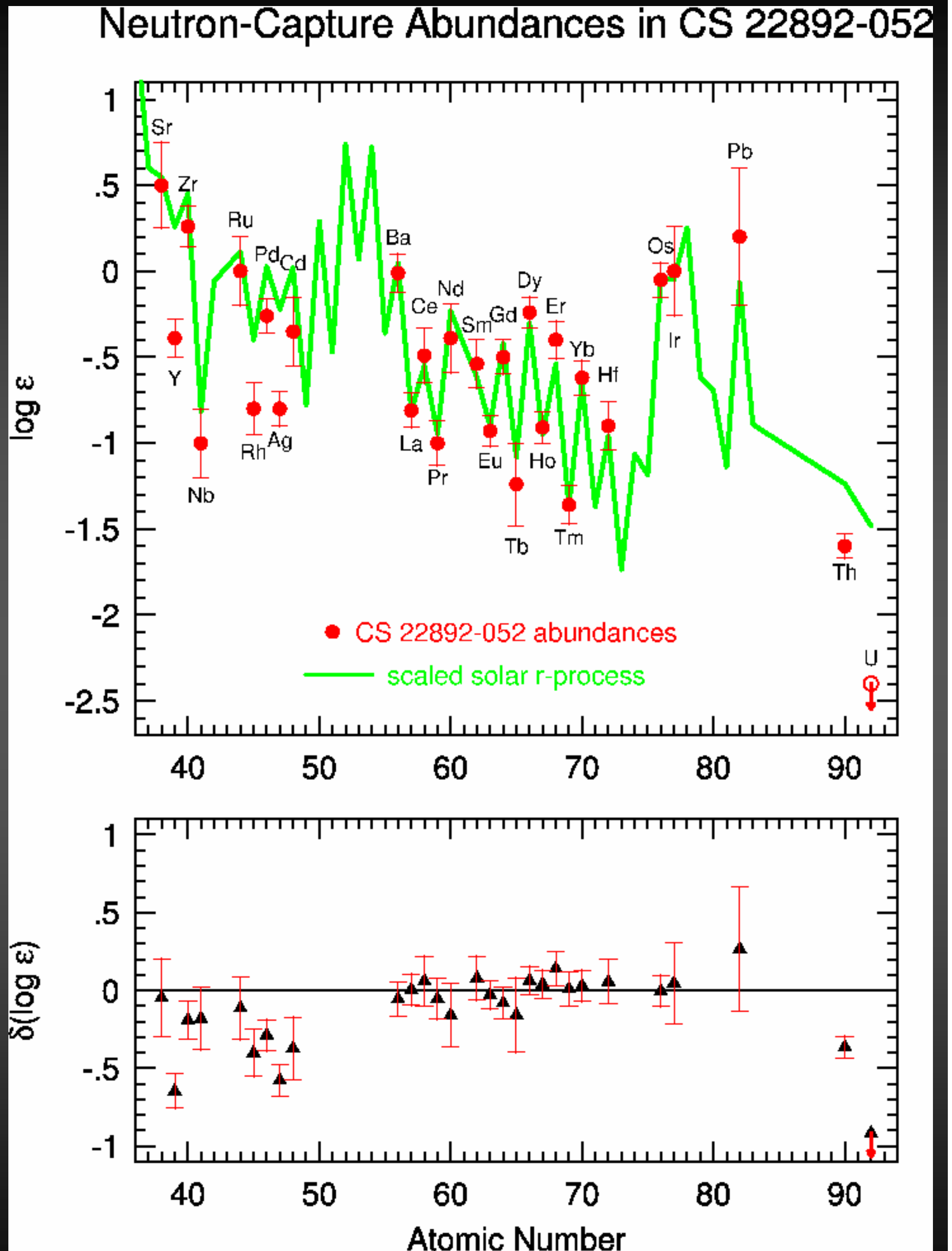




Nucleosynthesis: the s-process & the r-process residuals

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





n_TOF experiments 2002-4

Capture

^{151}Sm

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

^{232}Th

$^{24,25,26}Mg$

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

^{139}La

$^{186,187,188}Os$

$^{233,234}U$

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

Fission

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

^{232}Th

^{209}Bi

^{237}Np

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

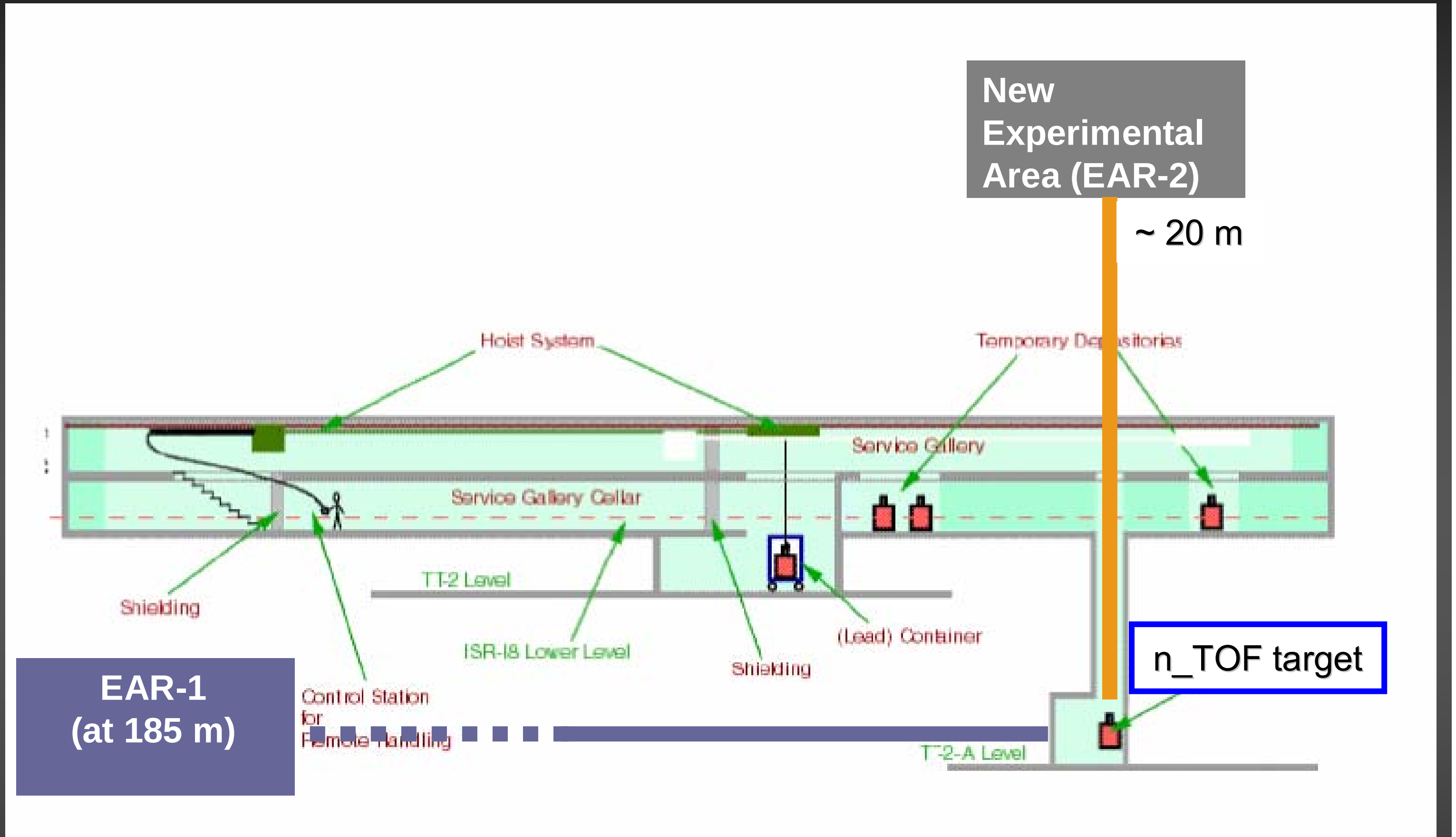
- Measurements of neutron cross sections relevant for Nuclear Waste Transmutation and related Nuclear Technologies
  - Th/U fuel cycle (capture & fission)
  - Transmutation of MA (capture & fission)
  - Transmutation of FP (capture)
- Cross sections relevant for Nuclear Astrophysics
  - s-process: branchings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

The n_TOF Collaboration

U.Abbondanno[14], G.Aerts[7], H.Álvarez[24], F.Alvarez-Velarde[20], S.Andriamonje[7], J.Andrzejewski[33], P.Assimakopoulos[9], L.Audouin[5], G.Badurek[1], P.Baumann[6], F. Bečvář [31], J.Benlliure[24], E.Berthoumieux[7], F.Calviño[25],D.Cano-Ott[20],R.Capote[23],A.Carrillo de Albornoz[30],P.Cennini[4], V.Chepel1[7], E.Chiaveri[4], N.Colonna1[3], G.Cortes[25], D.Cortina[24], A.Couture[29], J.Cox[29], S.David[5], R.Dolfini[15], C.Domingo-Pardo[21], W.Dridi[7], I.Duran[24], M.Embid-Segura[20], L.Ferrant[5], A.Ferrari[4], R.Ferreira-Marques[17], L.Fitzpatrick[4], H.Frais-Koelbl[3], K.Fujii[13], W.Furman[18], C.Guerrero[20], I.Goncalves[30], R.Gallino[36], E.Gonzalez-Romero[20], A.Goverdovski[19], F.Gramegna[12], E.Griesmayer[3], F.Gunsing[7], B.Haas[32], R.Haight[27], M.Heil[8], A.Herrera-Martinez[4], M.Igashira[37], S.Isaev[5], E.Jericha[1], Y.Kadi[4], F.Käppeler[8], D.Karamanis[9], D.Karadimos[9], M.Kerveno[6], V.Ketlerov[19], P.Koehler[28], V.Konovalov[18], E.Kossionides[39], M.Krtička[31], C.Lamboudis[10], H.Leeb[1], A.Lindote[17], I.Lopes[17], M.Lozano[23], S.Lukic[6], J.Marganiec[33], L.Marques[30], S.Marrone[13], P.Mastinu[12], A.Mengoni[4], P.M.Milazzo[14], C.Moreau[14], M.Mosconi[8], F.Neves[17], H.Oberhummer[1], S.O'Brien[29], M.Oshima[38], J.Pancin[7], C.Papachristodoulou[9], C.Papadopoulos[40], C.Paradela[24], N.Patronis[9], A.Pavlik[2], P.Pavlopoulos[34], L.Perrot[7], R.Plag[8], A.Plompen[16], A.Plukis[7], A.Poch[25], C.Pretel[25], J.Quesada[23], T.Rauscher[26], R.Reifarth[27], M.Rosetti1[1], C.Rubbia[5], G.Rudolf[6], P.Rullhusen[16], J.Salgado[30], L.Sarchiapone[4], C.Stephan[5], G.Tagliente[13], J.L.Tain[21], L.Tassan-Got[5], L.Tavora[30], R.Terlizzi[13], G.Vannini[35], P.Vaz[30], A.Ventura[11], D.Villamarin[20], M.C.Vincente[20], V.Vlachoudis[4], R.Vlastou[40], F.Voss[8], H.Wendler[4], M.Wiescher[29], K.Wisshak[8]

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.

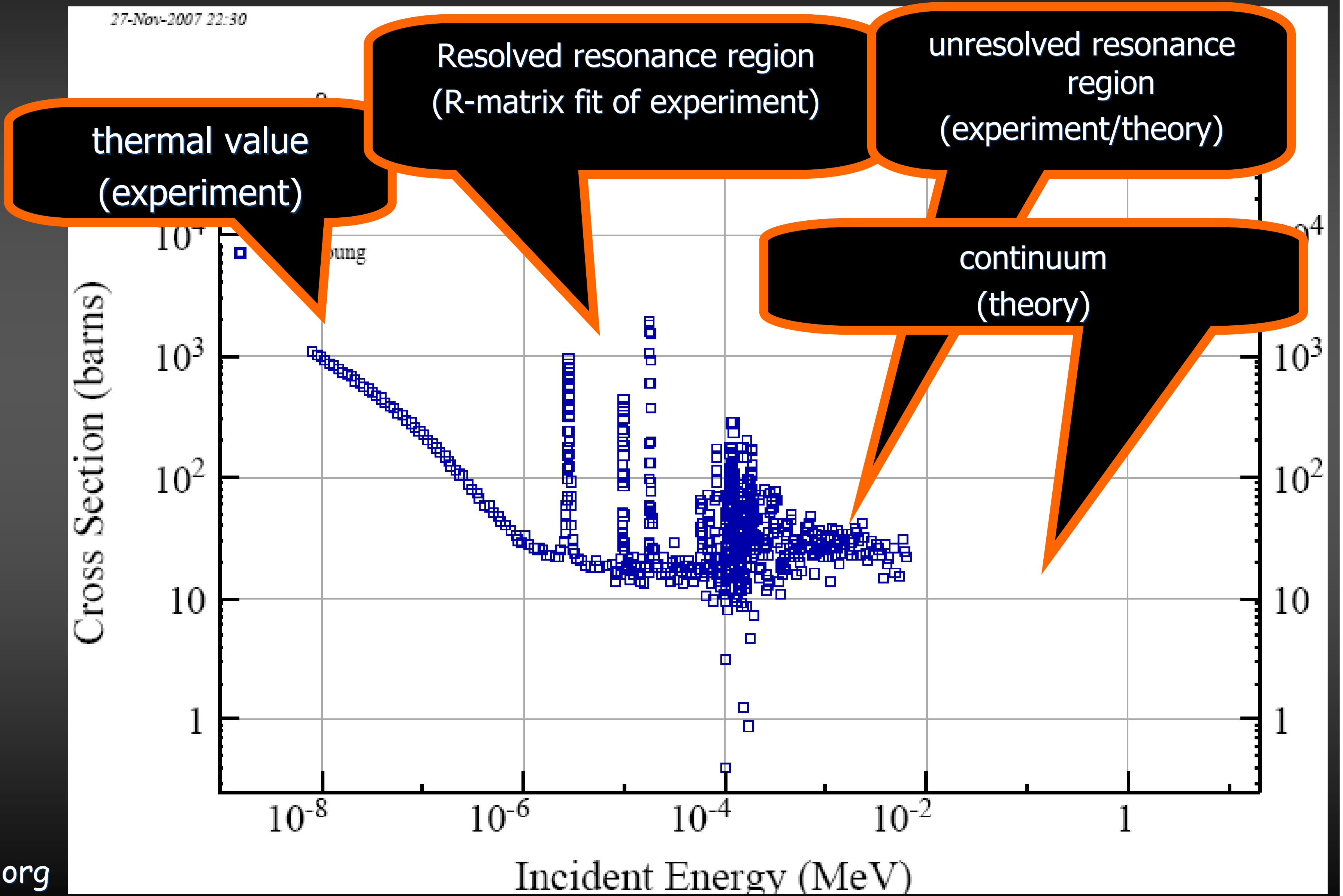
Thank you. Now that we know how measurements are done, how can we produce evaluated data libraries?

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.

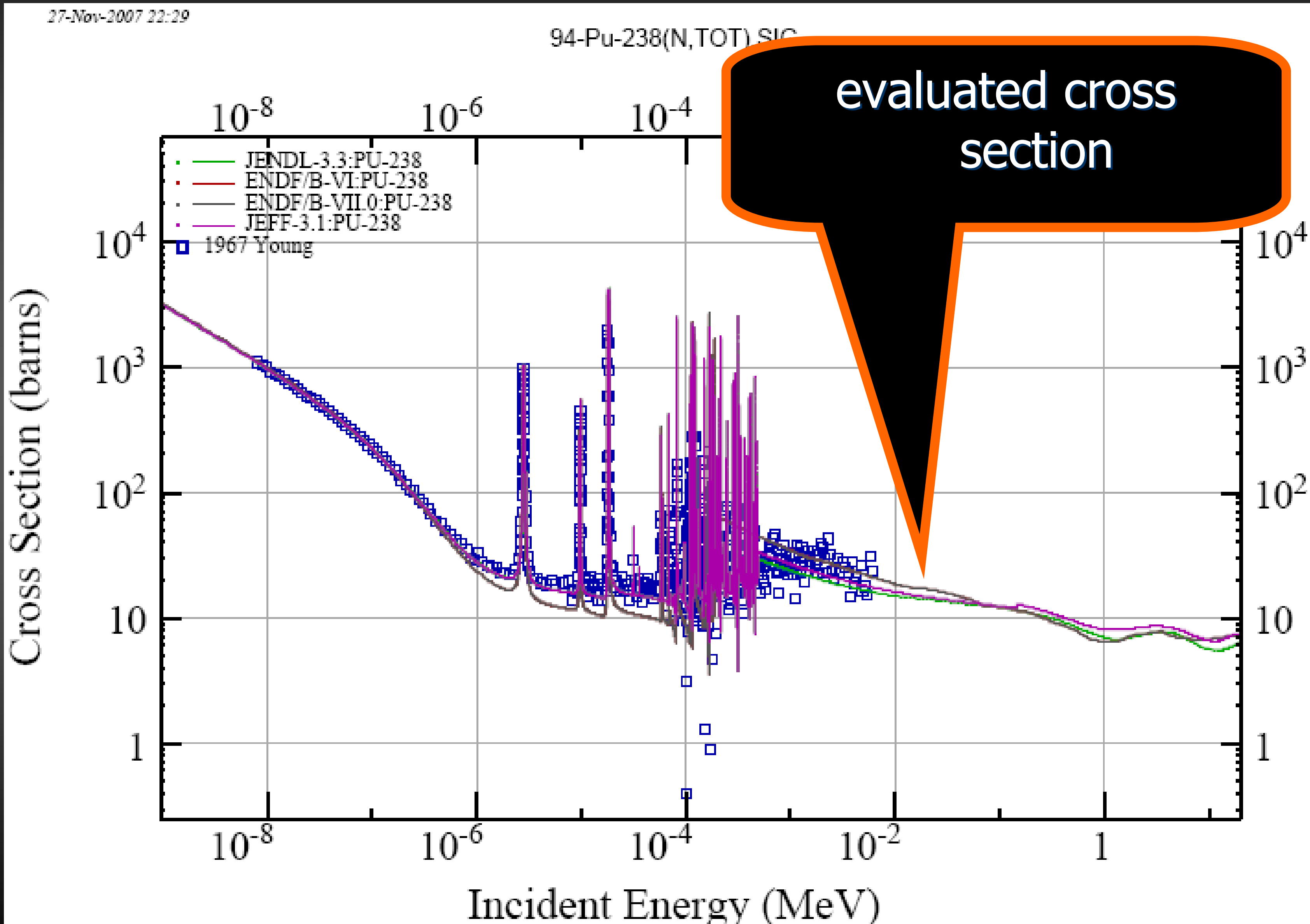
Evaluated Libraries are computer files of evaluated data which, appropriately processed, form the input data to computations for a wide variety of nuclear science and technology applications. Each of these evaluated libraries may consist of individual evaluated data sets for several hundred isotopes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

From experimental data...



www-nds.iaea.org

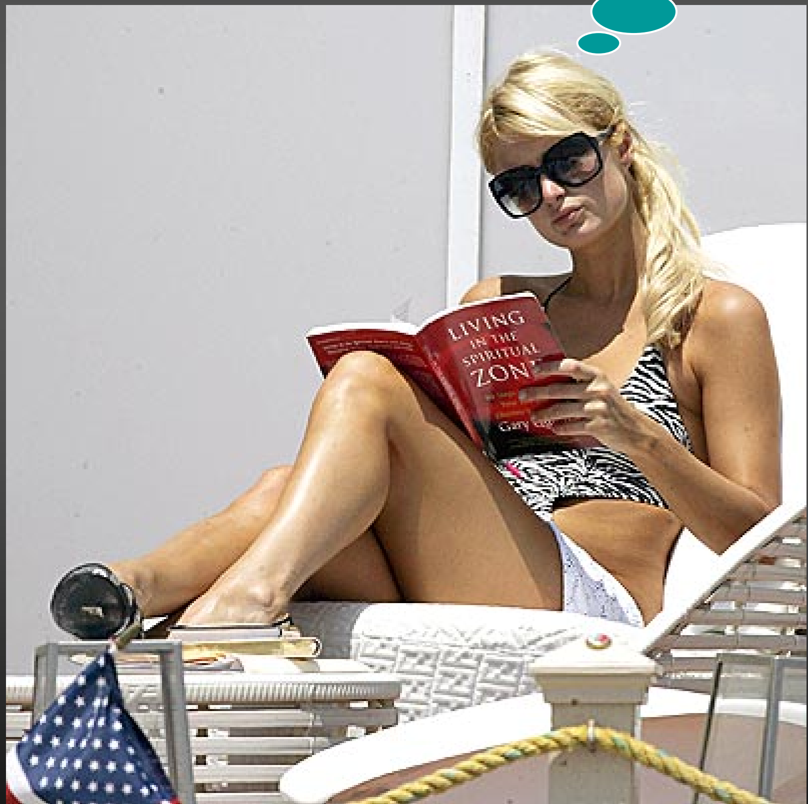
... to evaluated Data Libraries



www-nds.iaea.org

Uhmm… Interesting!

I wonder if I have to get nuclear data from printed stuff, or I ca get them online…

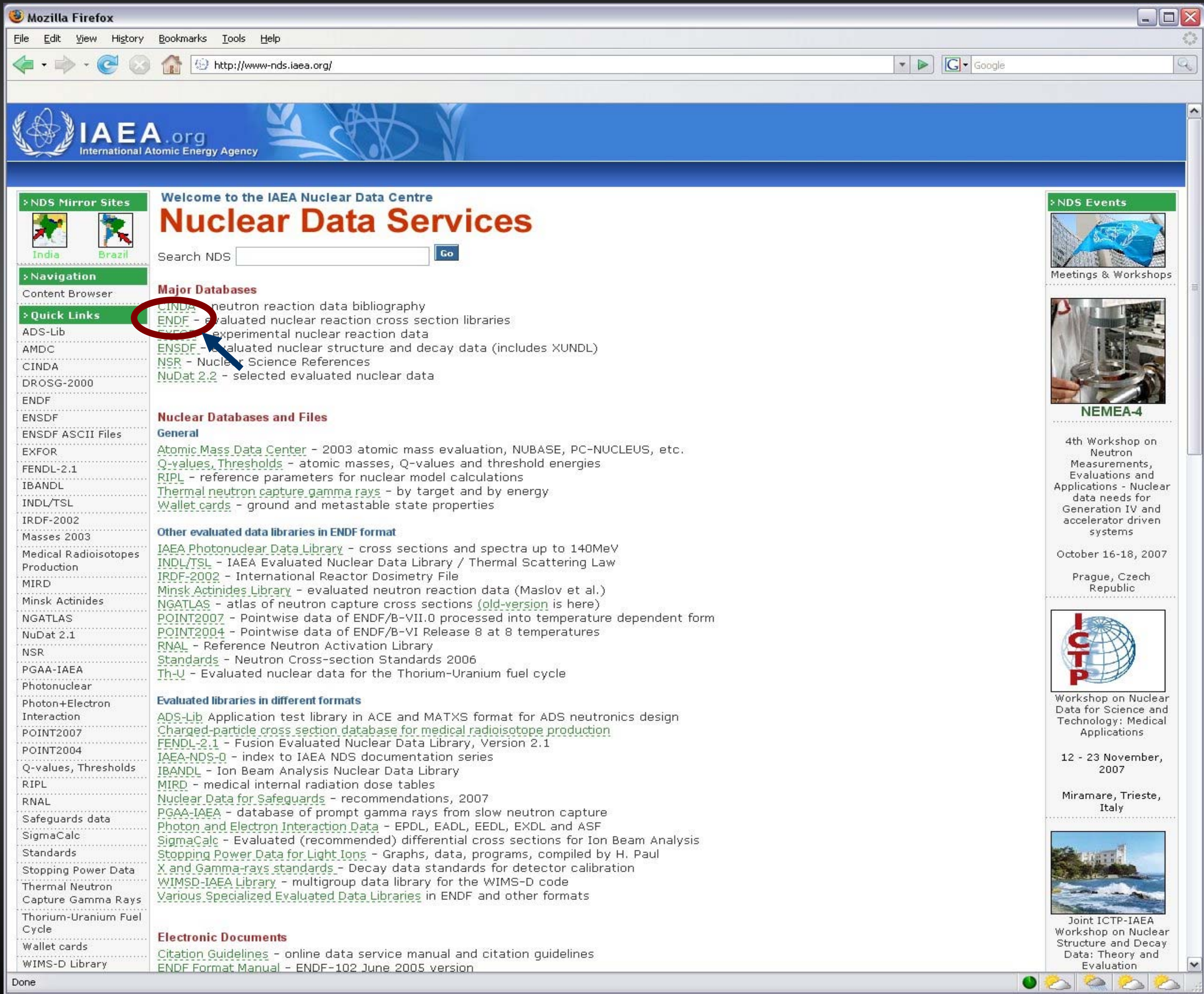


Providing On-line Services: Retrieval and Display Tools

Example:

what is the capture cross section of Zr-91 at E_n = 30 keV ?

Data Libraries



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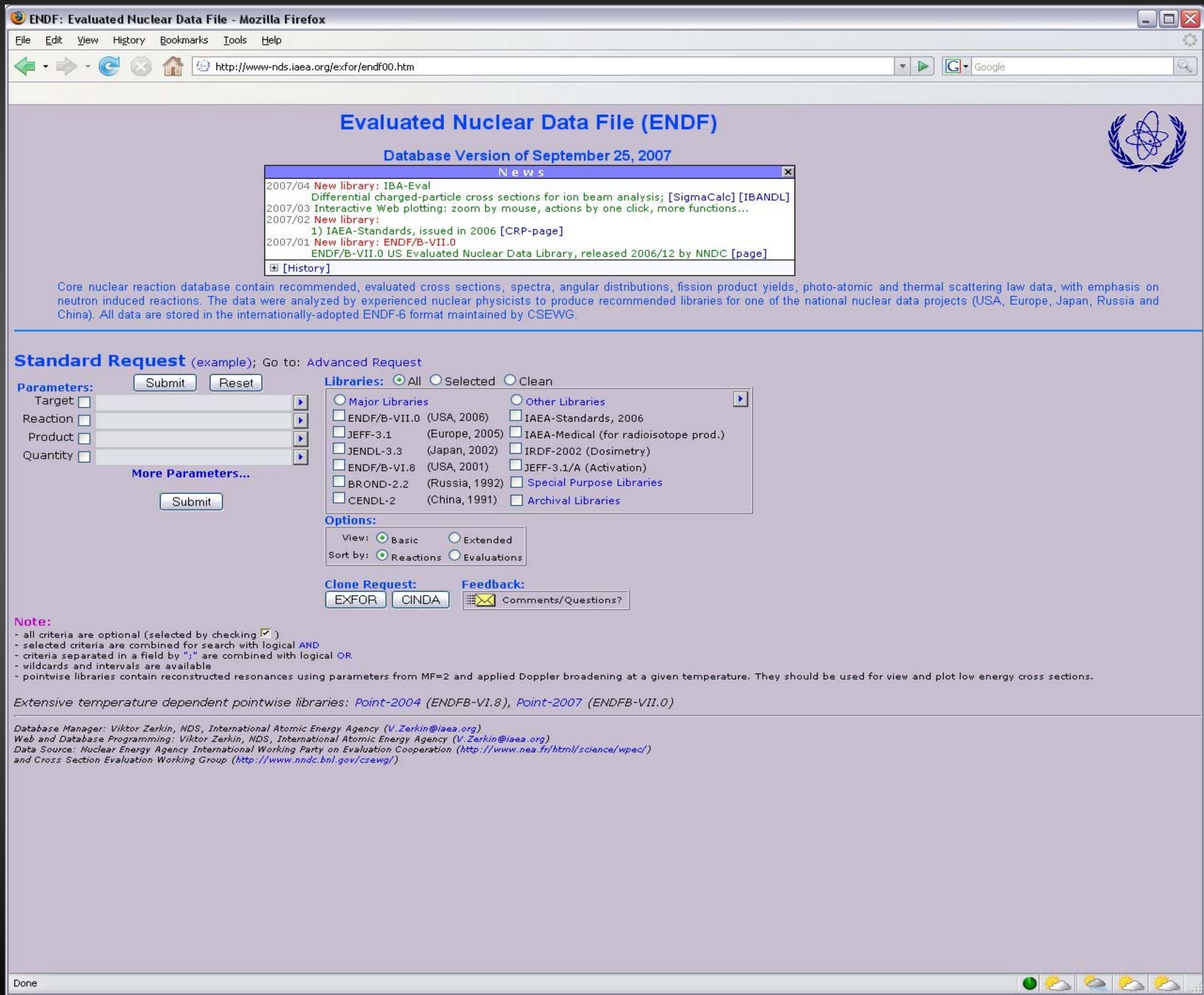
Data Libraries



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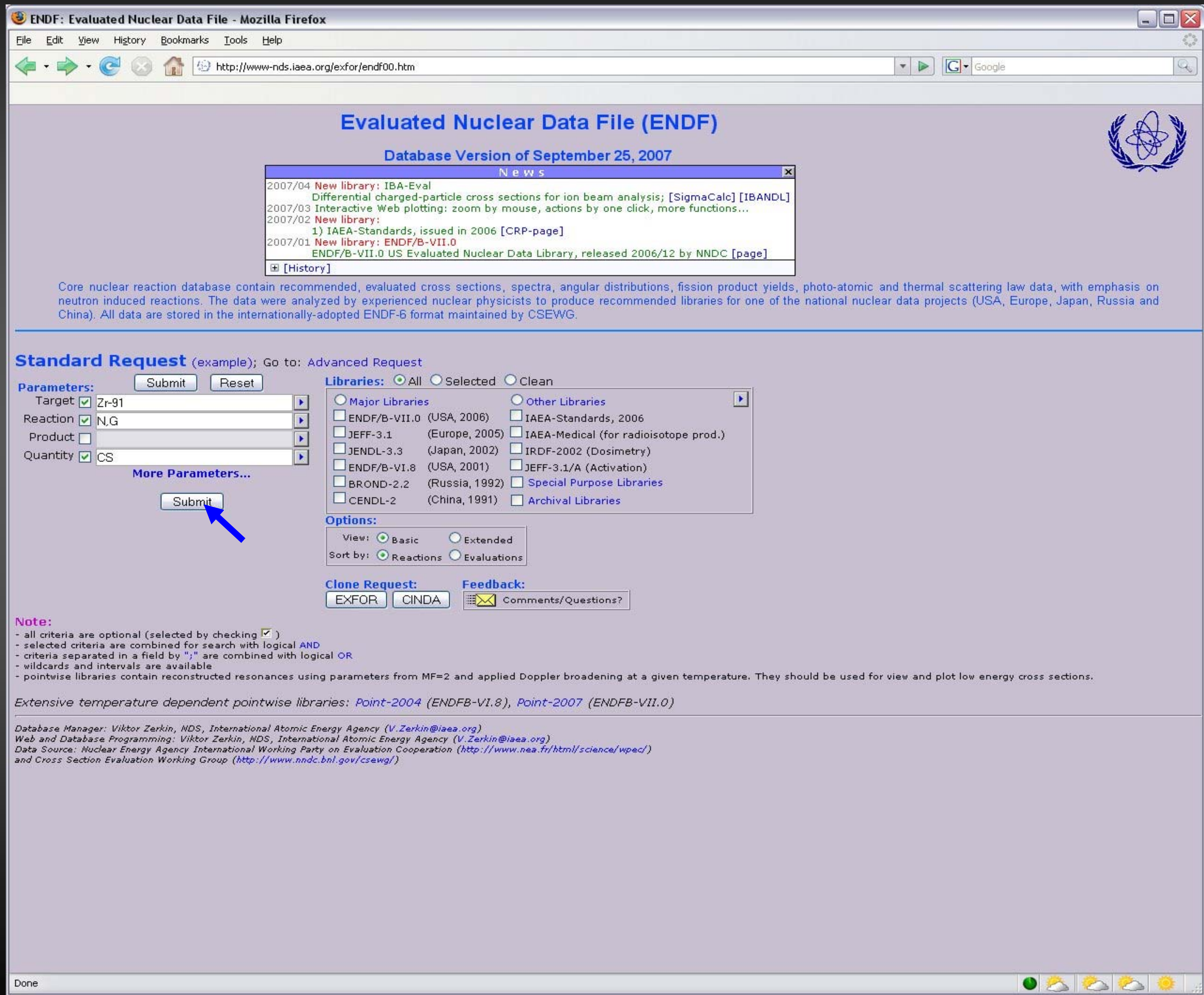
Data Libraries



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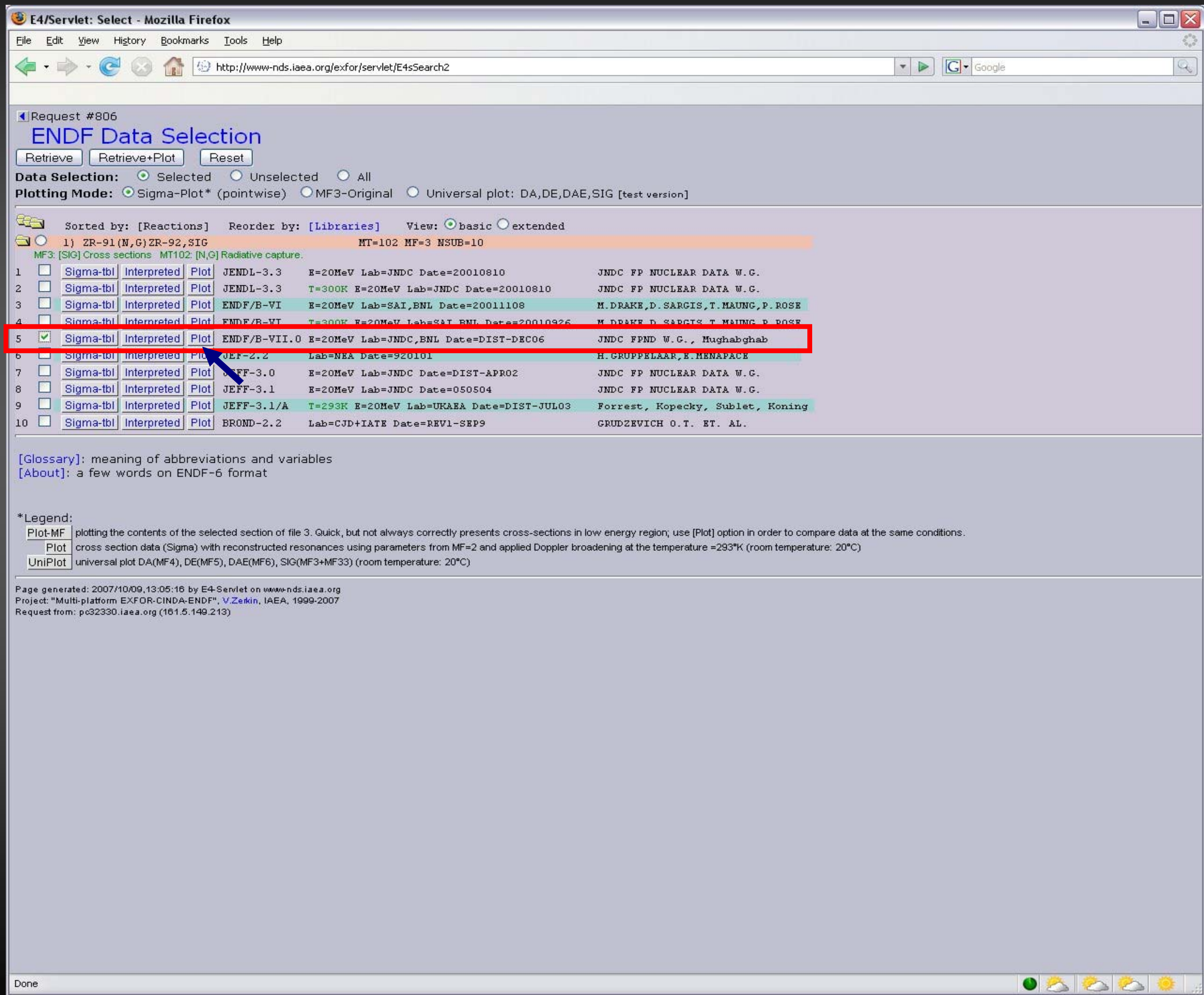
Data Libraries



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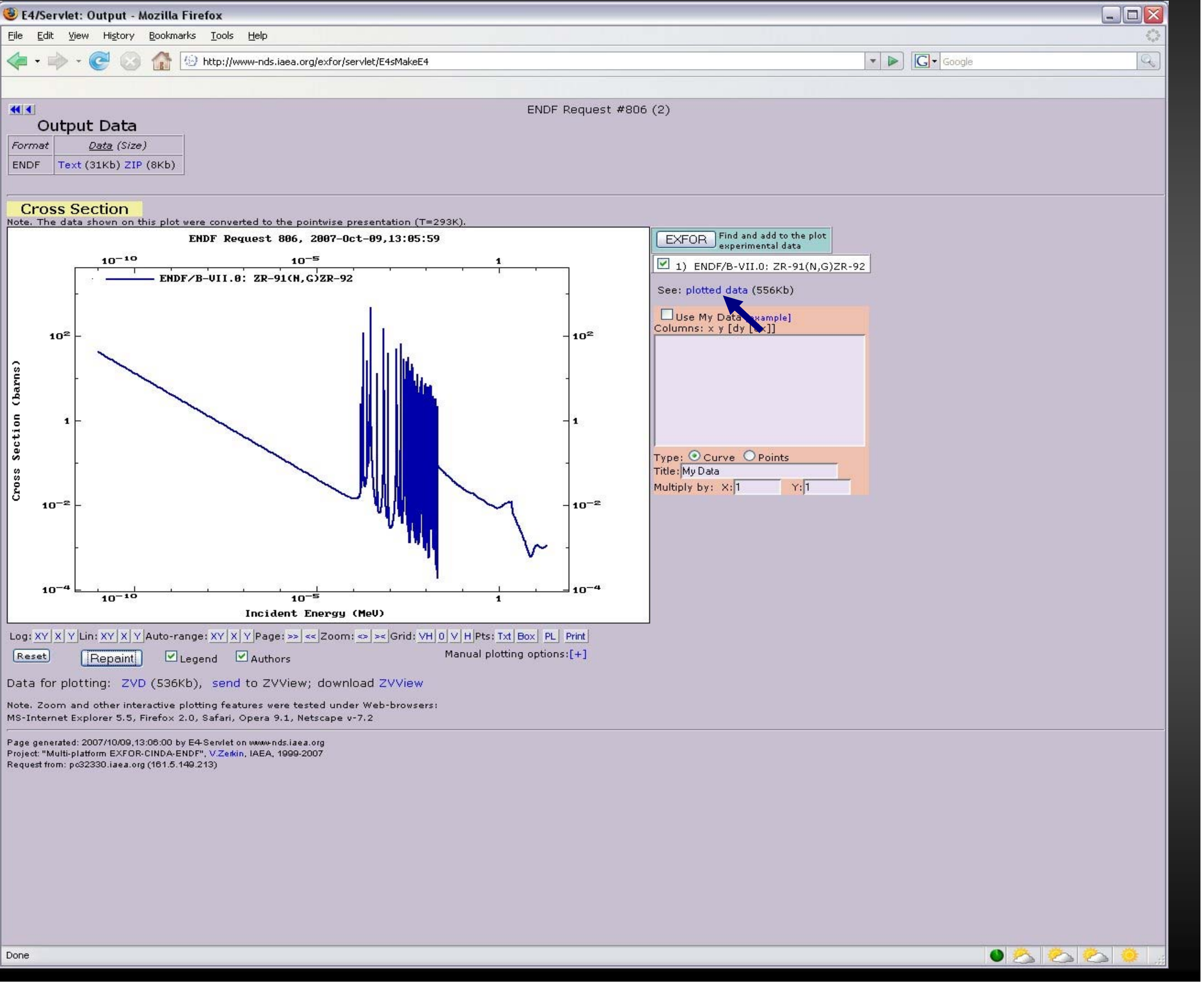
Data Libraries



