The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization
IAEA

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.**

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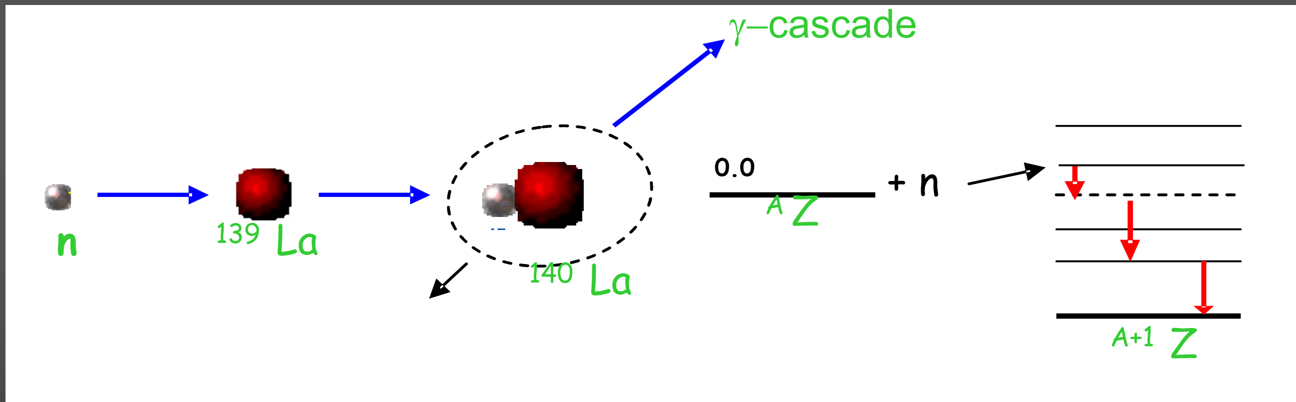
The n_TOF Collaboration

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.

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]

CAPTURE



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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.

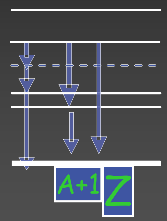
In this case the most important information are recorded in the resonance parameters: E_R, Γ_n, Γ_γ and Γ_f.

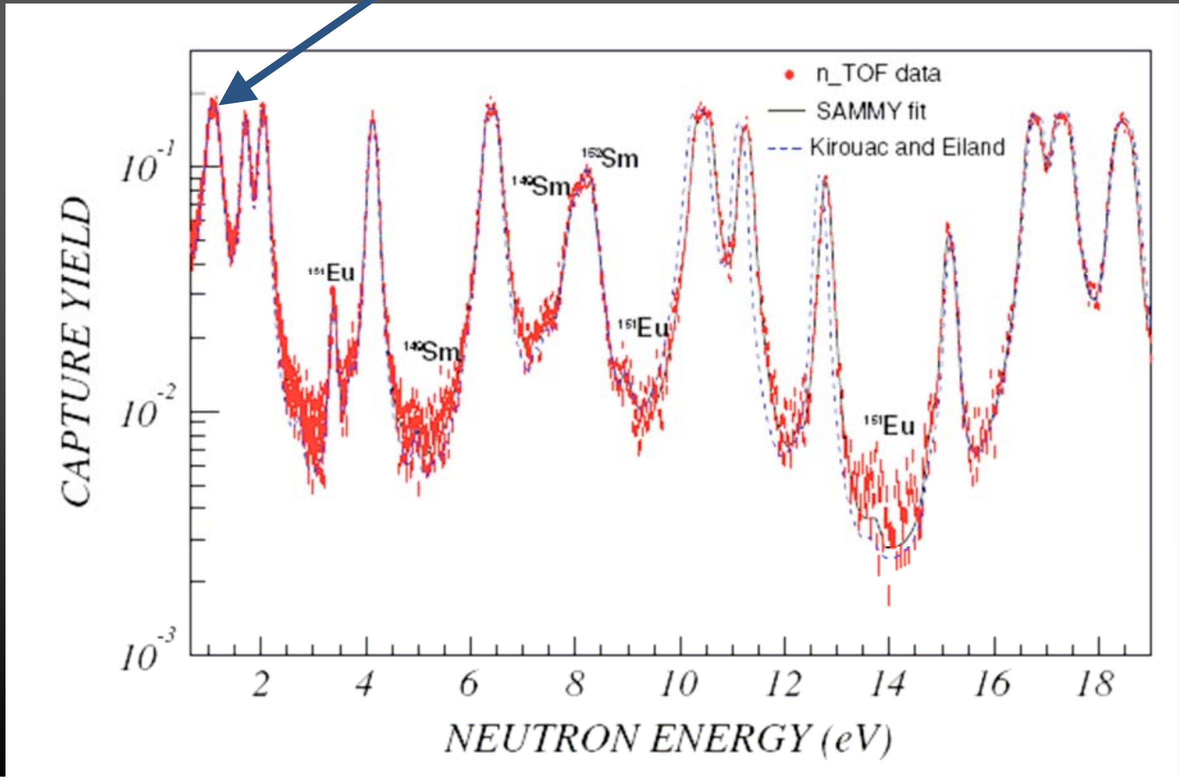
An example is given by the Single Level Breit-Wigner formula which links the resonance parameters with the XS.

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

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

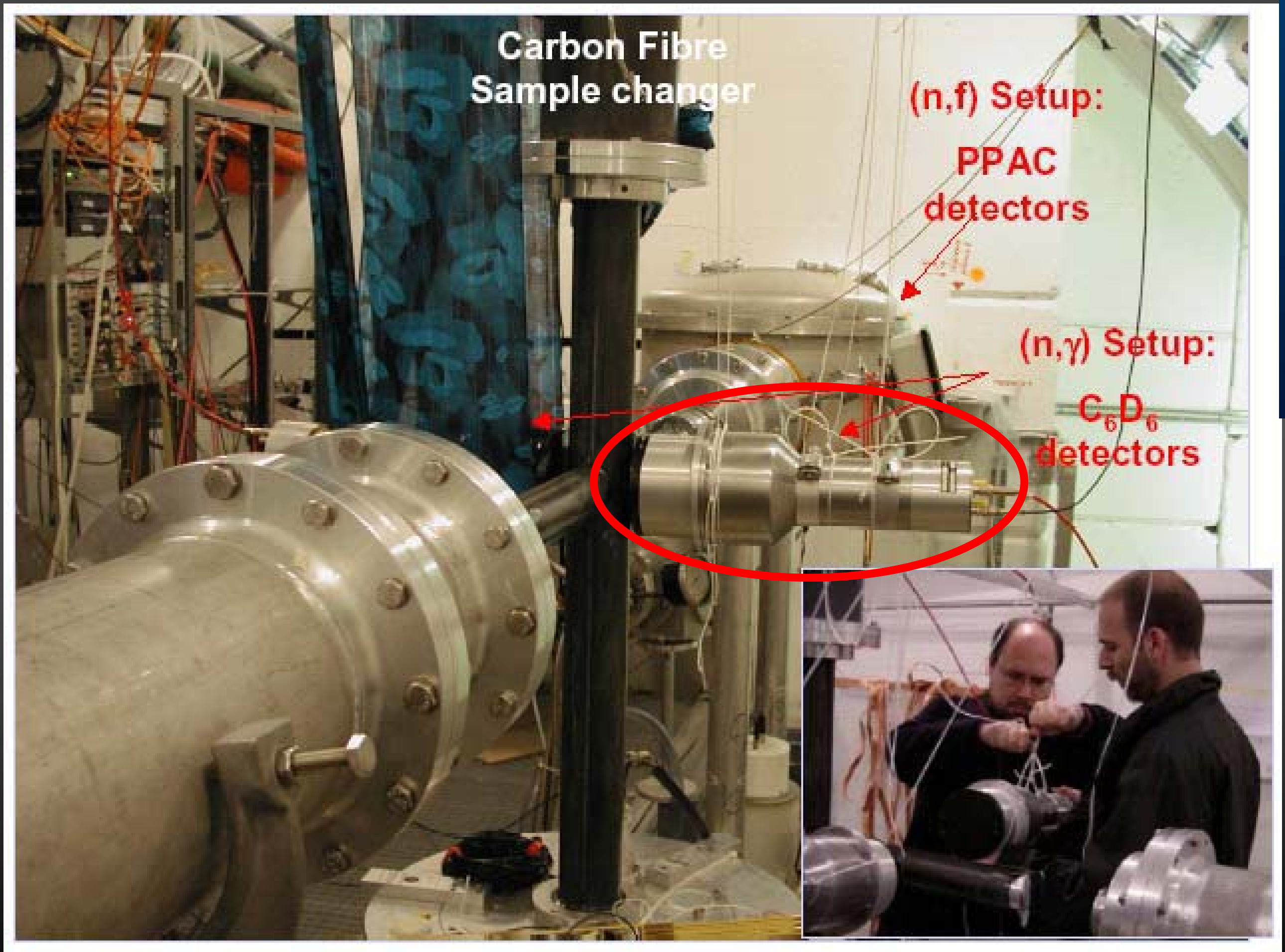
$$\Gamma = \Gamma_n + \Gamma_\gamma$$

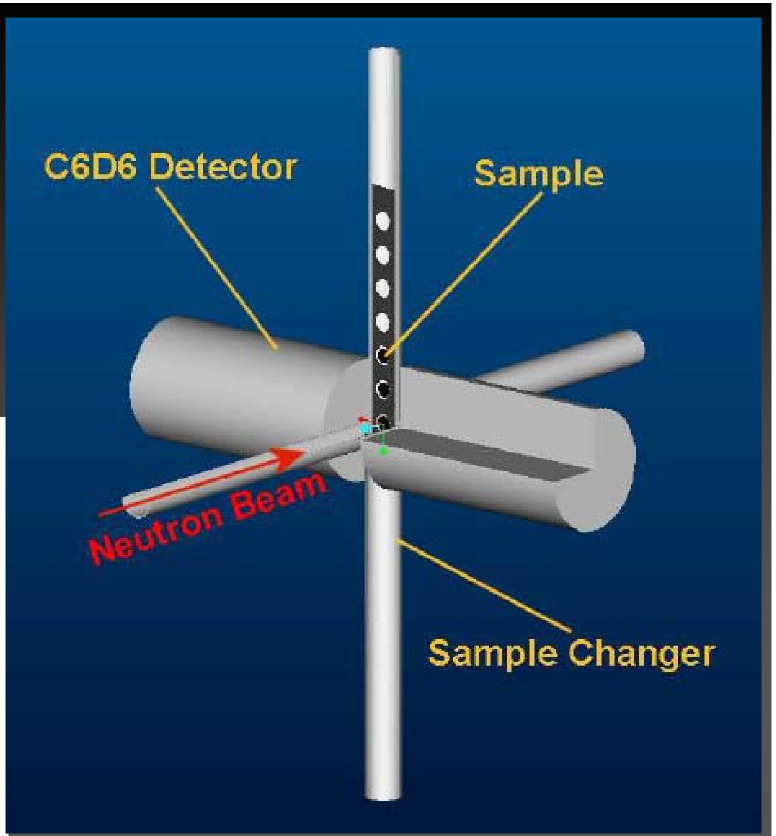




The real world

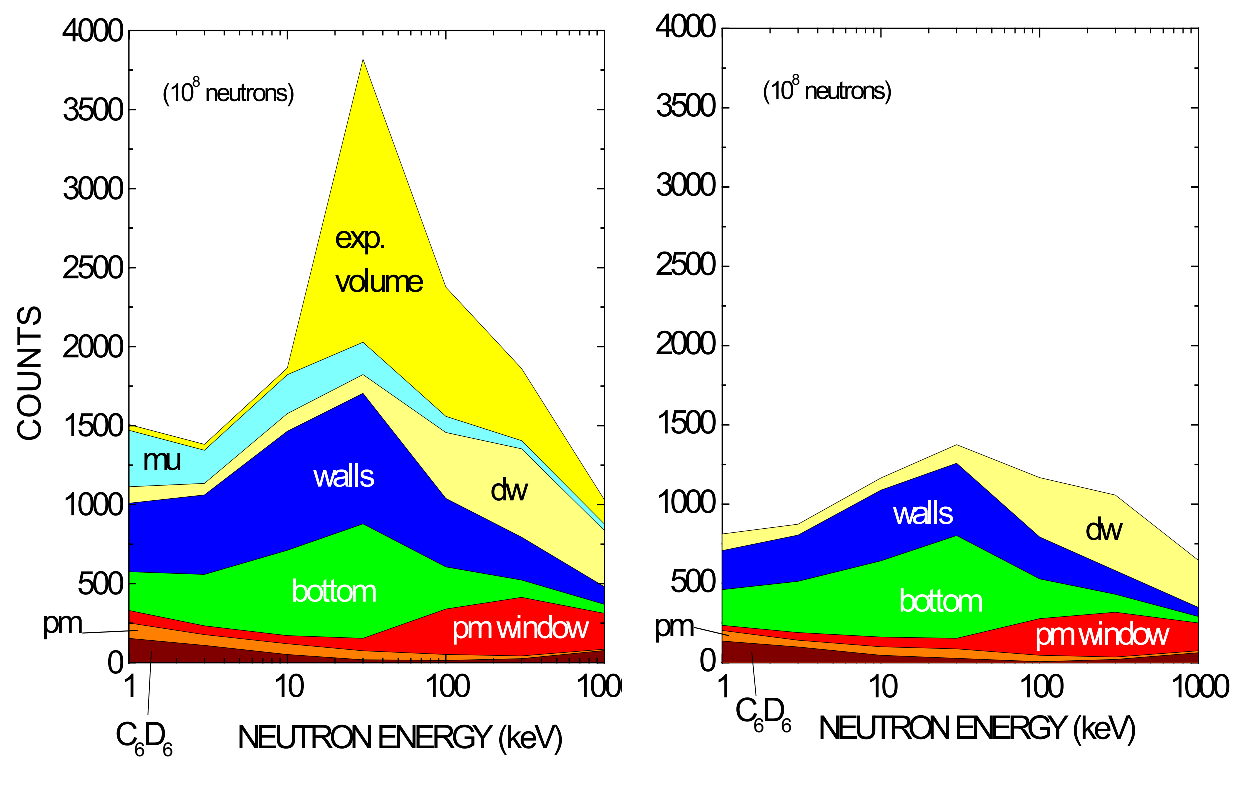
- n_TOF commissioned in 2001-2002

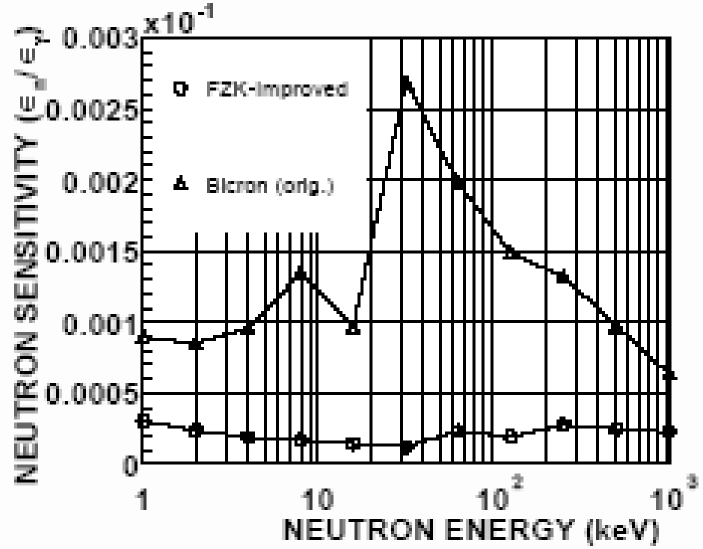




Zr, Pb, and Bi: background problems

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



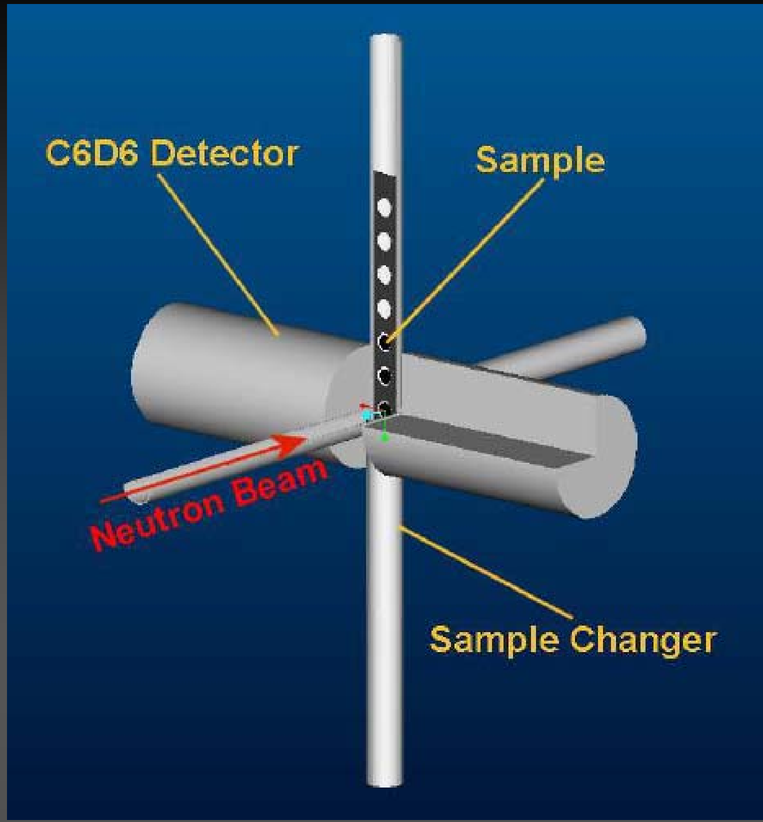


EFFICIENCY in C_6D_6

- The problem in the efficiency correction is the γ-cascade (multiplicity and energy).
- In BaF_2 4π calorimeter it is detected the whole cascade;
- In the C_6D_6 it is used the PHWF;
- This technique consists of modify the Response function of C_6D_6 through simulations (Geant-3 and Geant-4) to verify:

$$\varepsilon_\gamma = \textbf{const} \cdot E_\gamma;$$

- 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:

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

- $\Sigma R_i W_i$ 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.

