



The Abdus Salam
International Centre for Theoretical Physics



1944-27

**Joint ICTP-IAEA Workshop on Nuclear Reaction Data for Advanced
Reactor Technologies**

19 - 30 May 2008

Capture Cross Section Measurements.

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n_TOF/C6D6: present & future

Stefano Marrone

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WORKSHOP on Nuclear Reaction Data for Advanced
Reactor Technologies, Trieste 19-30 May, 2008.

OUTLINE

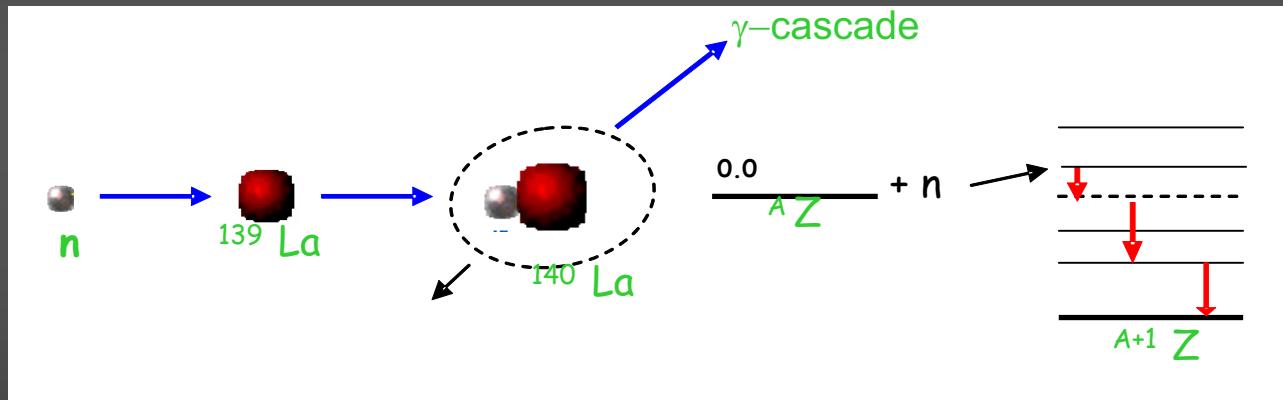
- n_TOF-Phase 1: Capture Results and Implications in Nuclear Astrophysics and Nuclear Technologies.
- Preliminary Results on Photon Strength Function
- n_TOF-Phase 2: Future Perspectives.

The n_TOF Collaboration

n_TOF is a well established collaboration operating since 1999. It is composed of 33 Research Teams and 120 Scientists from Europe, USA, Russia and Japan.

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CAPTURE



Resolved Resonance Region

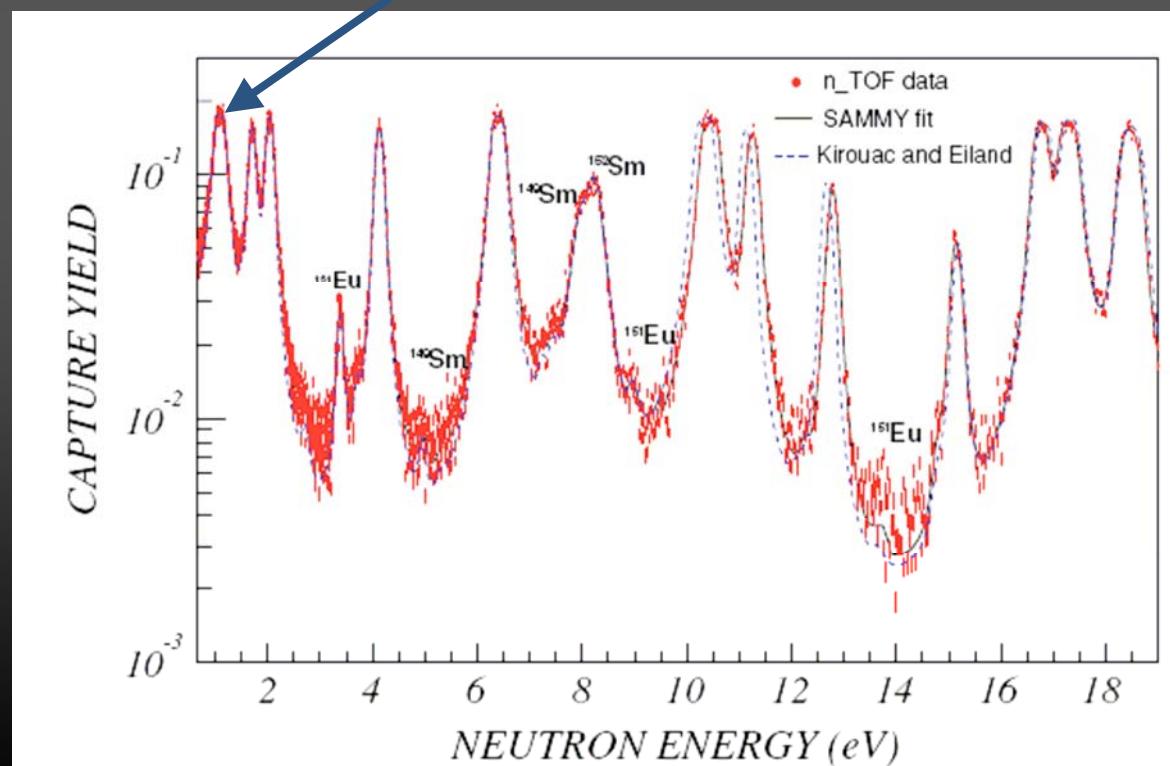
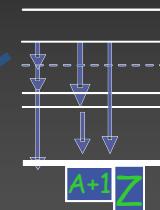
It is possible to resolve each neutron level. The variability of the XS is so high that is impossible to determine a smooth cross section.

In this case the most important information are recorded in the resonance parameters: E_R , Γ_n , Γ_γ and Γ_f .

An example is given by the Single Level Breit-Wigner formula which links the resonance parameters with the XS.

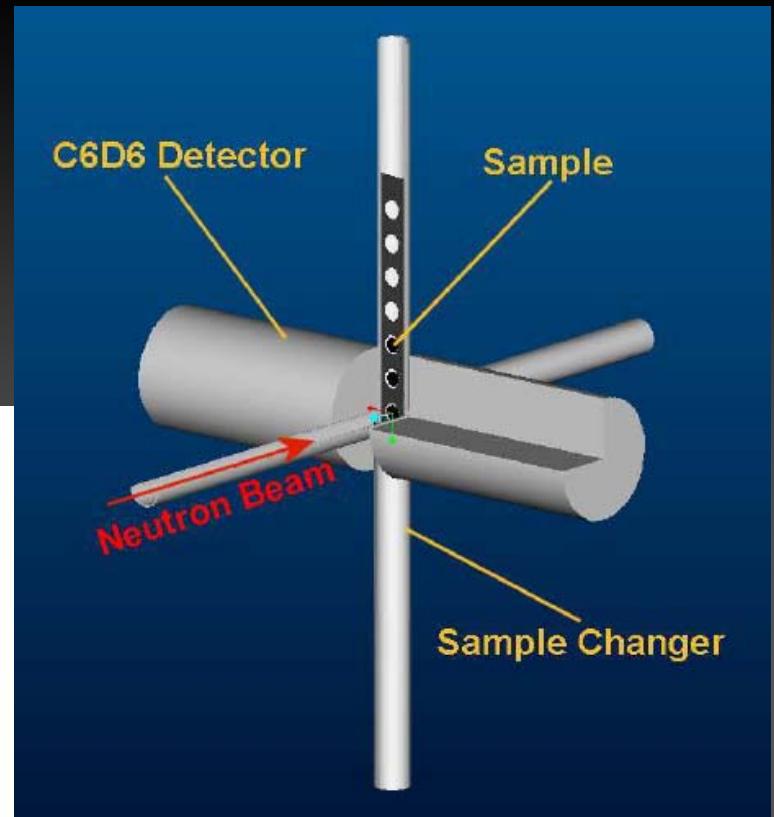
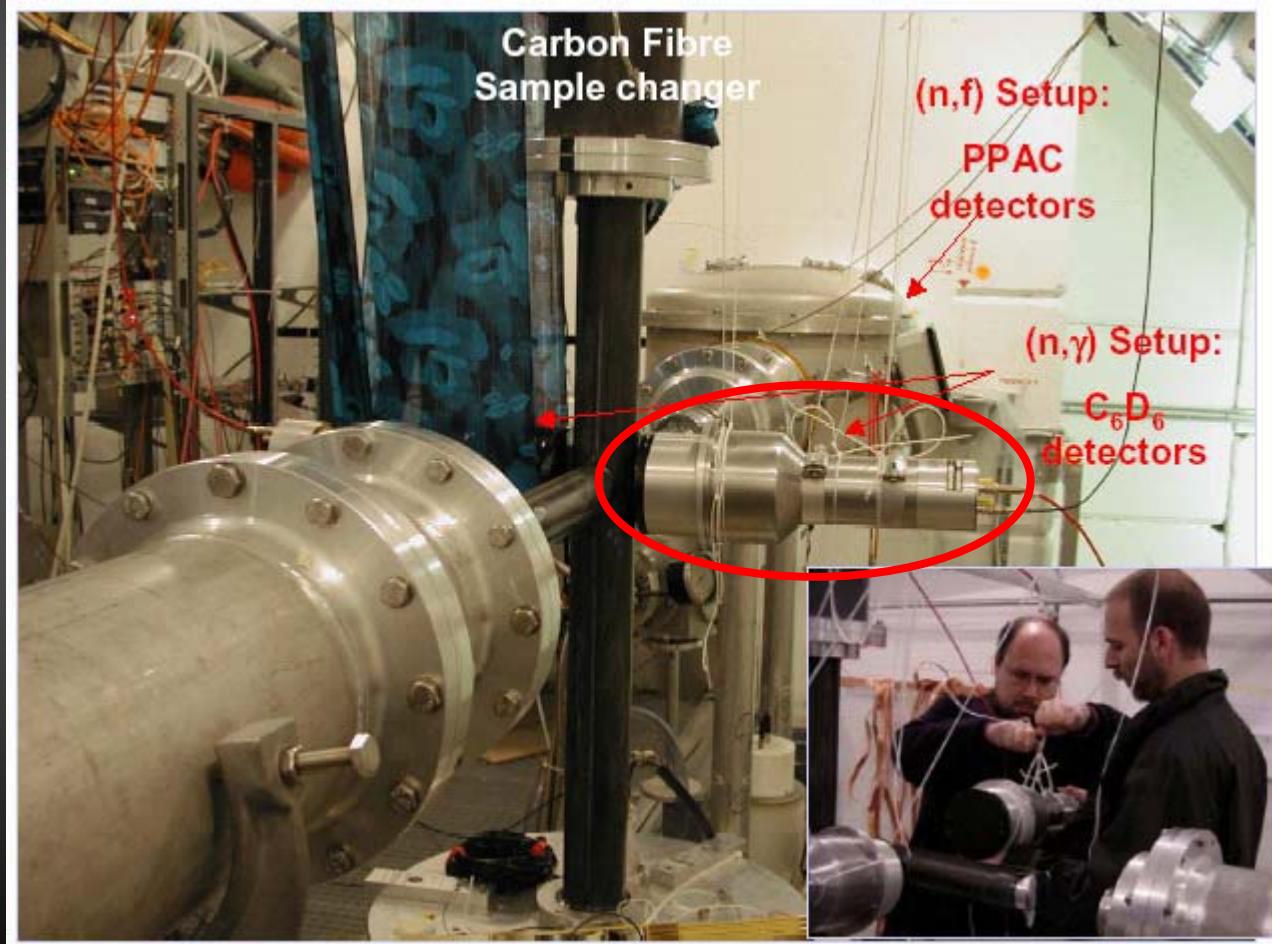
Several Codes like SAMMY and REFIT, fit the experimental data in order to extract the resonance parameters.

$$\sigma_{n,\gamma} = \frac{\pi}{k^2} g_J \frac{\Gamma_n \Gamma_\gamma}{(E - E_R)^2 + \Gamma^2}$$



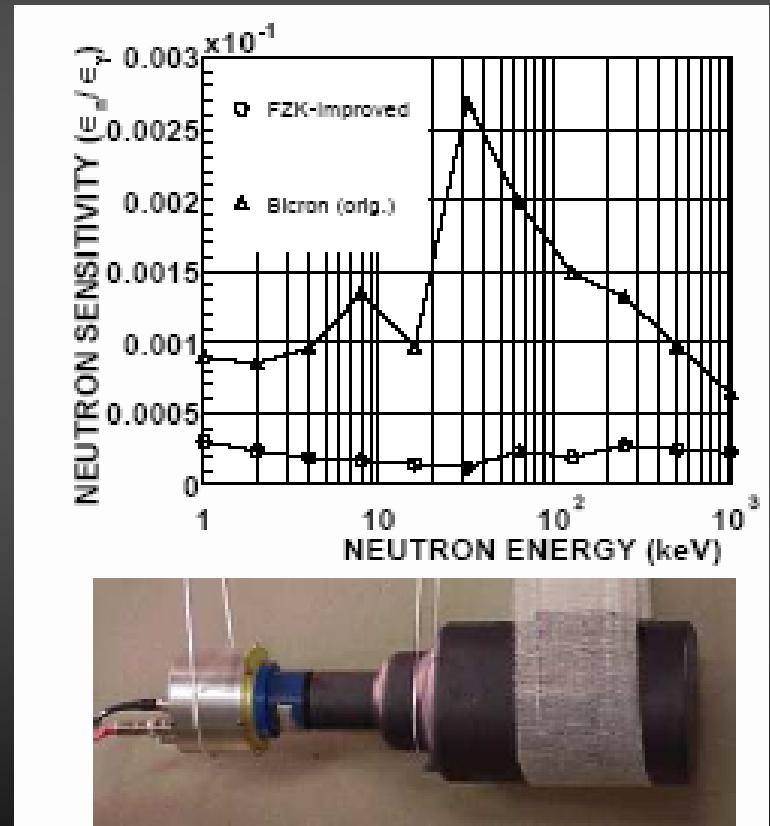
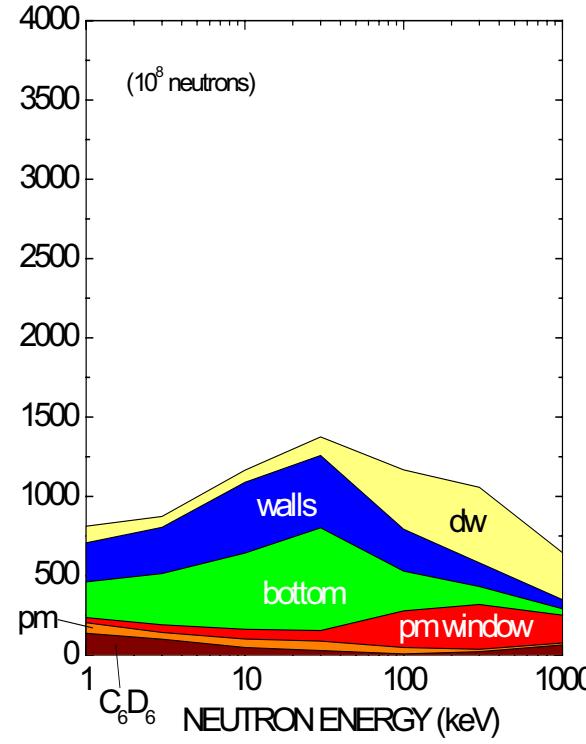
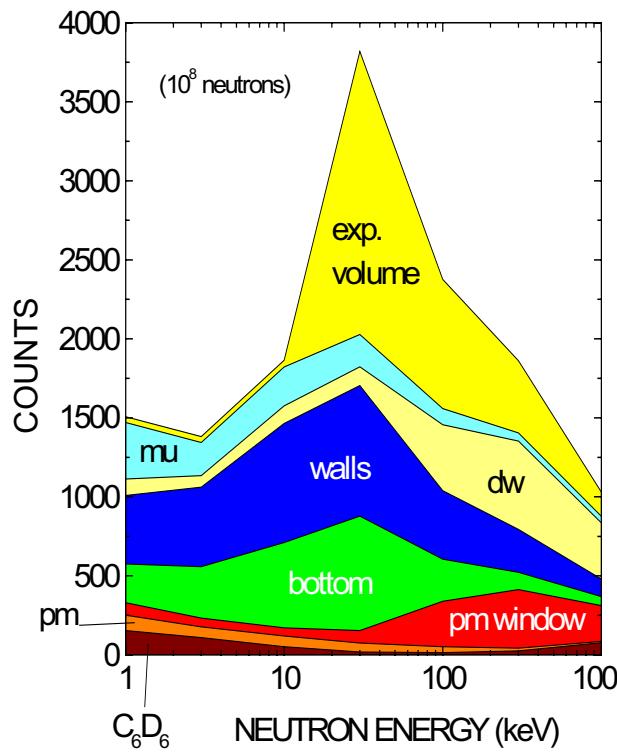
The real world

- n_TOF commissioned in 2001-2002



Zr, Pb, and Bi: background problems

Neutron sensitivity of commercial C_6D_6 detector improved very much with the detector assembled at FZK.
Carbon Fiber instead of Al can.



EFFICIENCY in C₆D₆

- The problem in the efficiency correction is the γ -cascade (multiplicity and energy).
- In BaF₂ 4 π calorimeter it is detected the whole cascade;
- In the C₆D₆ it is used the PHWF;
- This technique consists of modify the Response function of C₆D₆ through simulations (Geant-3 and Geant-4) to verify:
$$\varepsilon_{\gamma} = \text{const} \cdot E_{\gamma};$$
- This technique is reliable only if the total efficiency is very small (one γ detected);

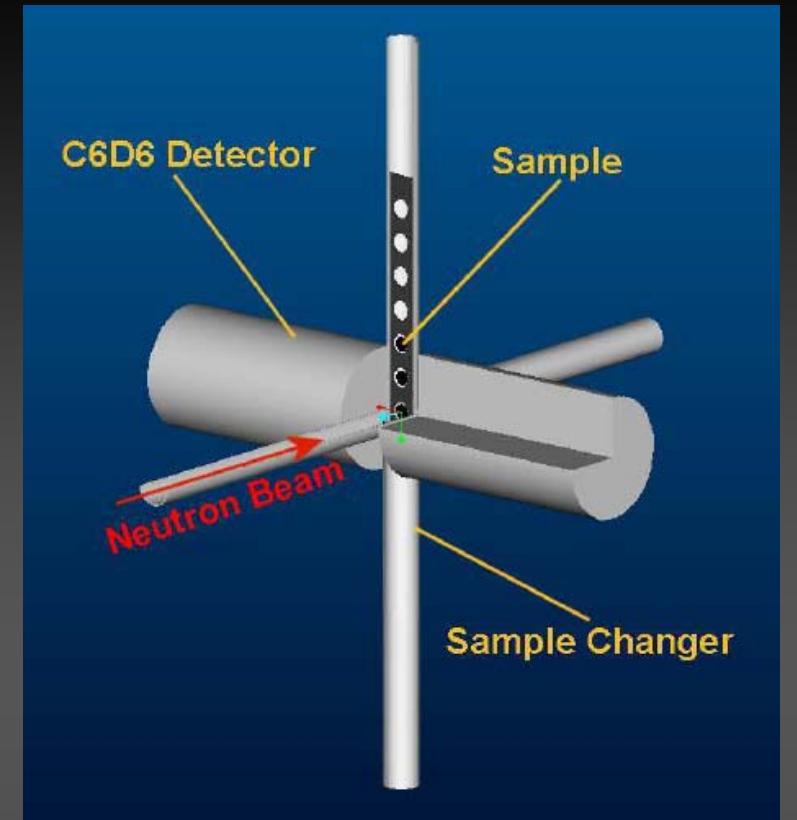
 Ref. Abbondanno et al. NIM A, 521, 454.

 Ref. Borella et al. NIM A, 577, 626.

The Raw Capture Yield is estimated according to the following equation:

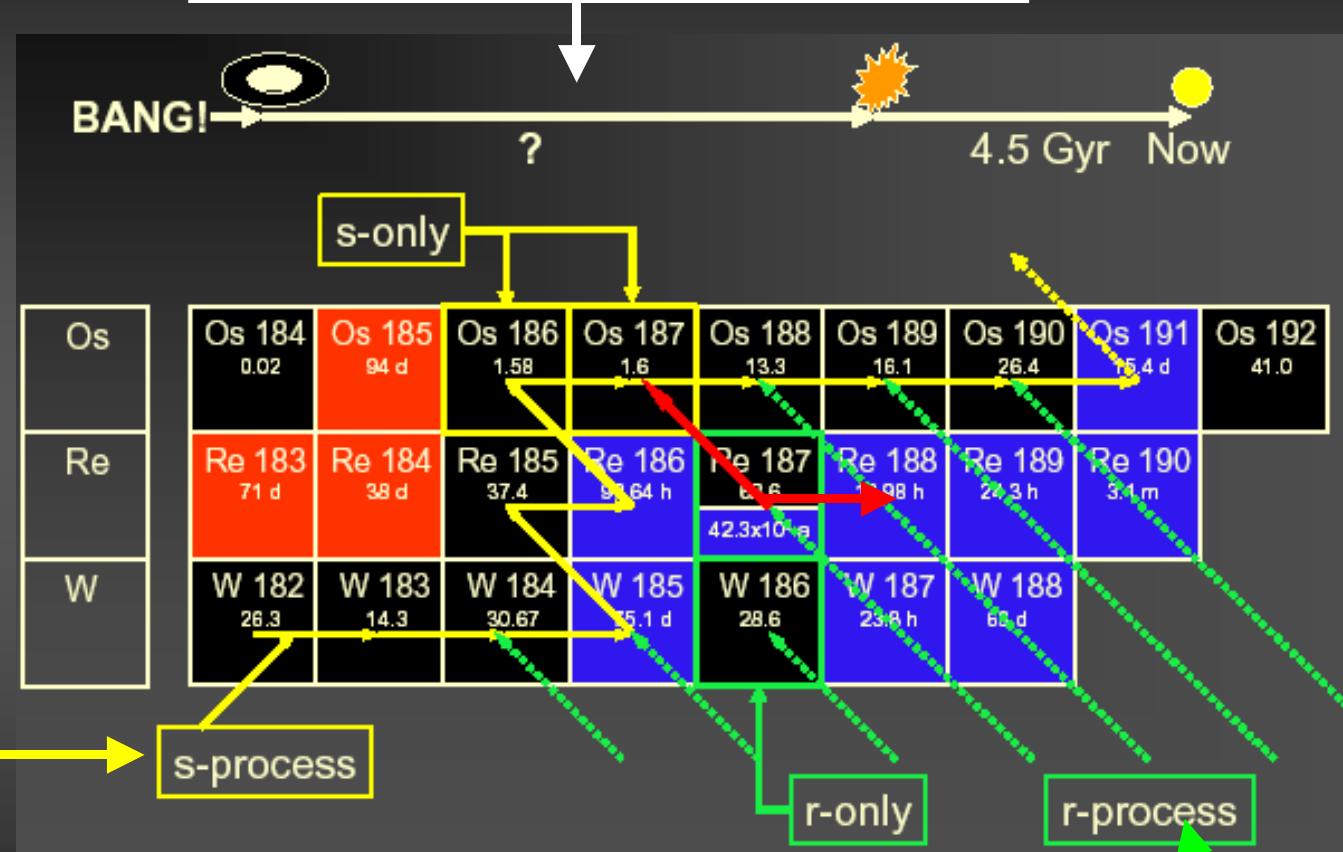
$$Y_{Raw}(E_n) = \frac{\sum_i R_i W_i}{E_{binding} \cdot \Phi(E_n)}$$

- $\sum_i R_i W_i$ number of weighted counts per bunch (SiMon) at E_n ;
- $E_{binding}$ capture energy for the sample under investigation;
- $\Phi(E_n)$ number of neutrons impinging on the sample.



Nuclear Astrophysics

Re/Os cosmo-chronometer



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

Residual Method

n_TOF experiments: Zr isotopes

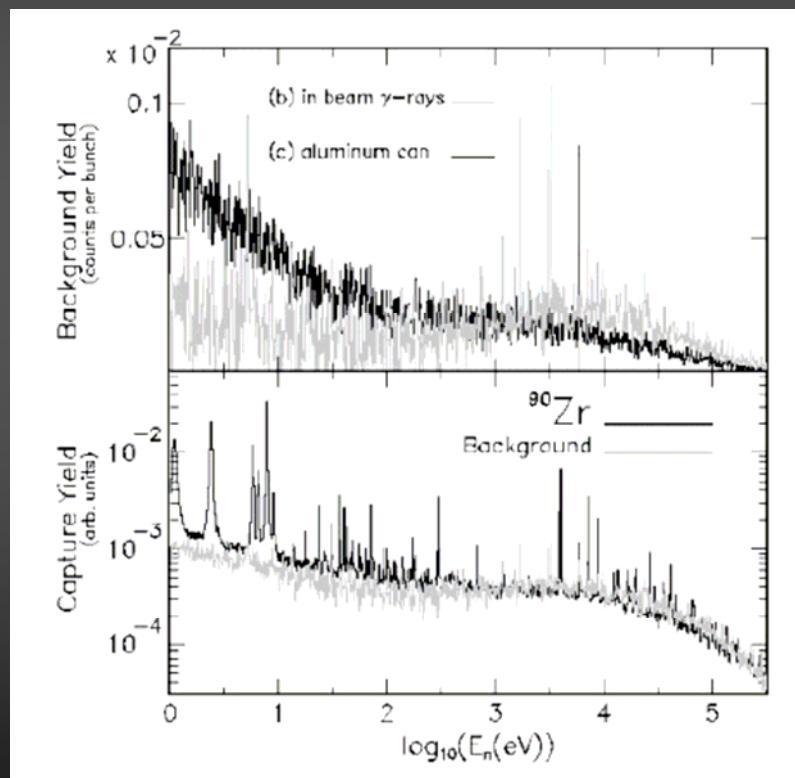
Zirconium Alloy is important for several components of Nuclear Reactors. The reason is because is corrosive resistant also at high temperatures.

Zirconium is important also for fuel composition. TRIGA reactor at ENEA Casaccia uses U-Zr-H fuel.

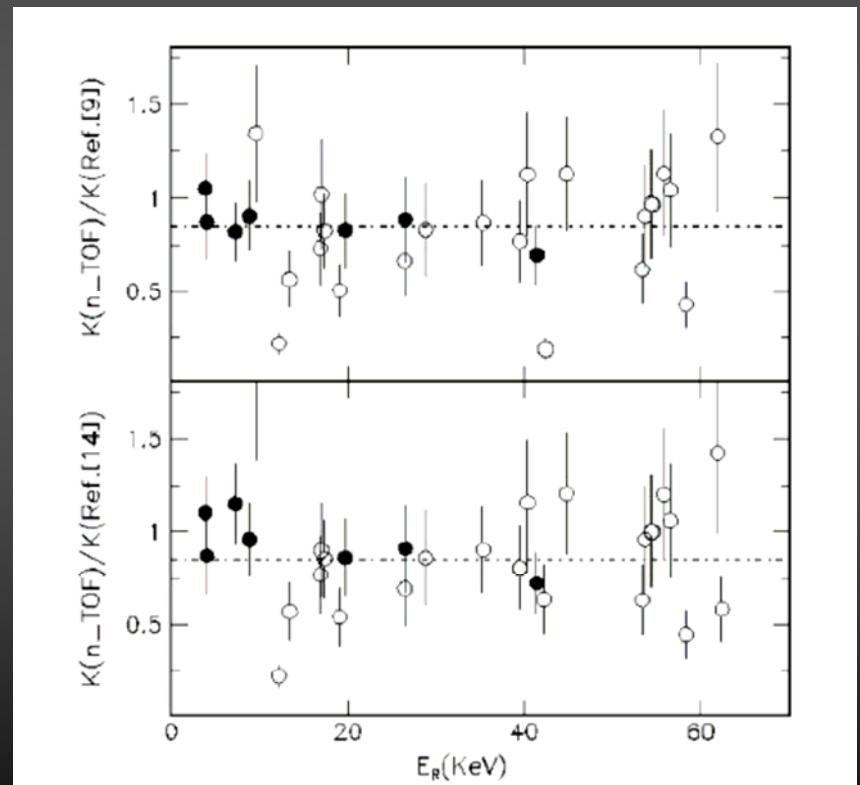
In '80 years 80% of Zr production was dedicated to the construction of Nuclear Reactors (Source American Society of Testing Materials).

n_TOF experiments

C Moreau, et al. - The n_TOF Collaboration
ND2004 Conference, Santa Fe, NM – September 2004
G. Tagliente et al. PRC 77 (2008)



$$K = g \frac{\Gamma_n \cdot \Gamma_\gamma}{(\Gamma_n + \Gamma_\gamma)},$$



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}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

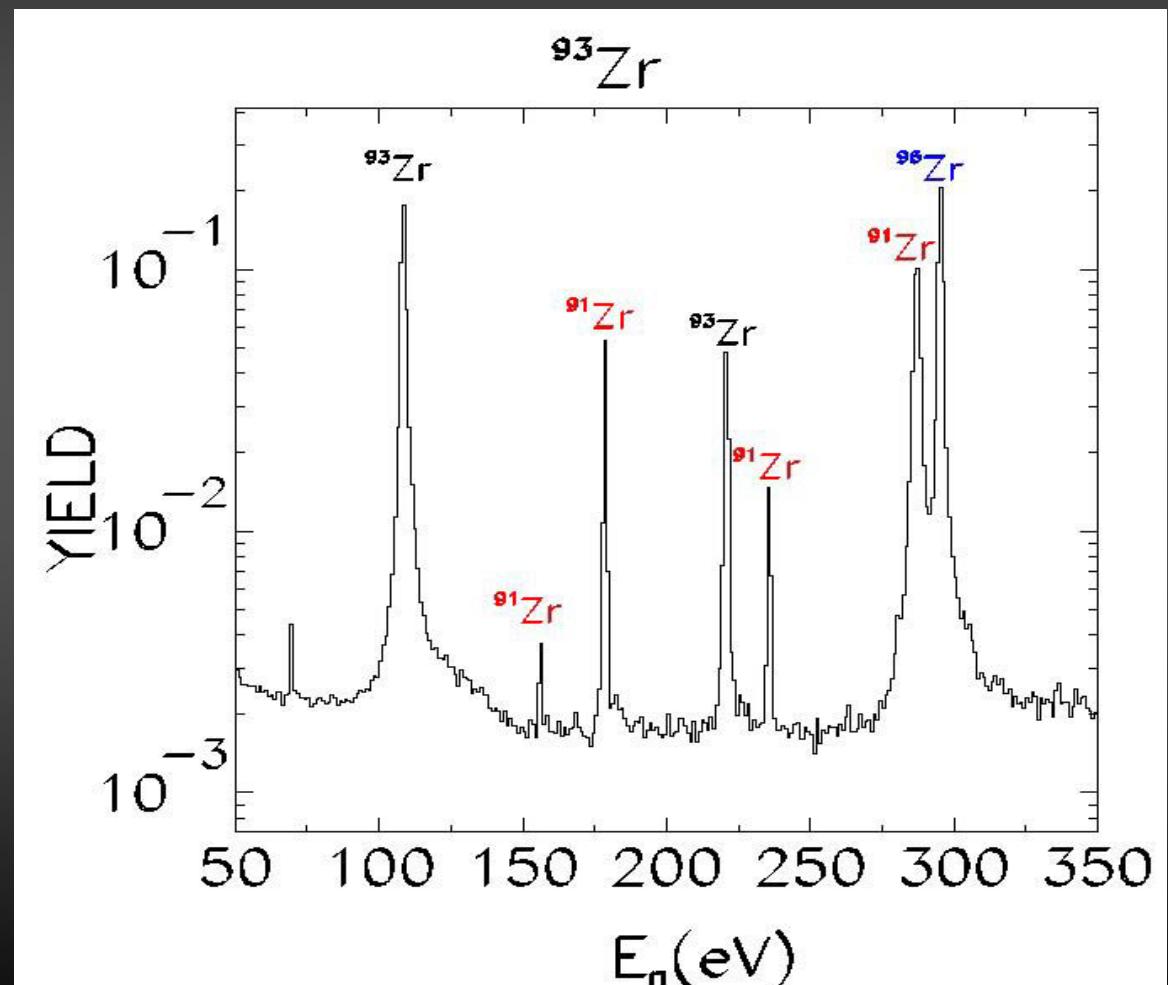
^{237}Np

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



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

$^{93}\text{Zr}: 92.6 \cdot 10^6 \text{ y}$
 $^{93}\text{Zr}(n,\gamma)$ raw data

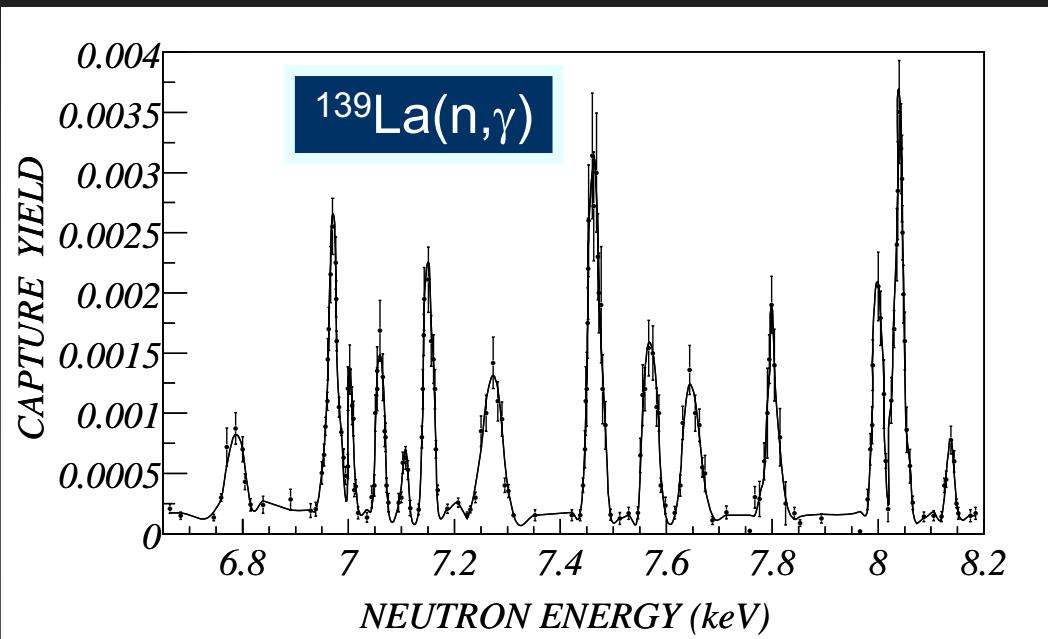


The **$n_{\text{-}}\text{TOF}$** Collaboration

$n_{_}$ TOF experiments: $^{139}\text{La}(n,\gamma)$

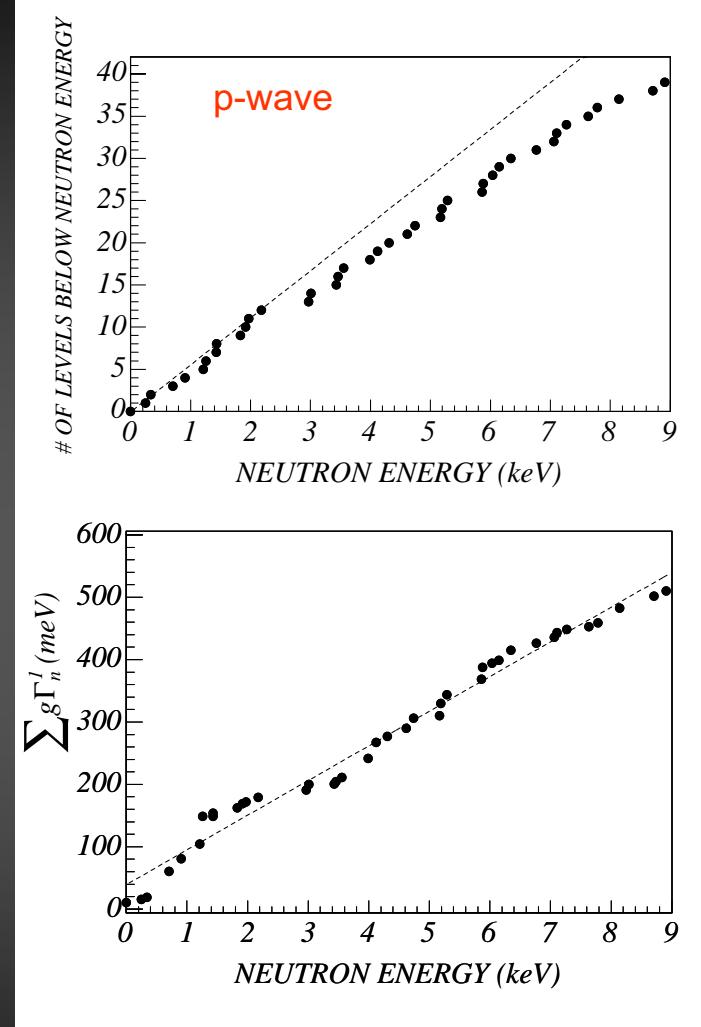
- Used as a Monitor of Neutron Flux in High radiation environment together with other isotopes (e.g. Cd and Au);
- Lanthanum is added to MA to stabilize the fuel (Mechanical and Thermal Properties) and it is used in samples to perform cross section measurements.
- It is one of the most abundant Fission Product produced in Thermal Reactors (~5%).
- Lanthanum is almost monoisotopic (^{140}La is 0.1%).

$n_{\text{-TOF}}$ experiments: $^{139}\text{La}(n,\gamma)$



Remarkable energy resolution and background conditions have allowed the determination of 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
 $\langle D_0 \rangle = 252 \pm 22$ eV
 $S_0 = (0.82 \pm 0.05) \times 10^{-4}$ $S_1 = (0.55 \pm 0.04) \times 10^{-4}$



R Terlizzi, et al. PRC 57.

n_TOF experiments: Pb and Bi

- ADVANTAGES
 - SODIUM is chemically very REACTIVE;
 - Pb-Bi boiling point (1670 °C) is higher than sodium (883 °C);
 - Heavy elements absorb better the radioactivity, especially γ -rays.
- DISADVANTAGES
 - Corrosion of Structural Materials
 - High density and small size reactors limits the safety from the seismic point of view;
 - Radioactivity and Contamination from Po isotopes.

n_TOF experiments: Pb and Bi

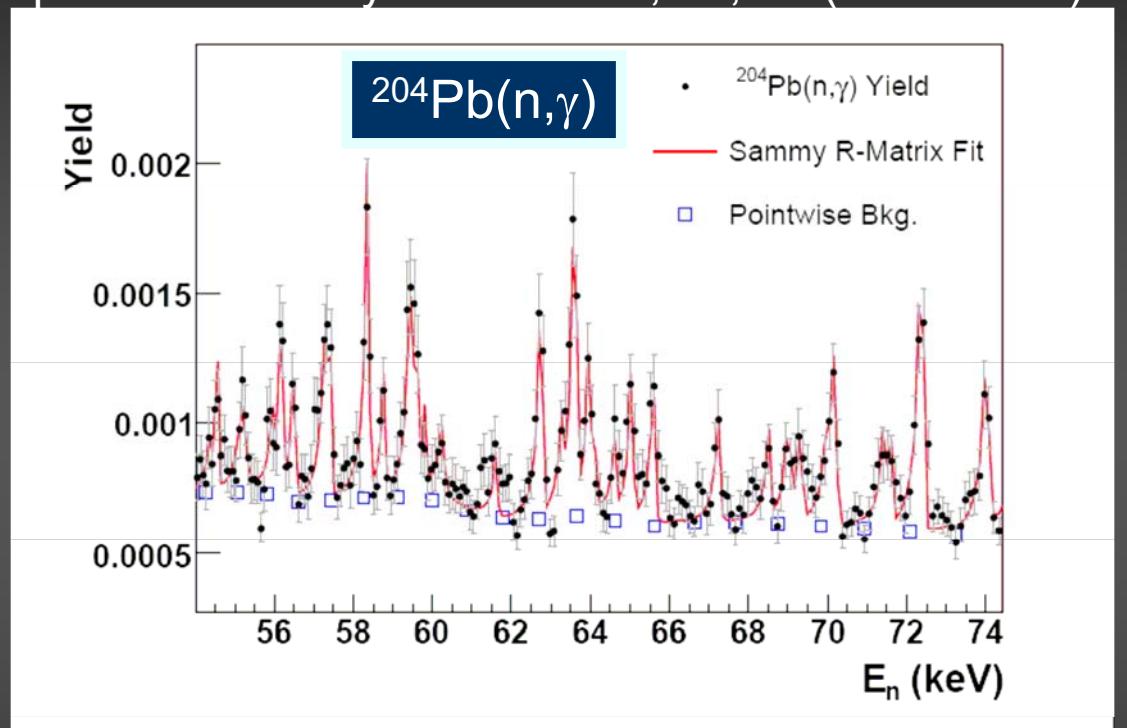
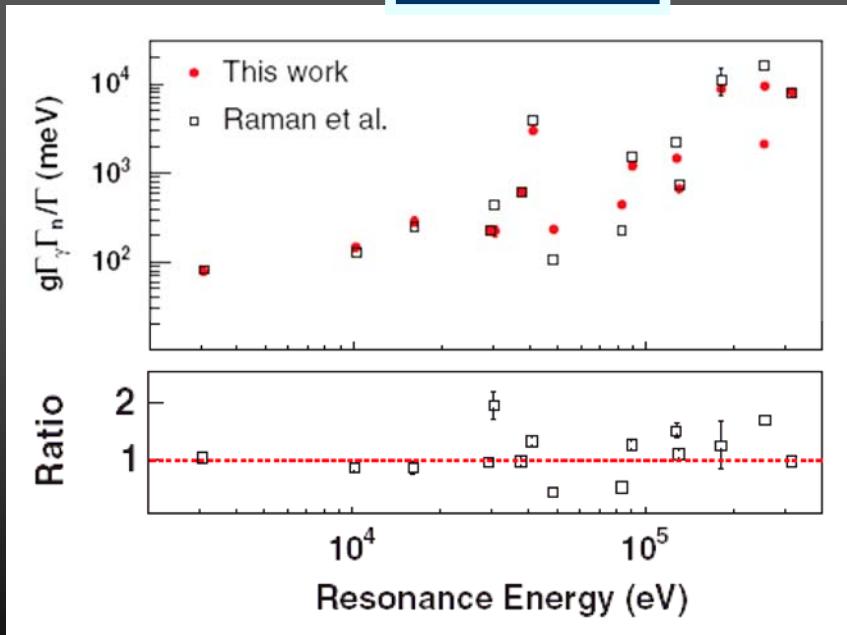
Very large energy neutron region to detect the neutron levels.

C Domingo-Pardo, et al. (The n_TOF Collaboration)

Very accurate determination of the resonance width.

At low neutron energy, the resonance levels are in agreement with the previous measurements.

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



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

$n_{\text{-}}\text{TOF}$ experiments: Pb and Bi

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

C Domingo-Pardo, et al. (The $n_{\text{-}}\text{TOF}$ Collaboration)
Phys. Rev. C 74, 025807 (2006)

NEW MEASUREMENT OF NEUTRON CAPTURE . . .

PHYSICAL REVIEW C 74, 025807 (2006)

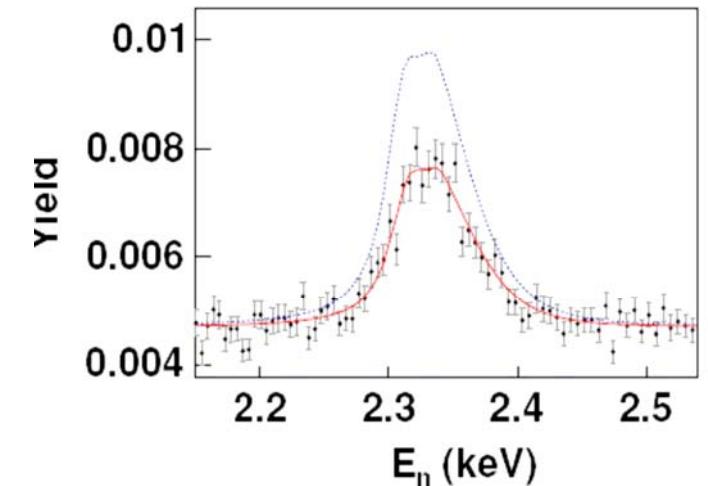
TABLE II. Resonance parameters^a and radiative kernels^b for ^{209}Bi .