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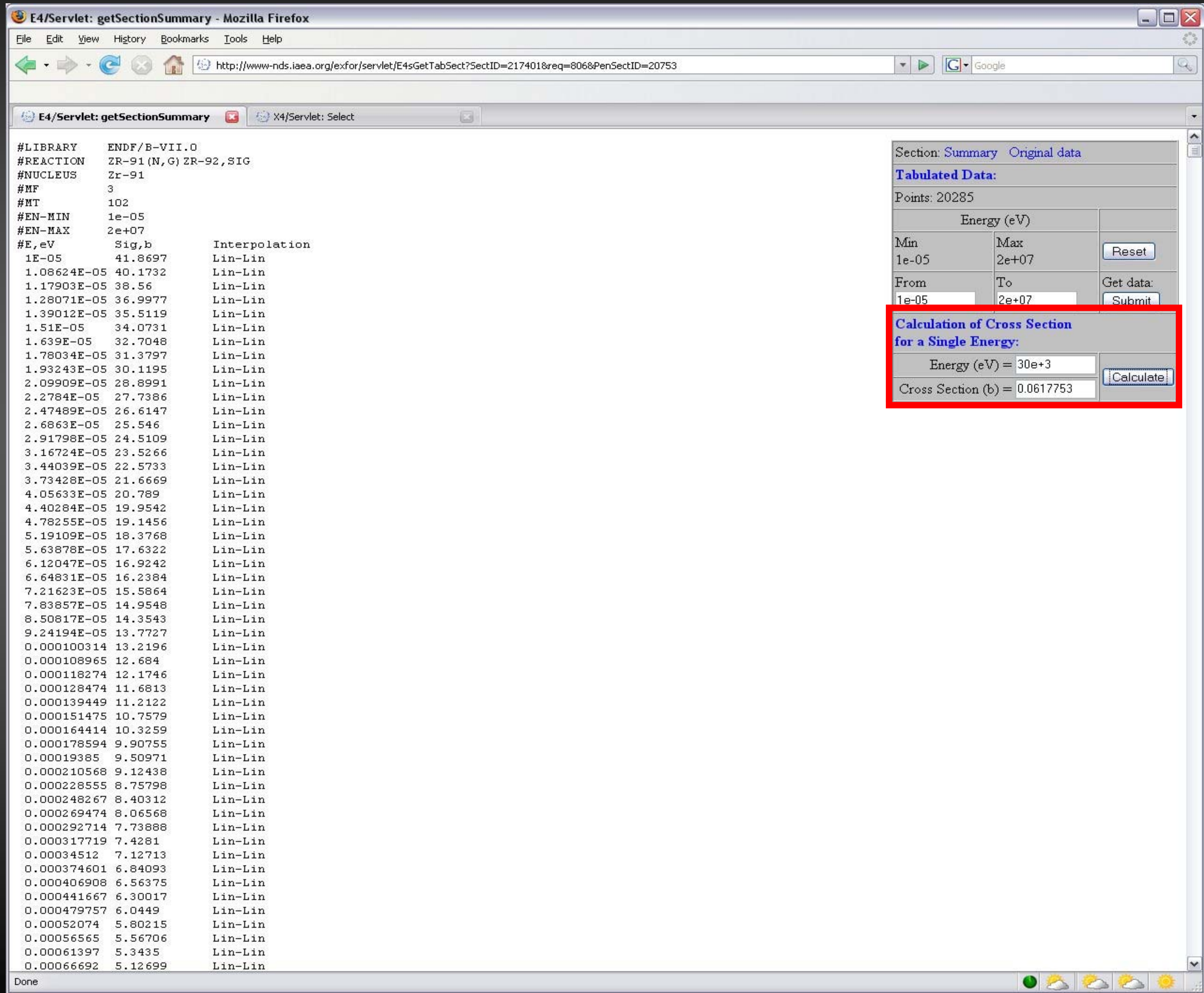
Data Libraries

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



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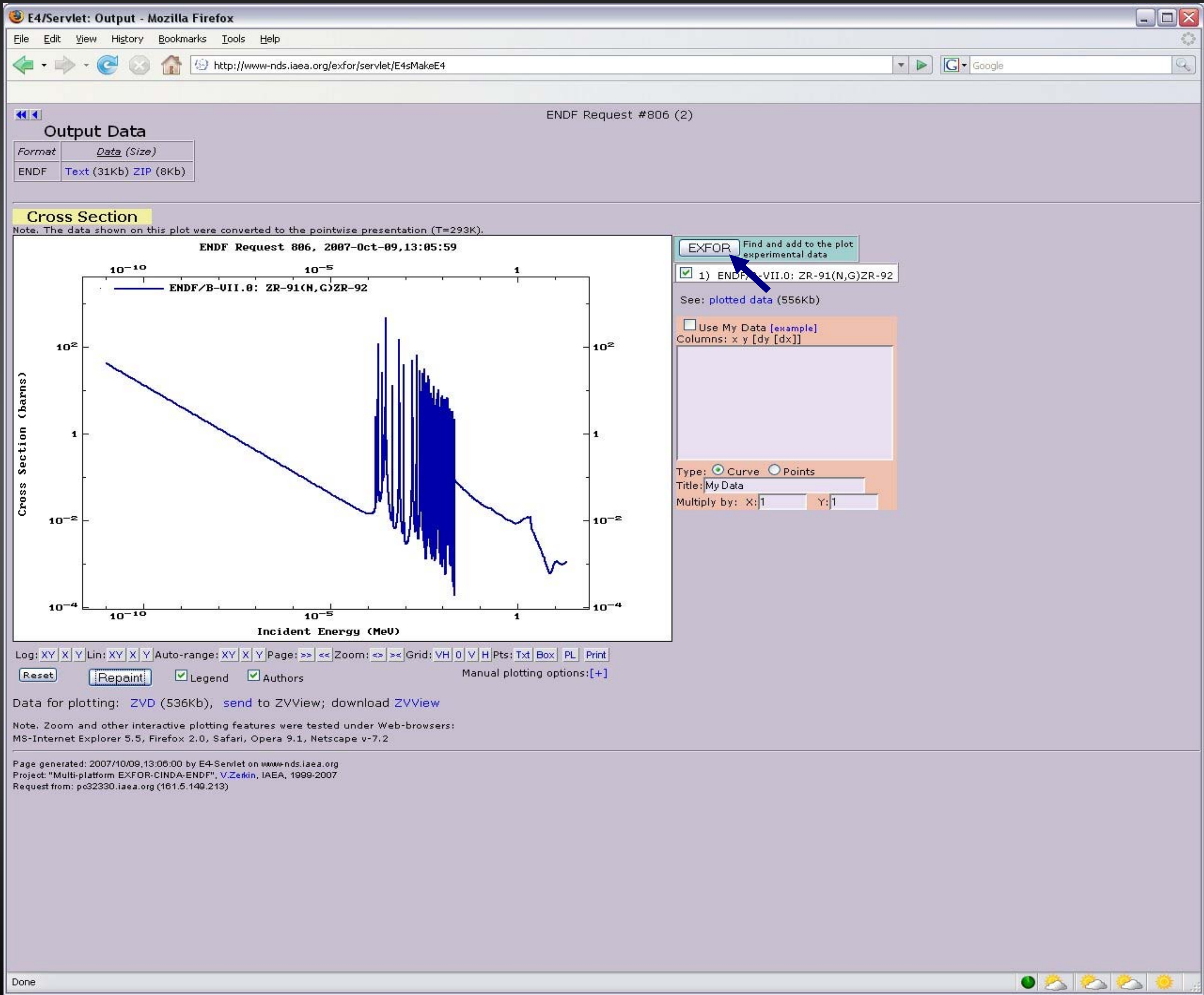
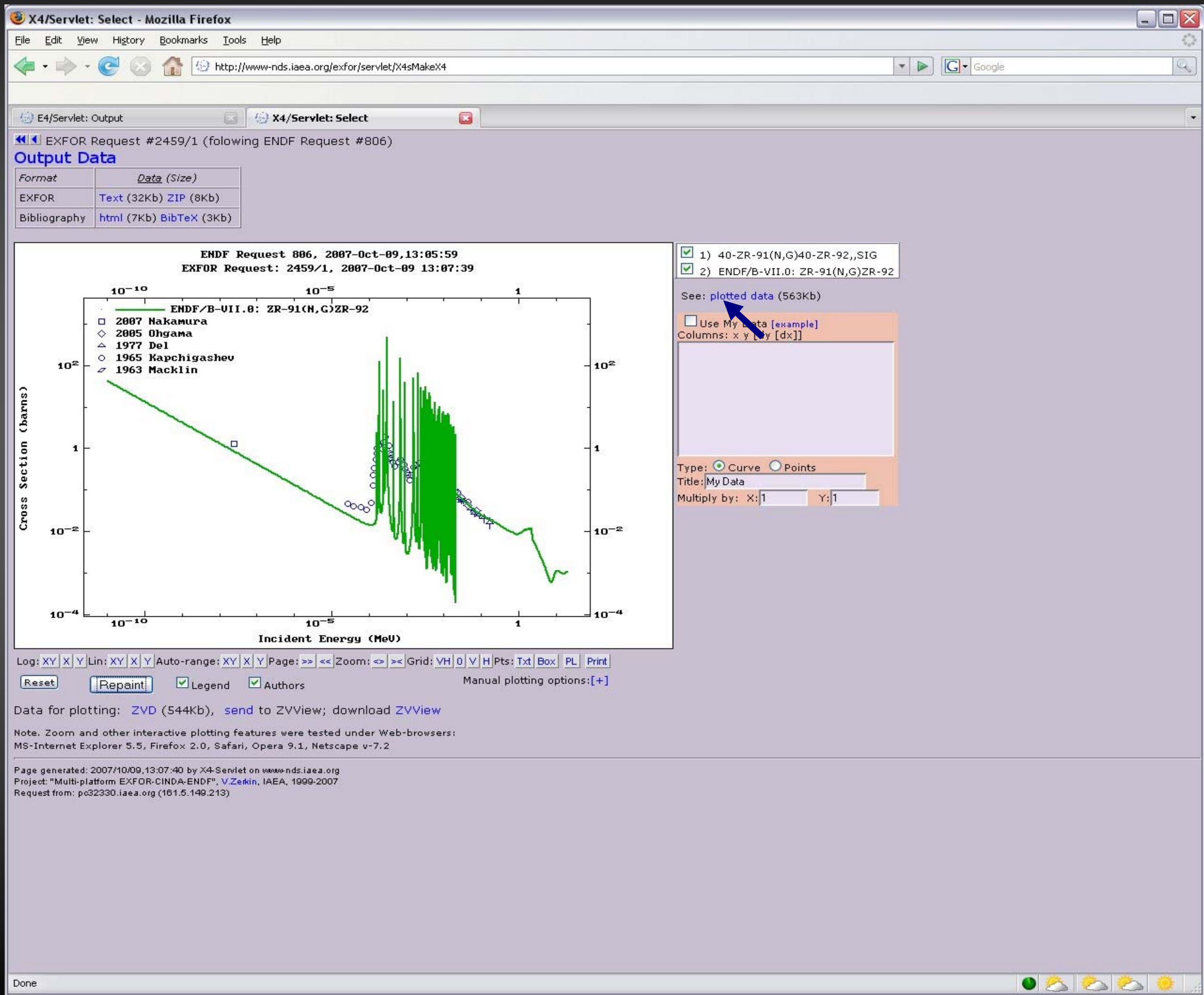
Data Libraries

How about experimental data?