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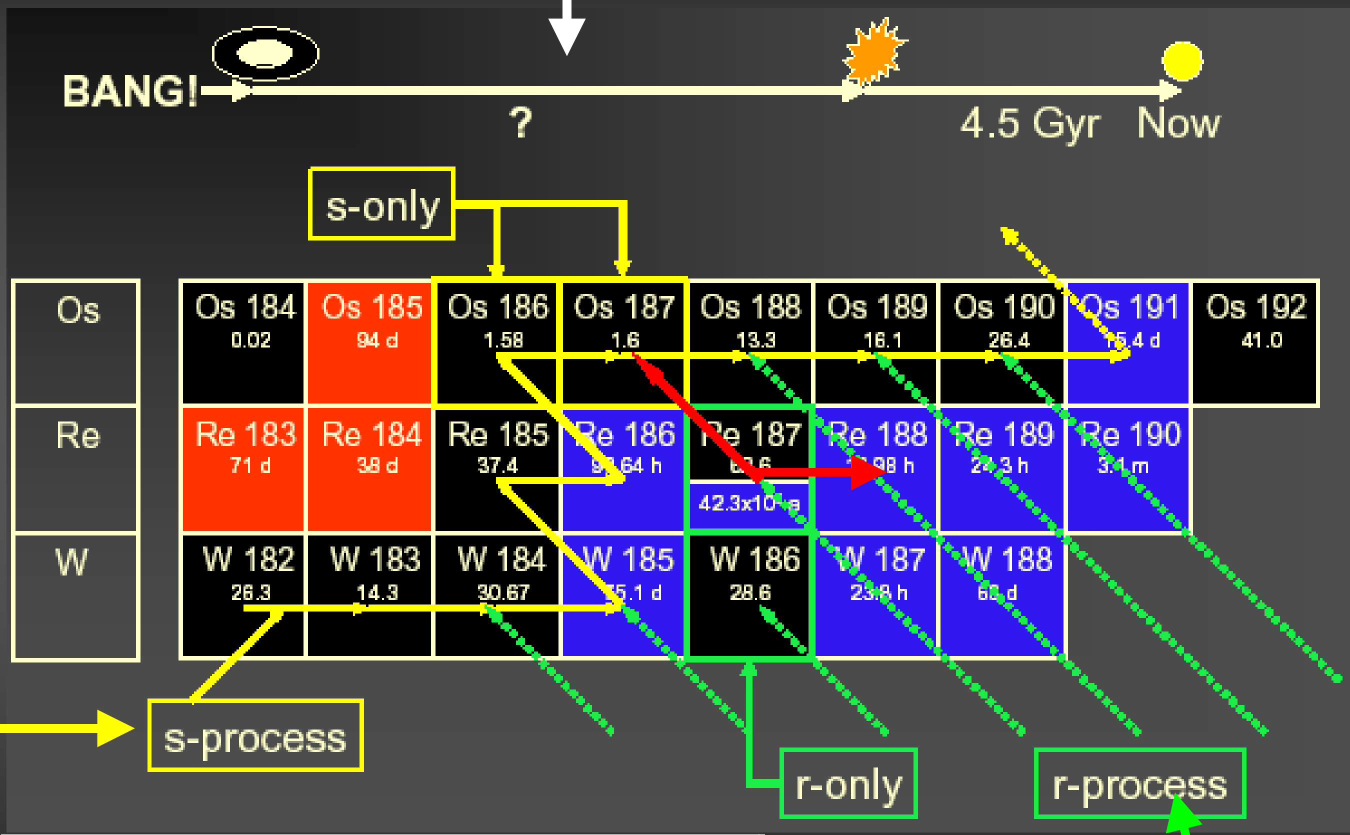
Nuclear Astrophysics

Re/Os cosmo-chronometer



Red Giants

Supernovae

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

Residual Method

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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.

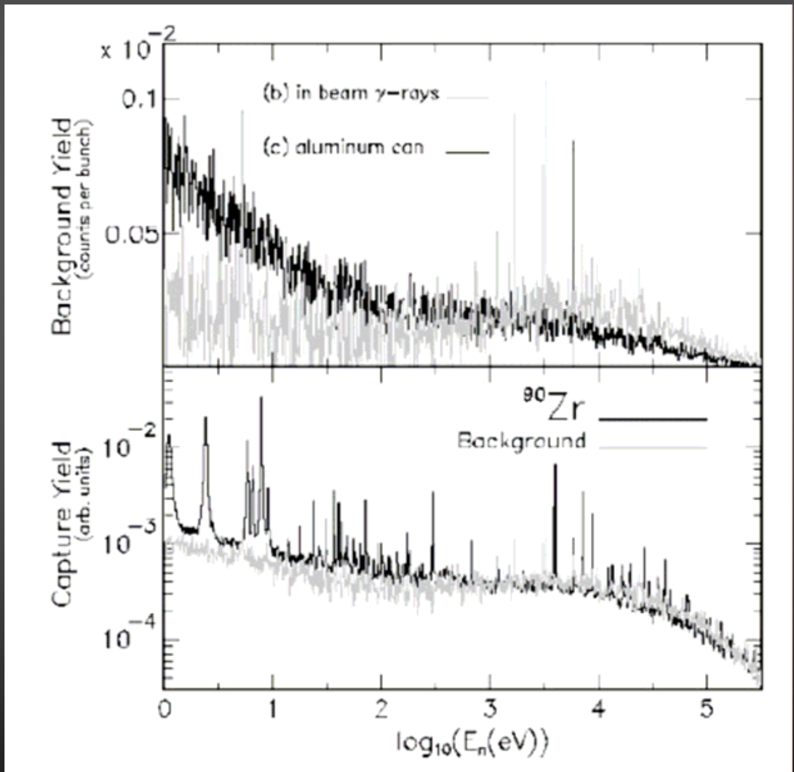
In ‘80 years 80% of Zr production was dedicated to the construction of Nuclear Reactors (Source American Society of Testing Materials).

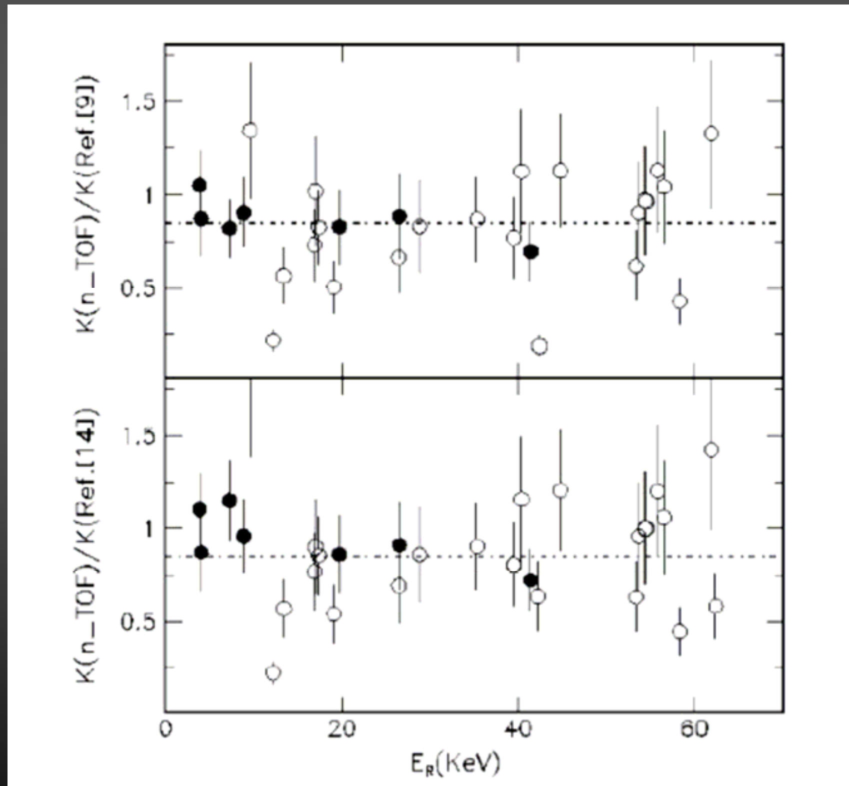
n_TOF experiments

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

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

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





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

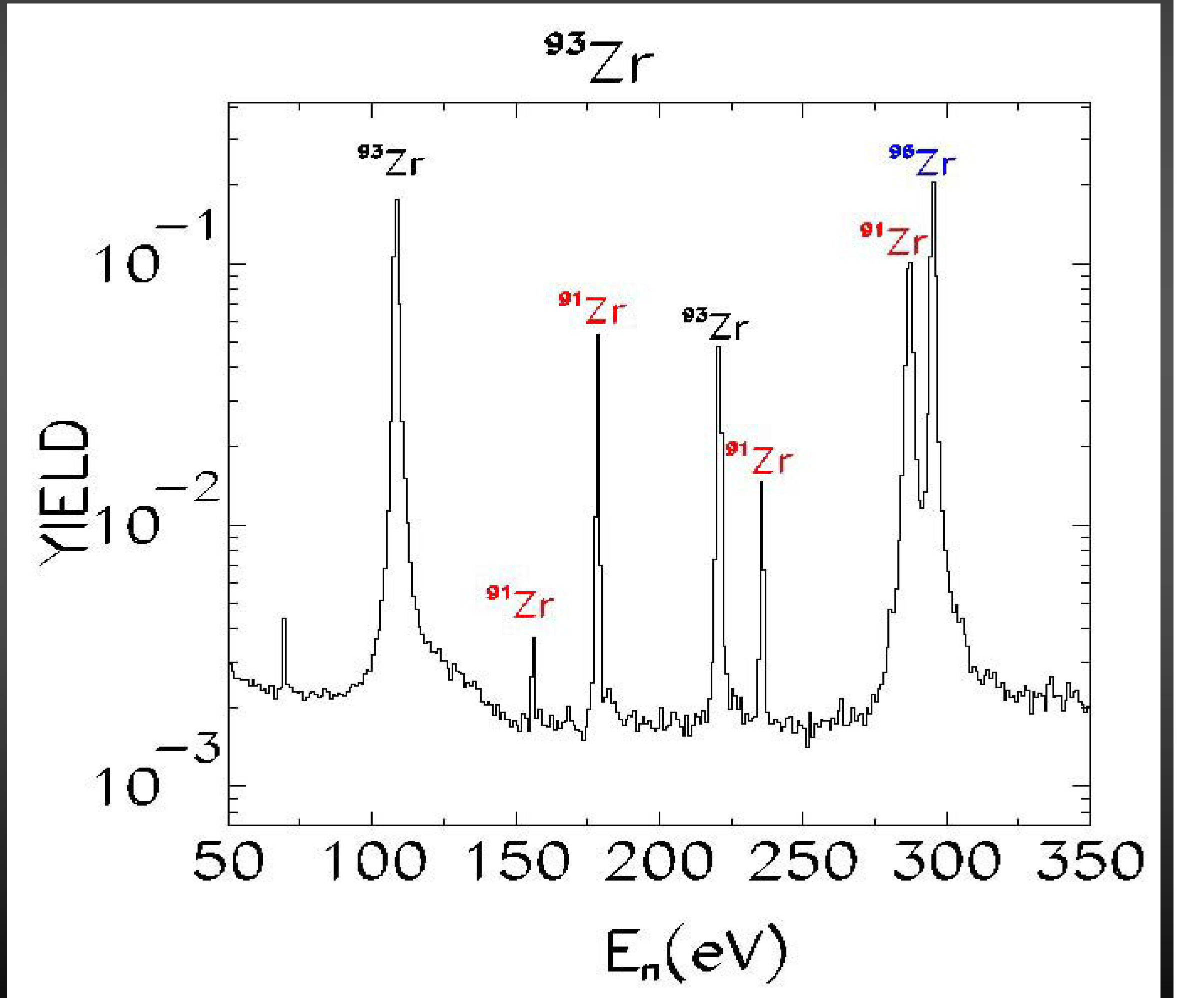
^{232}Th

^{209}Bi

^{237}Np

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

^{93}Zr: 92.6 10^6 y
^{93}Zr(n,γ) raw data



n_TOF experiments: 139La(n,γ)

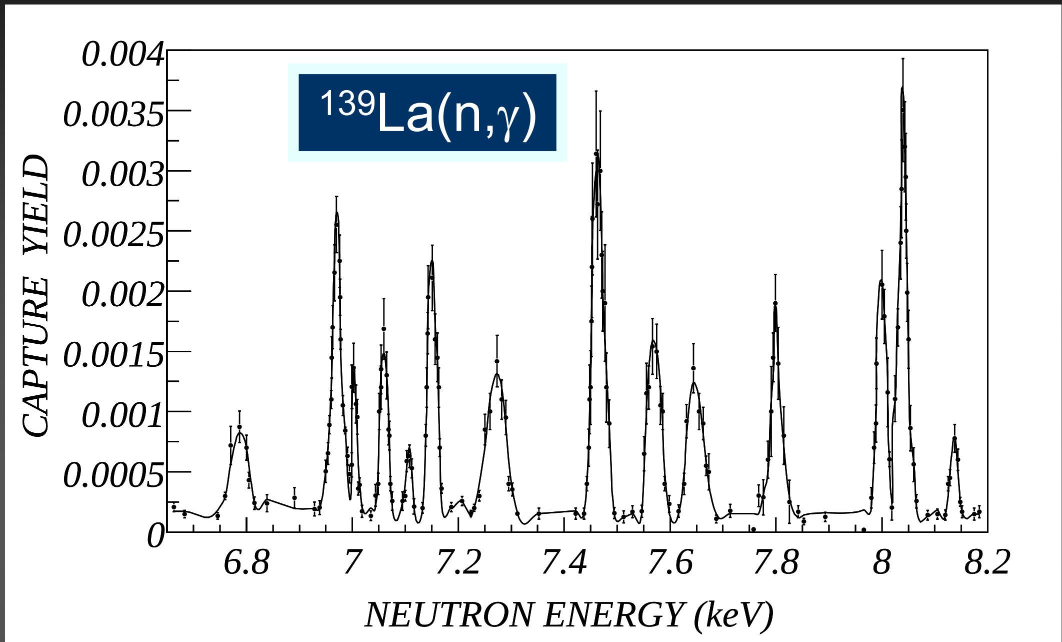
•Used as a Monitor of Neutron Flux in High radiation environment together with other isotopes (e.g. Cd and Au);

•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%).

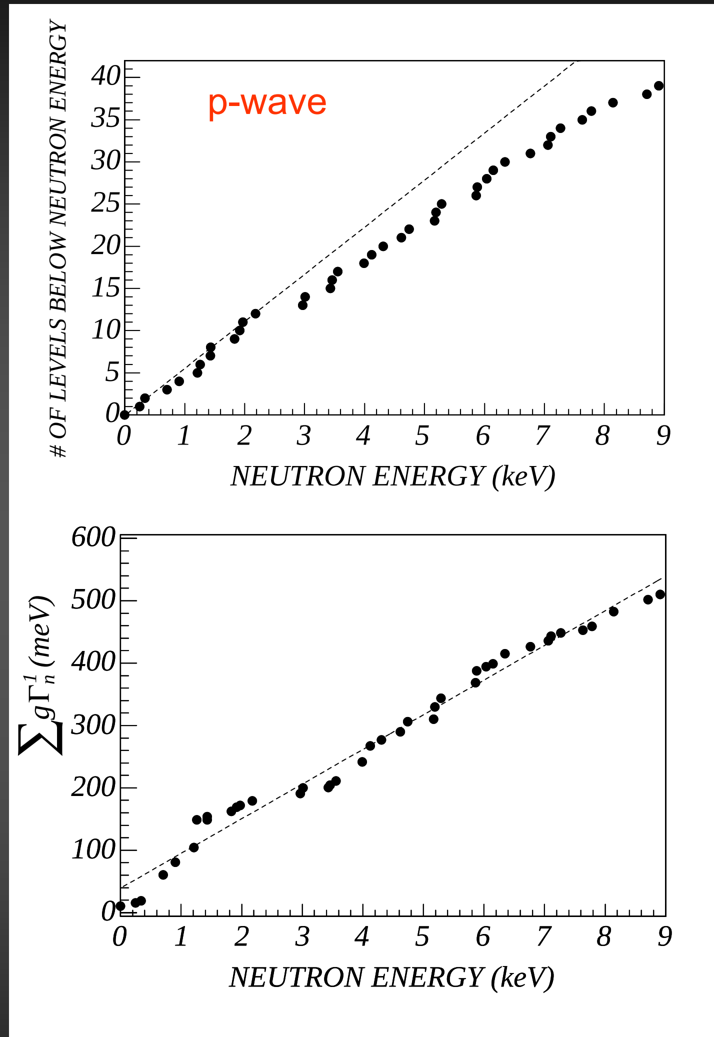
•Lanthanum is almost monoisotopic (140La is 0.1%).

n_TOF experiments: 139La(n,γ)



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
$<D_0>$= 252 ± 22 eV
$S_0 = (0.82 \pm 0.05)\times10^{-4}$ $S_1 = (0.55 \pm 0.04)\times10^{-4}$



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.