E_{ν} (eV)	l	J	Γ_n (meV)	Γ_{γ} (meV)	$g\Gamma_{\gamma}\Gamma_n/\Gamma$ (meV)
801.6(1)	0	5	4309(145)	33.3(12)	18.2(6)
2323.8(6)	0	4	17888(333)	26.8(17)	12.0(8)
3350.83(4)	1	5	87(9)	18.2(3)	9.5(2)
4458.74(2)	1	5	173(13)	23.2(22)	11.3(11)
5114.0(3)	0	5	5640(270)	65(2)	35.3(11)
6288.59(2)	1	4	116(18)	17.0(17)	6.7(7)
6525.0(3)	1	3	957(100)	25.3(14)	8.6(5)
9016.8(4)	1	6	408(77)	21.1(14)	13.0(9)
9159.20(7)	1	5	259(45)	21.4(21)	10.9(11)
9718.910(1)	1	4	104(22)	74(7)	19.5(21)
9767.2(3)	1	3	900(114)	90(8)	28.7(26)
12098					65(4) ^c
15649.8(1.0)	1	5	1000	47(4)	20.2(17)
17440.0(1.3)	1	6	1538(300)	32(3)	20.4(18)
17839.5(9)	1	5	464(181)	43(4)	21.7(20)
20870	1	5	954(227)	34.4(33)	18.3(17)
21050	1	4	7444(778)	33(3)	14.8(13)
22286.0(9)	1	5	181(91)	33.6(32)	15.1(15)
23149.1(1.3)	1	6	208(154)	25.3(25)	14.7(15)

^aAngular orbital momenta, l , resonance spins J , and neutron widths, Γ_n , are mainly from Refs. [27,28].

^bUncertainties are given as $18.2(6)\equiv 18.2 \pm 0.6$.

^cThis area corresponds to the sum of the areas of the broad s -wave resonance at the indicated energy, plus two p -wave resonances at 12.092 and 12.285 keV.



16% higher MACS for $kT = 5\text{-}8$ keV
81% r-process abundance for ^{209}Bi

The $n_{\text{-}}\text{TOF}$ Collaboration

Pb and Bi: MACS and Implications

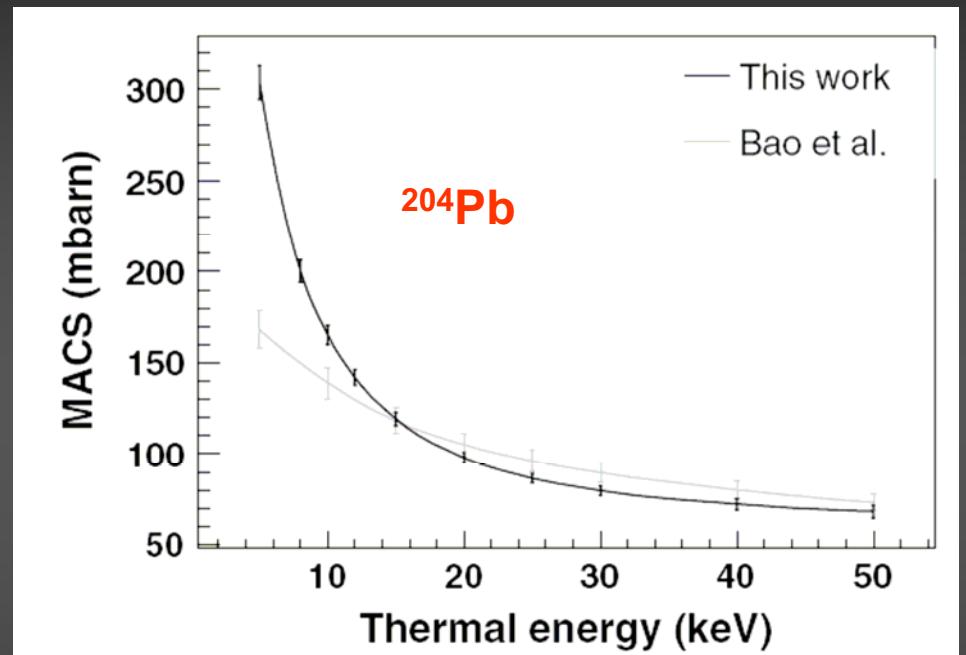
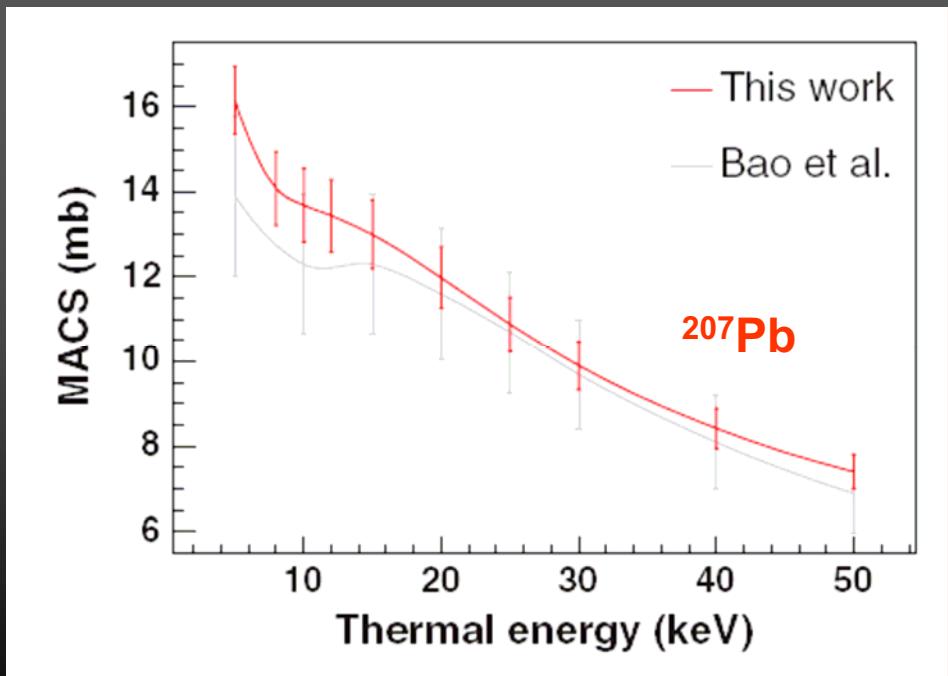
Main and Strong s-process Components.

Several branching ratios are present.

Alpha recycling.

Difficult to estimate the r-process contribution without accurate

Cross section measurements.

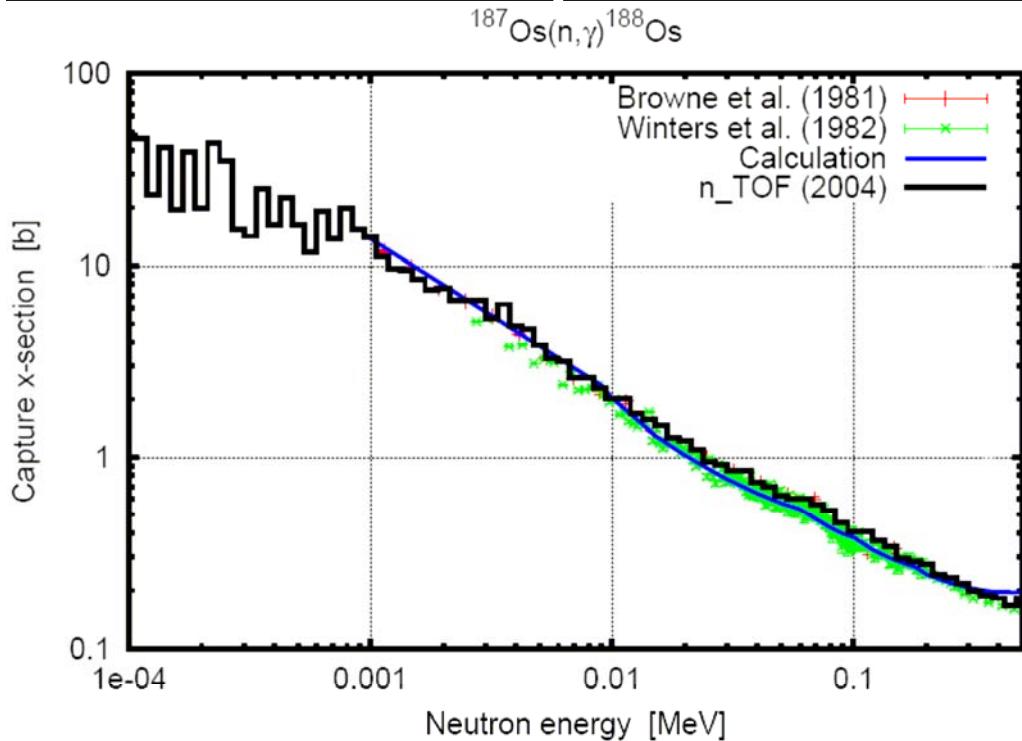


Larger cross section especially at low energies ($E_n < 15$ keV).

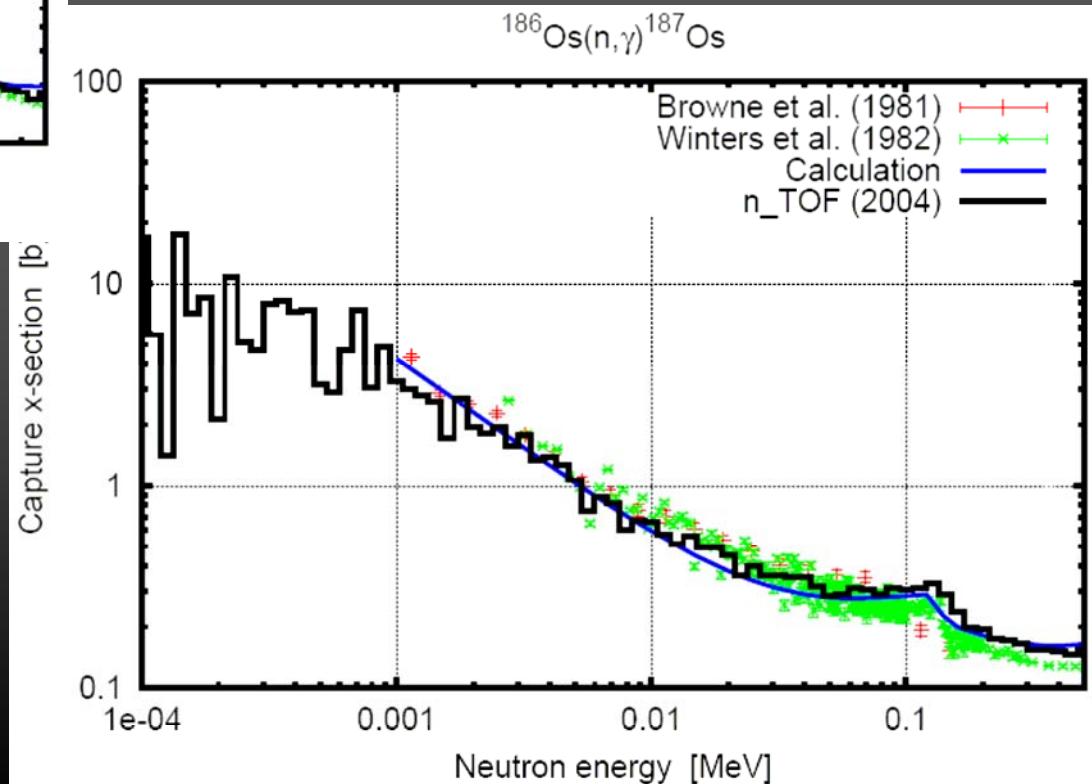
Relative isotopical abundance are 5% lower.

Other components higher

n_{TOF} experiments: $^{186,187,188}\text{Os}(n,g)$



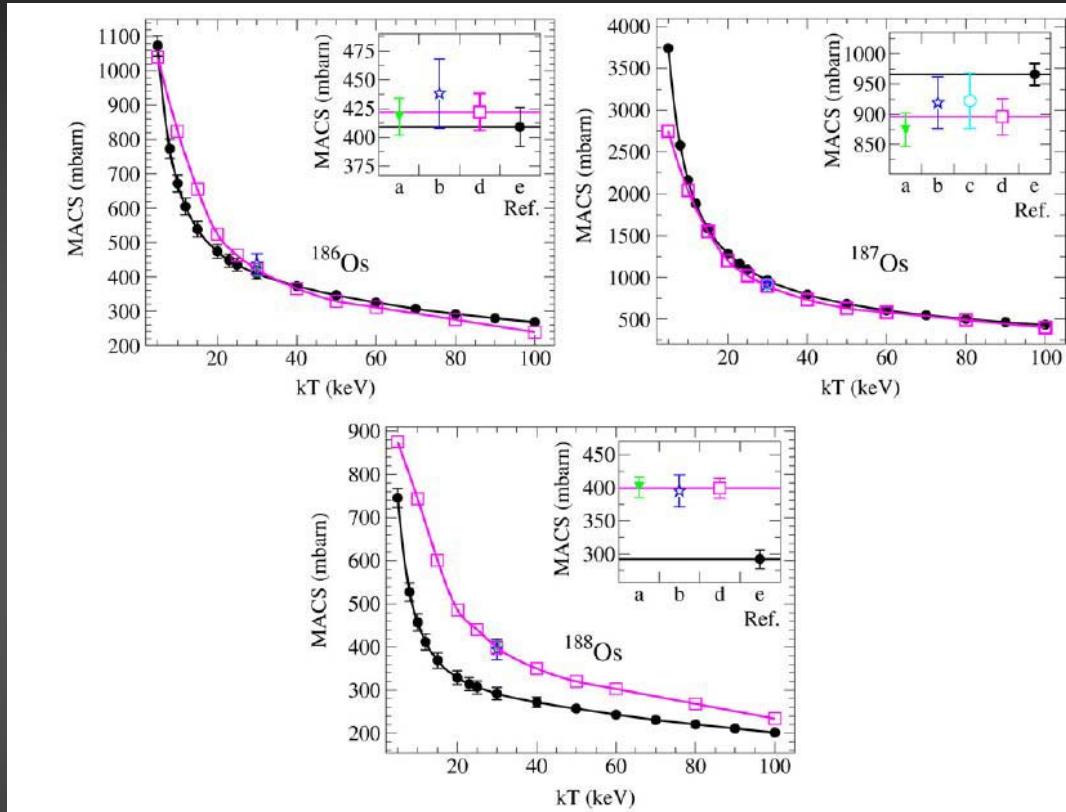
M Mosconi, *et al.* Progress in Particle and Nuclear Physics 59, 165.
NIC-IX Proceedings CERN, Geneva – June 2006



The cross section in the Unresolved Resonance region are measured.

The analysis in the resonance region is almost finished and soon will be published.

MACS $^{186,187,188}\text{Os}(n,\gamma)$



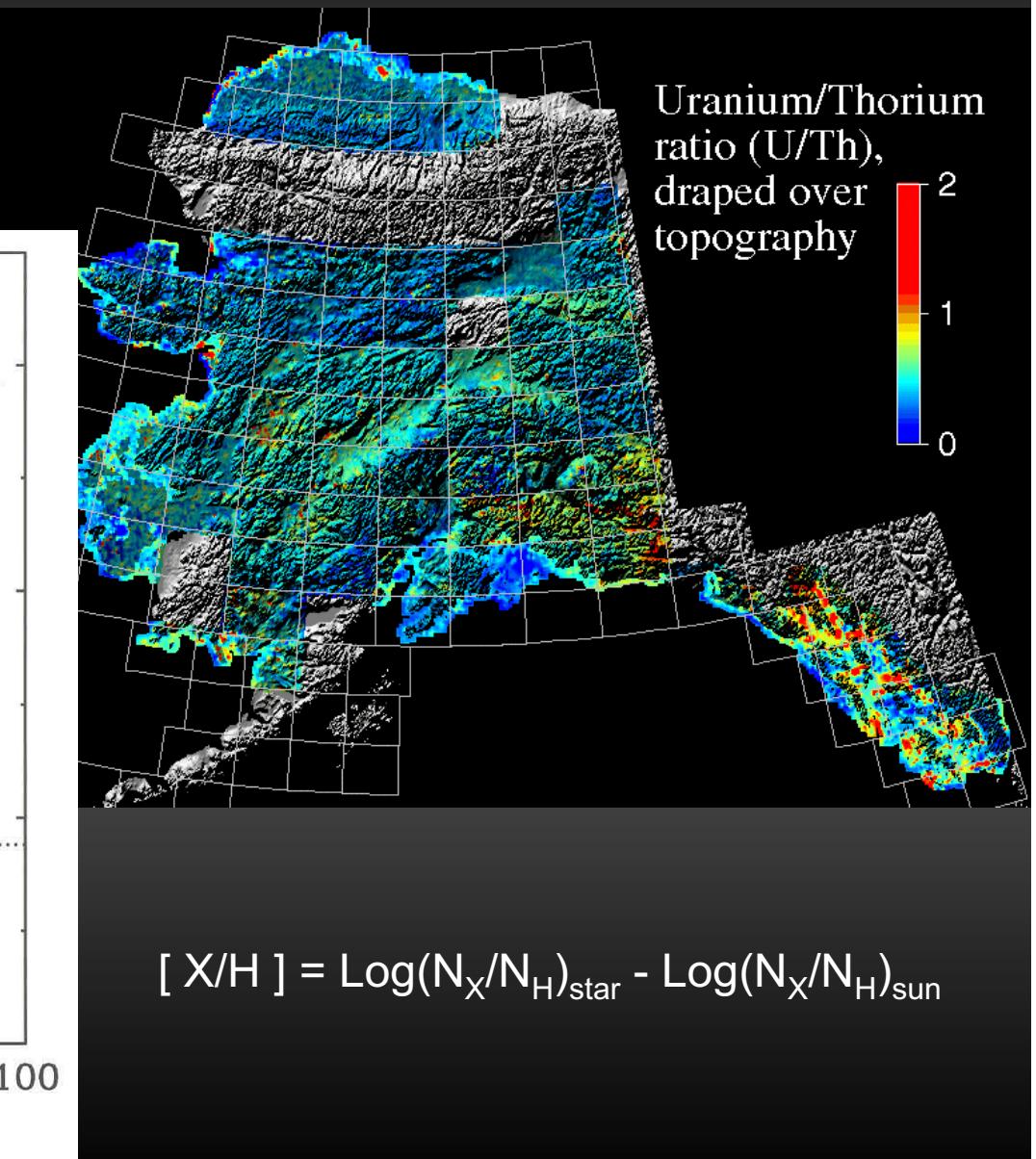
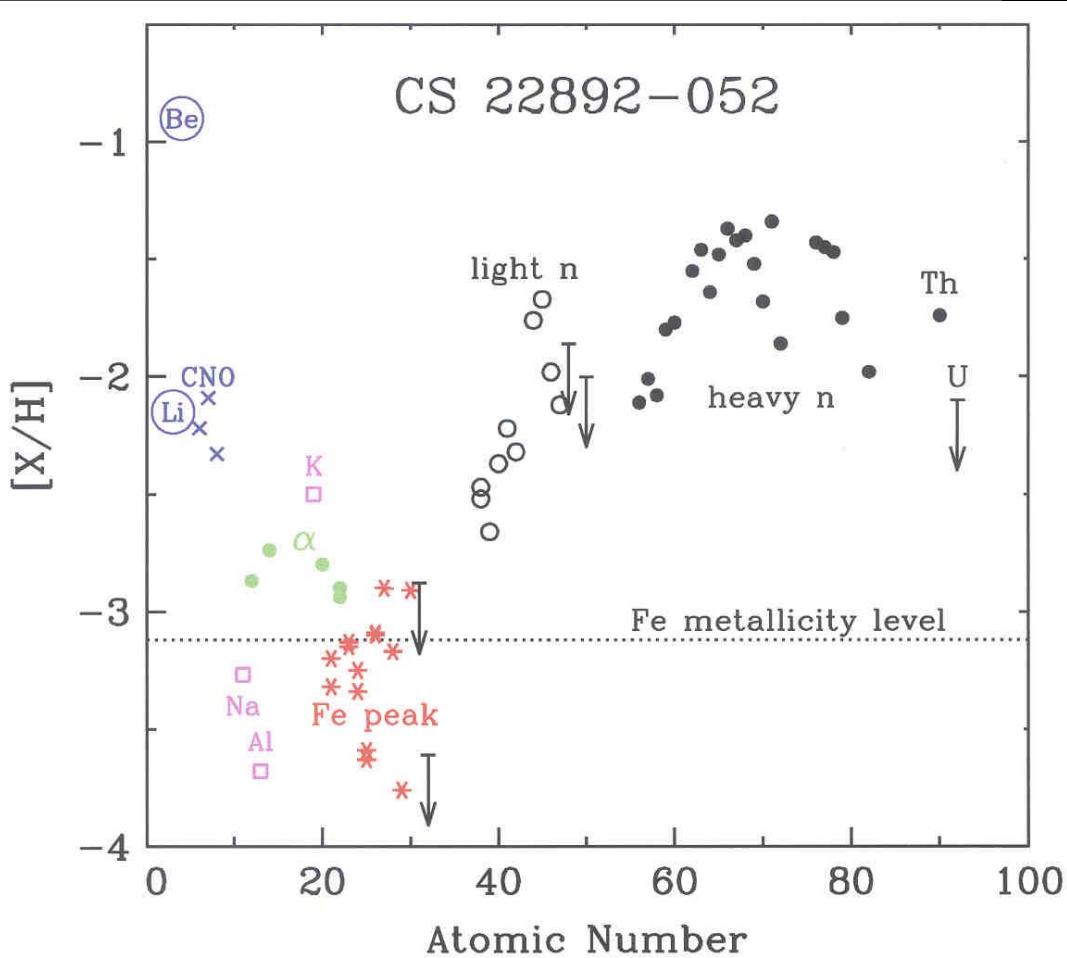
Largest differences for ^{188}Os .

Sizeable differences in the
low neutron energy region
10-20 keV.

$$\text{MACS}[186\text{Os}] / \text{MACS}[187\text{Os}] = 0.41$$

16.5 ± 2 Gyr higher than other cosmo-
chronometers (14.5 ± 2.5) but consistent.

$n_{\text{-TOF}}$ experiments: $^{232}\text{Th}(n,\gamma)$

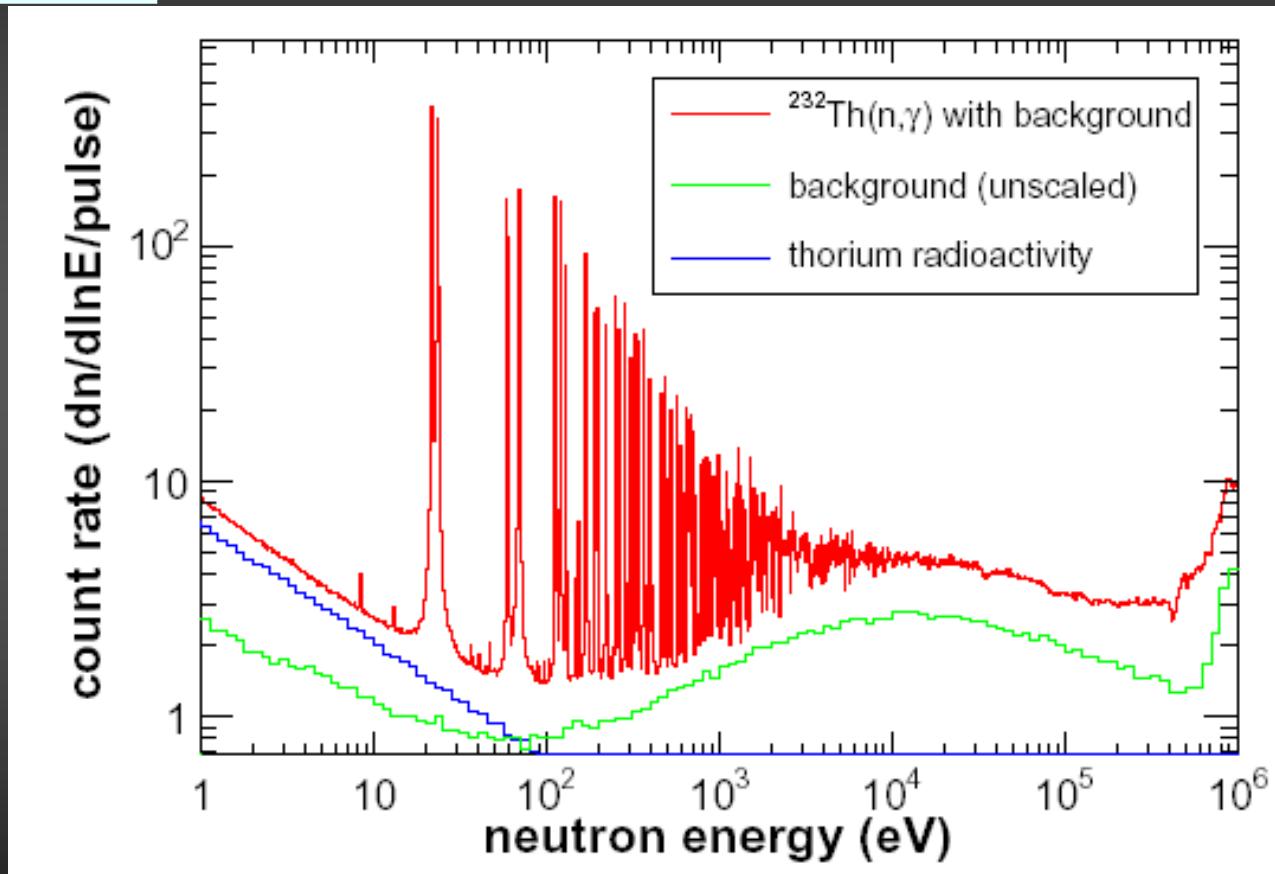




n_TOF experiments

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

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

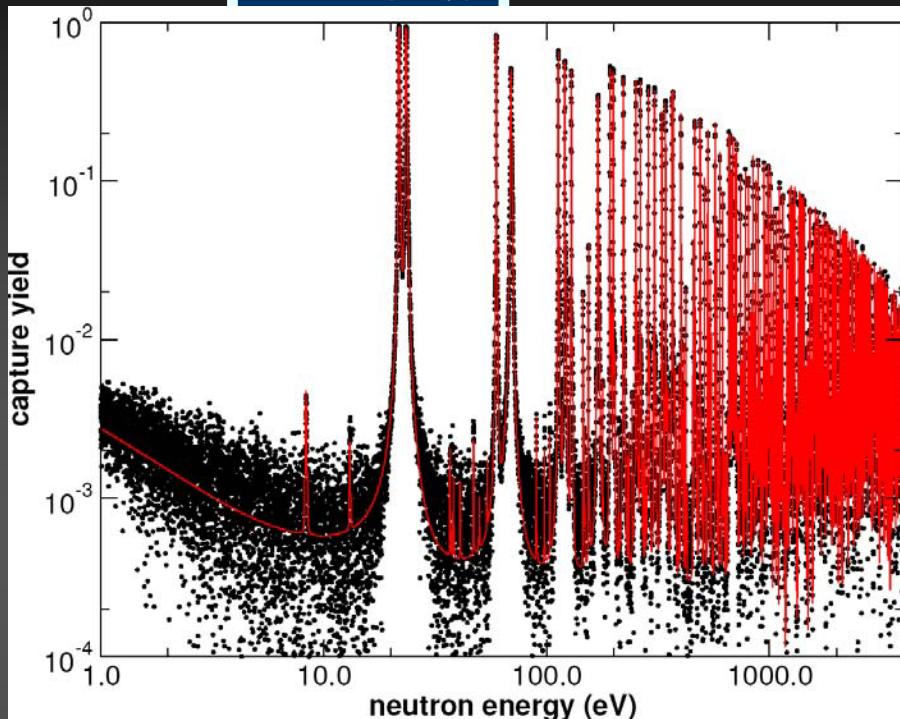


Low PS duty-cycle favours measurements on radioactive samples

The n_TOF Collaboration



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



Very large neutron energy range.

High resolution power of the neutron resonances.

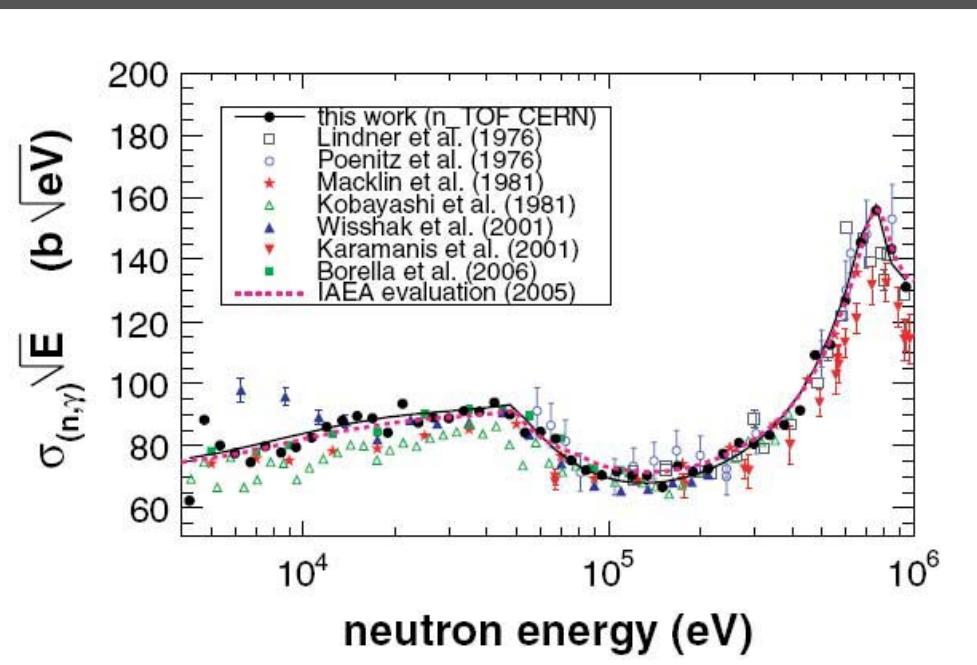
Interesting implications in Nuclear Astrophysics. (Th/U and Th/Eu chronometers).

The most important ones are in Th fuel cycle.

n_{TOF} experiments

F Gunsing, et al. - The n_{TOF} Collaboration
ND2004 Conference, Santa Fe, NM – Sept. 2004

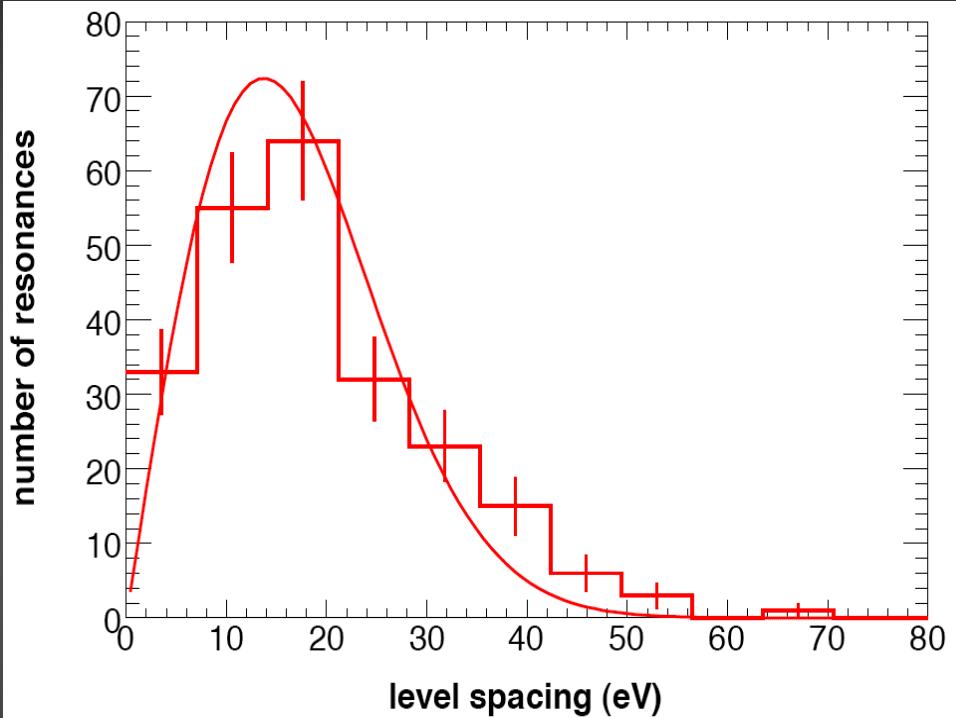
&
G. Aerts et al. (The n_{TOF} Collaboration)
Phys. Rev. C 73 (2006)



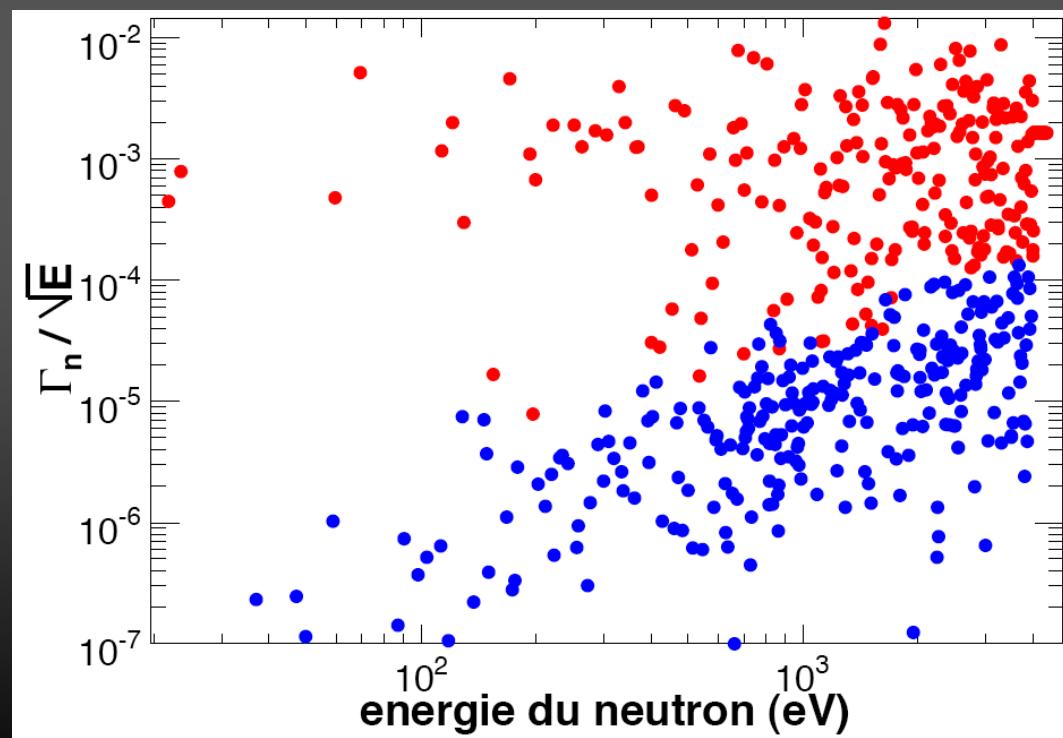


n_{TOF} experiments

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



F Gunsing, et al. - The n_{TOF} Collaboration
analysis in progress

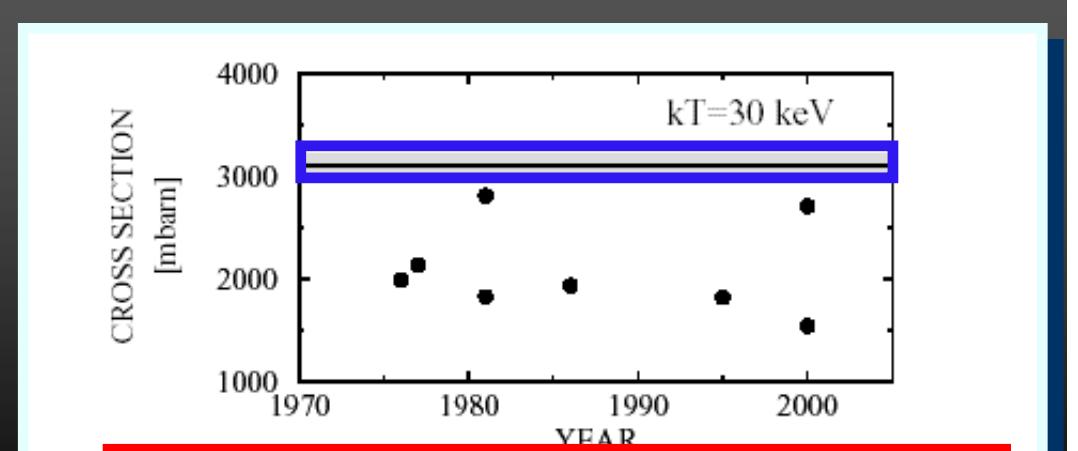
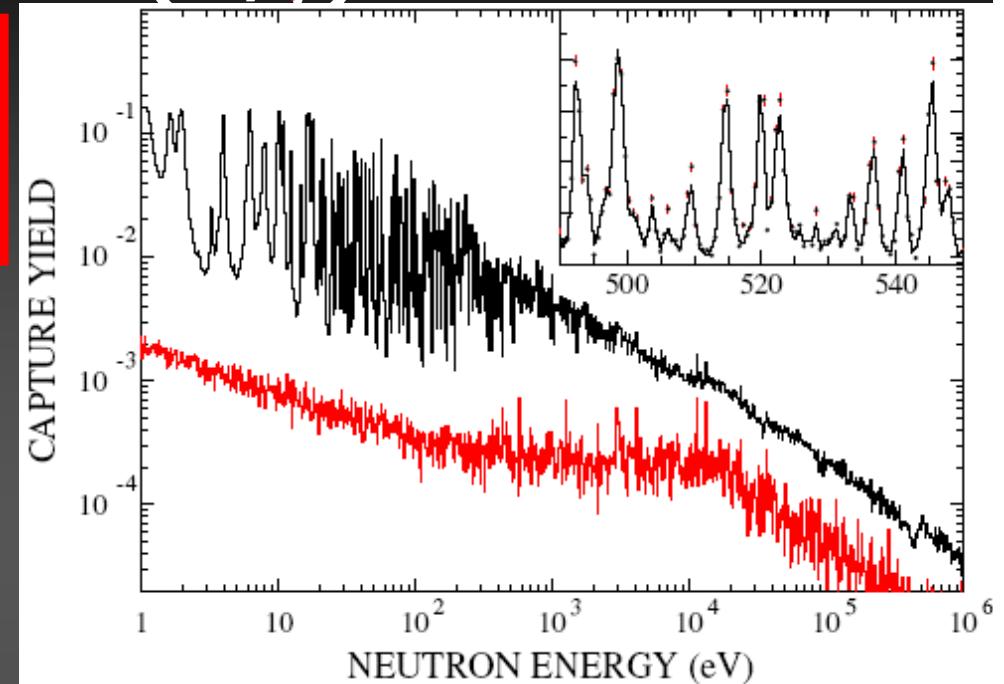
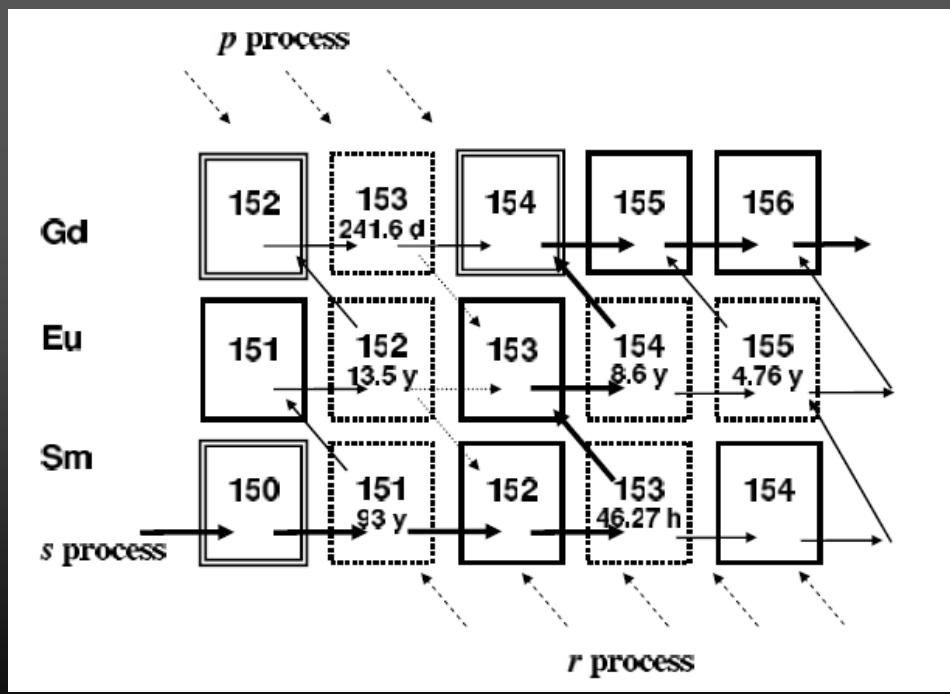




$^{151}\text{Sm}(n,\gamma)$

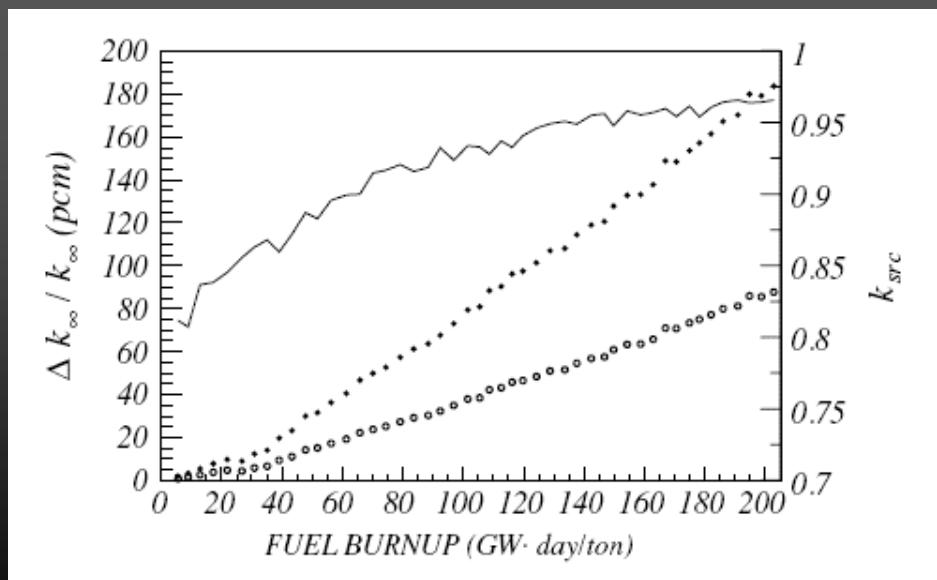
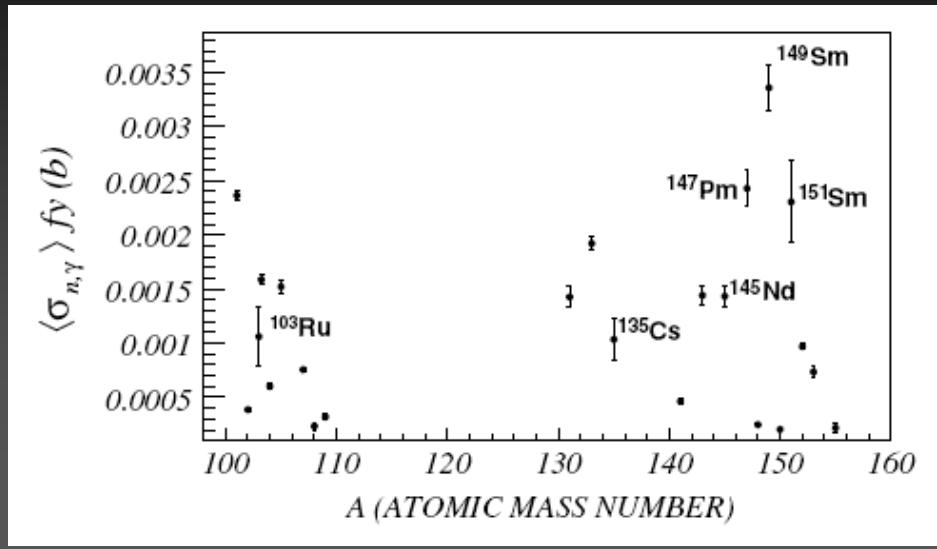
U Abbondanno et al. (The n_TOF Collaboration)
Phys. Rev. Lett. **93** (2004), 161103
S Marrone et al. (The n_TOF Collaboration)
Phys. Rev. C **73** 03604 (2006)

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



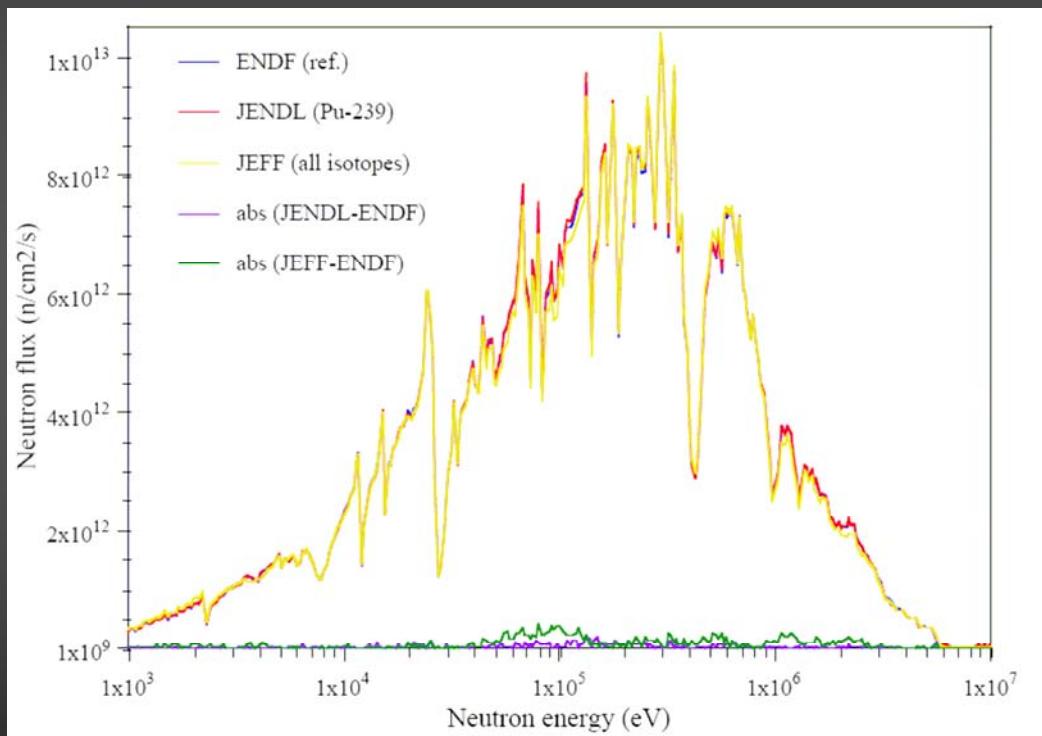
MACS-30 = 3100 ± 160 mb

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

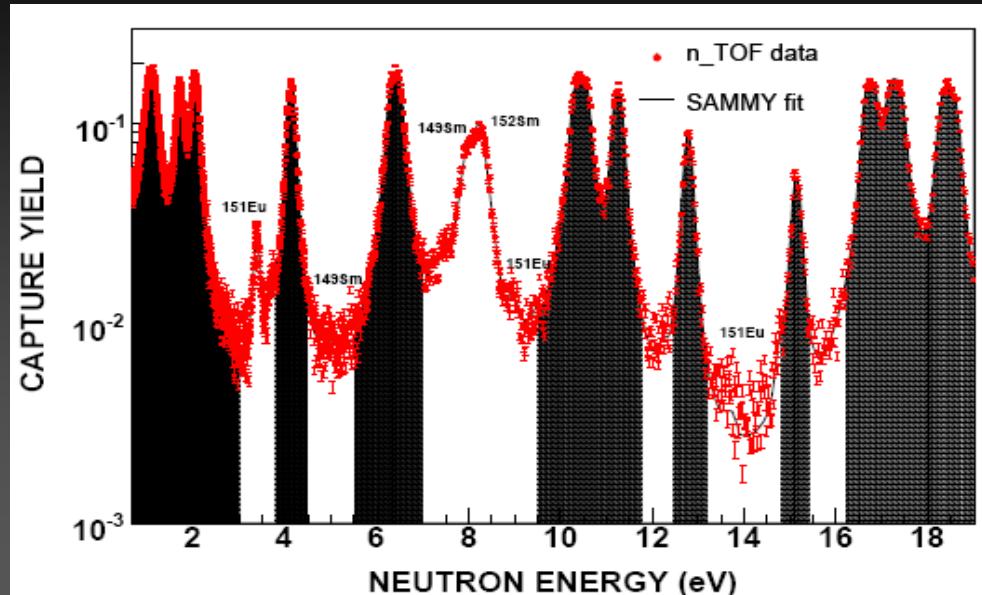
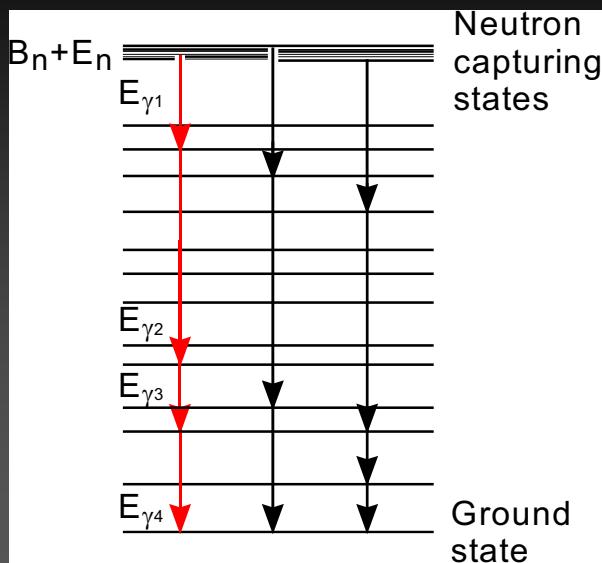


Energy Amplifier Demonstration Facility.