Data Libraries



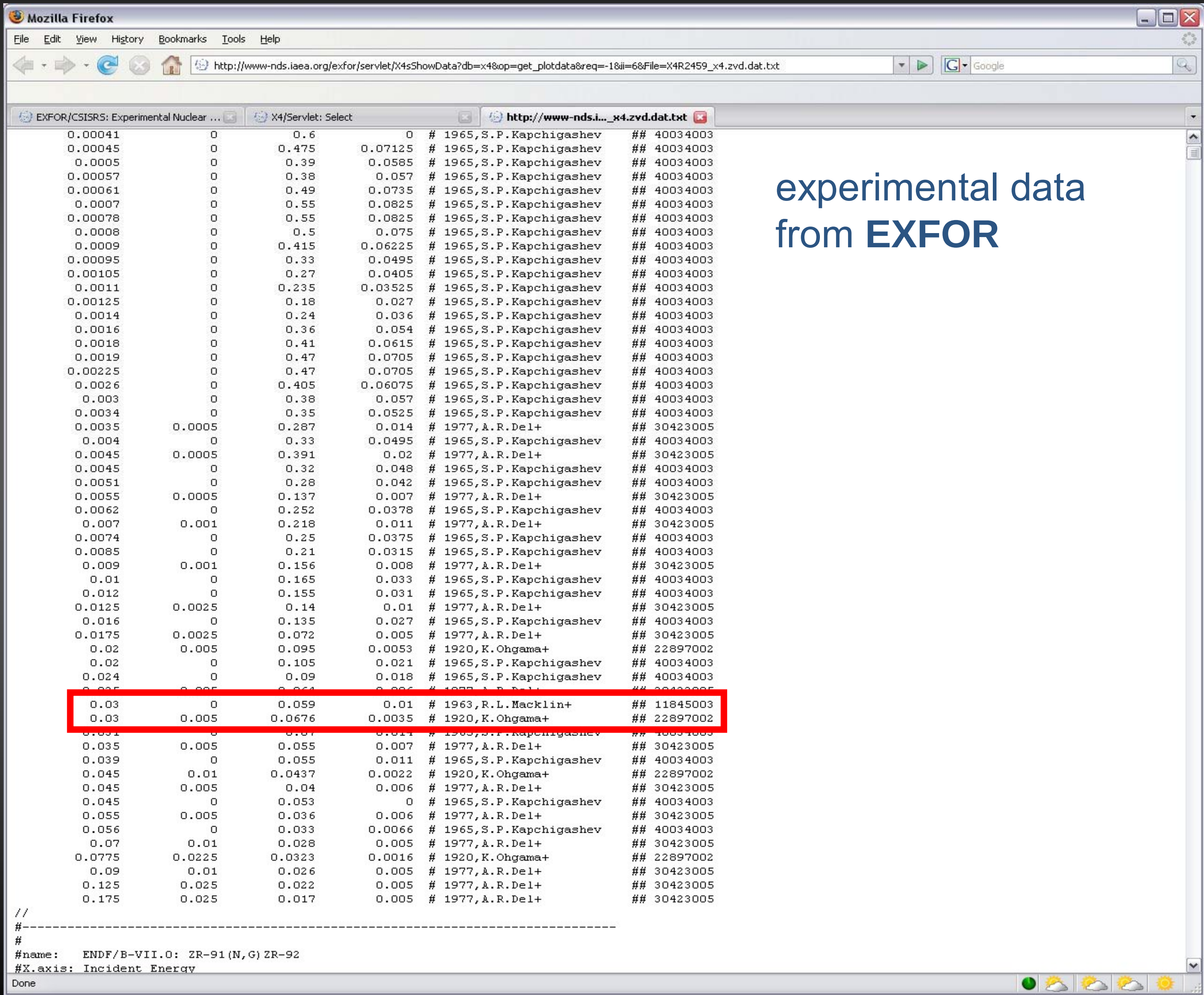
www-nds.iaea.org

Data Libraries

two experimental values:
59 ± 1 mb
67.6 ± 3.5 mb

weighted average:
σ = 61.0 ± 1.6 mb

value from evaluated library:
σ = 61.8 mb



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
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
0.03	0	0.059	0.01	# 1963,R.L.Macklin+	## 11845003
0.03	0.005	0.0676	0.0035	# 1920,K.Ohgama+	## 22897002
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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
```

experimental data from **EXFOR**

www-nds.iaea.org

Data Libraries

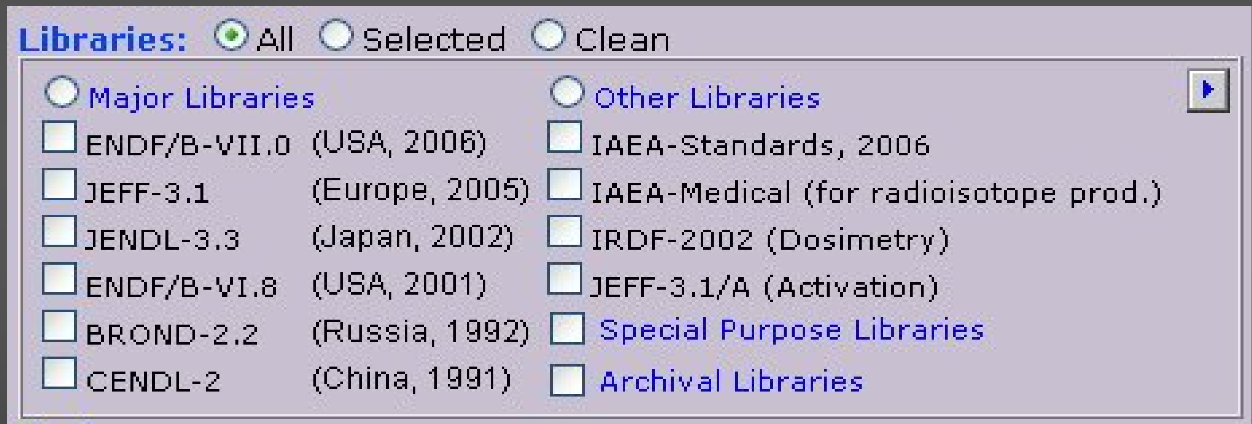
Uhmm…

σ = 61.0 ± 1.6 mb   at 30 keV

In perfect agreement with my own evaluation!

Data Libraries

Other major Nuclear Data libraries available for display & retrieval:



The End

a.mengoni@iaea.org

n_TOF experiments

Capture

^{151}Sm

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

^{232}Th

$^{24,25,26}Mg$

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

^{139}La

$^{186,187,188}Os$

$^{233,234}U$

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

Fission

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

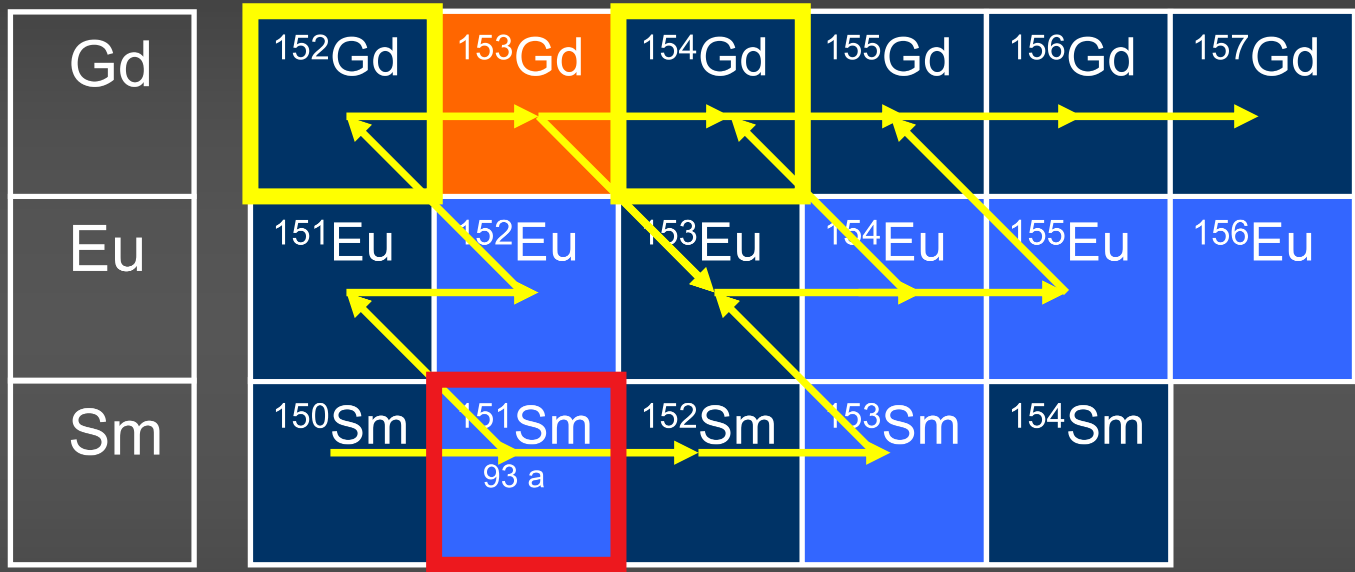
^{232}Th

^{209}Bi

^{237}Np

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

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

n_TOF experiments

Capture

^{151}Sm

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

^{232}Th

$^{24,25,26}Mg$

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

^{139}La

$^{186,187,188}Os$

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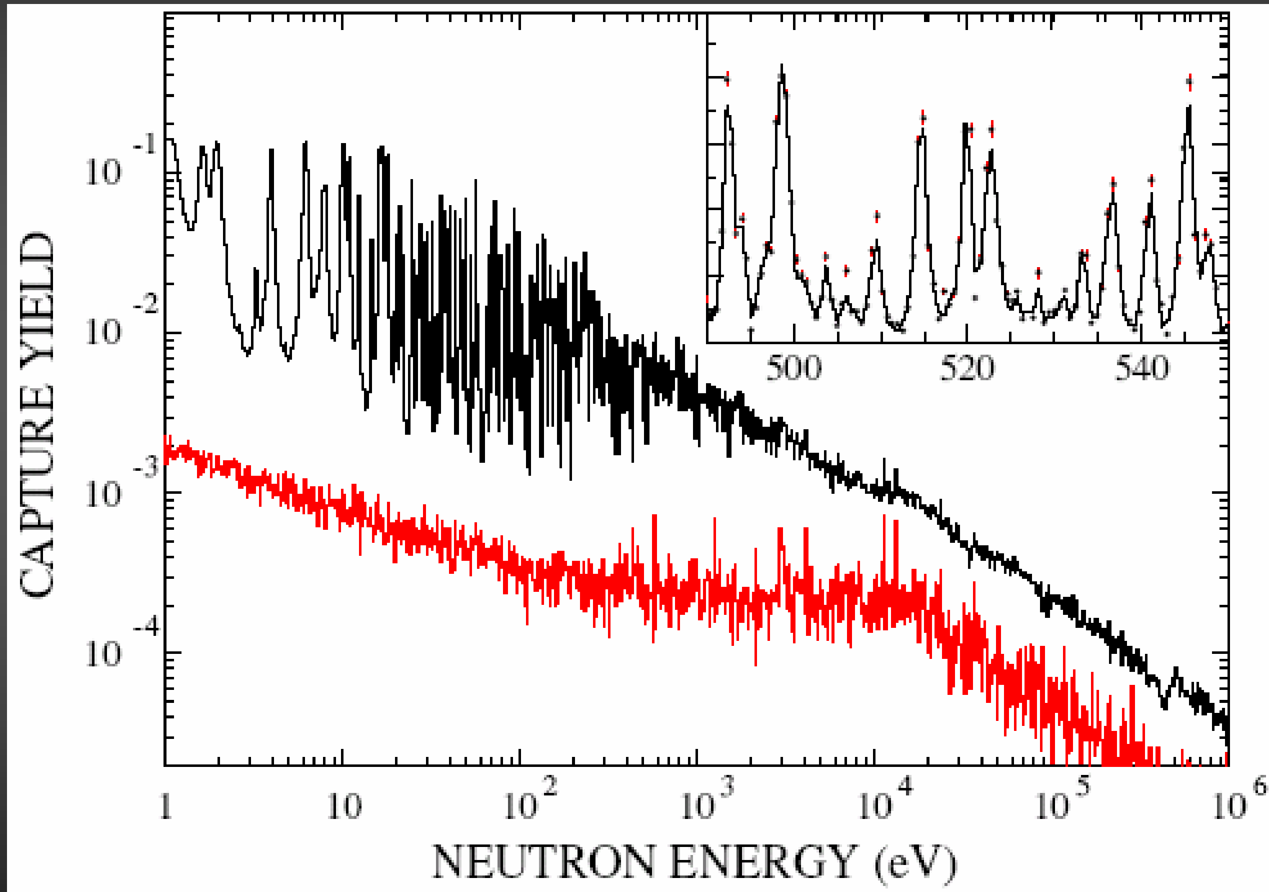
^{232}Th

^{209}Bi

^{237}Np

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

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



the 1st measurement at n_TOF

n_TOF experiments

Capture

^{151}Sm

^{204,206,207,208}Pb, ^{209}Bi

^{232}Th

^{24,25,26}Mg

^{90,91,92,94,96}Zr, ^{93}Zr

^{139}La

^{186,187,188}Os

^{233,234}U

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

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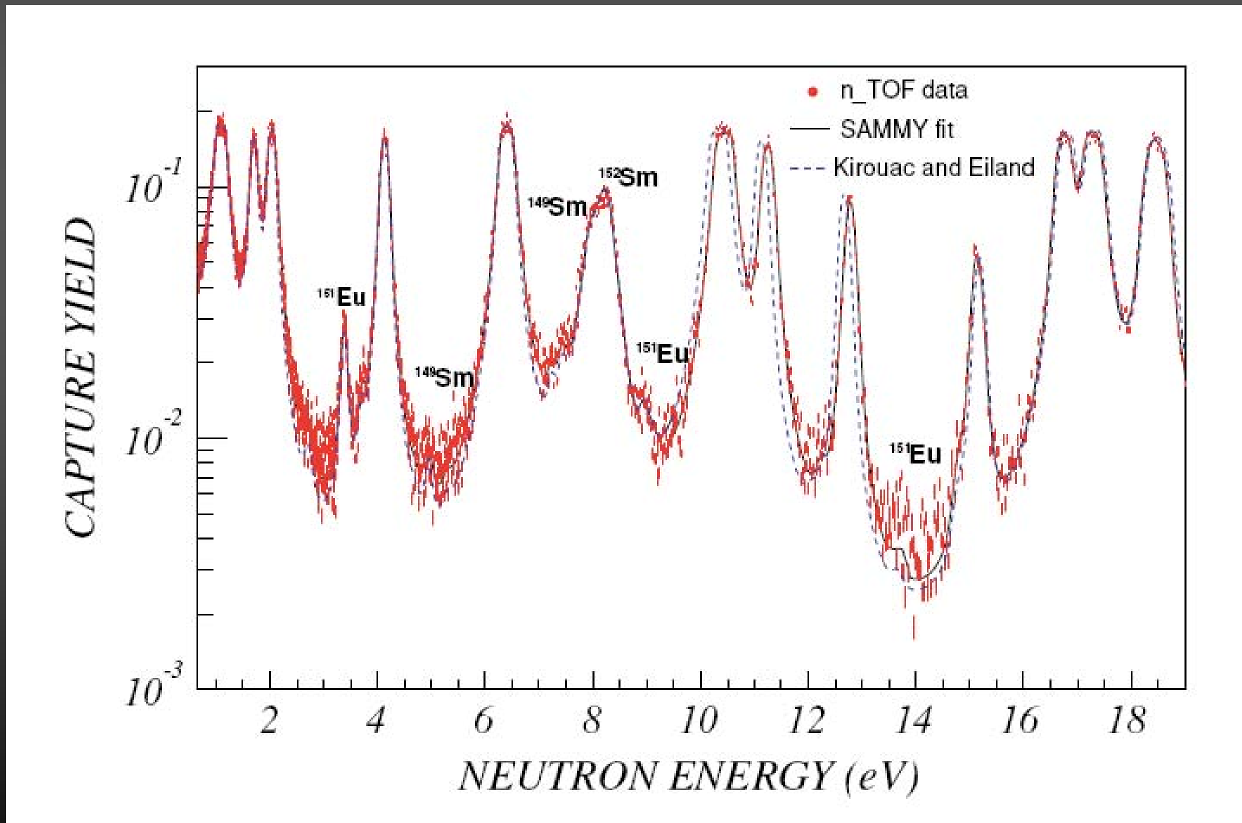
Phys. Rev. C 73 03604 (2006)



n_TOF experiments

Capture

^{151}Sm

^{204,206,207,208}Pb, ^{209}Bi

^{232}Th

^{24,25,26}Mg

^{90,91,92,94,96}Zr, ^{93}Zr

^{139}La

^{186,187,188}Os

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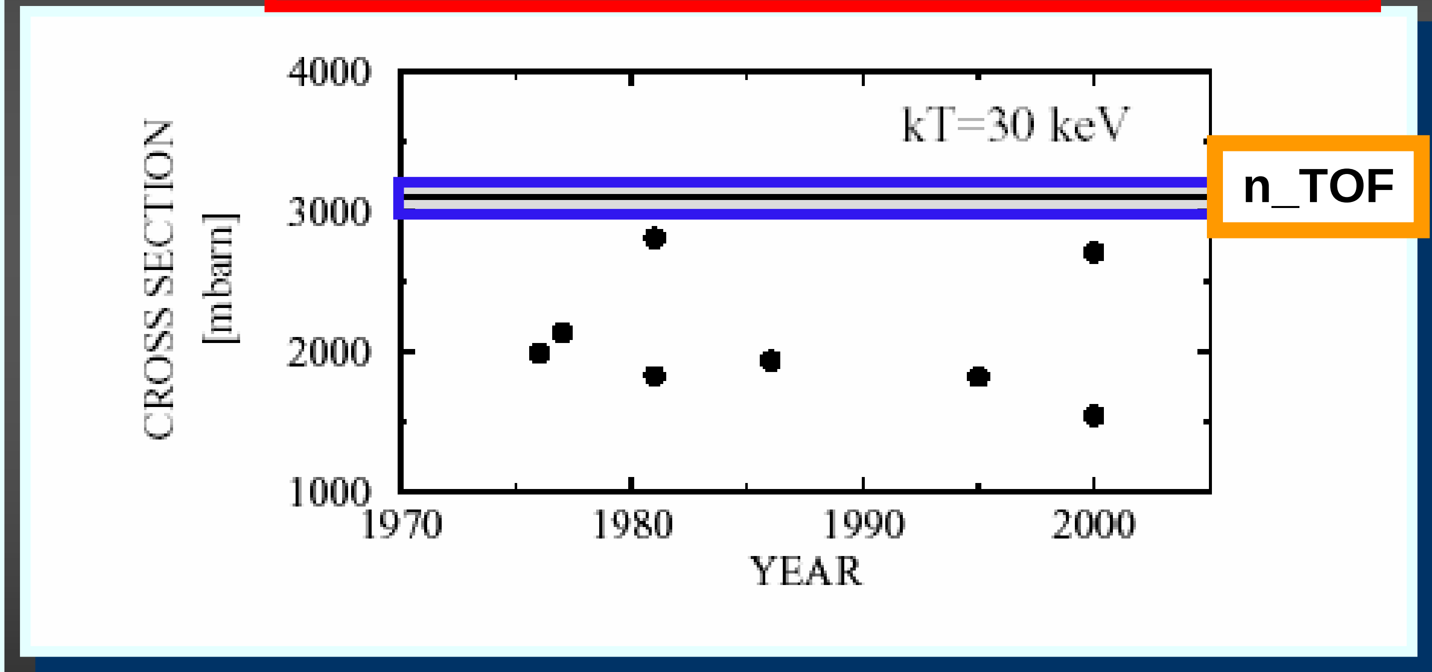

$\langle D_0 \rangle = 1.49 \pm 0.07$ eV

$S_0 = (3.87 \pm 0.33) \times 10^{-4}$

$R_l = 3575 \pm 210$ b

n_TOF experiments

Capture

^{151}Sm

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

^{232}Th

$^{24,25,26}Mg$

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

^{139}La

$^{186,187,188}Os$

$^{233,234}U$

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

Fission

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

^{232}Th

^{209}Bi

^{237}Np

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

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

n_TOF experiments

Capture

^{151}Sm

^{204,206,207,208}Pb, ^{209}Bi

^{232}Th

^{24,25,26}Mg

^{90,91,92,94,96}Zr, ^{93}Zr

^{139}La

^{186,187,188}Os

^{233,234}U

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

Fission

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

^{232}Th

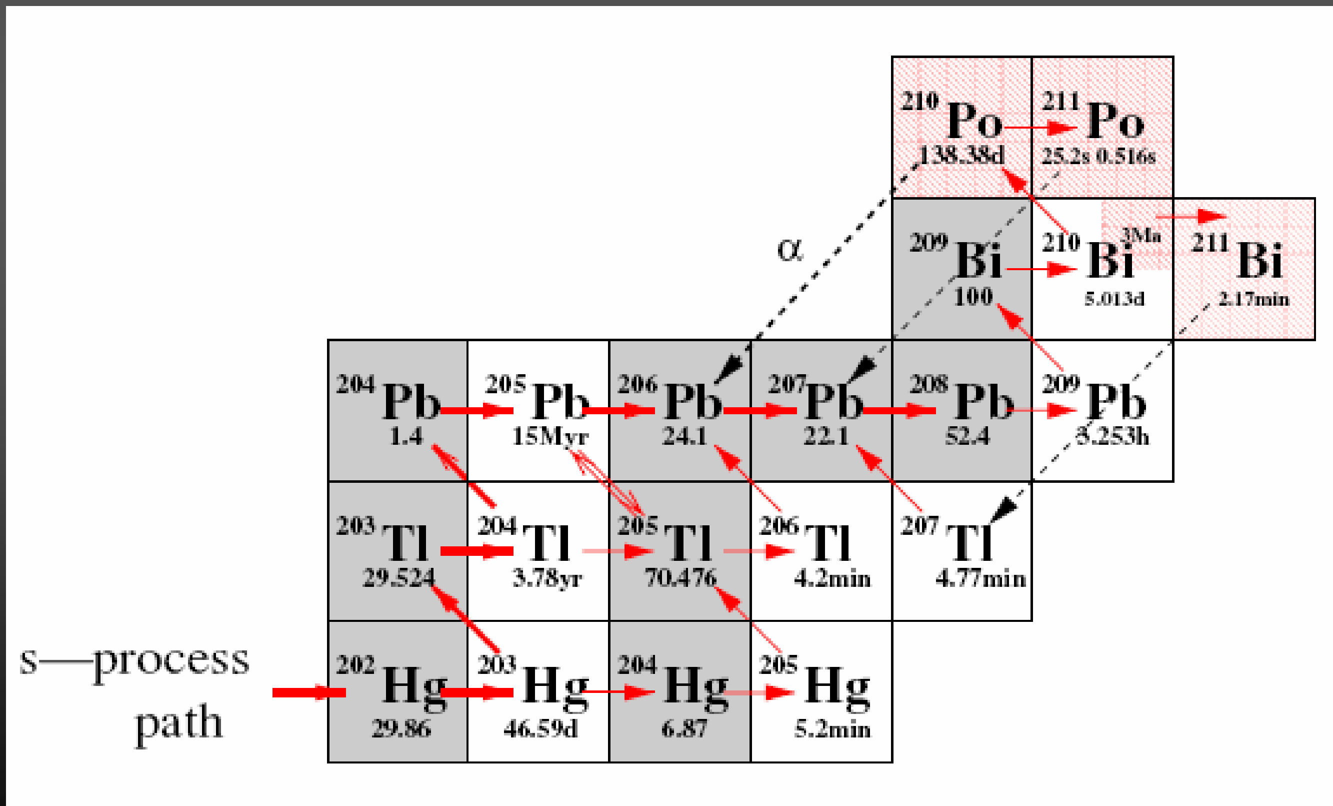
^{209}Bi

^{237}Np

^{241,243}Am, ^{245}Cm

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



n_TOF experiments

Capture

^{151}Sm

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

^{232}Th

$^{24,25,26}Mg$

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

^{139}La

$^{186,187,188}Os$

$^{233,234}U$

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

Fission

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

^{232}Th

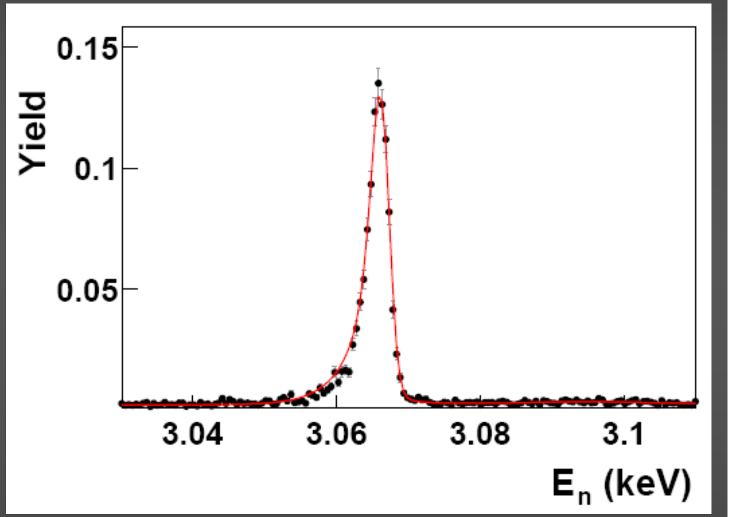
^{209}Bi

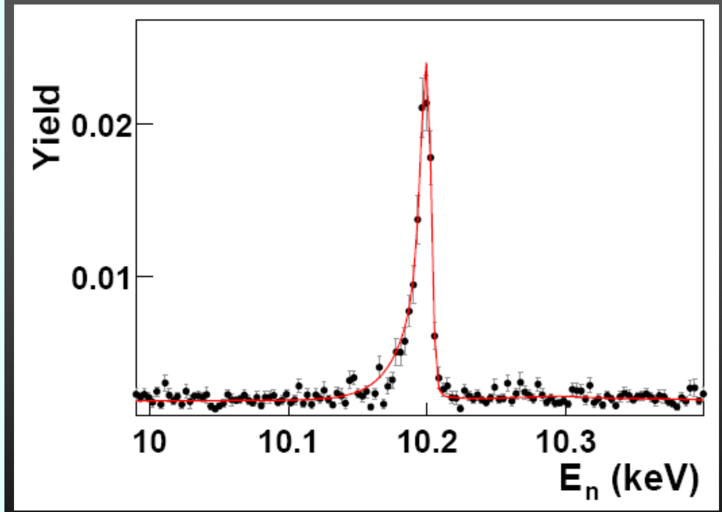
^{237}Np

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

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

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





n_TOF experiments

Capture

^{151}Sm

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

^{232}Th

$^{24,25,26}Mg$

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

^{139}La

$^{186,187,188}Os$

$^{233,234}U$

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

Fission

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

^{232}Th

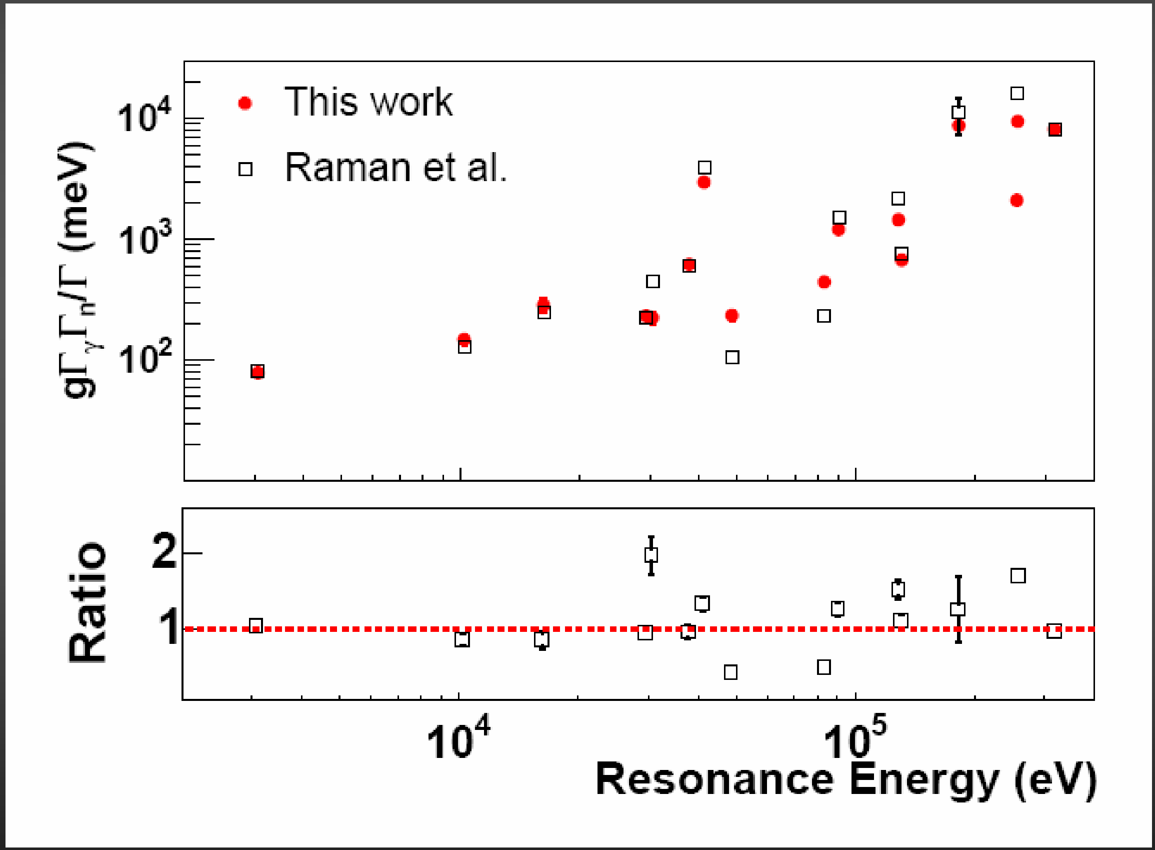
^{209}Bi

^{237}Np

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

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

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



substantial disagreement for E_n > 45 keV

n_TOF experiments

Capture

^{151}Sm

^{204,206,207,208}Pb, ^{209}Bi

^{232}Th

^{24,25,26}Mg

^{90,91,92,94,96}Zr, ^{93}Zr

^{139}La

^{186,187,188}Os

^{233,234}U

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

Fission

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

^{232}Th

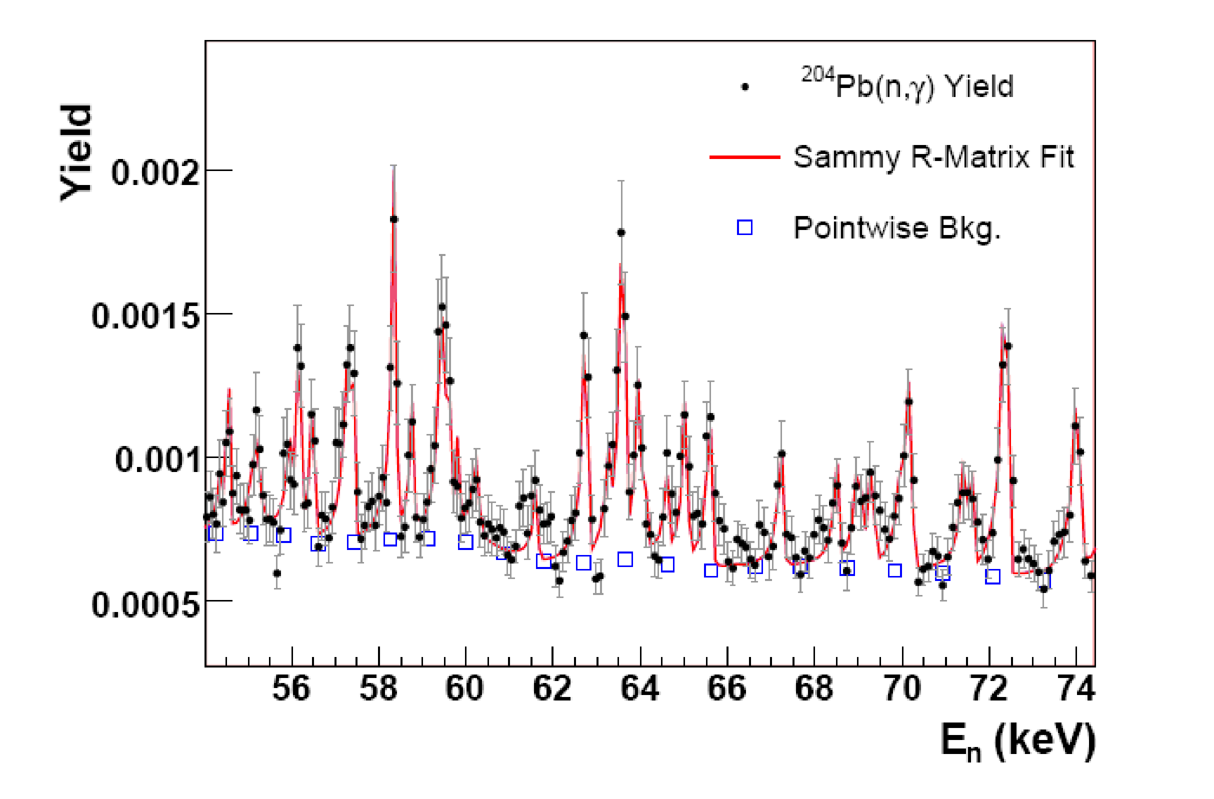
^{209}Bi