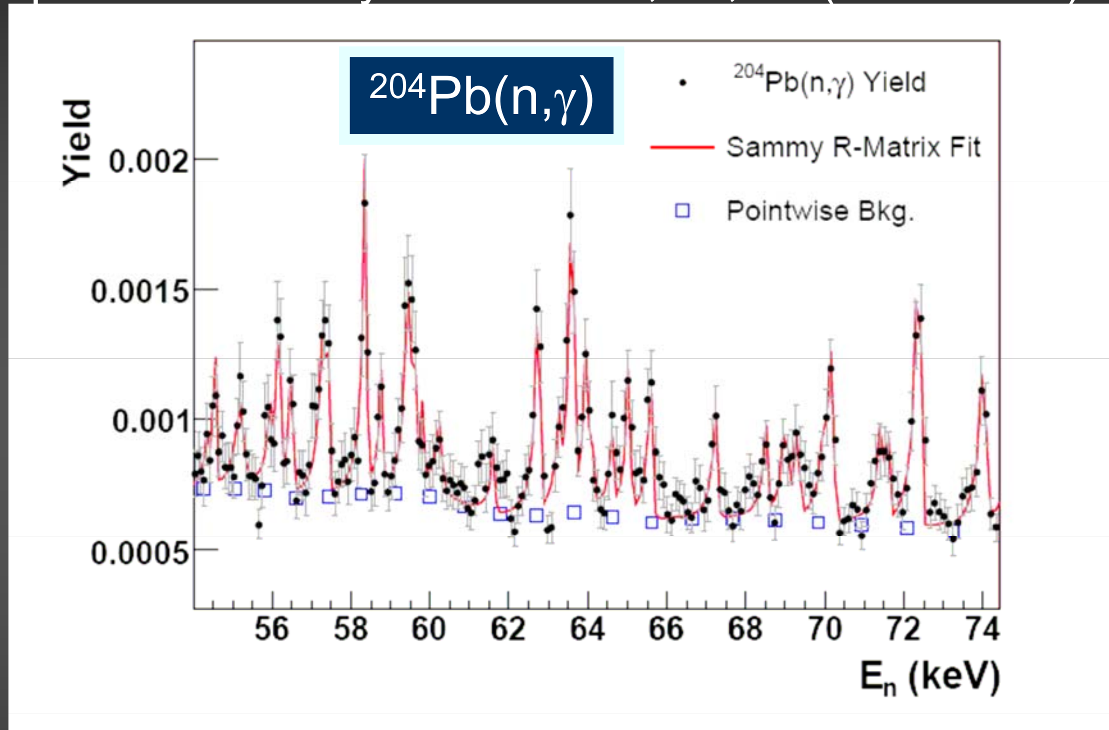
n_TOF experiments: Pb and Bi

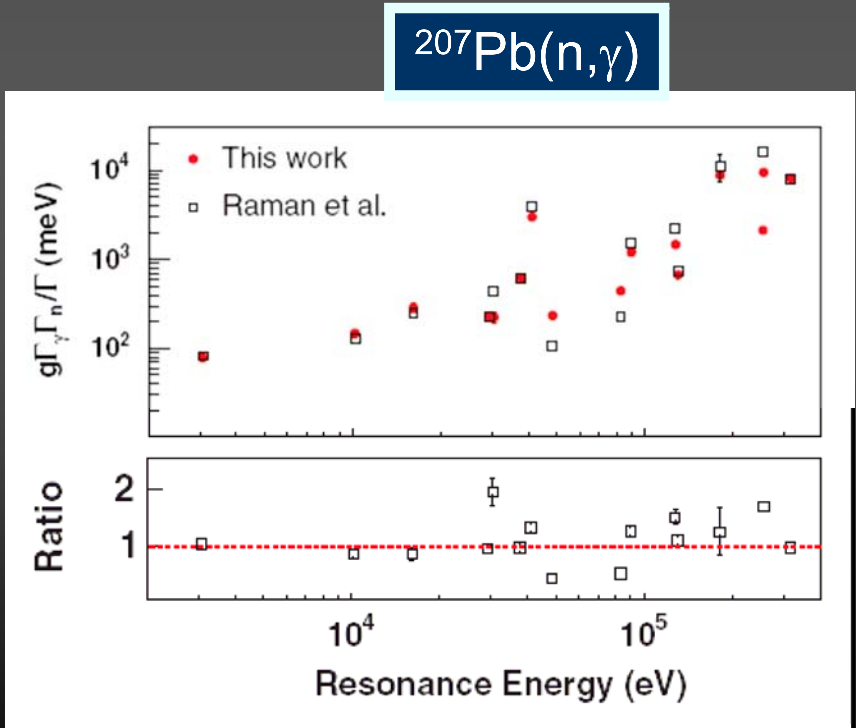
Very large energy neutron region to detect the neutron levels.

Very accurate determination of the resonance width.

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

C Domingo-Pardo, et al. (The n_TOF Collaboration)
3 Pb papers published in Phys. Rev. C **74**, 76, 77 (2006-2007)





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

n_TOF experiments: Pb and Bi

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

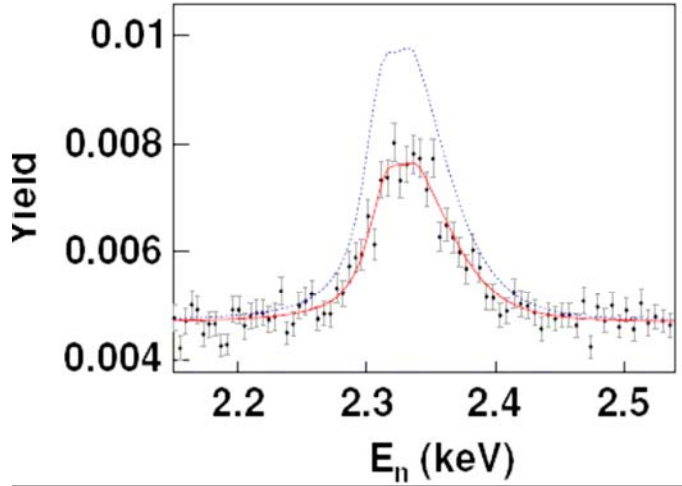
C Domingo-Pardo, et al. (The n_TOF Collaboration)
Phys. Rev. C **74**, 025807 (2006)

NEW MEASUREMENT OF NEUTRON CAPTURE . . . PHYSICAL REVIEW C 74, 025807 (2006)

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

$E_\circ$ (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)

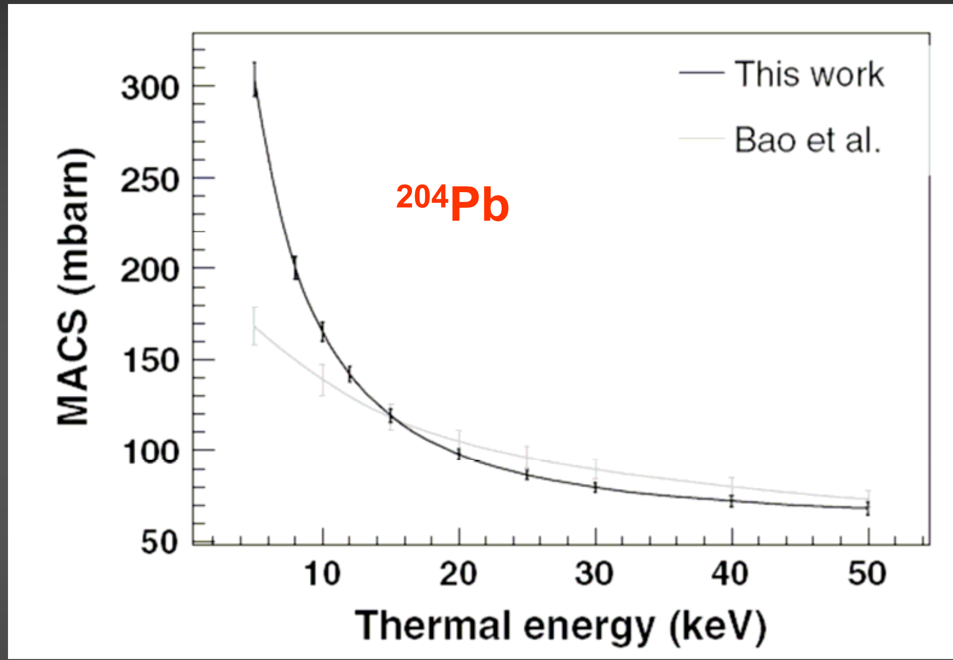
[a]Angular orbital momenta, l, resonance spins J, and neutron widths, Γ_n, are mainly from Refs. [27,28].
[b]Uncertainties are given as 18.2(6)≡18.2±0.6.
[c]This area corresponds to the sum of the areas of the broad s-wave resonance at the indicated energy, plus two p-wave resonances at 12.092 and 12.285 keV.

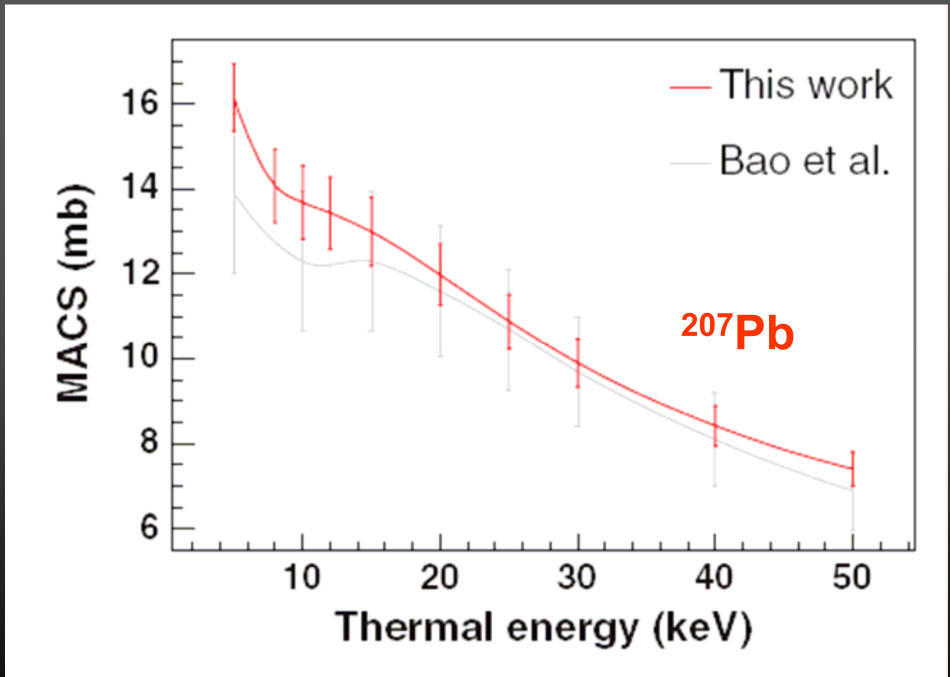


16% higher MACS for kT = 5-8 keV
81% r-process abundance for ^{209}Bi

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.



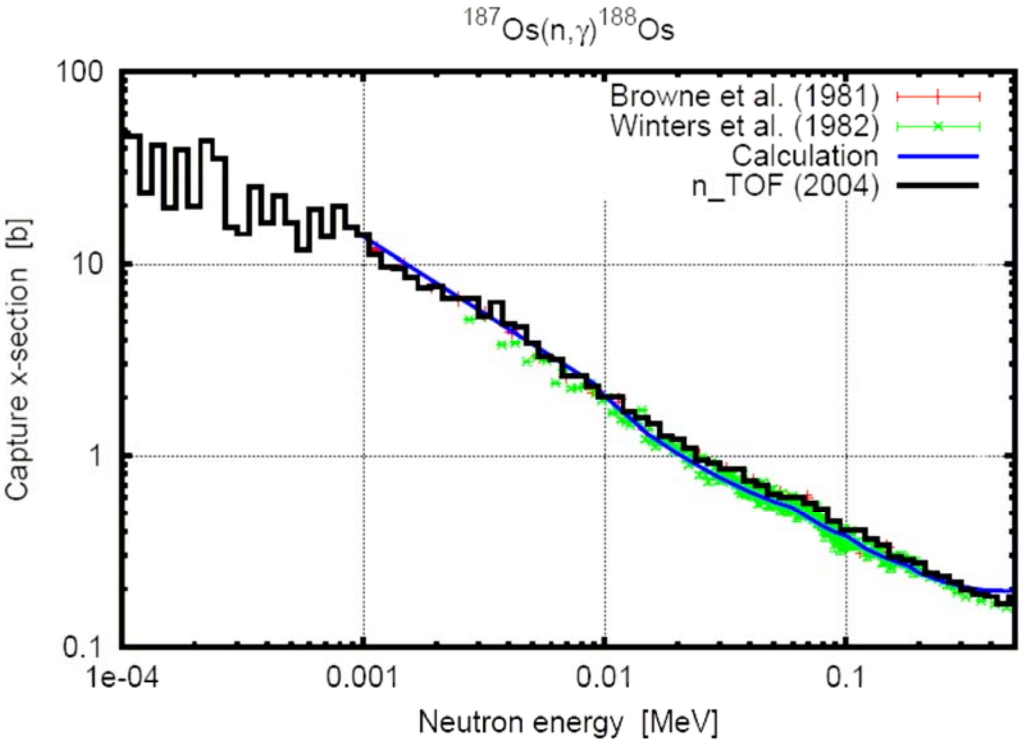


Larger cross section especially at low energies (E_n<15 keV).

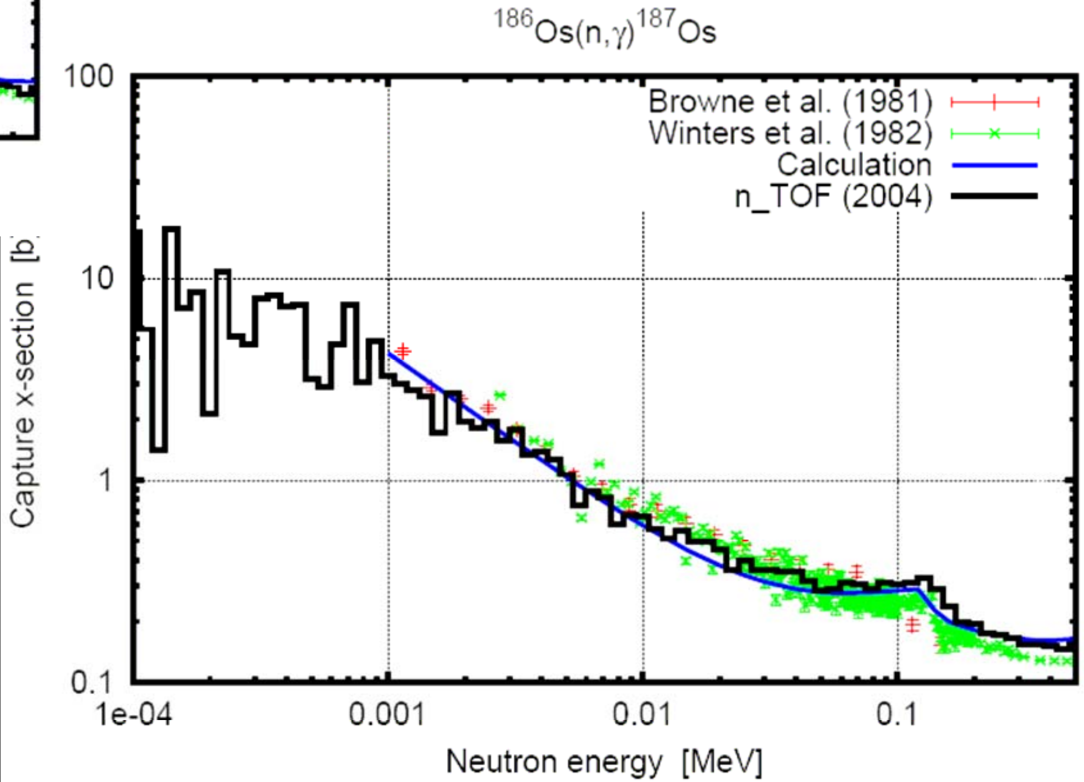
Relative isotopical abundance are 5% lower.

Other components higher

n_TOF experiments: 186,187,188Os(n,g)



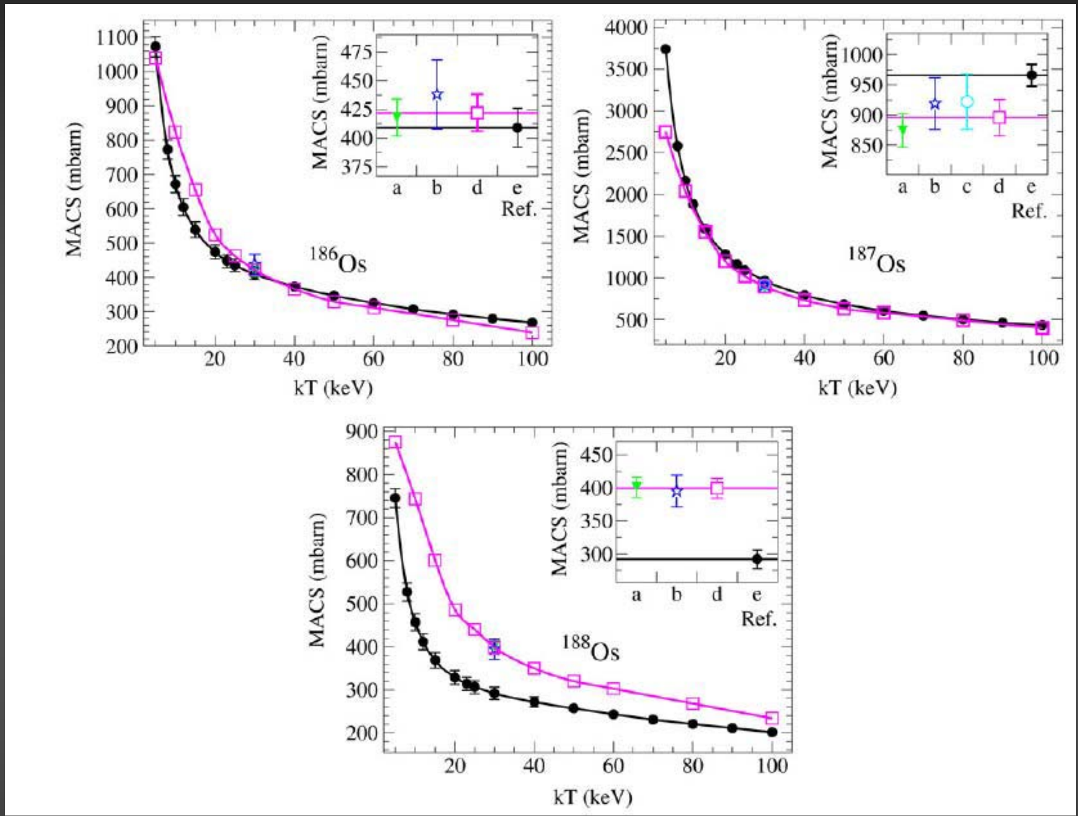
M Mosconi, *et al.* Progress in Particle and Nuclear Physics 59, 165.
NIC-IX Proceedings CERN, Geneva – June 2006



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



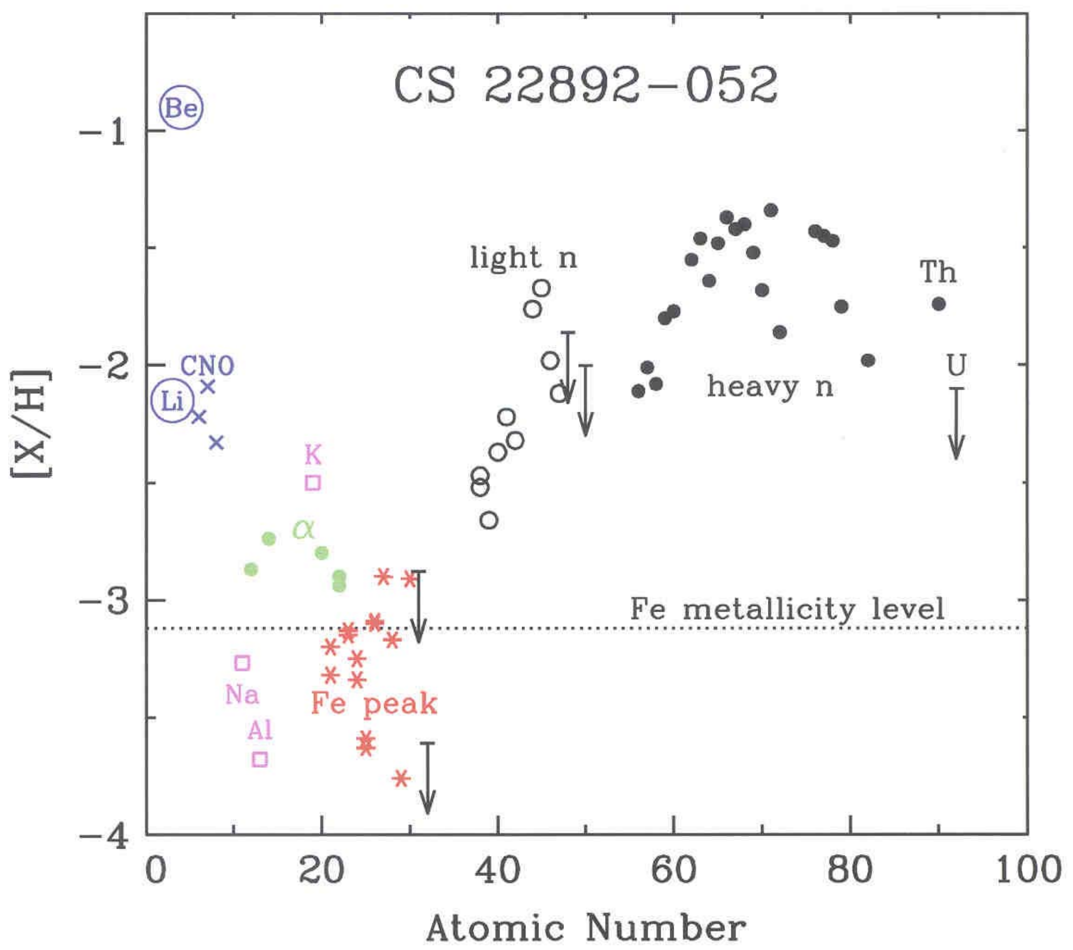
Largest differences for ^{188}Os.