PhD. Thesis: A. Herrera-Martinez



Photon Strength Function



^{151}Sm $J^\pi = 5/2^+$

Capture resonances $J = 2^+$ or 3^+

Selected different resonances between 1 and 400 eV

All s-wave (but impossible to tell J)

Advantages:

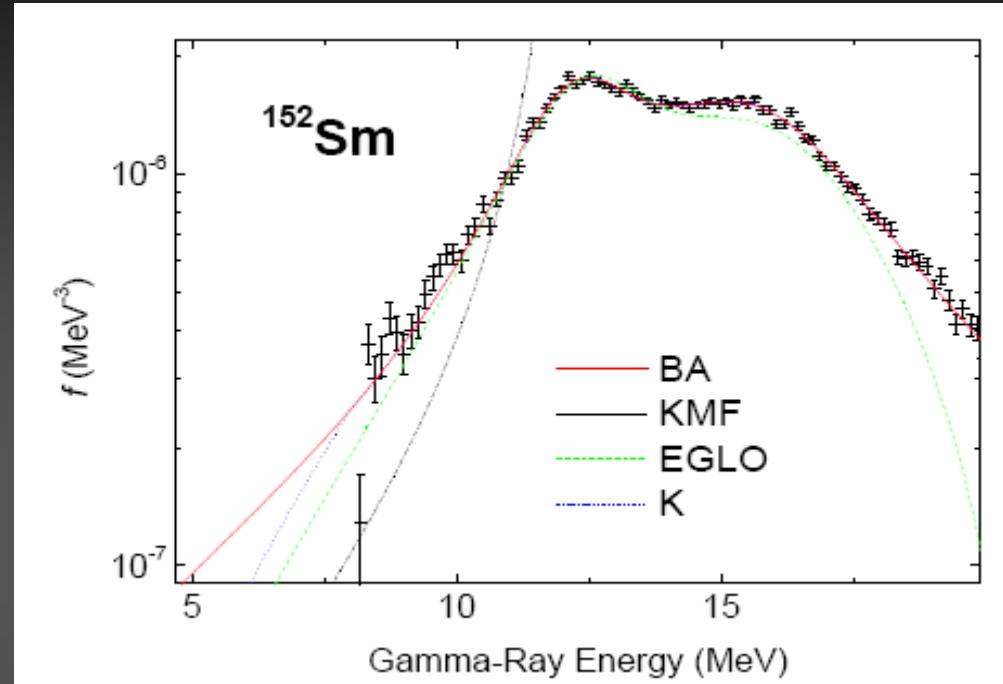
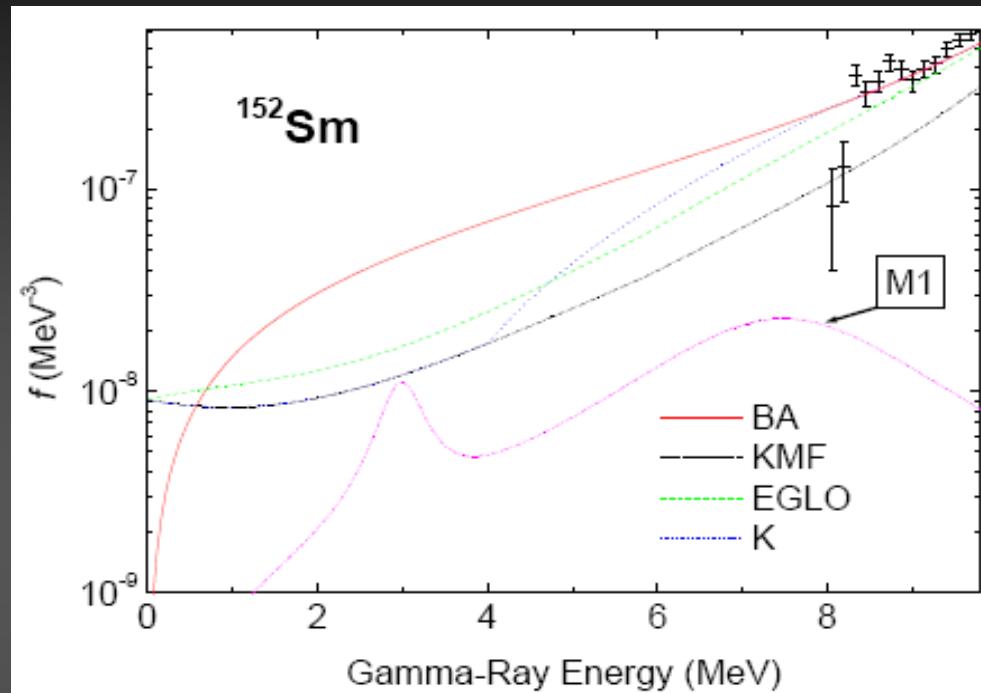
- very good signal-to-background ratio
 - high resolution allows to select different resonances
 - accurate study of the detector response (MC simulations and data)

Disadvantages:

- poor γ -ray resolution
 - statistics at high energy is limited

Proposed solution: filter model predictions through detector's response

Models of Photon Strength Function



Photon Strength Function are proportional to the γ -ray cross section on nuclei.

Several Models are under study: BA, KMF, EGLO, K.

Each models has few parameters to fit and reproduce at best some data
(neutron capture, photoabsorption, electron scattering etc...)

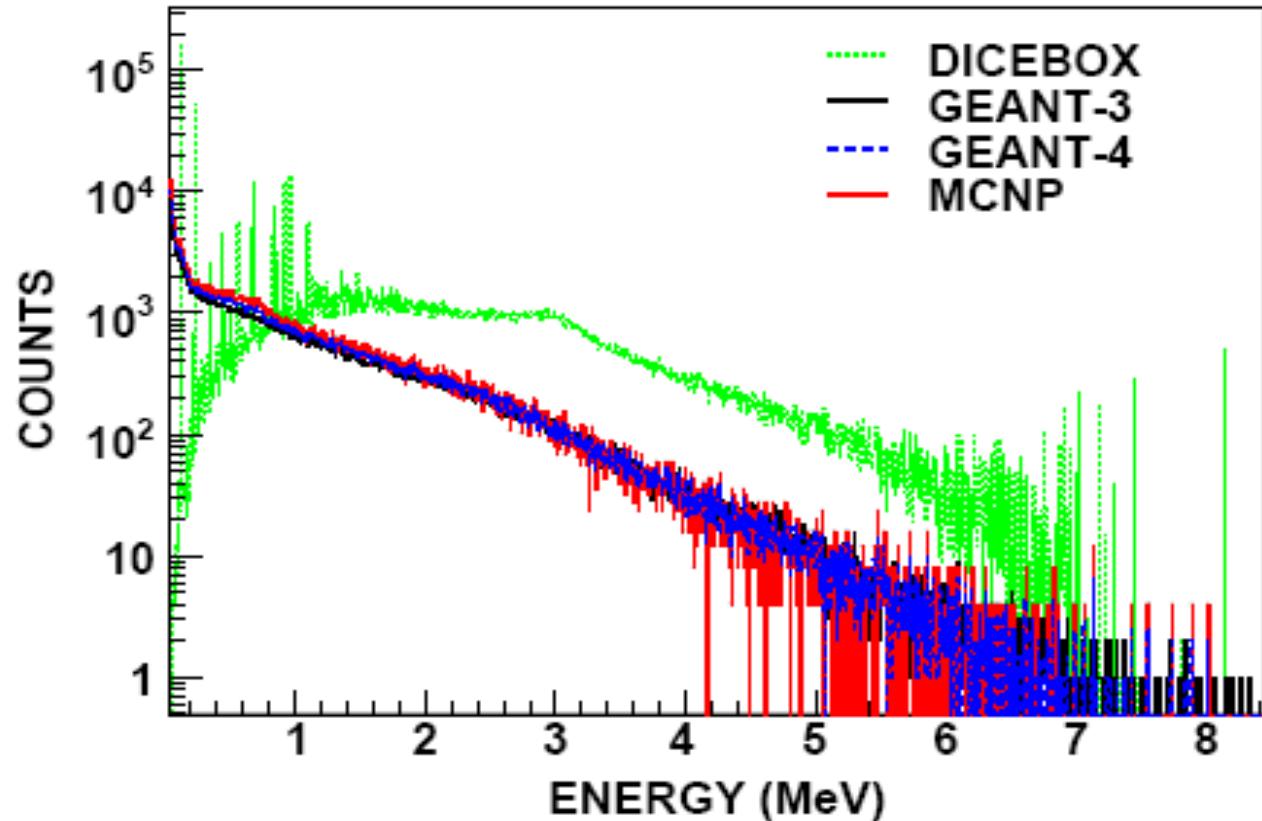
Large implications in Nuclear Astrophysics especially for the r-process stellar environments.

Monte Carlo Simulations

To simulate the detector response, used three different Monte Carlo codes:

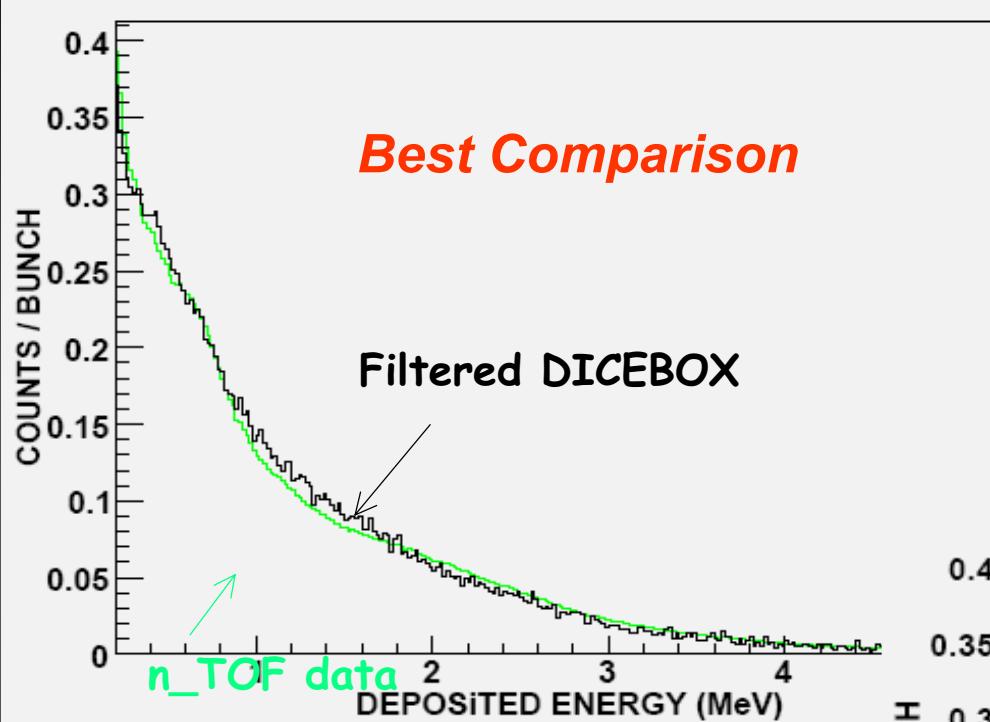
- MCNP-X
- GEANT 3.21
- GEANT 4

Accurate implementation of the materials and detailed geometry of experimental apparatus

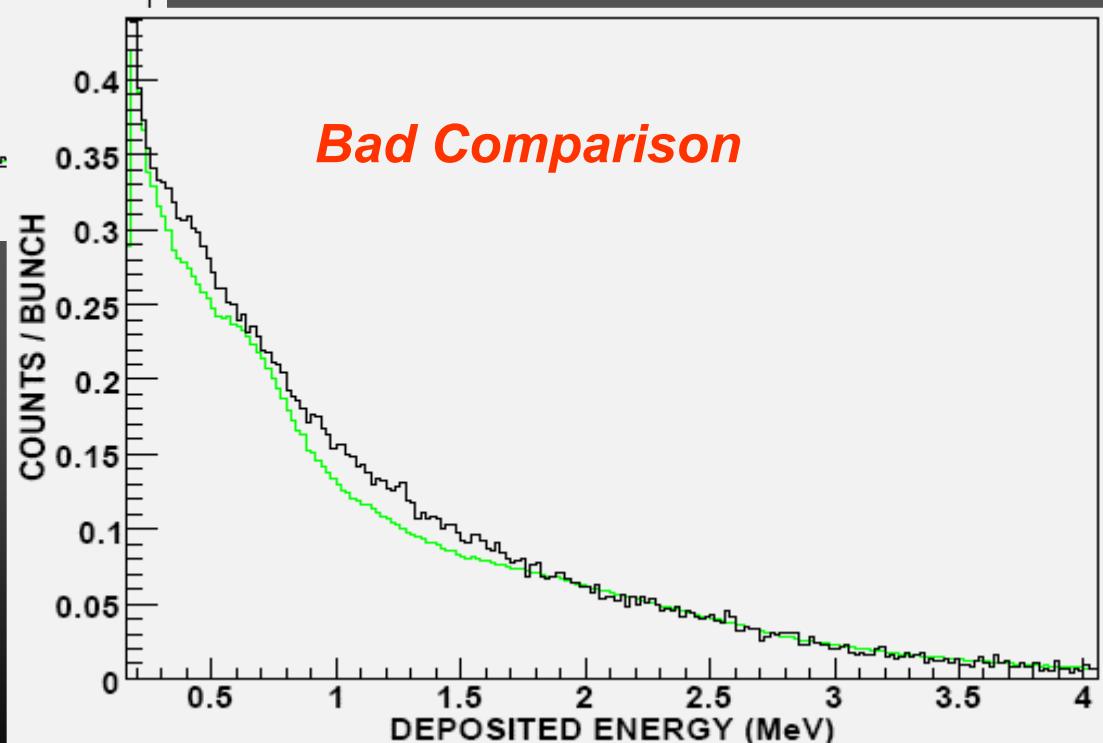


- γ -rays are generated uniformly in the sample
- Used same cuts as in the experiment (threshold of 200 keV)
- Energy resolution of the detectors included in the simulations

Comparison with the Experimental Data



The best agreement is obtained by combining BA+KMF, and assuming a Scissor resonance for M1. Need to consider also a constant SP background in M1.



The radiation width in this case is 86(2), close to the experimental value of 95(4).

A more accurate comparison (and conclusion) requires fixing some uncertainty in the MC filtering code.

The n_TOF-Ph2 experiments 2008 and beyond

Capture measurements

Mo, Ru, Pd stable isotopes

r-process residuals,
isotopic patterns in SiC grains

Fe, Ni, Zn, and Se (stable isotopes)

^{79}Se

s-process nucleosynthesis in massive stars
nuclear data needs for structural materials

$A \approx 150$ (isotopes vari)

s-process branching points
long-lived fission products

$^{234,236}\text{U}$, $^{231,233}\text{Pa}$

Th/U nuclear fuel cycle

$^{235,238}\text{U}$

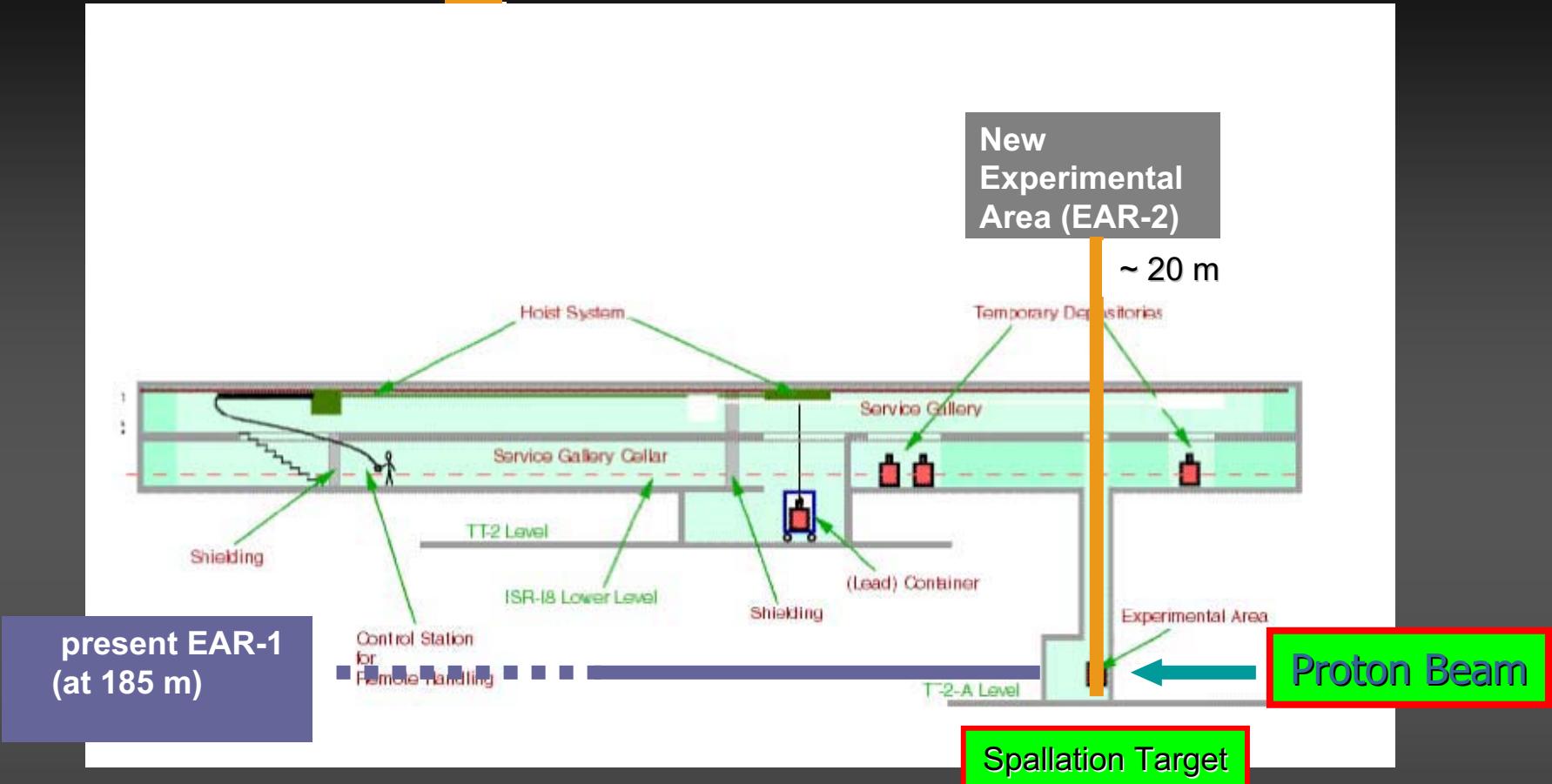
standards, conventional U/Pu fuel cycle

$^{239,240,242}\text{Pu}$, $^{241,243}\text{Am}$, ^{245}Cm

incineration of minor actinides

(*) endorsed by CERN Isolde-n_TOF Committee, execution in 2008

The second n_TOF beam line



- present EAR-1: Flight path ~ 185 m, Neutron Flux $\sim 10^6$ n per proton bunch; High resolution in neutron energy. (**RADIOACTIVE SAMPLES**)
- new EAR-2: Flight path ~ 20 m at 90° with respect to p-beam; neutron flux enhanced by factor ~ 100 ; drastic reduction of backgrounds. (**SMALL MASS or LOW CROSS SECTION**)

EAR-2: Optimized sensitivity

Improvements (ex: ^{151}Sm case)

- sample mass / 3
s/bkgd=1
- use BaF_2 TAC $\varepsilon \times 10$
- use D_2O $\Phi_{30} \times 5$
- use 20 m flight path $\Phi_{30} \times 100$

consequences for
sample mass

- ✓ 50 mg
- ✓ 5 mg
- 1 mg
- 10 μg

boosts sensitivity by a factor of 5000 !



→ problems of sample production and safety issues relaxed

Summary & Conclusions

- n_TOF is able to accurately measure neutron capture cross sections for several isotopes radioactive and not.
- Analysis in progress or almost finished of resonance parameters for several isotopes:
 - ✓ C₆D₆: Zr, Mg, Os, Th isotopes in the Resolved Resonance Region.
 - ✓ TAC: Am, Np, U isotopes.
- Preliminary results on Fission and Photon Strength Function;
- Large Plan of measurements in EAR-1:
ready to restart activities in 2008!
- Future perspectives: Construction of second beam line EAR-2.

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

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

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

$^{237}\text{Np}, ^{240}\text{Pu}$ ^{243}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 2002-4



data analysis completed, results published



data analysis completed, paper in preparation



data analysis in progress

The n_TOF-Ph2 experiments

Capture measurements

Mo, Ru, Pd stable isotopes

r-process residuals calculation
isotopic patterns in SiC grains

Fe, Ni, Zn, and Se (stable isotopes)

^{79}Se

s-process nucleosynthesis in massive stars
accurate nuclear data needs for structural materials

$A \approx 150$ (isotopes vari)

s-process branching points
long-lived fission products

$^{234,236}\text{U}$, $^{231,233}\text{Pa}$

Th/U nuclear fuel cycle

$^{235,238}\text{U}$

standards, conventional U/Pu fuel cycle

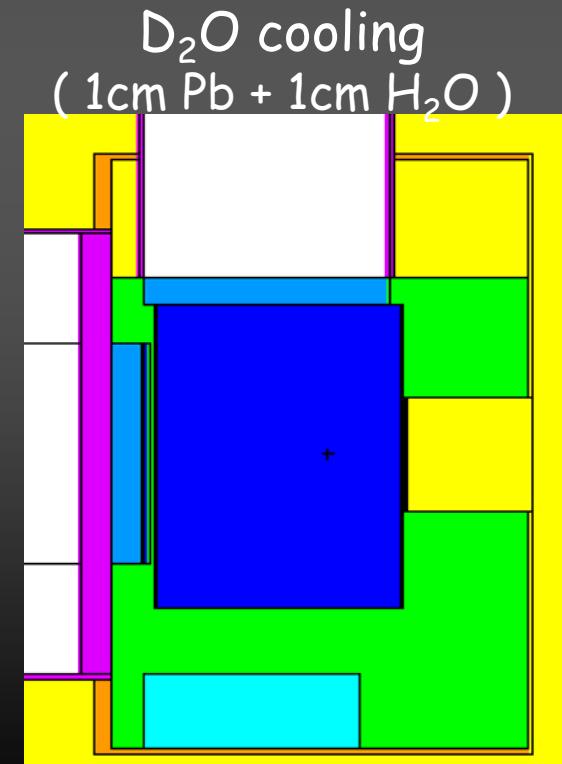
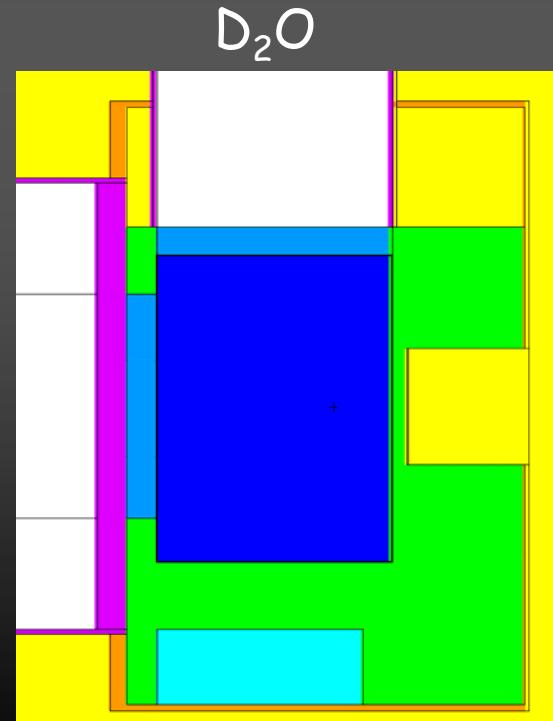
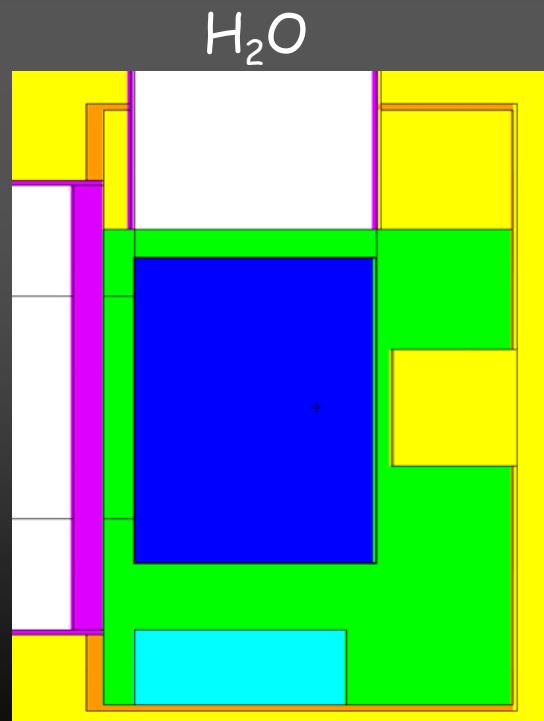
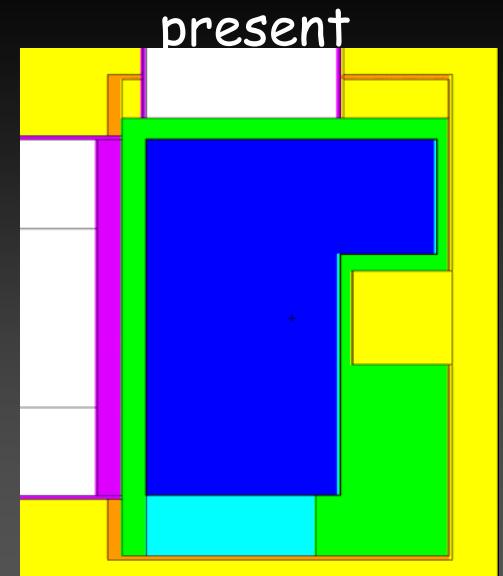
$^{239,240,242}\text{Pu}$, $^{241,243}\text{Am}$, ^{245}Cm

incineration of minor actinides

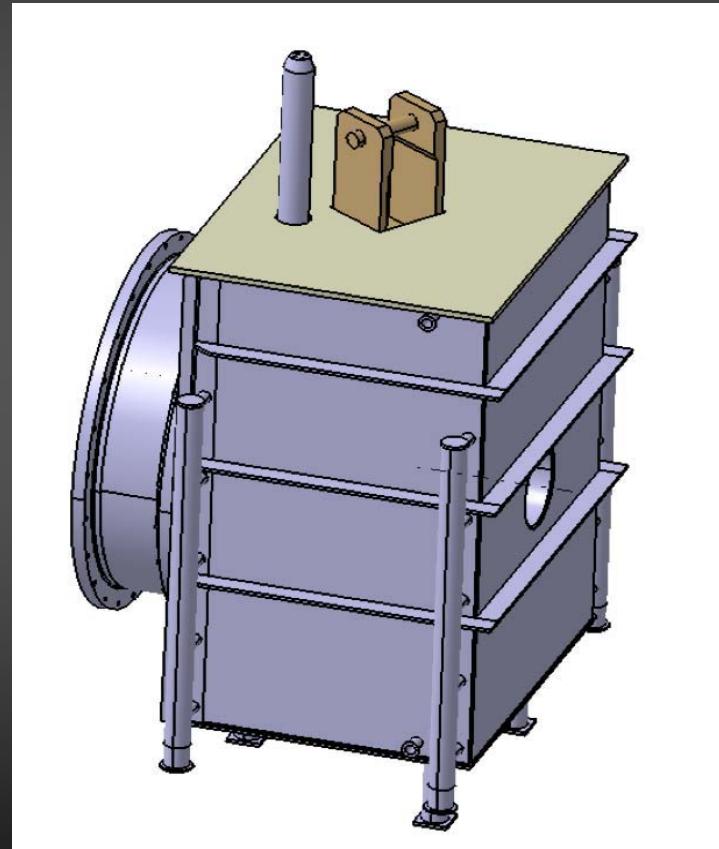
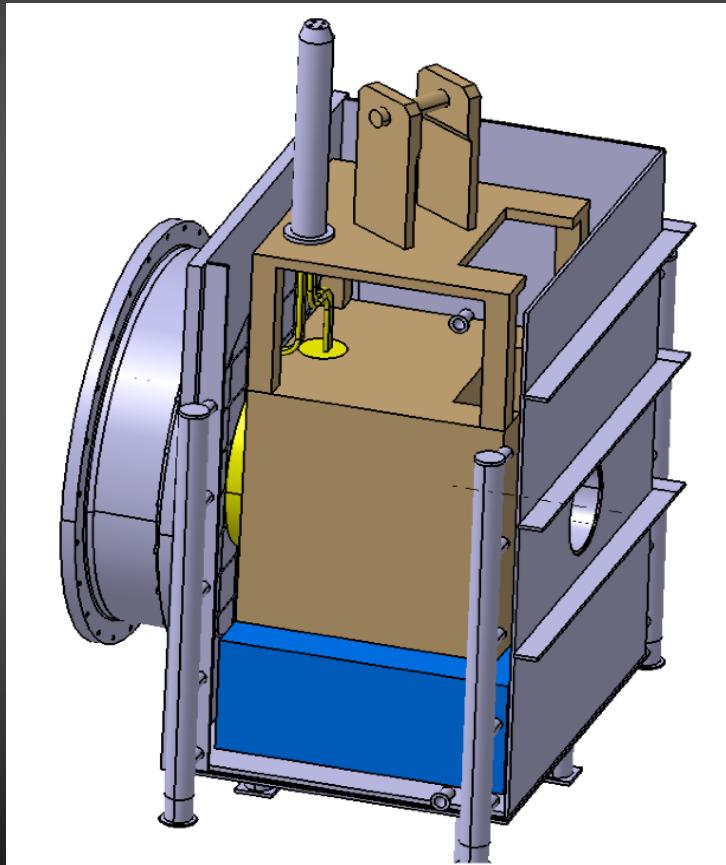
(*) approved by CERN Scientific Committee (planned for execution in 2007)

NEW target design

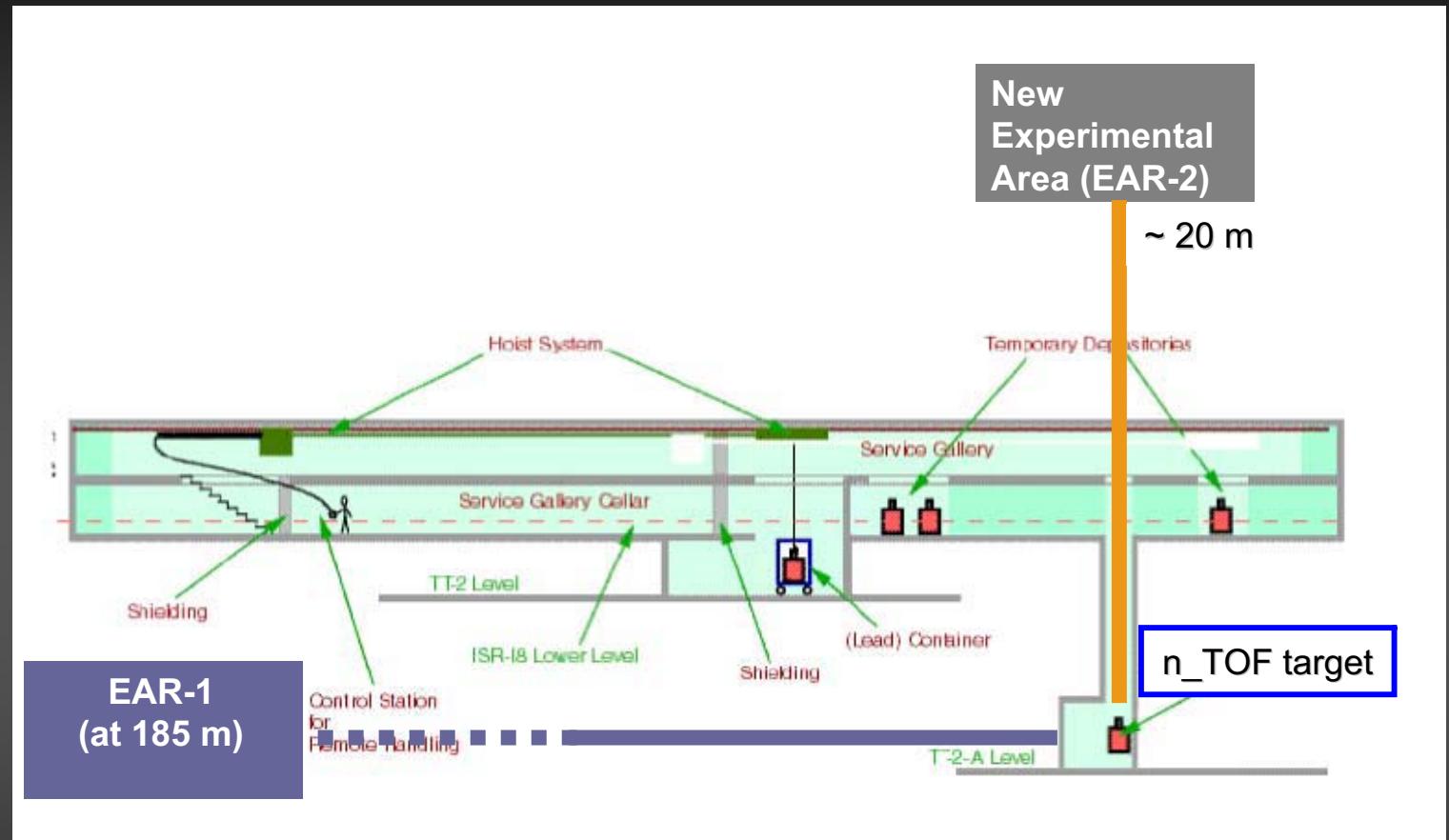
xz-squared target (40x40x55) with
5cm-thick cylinder moderator
containers



NEW: target design proposal



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

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.Becvář³¹, J.Benlliure²⁴, E.Berthoumieux⁷, F.Calviño²⁵, D.Cano-Ott²⁰, R.Capote²³, A.Carrillo de Albornoz³⁰, P.Cennini⁴, V.Chepel⁷, E.Chiaveri⁴, N.Colonna¹³, G.Cortes²⁵, D.Cortina²⁴, A.Couture²⁹, J.Cox²⁹, S.David⁵, R.Dolfini¹⁵, C.Domingo-Pardo²¹, W.Dridi⁷, I.Duran²⁴, M.Embidi-Segura²⁰, L.Ferrant⁵, A.Ferrari⁴, R.Ferreira-Marques¹⁷, L.Fitzpatrick⁴, H.Frais-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.Marganiec³³, 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.Plompens¹⁶, A.Plukis⁷, A.Poch²⁵, C.Pretel²⁵, J.Quesada²³, T.Rauscher²⁶, R.Reifarth²⁷, M.Rosetti¹¹, 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 End

PS: all quoted documents are available online at

www.cern.ch/ntof

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)

n_TOF

Capture

^{151}Sm

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

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

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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^{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
&
accepted for publication in PRC (in press)

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

substantial disagreement for $E_n > 45 \text{ keV}$

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

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n_TOF experiments

C Domingo-Pardo, et al. - The n_TOF Collaboration
ND2004 Conference, Santa Fe, NM – Sept. 2004
&
accepted for publication in PRC (in press)

TABLE II: Resonance parameters and radiative kernels from the analysis of the $^{207}\text{Pb}(n,\gamma)$ data measured at n_TOF^a.

E_\circ (eV)	l	J	Γ_n (meV)	Γ_γ (meV)	$g\Gamma_\gamma\Gamma_n/\Gamma$ (meV)
3064.700(3)	1	2	111.0(8)	145.0(9)	78.6(9)
10190.80(4)	1	2	656(50)	145.2(12)	149(14)
16172.80(10)	1	2	1395(126)	275(3)	287(30)
29396.1	1	2	16000	189(7)	234(9)
30485.9(5)	1	1	608(45)	592(50)	225(30)
37751(3)	1	1	50×10^3	843(40)	620(30)
41149(46)	0	1	1.220×10^6	3970(160)	2970(120)
48410(2)	1	2	1000	230(20)	235(20)
82990(12)	1	2	29×10^3	360(30)	444(30)
90228(24)	1	1	272×10^3	1615(100)	1200(80)
127900	1	1	613×10^3	1939(150)	1449(120)
130230	1	1	87×10^3	900(80)	675(60)
181510(6)	0	1	57.3×10^3	14709(500)	8780(300)
254440	2	3	111×10^3	1219(90)	2110(150)
256430	0	1	1.66×10^6	12740(380)	9482(280)
317000	0	1	850×10^3	10967(480)	8120(350)

^aOrbital angular momenta l and resonance spins J are from Ref. [17].

3% accuracy
of the capture kernel

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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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
&
submitted for publication to PRC, October 2006

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

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

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Fission

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^{232}Th

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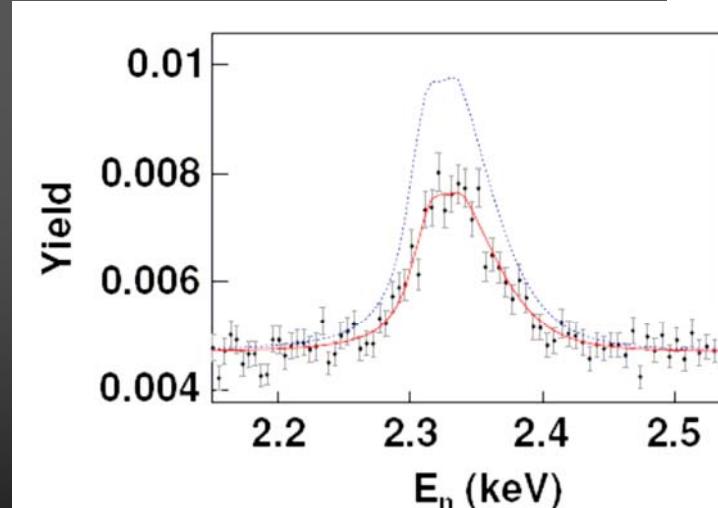
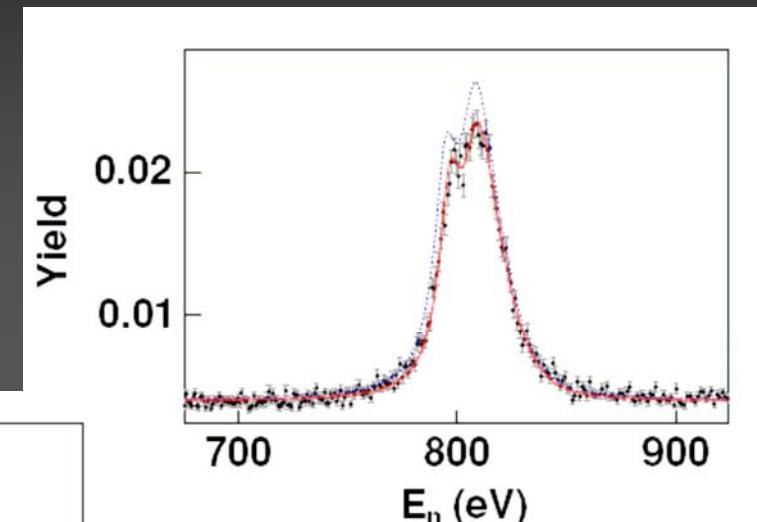
^{237}Np

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

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

NEW MEASUREMENT OF NEUTRON CAPTURE . . .