^{237}Np

^{241,243}Am, ^{245}Cm

^{204}Pb(n,γ)

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



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

Capture

^{151}Sm

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

^{232}Th

$^{24,25,26}Mg$

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

^{139}La

$^{186,187,188}Os$

$^{233,234}U$

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

Fission

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

^{232}Th

^{209}Bi

^{237}Np

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

n_TOF experiments

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

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

$E_\circ$ (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

[a] This value has to be added in quadrature with the overall systematic uncertainty of 10%.

n_TOF experiments

Capture

^{151}Sm

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

^{232}Th

$^{24,25,26}Mg$

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

^{139}La

$^{186,187,188}Os$

$^{233,234}U$

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

Fission

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

^{232}Th

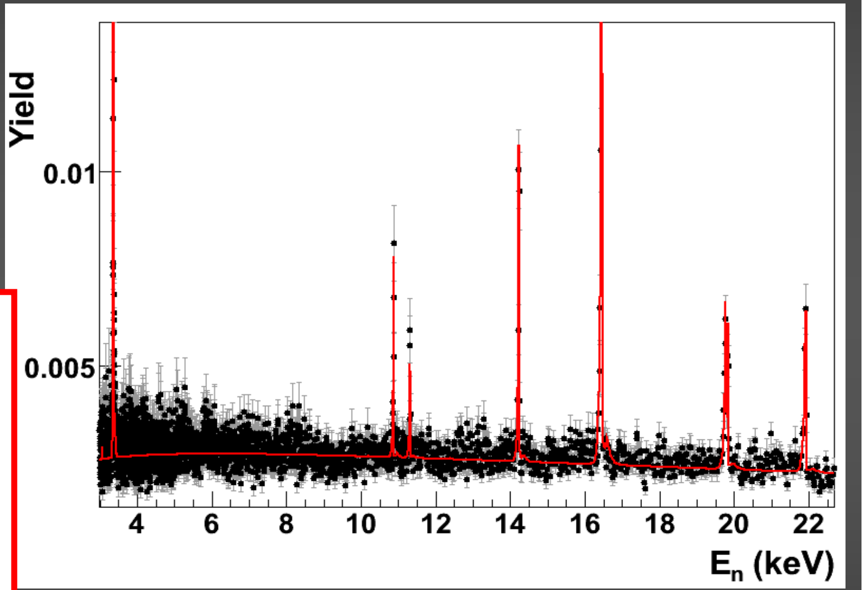
^{209}Bi

^{237}Np

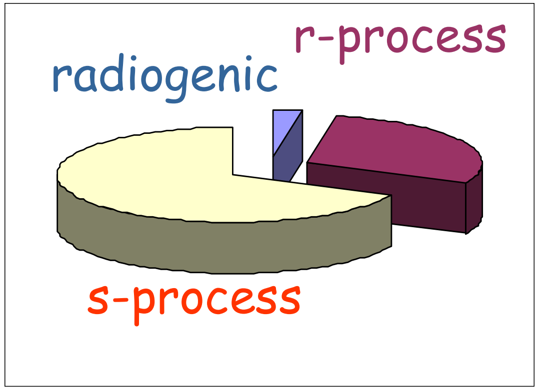
$^{241,243}Am$, ^{245}Cm

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

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



^{206}Pb abundances



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

n_TOF experiments

Capture

^{151}Sm

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

^{232}Th

$^{24,25,26}Mg$

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

^{139}La

$^{186,187,188}Os$

$^{233,234}U$

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

Fission

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

^{232}Th

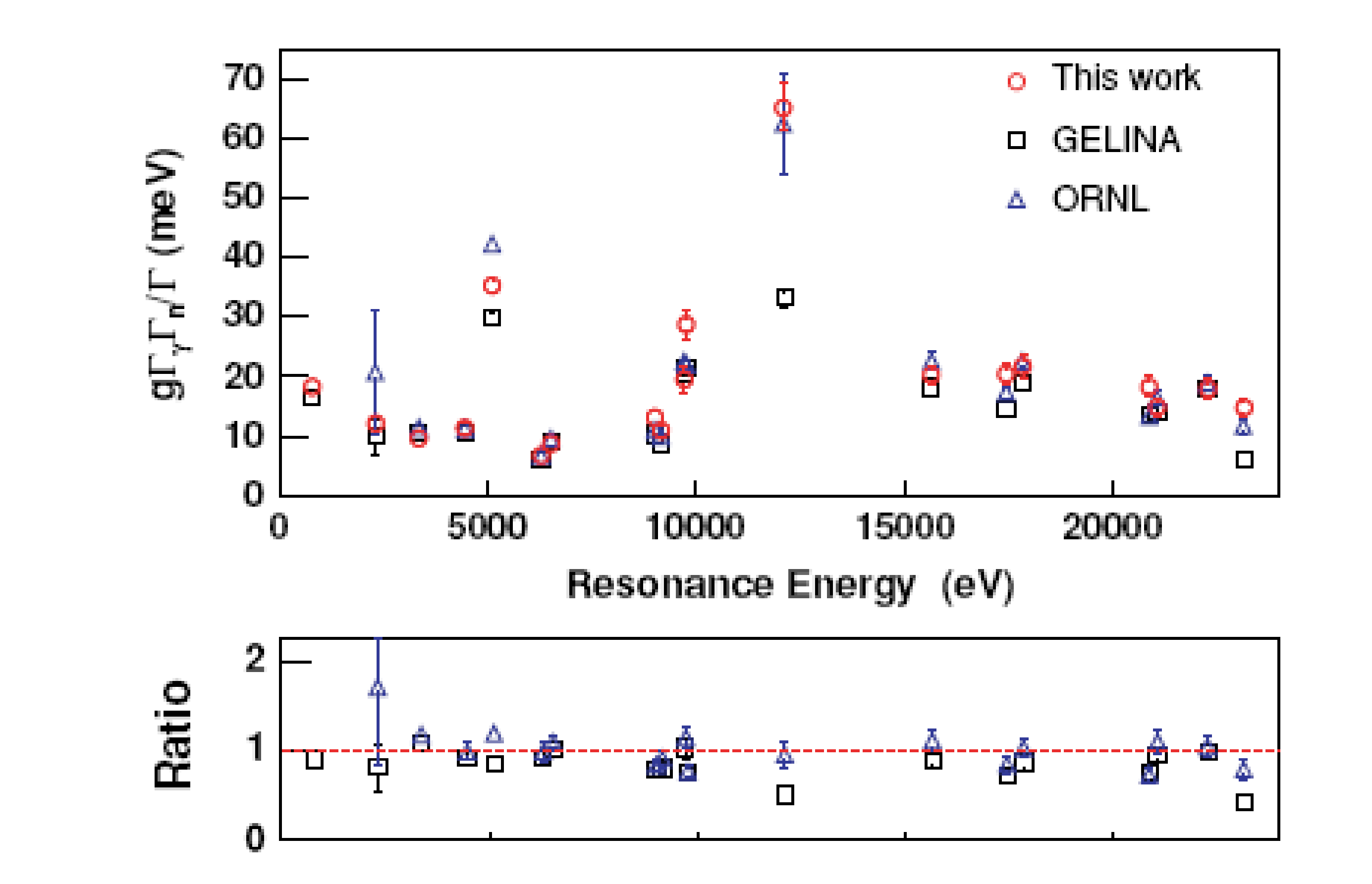
^{209}Bi

^{237}Np

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

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

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



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

n_TOF experiments

Capture

^{151}Sm

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

^{232}Th

$^{24,25,26}Mg$

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

^{139}La

$^{186,187,188}Os$

$^{233,234}U$

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

Fission

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

^{232}Th

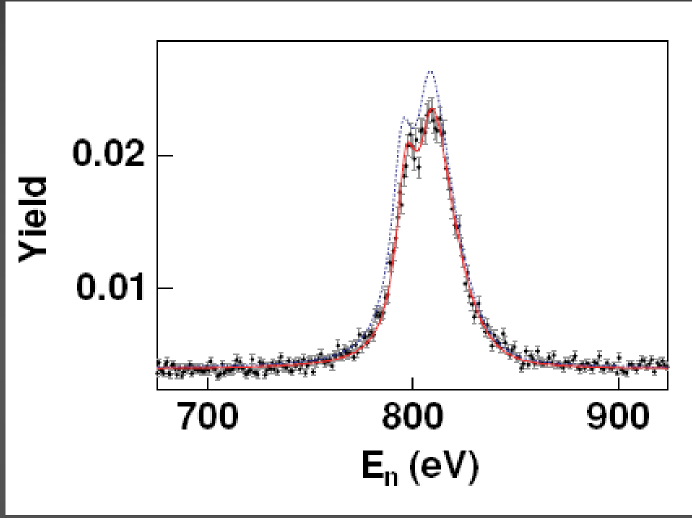
^{209}Bi

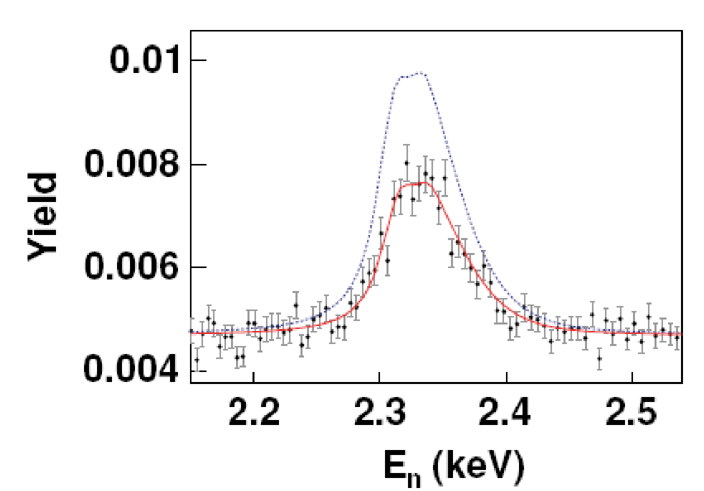
^{237}Np

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

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

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





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

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

^{232}Th

^{209}Bi

^{237}Np

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

	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

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Fission

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^{232}Th

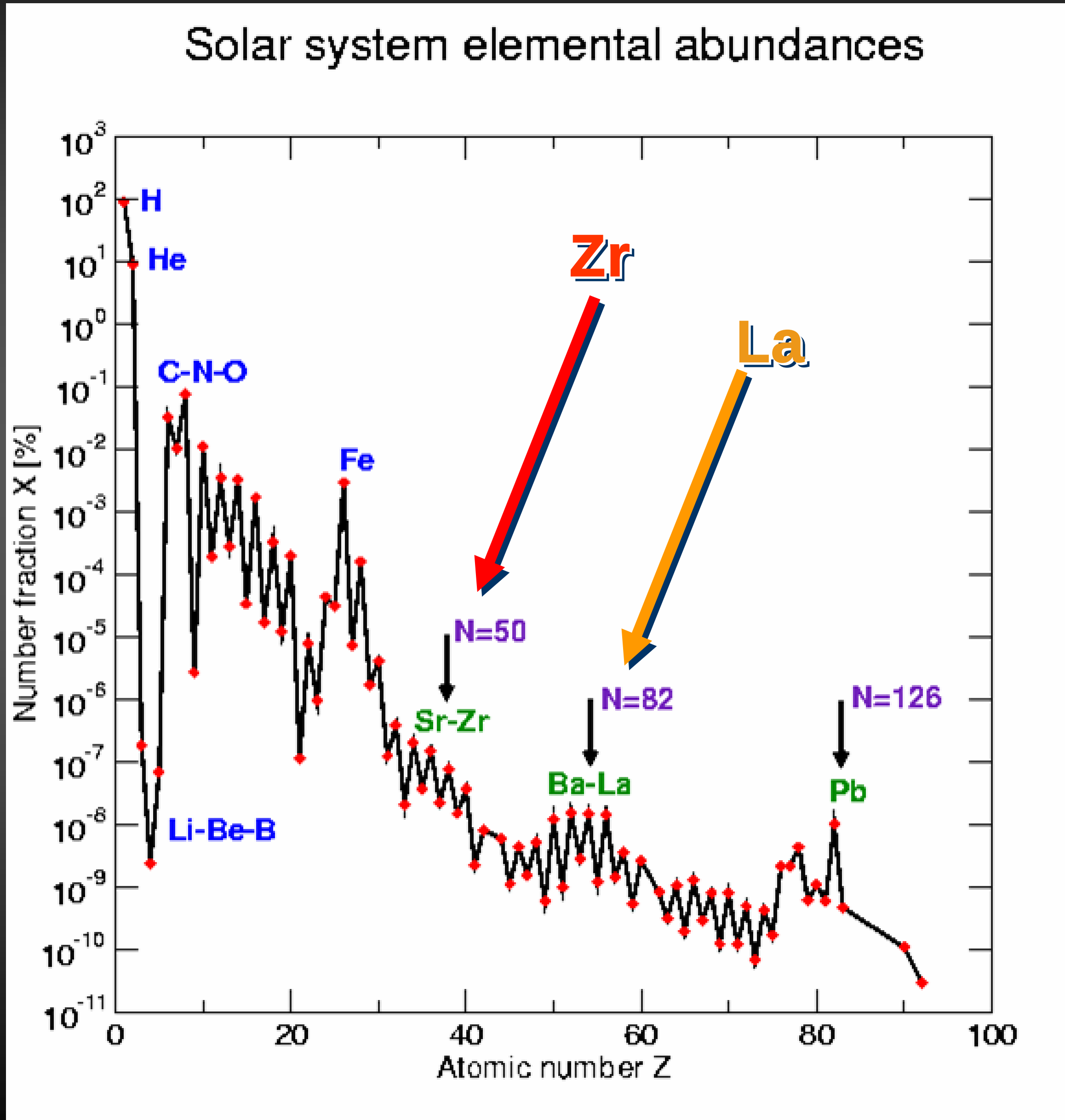
^{209}Bi

^{237}Np

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

canonical s-process

>>



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

Capture

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

Fission

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

^{232}Th

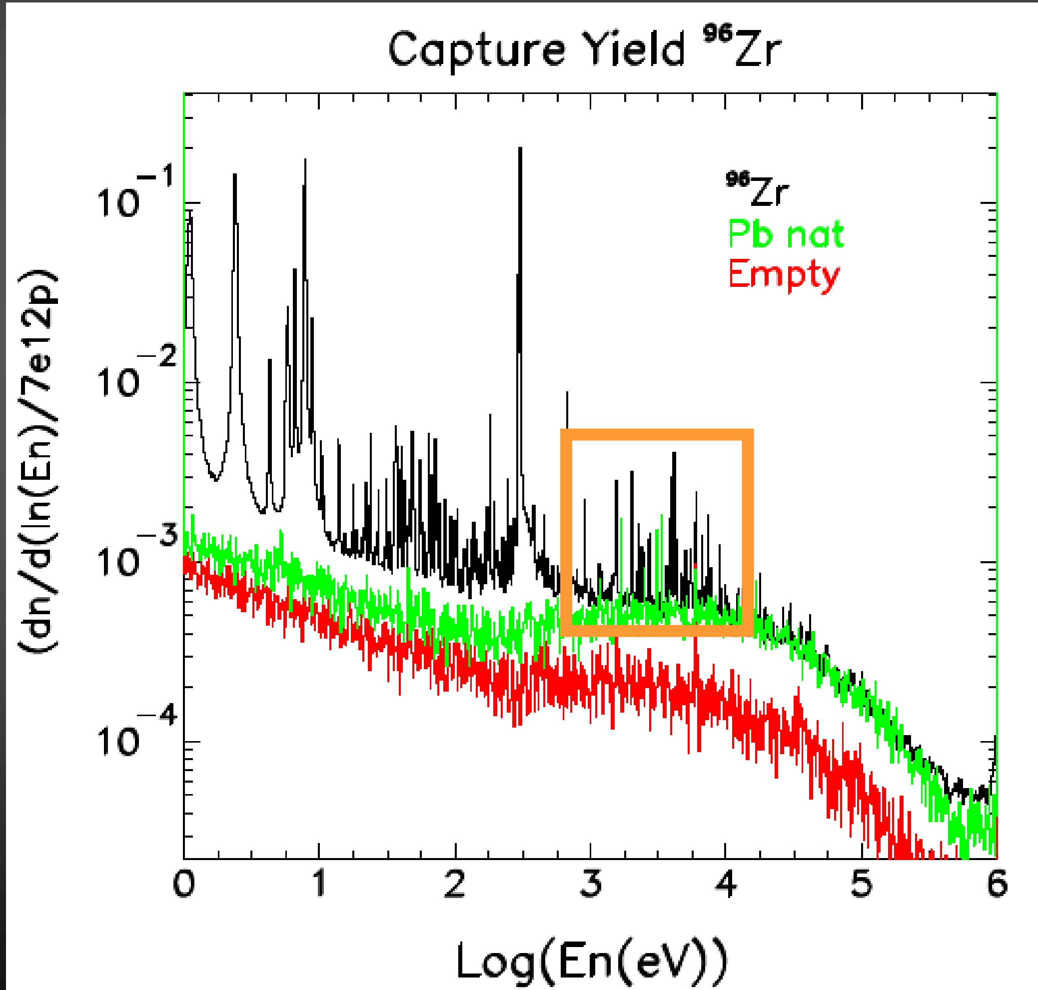
^{209}Bi

^{237}Np

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

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

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
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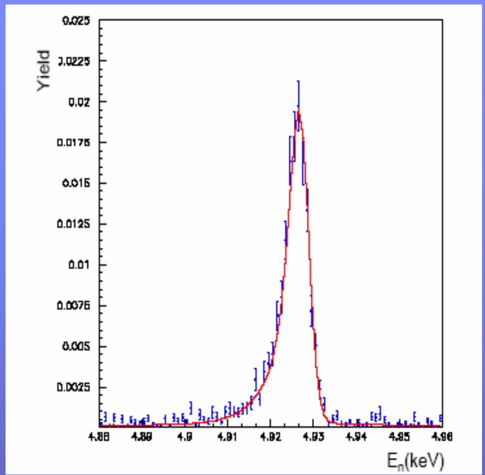
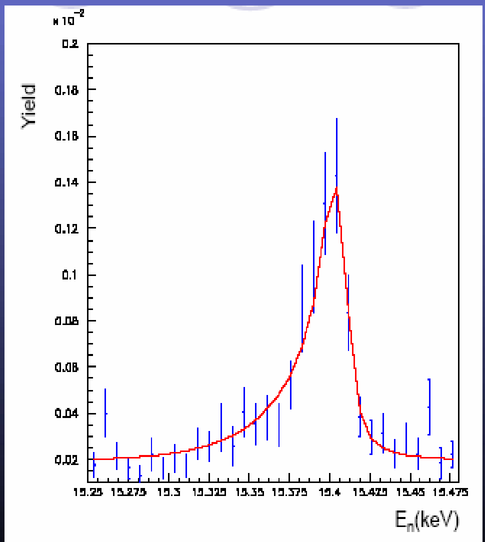
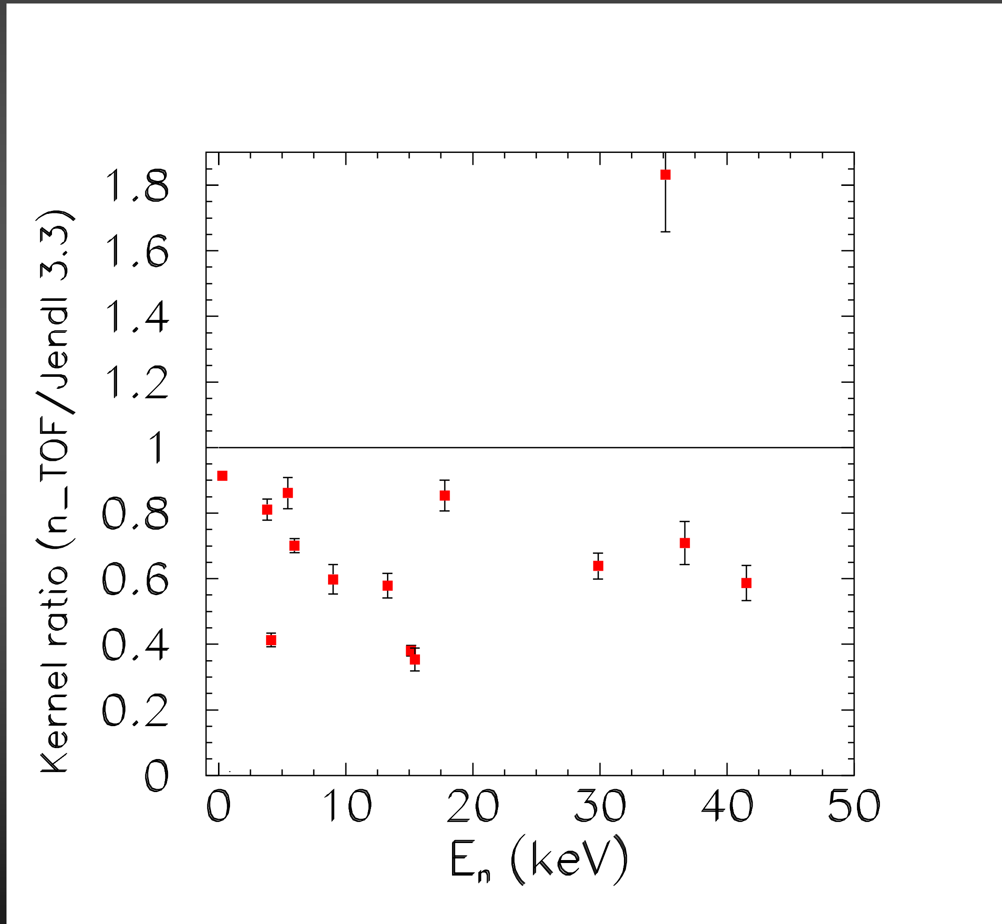
NIC-IX, CERN, June 2006





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

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

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Fission

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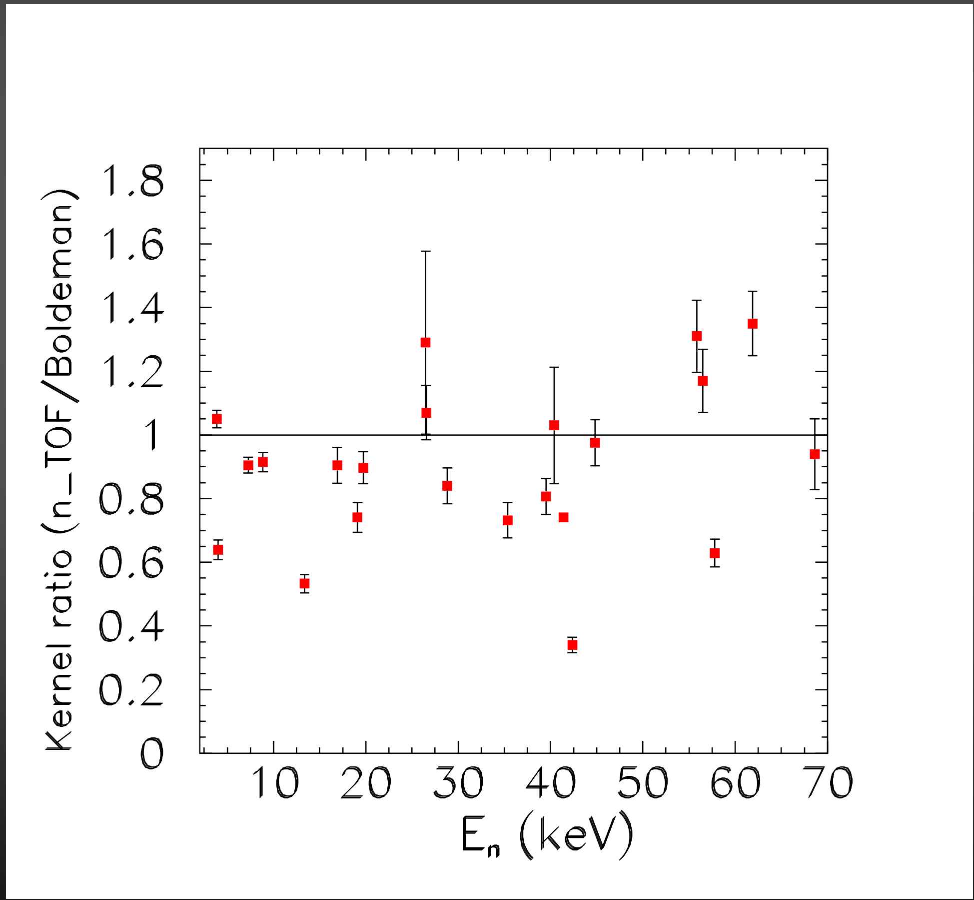
^{232}Th

^{209}Bi

^{237}Np

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

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



n_TOF experiments

Capture

^{151}Sm

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^{232}Th

$^{24,25,26}Mg$

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

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$^{233,234}U$

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

Fission

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

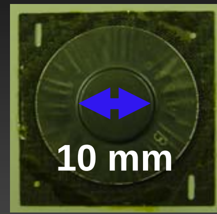
^{232}Th

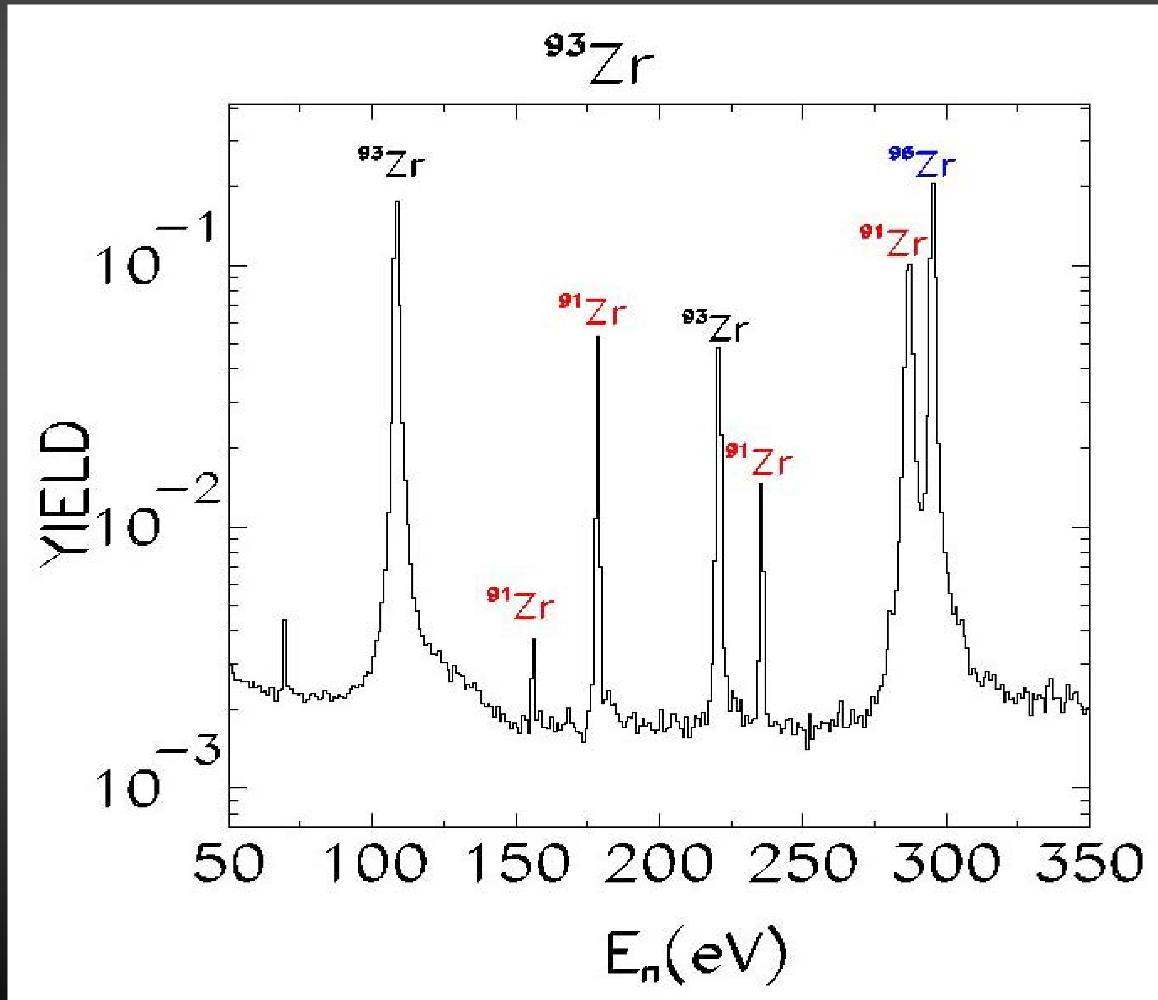
^{209}Bi

^{237}Np

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

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





n_TOF experiments

Capture

^{151}Sm

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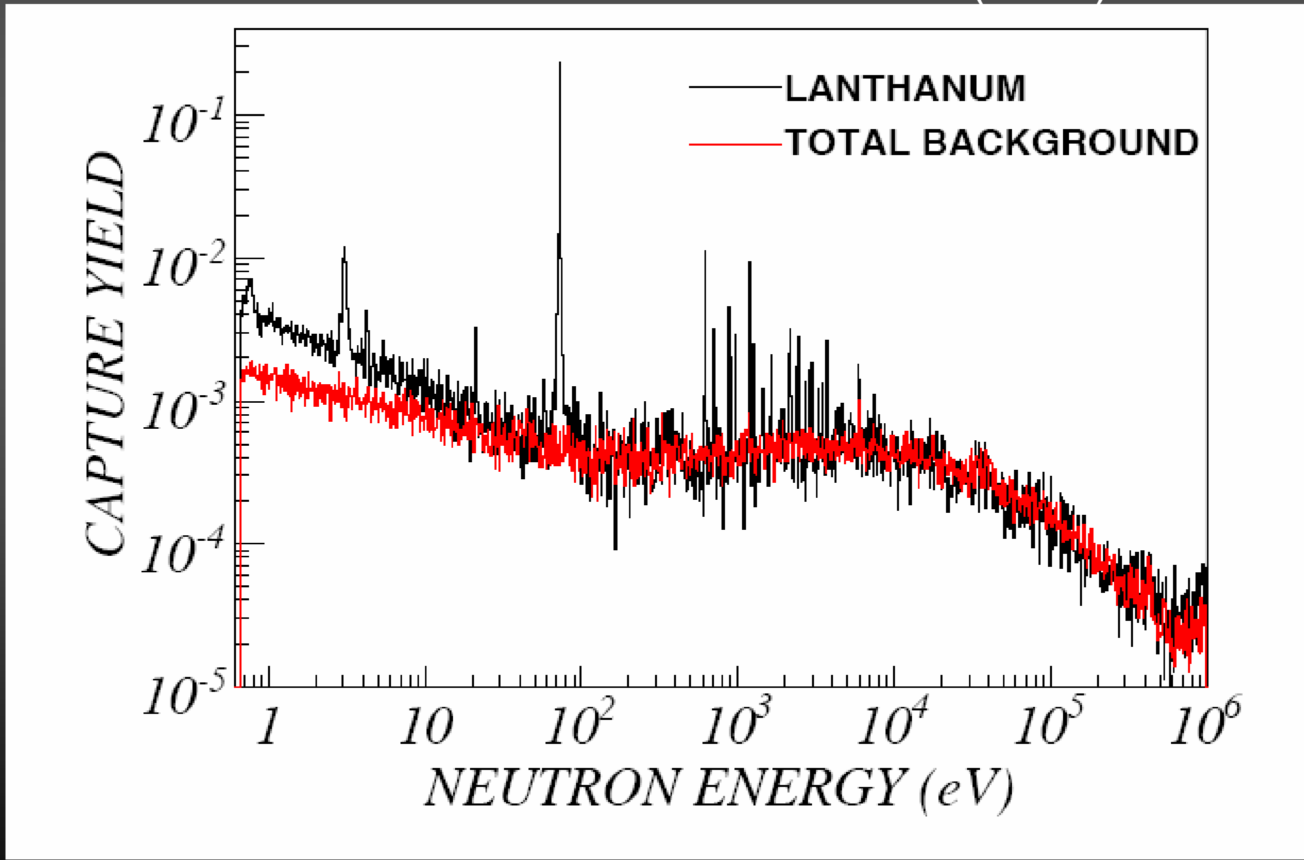