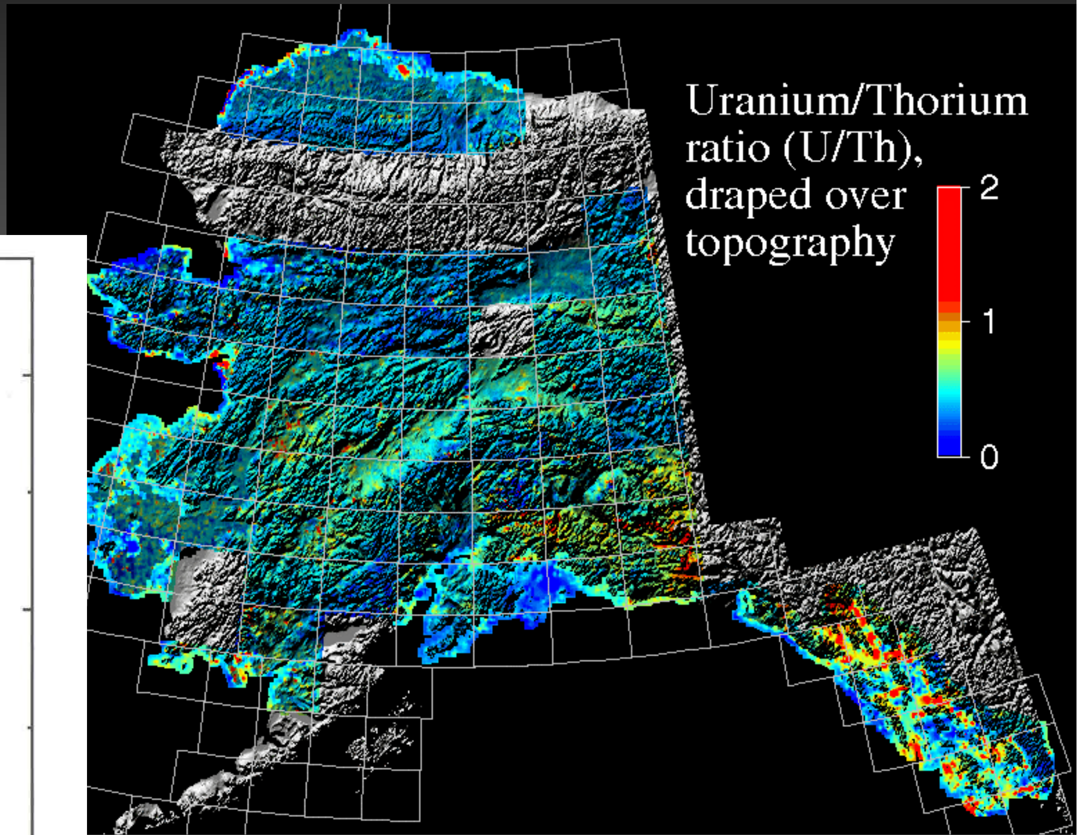
Sizeable differences in the low neutron energy region 10-20 keV.

MACS[186Os] / MACS[187Os] = 0.41

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

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



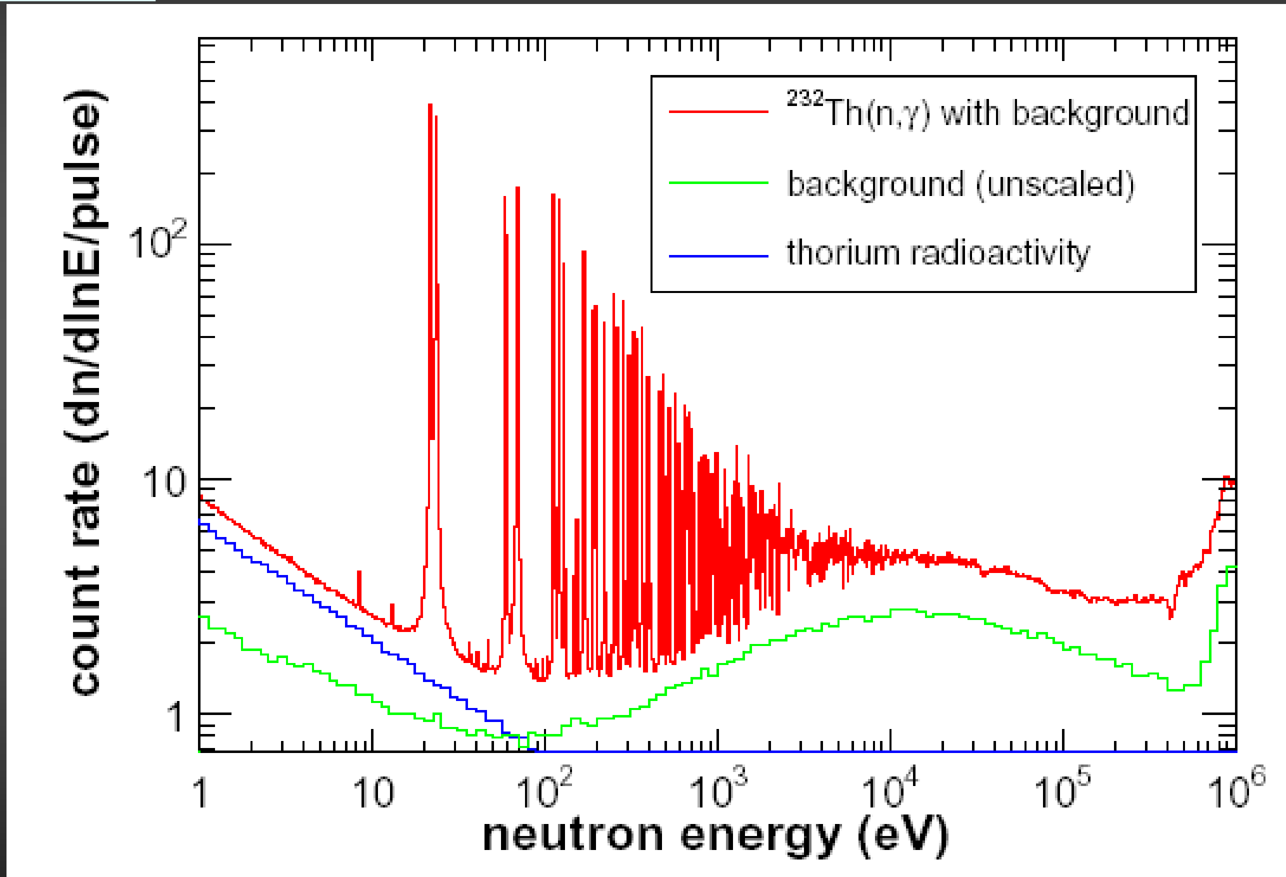


$$[\ X/H\ ] = \mathrm{Log}(N_X/N_H)_{star} - \mathrm{Log}(N_X/N_H)_{sun}$$

n_TOF experiments

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

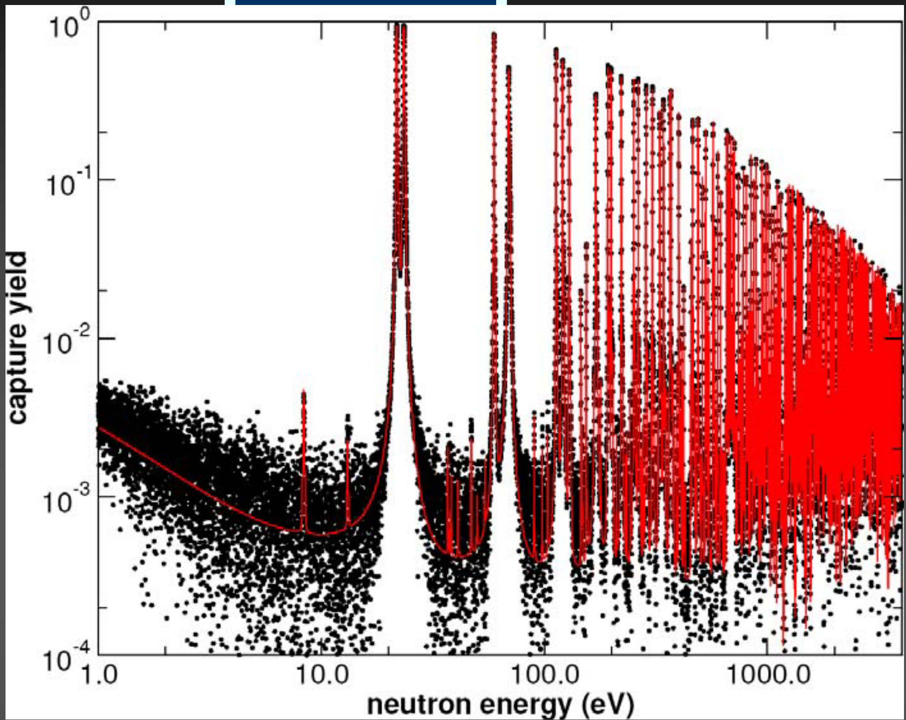
$^{232}Th(n,\gamma)$



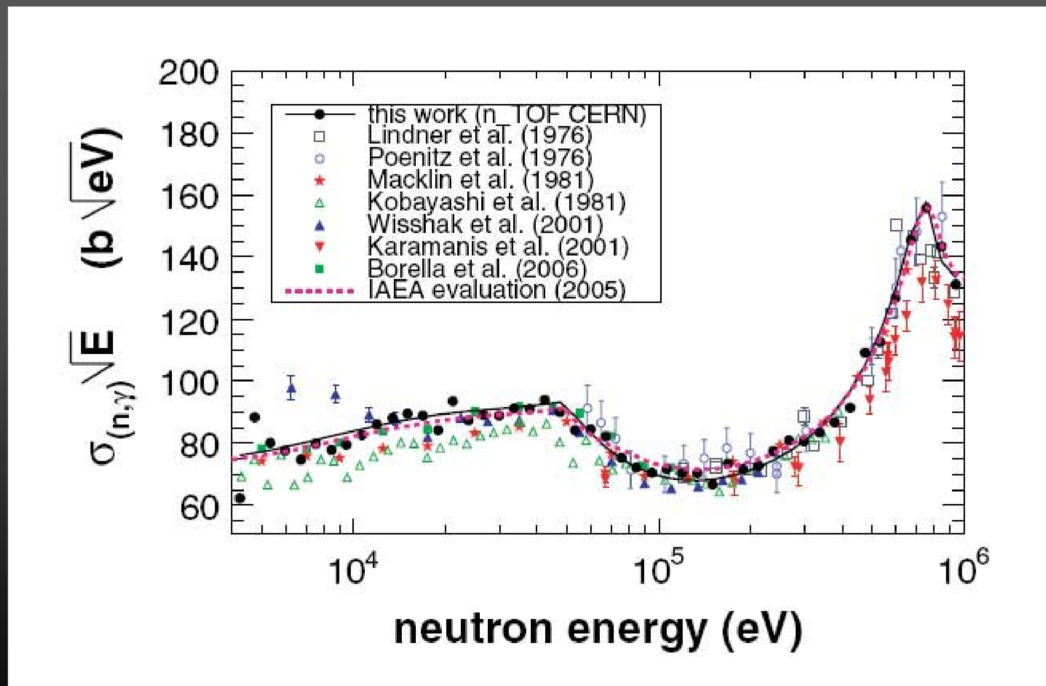
Low PS duty-cycle favours measurements on radiactive samples

n_TOF experiments

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



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)



Very large neutron energy range.

High resolution power of the neutron resonances.

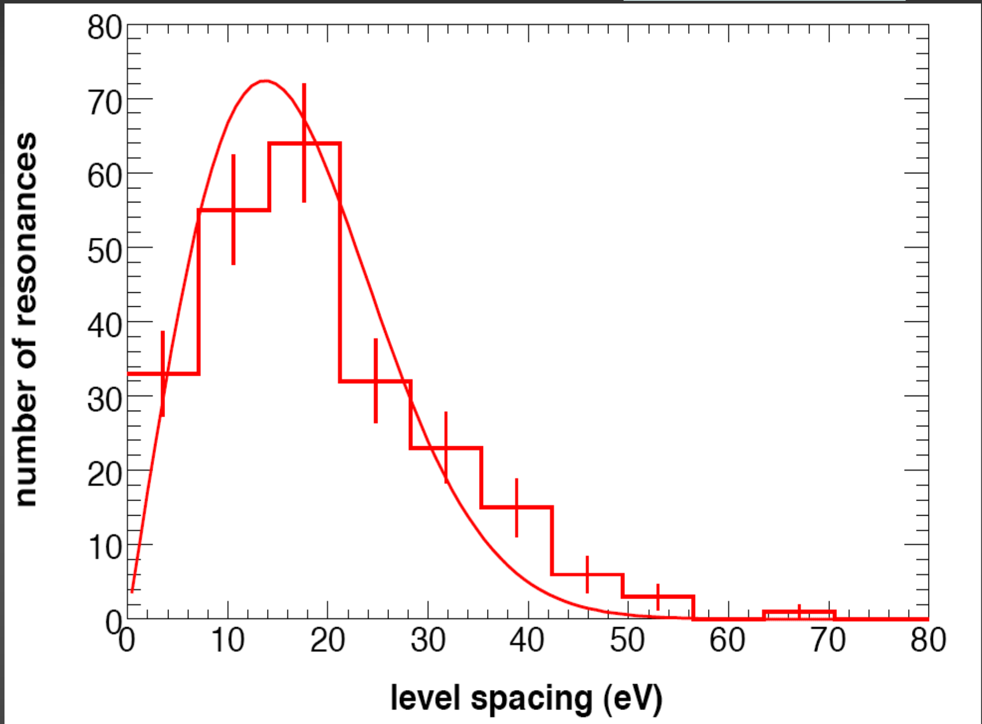
Interesting implications in Nuclear Astrophysics. (Th/U and Th/Eu chronometers).