PHYSICAL REVIEW C 74, 025807 (2006)

TABLE II. Resonance parameters^a and radiative kernels^b for ^{209}Bi .

E_0 (eV)	l	J	Γ_n (meV)	Γ_γ (meV)	$g\Gamma_\gamma\Gamma_n/\Gamma$ (meV)
801.6(1)	0	5	4309(145)	33.3(12)	18.2(6)
2323.8(6)	0	4	17888(333)	26.8(17)	12.0(8)
3350.83(4)	1	5	87(9)	18.2(3)	9.5(2)
4458.74(2)	1	5	173(13)	23.2(22)	11.3(11)
5114.0(3)	0	5	5640(270)	65(2)	35.3(11)
6288.59(2)	1	4	116(18)	17.0(17)	6.7(7)
6525.0(3)	1	3	957(100)	25.3(14)	8.6(5)
9016.8(4)	1	6	408(77)	21.1(14)	13.0(9)
9159.20(7)	1	5	259(45)	21.4(21)	10.9(11)
9718.910(1)	1	4	104(22)	74(7)	19.5(21)
9767.2(3)	1	3	900(114)	90(8)	28.7(26)
12098					65(4) ^c
15649.8(1.0)	1	5	1000	47(4)	20.2(17)
17440.0(1.3)	1	6	1538(300)	32(3)	20.4(18)
17839.5(9)	1	5	464(181)	43(4)	21.7(20)
20870	1	5	954(227)	34.4(33)	18.3(17)
21050	1	4	7444(778)	33(3)	14.8(13)
22286.0(9)	1	5	181(91)	33.6(32)	15.1(15)
23149.1(1.3)	1	6	208(154)	25.3(25)	14.7(15)

^aAngular orbital momenta, l , resonance spins J , and neutron widths, Γ_n , are mainly from Refs. [27,28].

^bUncertainties are given as $18.2(6) \equiv 18.2 \pm 0.6$.

^cThis area corresponds to the sum of the areas of the broad s -wave resonance at the indicated energy, plus two p -wave resonances at 12.092 and 12.285 keV.

16% higher MACS for $kT = 5\text{-}8$ keV
81% r-process abundance for ^{209}Bi

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



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

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

F Gunsing, et al. - The $n_{_}\text{TOF}$ Collaboration
ND2004 Conference, Santa Fe, NM – Sept. 2004

&
G Aerts et al. (The $n_{_}\text{TOF}$ Collaboration)
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

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

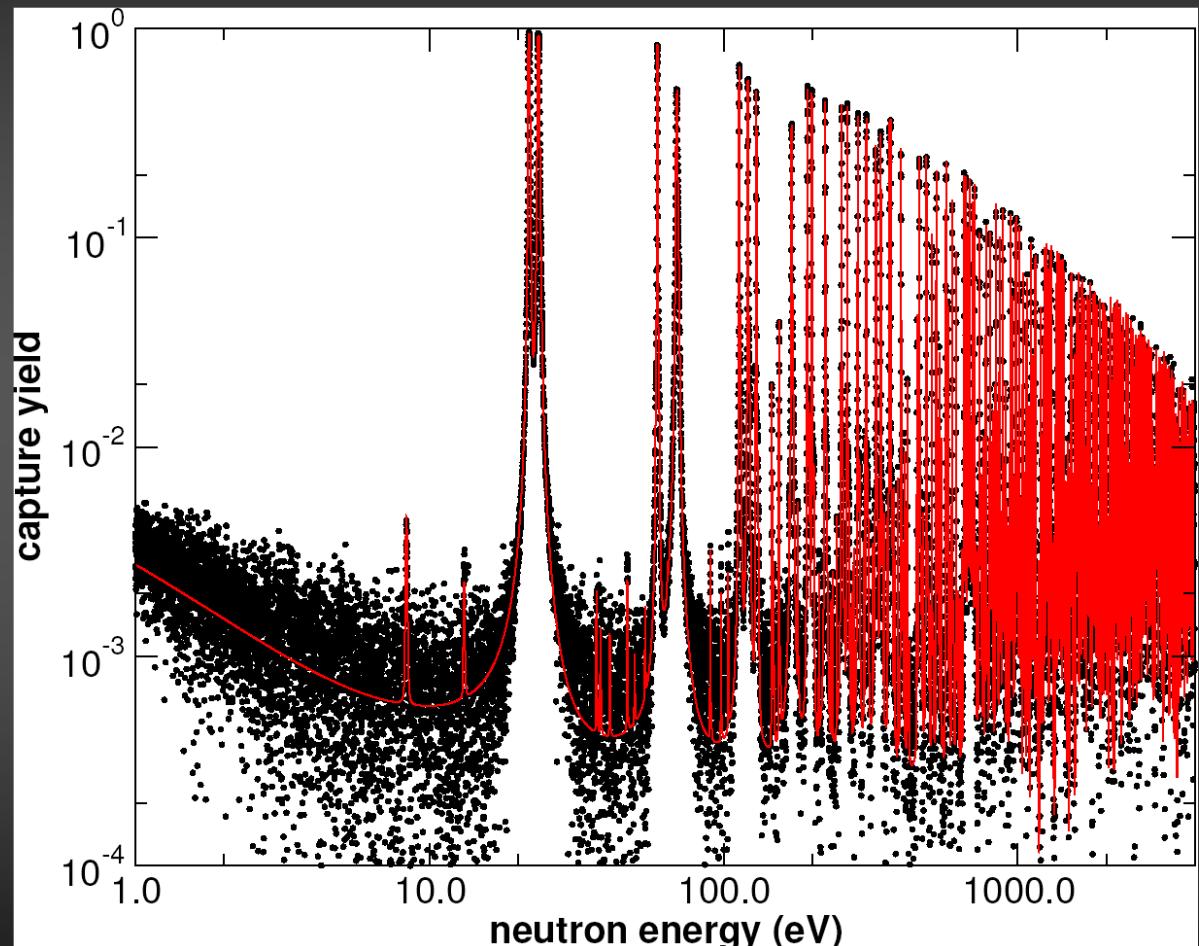
$^{241,243}\text{Am}$, ^{245}Cm



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

n_TOF experiments

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



RRR region analysis in progress

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

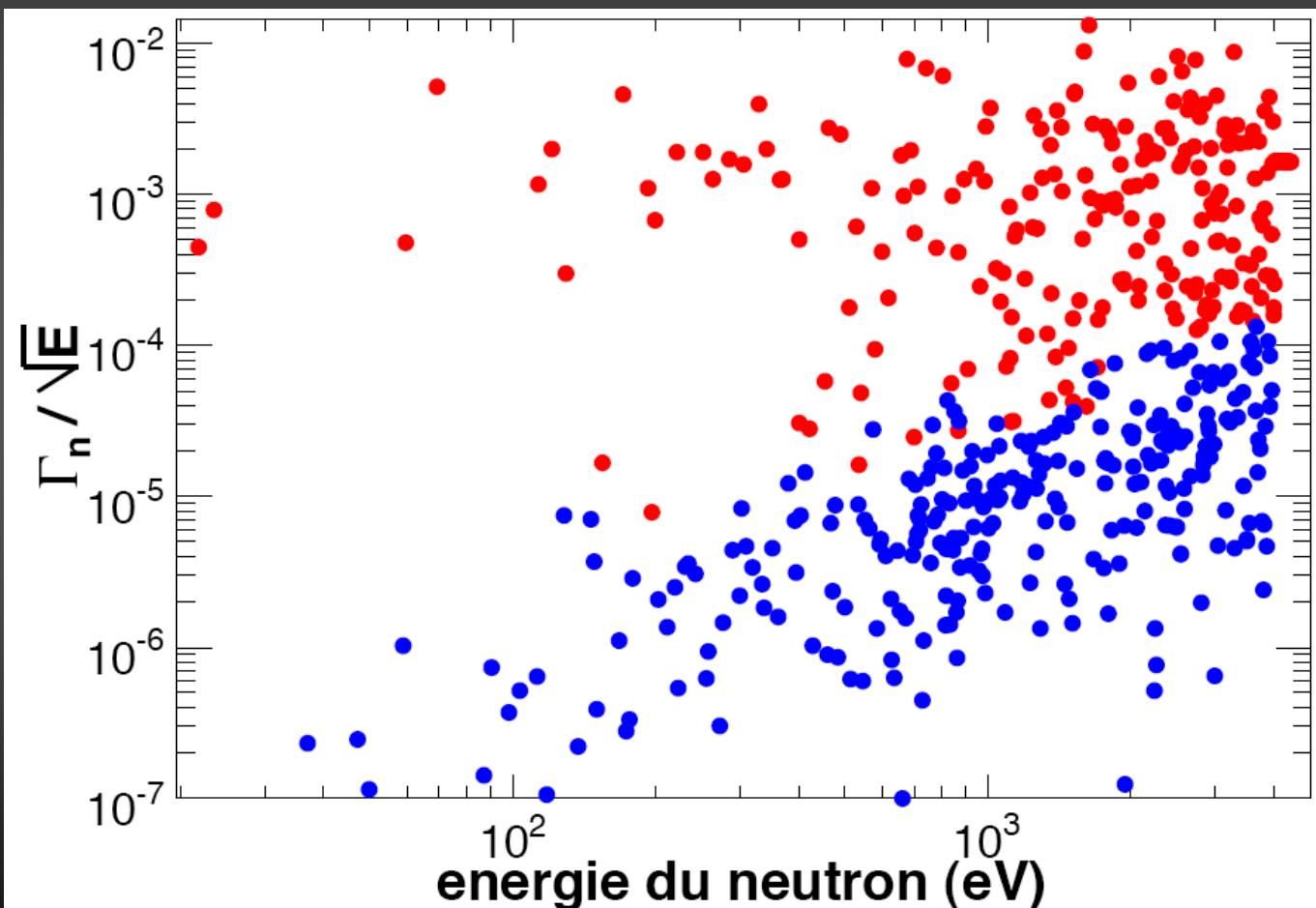
$^{241,243}\text{Am}, ^{245}\text{Cm}$



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

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

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

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

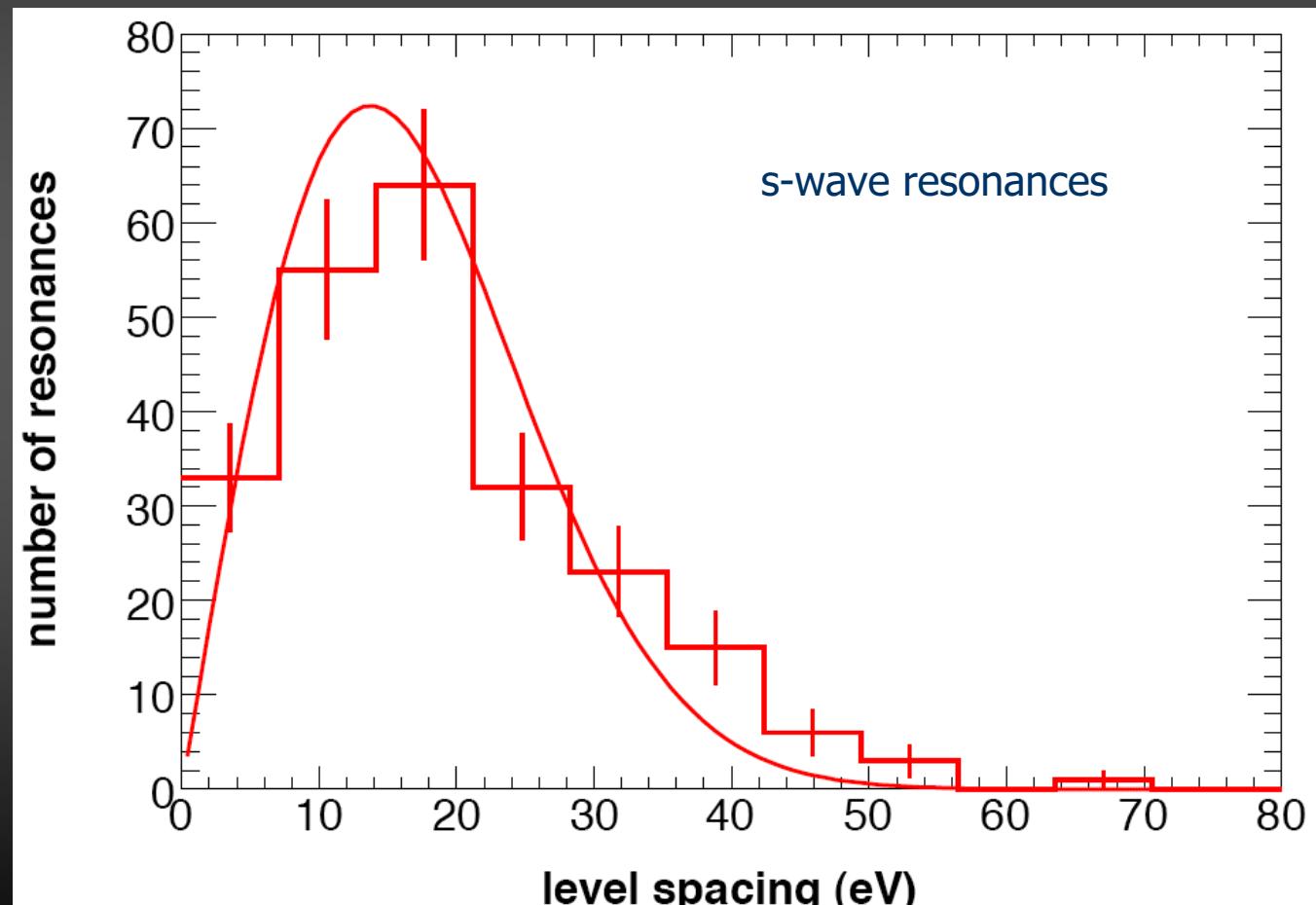
$^{241,243}\text{Am}$, ^{245}Cm



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

n_TOF experiments

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



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

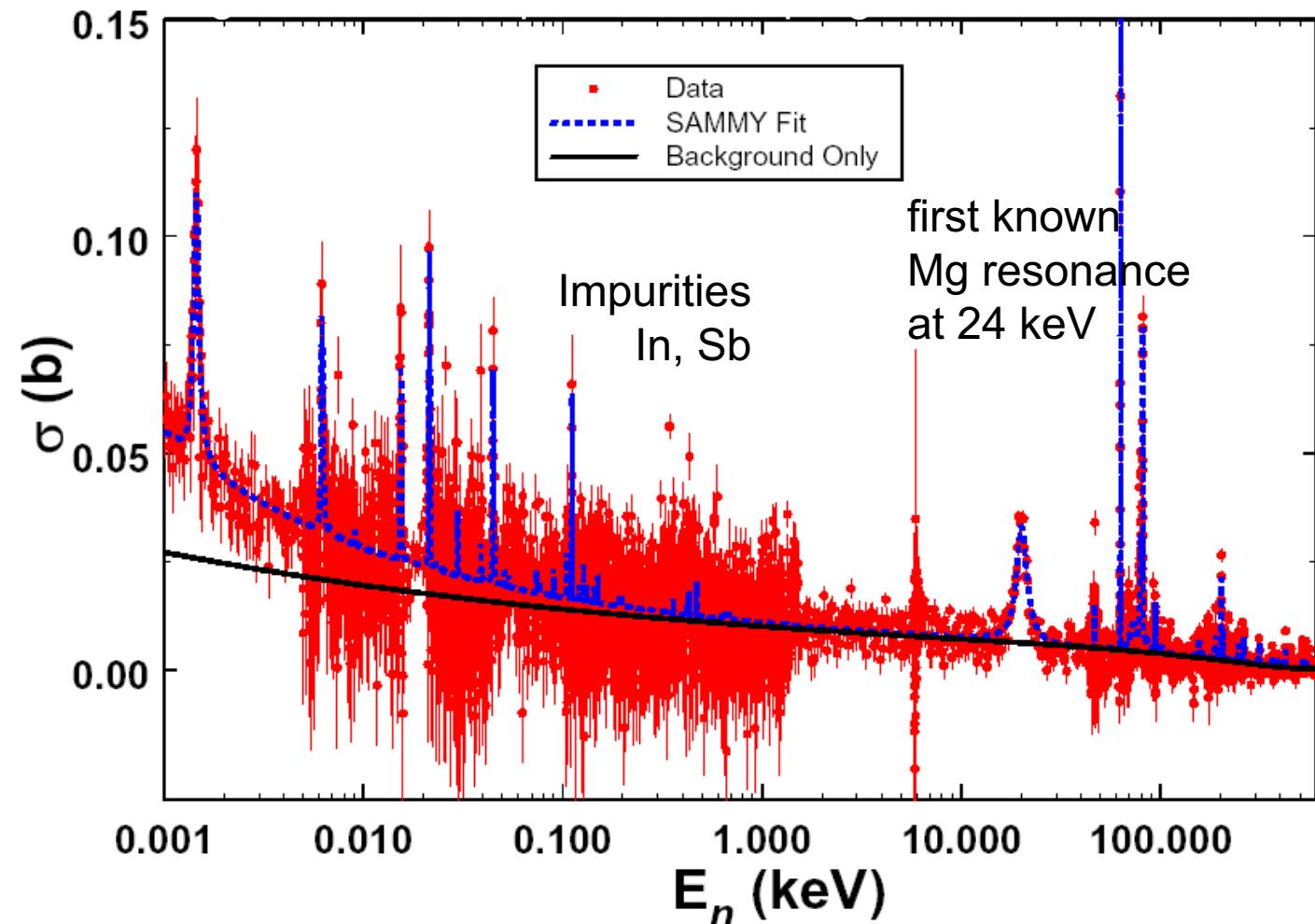
^{209}Bi

^{237}Np

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

n_TOF experiments

$^{25}\text{Mg}(n,\gamma)$ From n_TOF



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

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

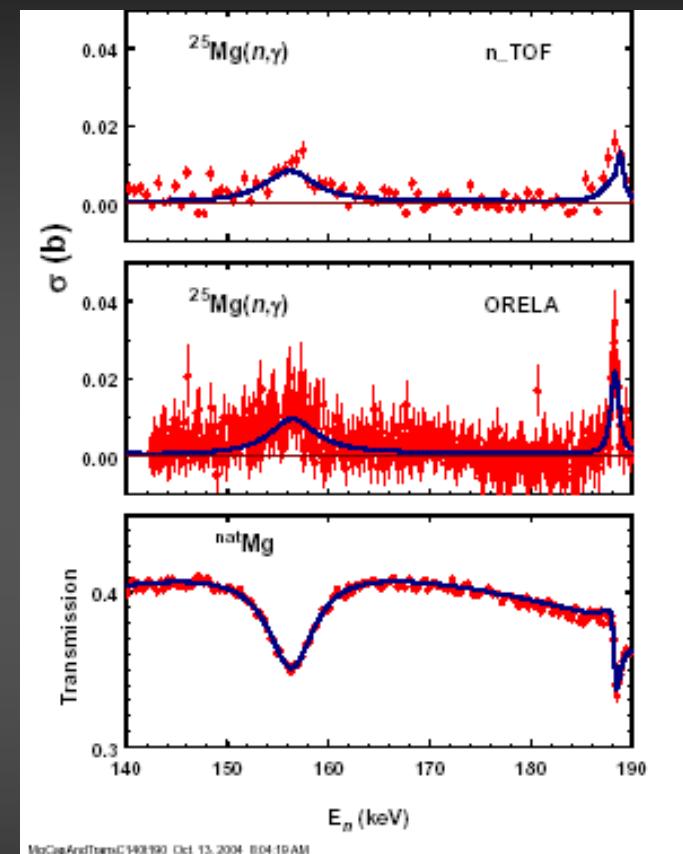
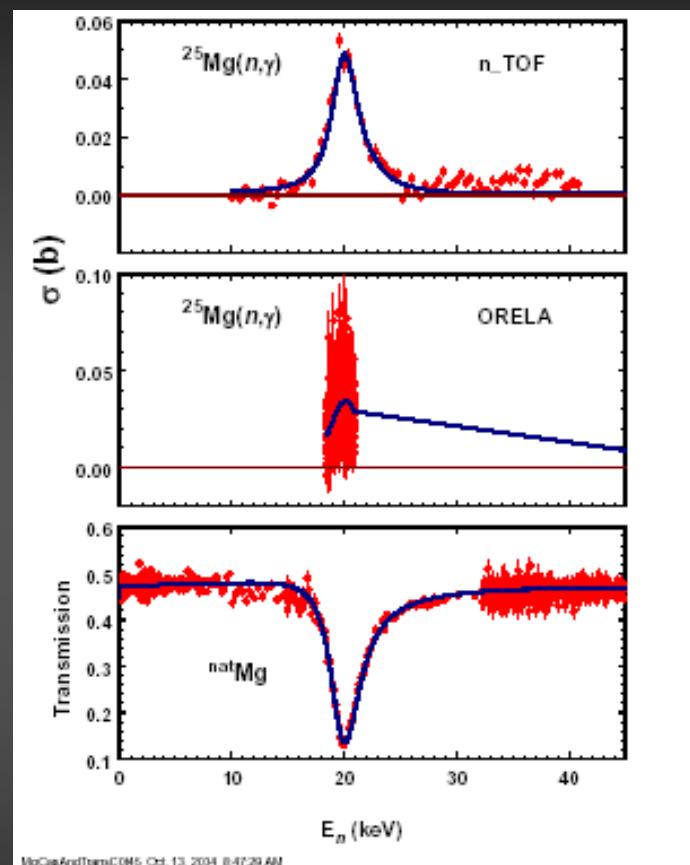
^{232}Th

^{209}Bi

^{237}Np

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

n_TOF experiments



Source: P Koehler & S O'Brien

Capture & transmission data (from ORELA)
analyzed simultaneously

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

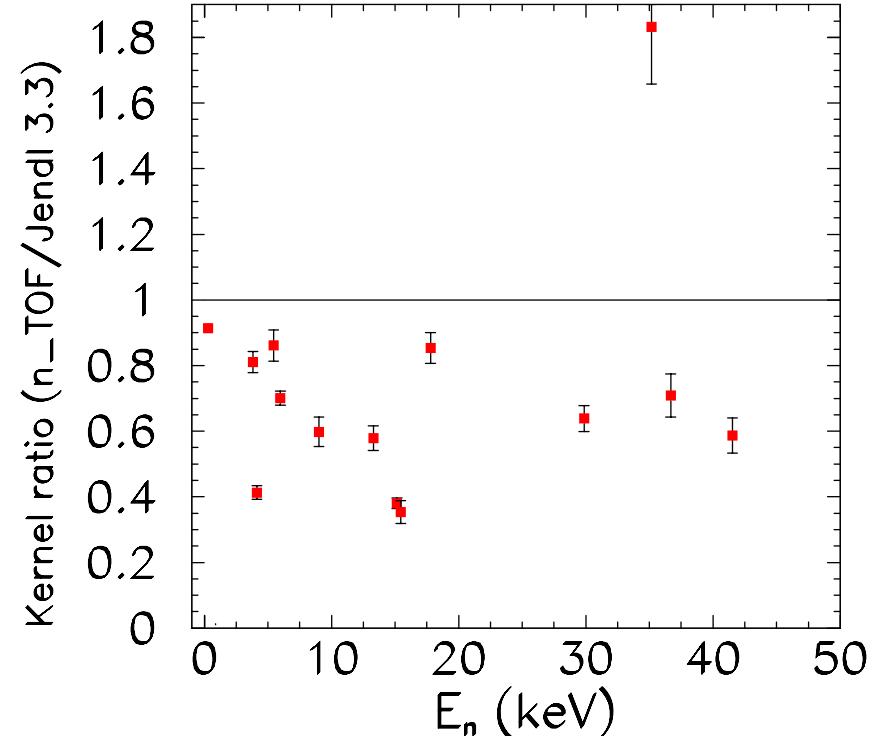
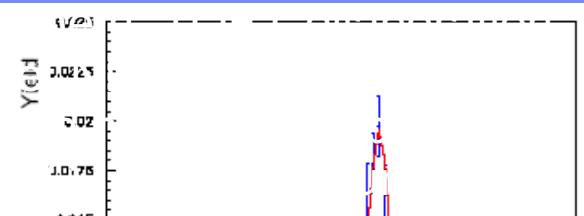
$^{241,243}\text{Am}, ^{245}\text{Cm}$

n_TOF experiments

C Moreau, et al.
ND2004 Conference, Santa
G Tagliente et al.

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

20% reduction
in the capture
strength
(average)



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

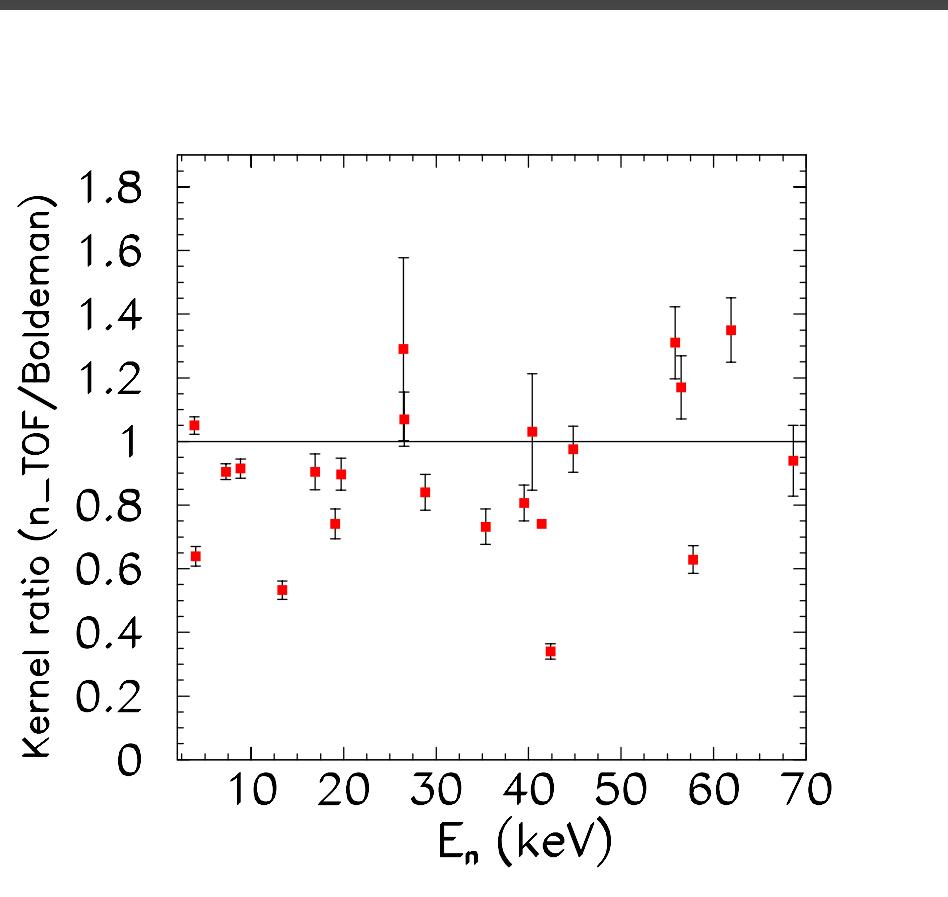
^{237}Np

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

n_TOF experiments

C 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

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



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}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

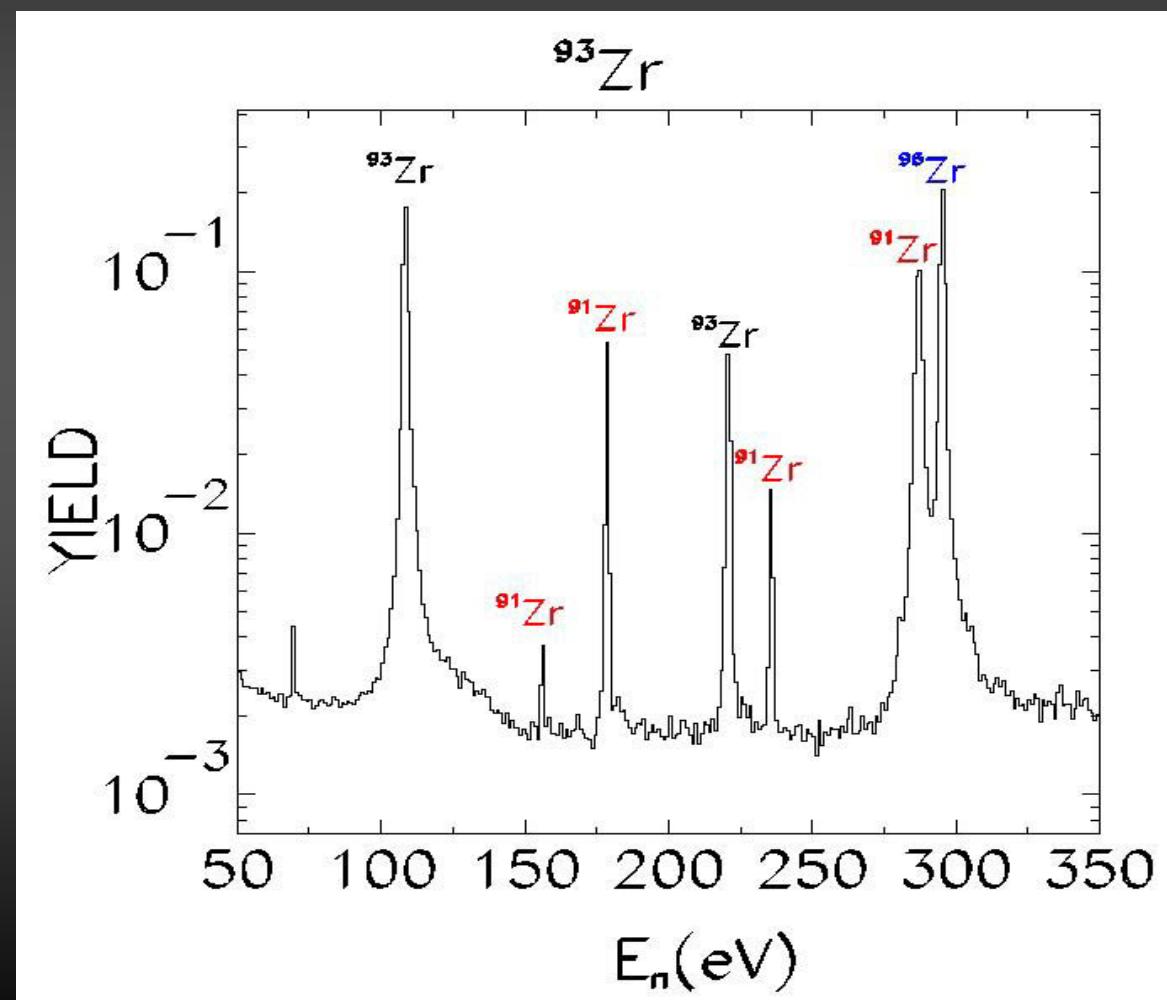
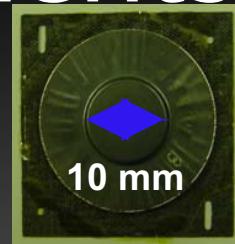
^{237}Np

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



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

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



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

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

R Terlizzi, et al. (The n_TOF Collaboration)

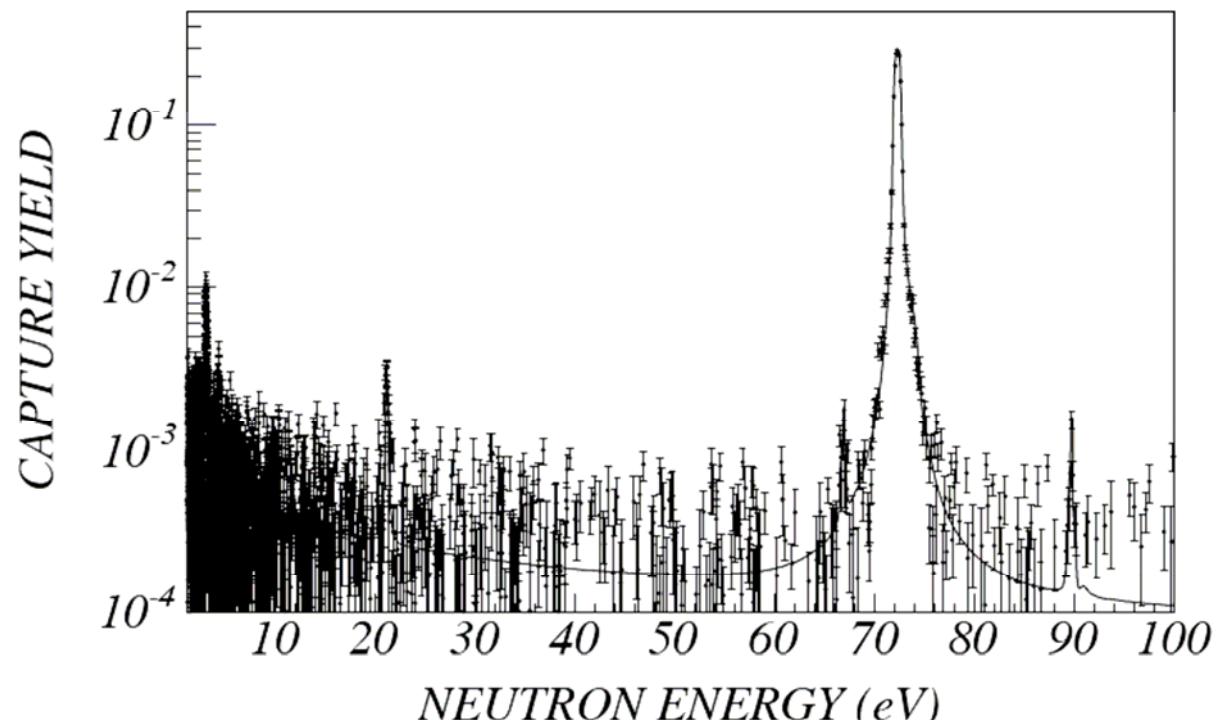
CGS12

Notre Dame, IN, USA

AIP Conference Proceedings 819

&

submitted for publication to PRC, October 2006



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

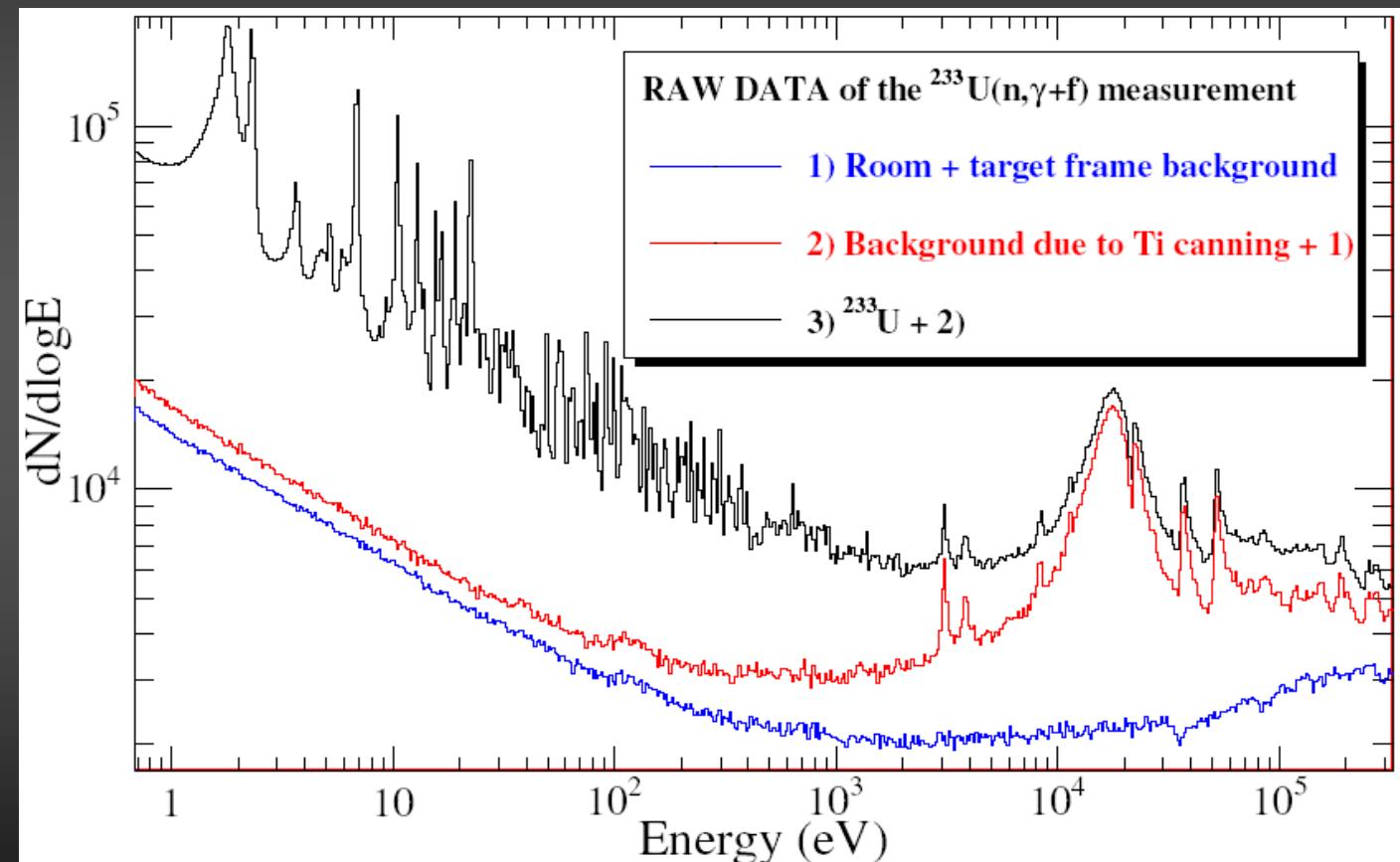
$^{241,243}\text{Am}, ^{245}\text{Cm}$



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

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

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



$n_{\text{-}}\text{TOF TAC in operation}$

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

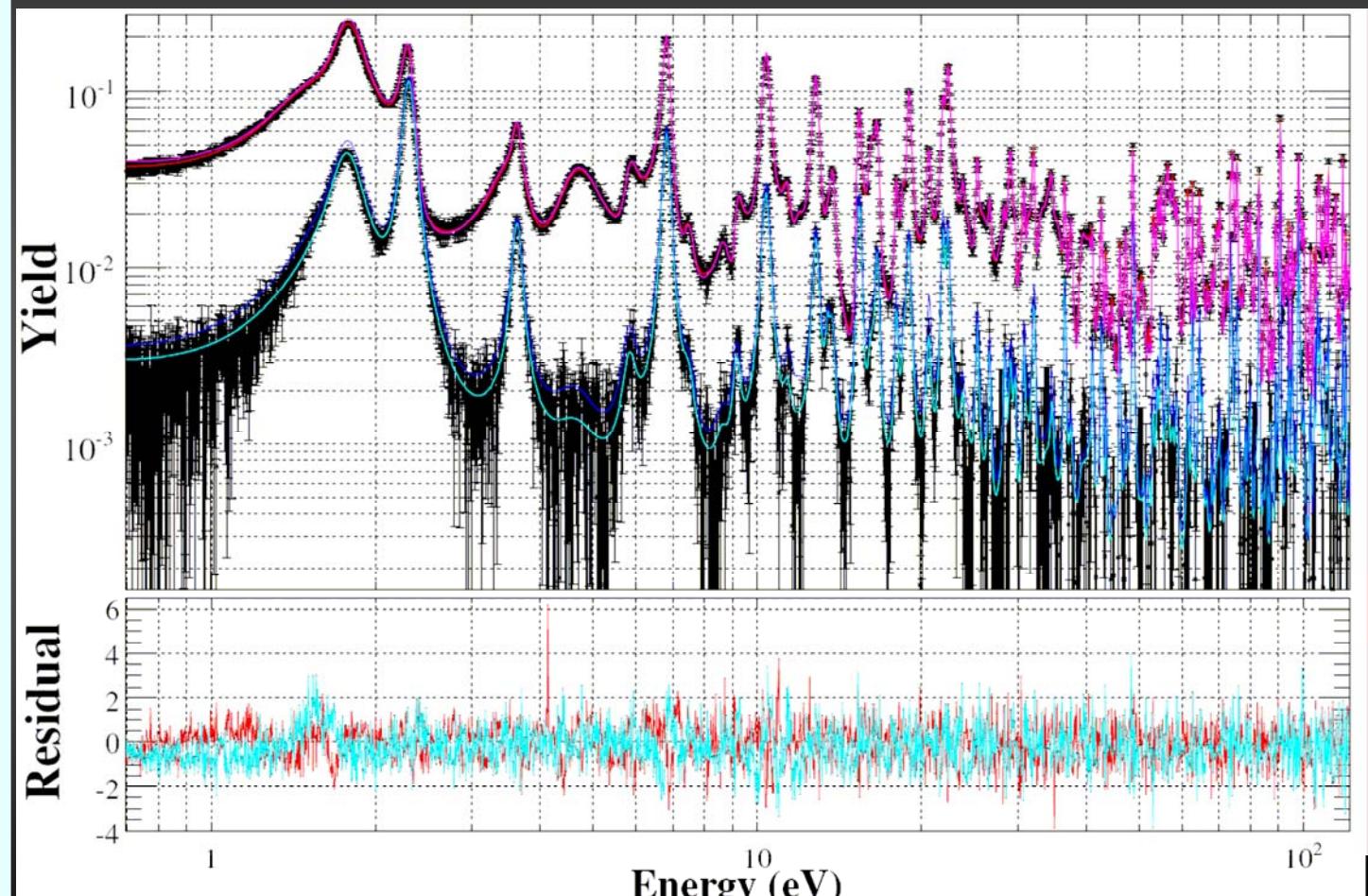
$^{241,243}\text{Am}, ^{245}\text{Cm}$



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

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

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



$n_{\text{-}}\text{TOF TAC}$ in operation: capture & fission discrimination

The $n_{\text{-}}\text{TOF}$ 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

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

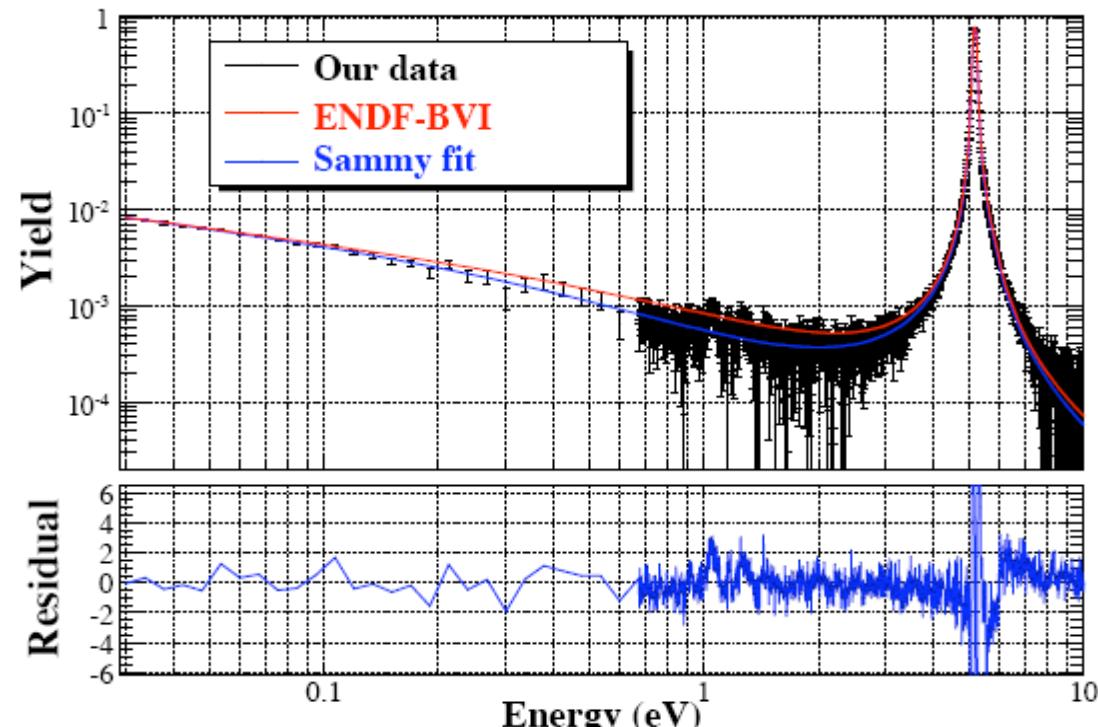


$n_{\text{-}}\text{TOF}$ experiments

W Dridi, E Berthoumieux, et al. (The $n_{\text{-}}\text{TOF}$ 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.