^{241,243}Am, ^{245}Cm

^{139}La(n,γ)

R Terlizzi, et al. (The n_TOF Collaboration)
CGS12
Notre Dame, IN, USA
AIP Conference Proceedings 819
&
PRC **75** (2007) 035807



n_TOF experiments

Capture

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R Terlizzi, et al. (The n_TOF Collaboration)
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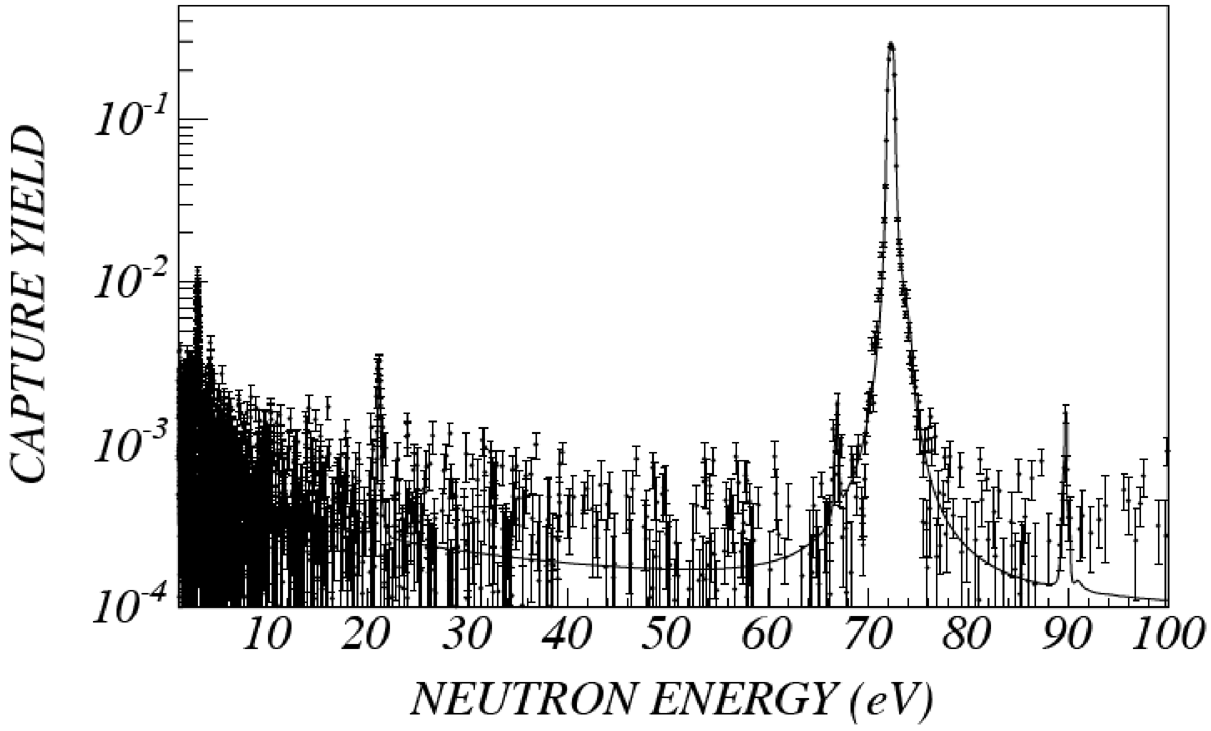

n_TOF experiments

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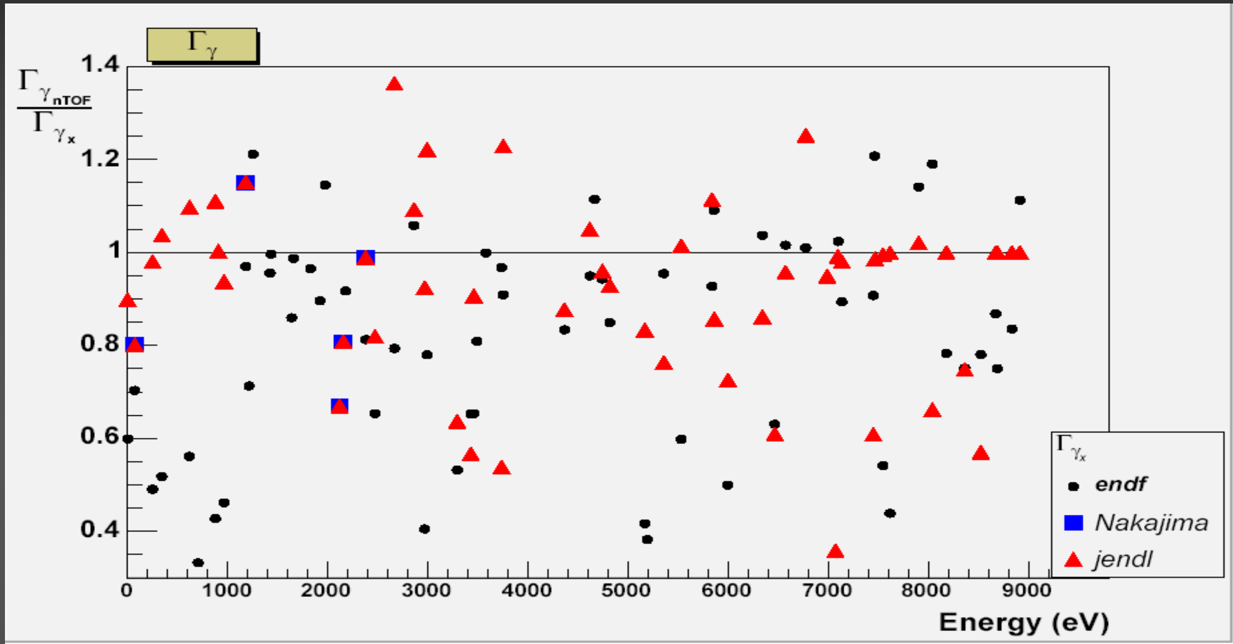
^{209}Bi

^{237}Np

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

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



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

RI = 10.8 ± 1.0 barn
average γ-widths:
s-waves = 50.7 ± 5.4 meV
p-waves = 33.6 ± 6.9 meV
$<D_0>$= 252 ± 22 eV
$S_0 = (0.82 \pm 0.05)\times10^{-4}$ $S_1 = (0.55 \pm 0.04)\times10^{-4}$

The n_TOF Collaboration

n_TOF experiments

Capture

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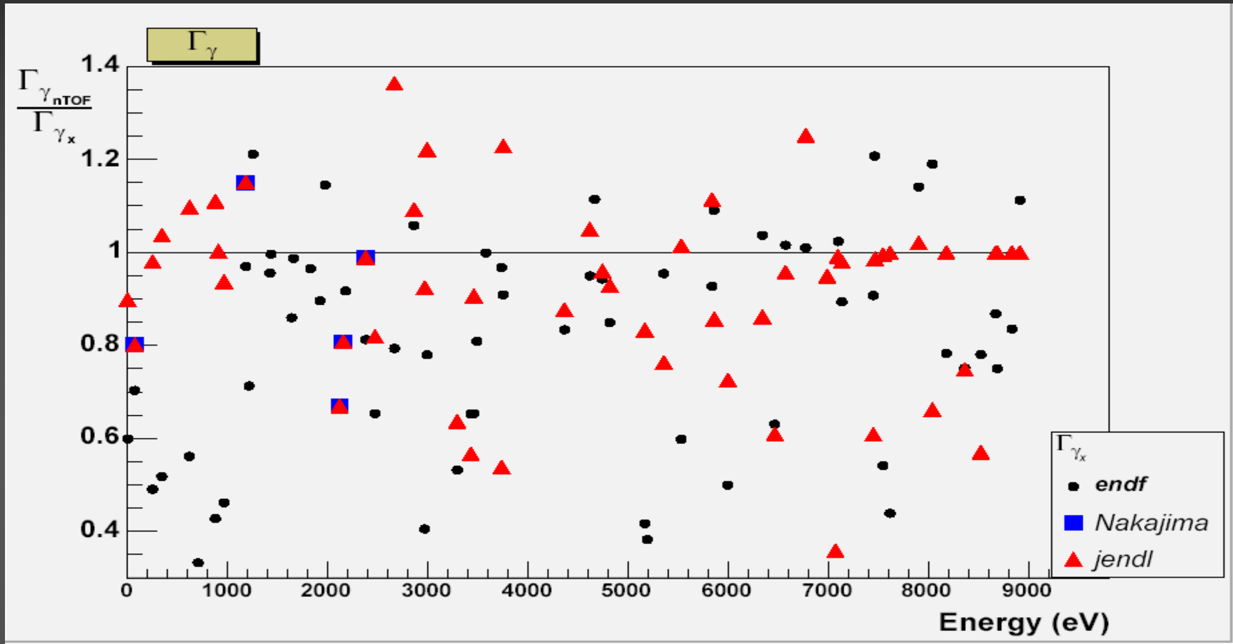
$^{139}La(n,\gamma)$



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

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^{204,206,207,208}Pb, ^{209}Bi

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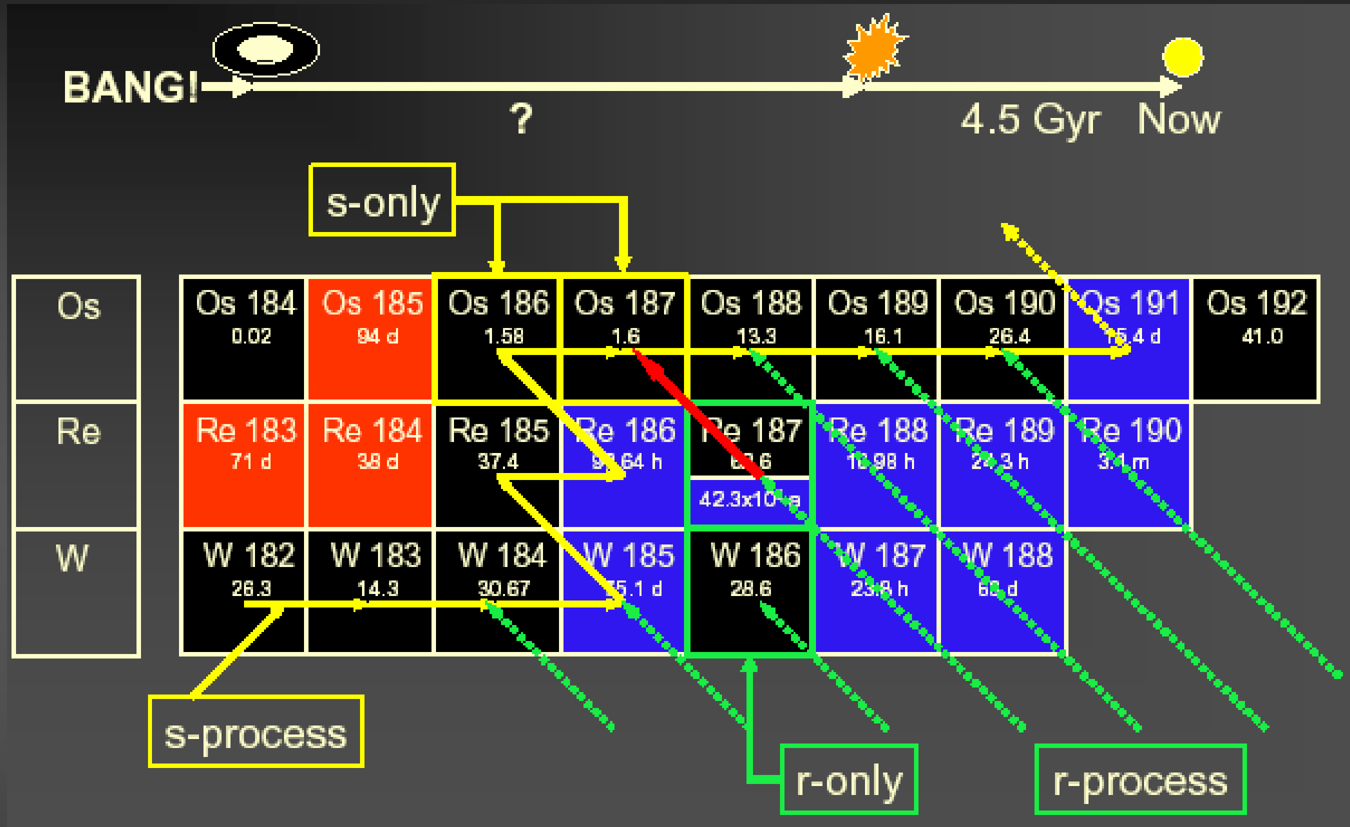

[Re/Os clock](#)

<< back

n_TOF experiments

Capture

^{151}Sm

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^{232}Th

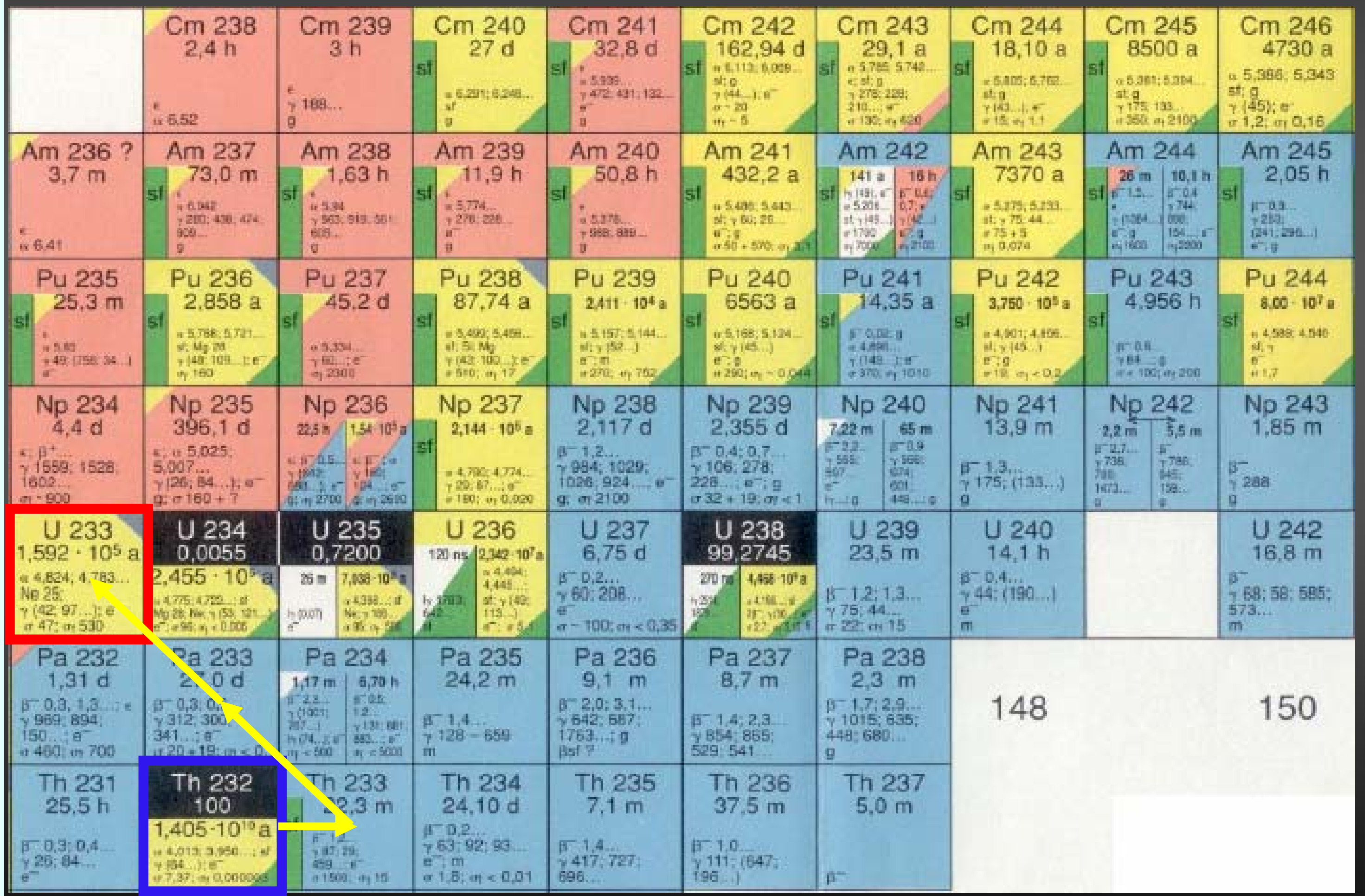
^{209}Bi

^{237}Np

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

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

Th/U nuclear fuel cycle



n_TOF experiments

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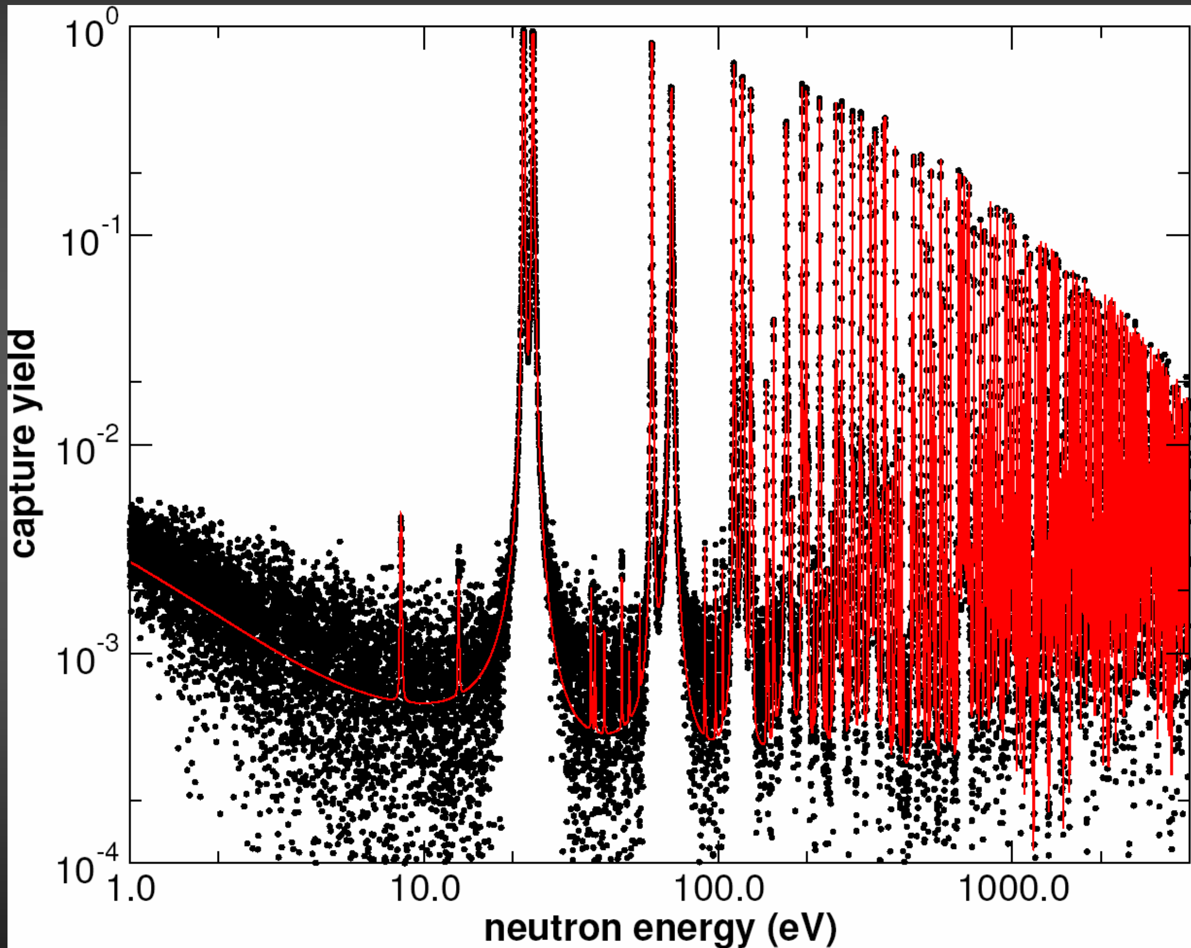
$^{241,243}Am$, ^{245}Cm

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

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



extremely high-resolution data!

n_TOF experiments

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

^{232}Th

$^{24,25,26}Mg$

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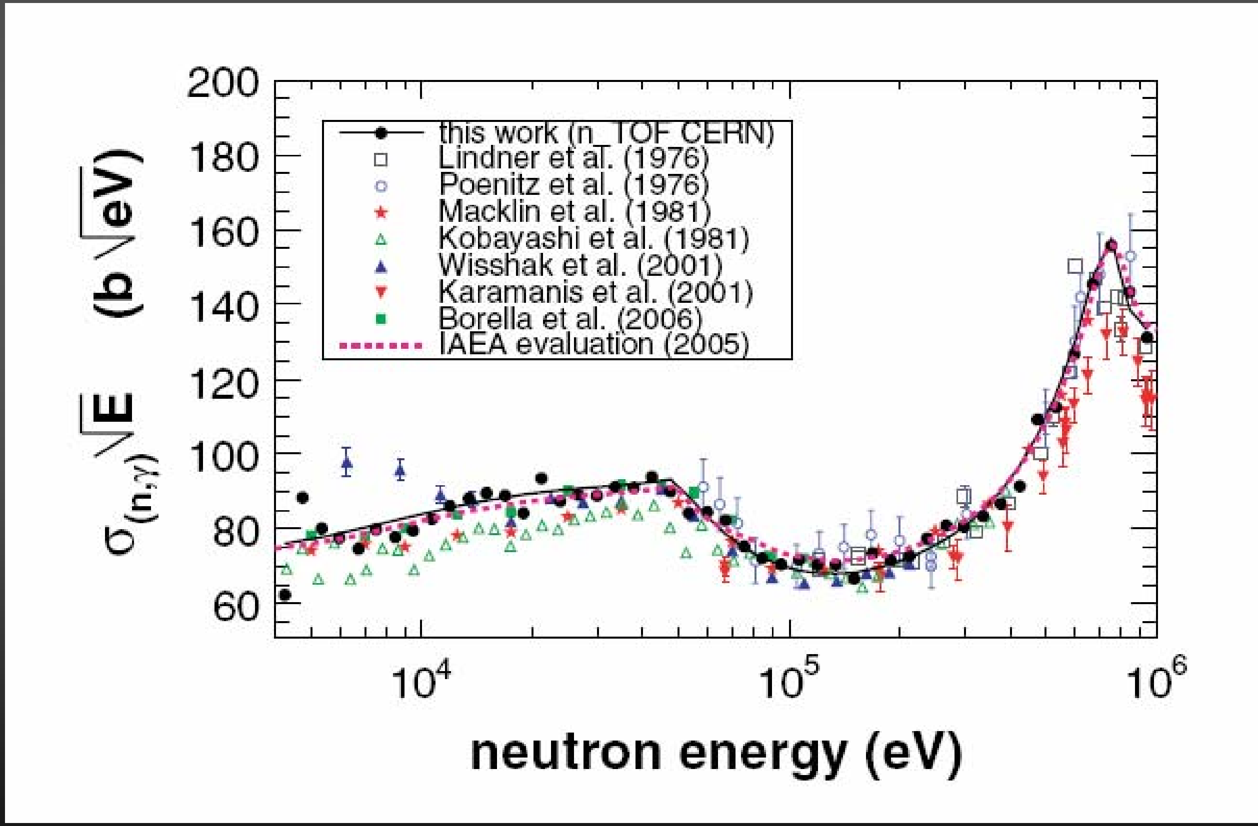
ND2004 Conference, Santa Fe, NM – Sept. 2004
&
G Aerts et al. (The n_TOF Collaboration)
Phys. Rev. C 73, 054610 (2006)



n_TOF experiments

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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

n_TOF experiments

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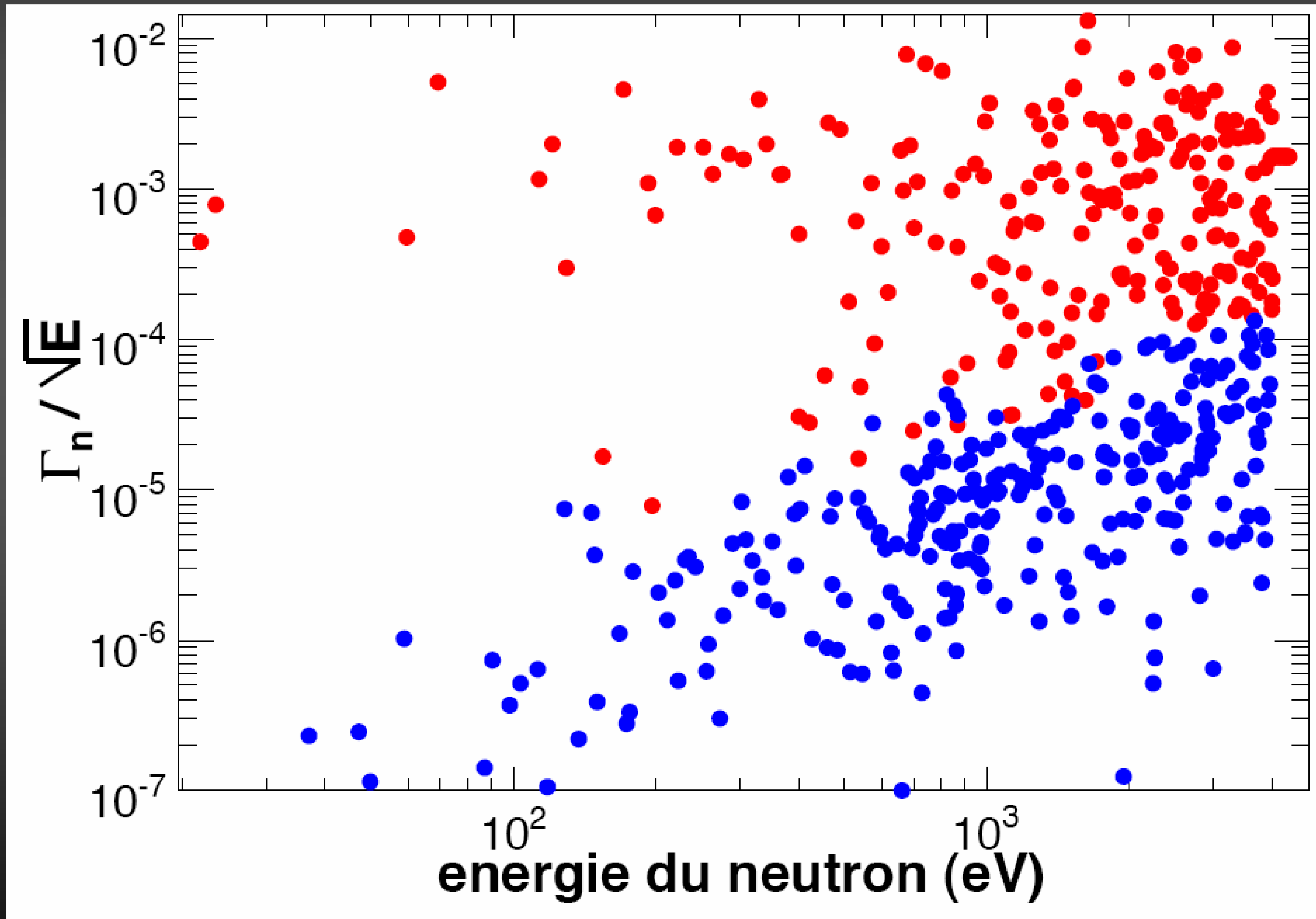
$^{241,243}Am$, ^{245}Cm

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

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



n_TOF experiments

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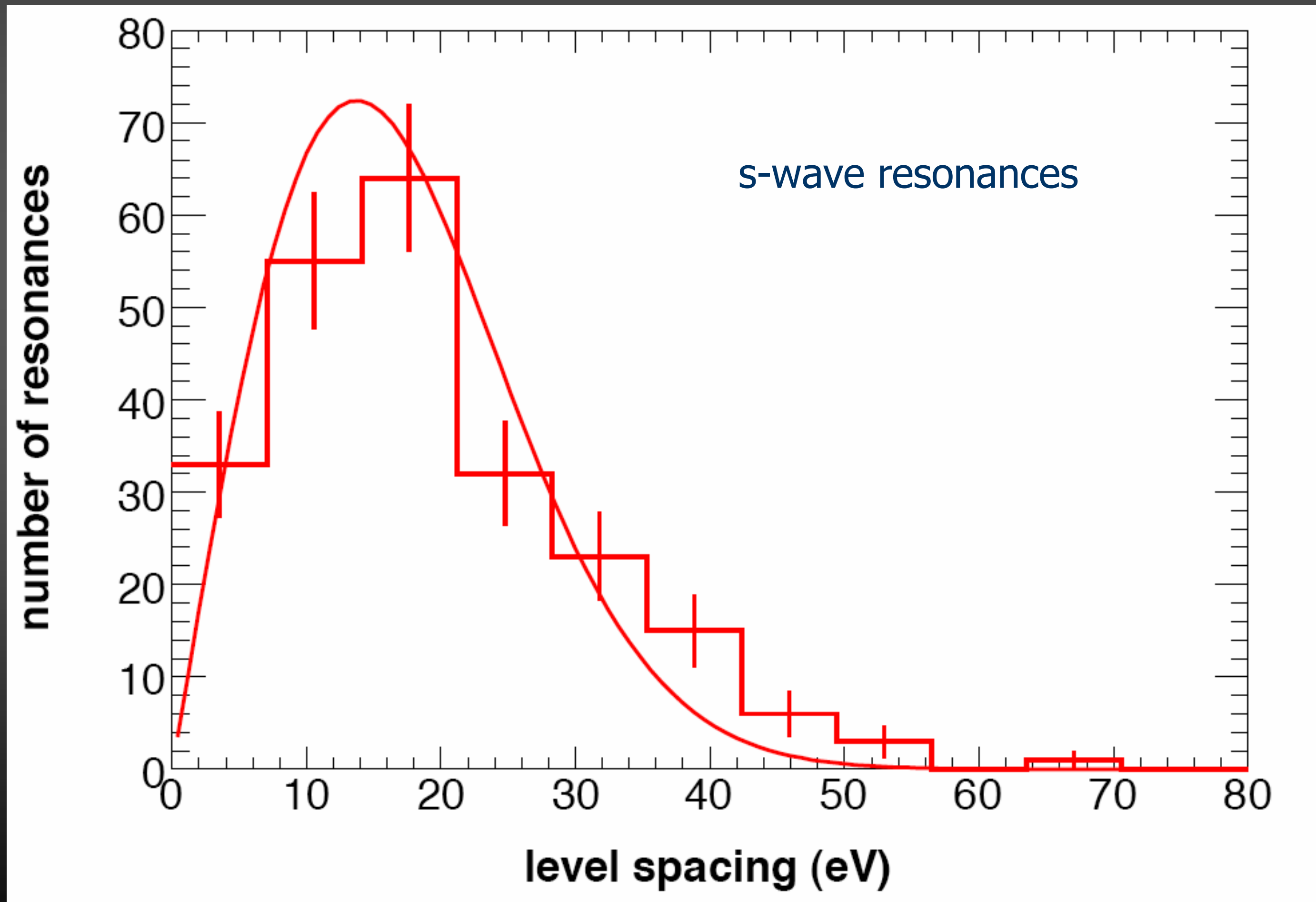
$^{232}Th(n,\gamma)$

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



n_TOF experiments

Capture

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^{209}Bi

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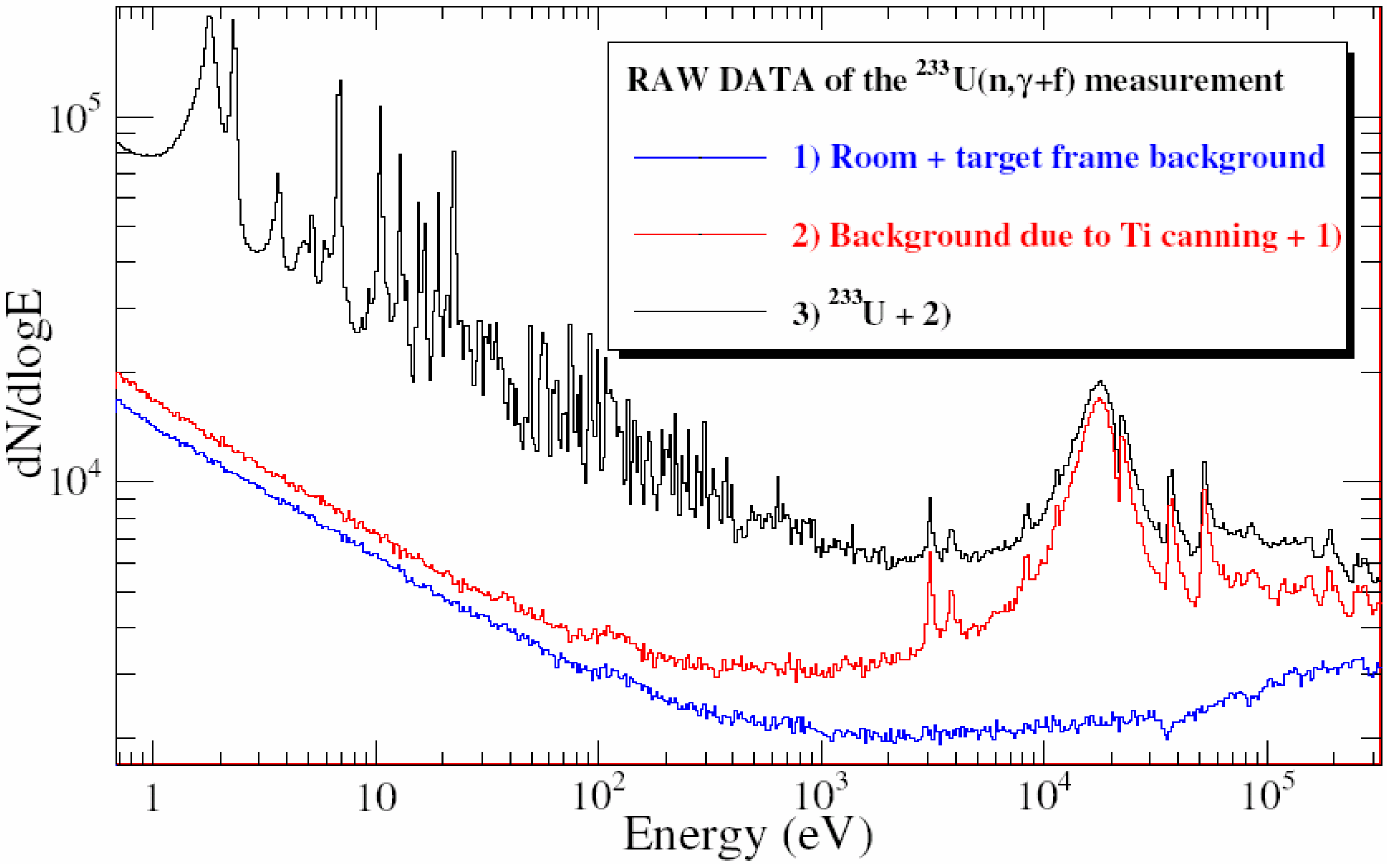
$^{241,243}Am$, ^{245}Cm

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

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



n_TOF TAC in operation

n_TOF experiments

Capture

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^{232}Th

$^{24,25,26}Mg$

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

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Fission

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^{232}Th

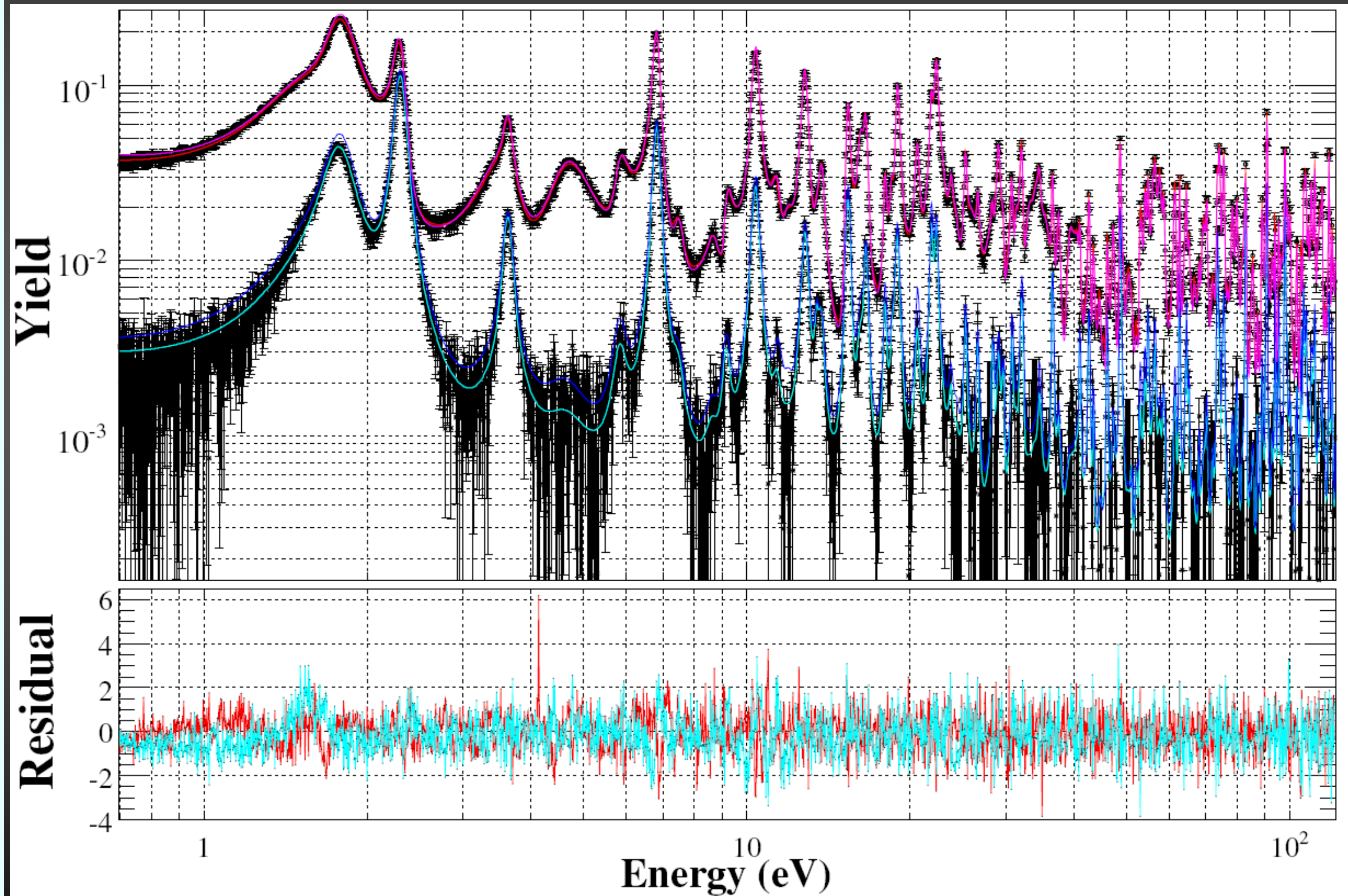
^{209}Bi

^{237}Np

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

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

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

n_TOF experiments

Capture

^{151}Sm

^{204,206,207,208}Pb, ^{209}Bi

^{232}Th

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^{232}Th

^{209}Bi

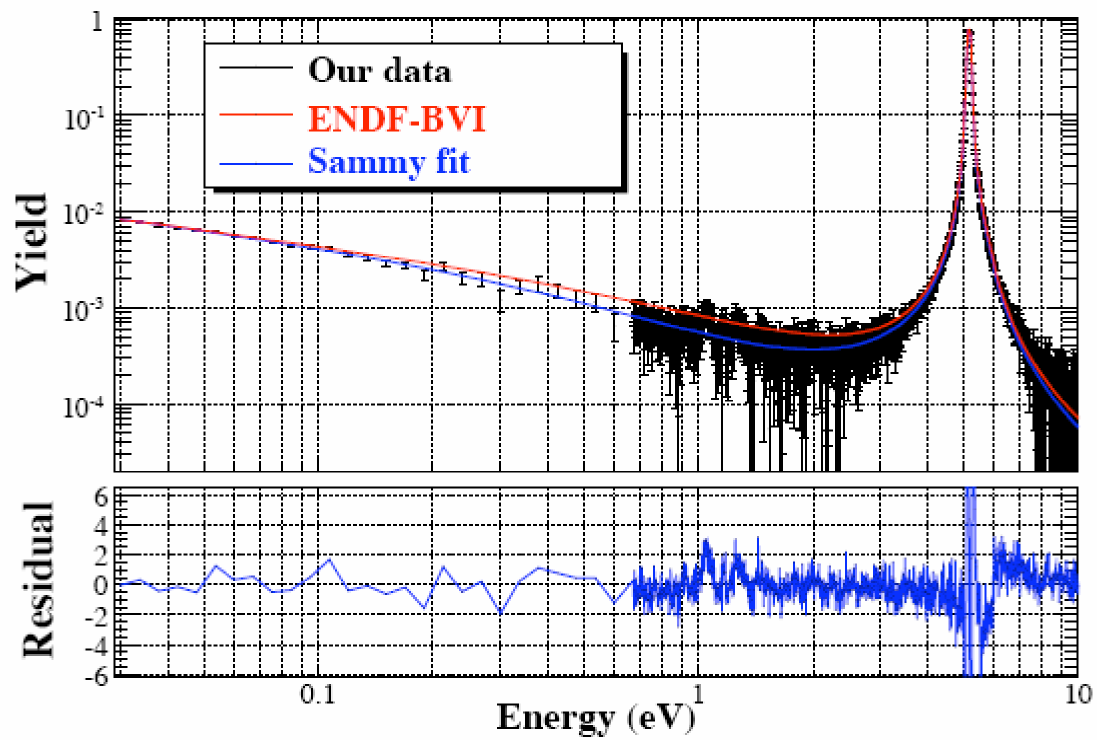
^{237}Np

^{241,243}Am, ^{245}Cm

^{234}U(n,γ)

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

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

n_TOF experiments

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^{232}Th

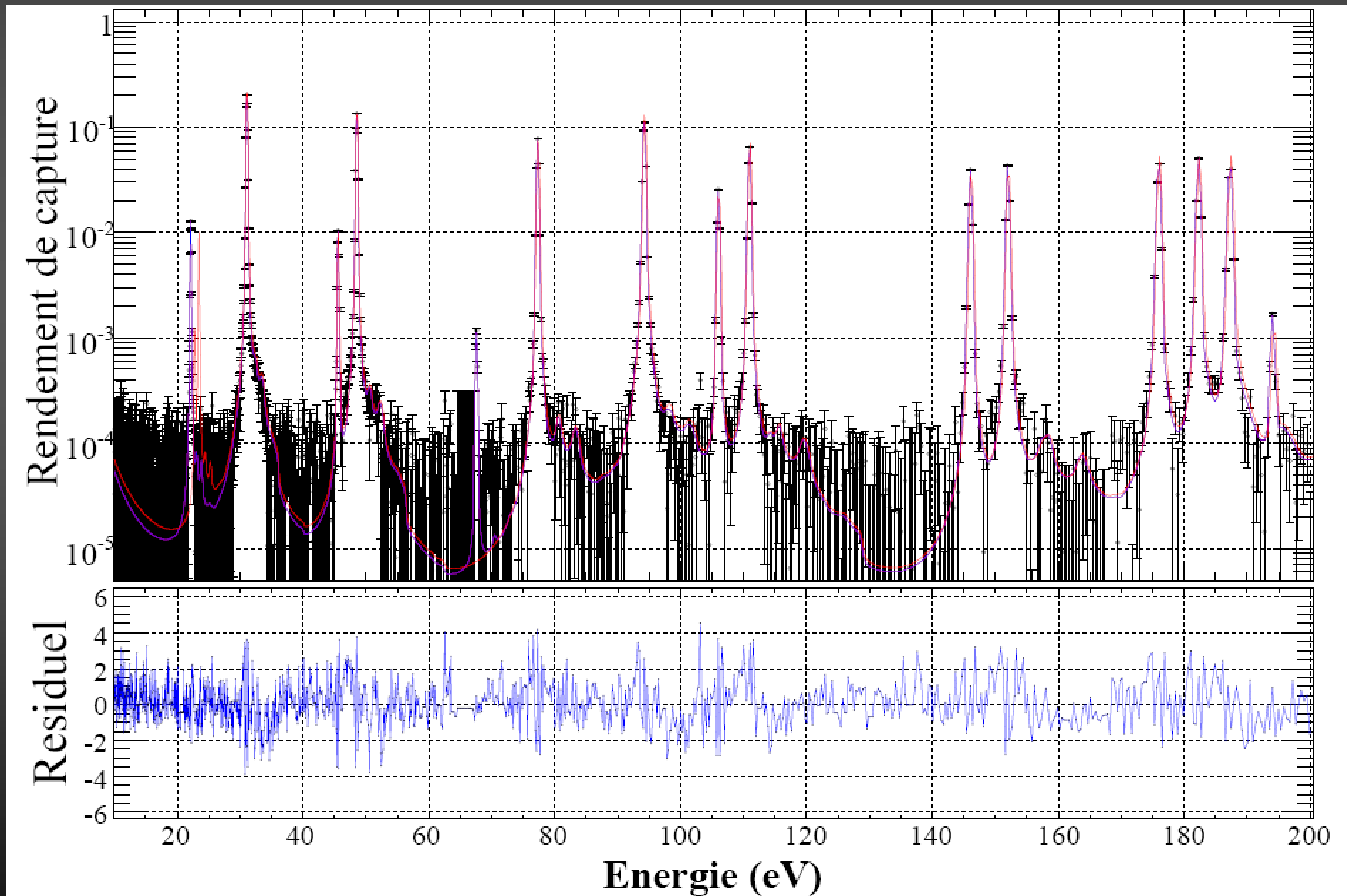
^{209}Bi

^{237}Np

^{241,243}Am, ^{245}Cm

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

^{234}U(n,γ)



n_TOF TAC in operation

Capture

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

^{232}Th

$^{24,25,26}Mg$

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

^{139}La

$^{186,187,188}Os$

$^{233,234}U$

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

Fission

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

^{232}Th

^{209}Bi

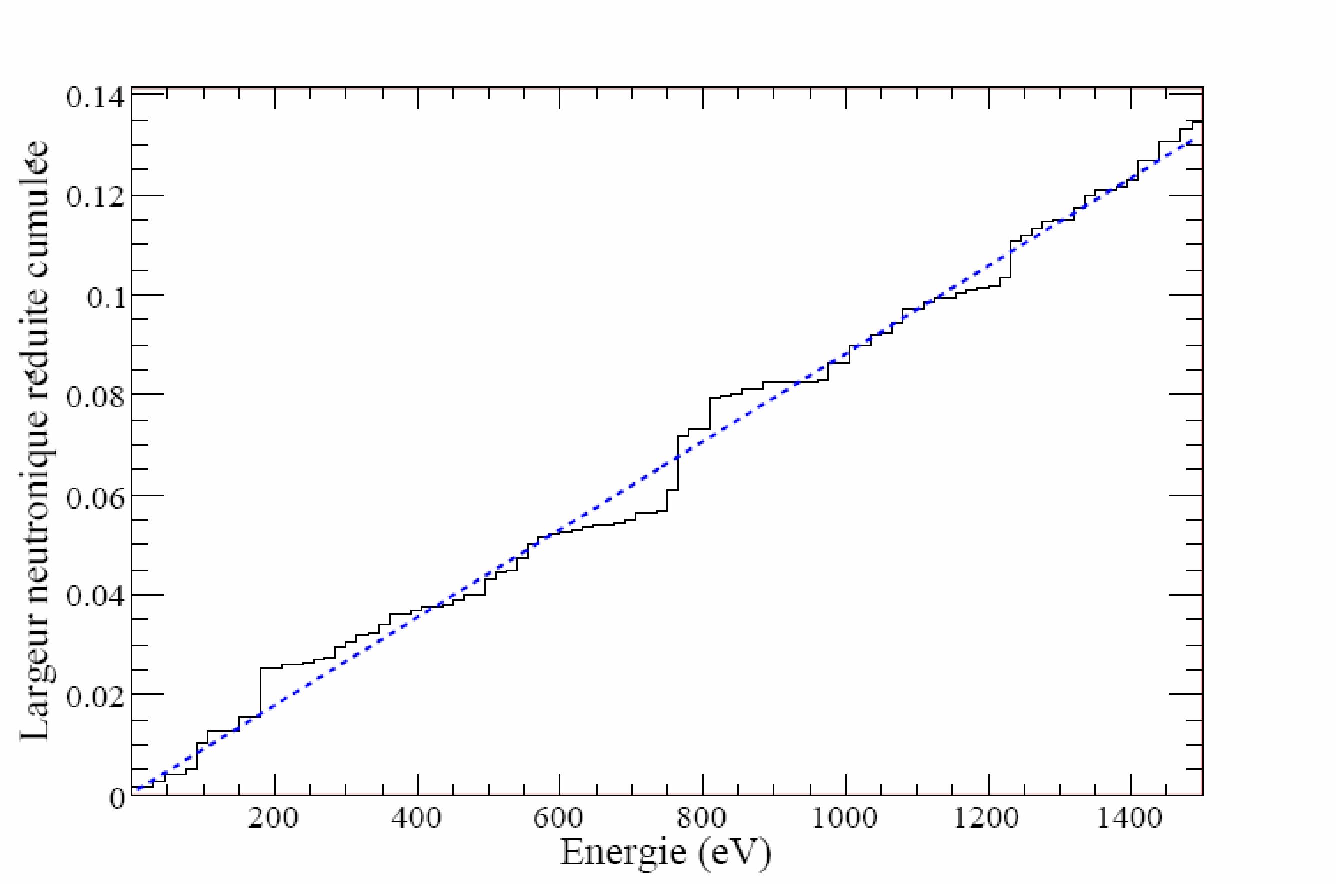
^{237}Np

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

n_TOF experiments

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

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



n_TOF TAC in operation

n_TOF experiments

Capture

^{151}Sm

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

^{232}Th

$^{24,25,26}Mg$

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

^{139}La

$^{186,187,188}Os$