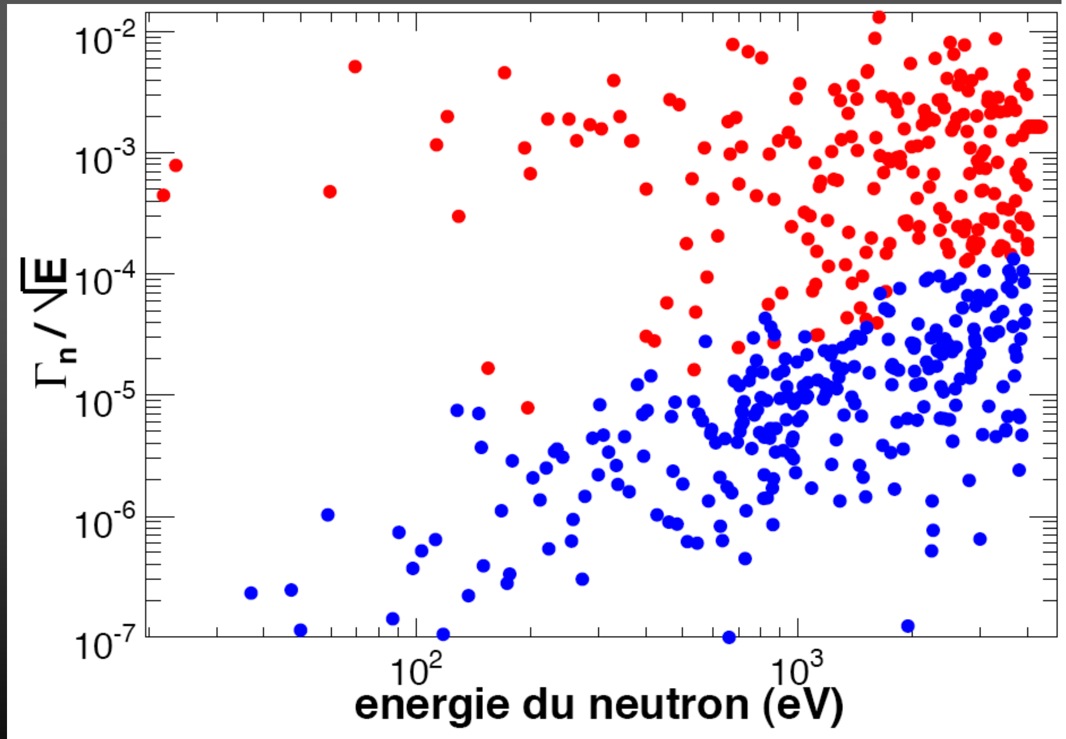
The most important ones are in Th fuel cycle.

n_TOF experiments

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

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

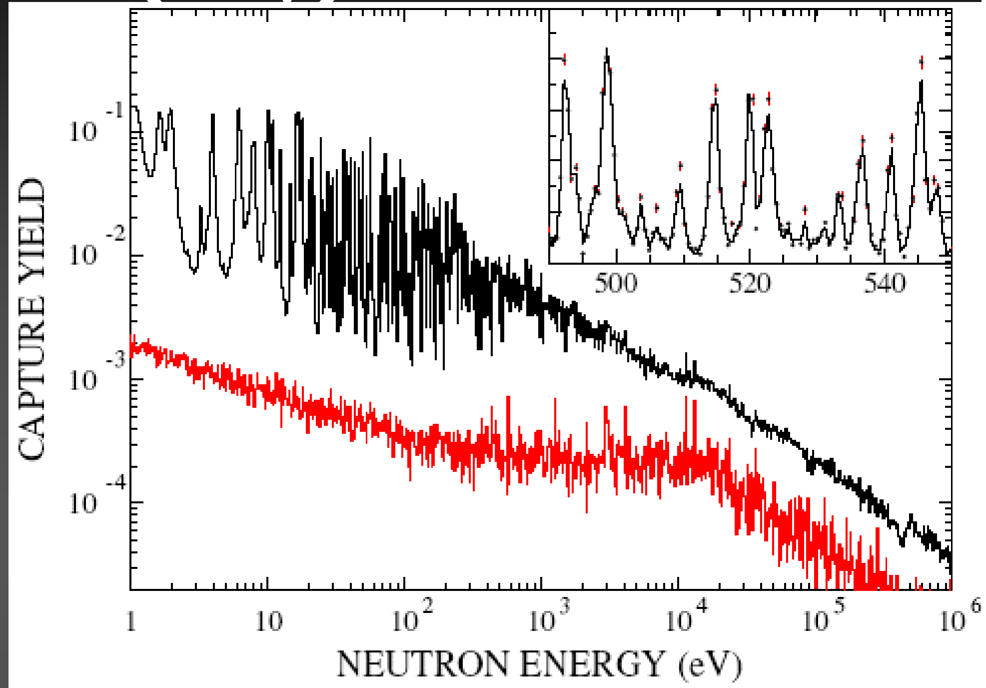


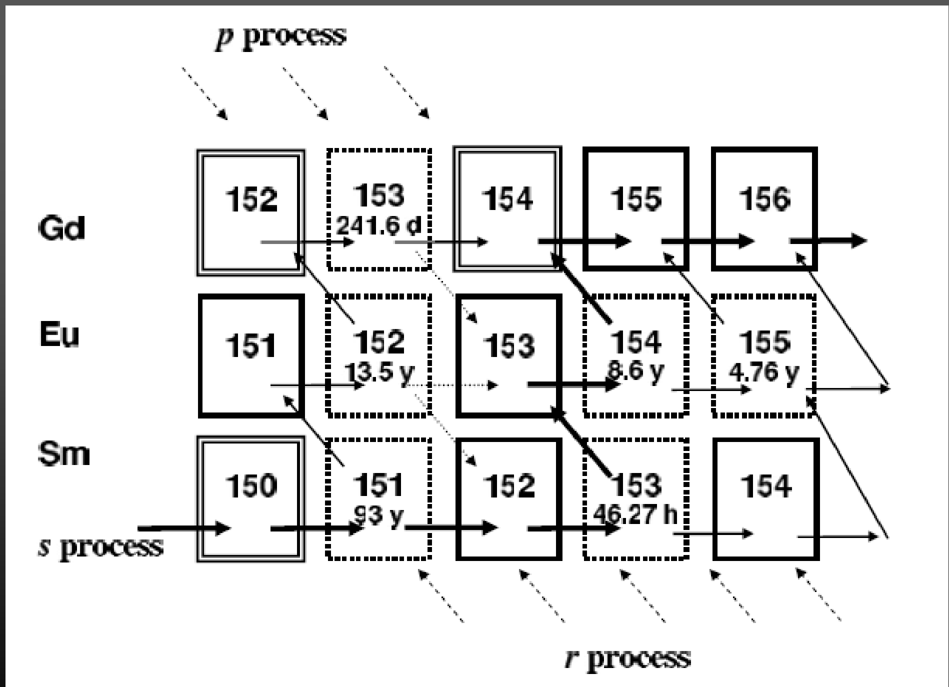


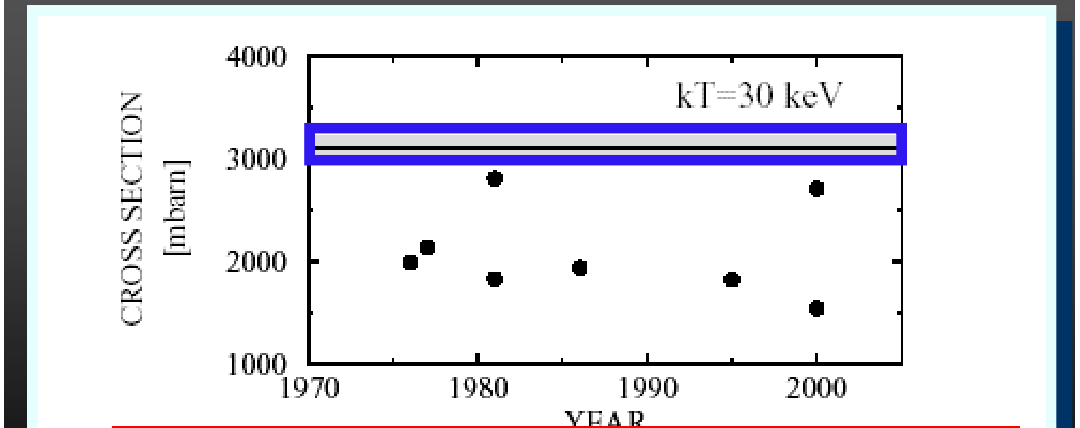
$^{151}Sm(n,\gamma)$

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)

$\langle D_0 \rangle = 1.49 \pm 0.07$ eV
$S_0 = (3.87 \pm 0.33)\times 10^{-4}$
$R_l = 3575 \pm 210$ b



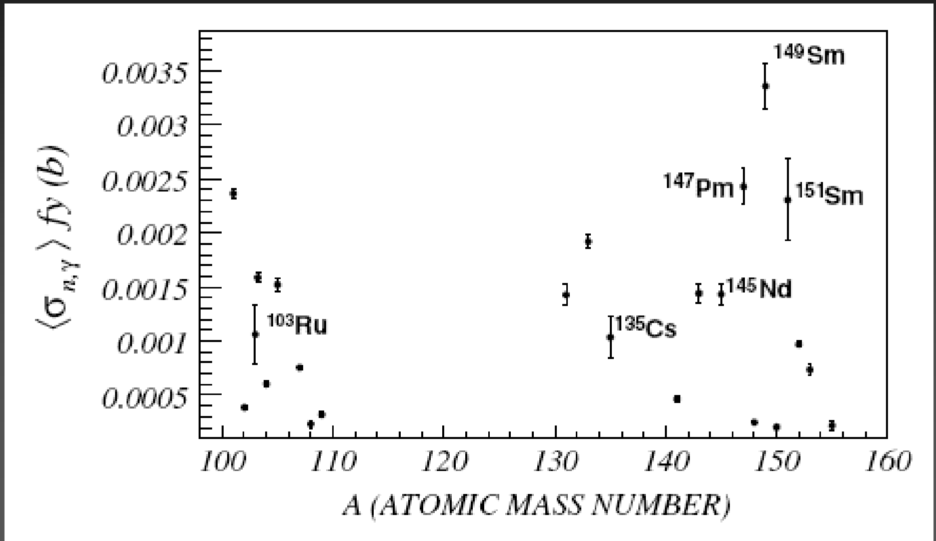




MACS-30 = 3100 ± 160 mb

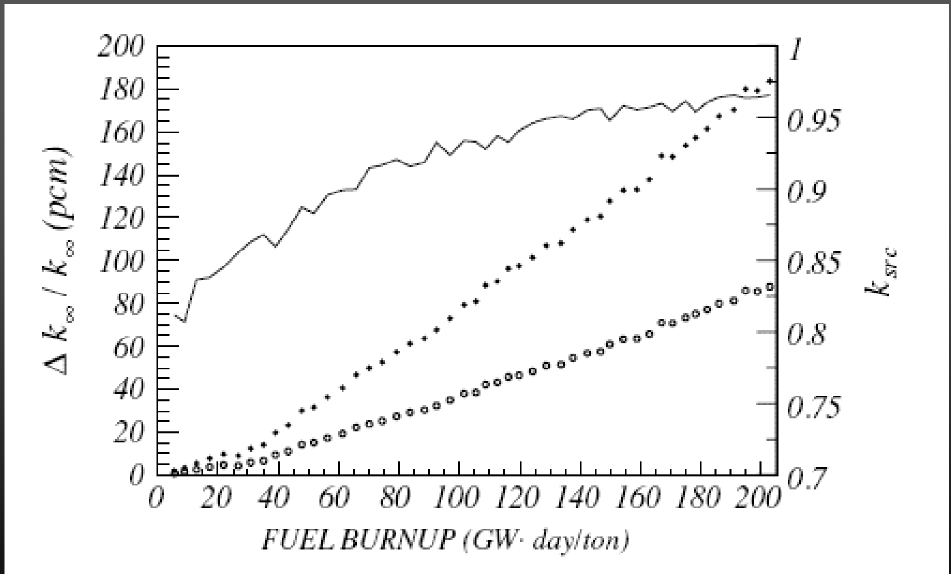
www.cern.ch/n_TOF

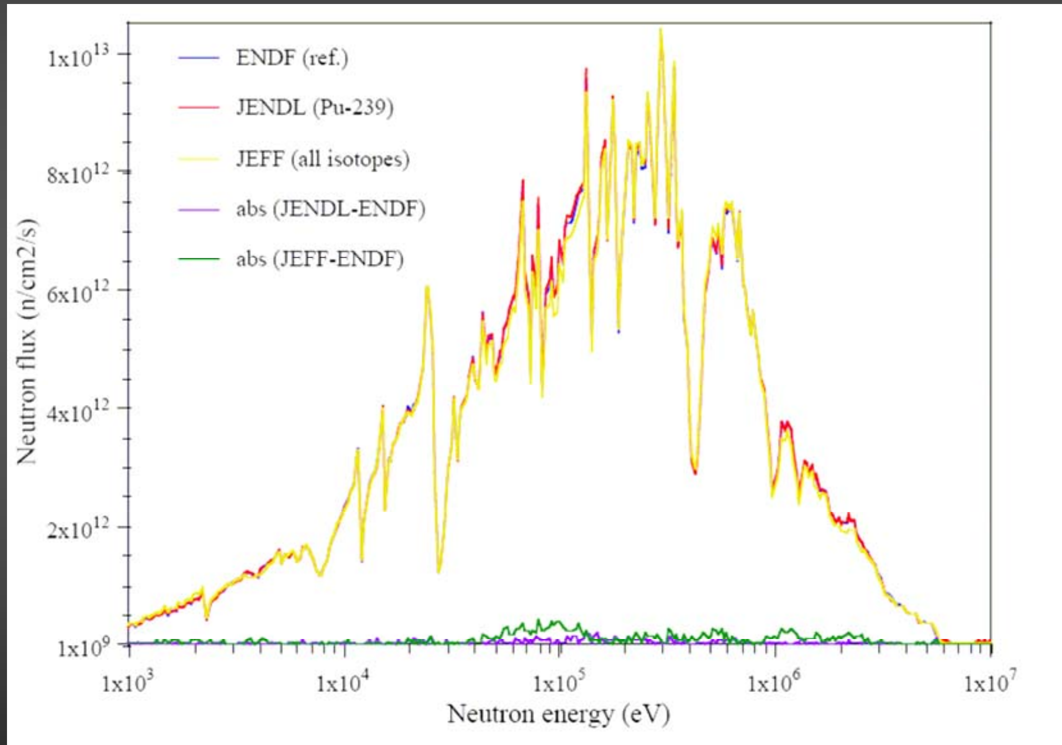
n_TOF experiment: 151Sm(n,γ)



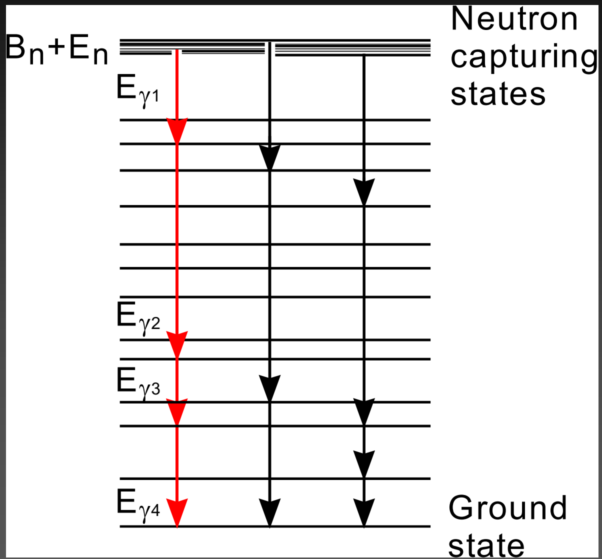
Energy Amplifier Demonstration Facility.

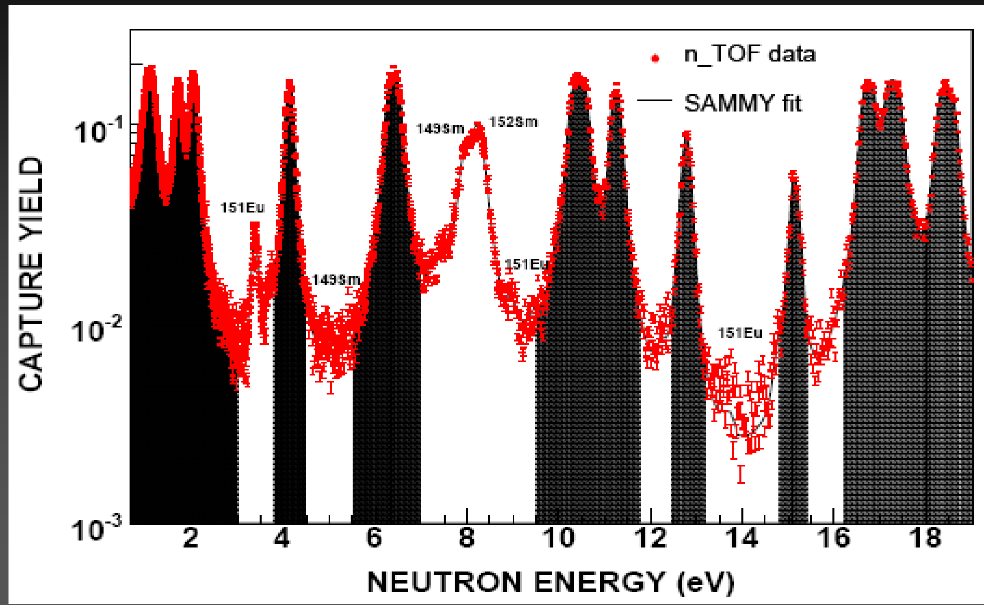
PhD. Thesis: A. Herrera-Martinez





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:

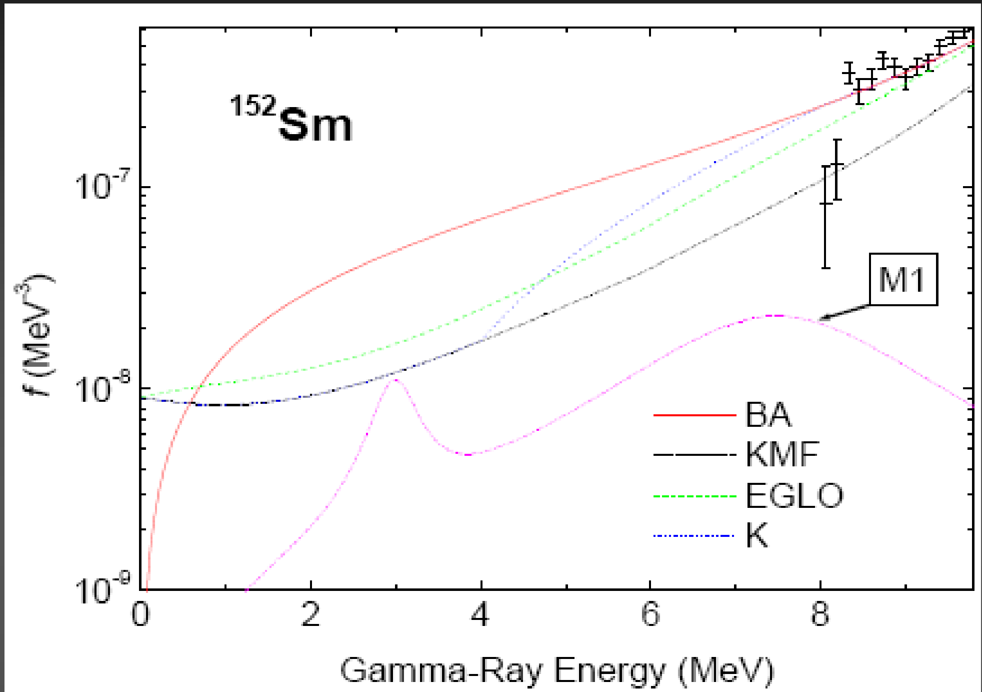
- very good signal-to-background ratio
- high resolution allows to select different resonances
- accurate study of the detector response (MC simulations and data)