$n_{\text{-}}\text{TOF TAC in operation}$

The $n_{\text{-}}\text{TOF}$ 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

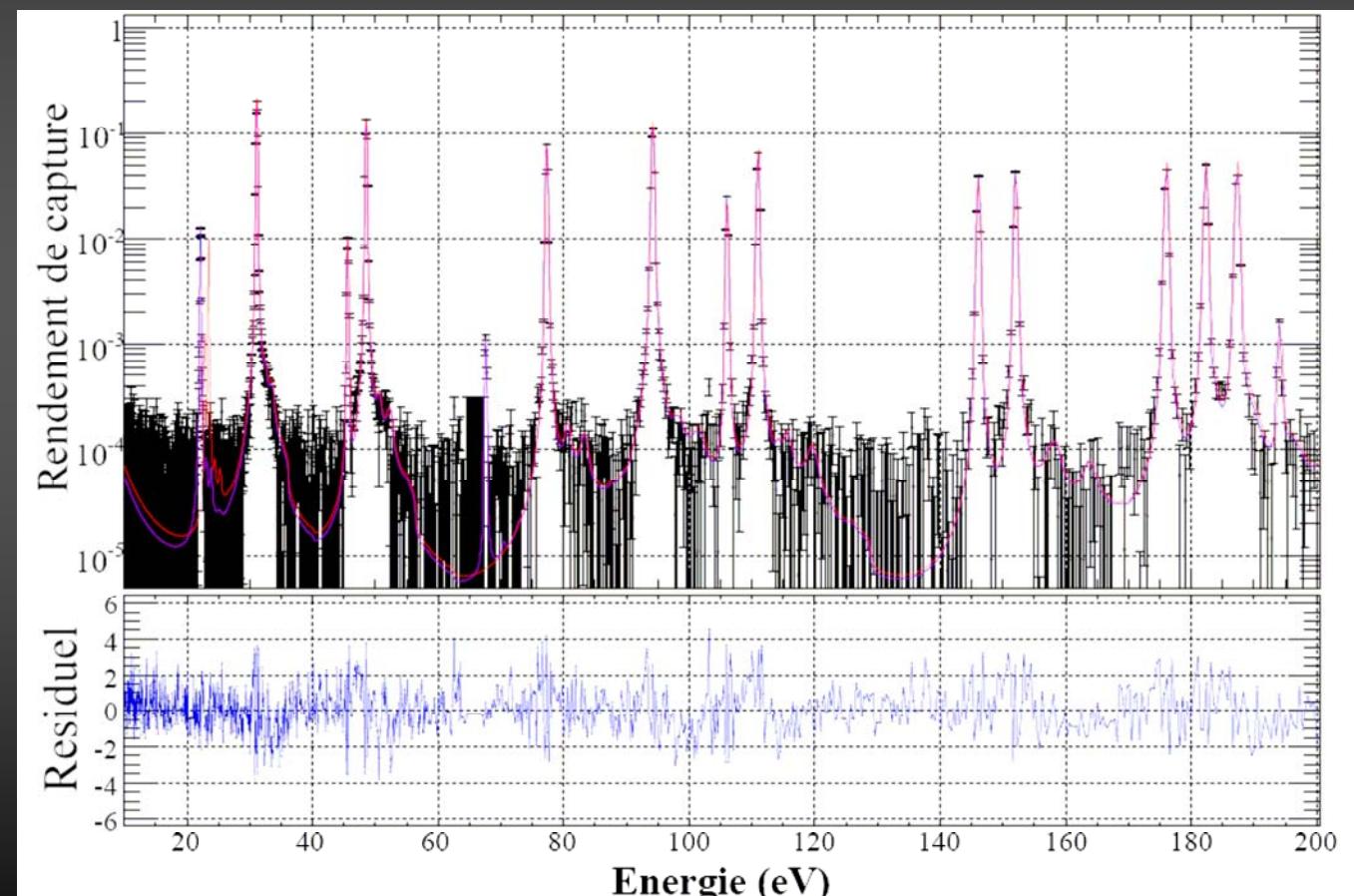
$^{241,243}\text{Am}$, ^{245}Cm



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

W Dridi, E Berthoumieux, et al. (The $n_{\text{-}}\text{TOF}$ Collaboration)
PHYSOR-2006, Vancouver, September 2006
full paper in preparation

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



$n_{\text{-}}\text{TOF TAC in operation}$

The $n_{\text{-}}\text{TOF}$ 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

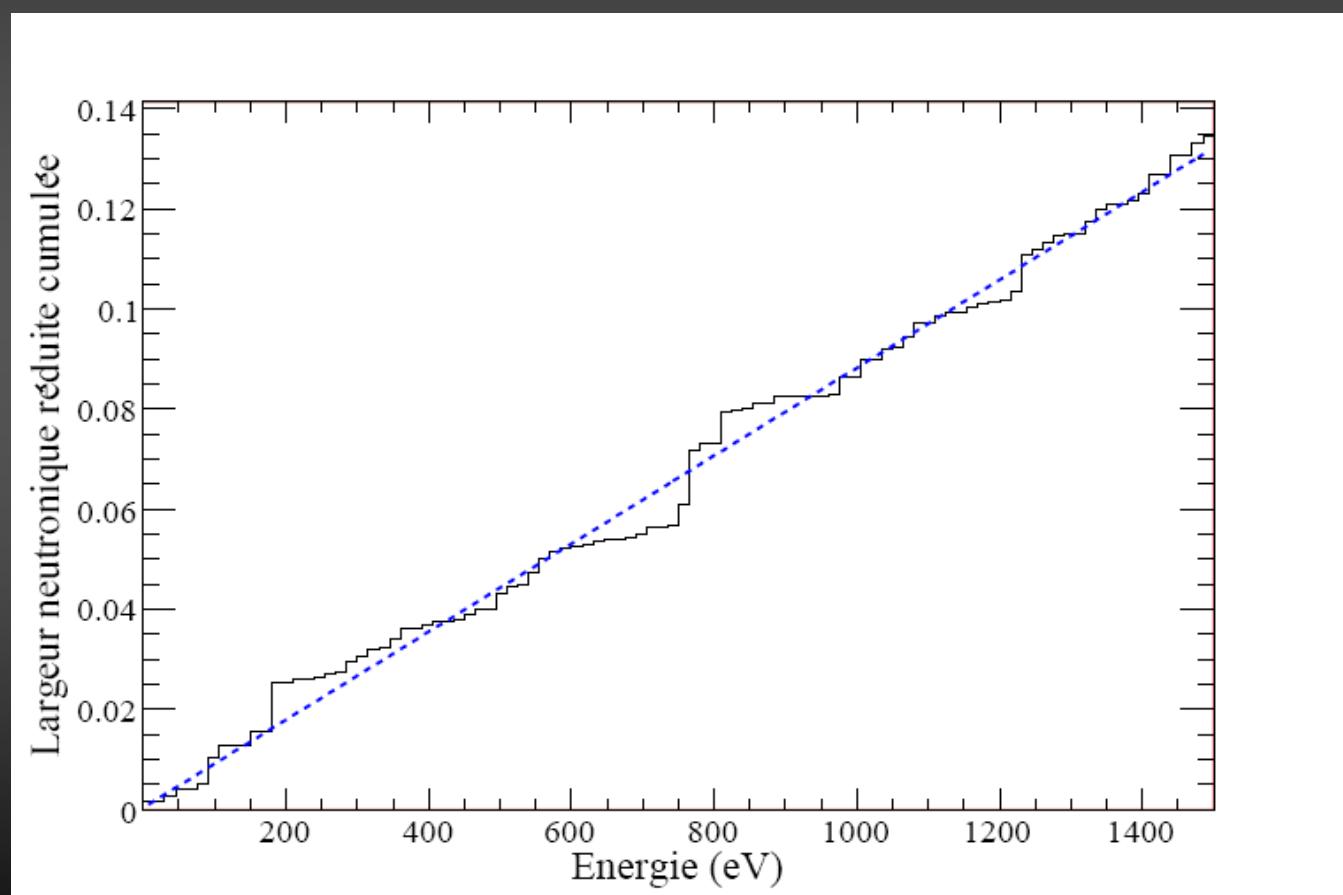
$^{241,243}\text{Am}$, ^{245}Cm



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

W Dridi, E Berthoumieux, et al. (The $n_{\text{-}}\text{TOF}$ Collaboration)
PHYSOR-2006, Vancouver, September 2006
full paper in preparation

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



$n_{\text{-}}\text{TOF TAC in operation}$

The $n_{\text{-}}\text{TOF}$ 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

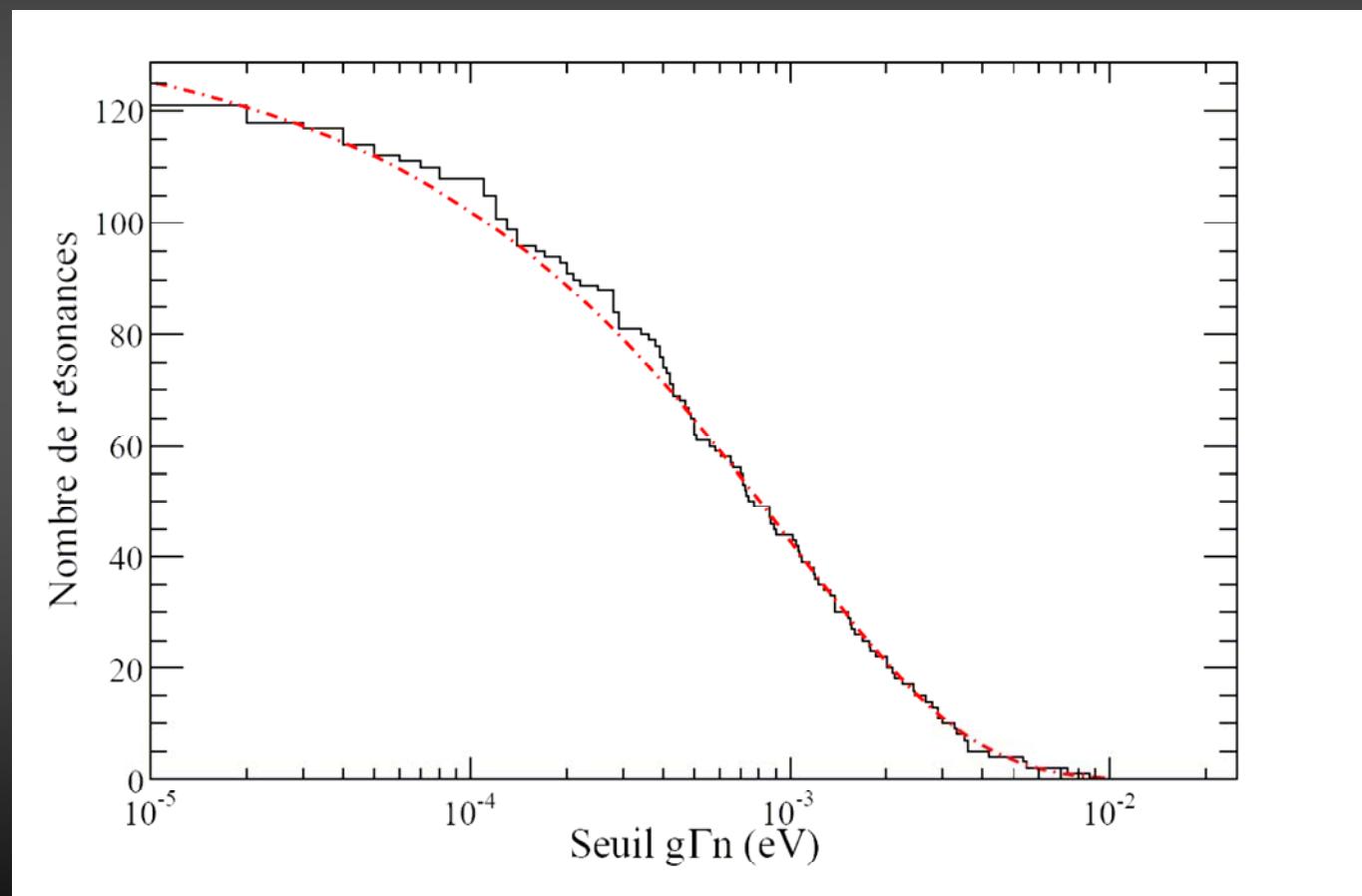
$^{241,243}\text{Am}, ^{245}\text{Cm}$



n_TOF experiments

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

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



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

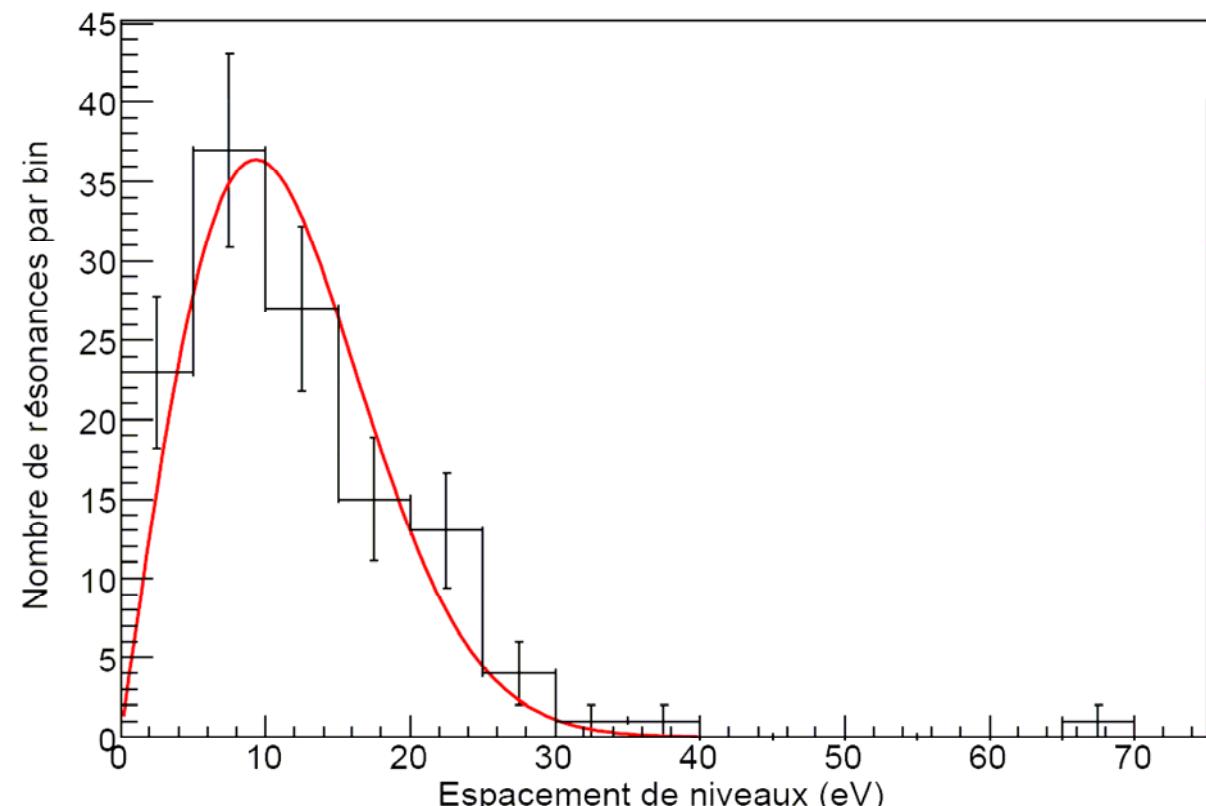
$^{241,243}\text{Am}$, ^{245}Cm



n_TOF experiments

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

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



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

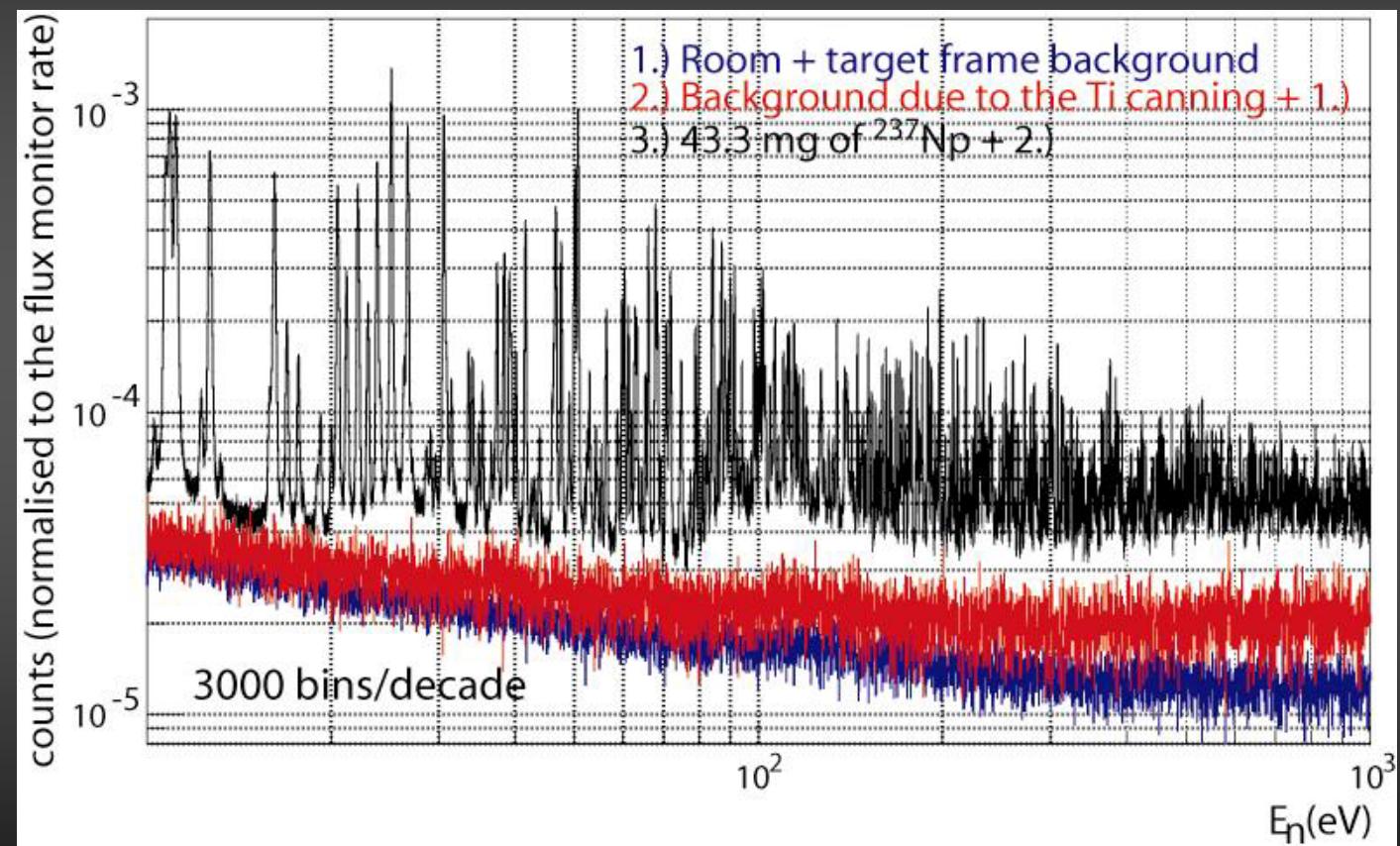
^{237}Np

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



n_TOF experiments

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



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

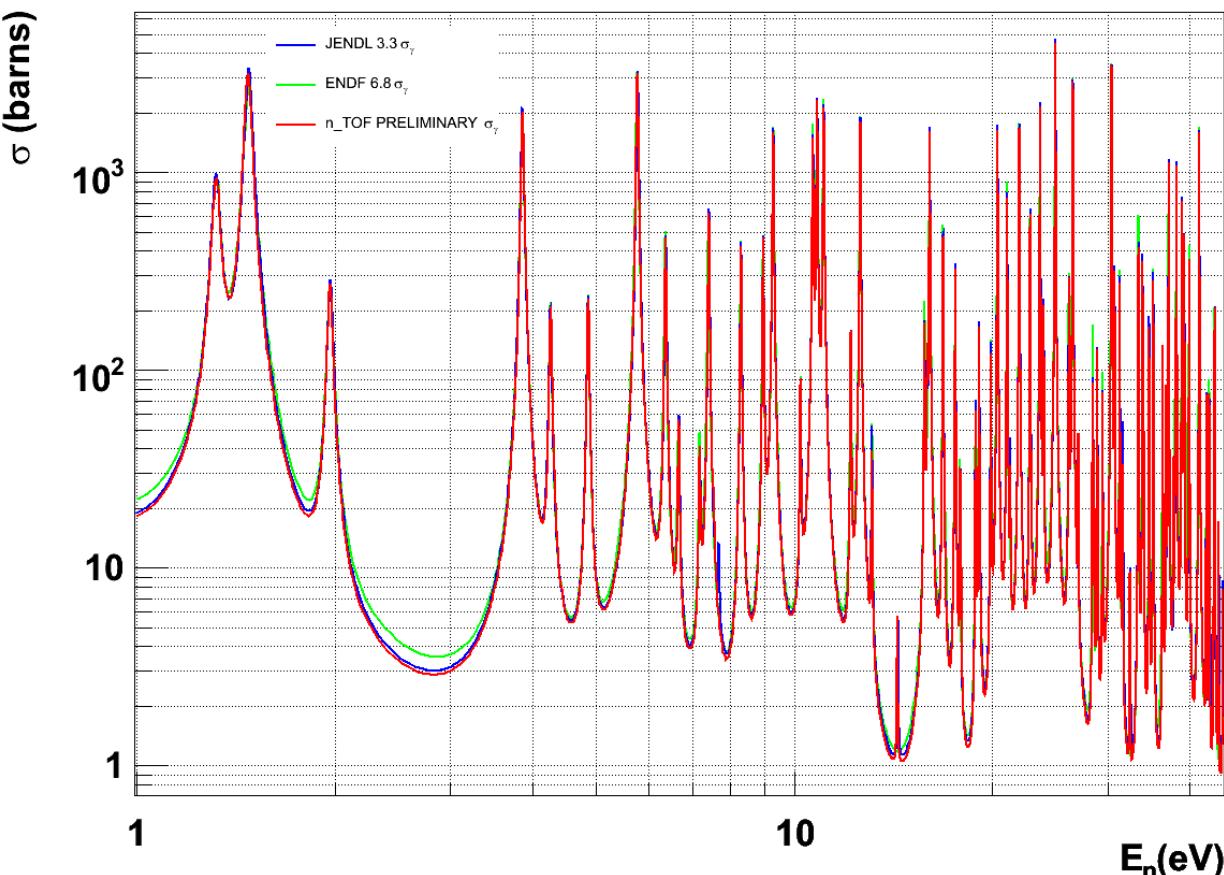
$^{241,243}\text{Am}$, ^{245}Cm



n_TOF experiments

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

n_TOF ^{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

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

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

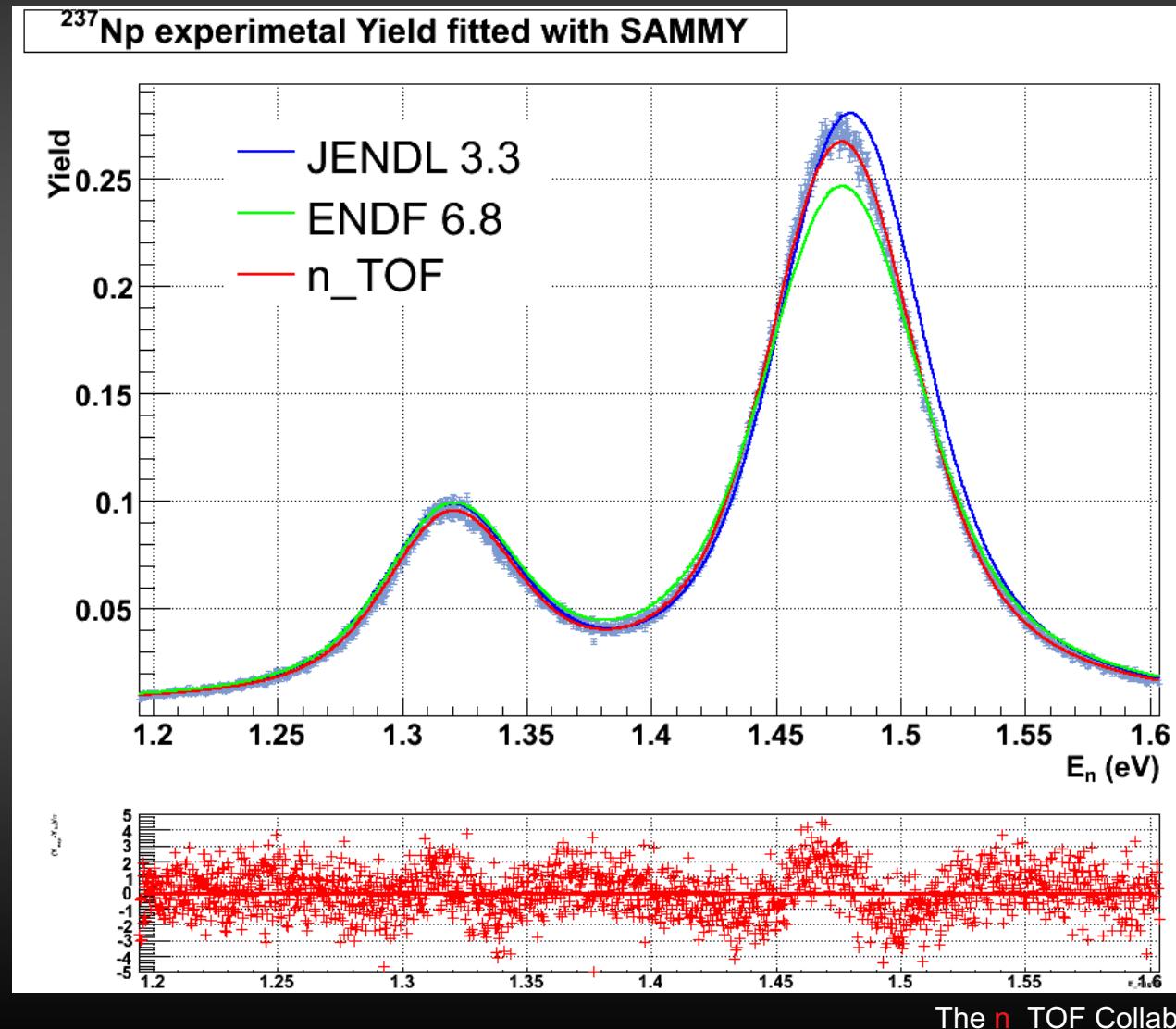
^{237}Np

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



n_TOF experiments

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



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

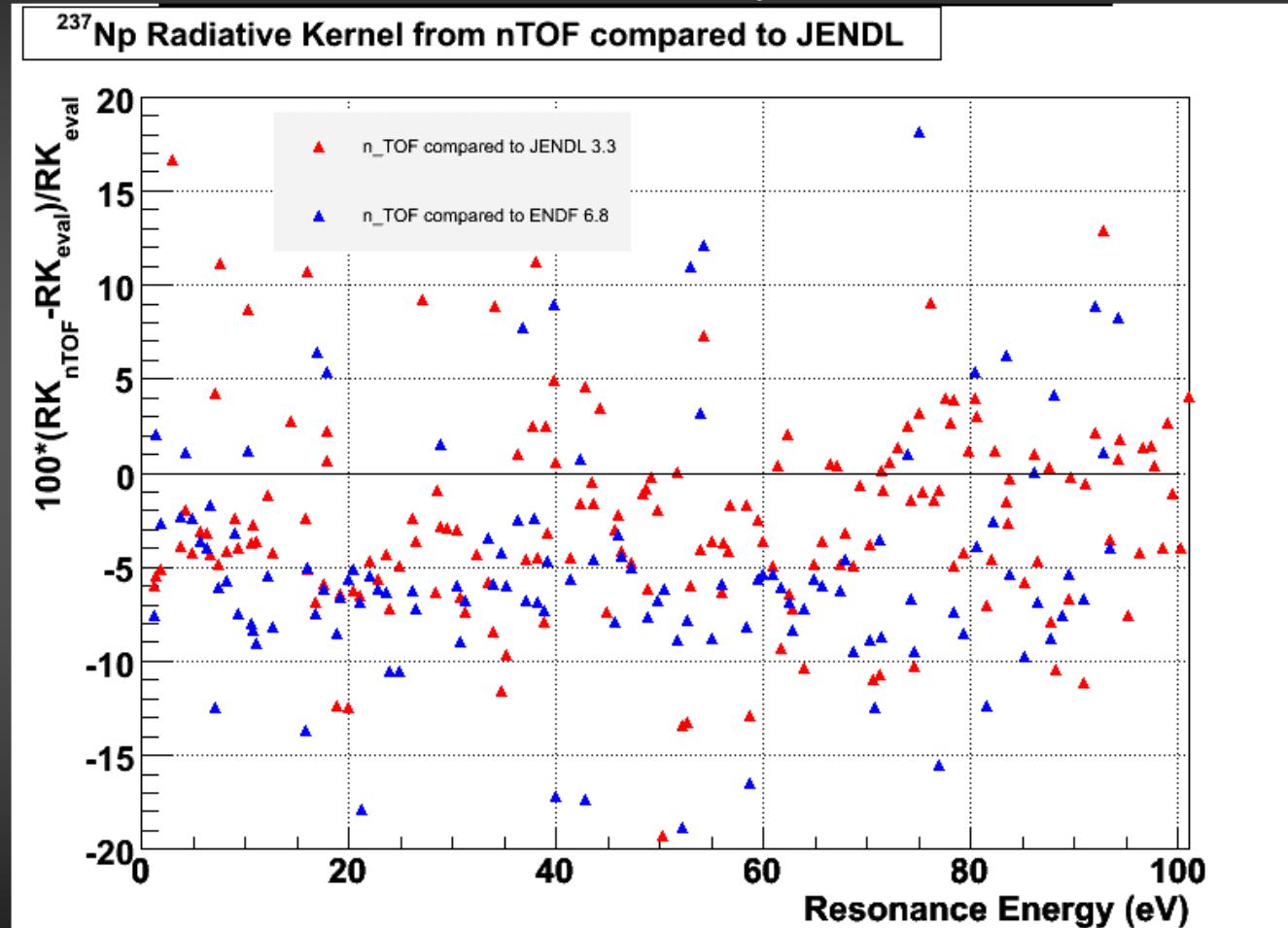
^{237}Np

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



n_TOF experiments

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



$\text{RK}_{\text{n_TOF}}$ 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

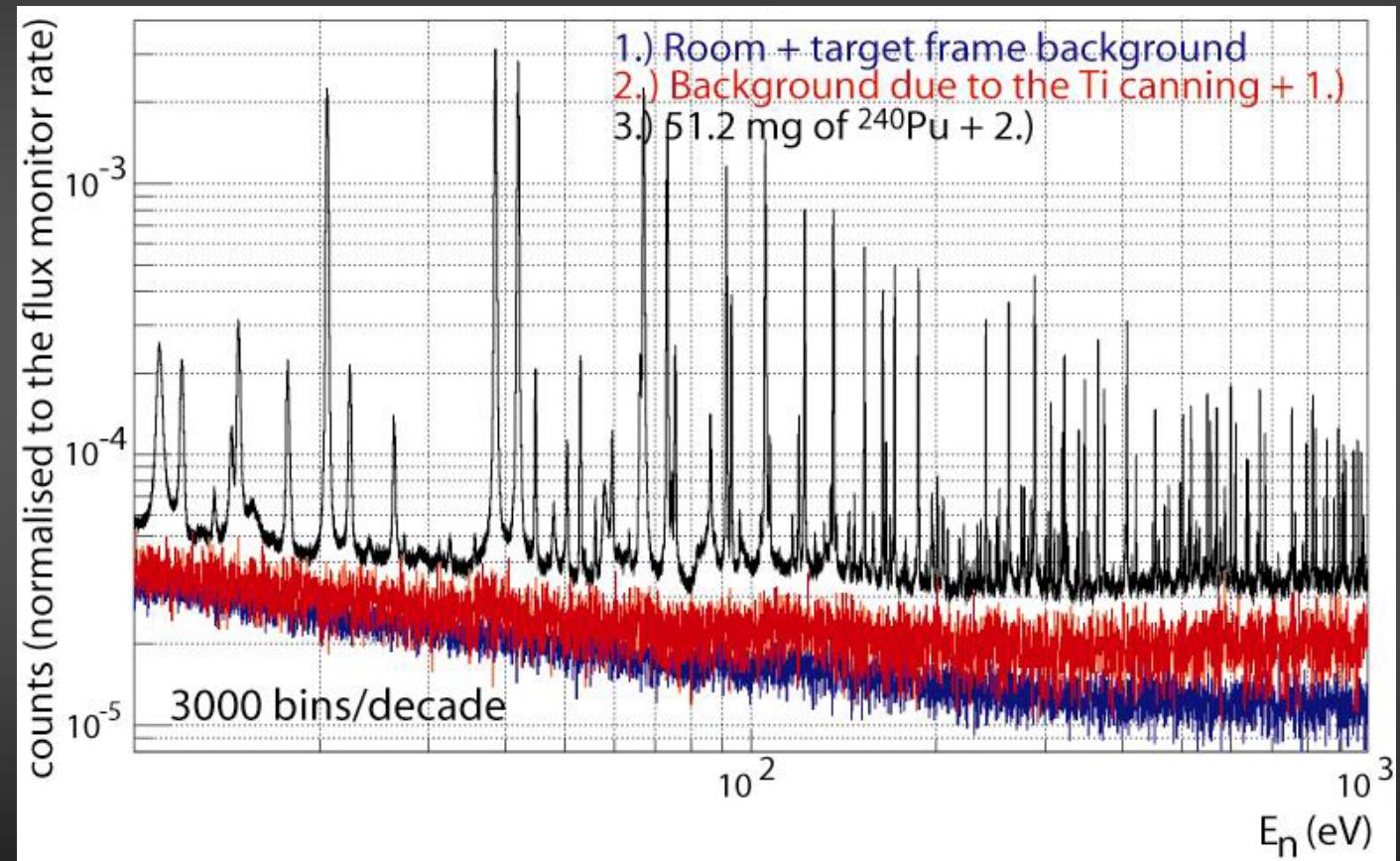
^{237}Np

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



n_TOF experiments

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



n_TOF TAC in operation

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

Fission

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

^{232}Th

^{209}Bi

^{237}Np

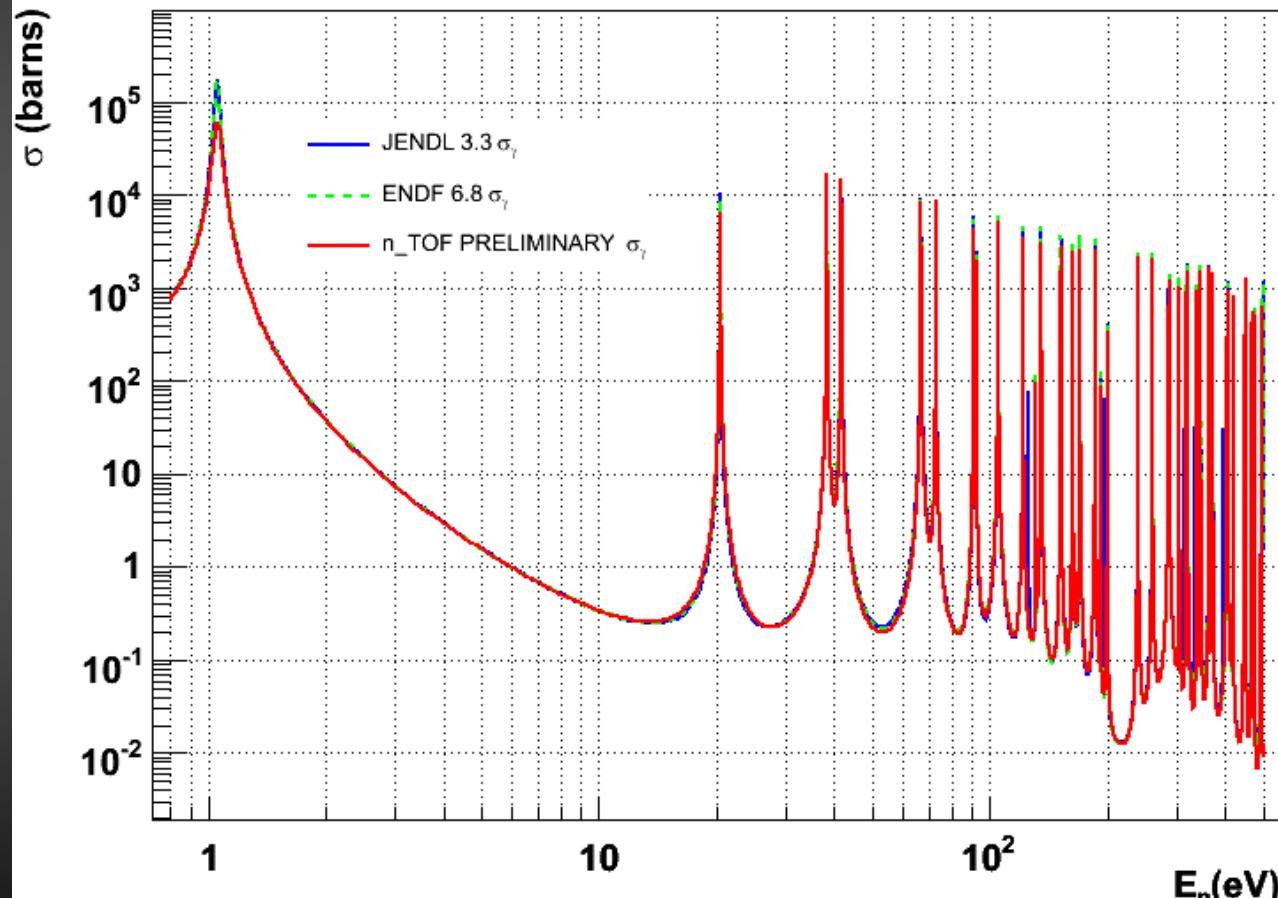
$^{241,243}\text{Am}, ^{245}\text{Cm}$



n_TOF experiments

C 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

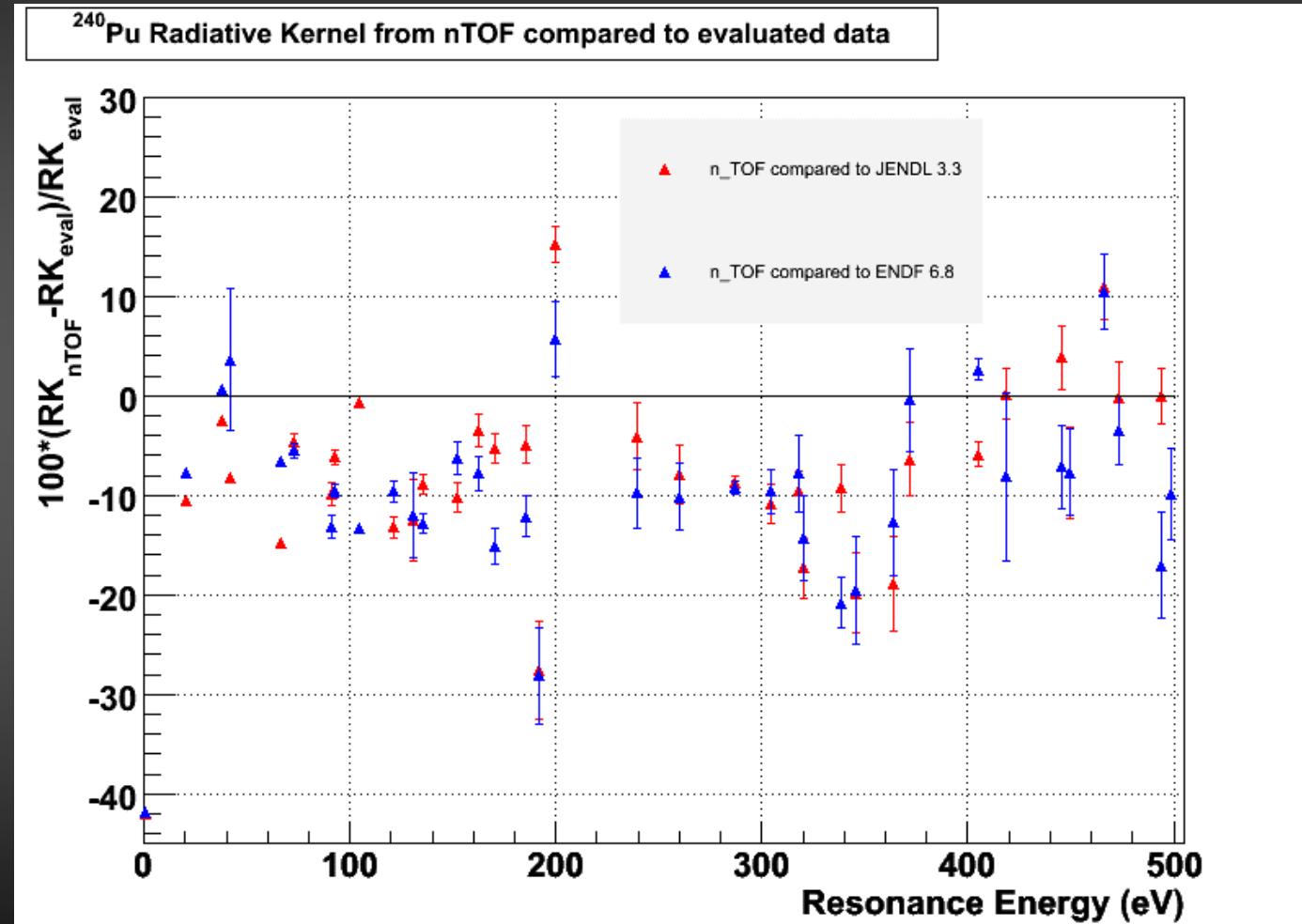
^{237}Np

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

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

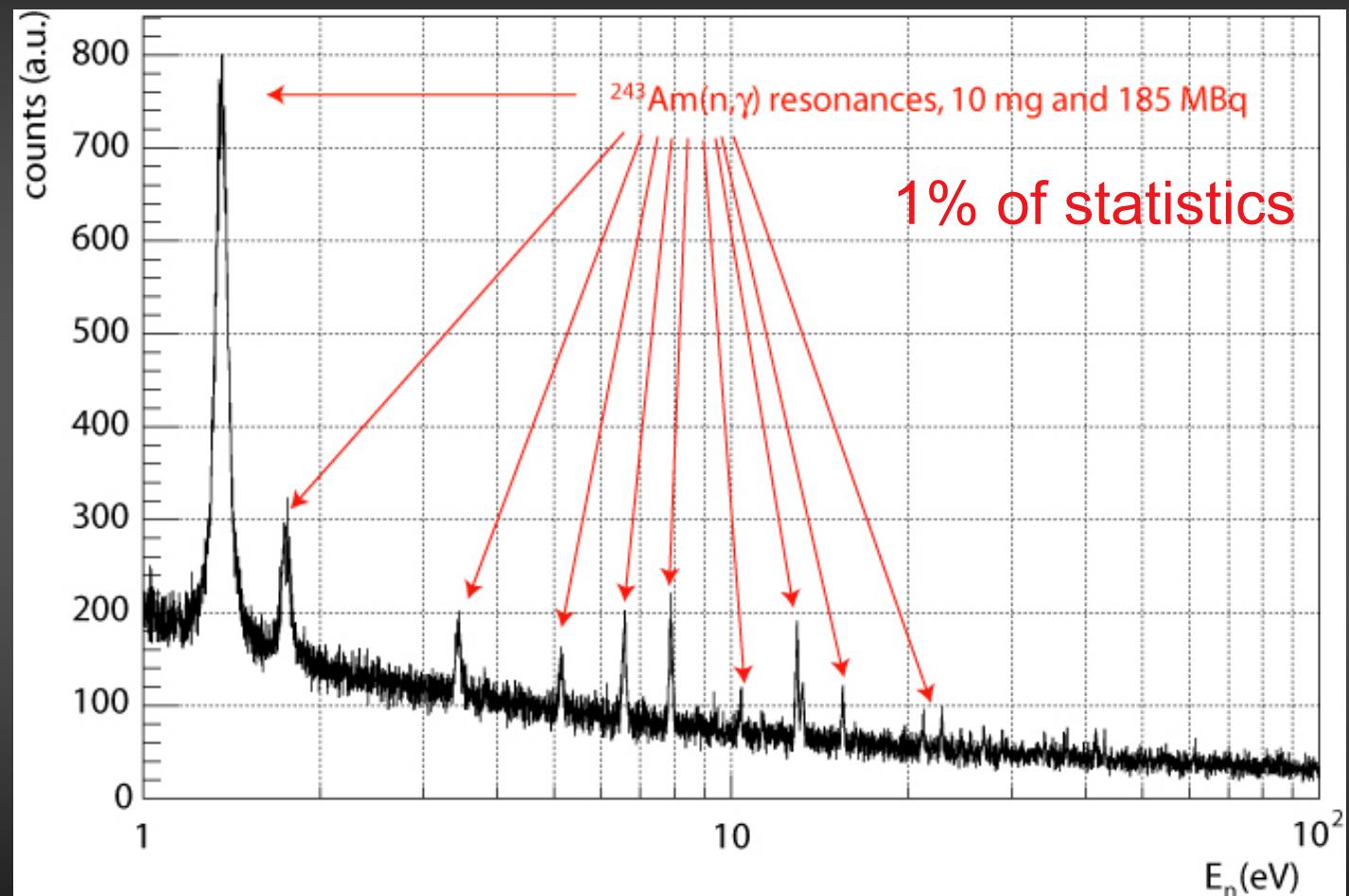
^{237}Np

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



n_TOF experiments

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



n_TOF TAC in operation

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

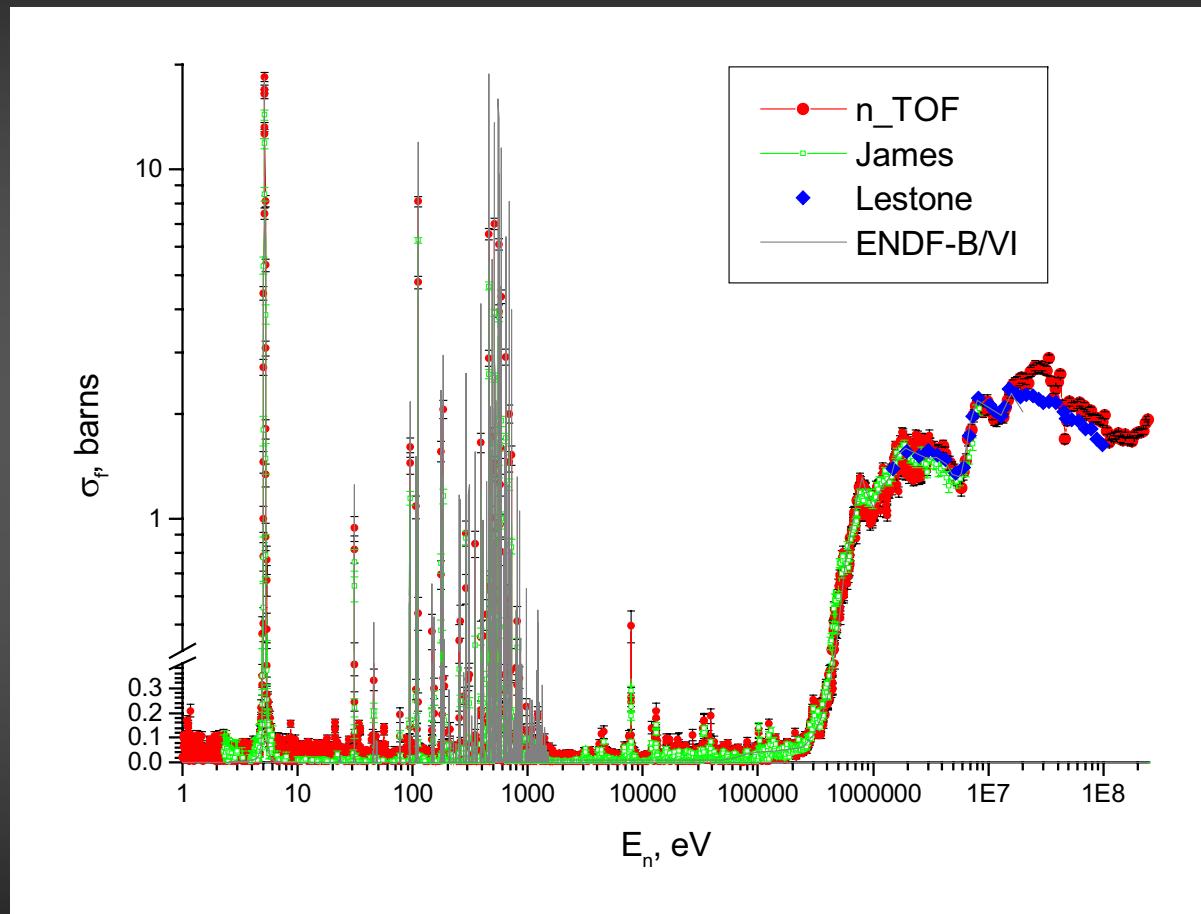
$^{241,243}\text{Am}, {}^{245}\text{Cm}$