$^{233,234}U$

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

Fission

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

^{232}Th

^{209}Bi

^{237}Np

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

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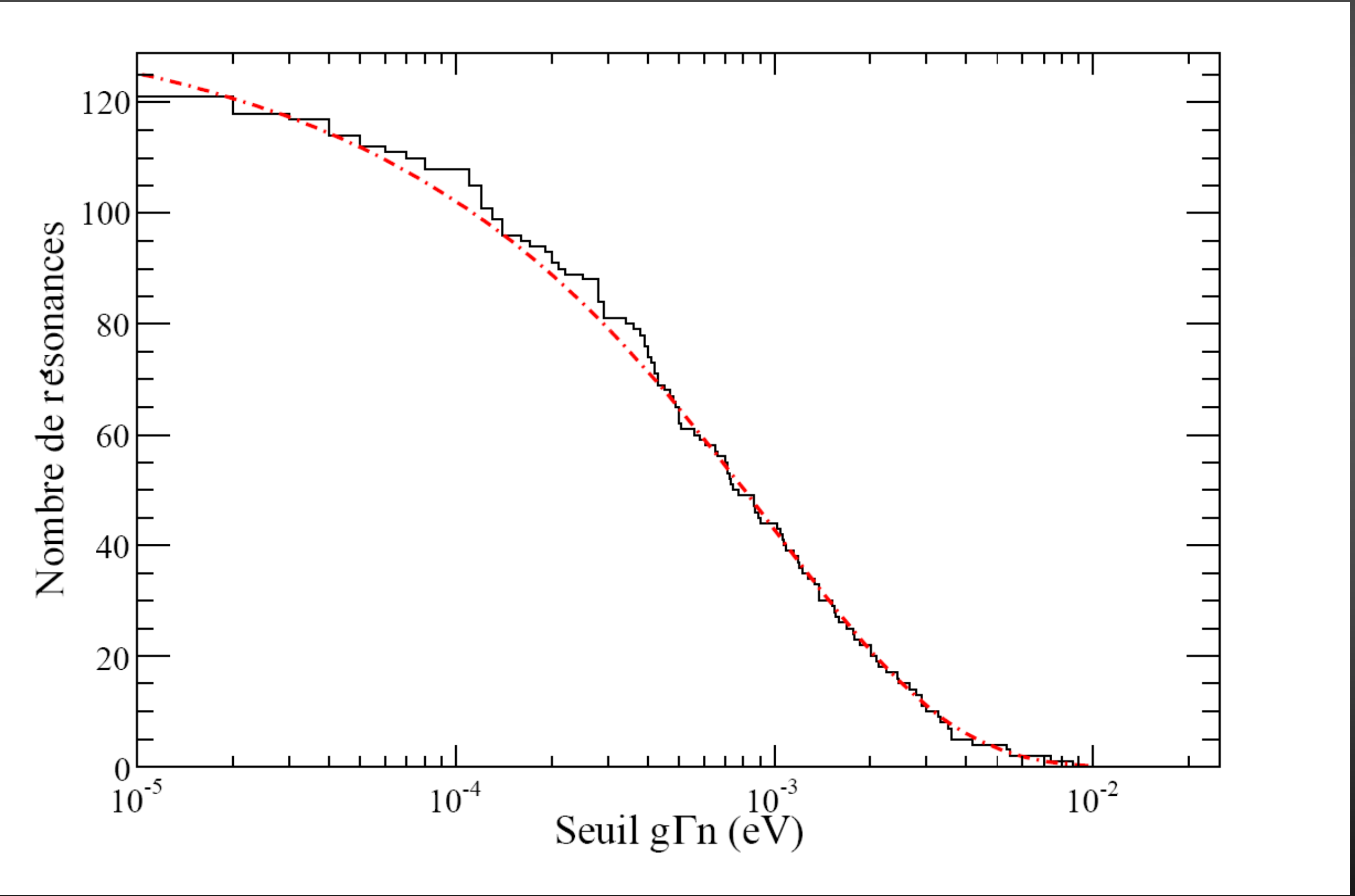

n_TOF TAC in operation

n_TOF experiments

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

^{232}Th

$^{24,25,26}Mg$

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

^{139}La

$^{186,187,188}Os$

$^{233,234}U$

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

Fission

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

^{232}Th

^{209}Bi

^{237}Np

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

W Dridi, E Berthoumieux, et al. (The n_TOF Collaboration)
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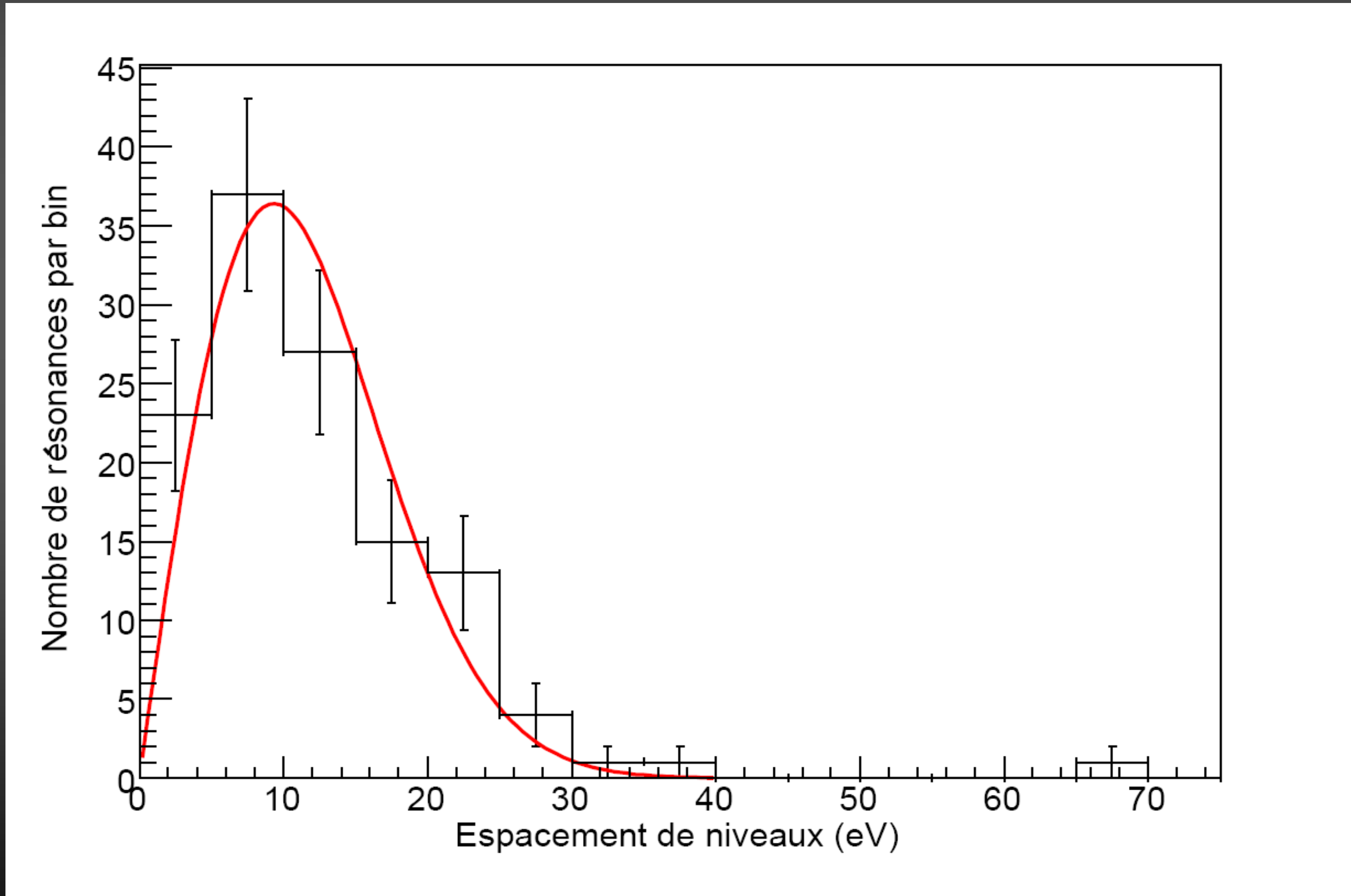
full paper in preparation

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



n_TOF TAC in operation

n_TOF experiments

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

Capture

^{151}Sm

^{204,206,207,208}Pb, ^{209}Bi

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^{90,91,92,94,96}Zr, ^{93}Zr

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^{186,187,188}Os

^{233,234}U

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

Fission

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

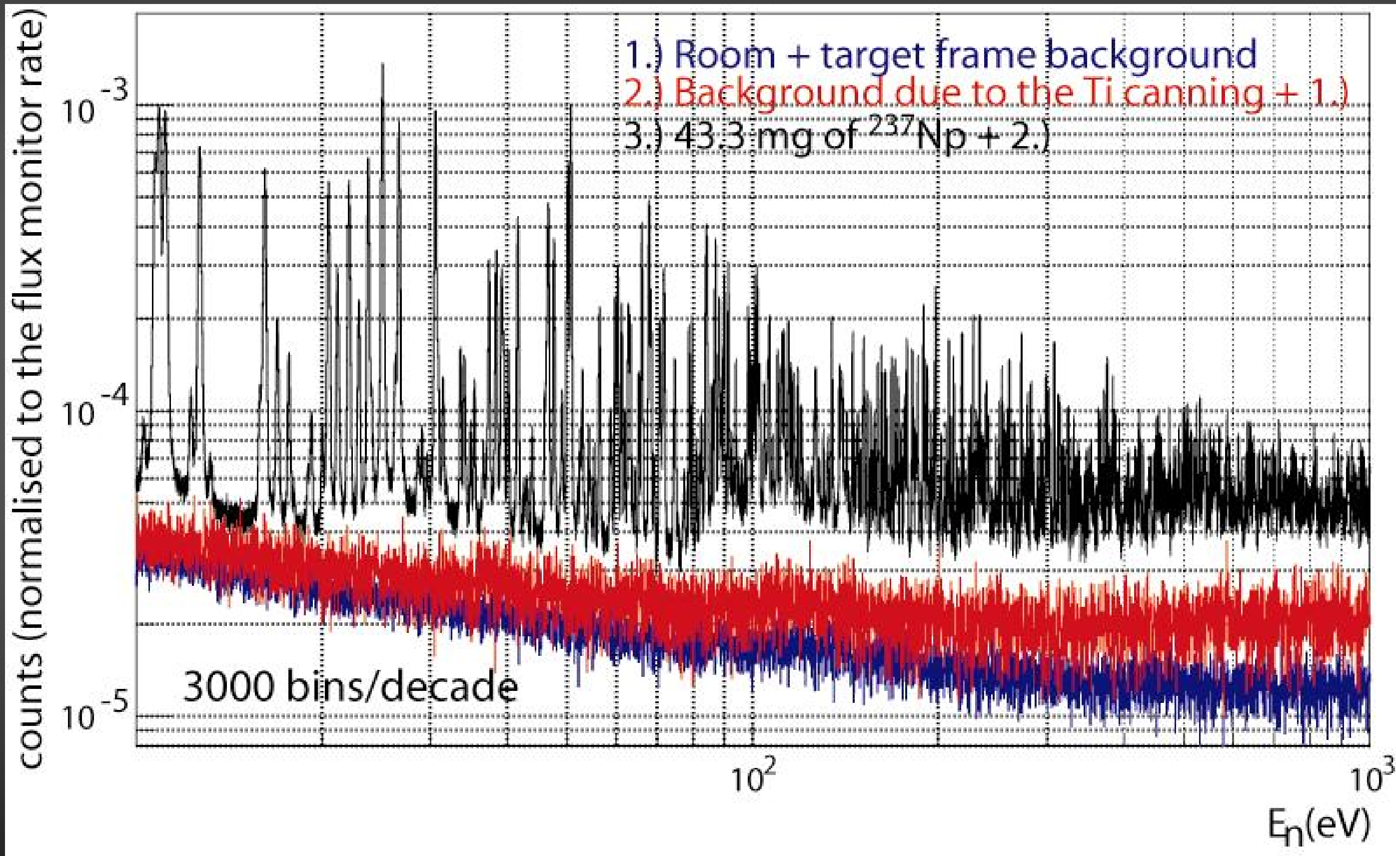
^{232}Th

^{209}Bi

^{237}Np

^{241,243}Am, ^{245}Cm

^{237}Np(n,γ)



n_TOF TAC in operation

n_TOF experiments

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

^{232}Th

$^{24,25,26}Mg$

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

^{139}La

$^{186,187,188}Os$

$^{233,234}U$

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

Fission

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

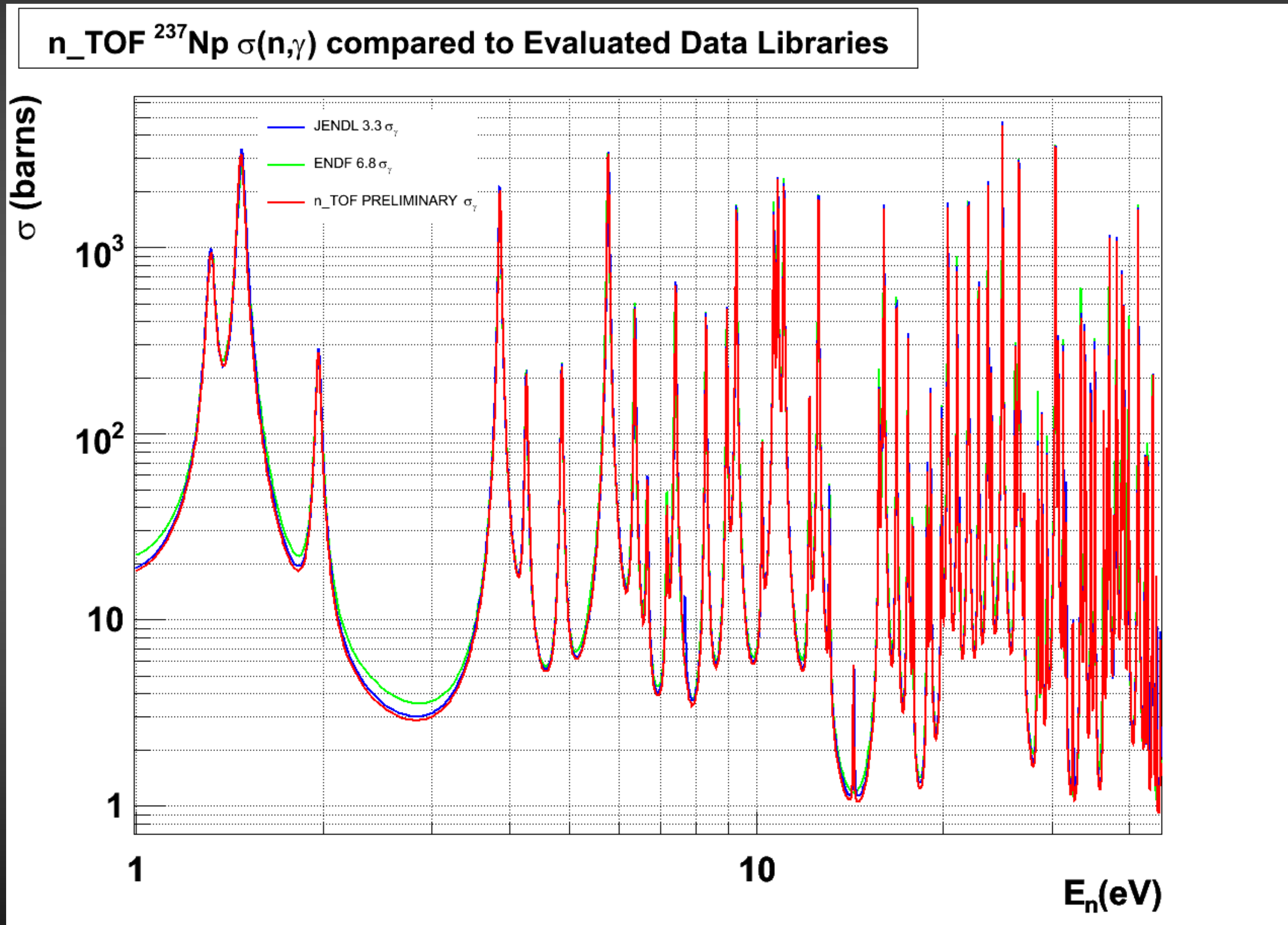
^{232}Th

^{209}Bi

^{237}Np

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

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



n_TOF TAC in operation

n_TOF experiments

Capture

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

^{232}Th

$^{24,25,26}Mg$

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

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$^{186,187,188}Os$

$^{233,234}U$

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

Fission

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

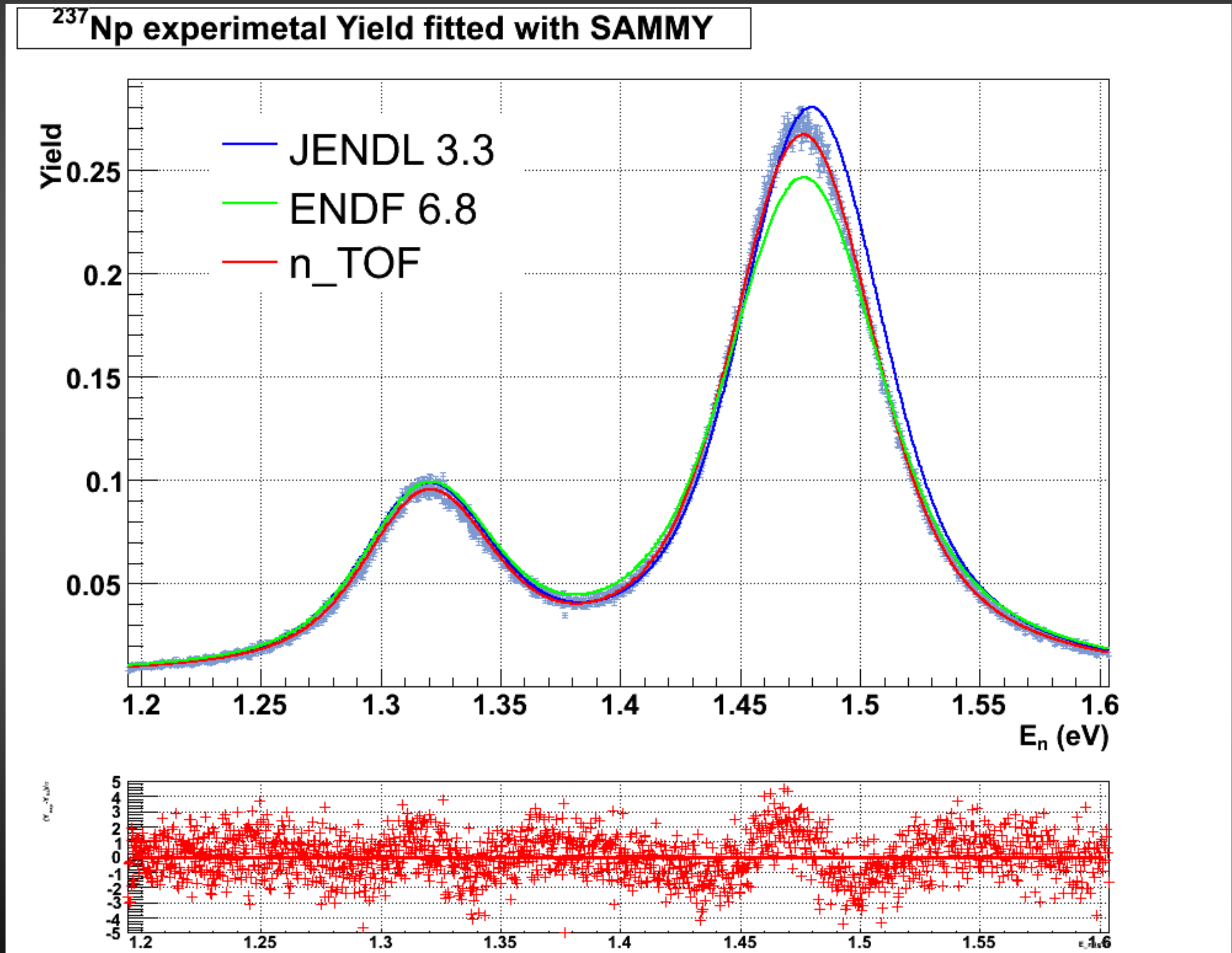
^{232}Th

^{209}Bi

^{237}Np

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

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



n_TOF experiments

Capture

^{151}Sm

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

^{232}Th

$^{24,25,26}Mg$

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

^{139}La

$^{186,187,188}Os$

$^{233,234}U$

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

Fission

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

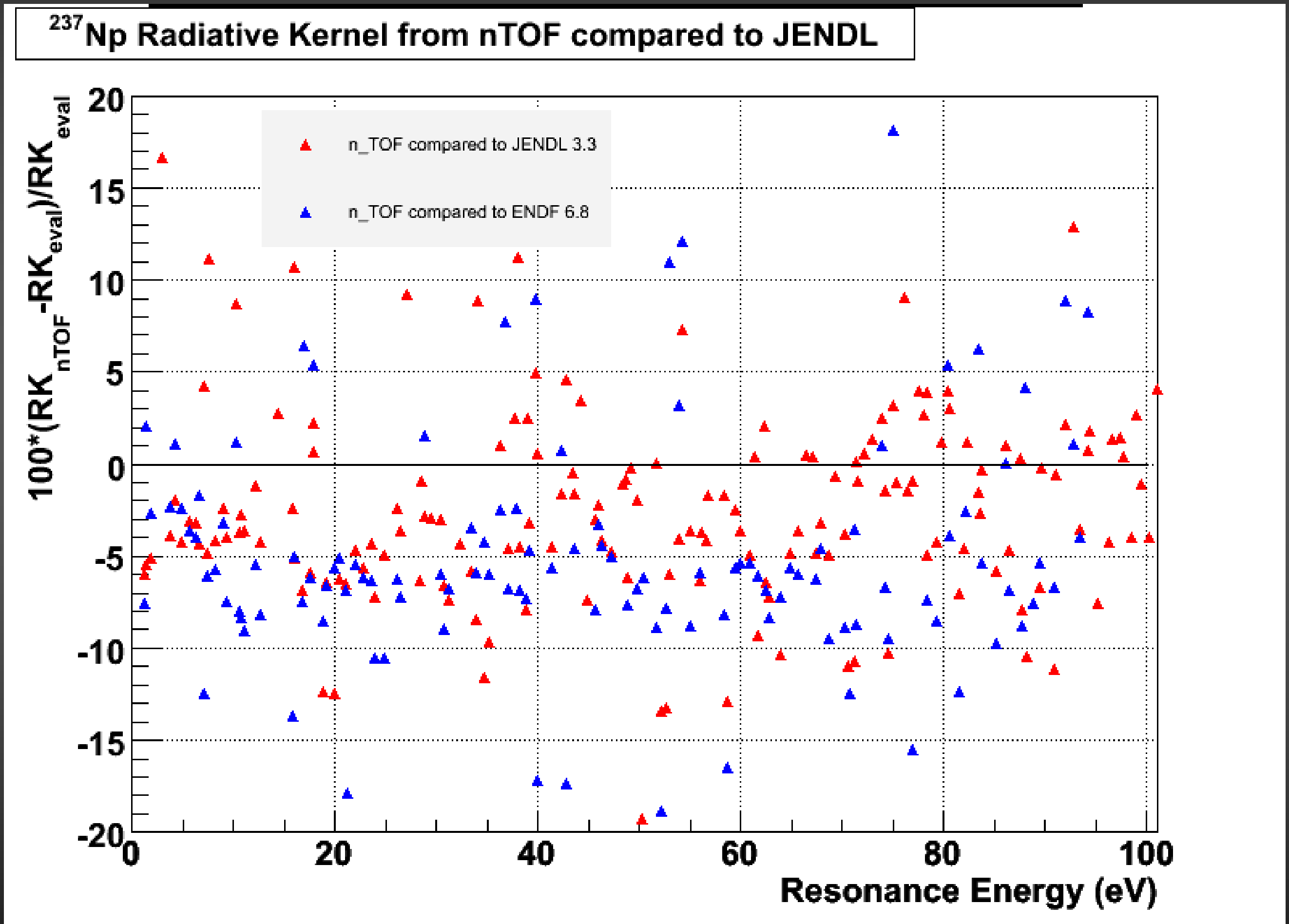
^{232}Th

^{209}Bi

^{237}Np

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

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



RK_{n_TOF} on average 3% below the RK_{JENDL} and 6% below the RK_{ENDF}

n_TOF experiments

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

Capture

^{151}Sm

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

^{232}Th

$^{24,25,26}Mg$

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

^{139}La

$^{186,187,188}Os$

$^{233,234}U$

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

Fission

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

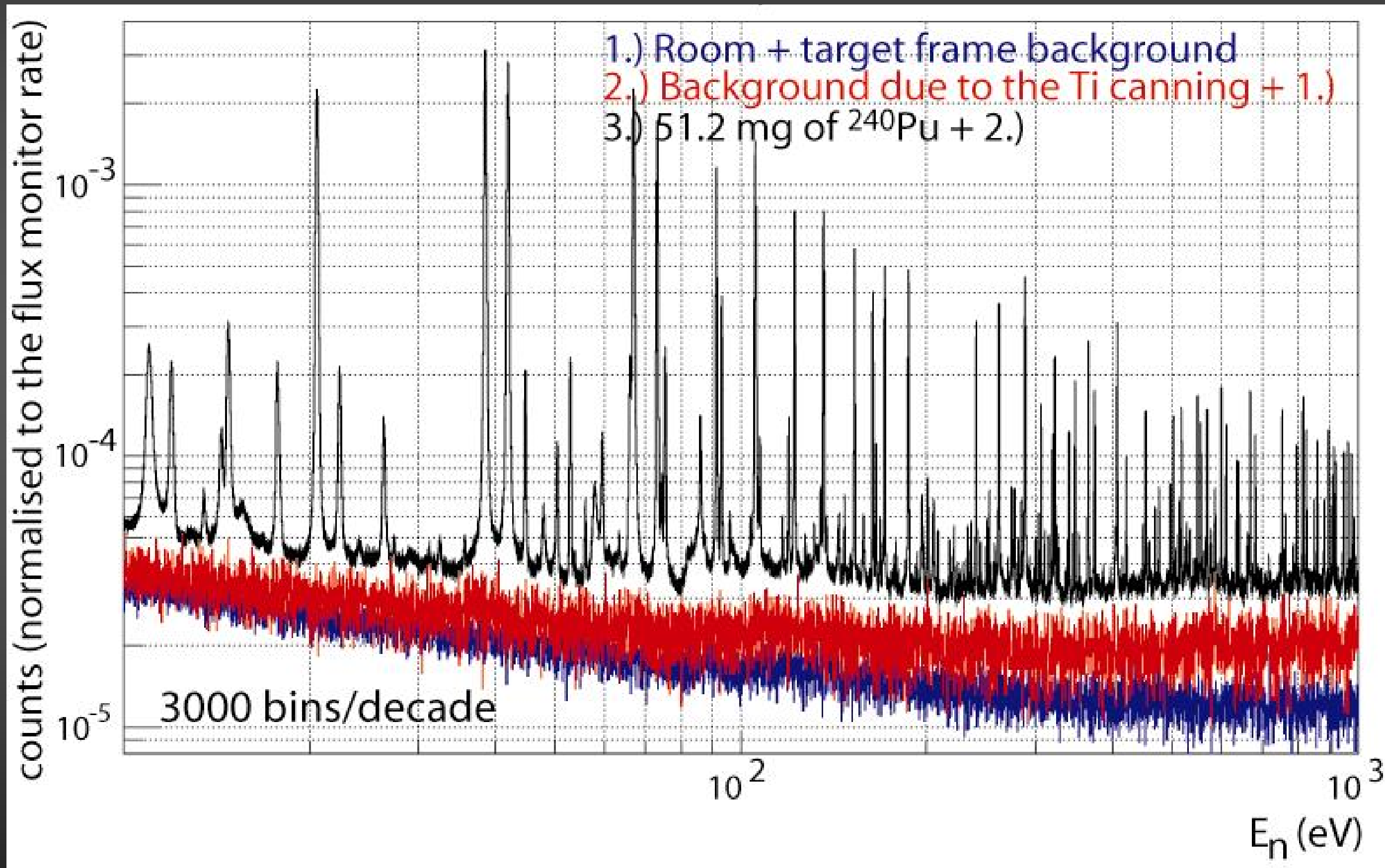
^{232}Th

^{209}Bi

^{237}Np

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

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



n_TOF TAC in operation

n_TOF experiments

Capture

^{151}Sm

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

^{232}Th

$^{24,25,26}Mg$

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

^{139}La

$^{186,187,188}Os$

$^{233,234}U$

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

Fission

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

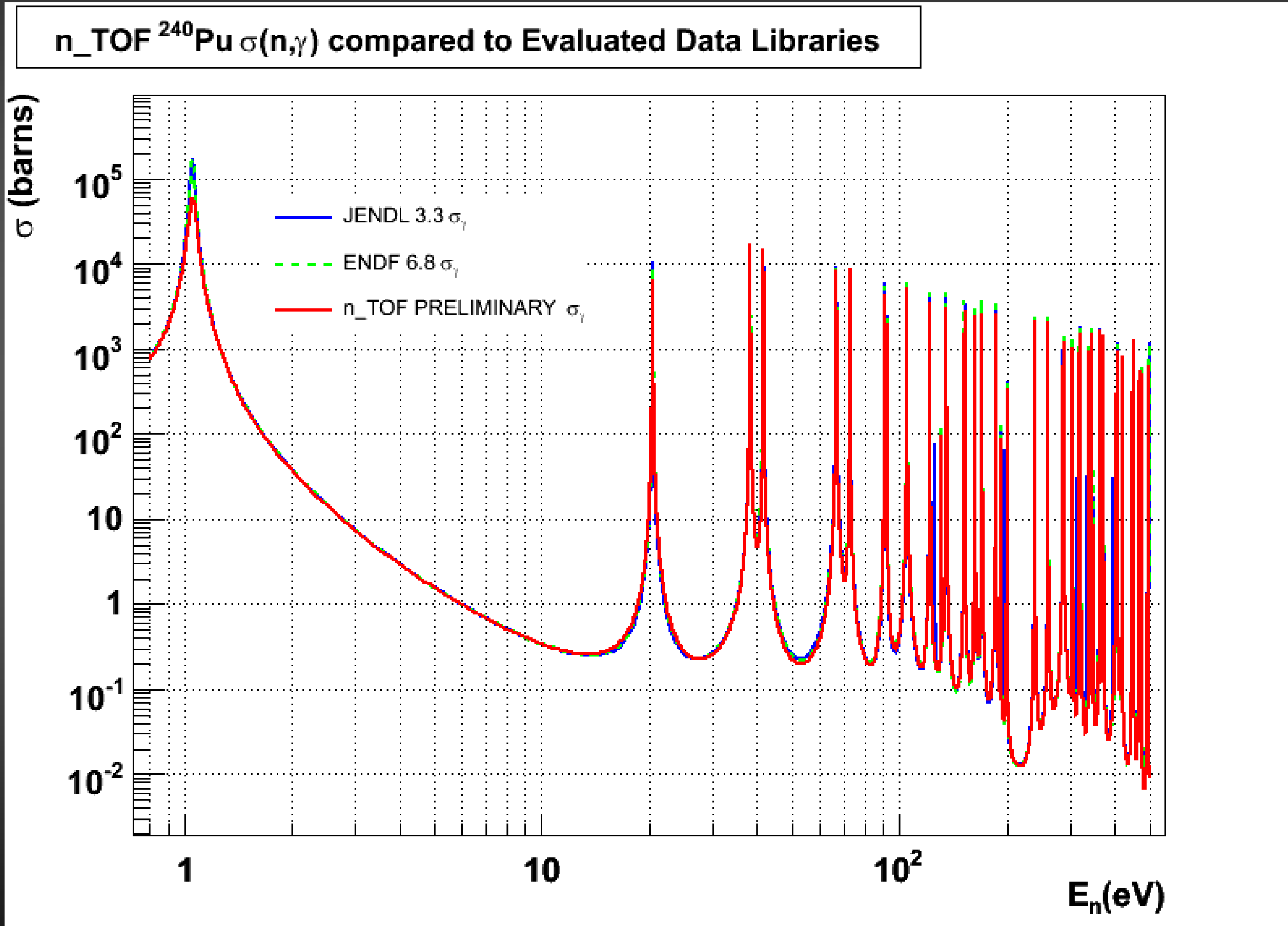
^{232}Th

^{209}Bi

^{237}Np

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

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



n_TOF TAC in operation

The n_TOF Collaboration

Capture

^{151}Sm

^{204,206,207,208}Pb, ^{209}Bi

^{232}Th

^{24,25,26}Mg

^{90,91,92,94,96}Zr, ^{93}Zr

^{139}La

^{186,187,188}Os

^{233,234}U

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

Fission

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

^{232}Th

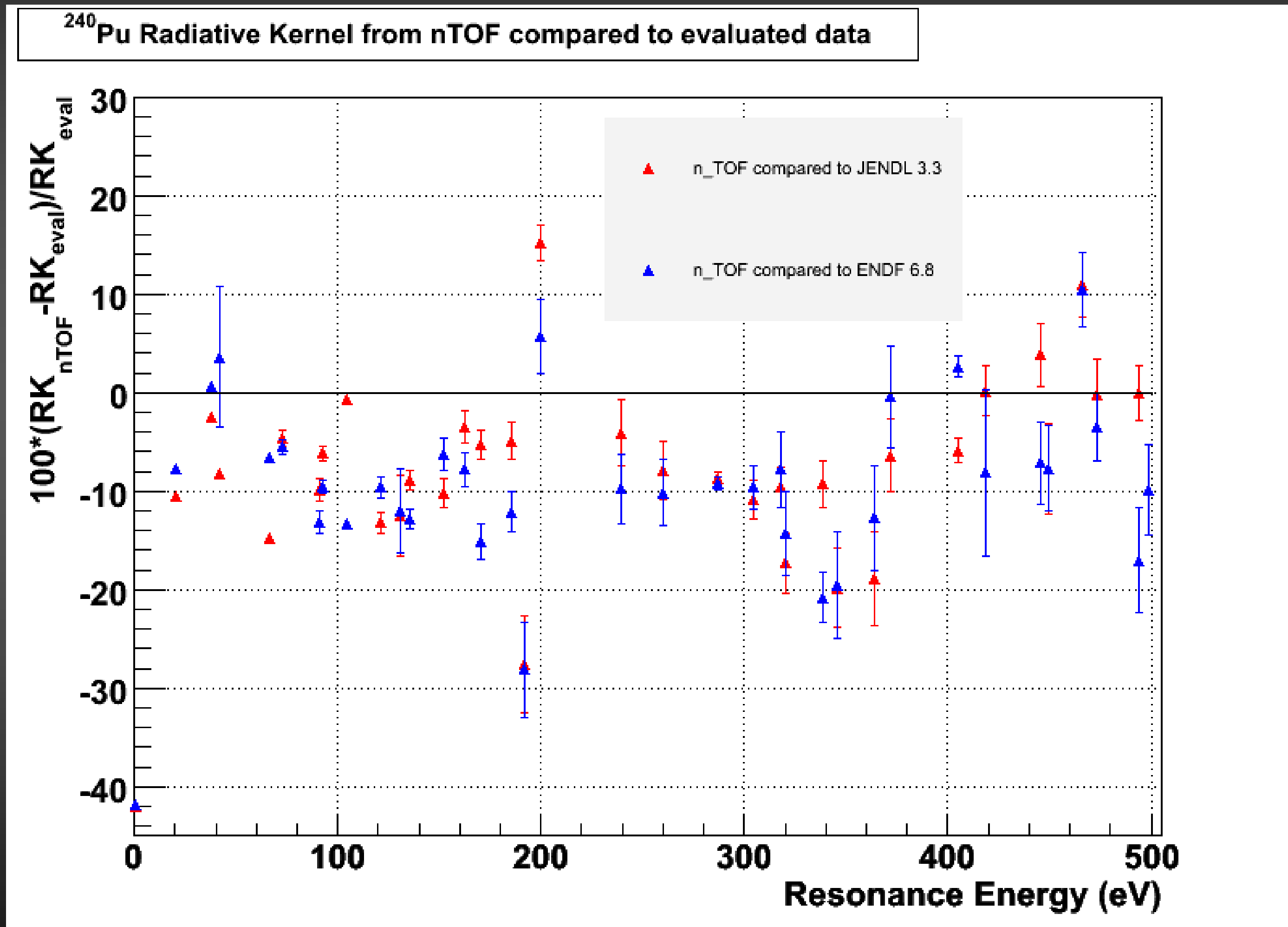
^{209}Bi

^{237}Np

^{241,243}Am, ^{245}Cm

n_TOF experiments

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



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

n_TOF experiments

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

Capture

^{151}Sm

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

^{232}Th