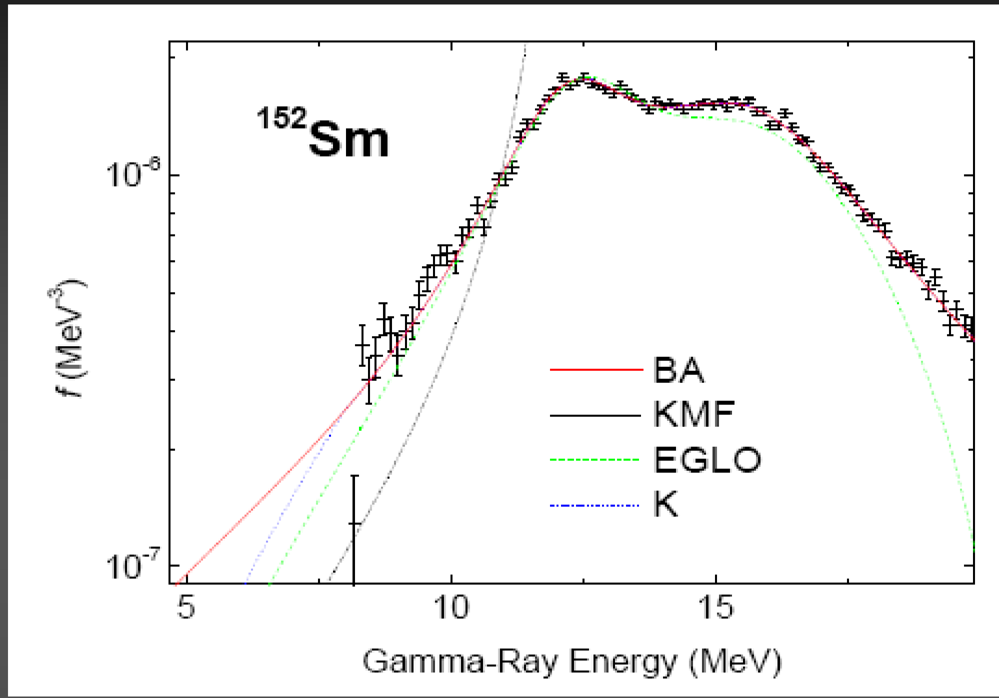
Disadvantages:

- 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…)

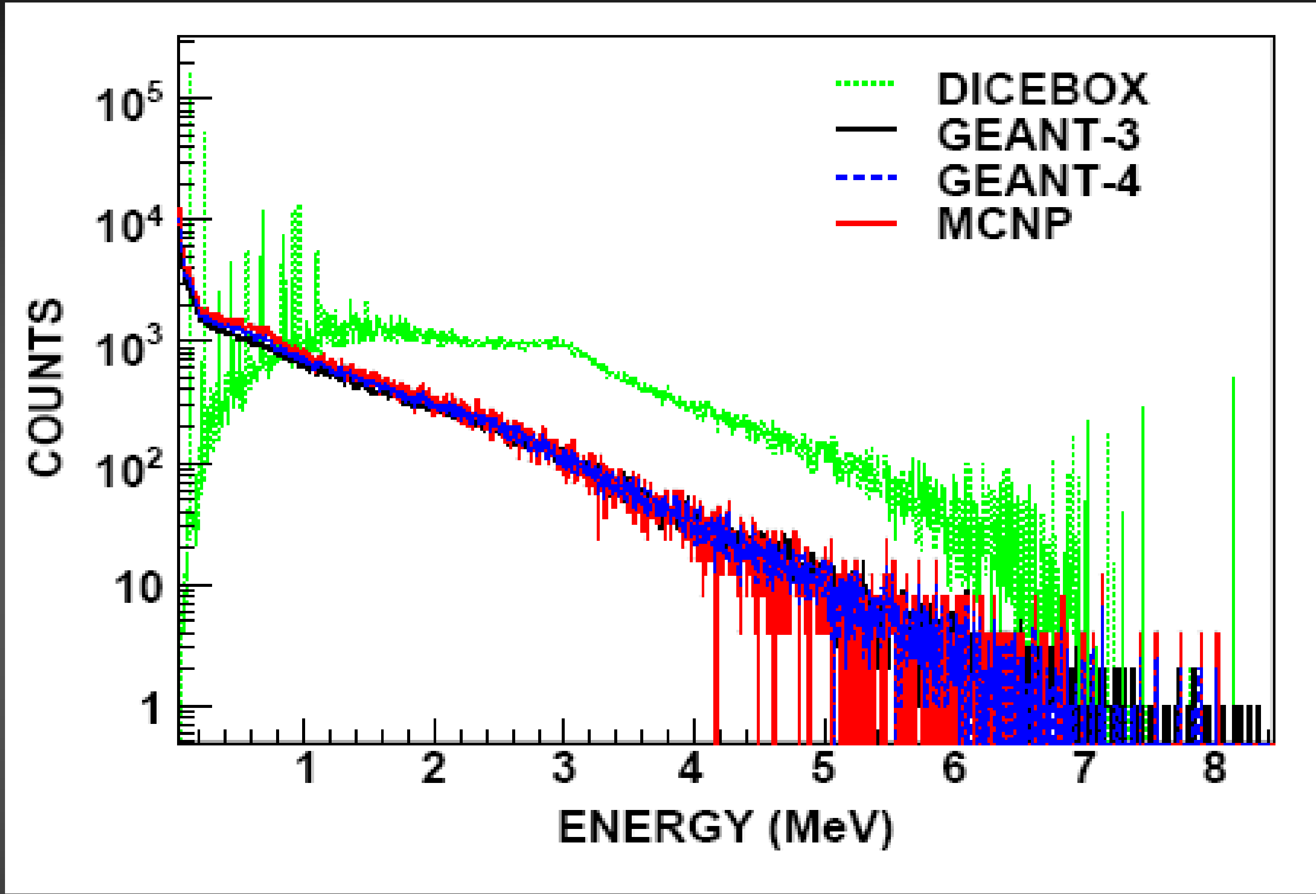
Large implications in Nuclear Astrophysics especially for the r-process stellar environments.

Monte Carlo Simulations

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

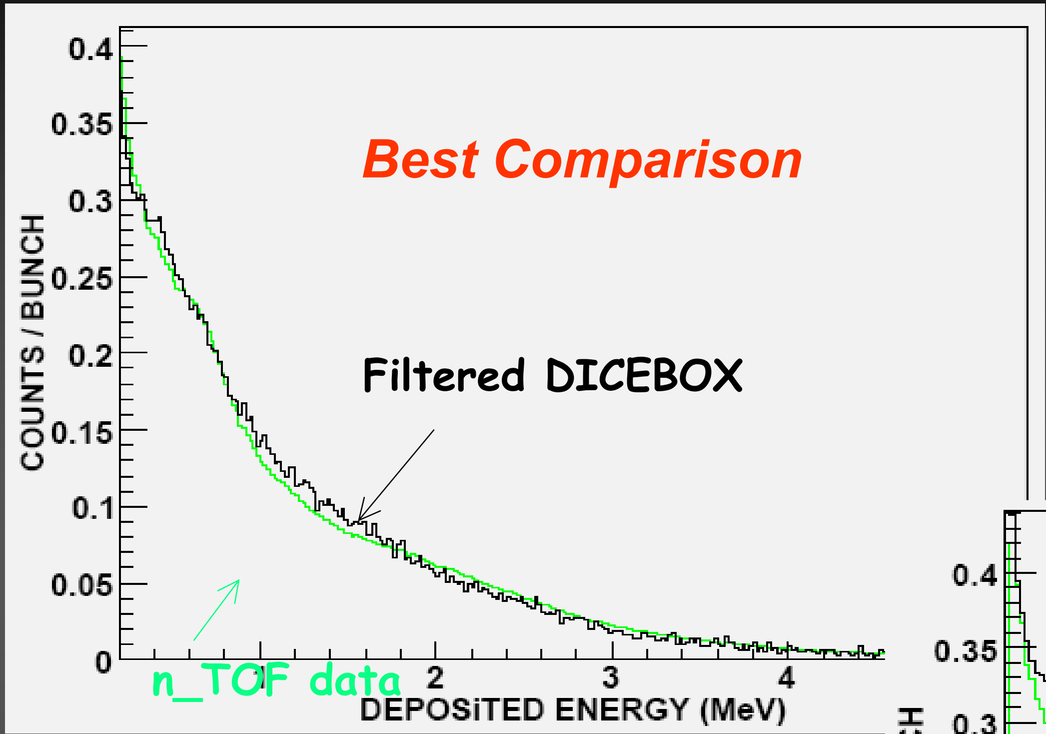
- MCNP-X
- GEANT 3.21
- GEANT 4

Accurate implementation of the materials and detailed geometry of experimental apparatus



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

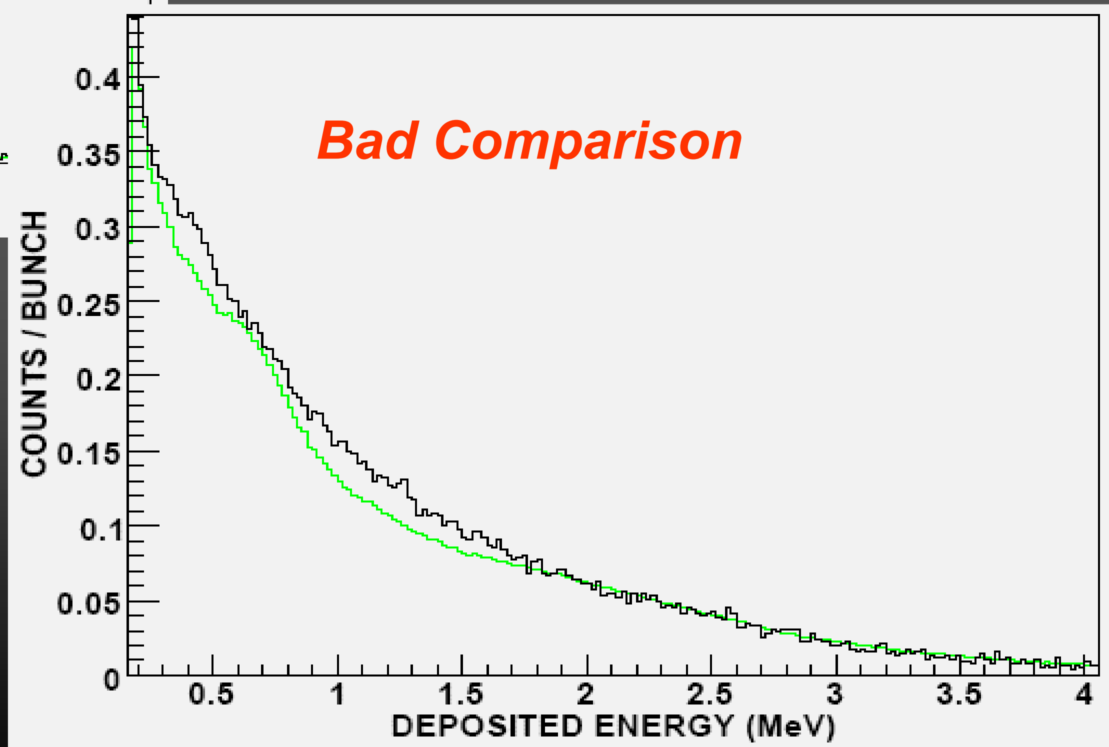
Comparison with the Experimental Data



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.



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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≈150 (isotopes varii)	s-process branching points long-lived fission products
^{234,236}U, ^{231,233}Pa	Th/U nuclear fuel cycle
^{235,238}U	standards, conventional U/Pu fuel cycle
^{239,240,242}Pu, ^{241,243}Am, ^{245}Cm	incineration of minor actinides

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

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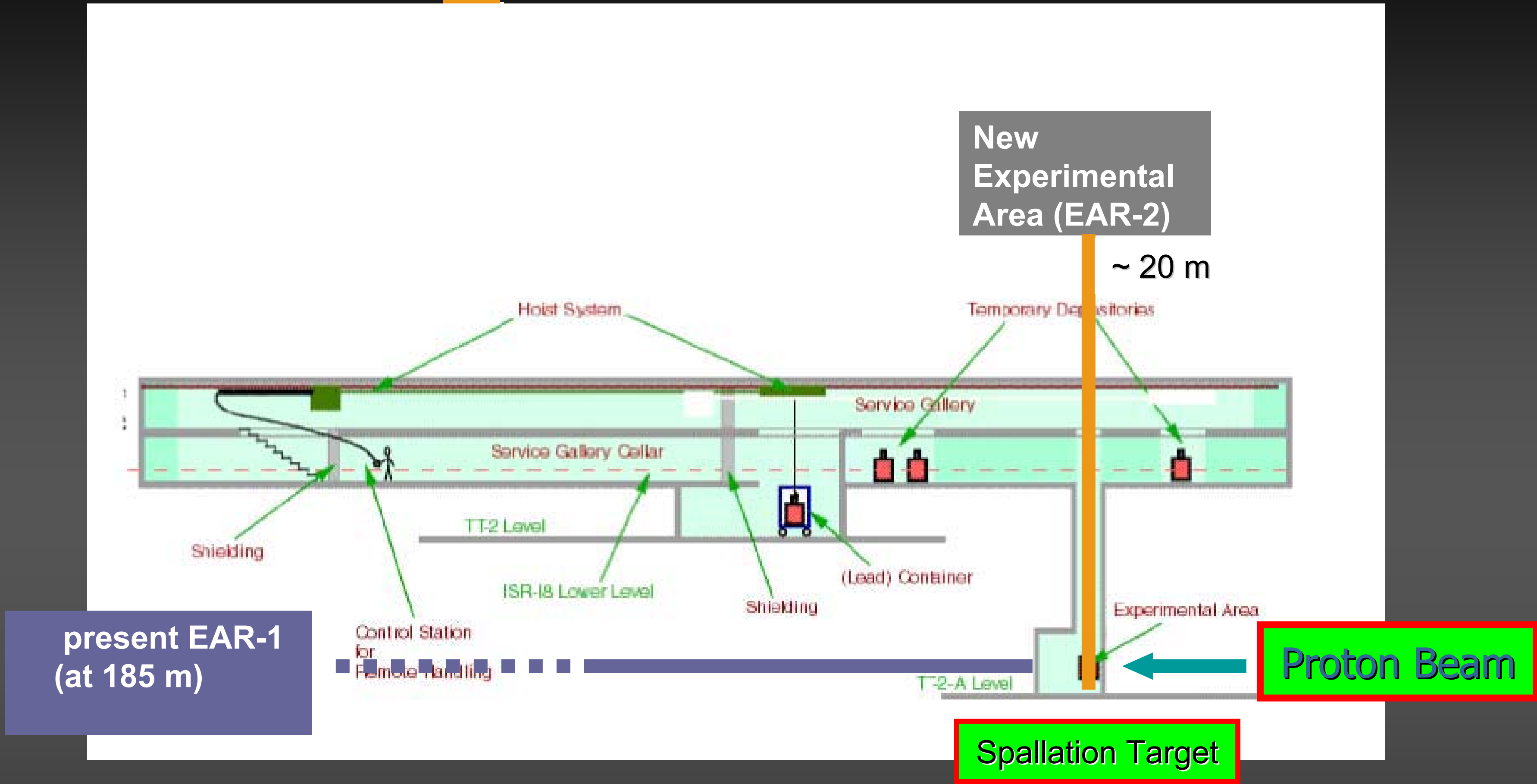
The second n_TOF beam line



- present EAR-1: Flight path ~185 m, Neutron Flux~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**)

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EAR-2: Optimized sensitivity

Improvements (ex: ^{151}Sm case)		consequences for sample mass
■ sample mass / 3 s/bkgd=1		✓ 50 mg
■ use BaF_2 TAC	ε x 10	✓ 5 mg
■ use D_2O	Φ_{30} x 5	■ 1 mg
■ use 20 m flight path	Φ_{30} x 100	■ 10 μg

boosts sensitivity by a **factor of 5000 !**

→ problems of sample production and safety issues relaxed

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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:
  - ✓C_6D_6: 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.