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

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

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

^{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

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

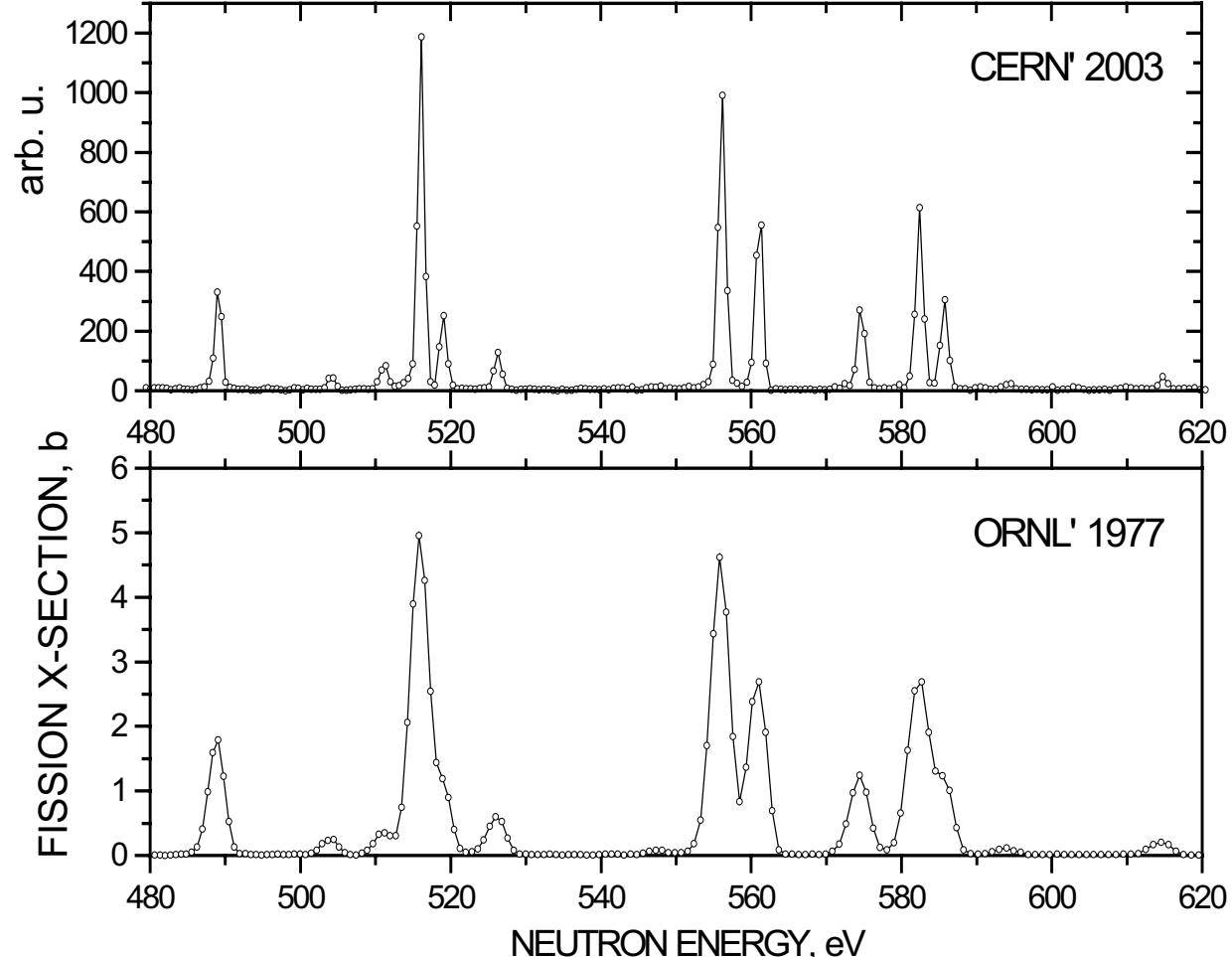


$^{234}\text{U}(n,f)$

n_TOF experiments

PPACs & FIC-0 (2003)

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



High-resolution data up to high(er) energies

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

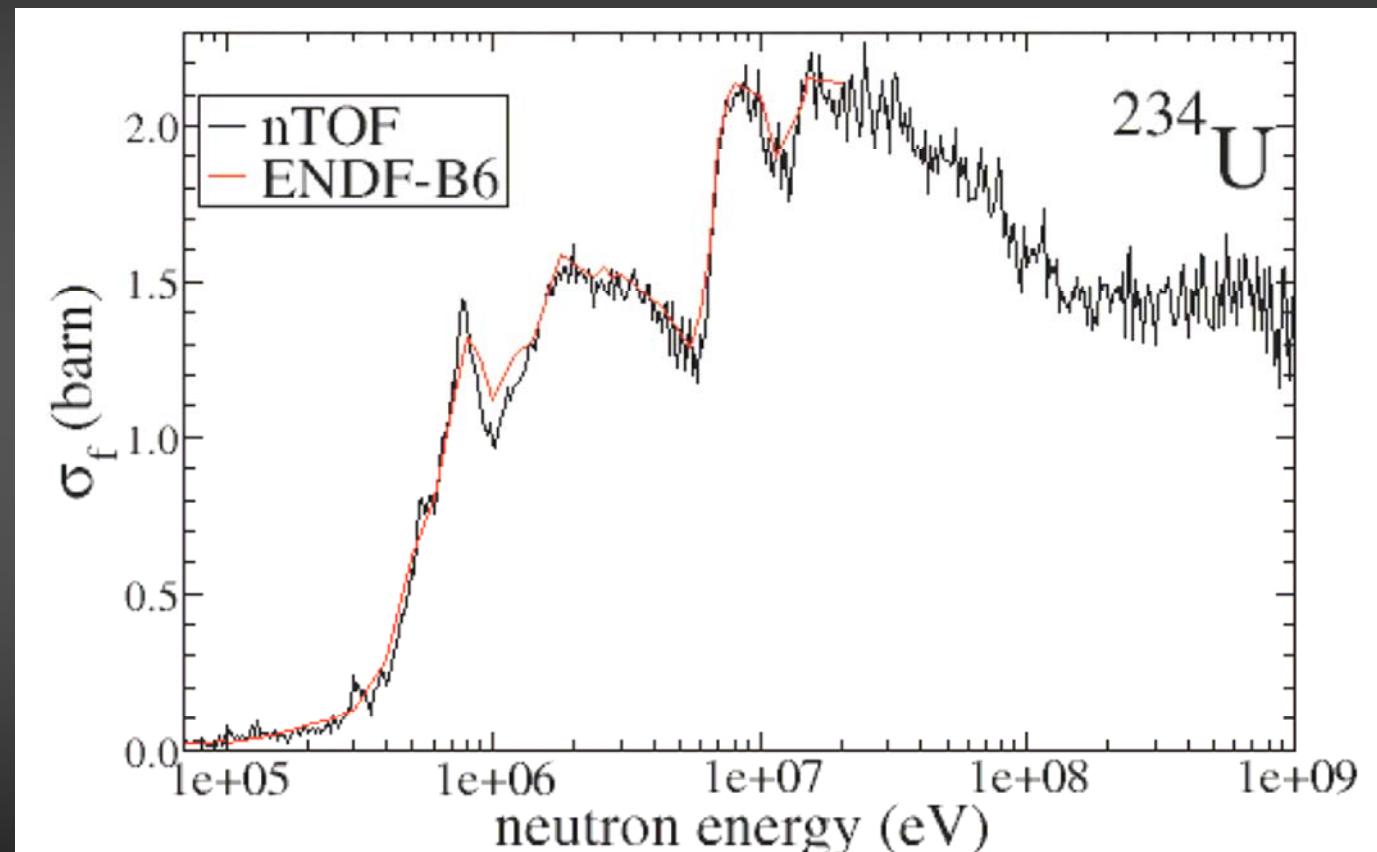
$^{241,243}\text{Am}, ^{245}\text{Cm}$



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

n_TOF experiments

PPACs & FIC-0 (2003)



High-resolution data up to high(er) energies

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

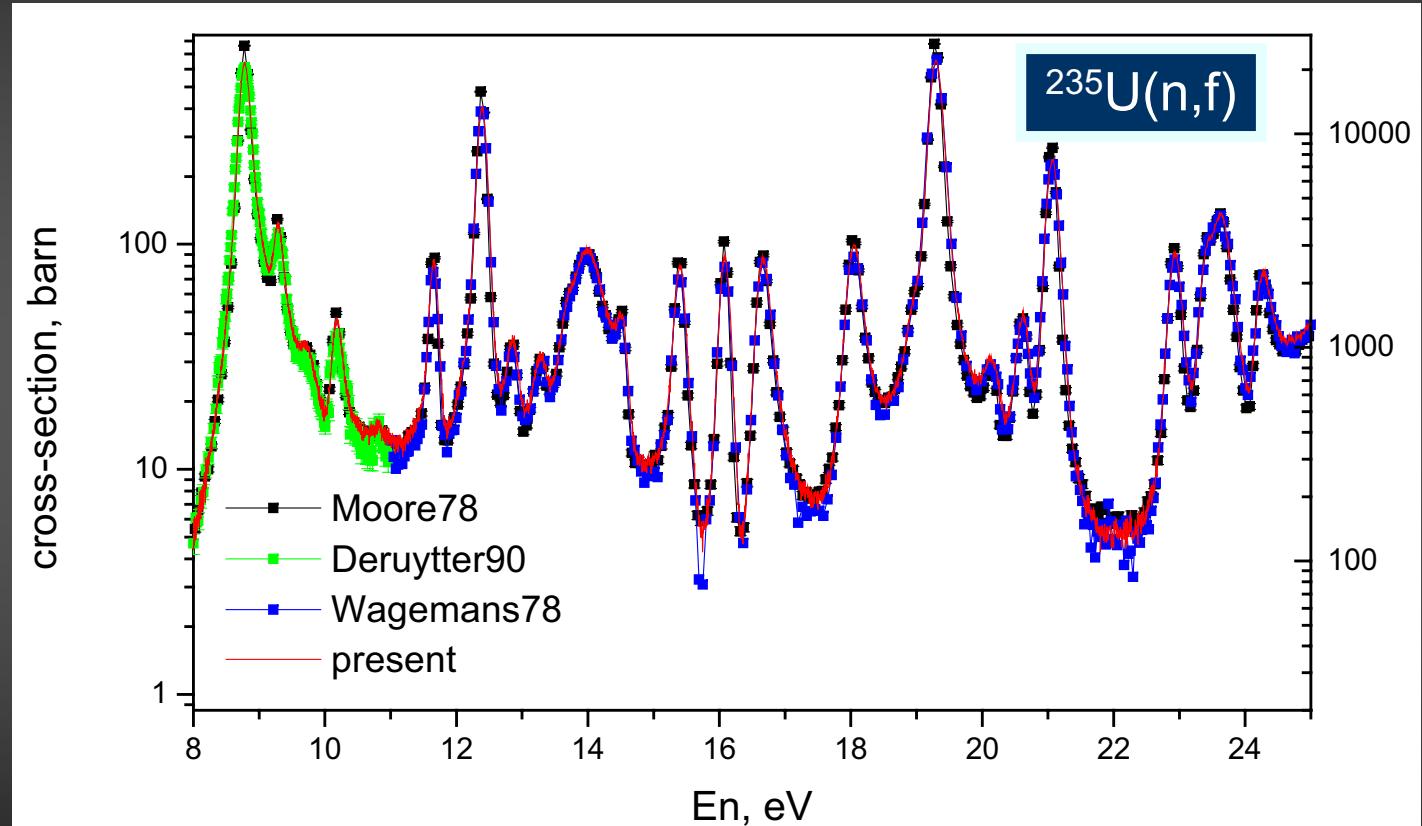
^{237}Np

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



n_TOF experiments

FIC-0 (2003)



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

Capture

^{151}Sm

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

^{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

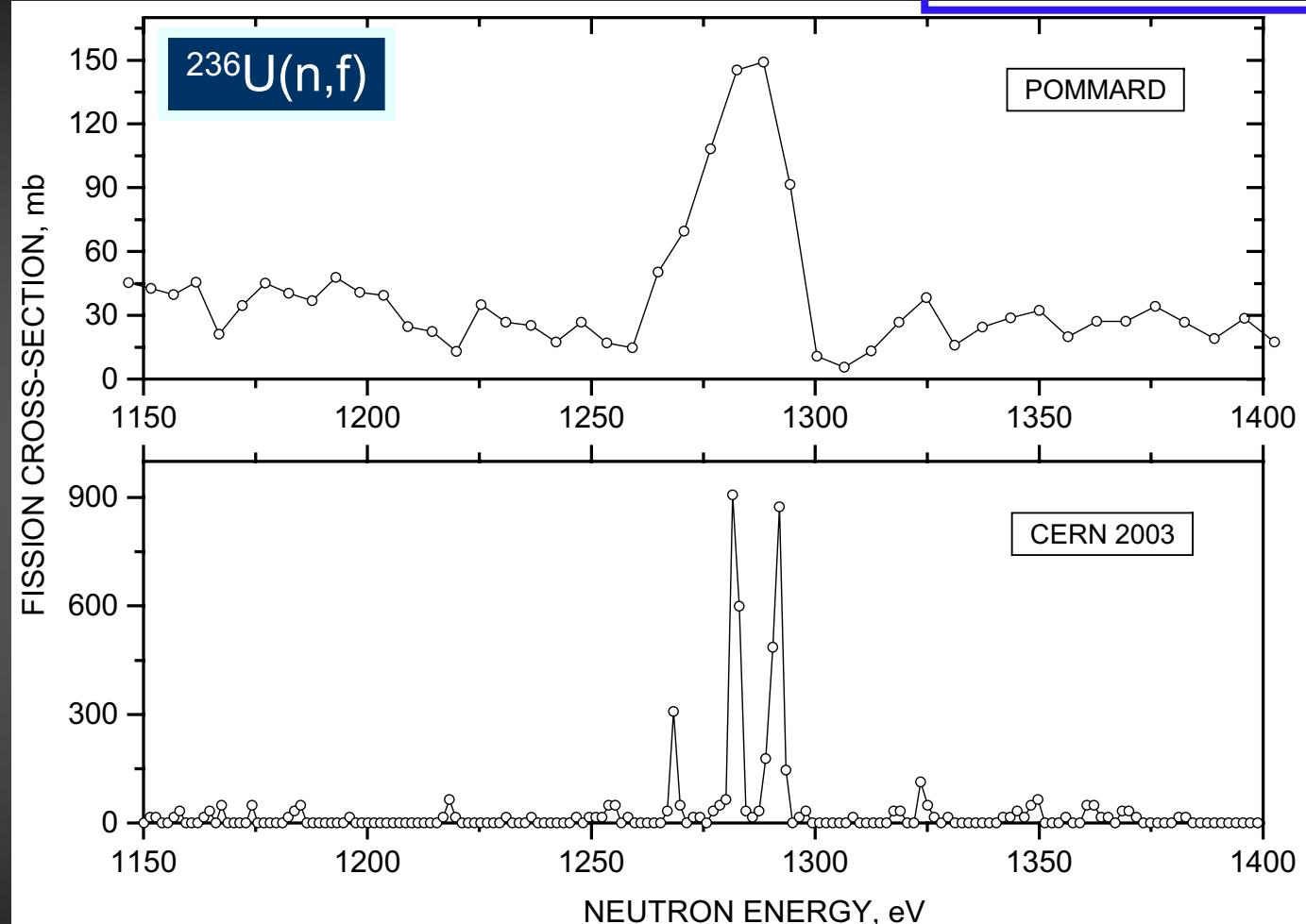
^{237}Np

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



n_TOF experiments

FIC-1 (2003)



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

Capture

^{151}Sm
 $^{204,206,207,208}\text{Pb}, ^{209}\text{Bi}$

^{232}Th

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

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

^{139}La

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

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

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

Fission

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

^{232}Th

^{209}Bi

^{237}Np

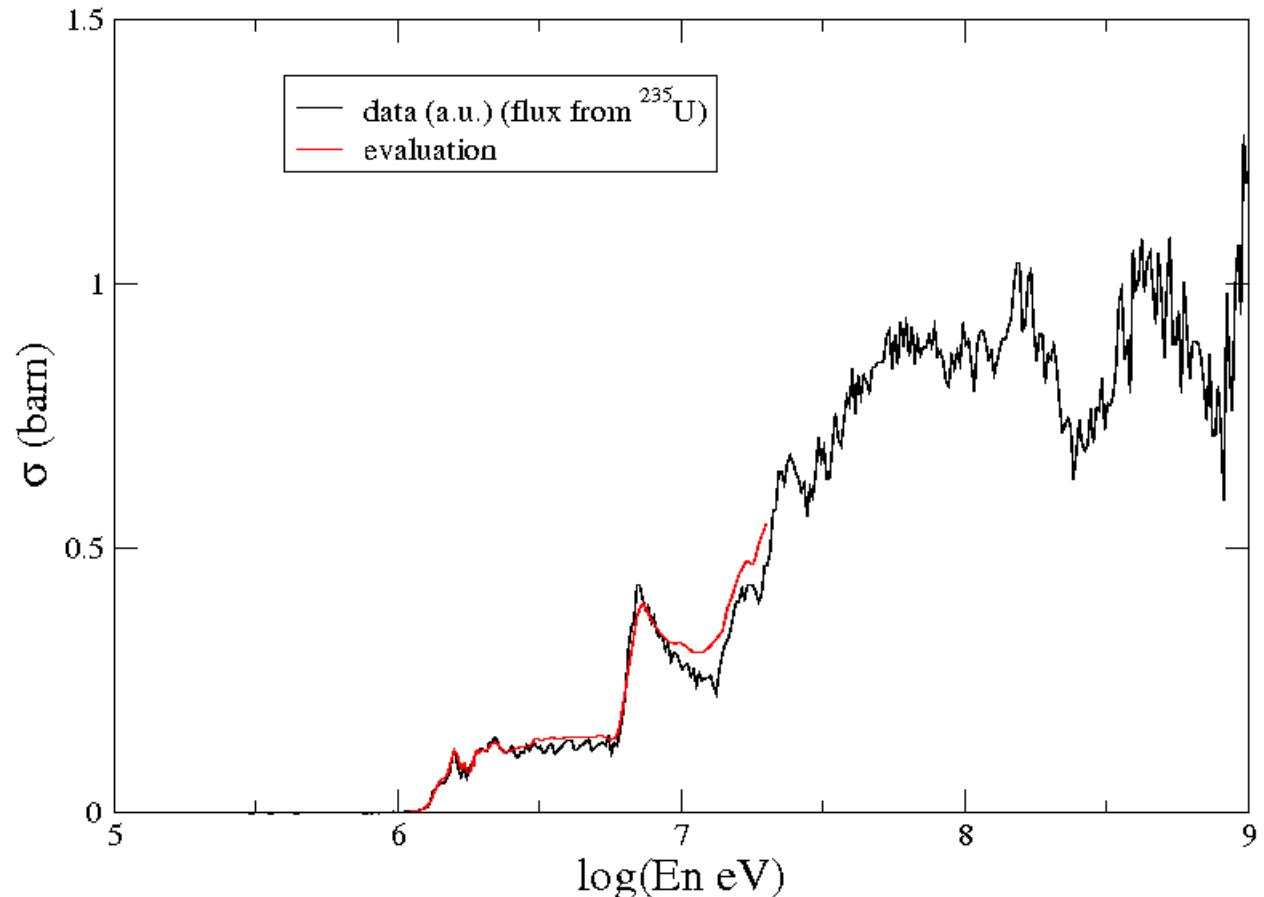
$^{241,243}\text{Am}, ^{245}\text{Cm}$



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

n_TOF experiments

PPAC detectors



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

Capture

^{151}Sm

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

^{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

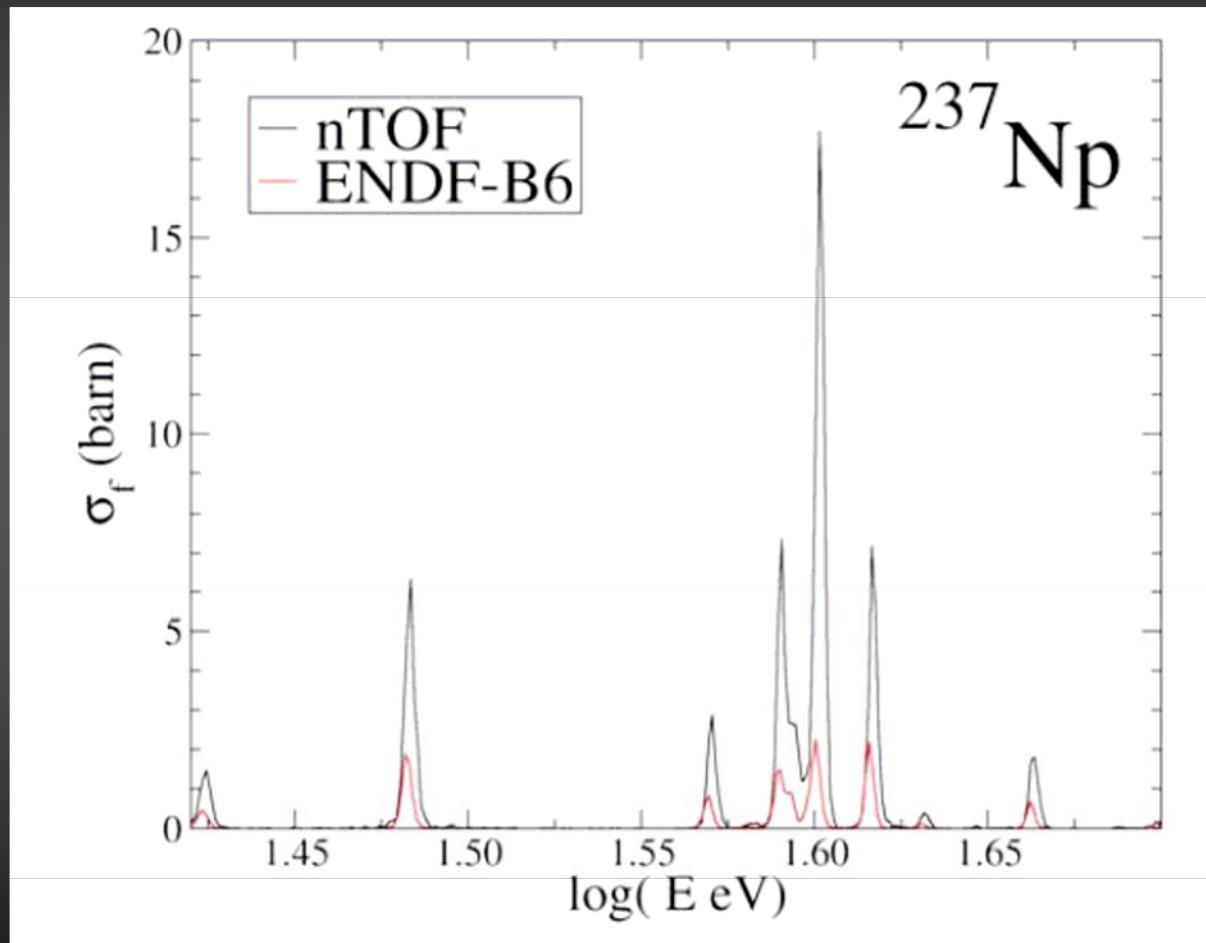
$^{241,243}\text{Am}, ^{245}\text{Cm}$



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

n_TOF experiments

FIC-0 (2003)



Higher fission x-section in the sub-threshold region

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

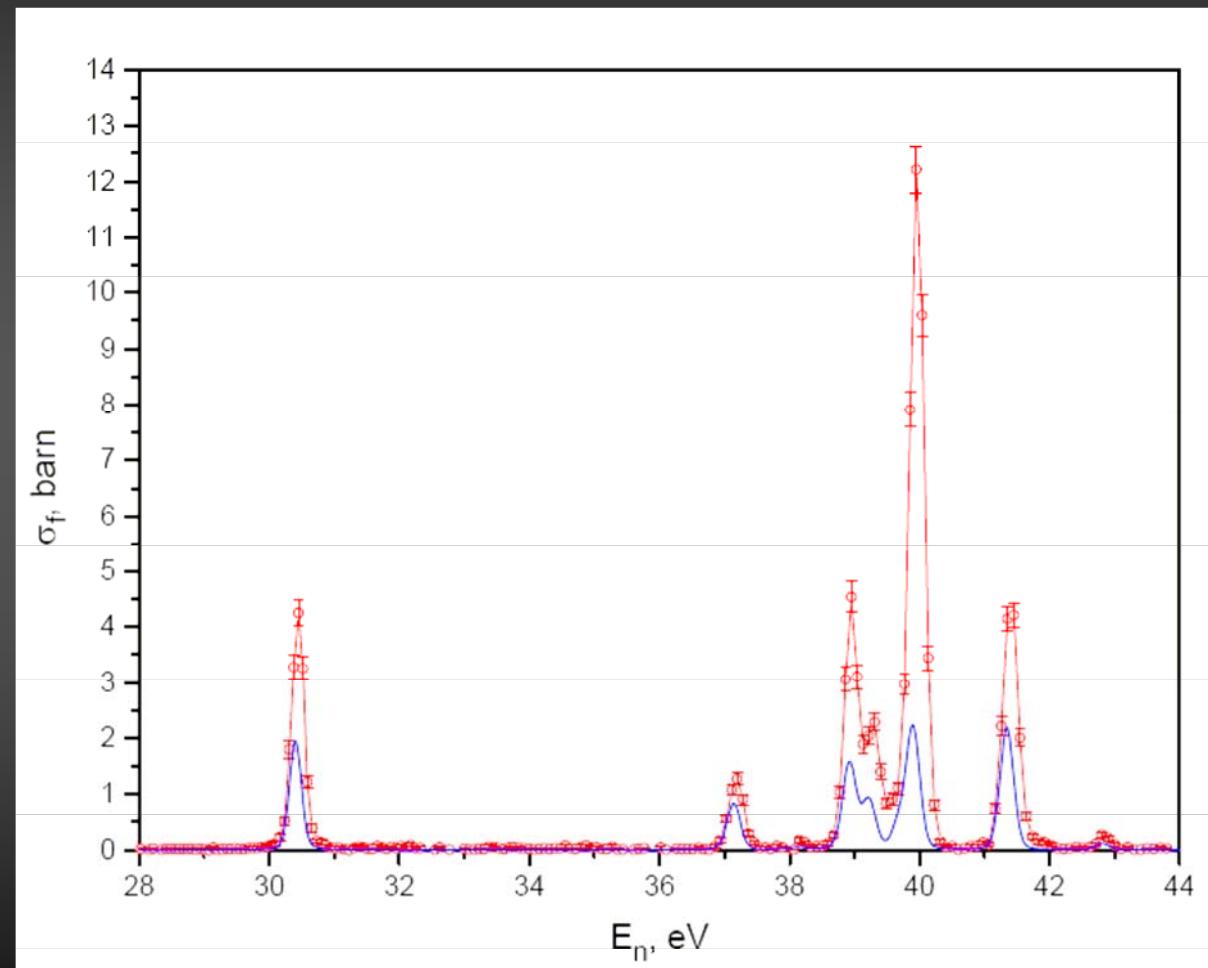
$^{241,243}\text{Am}, ^{245}\text{Cm}$



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

$n_{_}$ TOF experiments

PPACs (2003)



Higher fission x-section in the sub-threshold region

The $n_{_}$ TOF Collaboration

Capture

^{151}Sm

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

^{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

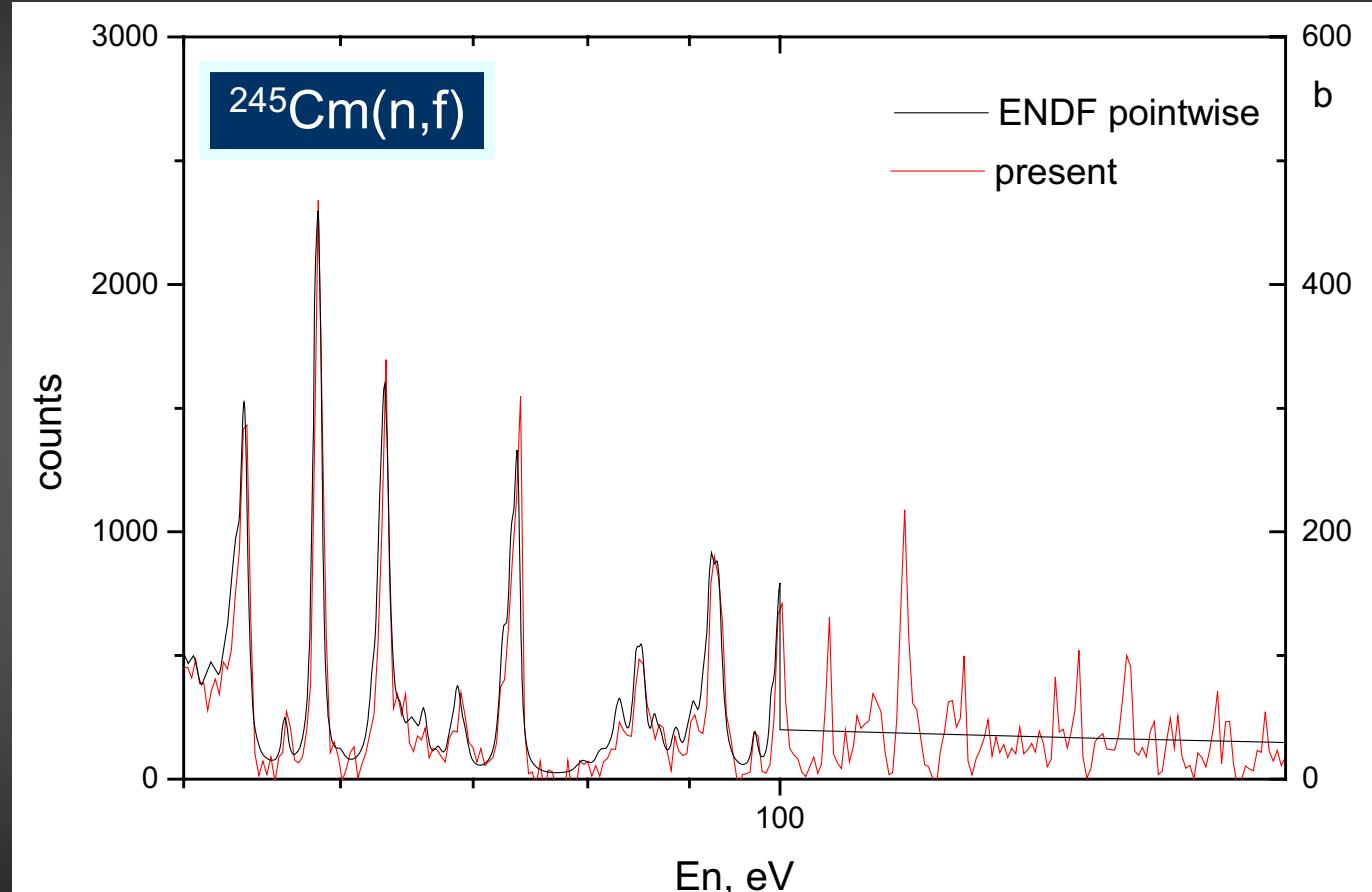
^{237}Np

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



n_TOF experiments

FIC-1 (2003)



High-resolution data up to high(er) energies

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

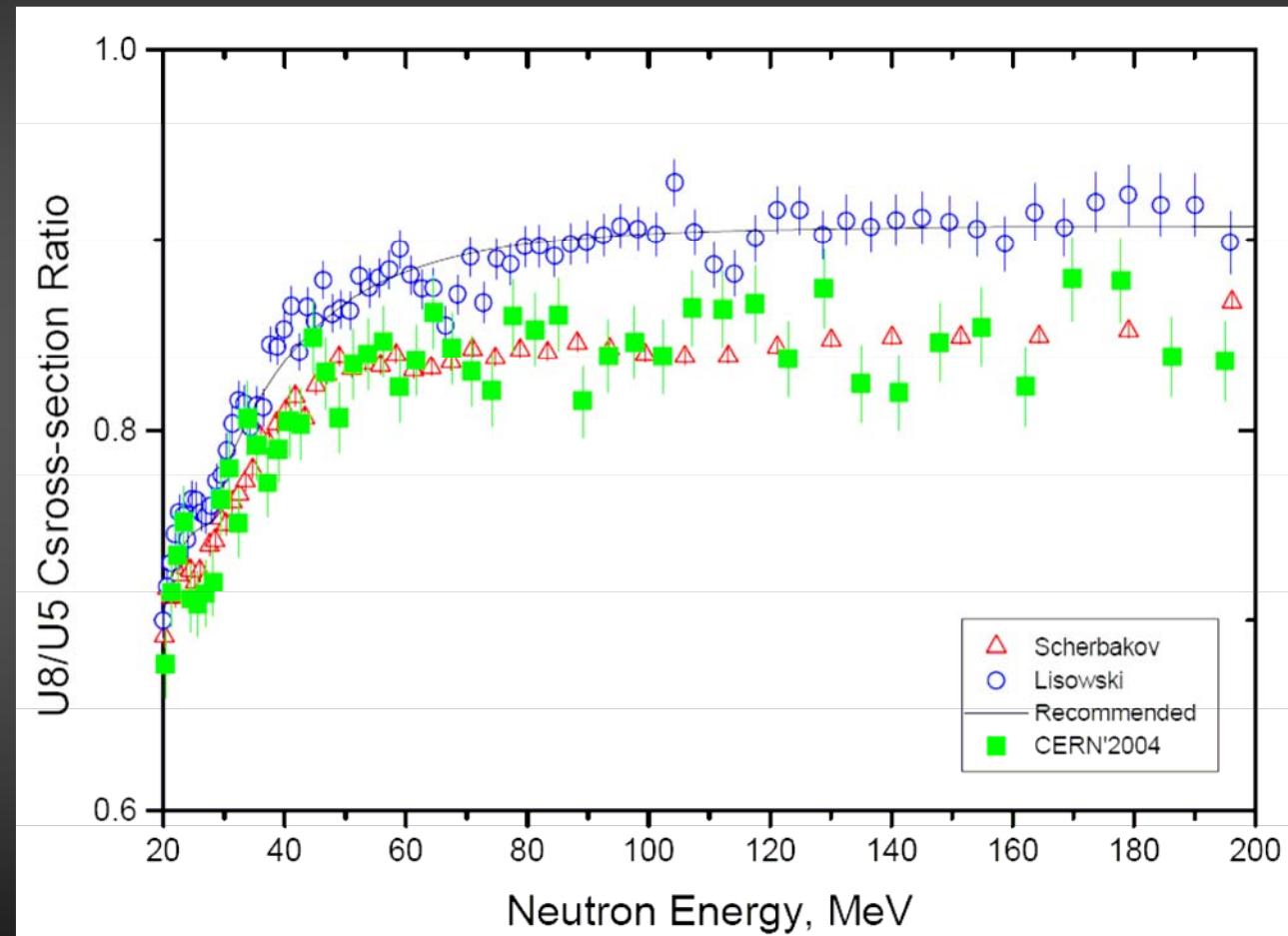
$^{241,243}\text{Am}$, ^{245}Cm



n_TOF experiments

FIC-0 (2003)

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



15% lower U_8/U_5 ratio at high energies

The n_TOF Collaboration

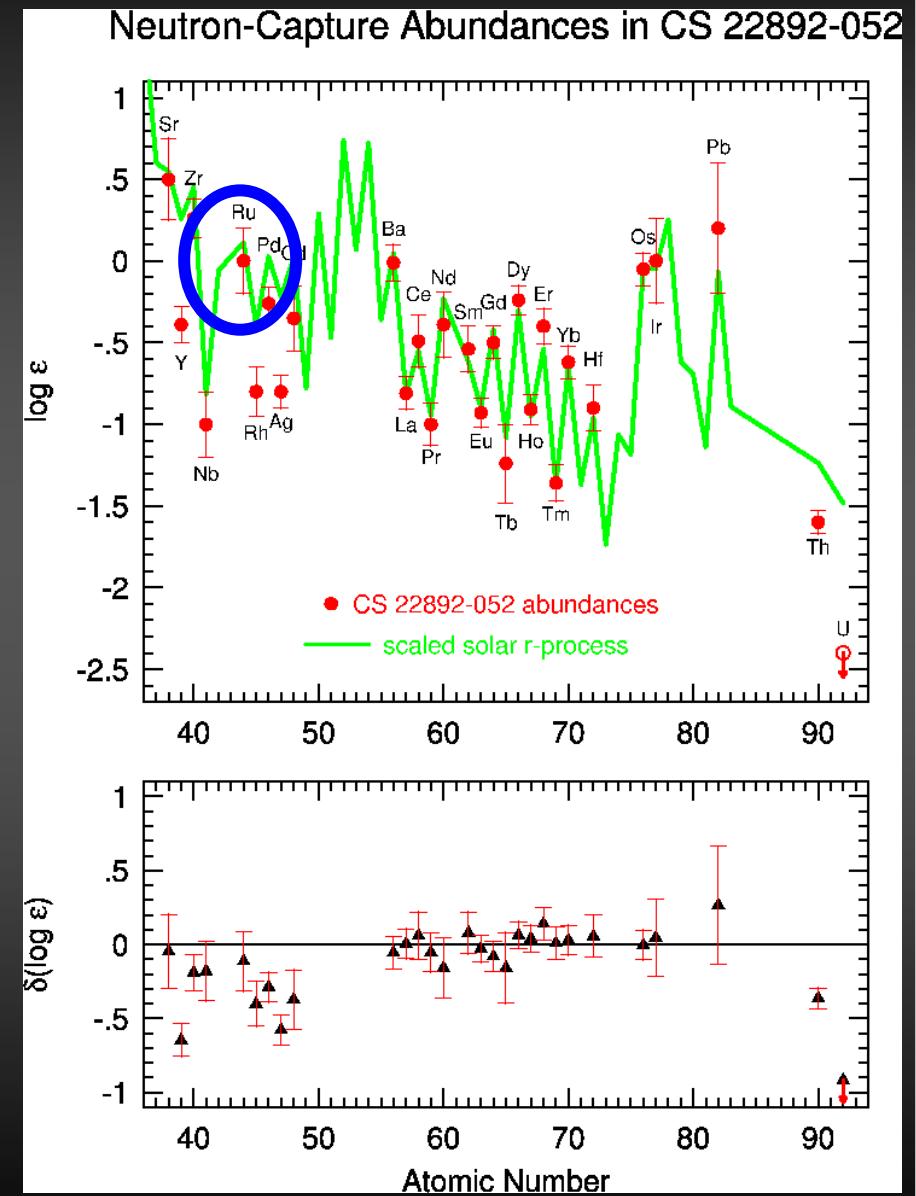
back

Capture studies: Mo, Ru and Pd

Motivations:

- Accurate determination of the r-process abundances (r-process residuals) from observations
- SiC grains carry direct information on s-process efficiencies in individual AGB stars. Abundance ratios in SiC grains strongly depend on available capture cross sections data.