$^{24,25,26}Mg$

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

^{139}La

$^{186,187,188}Os$

$^{233,234}U$

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

Fission

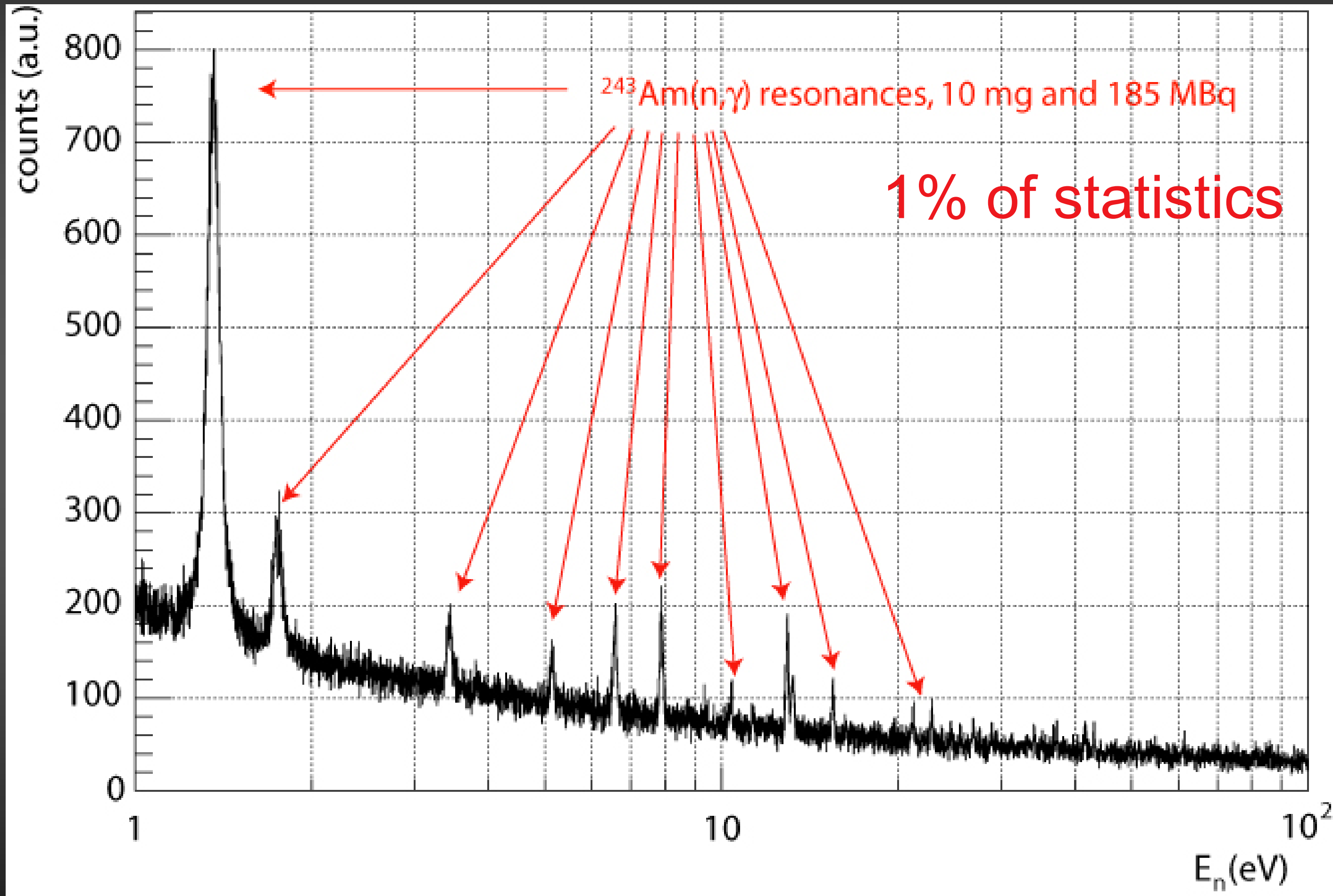
$^{233,234,235,236,238}U$

^{232}Th

^{209}Bi

^{237}Np

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



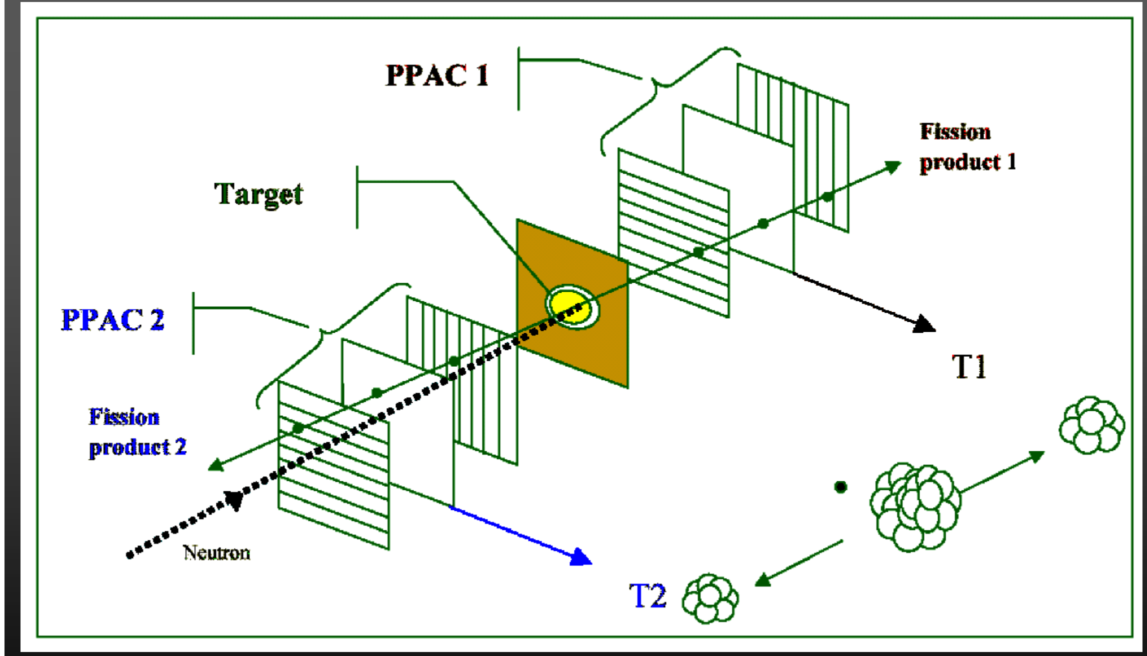
n_TOF TAC in operation

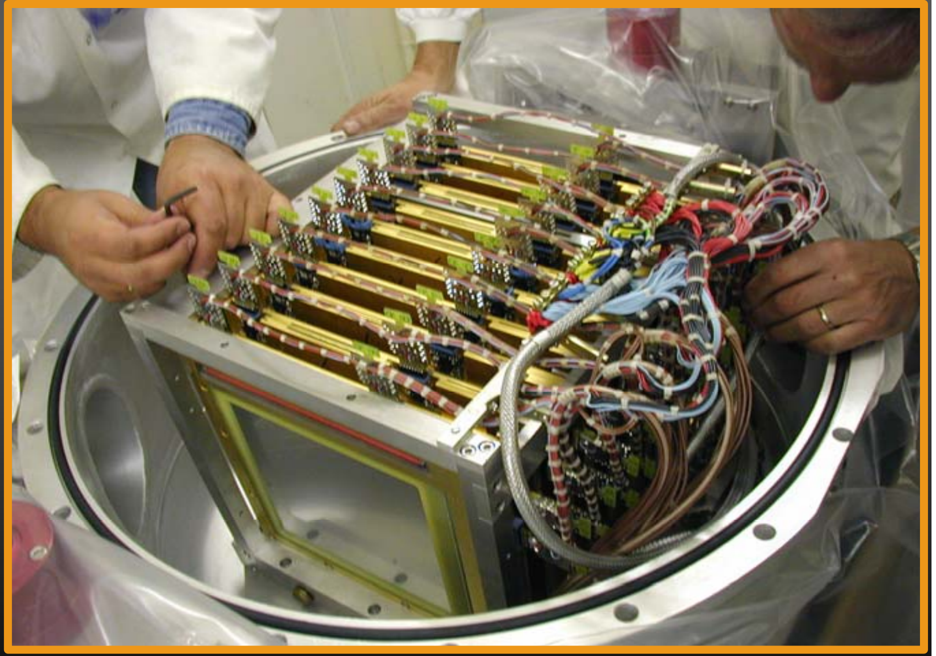
n_TOF experiments:
fission measurements

n_TOF experiments: fission measurements

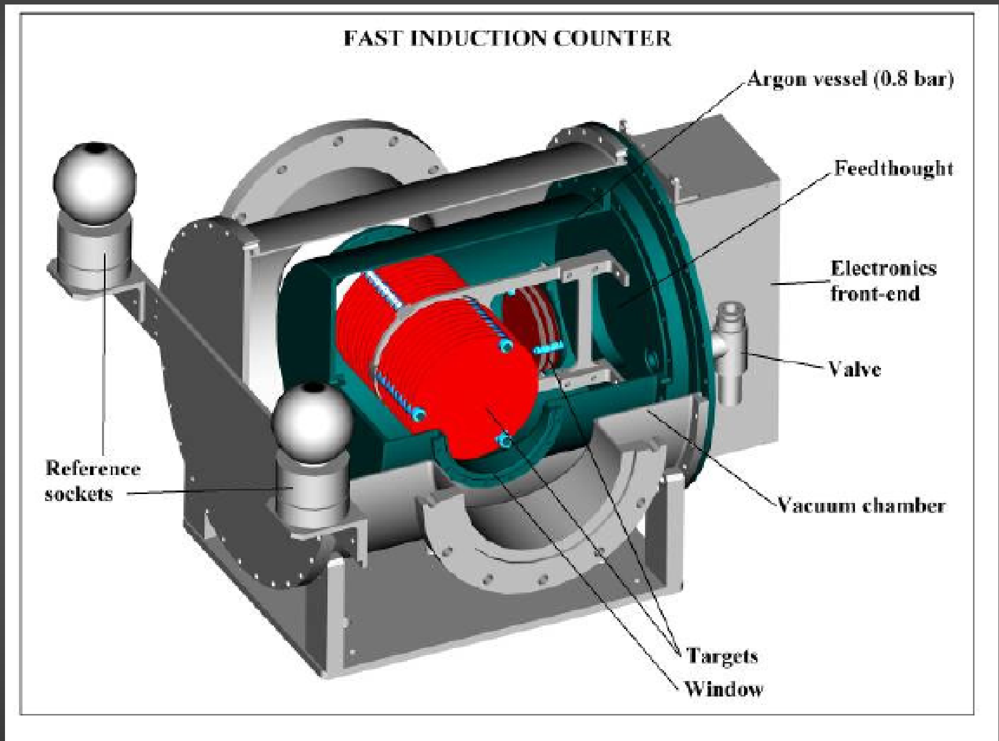
- 20x20 cm^2
- Isobutane gas 7 mbar
- HV 500-600 V
- 3 mm between electrodes
- 1 anode (a few ns signal width)
- Electrode thickness: 1.5 μm (Mylar+Al)
- Deposit thickness : 100-300 μg/cm^2
- Backing thickness : 0.1 μm (Al)
- : 1.5 μm (Mylar)
- Fission event identification: T2 in coincidence with T1

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 $\mu m/cm^2$
- Backing thickness : 100 μm (Al)
- Window thickness : 125 μm

developed by a CERN/Obninsk/Dubna team

n_TOF experiments

Capture

^{151}Sm

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

^{232}Th

$^{24,25,26}Mg$

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

^{139}La

$^{186,187,188}Os$

$^{233,234}U$

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

Fission

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

^{232}Th

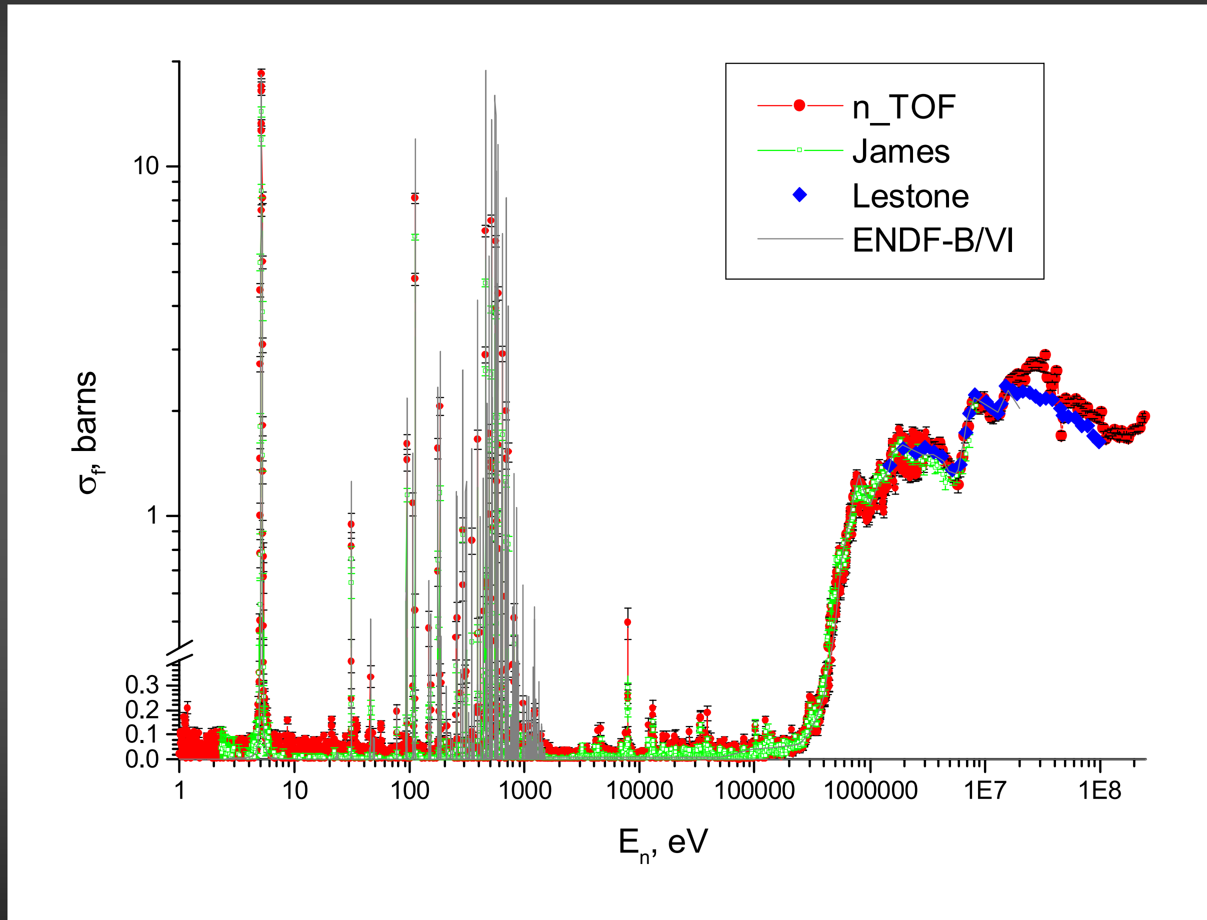
^{209}Bi

^{237}Np

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

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

PPACs & FIC-0 (2003)



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

The n_TOF Collaboration

n_TOF experiments

PPACs & FIC-0 (2003)

Capture

^{151}Sm

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

^{232}Th

$^{24,25,26}Mg$

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

^{139}La

$^{186,187,188}Os$

$^{233,234}U$

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

Fission

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

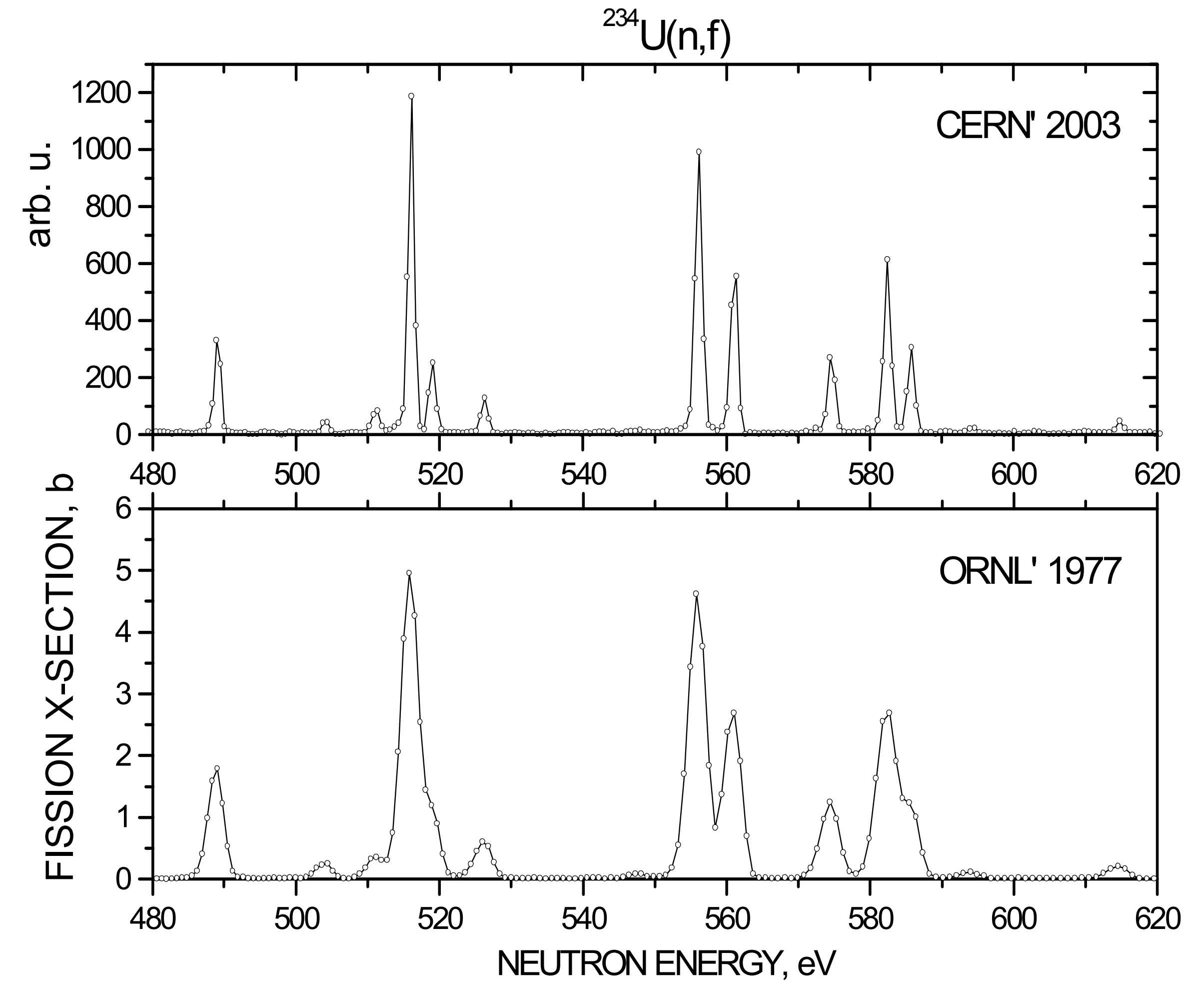
^{232}Th

^{209}Bi

^{237}Np

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

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



High-resolution data up to high(er) energies

n_TOF experiments

PPACs & FIC-0 (2003)

Capture

^{151}Sm

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

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$^{24,25,26}Mg$

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

^{139}La

$^{186,187,188}Os$

$^{233,234}U$

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

Fission

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

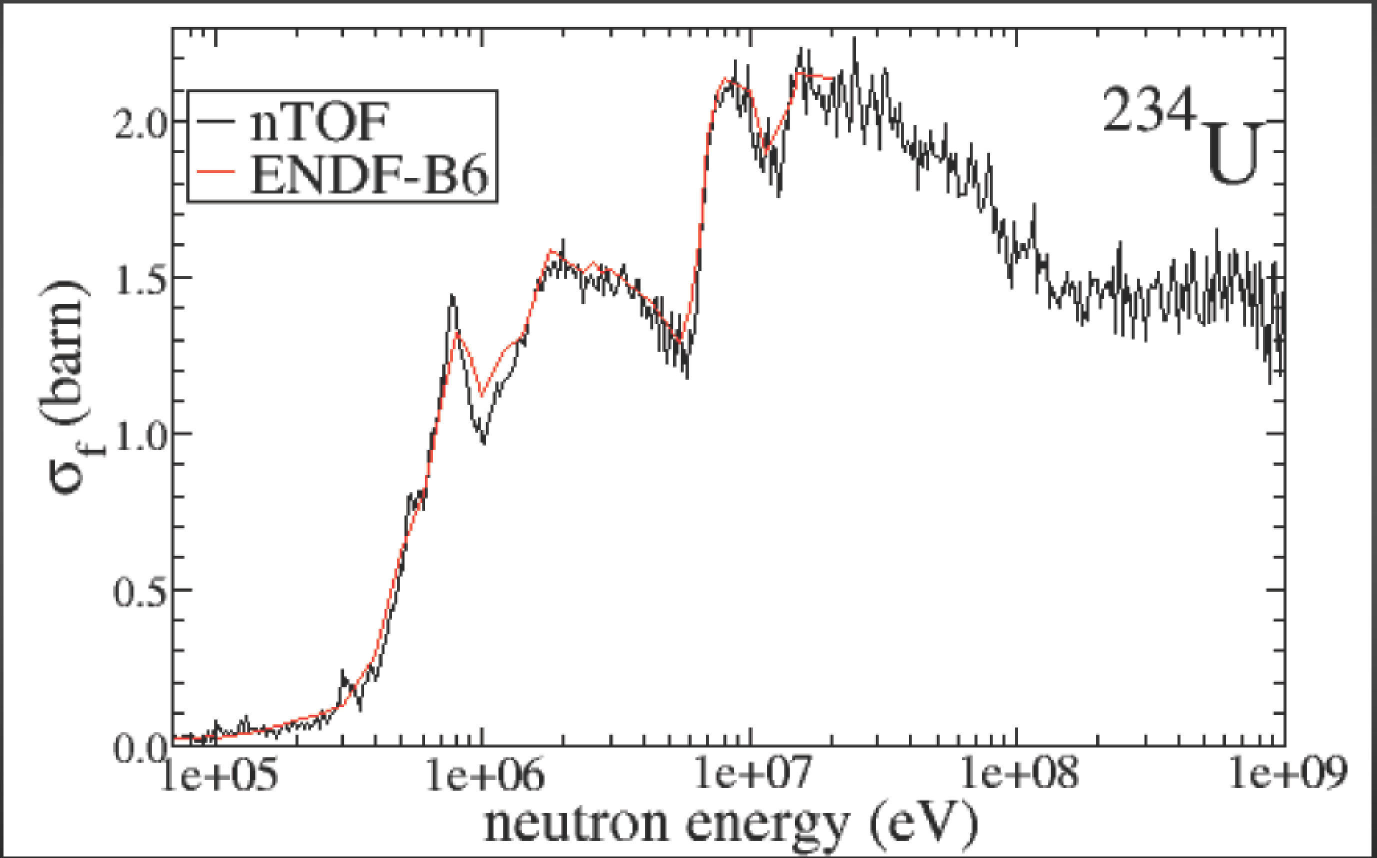
^{232}Th

^{209}Bi

^{237}Np

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

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

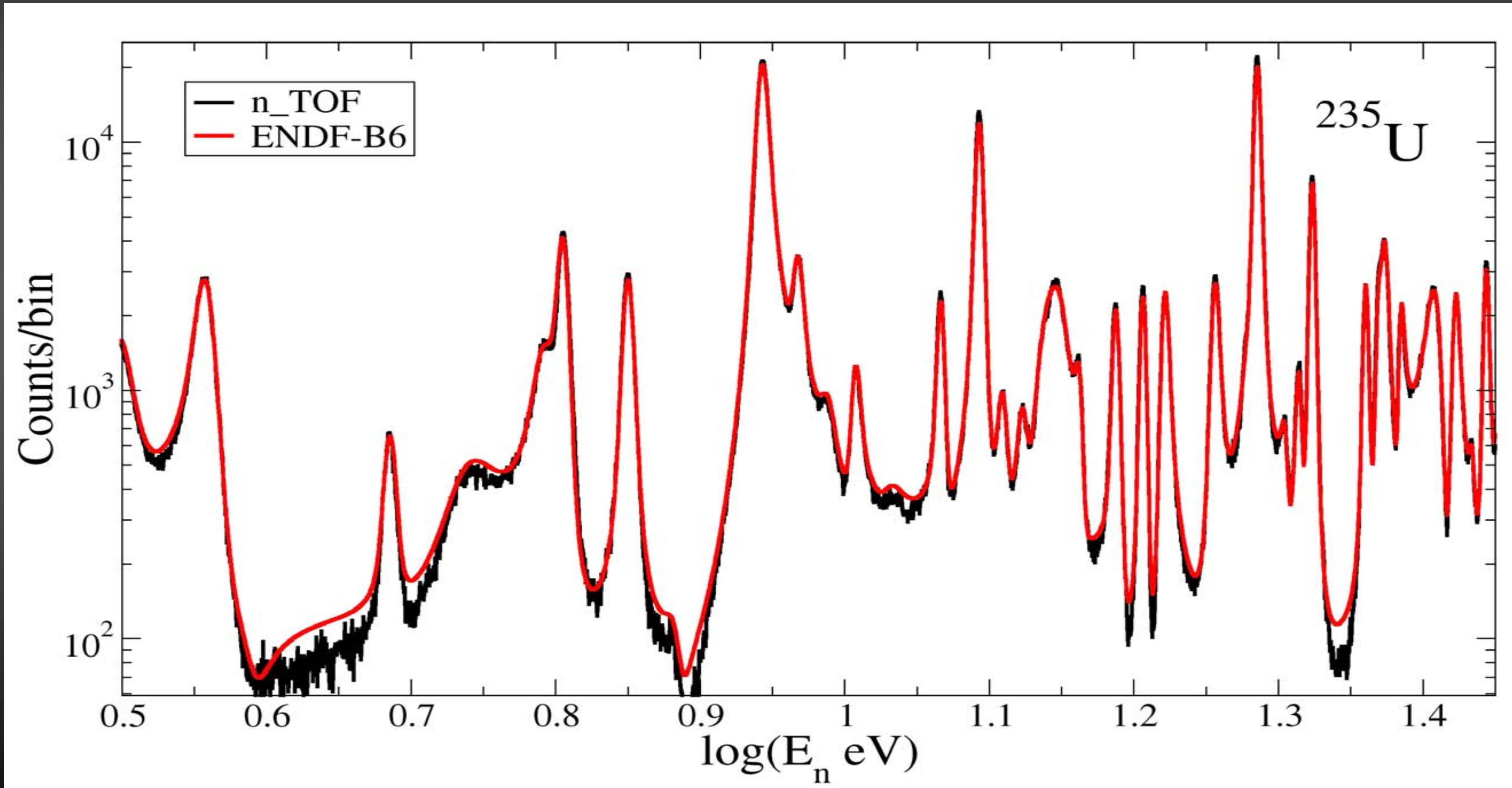


High-resolution data up to high(er) energies

n_TOF experiments

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

PPACs (2002 & 2003)



n_TOF experiments

FIC-1 (2003)

Capture

^{151}Sm

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

^{232}Th

$^{24,25,26}Mg$

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

^{139}La

$^{186,187,188}Os$

$^{233,234}U$

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

Fission

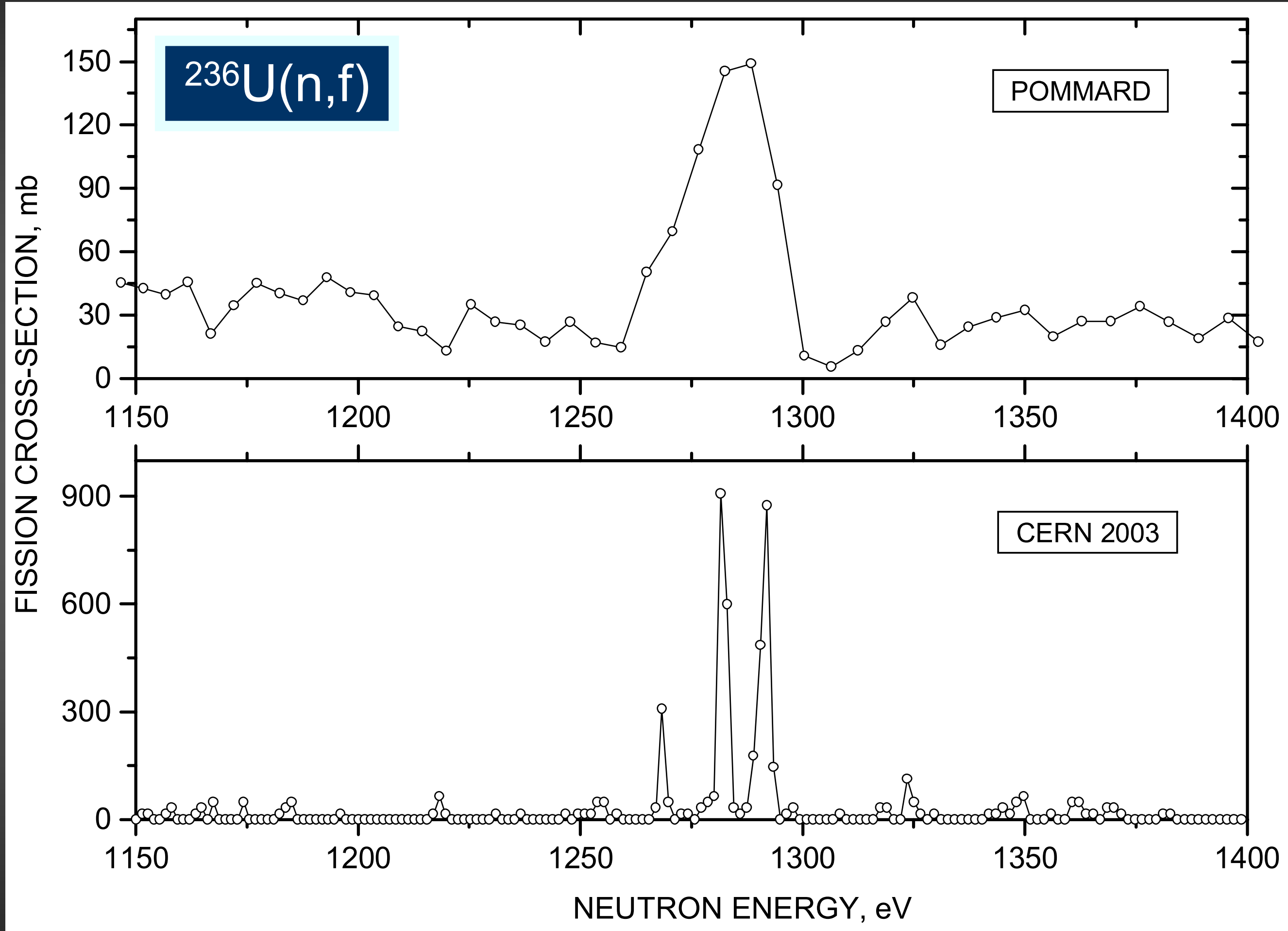
$^{233,234,235,236,238}U$

^{232}Th

^{209}Bi

^{237}Np

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



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

n_TOF experiments

Capture

^{151}Sm

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

^{232}Th

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

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$^{233,234}U$

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

Fission

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

^{232}Th

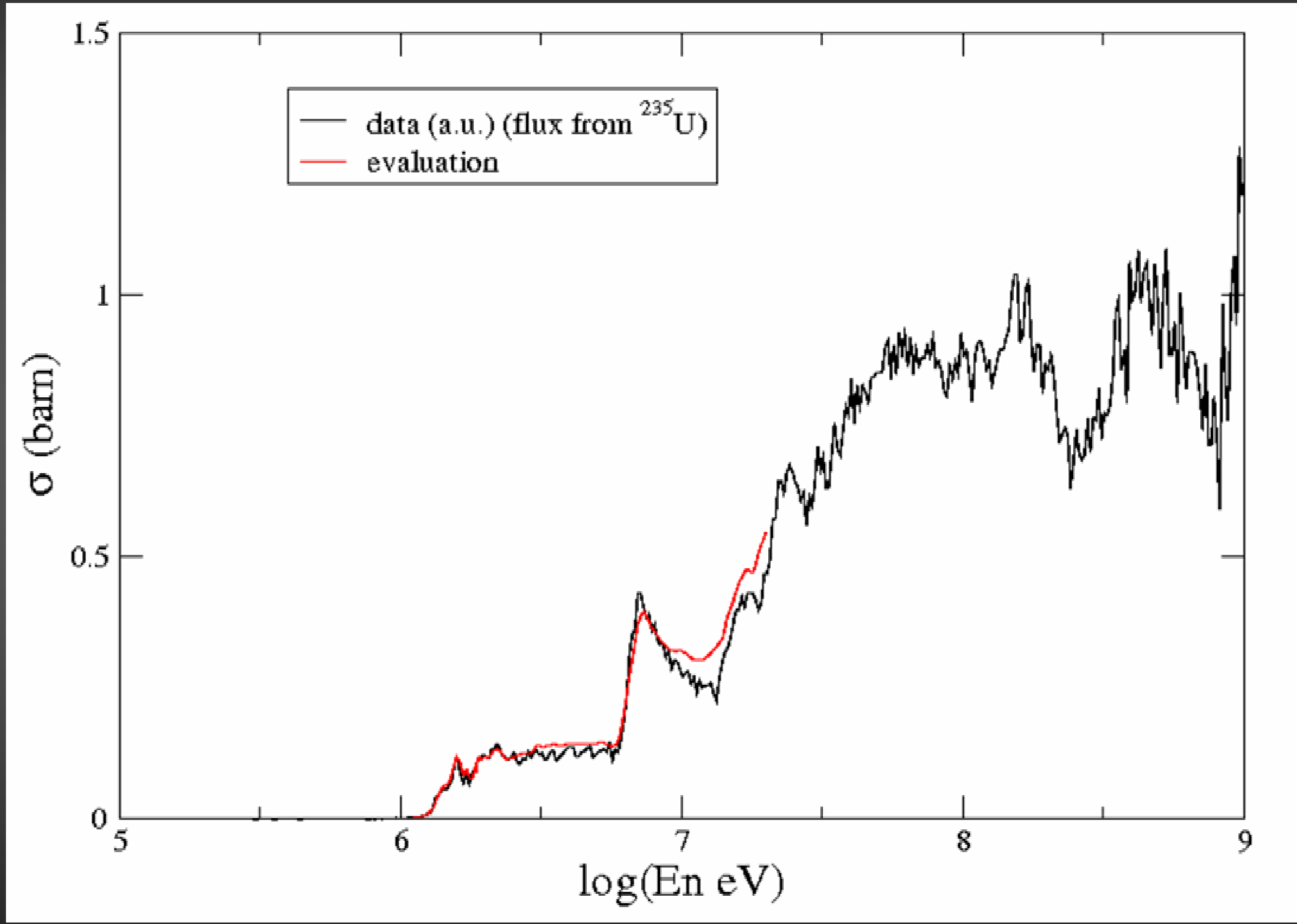
^{209}Bi

^{237}Np

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

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

PPAC detectors



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

n_TOF experiments

FIC-0 (2003)

Capture

^{151}Sm

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

^{232}Th

$^{24,25,26}Mg$

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

^{139}La

$^{186,187,188}Os$

$^{233,234}U$

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

Fission

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

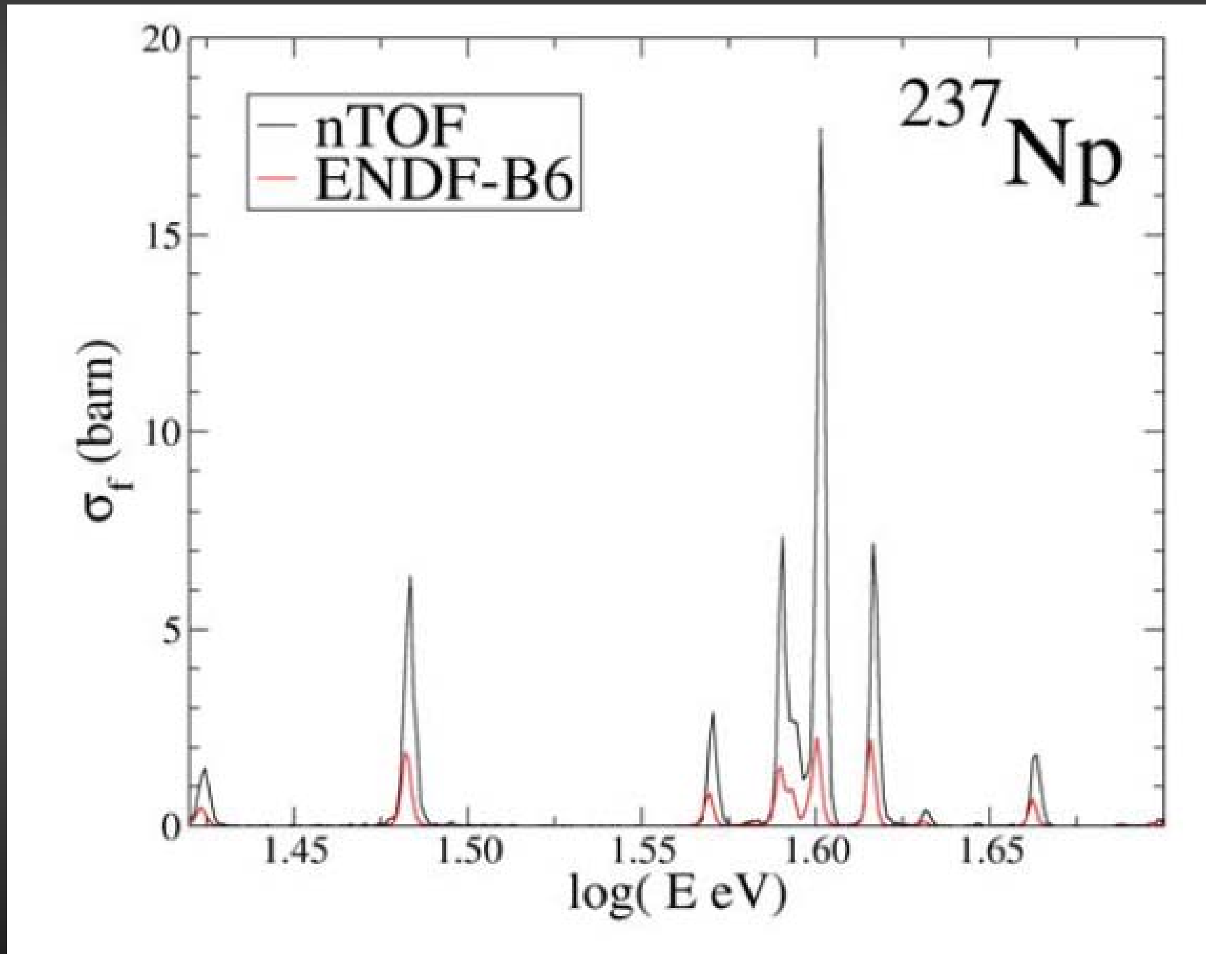
^{232}Th

^{209}Bi

^{237}Np

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

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



Higher fission x-section in the sub-threshold region

The n_TOF Collaboration

n_TOF experiments

PPACs (2003)

Capture

^{151}Sm

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

^{232}Th

$^{24,25,26}Mg$

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

^{139}La

$^{186,187,188}Os$

$^{233,234}U$

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

Fission