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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

- data analysis completed, results published
- data analysis completed, paper in preparation
- data analysis in progress

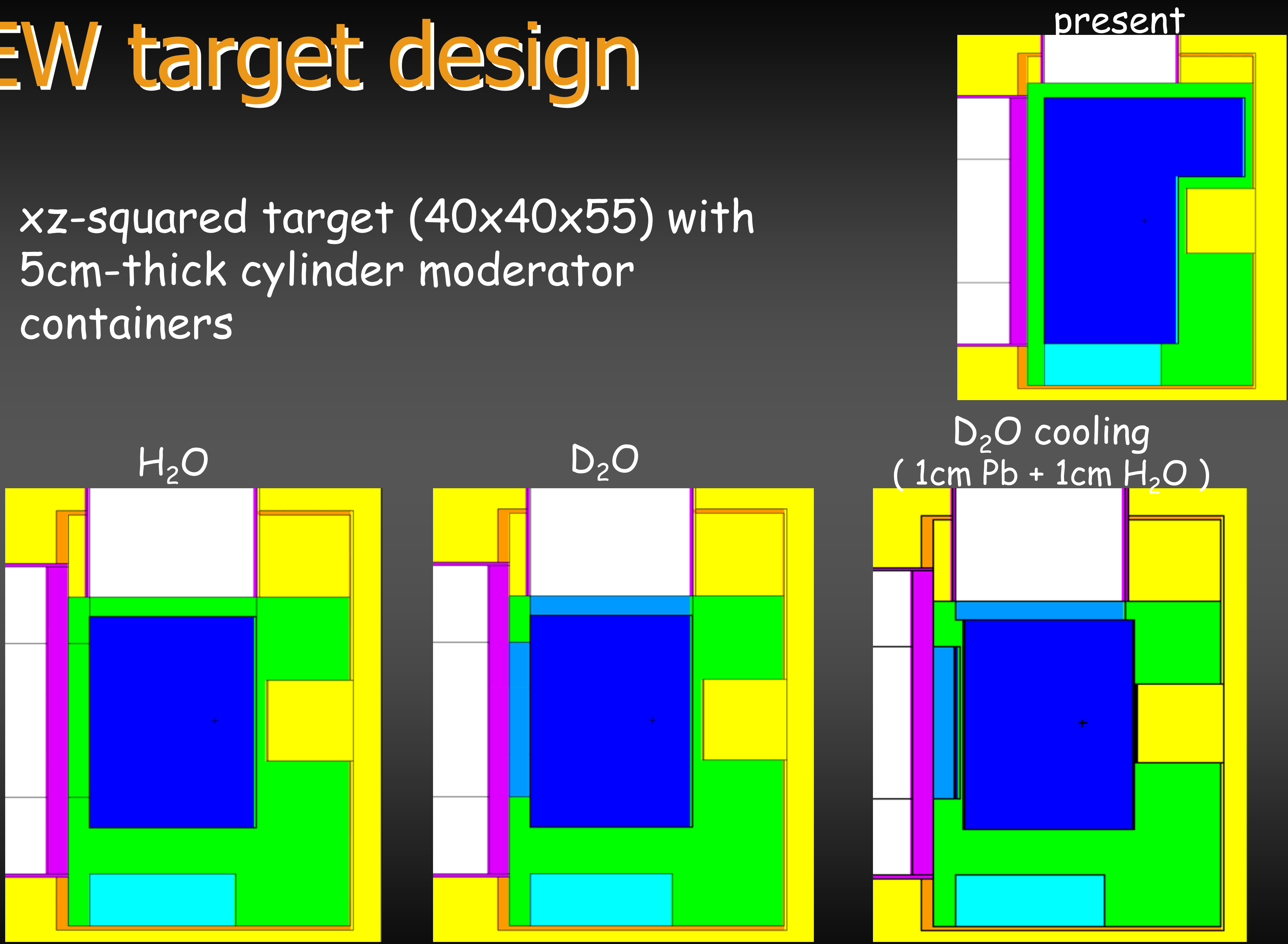
The n_TOF-Ph2 experiments

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≈150 (isotopes varii)	s-process branching points long-lived fission products
^{234,236}U, ^{231,233}Pa	Th/U nuclear fuel cycle
^{235,238}U	standards, conventional U/Pu fuel cycle
^{239,240,242}Pu, ^{241,243}Am, ^{245}Cm	incineration of minor actinides

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

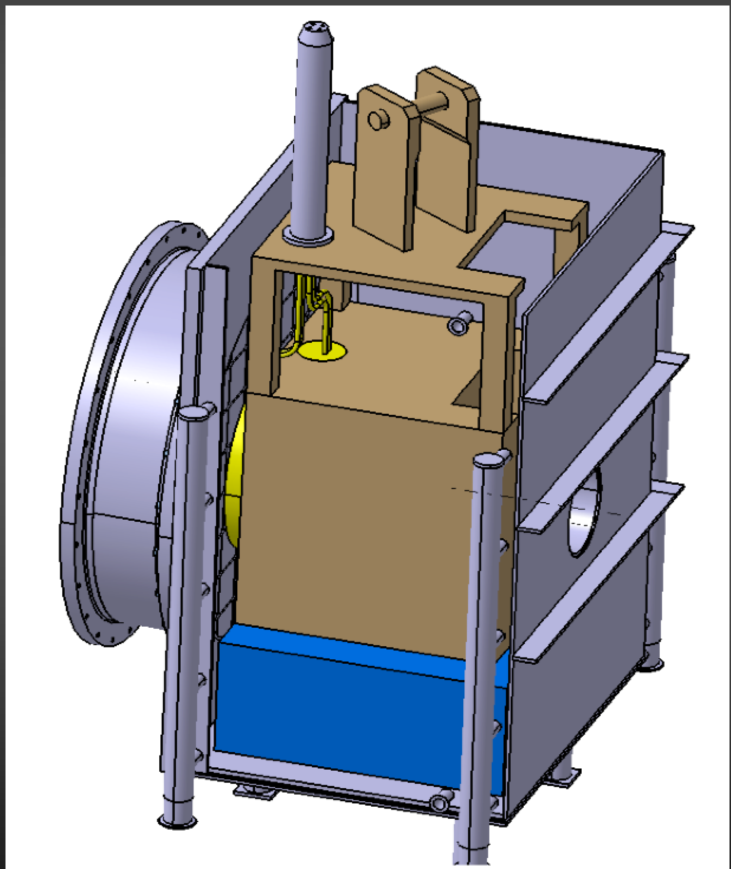
NEW target design

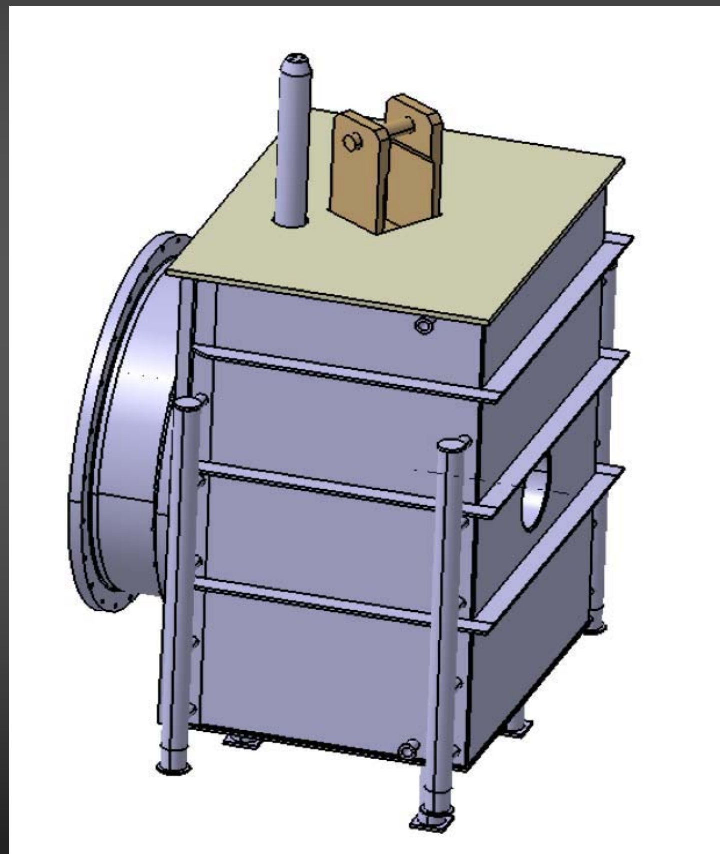
xz-squared target (40x40x55) with 5cm-thick cylinder moderator containers



P Cennini, V Vlachoudis, K Tsoulou, et al. (CERN/AB/ATB), October 2006

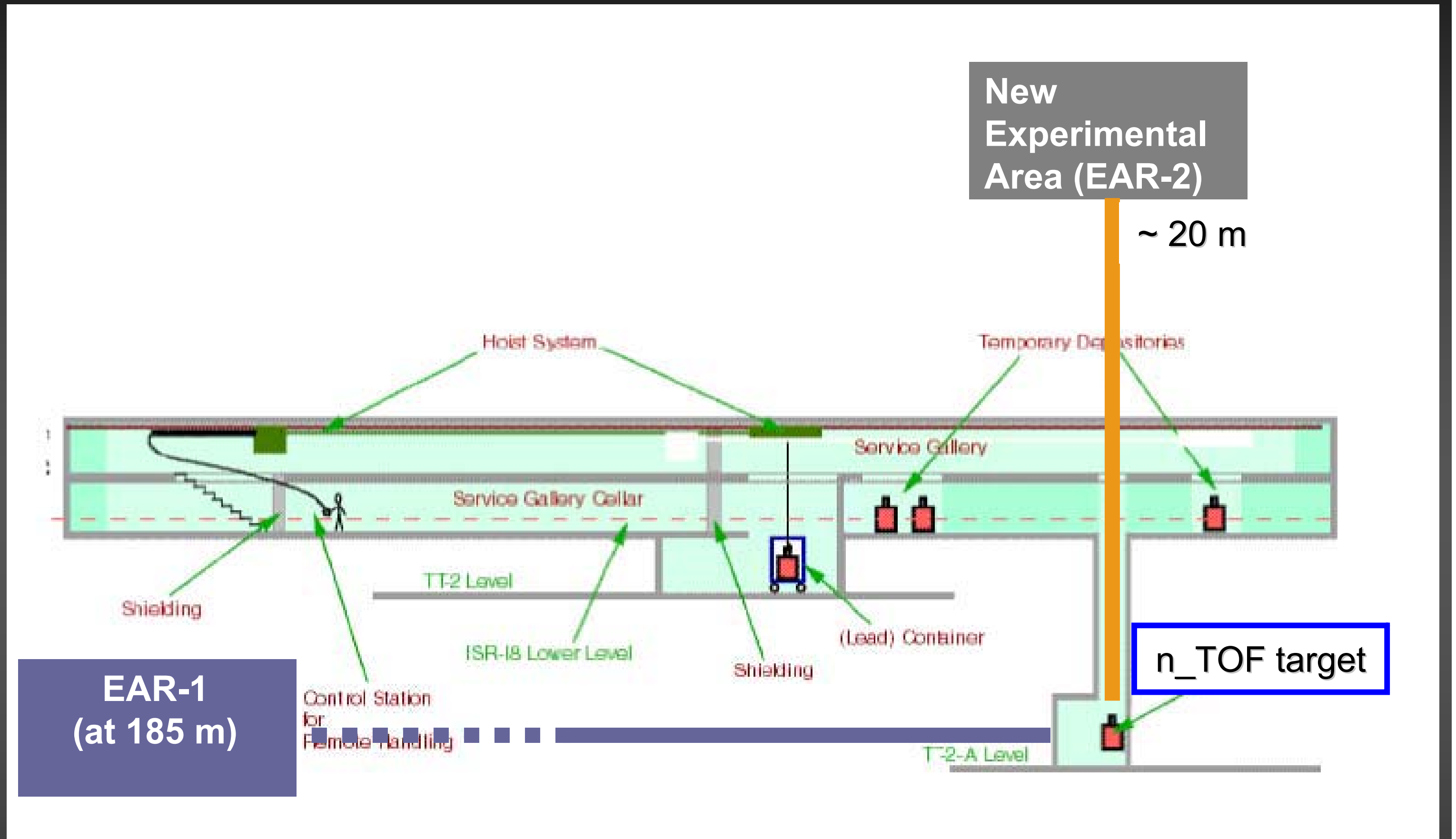
NEW: target design proposal





P Cennini, V Vlachoudis, K Tsoulou, et al. (CERN/AB/ATB), October 2006

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.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 End

PS: all quoted documents are available online at

www.cern.ch/ntof

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)

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

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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,γ) cross section in the unresolved resonance region from 1 keV to 1 MeV.

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

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
&
accepted for publication in PRC (in press)

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

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^{207}Pb(n,γ)

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}Pb(n,γ) 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)

[a]Orbital angular momenta l and resonance spins J are from Ref. [17].

3% accuracy of the capture kernel

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

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

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

[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

$^{186,187,188}Os$

$^{233,234}U$

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Fission

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

^{232}Th

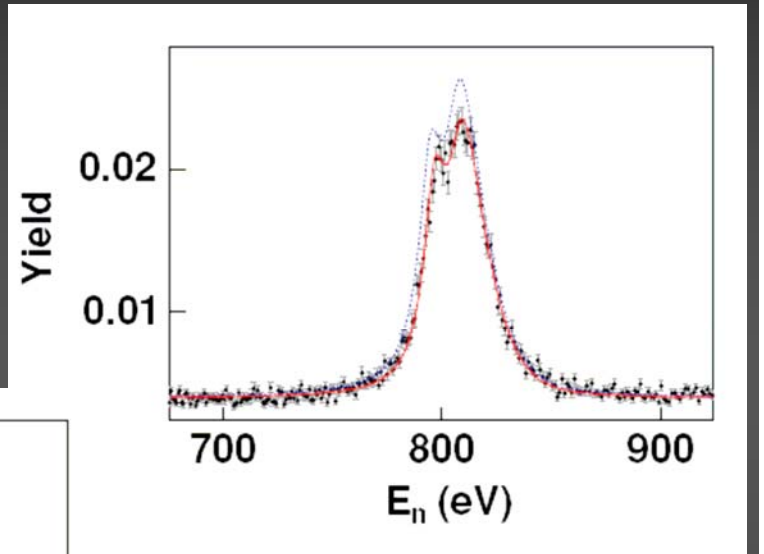
^{209}Bi

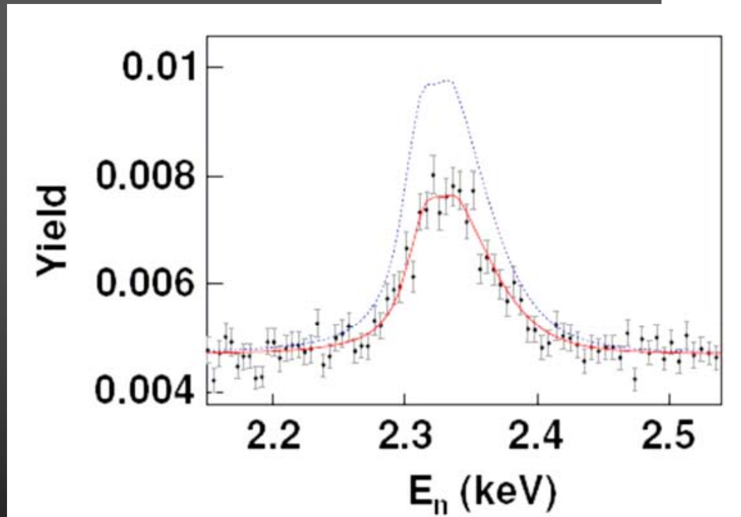
^{237}Np

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

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^{232}Th

^{209}Bi

^{237}Np

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

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

NEW MEASUREMENT OF NEUTRON CAPTURE . . . PHYSICAL REVIEW C **74**, 025807 (2006)

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

$E_\circ$ (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)

[a] Angular orbital momenta, l, resonance spins J, and neutron widths, Γ_n, are mainly from Refs. [27,28].
[b] Uncertainties are given as 18.2(6)≡18.2±0.6.
[c] This 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 = 5-8 keV
81% r-process abundance for ^{209}Bi