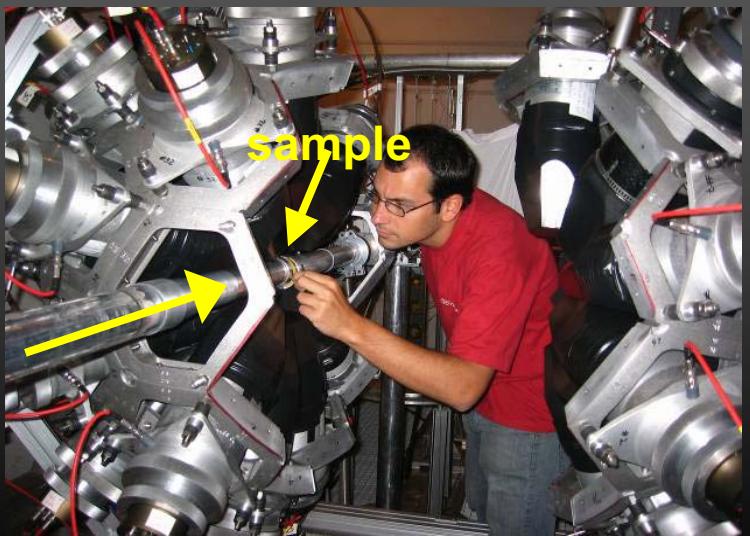
$$N_r = N_{\text{solar}} - N_s$$



Capture studies: Mo, Ru and Pd

- Setup: The n_TOF TAC in EAR-1
(a few cases with C₆D₆ if larger neutron scattering)
- All samples are stable and non-hazardous
- Metal samples preferable (oxides acceptable)

Estimated # of protons
 $20 \times 5 \times 10^{16} = 10^{18}$

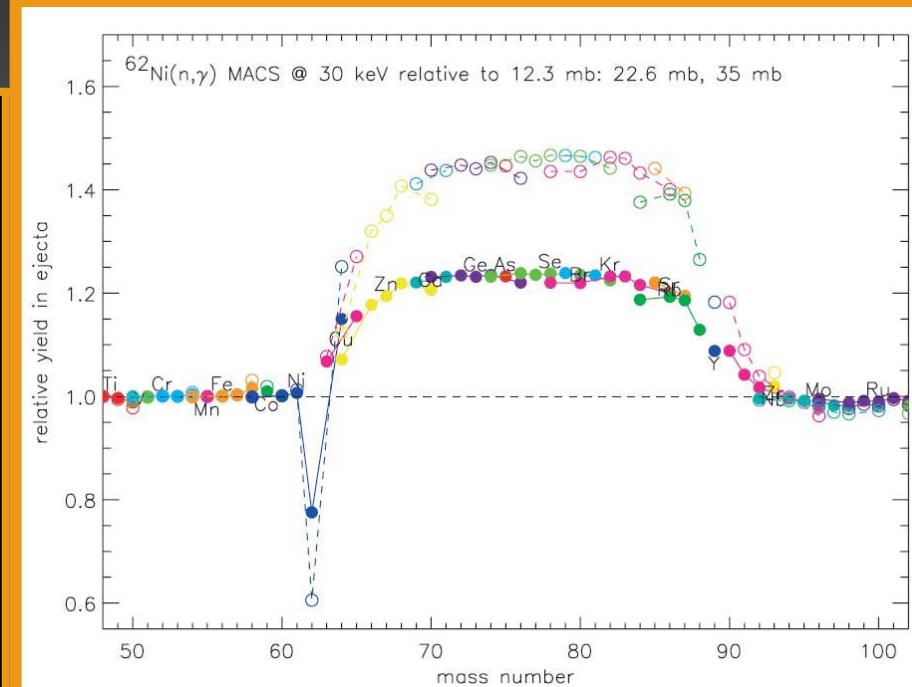


Cd 97	3 s	Cd 98	9.2 s	Cd 99	16 s	Cd 100	49.1 s	Cd 101	1.2 m	Cd 102	5.5 m	Cd 103	7.3 m	Cd 104	57.7 m	Cd 105	55.5 m	Cd 106	1.25	Cd 107	6.5 h	Cd 108	0.89	Cd 109	462.6 d	Cd 110	12.49	Cd 111	49 m	Cd 112	24.13	Cd 113	12.22								
P ³²	P ³³	P ³⁴	P ³⁵	P ³⁶	P ³⁷	P ³⁸	P ³⁹	P ⁴⁰	P ⁴¹	P ⁴²	P ⁴³	P ⁴⁴	P ⁴⁵	P ⁴⁶	P ⁴⁷	P ⁴⁸	P ⁴⁹	P ⁵⁰	P ⁵¹	P ⁵²	P ⁵³	P ⁵⁴	P ⁵⁵	P ⁵⁶	P ⁵⁷	P ⁵⁸	P ⁵⁹	P ⁶⁰													
Ag 96	5.1 s	Ag 97	19 s	Ag 98	46.7 s	Ag 99	105 s	Ag 100	2.1 m	Ag 101	11.1 m	Ag 102	8 m	Ag 103	1.8 m	Ag 104	33.5 m	Ag 105	69.2 m	Ag 106	72 m	Ag 107	44.3 s	Ag 108	51.639	Ag 109	418 s	Ag 110	248.8 s	Ag 111	45 s	Ag 112	74.4 s	Ag 113	31.2 h						
P ¹⁰⁷	P ¹⁰⁸	P ¹⁰⁹	P ¹¹⁰	P ¹¹¹	P ¹¹²	P ¹¹³	P ¹¹⁴	P ¹¹⁵	P ¹¹⁶	P ¹¹⁷	P ¹¹⁸	P ¹¹⁹	P ¹²⁰	P ¹²¹	P ¹²²	P ¹²³	P ¹²⁴	P ¹²⁵	P ¹²⁶	P ¹²⁷	P ¹²⁸	P ¹²⁹	P ¹³⁰	P ¹³¹	P ¹³²	P ¹³³	P ¹³⁴	P ¹³⁵	P ¹³⁶	P ¹³⁷	P ¹³⁸										
Pd 95	14 s	Pd 96	2.0 m	Pd 97	3.1 m	Pd 98	17.7 m	Pd 99	21.4 m	Pd 100	3.7 d	Pd 101	4.02 h	Pd 102	1.02	Pd 103	16.96 d	Pd 104	11.14	Pd 105	22.33	Pd 106	27.33	Pd 107	21.3 s	Pd 108	26.46	Pd 109	48 m	Pd 110	11.72	Pd 111	5.5 h	Pd 112	20.4 h	Pd 113	1.72 h				
Rh 94	70.6 s	Rh 95	1.86 m	Rh 96	3.0 m	Rh 97	31 m	Rh 98	3.5 m	Rh 99	47 h	Rh 100	16 d	Rh 101	20.8 h	Rh 102	16 d	Rh 103	103 s	Rh 104	103 s	Rh 105	104 s	Rh 106	104 s	Rh 107	21.7 m	Rh 108	80 s	Rh 109	27.1 s	Rh 110	3.3 s	Rh 111	1.43 s	Rh 112	1.23 s	Rh 113	1.15 s		
Ru 93	10.8 s	Ru 94	51.8 m	Ru 95	1.65 h	Ru 96	5.52	Ru 97	2.9 d	Ru 98	1.88	Ru 99	12.7	Ru 100	12.6	Ru 101	17.0	Ru 102	31.6	Ru 103	39.35 d	Ru 104	18.7	Ru 105	4.44 h	Ru 106	373.6 d	Ru 107	3.8 m	Ru 108	4.5 m	Ru 109	34.5 s								
Tc 92	0.14 s	Tc 93	1.52 s	Tc 94	1.52 s	Tc 95	1.2	Tc 96	4.4 d	Tc 97	4.2 - 10 ⁻⁴ a	Tc 98	4.2 - 10 ⁻⁴ a	Tc 99	0.6 h	Tc 100	15.8 s	Tc 101	14.2 m	Tc 102	52 s	Tc 103	54.2 s	Tc 104	21.8 m	Tc 105	7.6 m	Tc 106	36 s	Tc 107	21.5 s	Tc 108	5.17 s	Tc 109	1.42 s	Tc 110	1.22 s	Tc 111	1.15 s	Tc 112	1.08 s
Mo 91	0.5 s	Mo 92	14.84	Mo 93	9.25	Mo 94	15.92	Mo 95	16.68	Mo 96	9.55	Mo 97	24.13	Mo 98	1.2	Mo 99	68.0 s	Mo 100	9.63	Mo 101	14.6 m	Mo 102	11.2 m	Mo 103	67.5 s	Mo 104	1.0 m	Mo 105	35.6 s	Mo 106	8.7 s	Mo 107	3.5 s								
Nb 90	16.8 s	Nb 91	14.0 s	Nb 92	4.5 d	Nb 93	16.13 s	Nb 94	2.10 ⁴ s	Nb 95	16.6 s	Nb 96	34.07 d	Nb 97	23.4 h	Nb 98	53 s	Nb 99	74 m	Nb 100	2.6 s	Nb 101	1.64 s	Nb 102	1.5 s	Nb 103	1.5 s	Nb 104	2.95 s	Nb 105	1.0 s										
Zr 89	4.18 s	Zr 90	51.45	Zr 91	11.22	Zr 92	17.15	Zr 93	1.5 - 10 ⁻⁴ a	Zr 94	0.06	Zr 95	64.0 d	Zr 96	2.89	Zr 97	16.8 h	Zr 98	30.7 s	Zr 99	2.1 s	Zr 100	7.1 s	Zr 101	2.1 s	Zr 102	2.9 s	Zr 103	1.3 s	Zr 104	1.2 s	Zr 105	~ 1 s								
Y 88	Y 89	Y 90	Y 91	Y 92	Y 93	Y 94	Y 95	Y 96	Y 97	Y 98	Y 99	Y 100	10.1 h	Y 99	18.7 m	Y 95	10.3 m	Y 96	3.34	Y 97	3.75 s	Y 98	0.35 s	Y 99	1.47 s	Y 100	448 ms	Y 101	1.47 s	Y 102	3.7 s	Y 103	Y 104								
4.764	5.835	5.866	5.979	6.300	6.469	6.545	6.6270	6.753	6.161	6.199	5.116	4.271	3.016	50	52	54	56	58	60	62	64																				

Capture studies: Fe, Ni, Zn, and Se

Motivations:

- Study of the weak s-process component (nucleosynthesis up to A ~ 90)
- Contribution of massive stars (core He-burning phase) to the s-process nucleosynthesis.
- s-process efficiency due to bottleneck cross sections (Example: ^{62}Ni)



In addition:

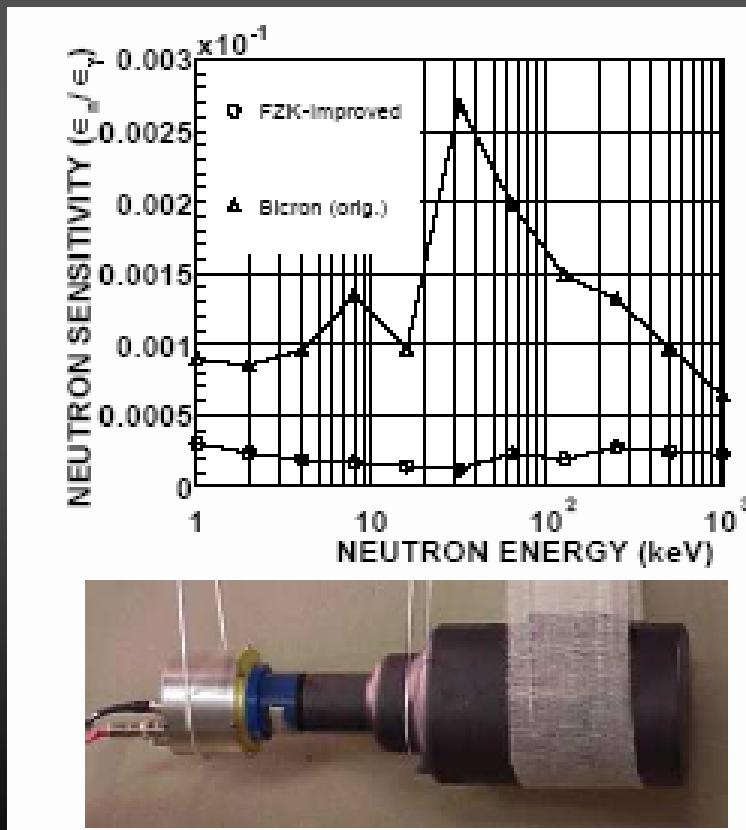
Fe and Ni are the most important structural materials for nuclear technologies. Results of previous measurements at n_TOF show that capture rates for light and intermediate-mass isotopes need to be revised.

Capture studies: Fe, Ni, Zn, and Se

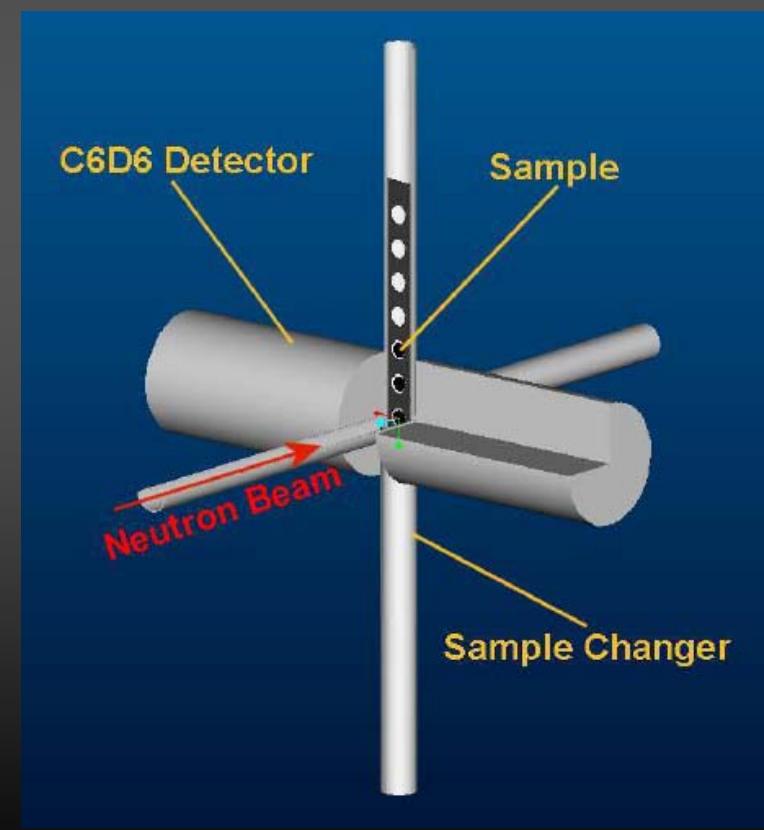
	Kr 73 26 s	Kr 74 11.5 m	Kr 75 4.5 m	Kr 76 14.6 h	Kr 77 1.24 h	Kr 78 0.35	Kr 79 50 s	Kr 80 2.25	Kr 81 13.1 s	Kr 82 11.6	Kr 83 1.83 h	Kr 84 57.0	Kr 85 4.48 h	Kr 86 10.76 s	Kr 86 17.3
34	β^+ 5.6... γ 178; 241; 455... $\beta\beta$ 1.5–3.0	β^+ 2.0; 2.2... γ 90; 203; 297; 63; 307	β^+ 3.2... γ 133; 155...	β^+ 316; 270; 45; 407... g	β^+ 1.9... γ 136; 147... g	ν 0.17 + 0	ν 196	ν 2.6 + 7	ν 160	ν 14 + 7	ν 5... g	ν 0.09 + 0.02	ν 0.09	ν 0.03	
32	Br 72 10.9 s	Br 73 3.3 m	Br 74 46 m	Br 75 25.4 m	Br 76 1.6 h	Br 77 1.32 s	Br 78 4.3 m	Br 79 57.0 h	Br 80 6.46 m	Br 81 4.42 h	Br 82 49.31	Br 83 6.1 m	Br 84 35.34 h	Br 85 6.0 s	Br 86 31.8 m
30	Se 71 4.74 m	Se 72 8.5 d	Se 73 39 m	Se 74 7.1 s	Se 75 0.89	Se 76 119.64 d	Se 77 9.36	Se 78 17.5 s	Se 79 7.63	Se 80 23.78	Se 81 3.9 m	Se 82 49.61	Se 83 57.3 m	Se 84 18 m	Se 85 22.4 m
	β^+ 3.4... γ 147; 1095; 830... γ 46	β^+ no β^+ γ 46	β^+ 2.2... γ 122; 132; 138; 142; 150; 156; 161; 166; 171; 176; 181; 186; 191; 196; 201; 206; 211; 216; 221; 226; 231; 236; 241; 246; 251; 256; 261; 266; 271; 276; 281; 286; 291; 296; 301; 306; 311; 316; 321; 326; 331; 336; 341; 346; 351; 356; 361; 366; 371; 376; 381; 386; 391; 396; 401; 406; 411; 416; 421; 426; 431; 436; 441; 446; 451; 456; 461; 466; 471; 476; 481; 486; 491; 496; 501; 506; 511; 516; 521; 526; 531; 536; 541; 546; 551; 556; 561; 566; 571; 576; 581; 586; 591; 596; 601; 606; 611; 616; 621; 626; 631; 636; 641; 646; 651; 656; 661; 666; 671; 676; 681; 686; 691; 696; 701; 706; 711; 716; 721; 726; 731; 736; 741; 746; 751; 756; 761; 766; 771; 776; 781; 786; 791; 796; 801; 806; 811; 816; 821; 826; 831; 836; 841; 846; 851; 856; 861; 866; 871; 876; 881; 886; 891; 896; 901; 906; 911; 916; 921; 926; 931; 936; 941; 946; 951; 956; 961; 966; 971; 976; 981; 986; 991; 996; 1001; 1006; 1011; 1016; 1021; 1026; 1031; 1036; 1041; 1046; 1051; 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Capture studies: Fe, Ni, Zn, and Se

- Setup: C_6D_6 in EAR-1
- All samples are stable(*) and non-hazardous
- Metal samples preferable (oxides acceptable)

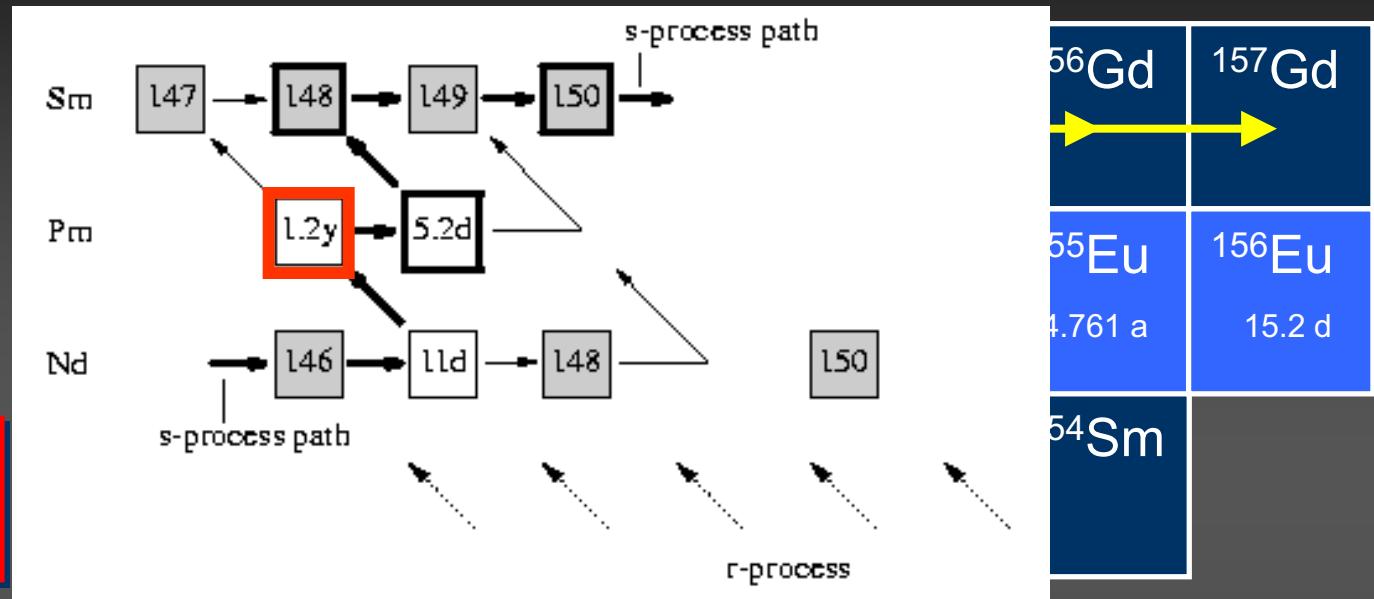


(*) except ^{79}Se



Capture studies: $A \approx 150$

- EAR-2 required
- Sample from ISOLDE?



- branching isotope in the Sm-Eu-Gd region:
test for low-mass TP-AGB
- branching ratio (capture/ β -decay) provides infos on
the thermodynamical conditions of the s-processing
(if accurate capture rates are known!)

Capture studies: actinides

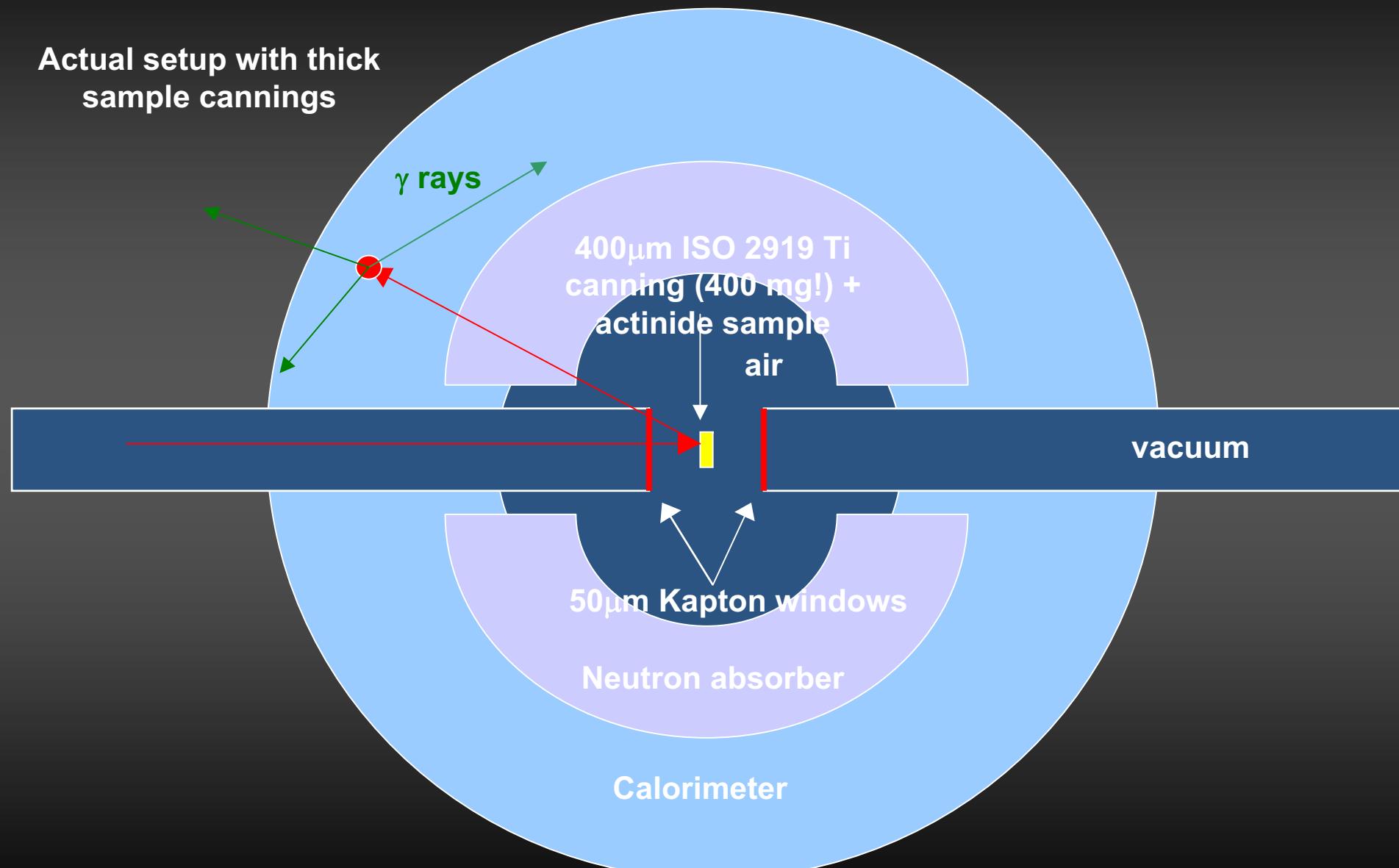
Neutron cross section measurements for nuclear waste transmutation and advanced nuclear technologies

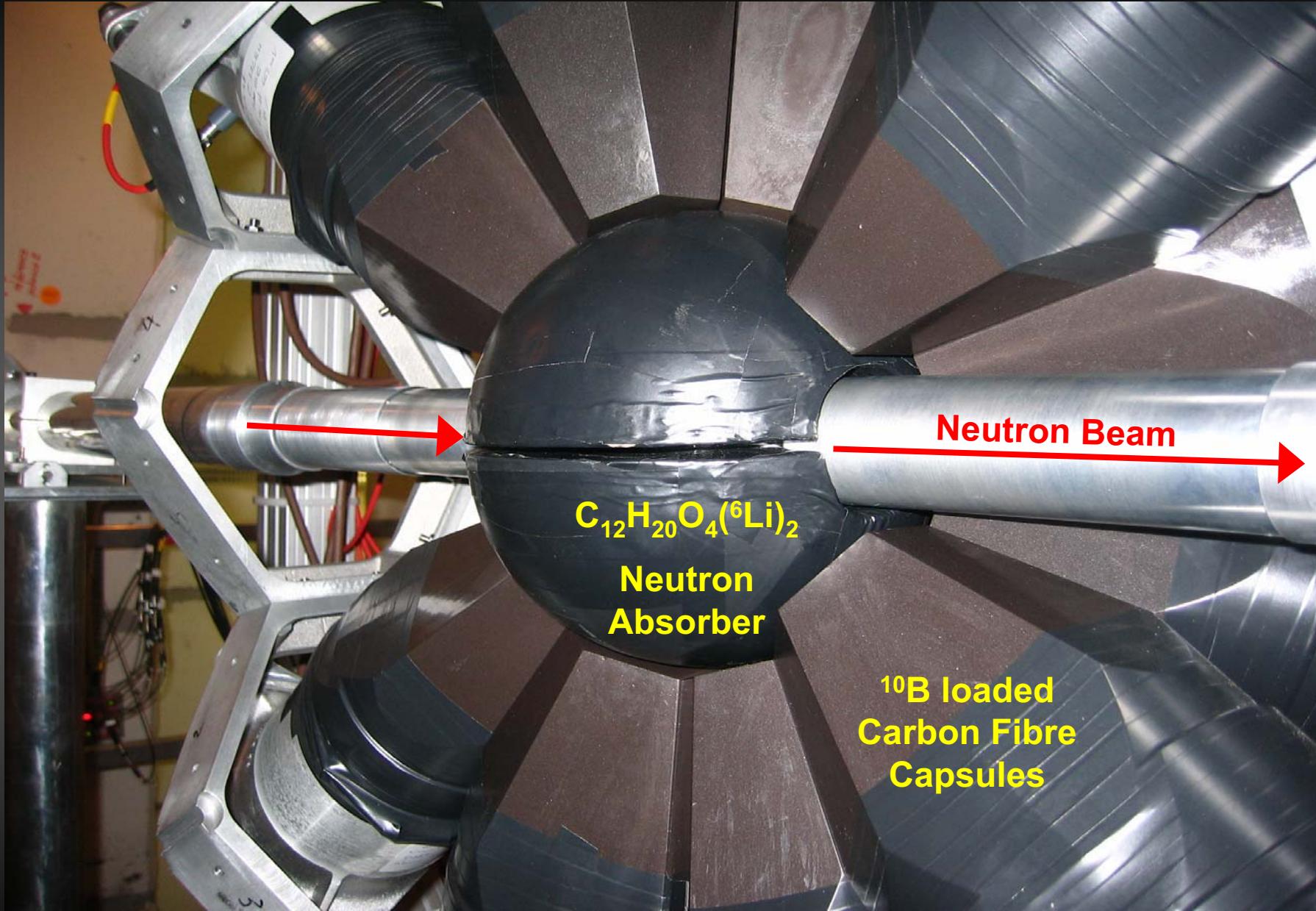
$^{241,243}\text{Am}$	The most important neutron poison in the fuels proposed for transmutation scenarios. Build up of Cm isotopes.
$^{239,240,242}\text{Pu}$	(n, γ) and (n,f) with active canning. Build up of Am and Cm isotopes.
^{245}Cm	No data available.
$^{235,238}\text{U}$	Improvement of standard cross sections.
$^{232}\text{Th}, ^{233,234}\text{U}$ $^{231,233}\text{Pa}$	Th/U advanced nuclear fuels. ^{233}U fission with active canning.

All measurements can be done in EAR-1 (except ^{241}Am and ^{233}Pa)

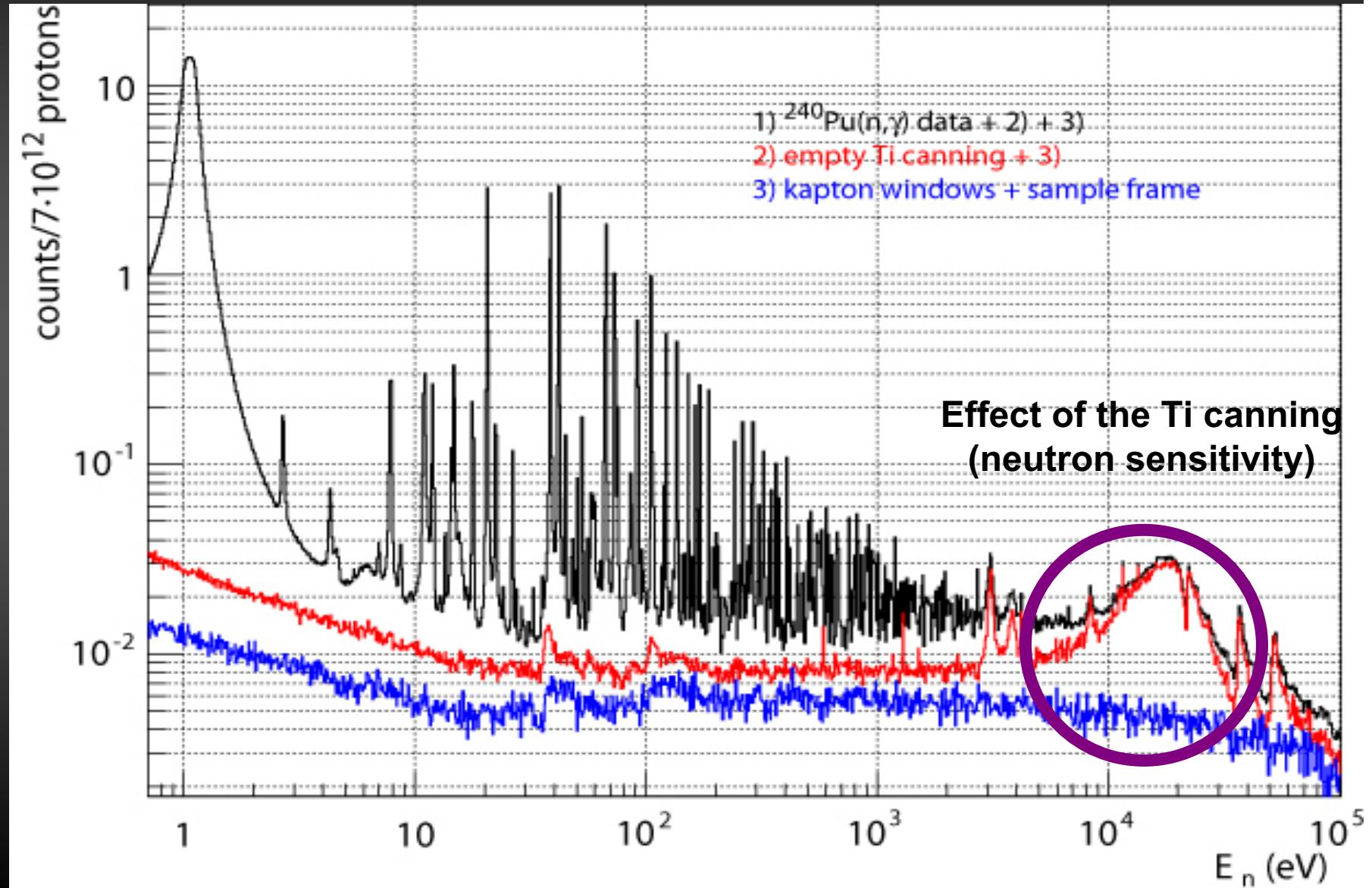
Capture studies: actual TAC setup

Actual setup with thick sample cannings

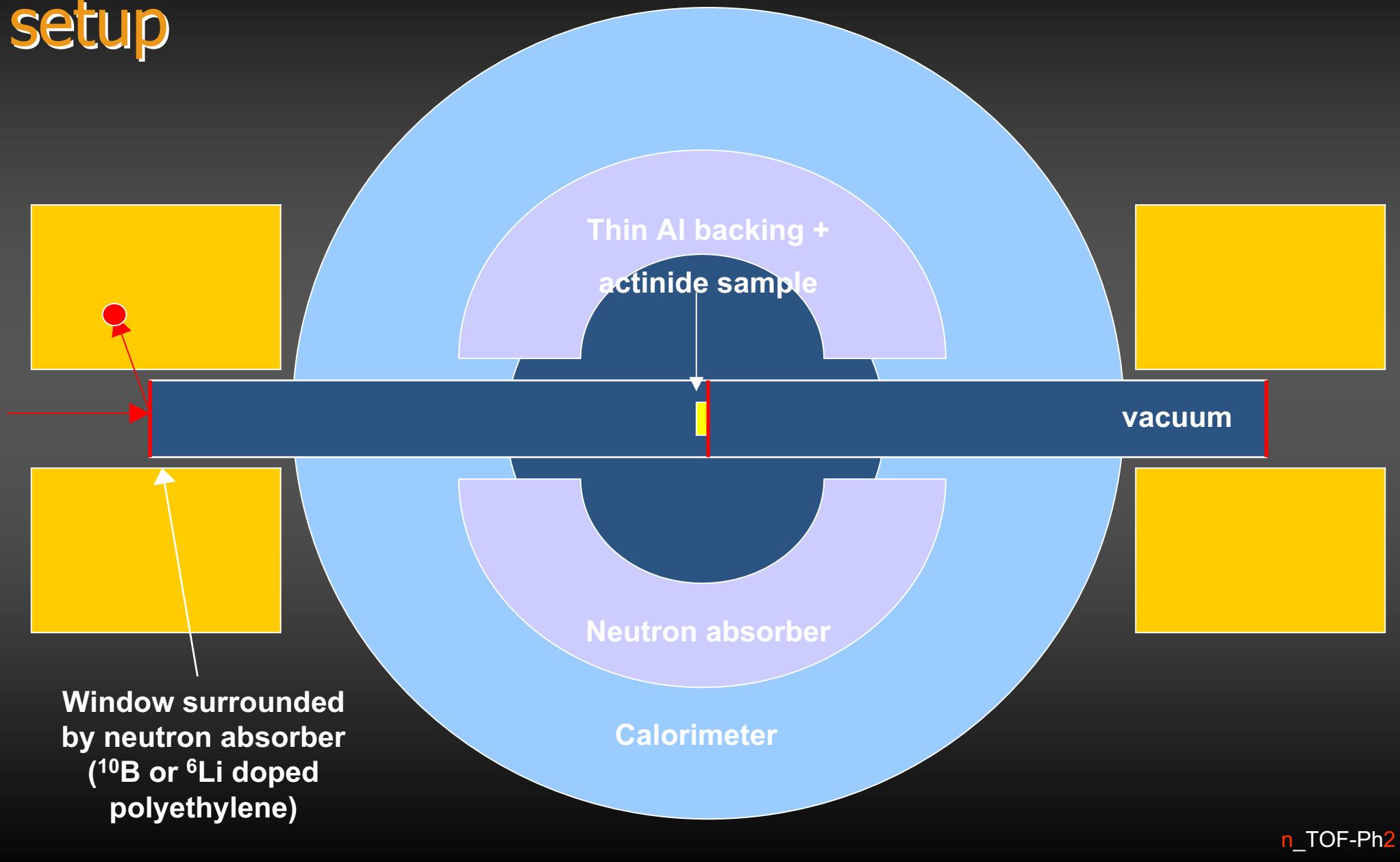




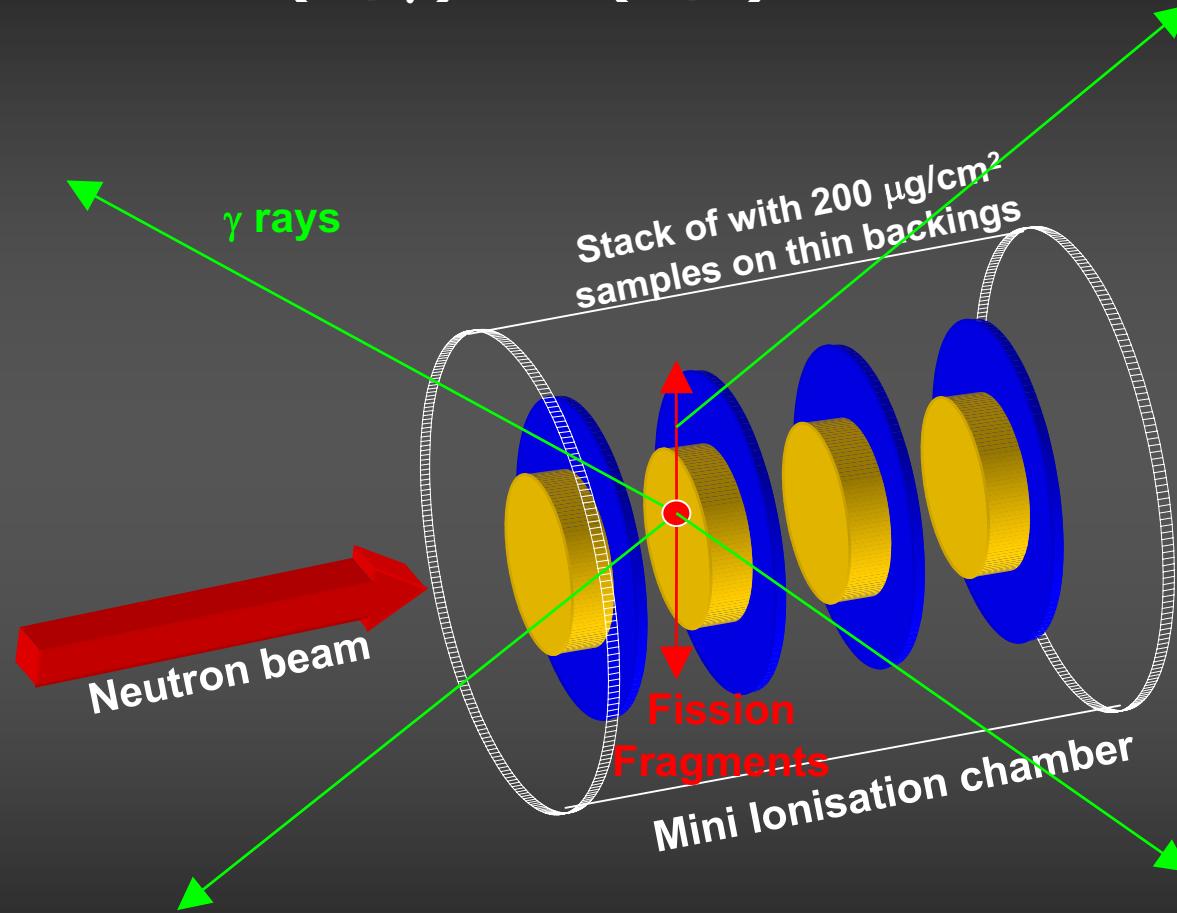
Capture studies: actual TAC setup



Capture studies: Low neutron sensitivity setup



Capture studies: active canning for simultaneous (n,γ) & (n,f) measurements



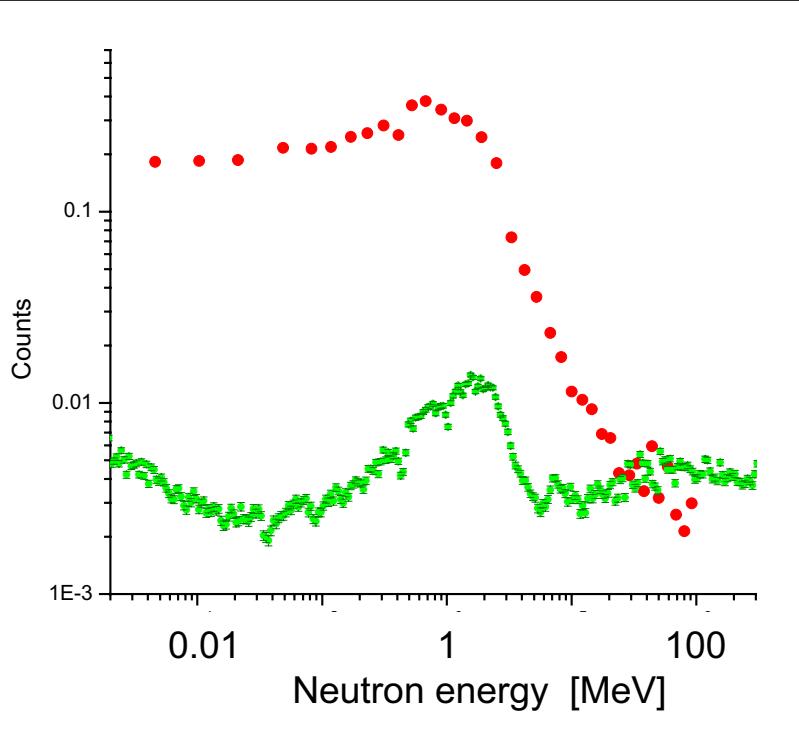
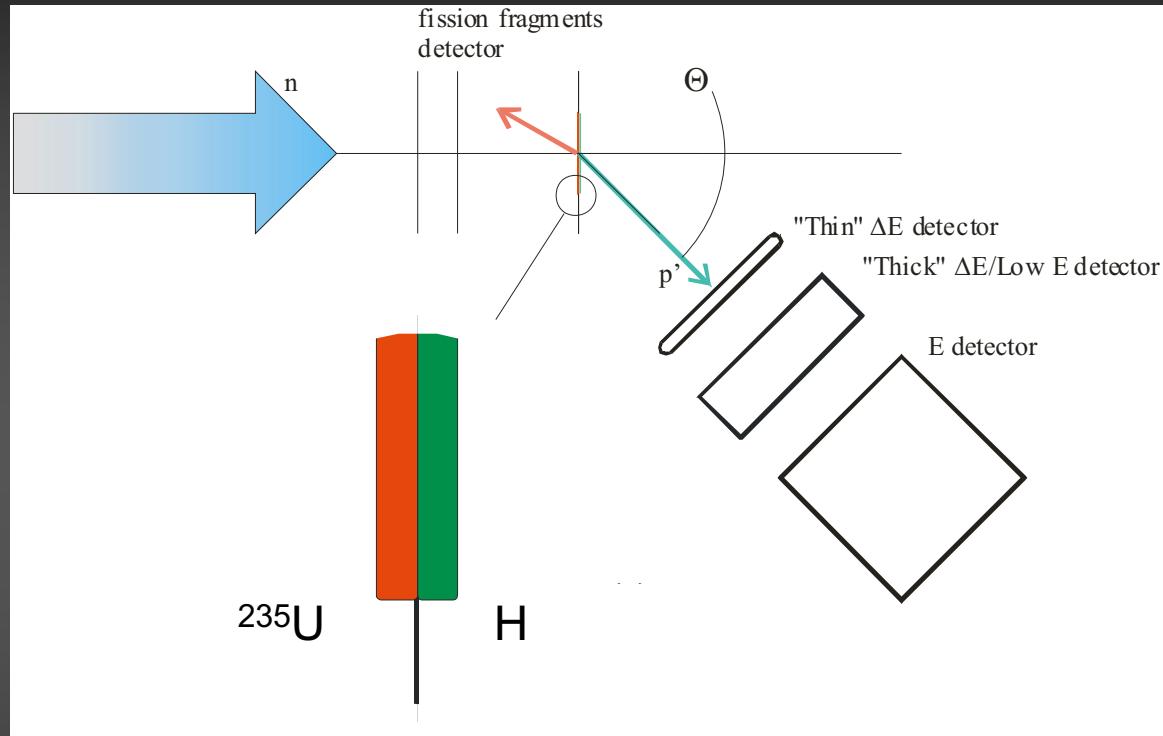
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Measurement of capture cross sections of fissile materials (veto) and measurement of the $(n,\gamma)/(n,f)$ ratio.