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

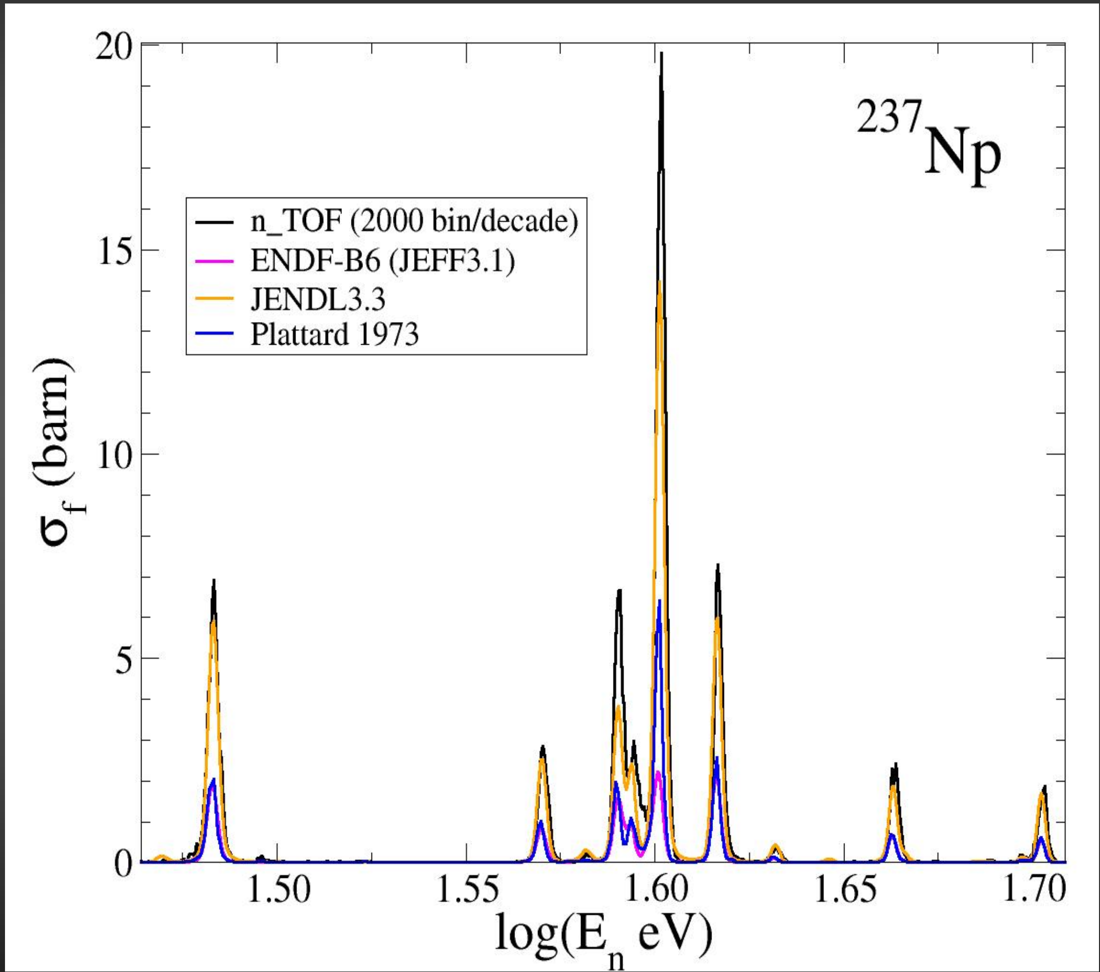
^{232}Th

^{209}Bi

^{237}Np

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

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



Higher fission x-section in the sub-threshold region

n_TOF experiments

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^{204,206,207,208}Pb, ^{209}Bi

^{232}Th

^{24,25,26}Mg

^{90,91,92,94,96}Zr, ^{93}Zr

^{139}La

^{186,187,188}Os

^{233,234}U

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

Fission

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

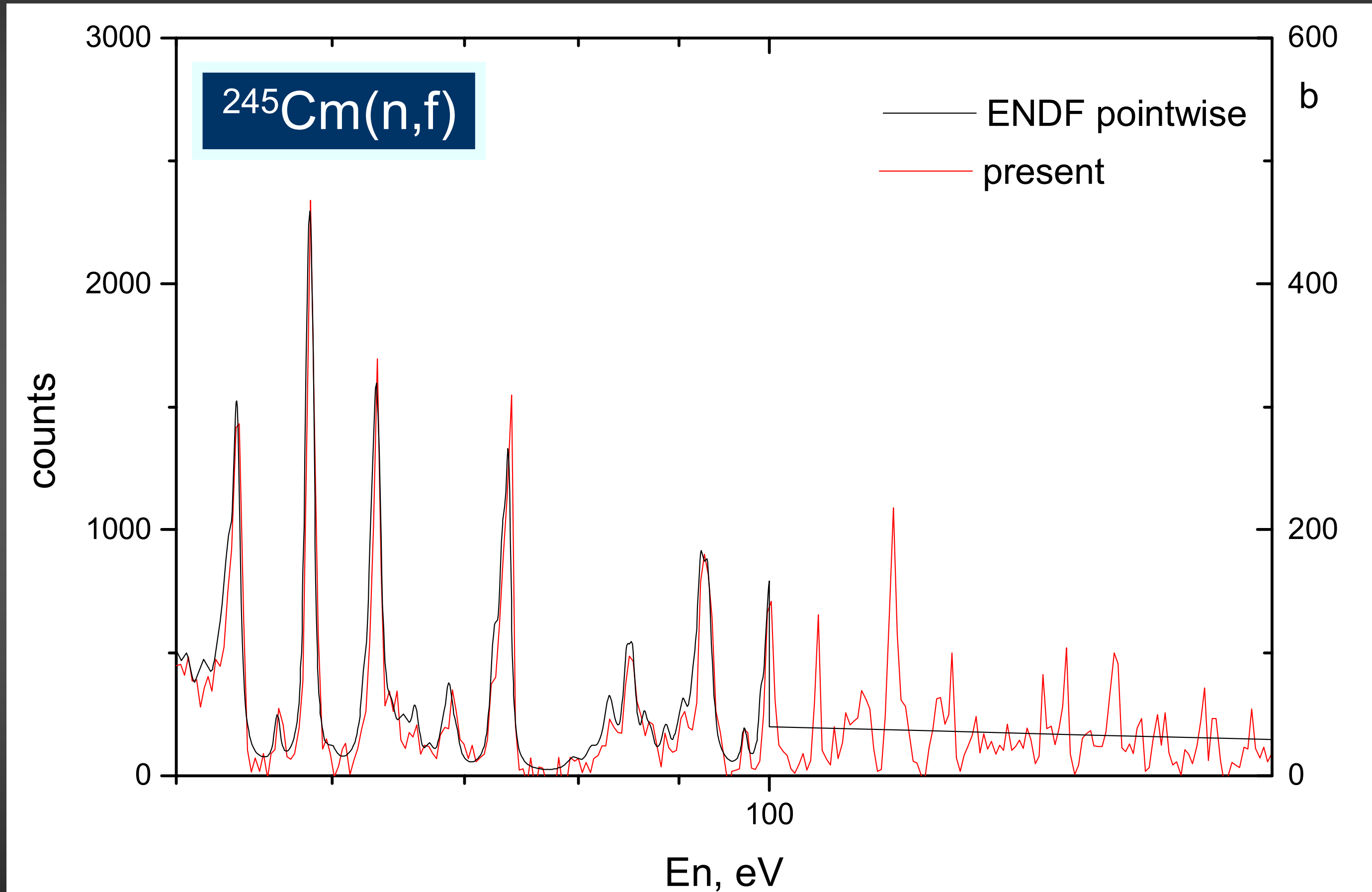
^{232}Th

^{209}Bi

^{237}Np

^{241,243}Am, ^{245}Cm

FIC-1 (2003)



High-resolution data up to high(er) energies

n_TOF experiments

Capture

^{151}Sm

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

^{232}Th

$^{24,25,26}Mg$

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

^{139}La

$^{186,187,188}Os$

$^{233,234}U$

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

Fission

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

^{232}Th

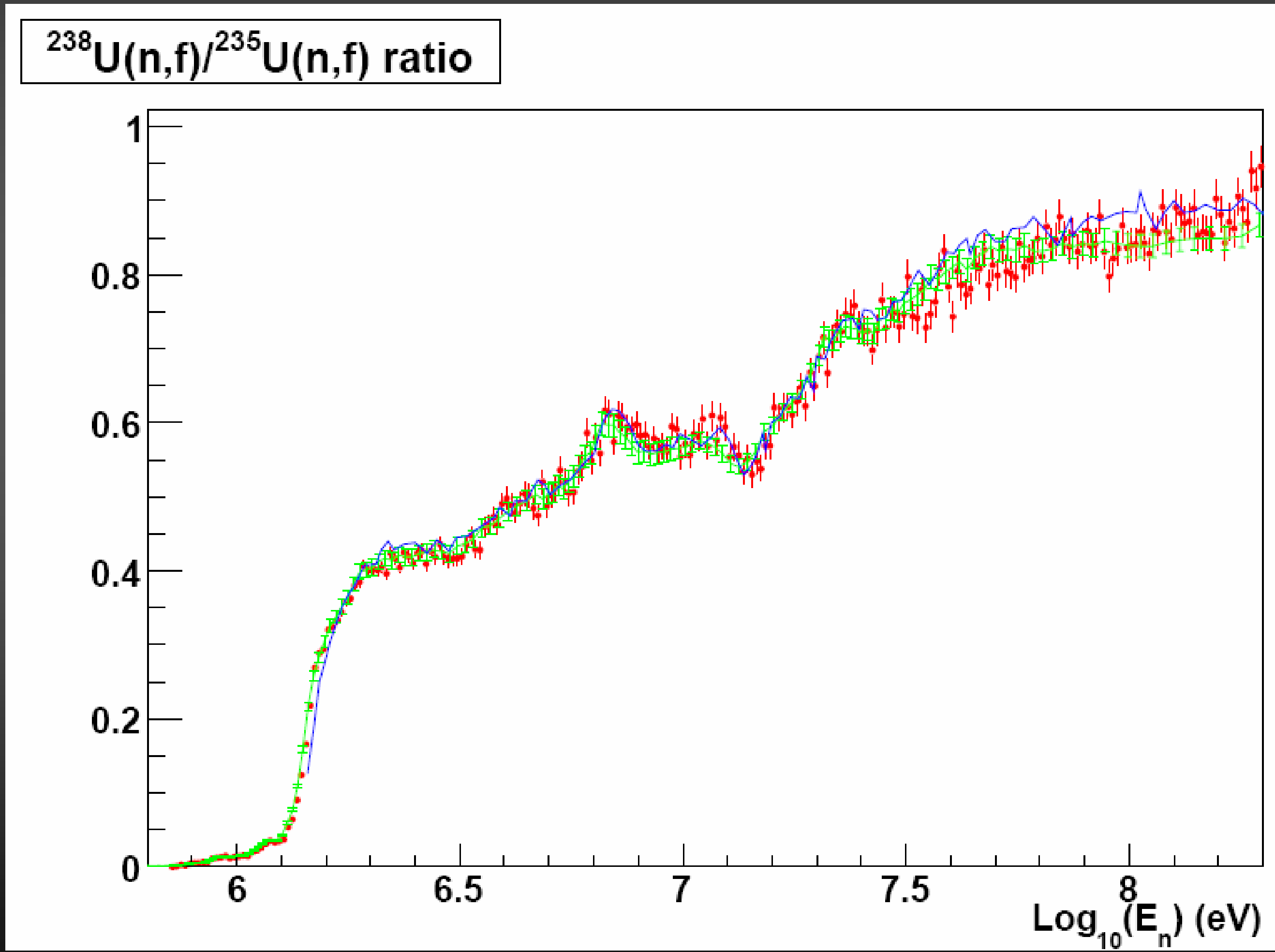
^{209}Bi

^{237}Np

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

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

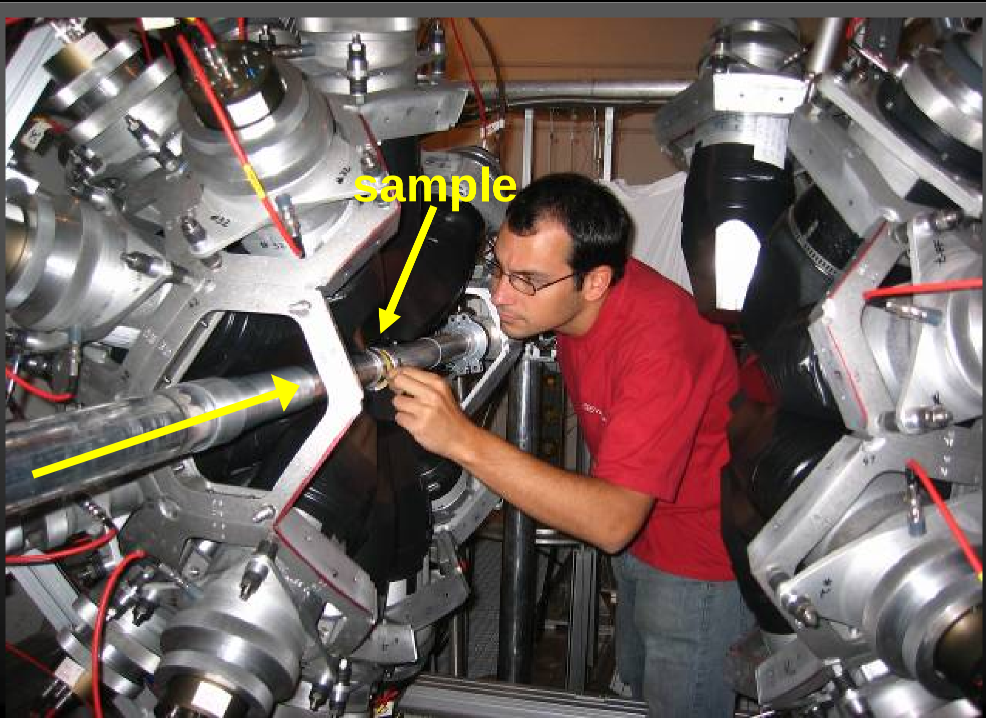
FIC1 data
source: M Calviani et al. (INFN)

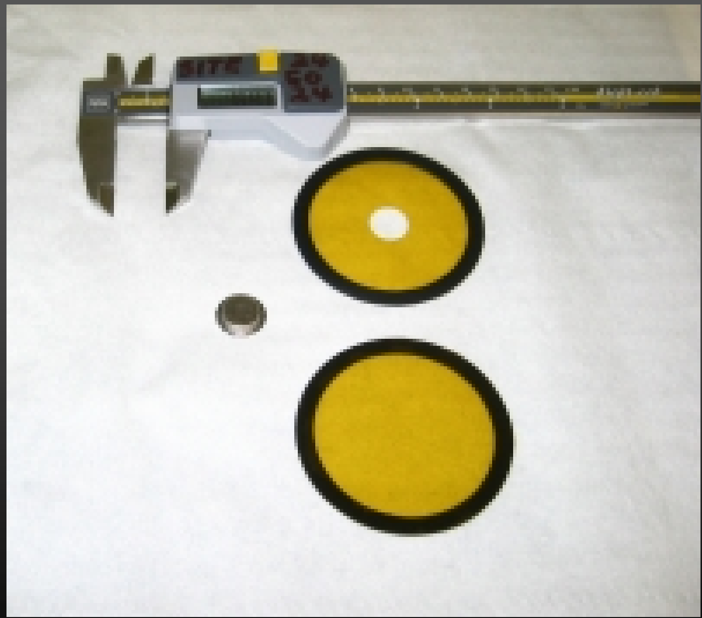


back

Capture samples

Sample	A	half-life yr	half-life s	Lambda 1/s	Mass mg	N	Activity Bq	Activity Ci	LA Bq	# of LA
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





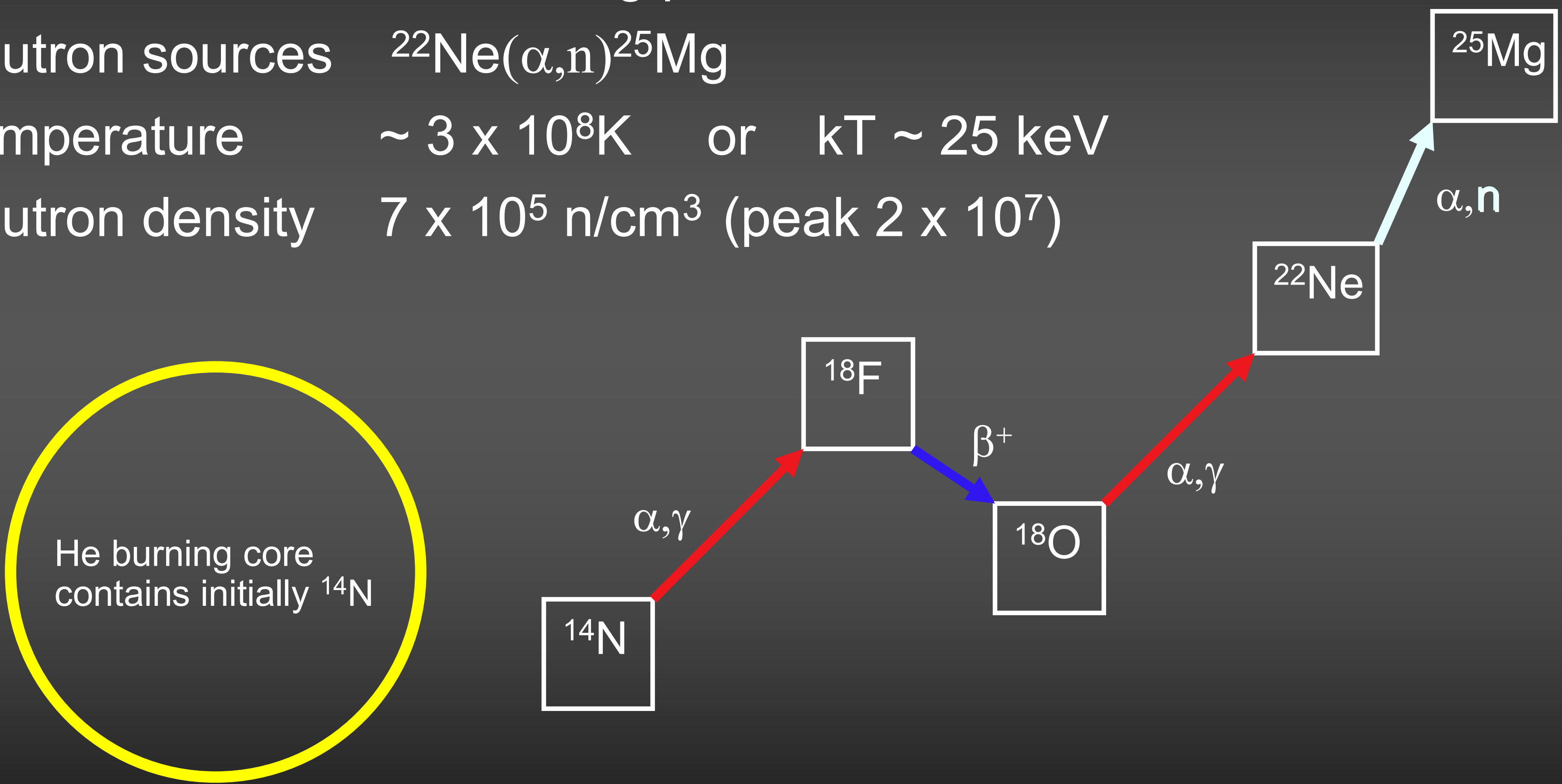
Fission samples (FIC detectors)

Isotope	Diam. [mm]	Density [μg/cm2]	# 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

back

s-process site-s & conditions: weak

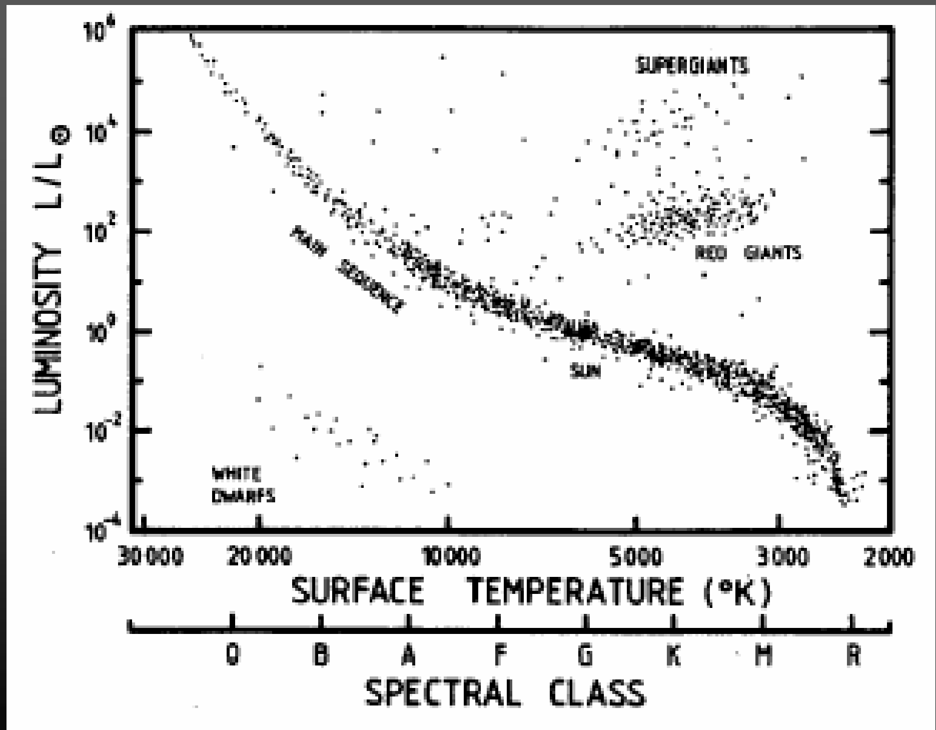
Site	He-burning phase of intermediate/massive stars
Neutron sources	$^{22}Ne(\alpha,n)^{25}Mg$
Temperature	~ 3 x 10^8K or kT ~ 25 keV
Neutron density	7 x 10^5 n/cm^3 (peak 2 x 10^7)



at the end of the He burning T ≈ 3 x 10^8: $^{22}Ne(\alpha,n)$ 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	$^{13}C(\alpha,n)^{16}O$	$^{22}Ne(\alpha,n)^{25}Mg$
Temperature	10^8K	kT ~ 8 keV
Neutron density	7×10^7 n/cm^3	10^{10} n/cm^3



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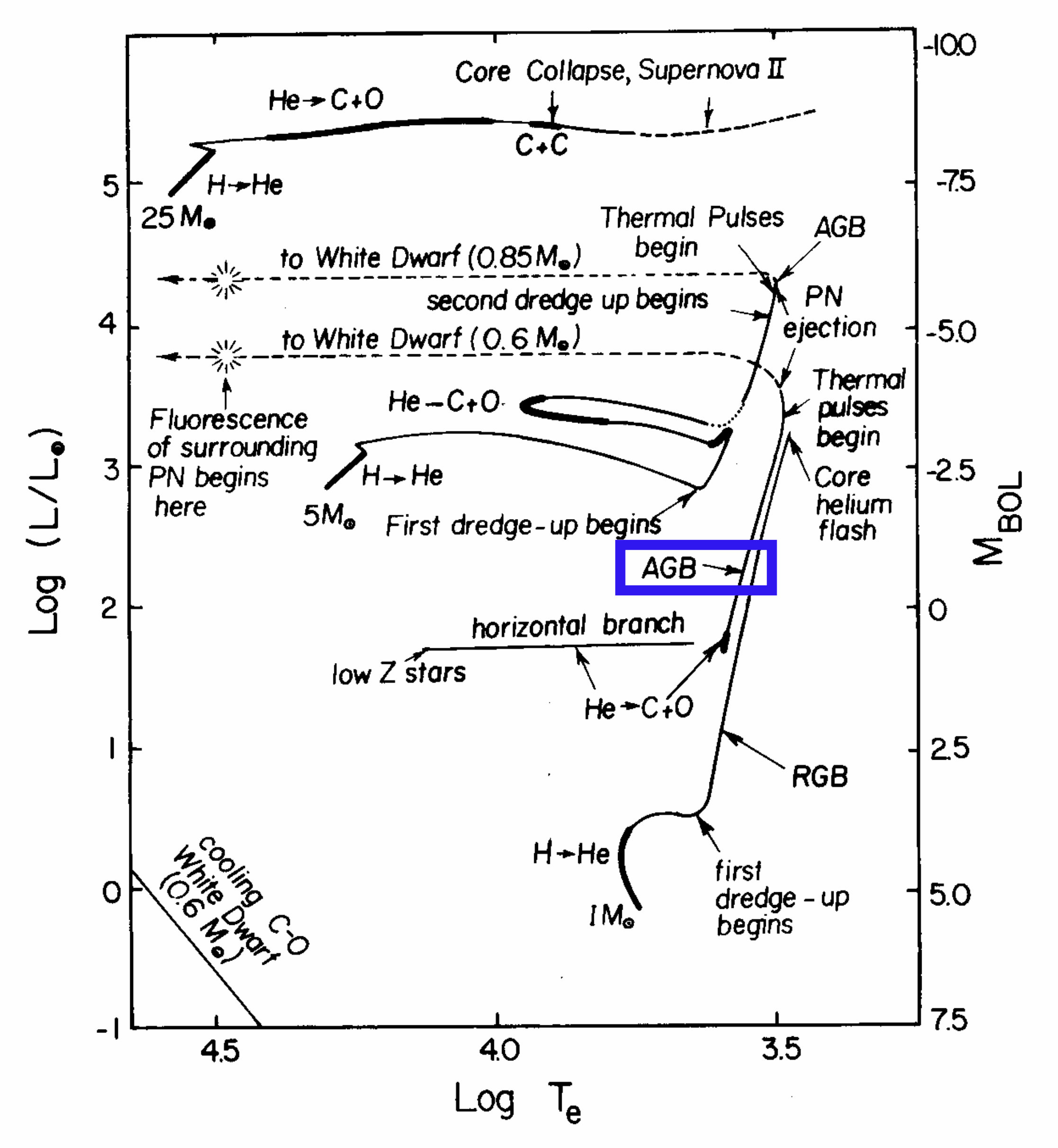
s-process site-s & conditions: main



Thermal pulses
of AGB stars (He-burning shell)

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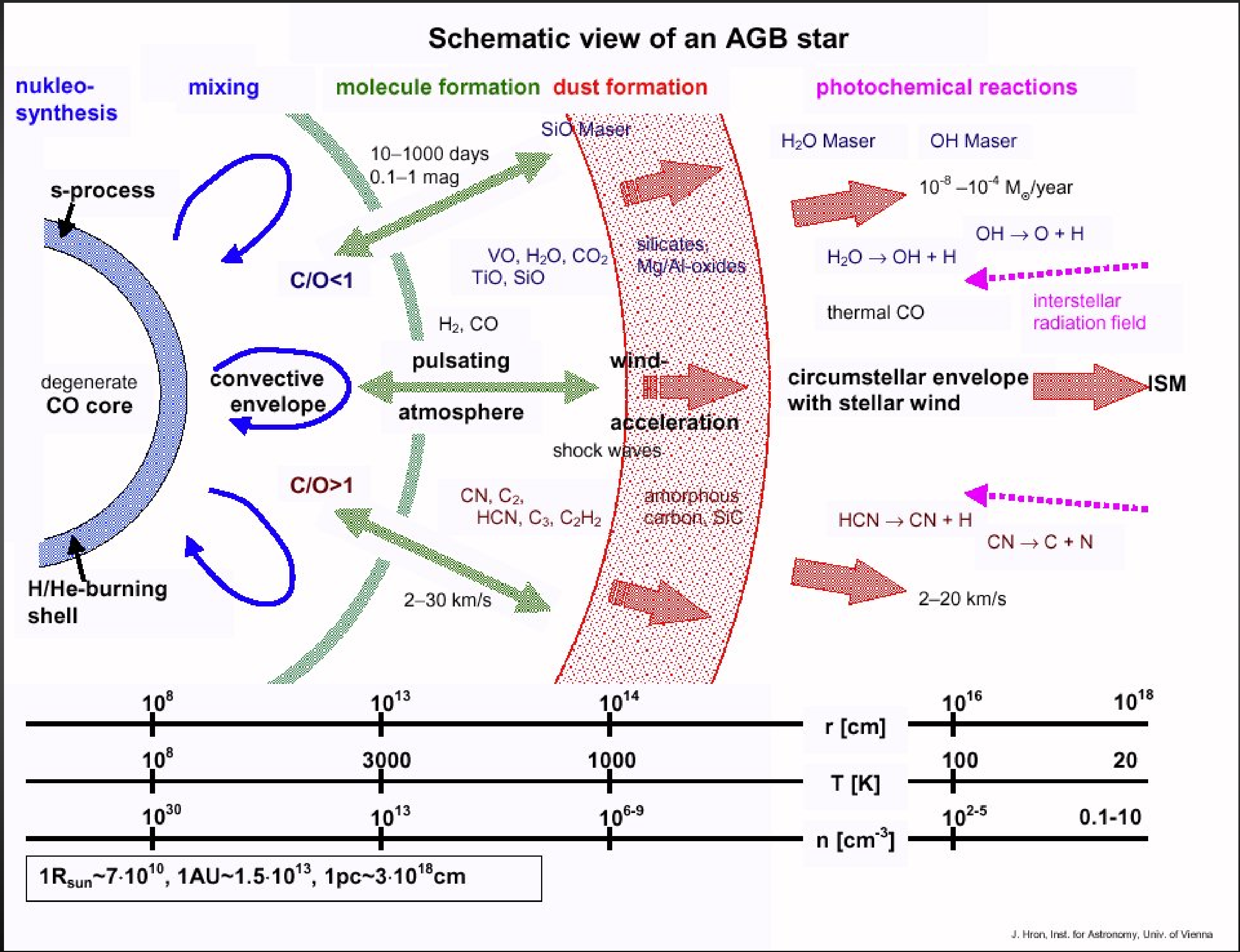
AGB stars

Source: F Erwig



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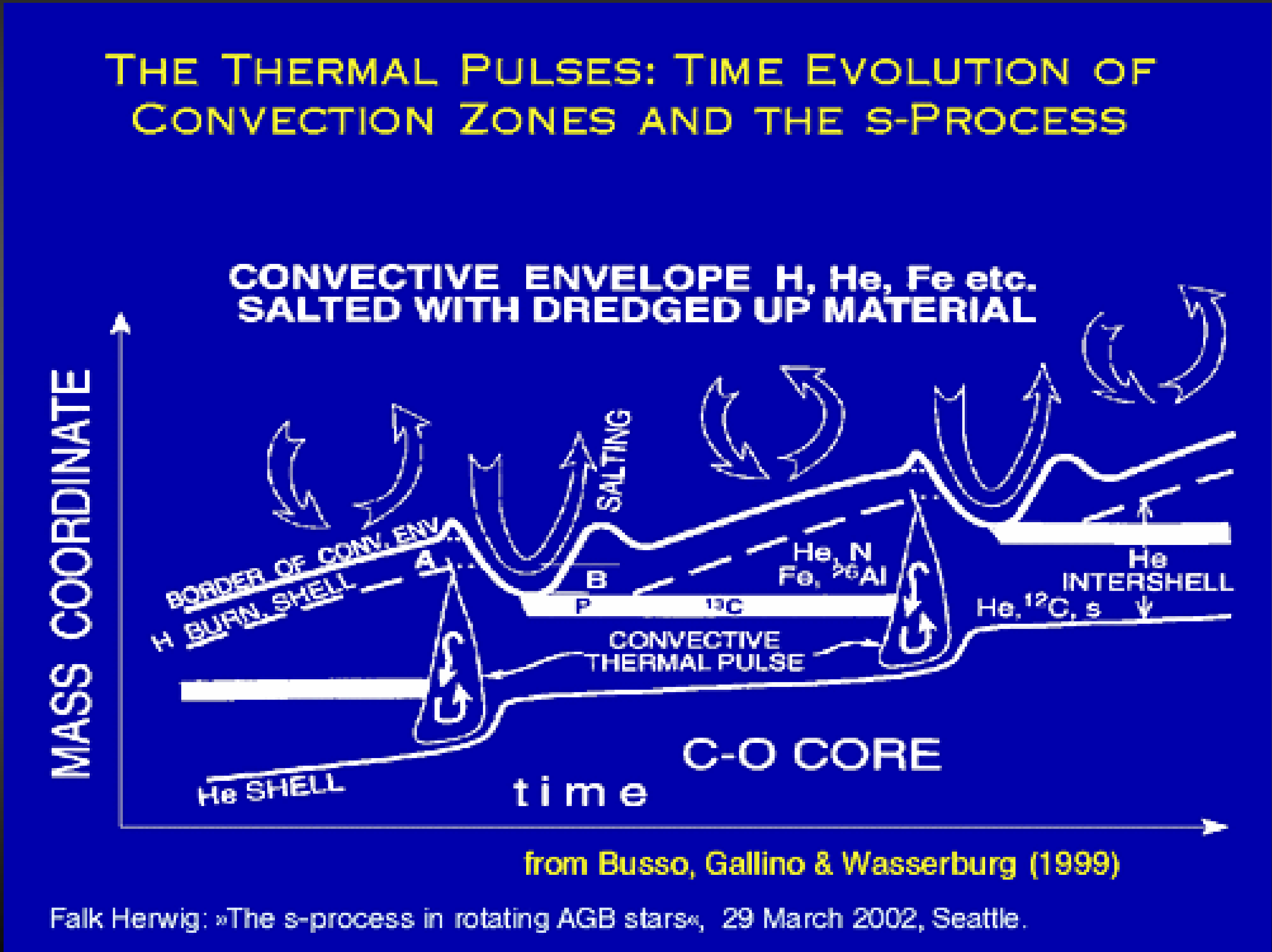
AGB stars: s-processing



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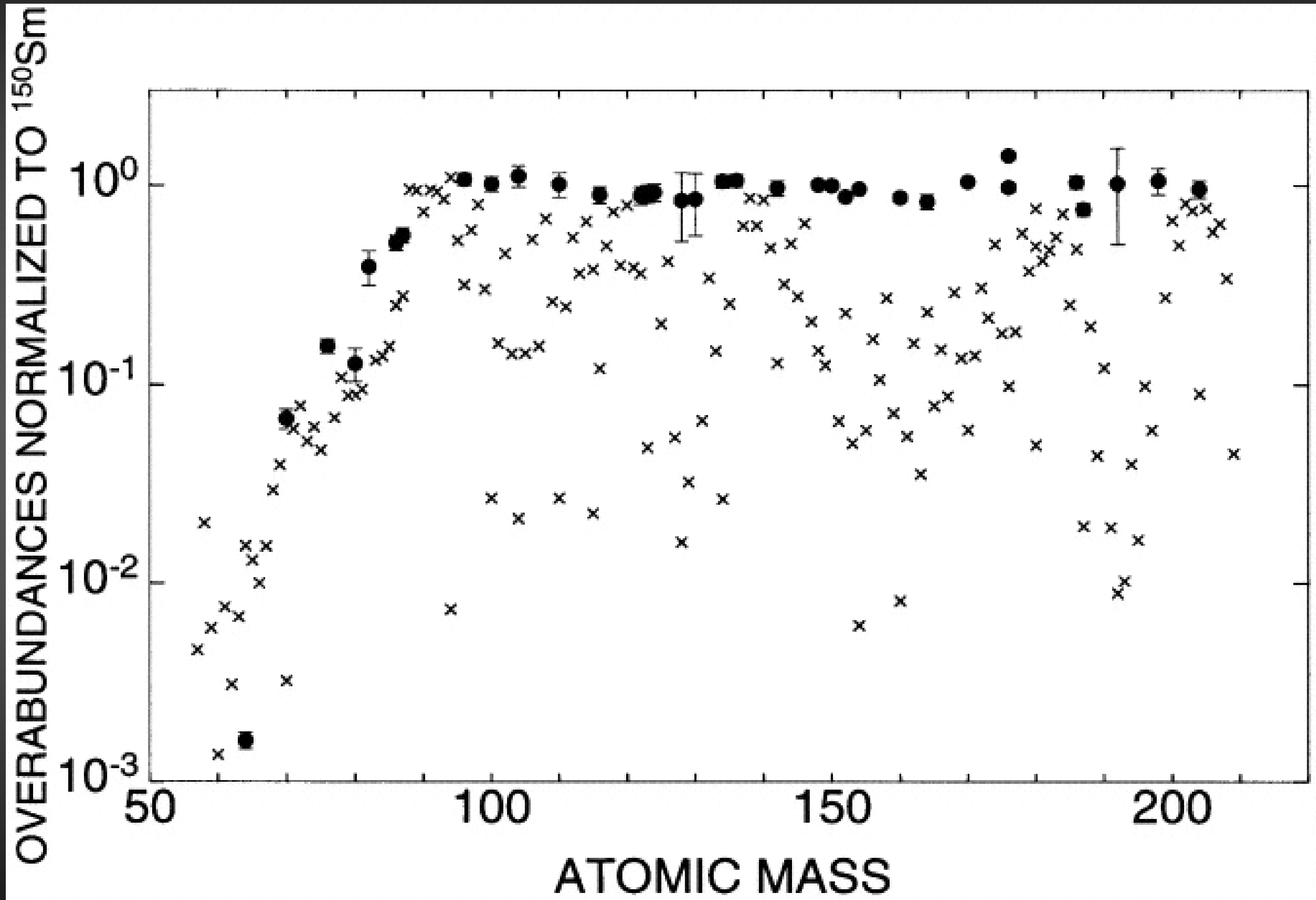
AGB stars: s-processing

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



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

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AGB stars: s-processing

- $M = 2\ M_\odot$
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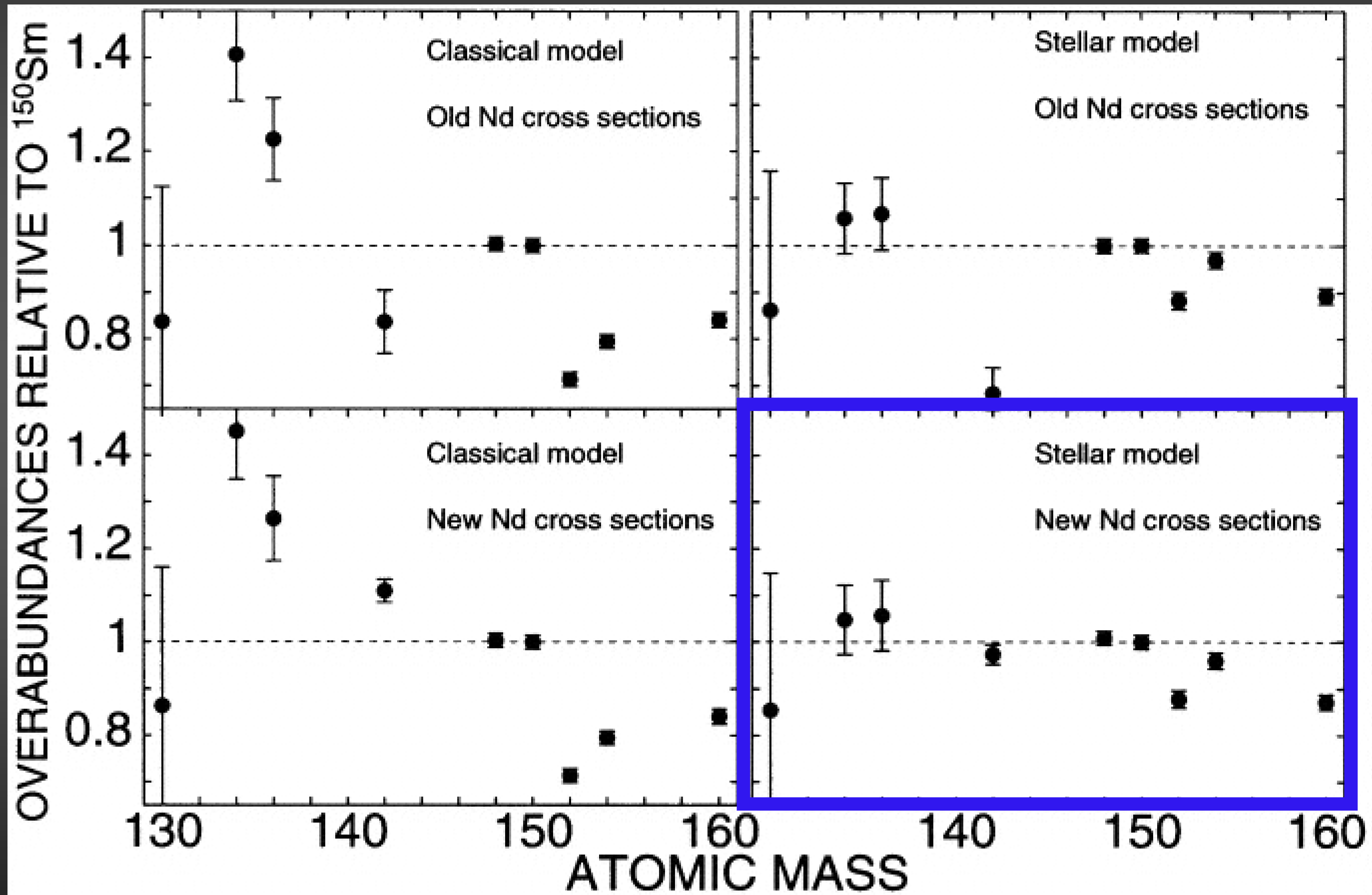

C Arlandini, *et al.:* ApJ 525 (1999) 886

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The canonical s-process

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

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

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) $\lambda_\beta << \lambda_{n,\gamma}$ (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:

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

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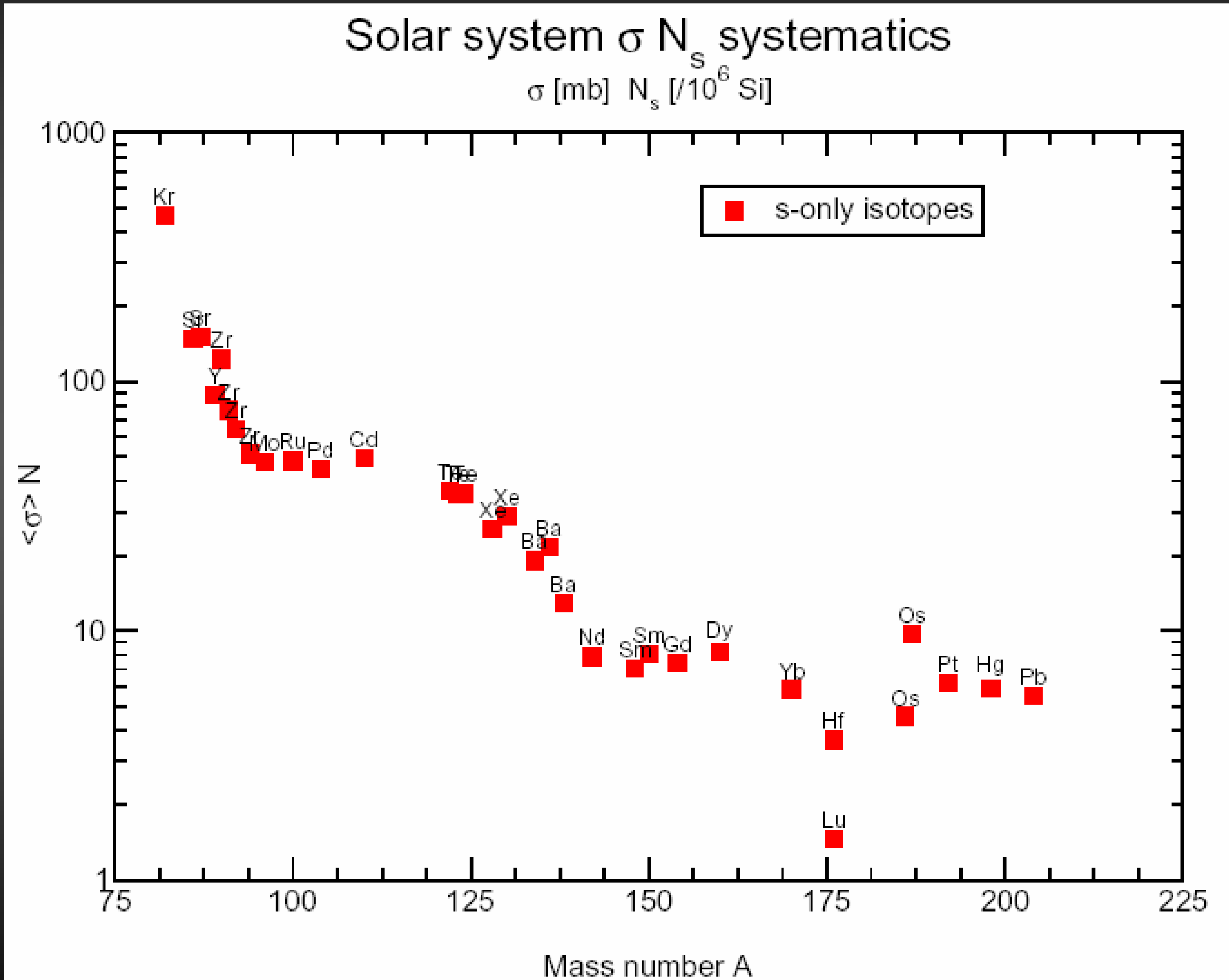
The canonical s-process



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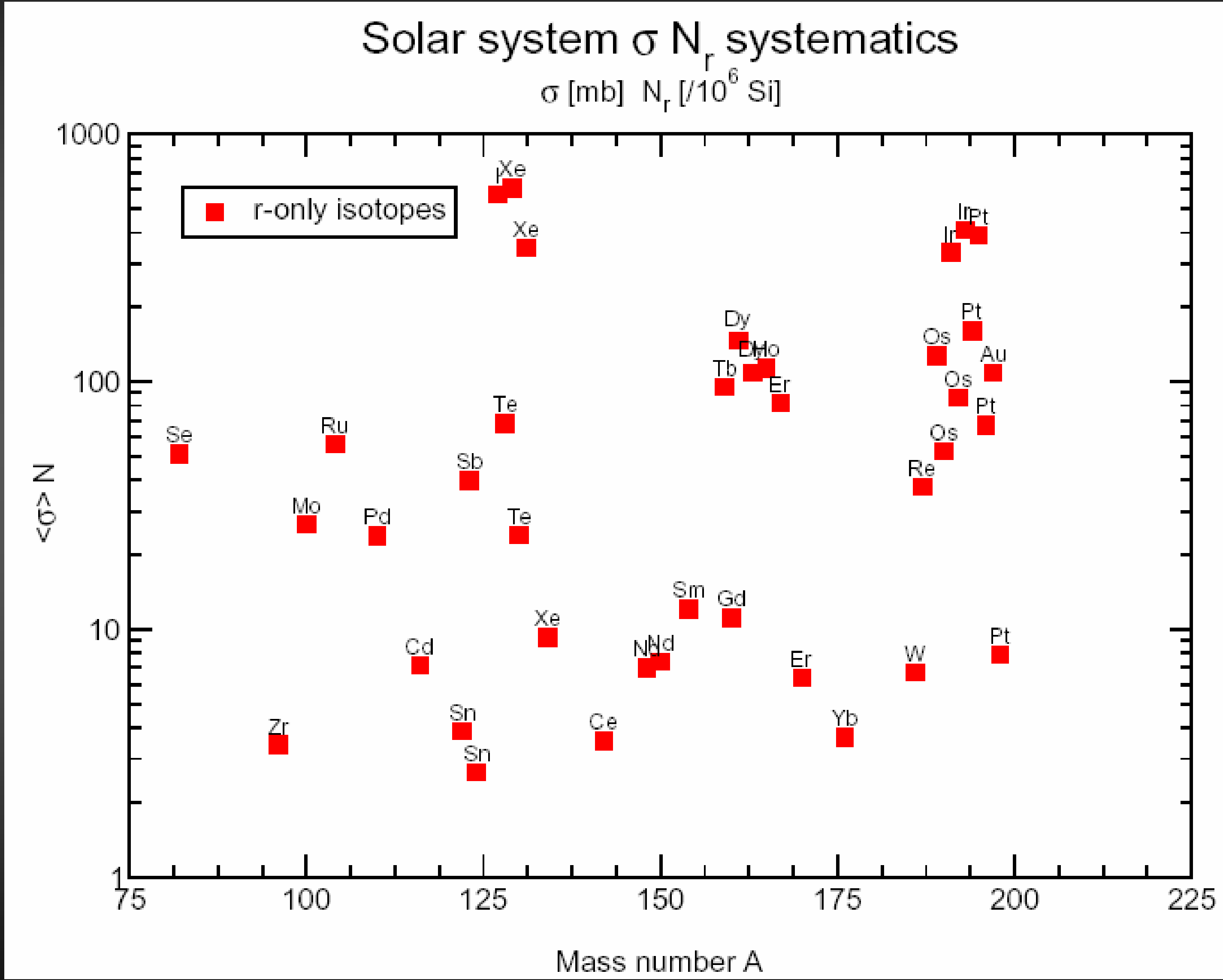
The canonical s-process

No <σ>N correlation observed for nuclei **not** in the s-process path



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The canonical s-process

Assuming an esponential 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

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

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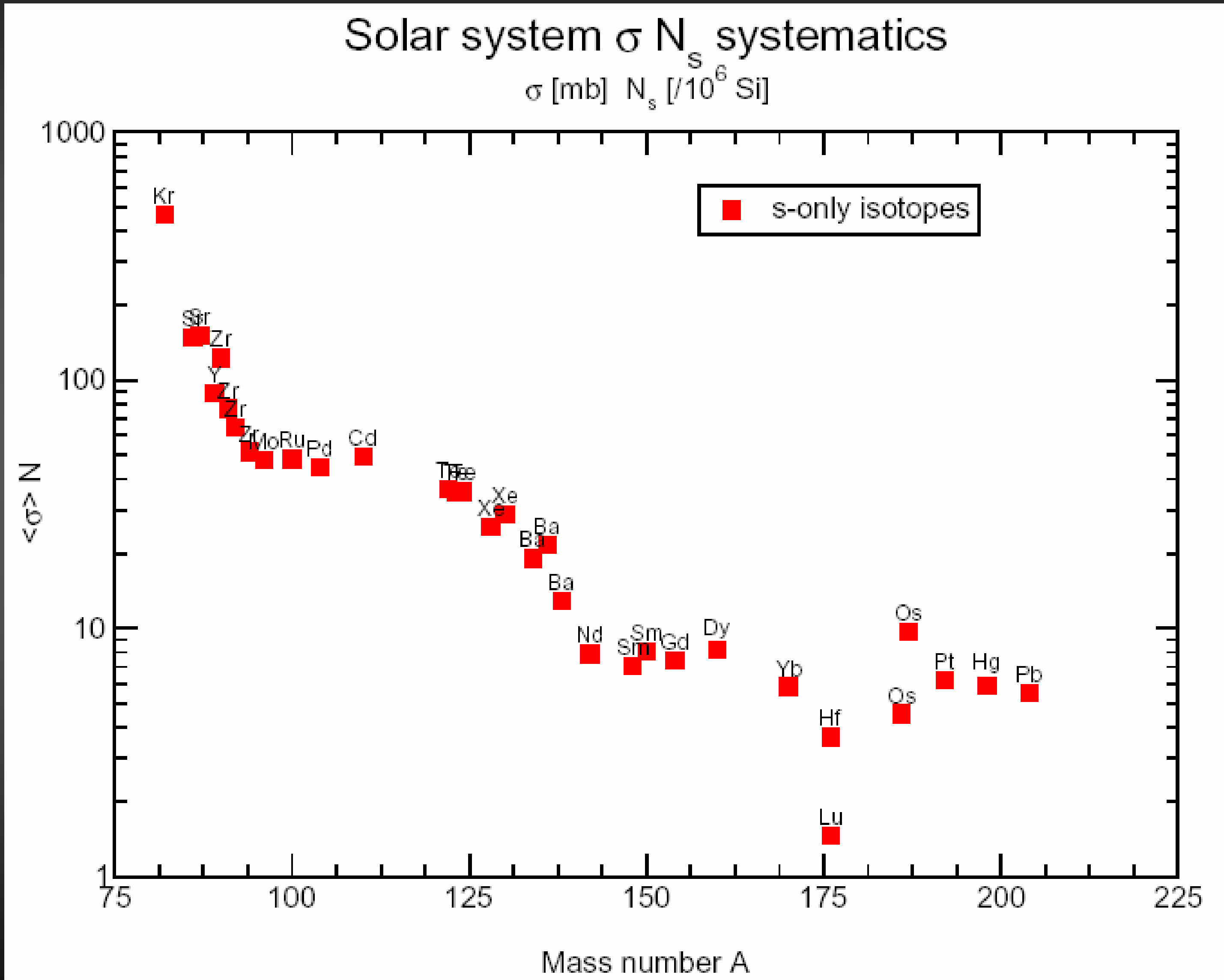
The canonical s-process



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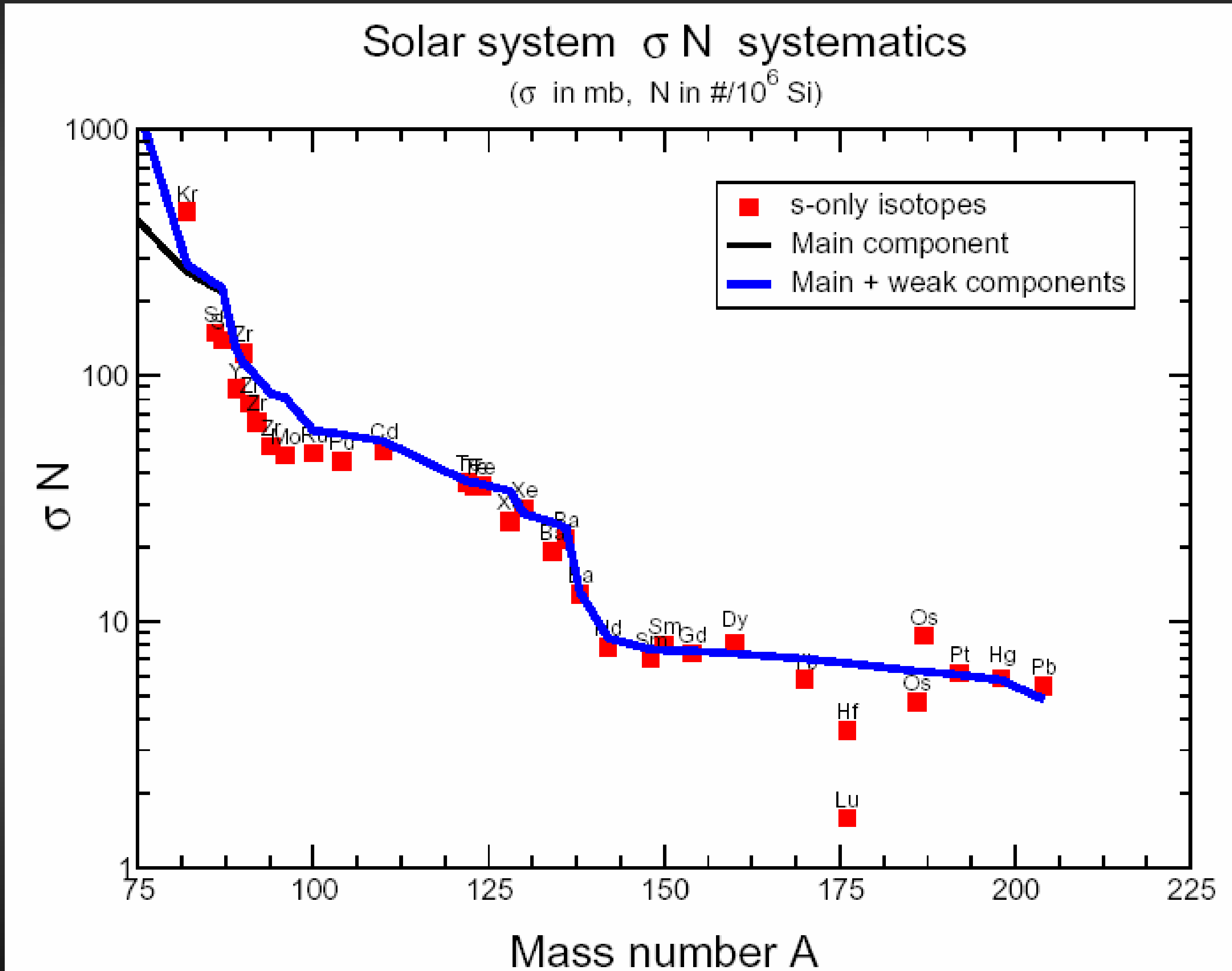
The canonical s-process



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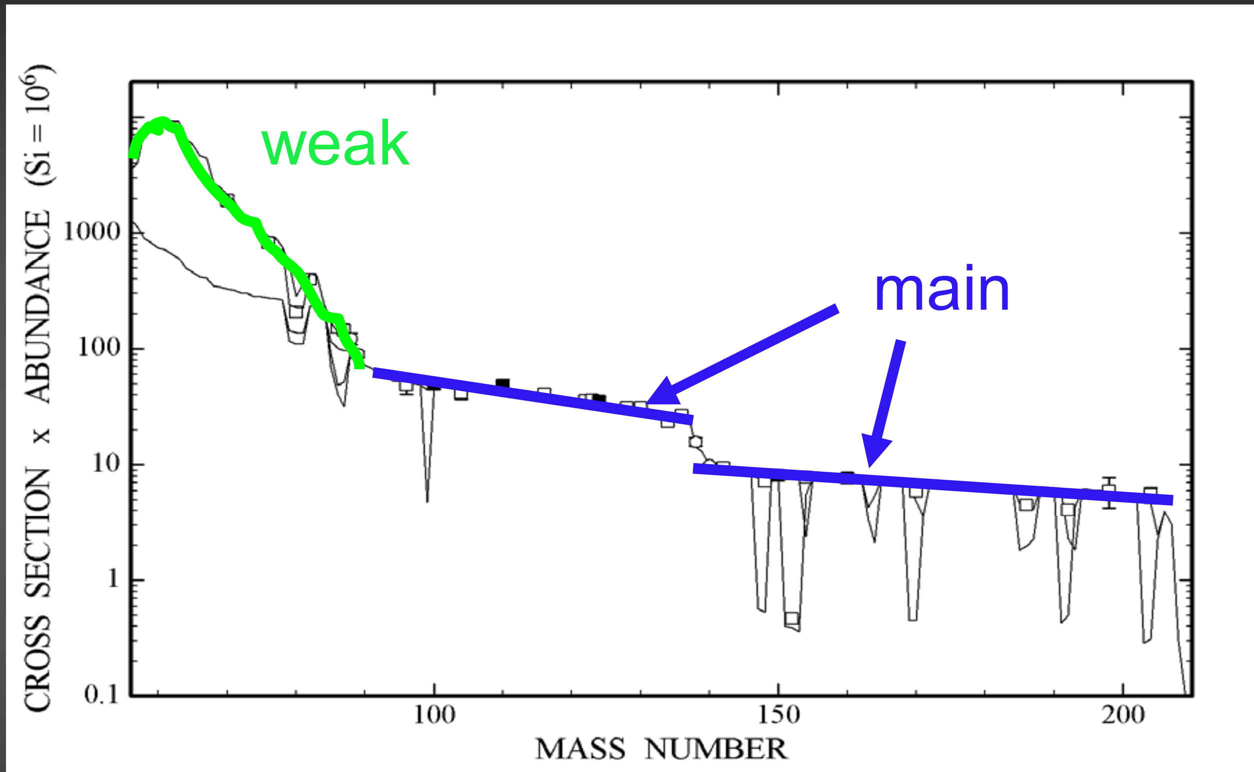
The canonical s-process



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

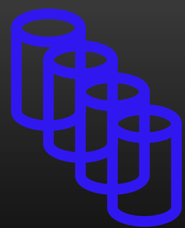
weak: core He burning in massive stars (e.g. 25 solar masses)

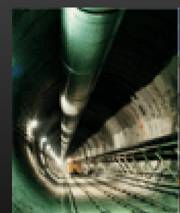
main: He shell flashes in low massTP-AGB stars

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 (≈ 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!

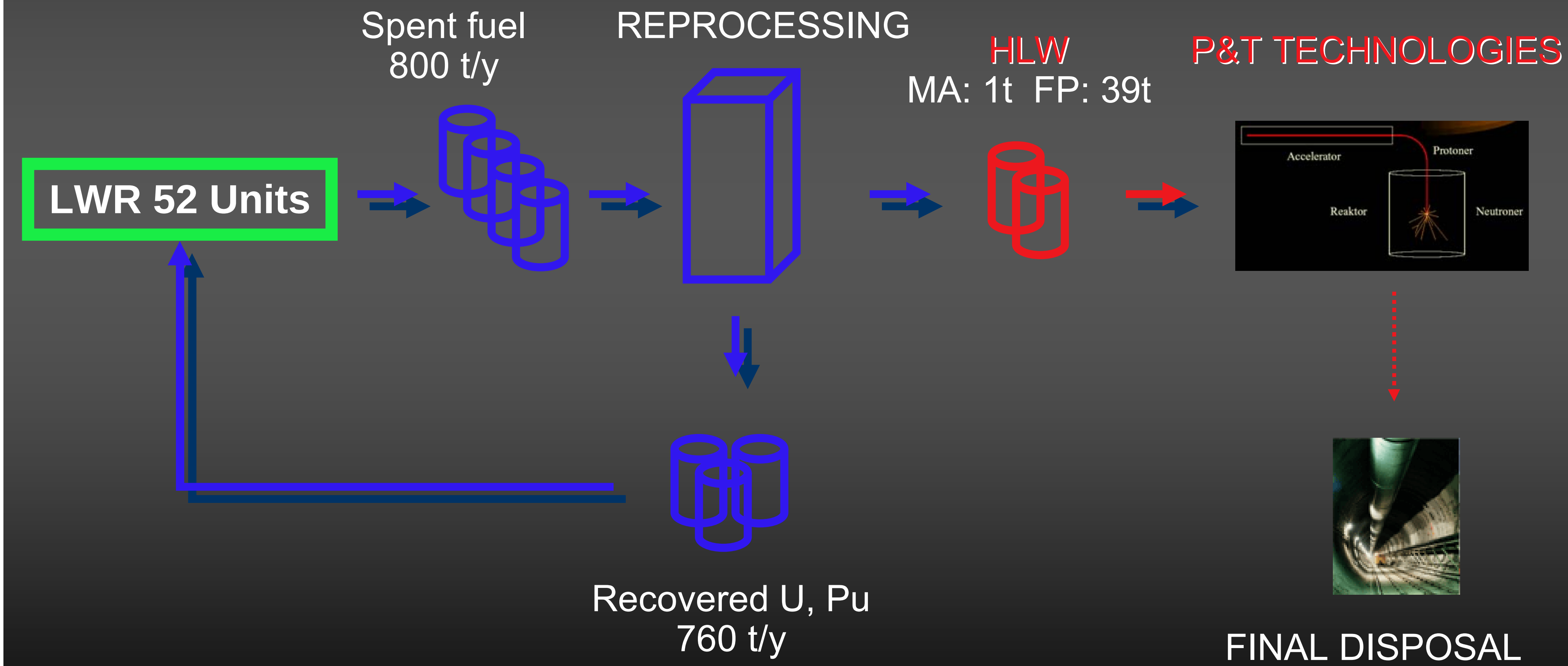
Nuclear power → Spent fuel → Disposal



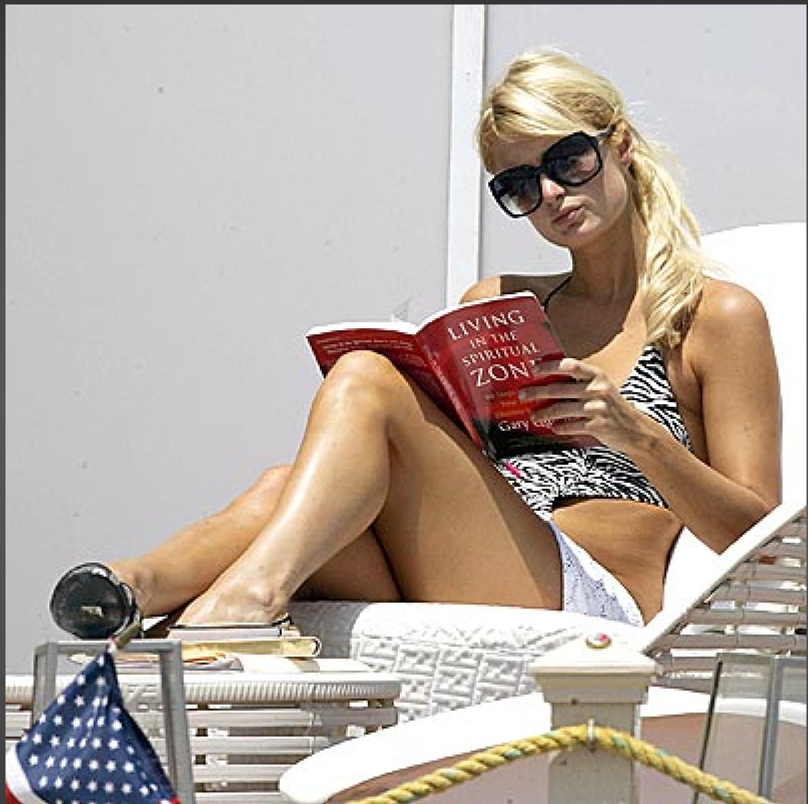


source: C Rubbia

Partitioning and Transmutation (P&T)



Source: Y Oigawa (JAERI)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