Fission studies

Fission studies

absolute $^{235}\text{U}(n,f)$ cross section from (n,p) scattering

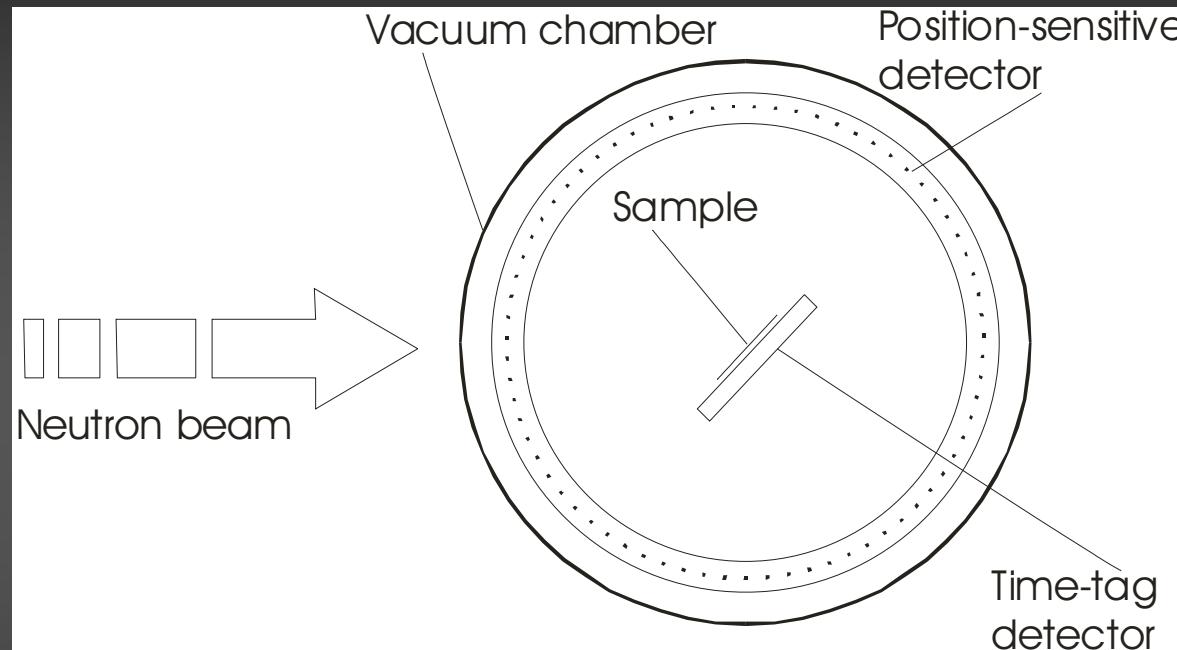


Beam	capture mode (2 mm Ø)
Scattering angle	30°
Target thickness	250 $\mu\text{g}/\text{cm}^2$
Detector radius	20 mm
Target-to-detector distance	250 mm

(n,p) larger or comparable up to 100 MeV

Fission studies

FF distributions in vibrational resonances

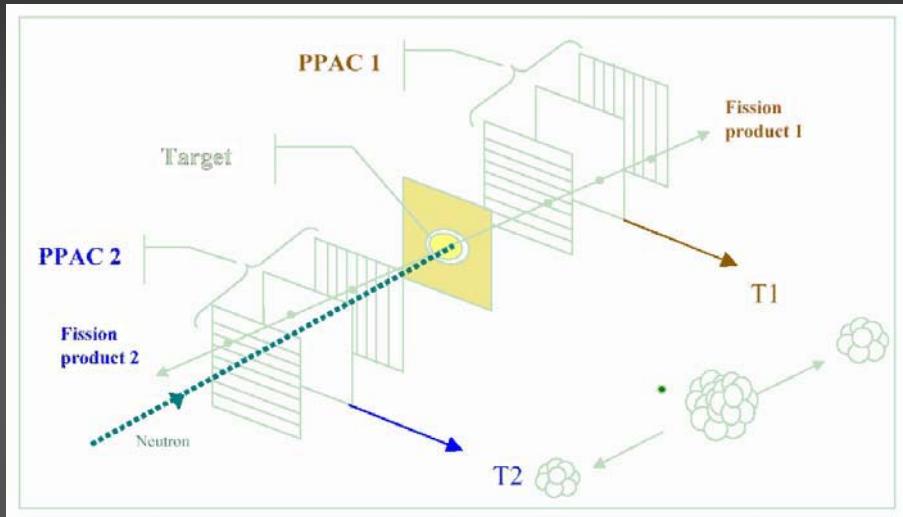


Principles:

- Time-tag detector for the “start” signal
- Masses (kinetic energies) of FF from position-sensitive detectors (MICROMEGAS or semiconductors)

Fission studies

cross sections with PPAC detectors: present setup



Measurements:

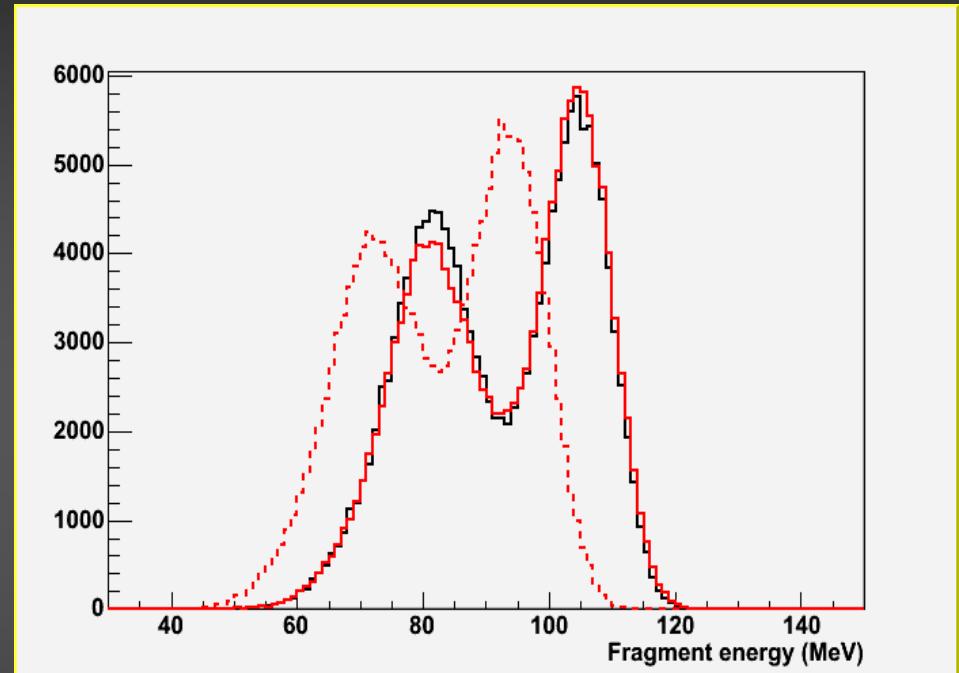
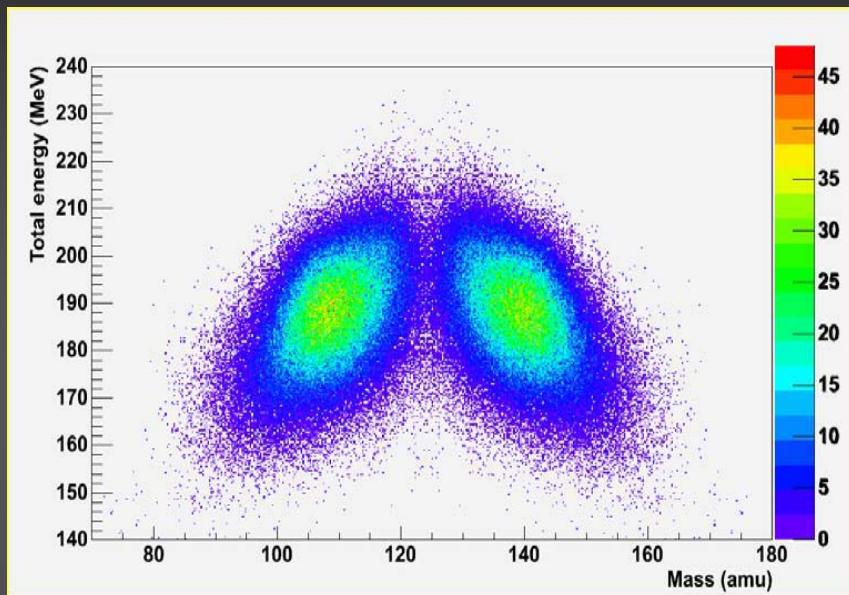
- $^{231}\text{Pa}(n,\text{f})$
- Fission fragments angular distributions (45° tilted targets) for ^{232}Th , ^{238}U and other low-activity actinides

EAR-2 boost:

- measurements of $^{241,243}\text{Am}$ (in class-A lab)
- measurements of ^{241}Pu and ^{244}Cm (in class-A lab)

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n_TOF-Ph2

Fission studies with twin ionization chamber



Twin ionization detector with measurement of both FF (PPAC principle)

Measurements:

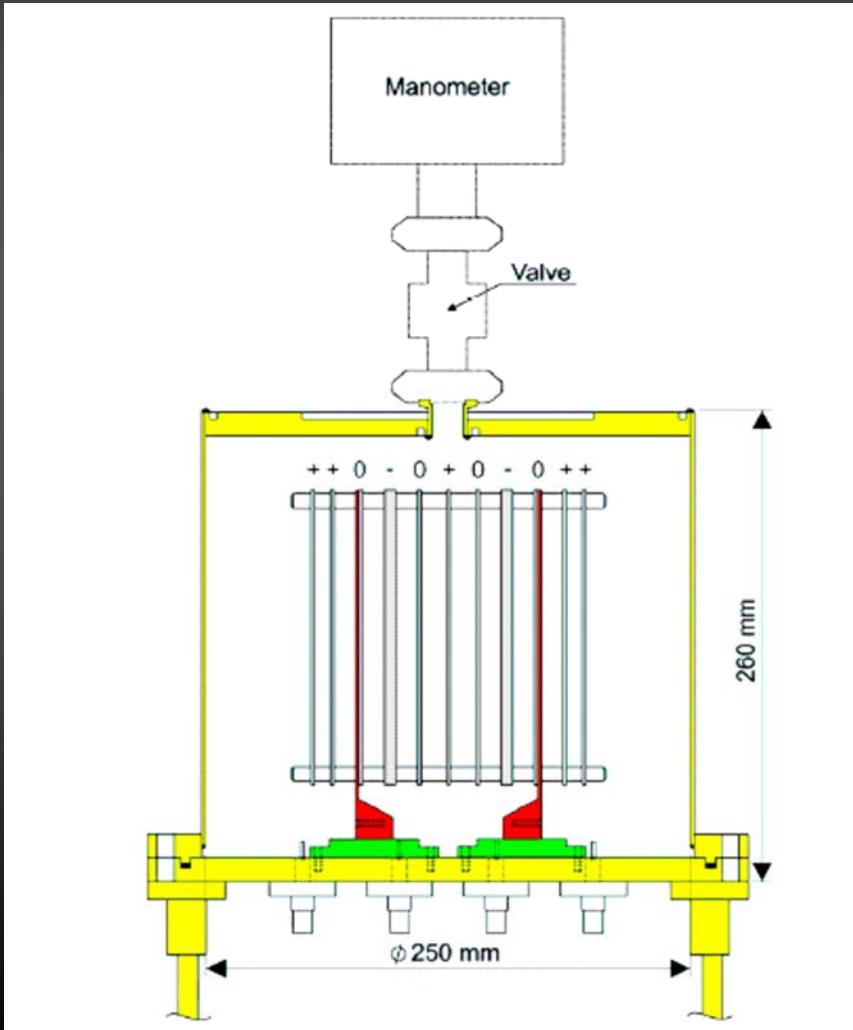
- FF yields: mass & charge
- Test measurement with ^{235}U then measurements of other MA

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n_TOF-Ph2

(n,p) , (n,α) & (n,lcp) measurements

1. CIC: compensated ion chamber
already tested at n_{TOF}



For $n_{\text{TOF-Ph2}}$:

- four chambers in the same volume for multi-sample measurements

Measurements:

- $^{147}\text{Sm}(n,\alpha)$ (tune up experiment)
- ^6LiF target for calibration

EAR-2 boost:

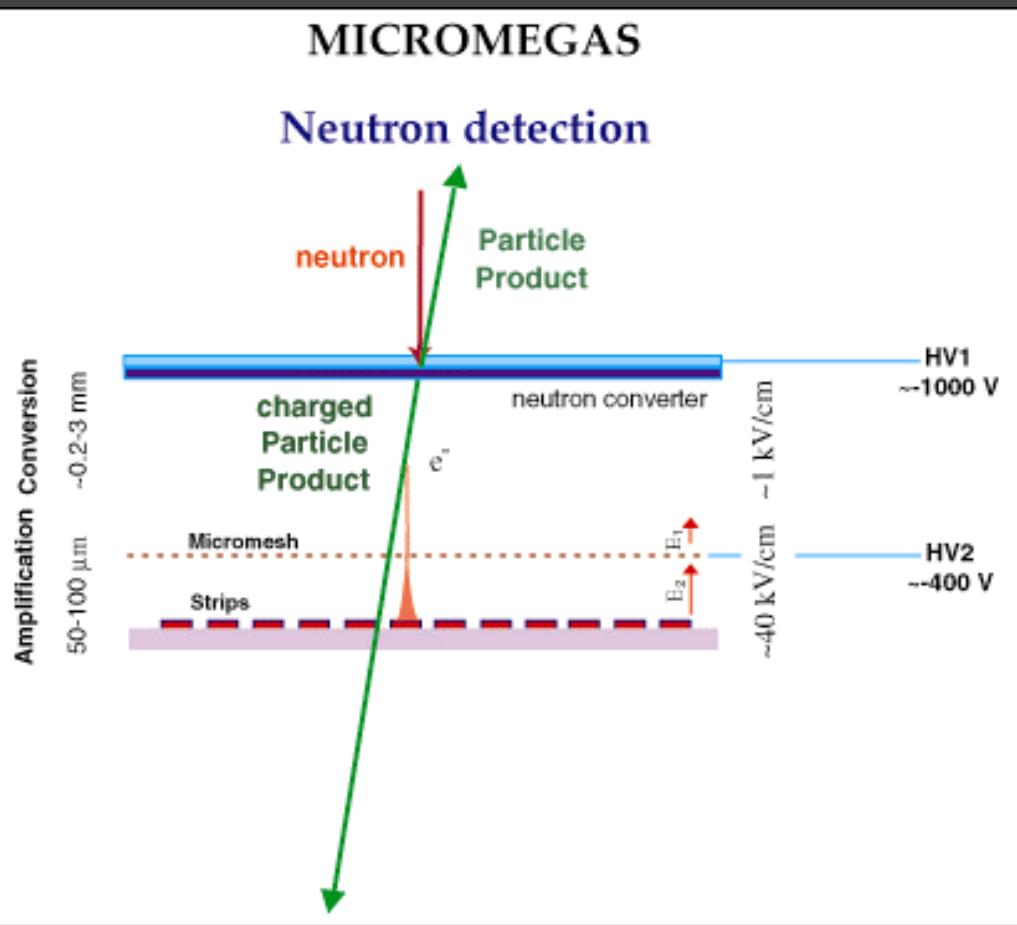
- approx 100 times the ORELA count rate expected
- ^{67}Zn and ^{99}Ru (n,α) measurements

$n_{\text{TOF-Ph2}}$

(n,p) , (n,α) & (n,lcp) measurements

2. MICROMEGAS

already used for measurements of nuclear recoils at n_TOF



For n_TOF-Ph2:

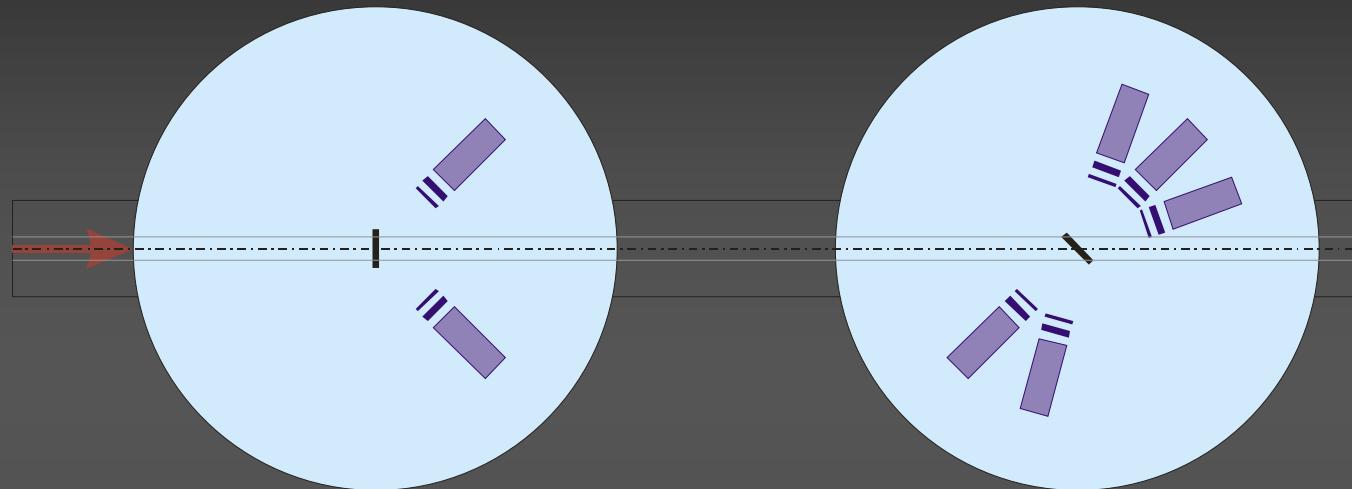
- converter replaced by sample
- expected count rate: 1 reaction/pulse ($\sigma=200 \text{ mb}$, $\varnothing=5\text{cm}$, $1\mu\text{m}$ thick)

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n_TOF-Ph2

(n,p) , (n,α) & (n,lcp) measurements

3. Scattering chambers with ΔE - E or ΔE - ΔE - E telescopes



Setup: in parallel with fission detectors

- ✓ production cross sections $\sigma(E_n)$ for (n,xc)
- ✓ $c = p, \alpha, d$
- ✓ differential cross sections $d\sigma/d\Omega, d\sigma/dE$

Measurements:

- ^{56}Fe and ^{208}Pb (tune up experiment)
- Al, V, Cr, Zr, Th, and ^{238}U
- a few $\times 10^{18}$ protons/sample in fission mode

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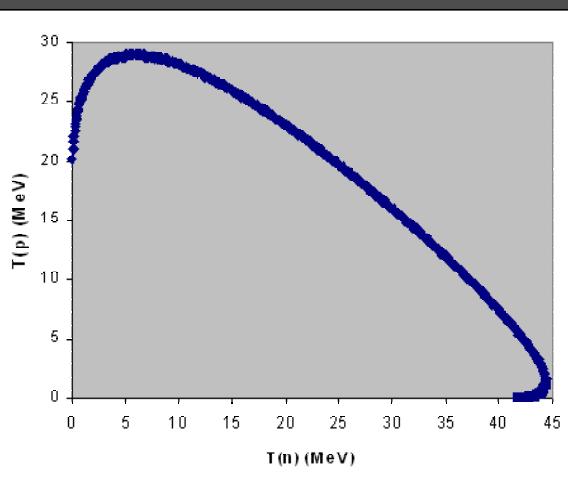
n_TOF-Ph2

Neutron scattering reactions

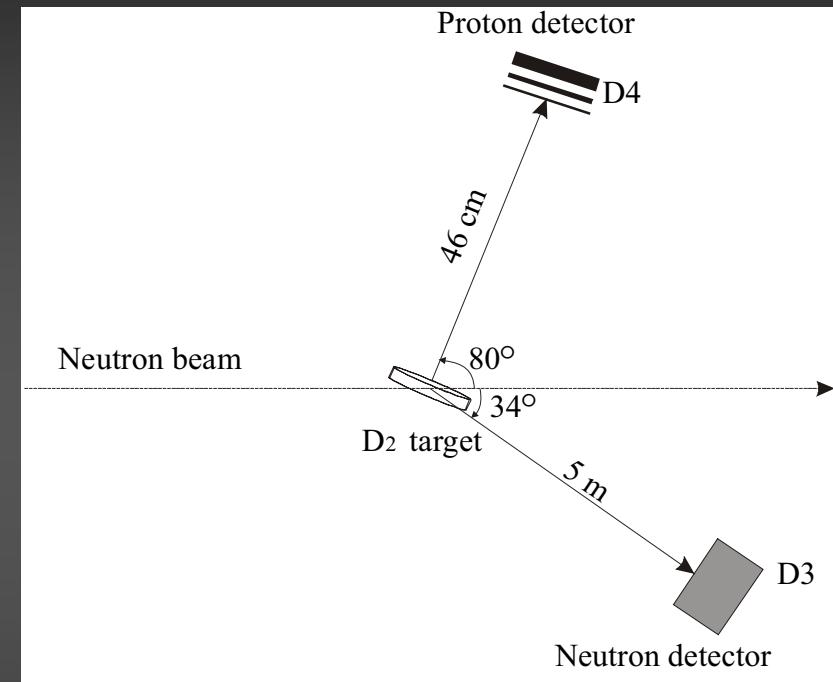
Direct $n + n$ scattering experiment not feasible!

Alternatively, interaction of two neutrons in the final state of a nuclear reaction. Examples of such reactions are:

- $\pi^+ + {}^2H \rightarrow n + n + \gamma$
- $n + {}^2H \rightarrow n + n + p$



Kinematic locus of the $n + {}^2H \rightarrow n + p + n$ reaction for:
 $E_n = 50$ MeV
 $\Theta_n = 20^\circ, \Phi_n = 0^\circ$
 $\Theta_p = 50^\circ, \Phi_p = 180^\circ$



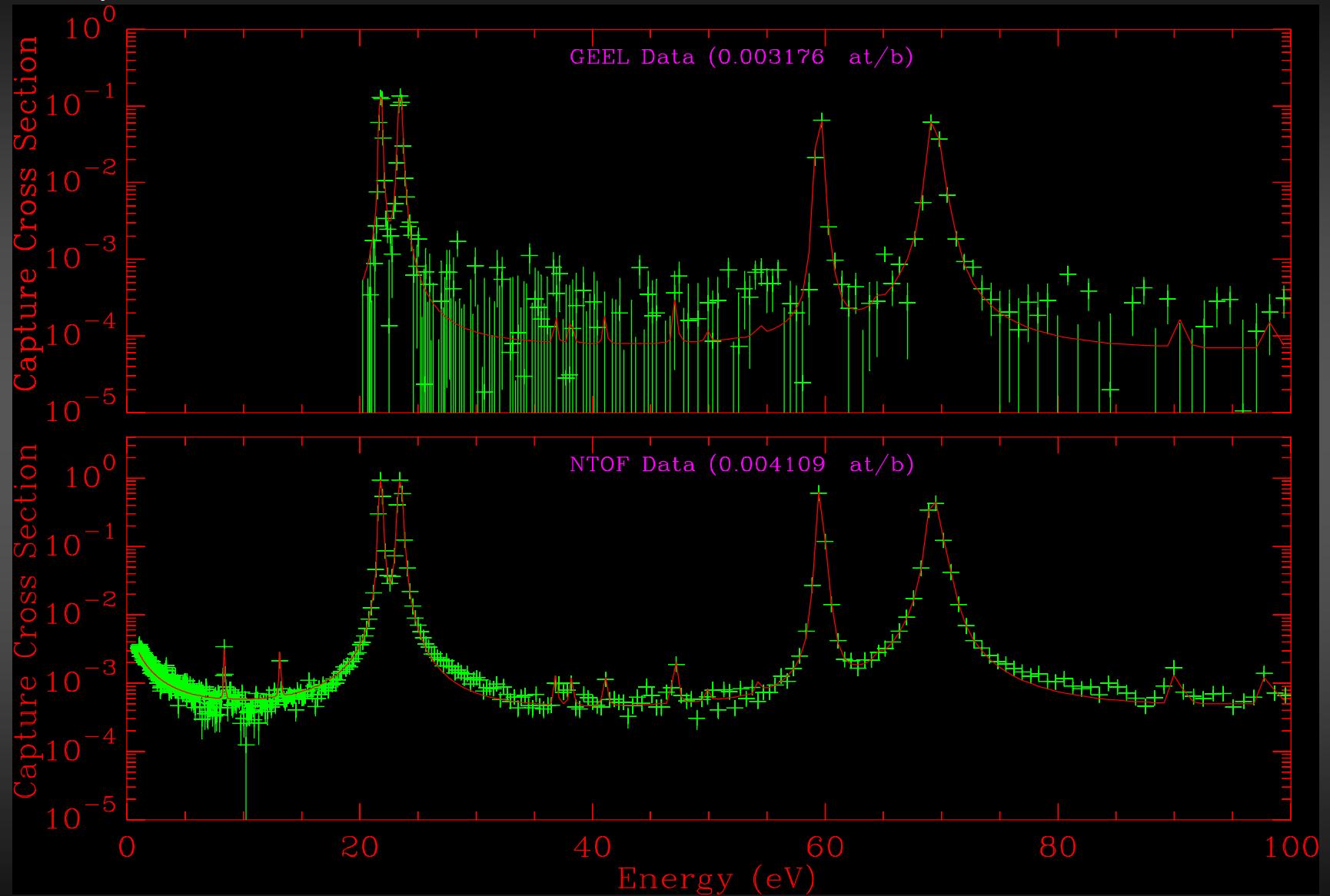
Neutron incident energy 30 – 75 MeV
in 2.5 MeV bins

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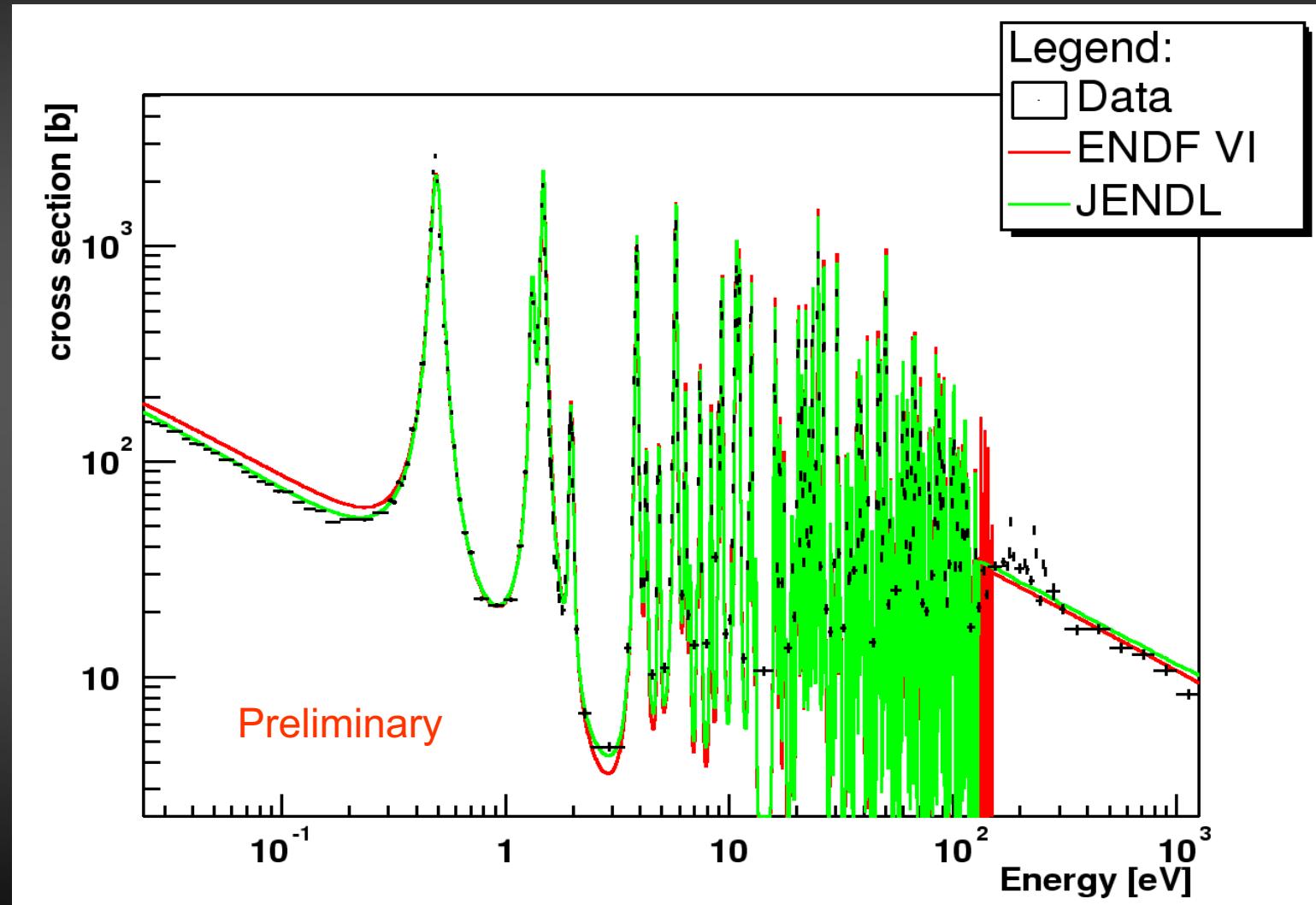
n_TOF-Ph2

$^{232}\text{Th}(n,\gamma)$: n_TOF & GELINA



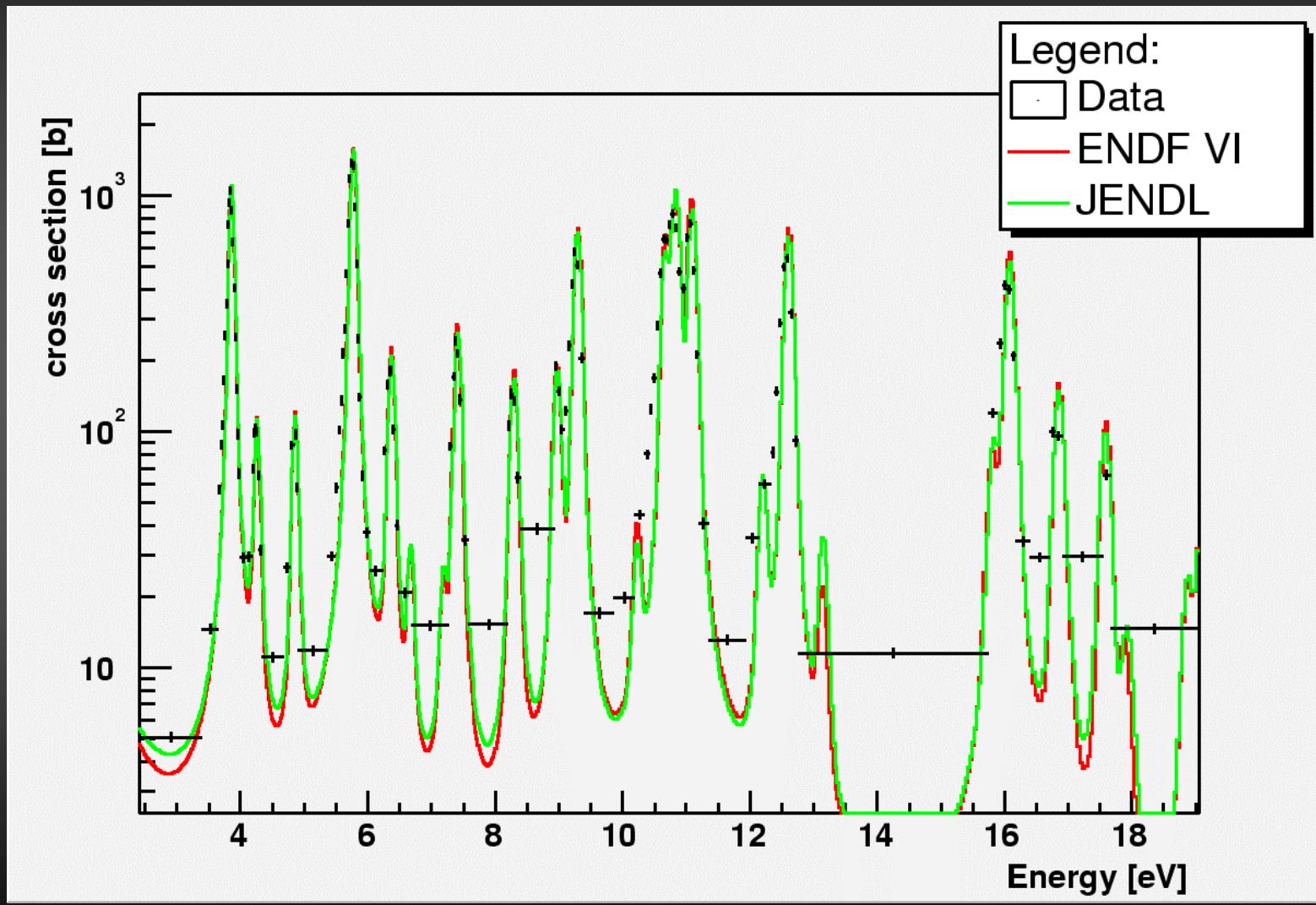
Source: L Leal, IAEA CRP meeting, December 2004

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



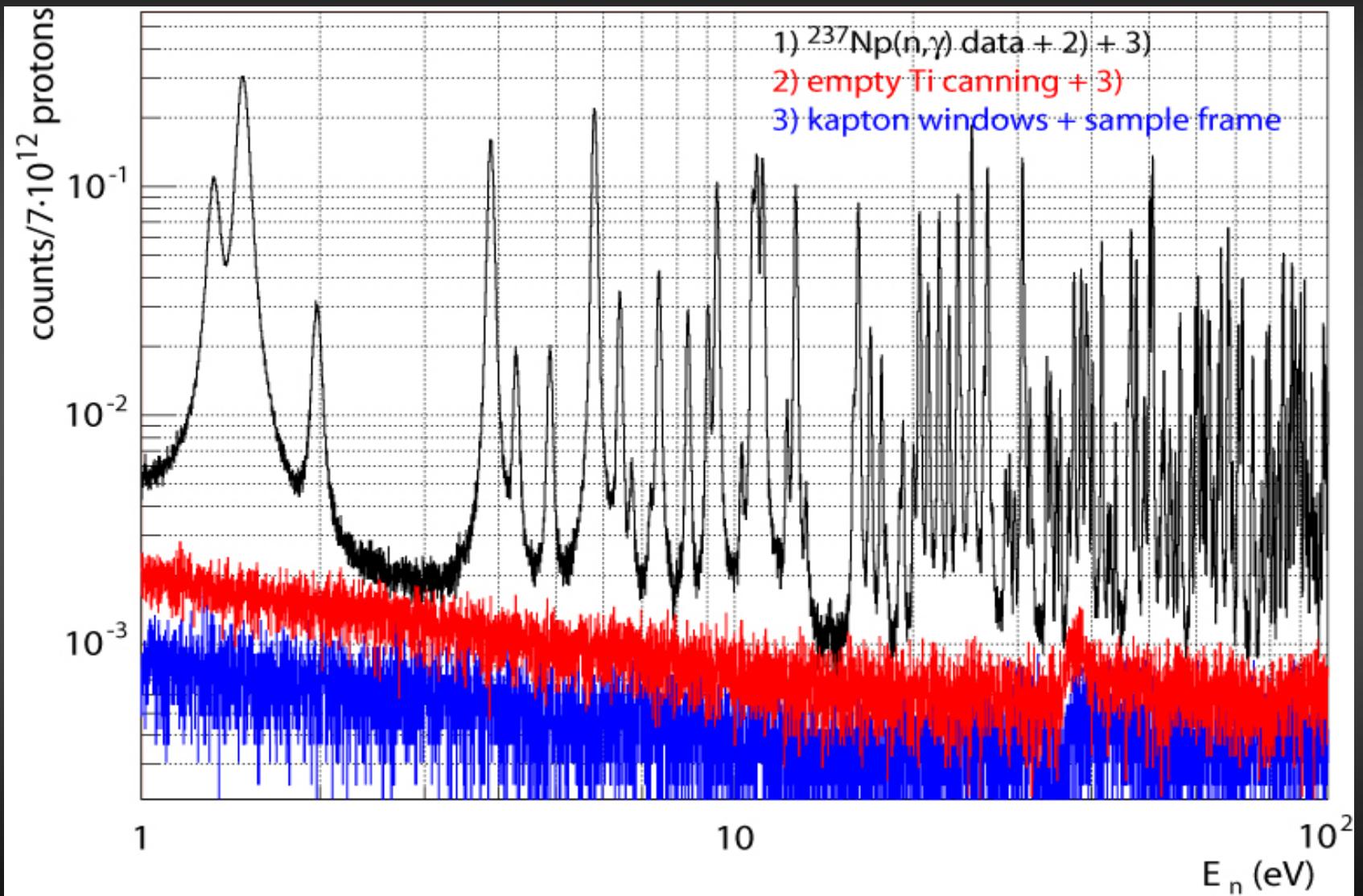
Source: J Ullman, n_BANT workshop, CERN, March 2005

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



Source: J Ullman, n_BANT workshop, CERN, March 2005

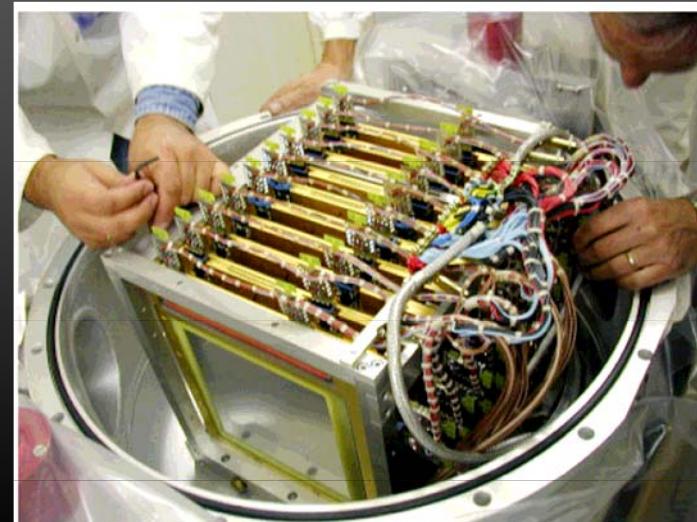
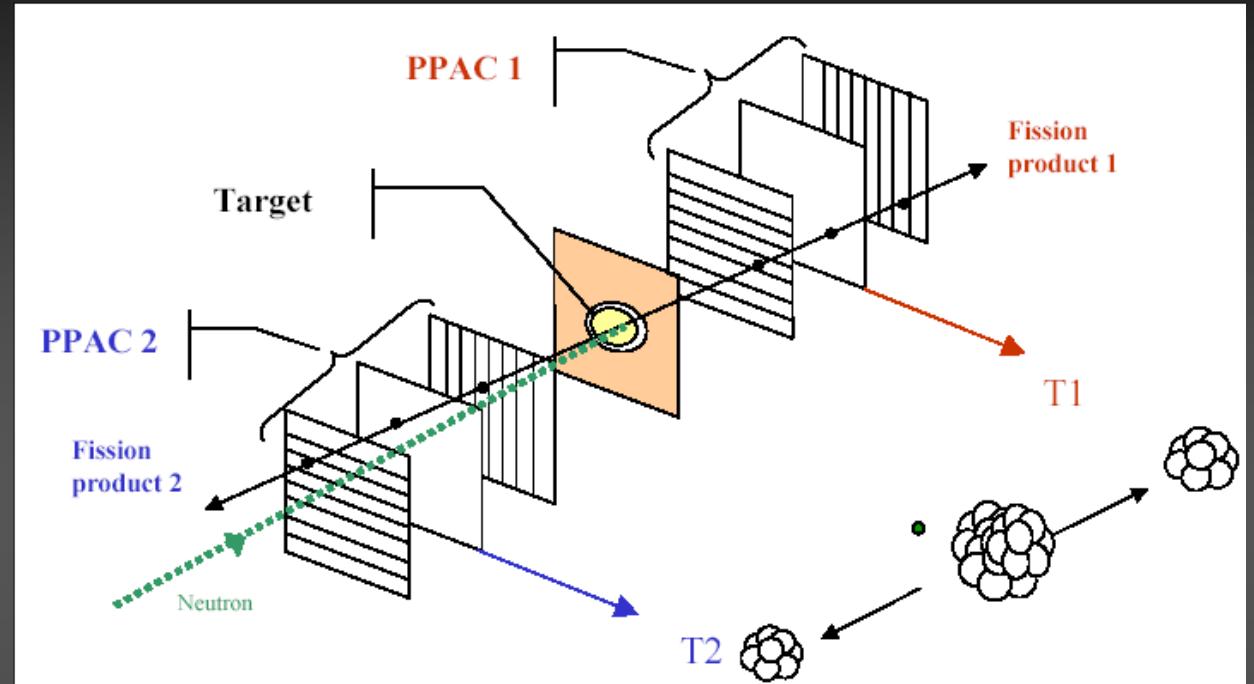
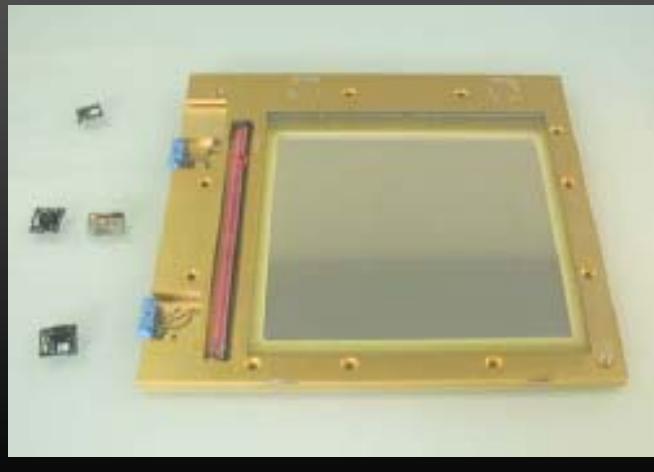
$^{237}\text{Np}(n,\gamma)$ at n_TOF



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Parallel Plate Avalanche Counters (PPACs)

- 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



IN2P3 (IPN Orsay)

- position-sensitive!