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

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

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

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

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

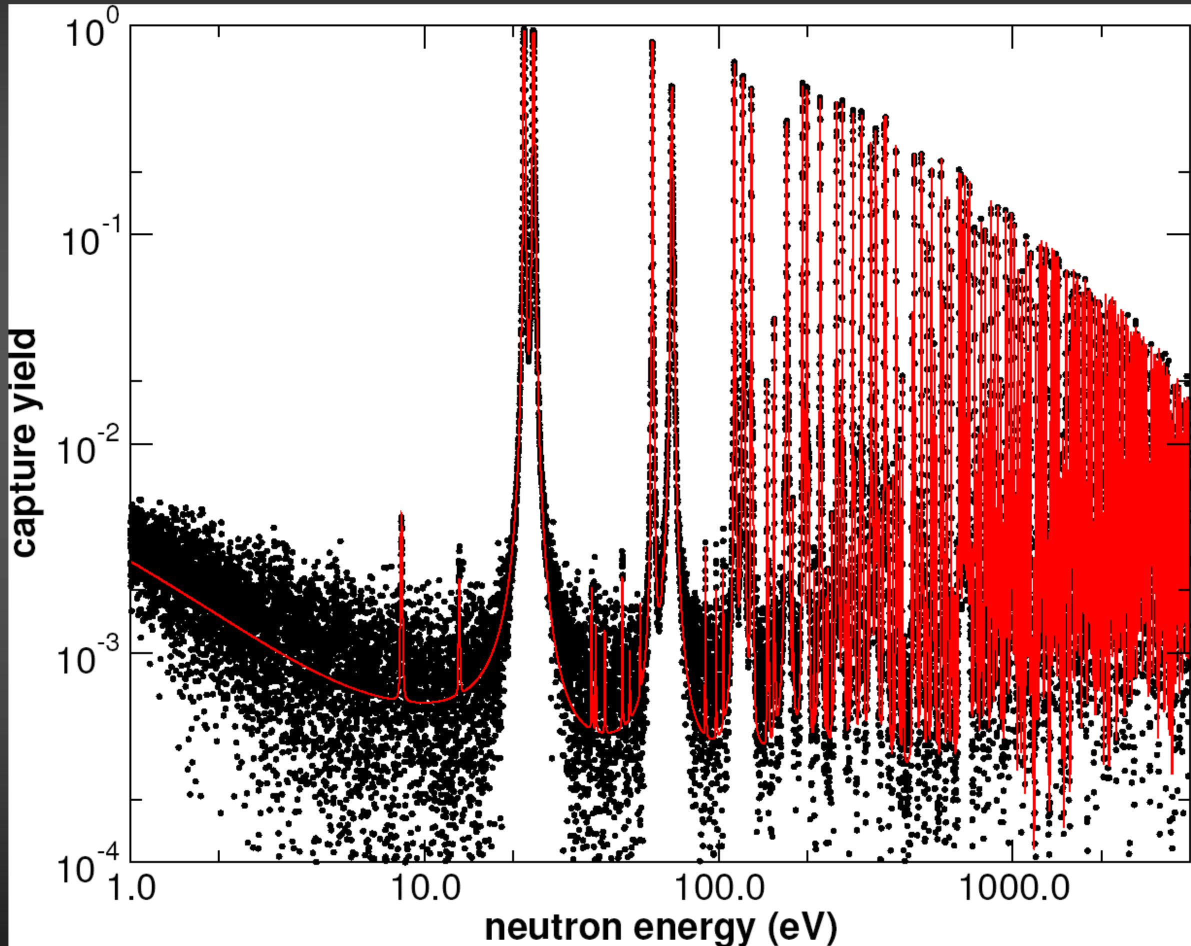
^{209}Bi

^{237}Np

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

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

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



RRR region analysis in progress

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

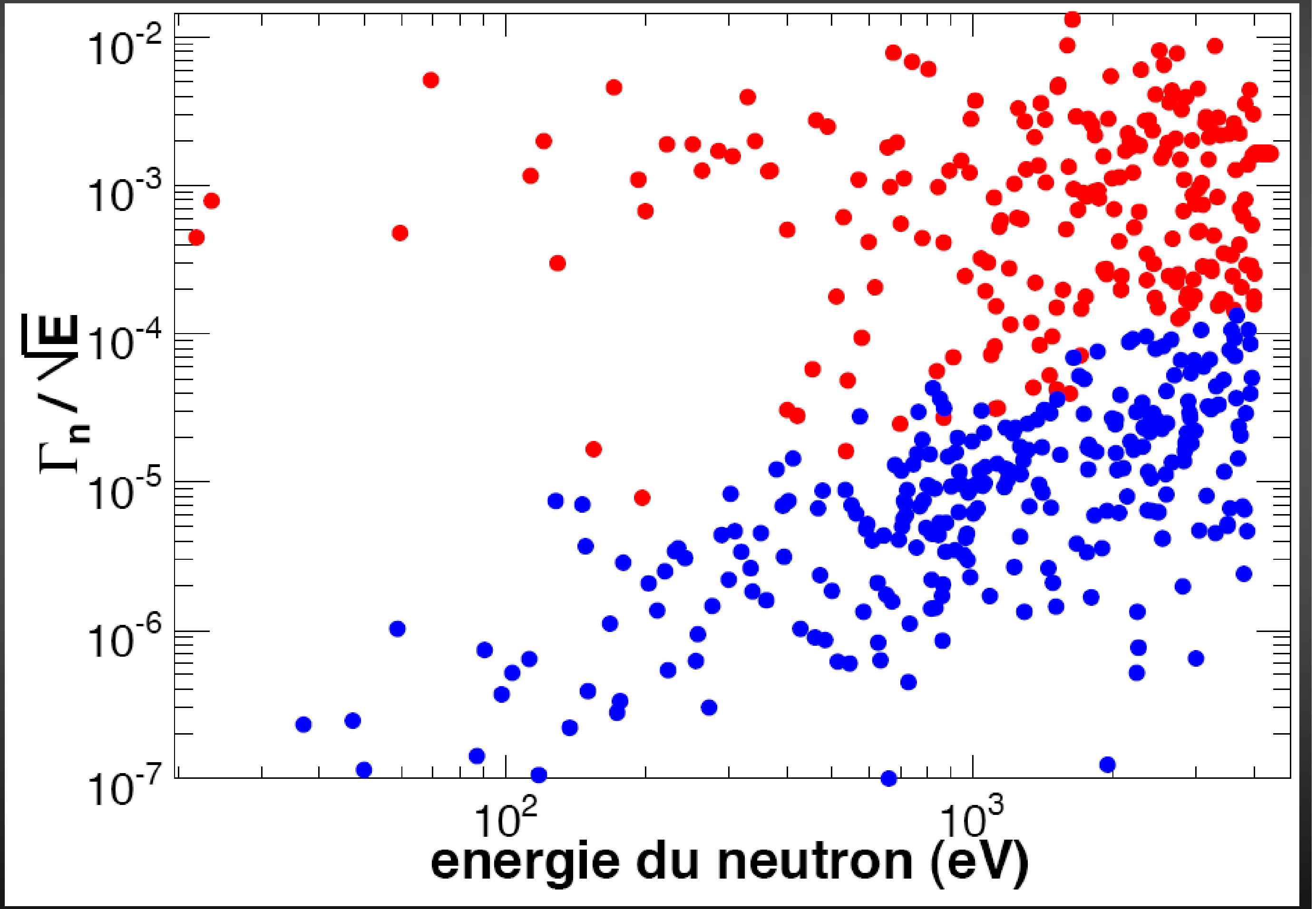
^{209}Bi

^{237}Np

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

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

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



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

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

^{232}Th

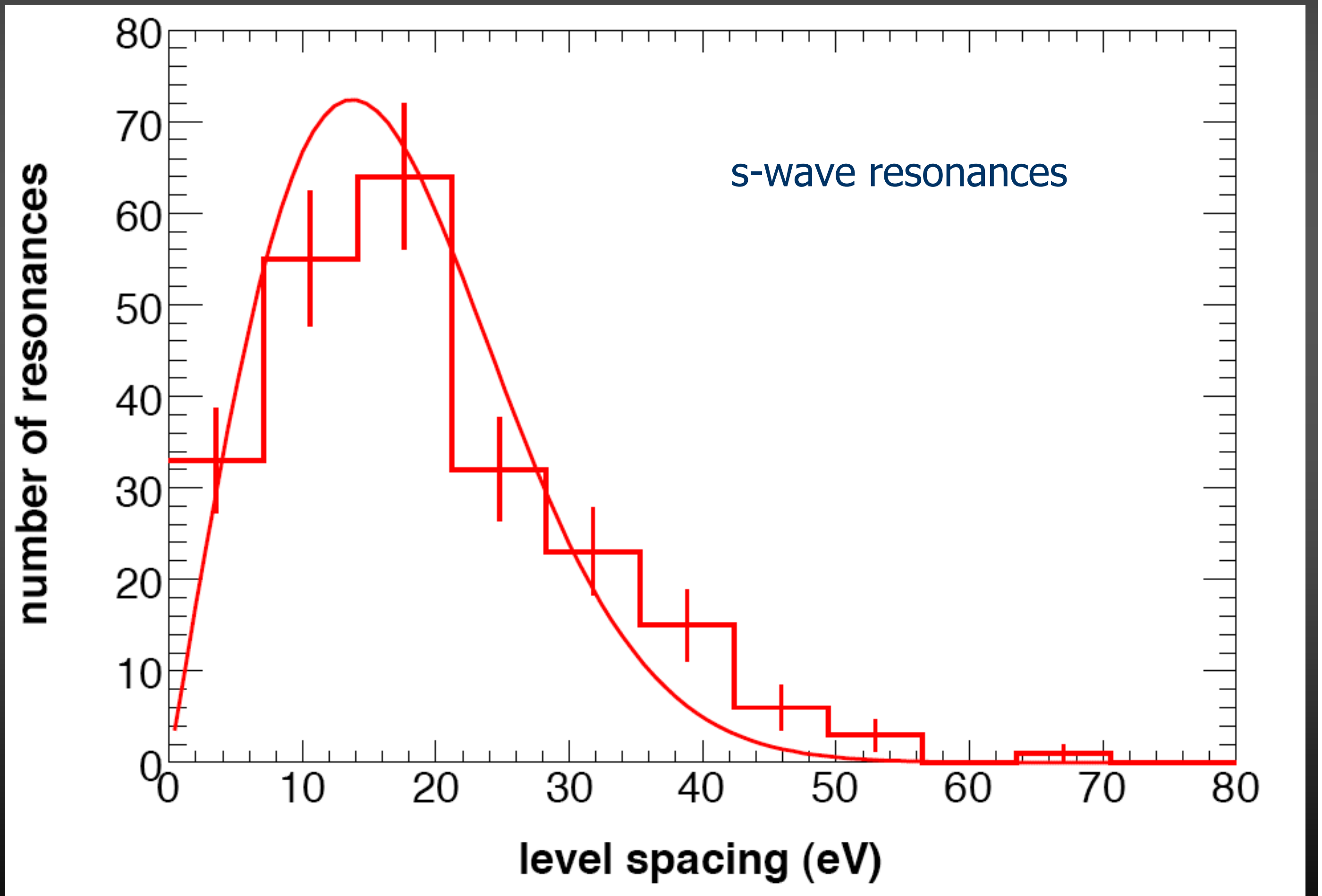
^{209}Bi

^{237}Np

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

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

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



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

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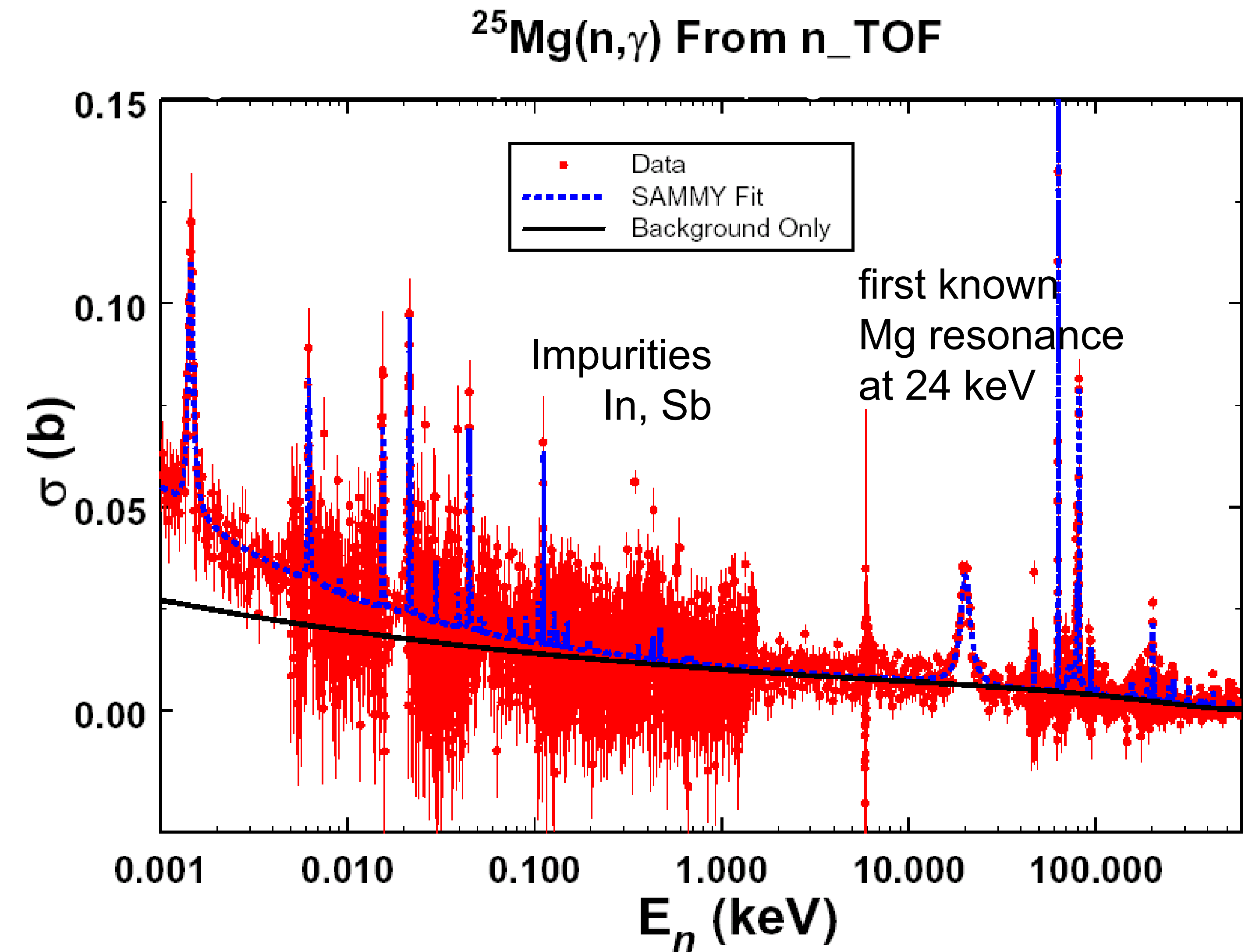
$^{233,234,235,236,238}U$

^{232}Th

^{209}Bi

^{237}Np

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



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

The n_TOF Collaboration

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

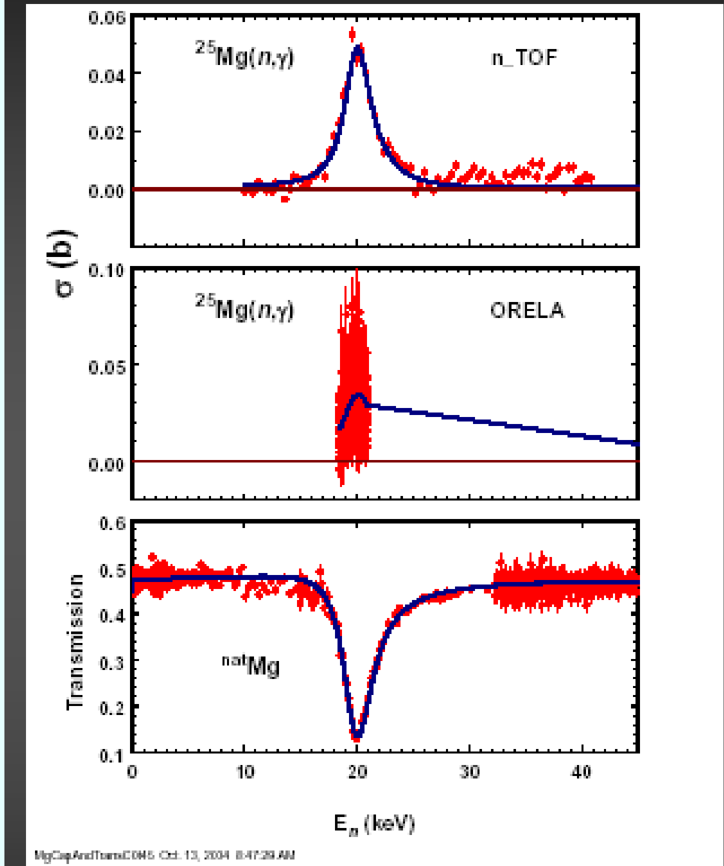
^{233,234,235,236,238}U

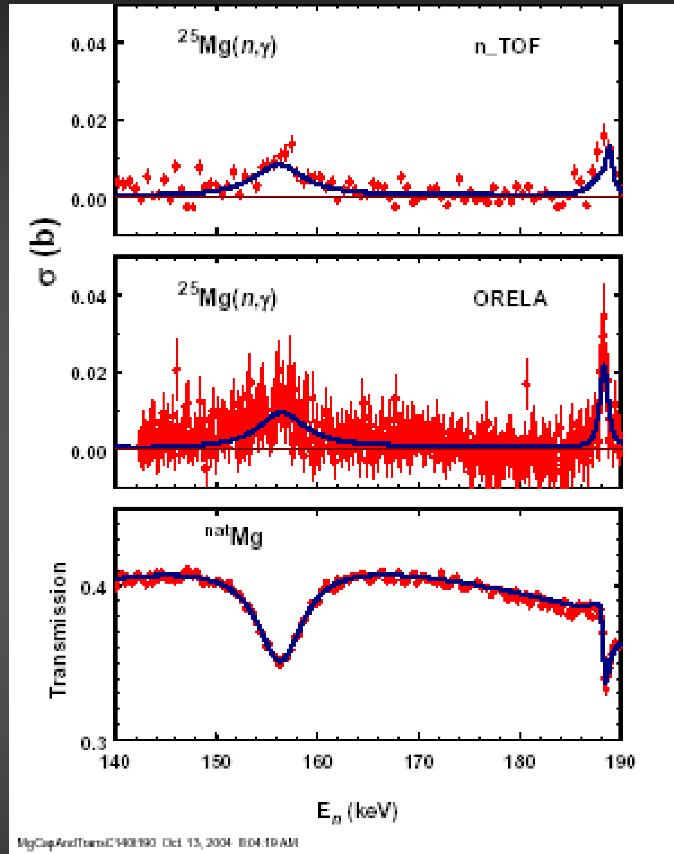
^{232}Th

^{209}Bi

^{237}Np

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





Source: P Koehler & S O'Brien

Capture & transmission data (from ORELA) analyzed simultanously

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

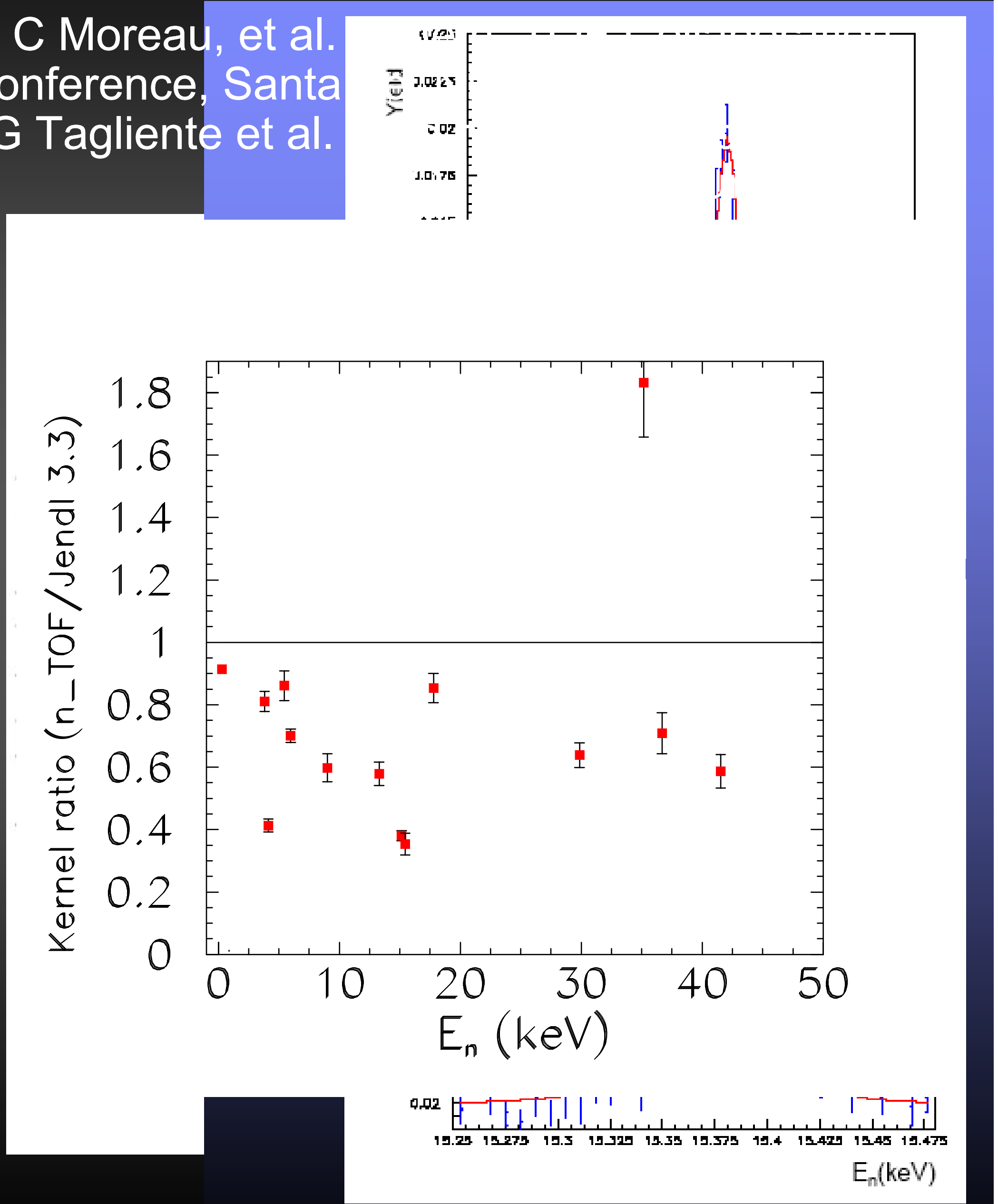
^{237}Np

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

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

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

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

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

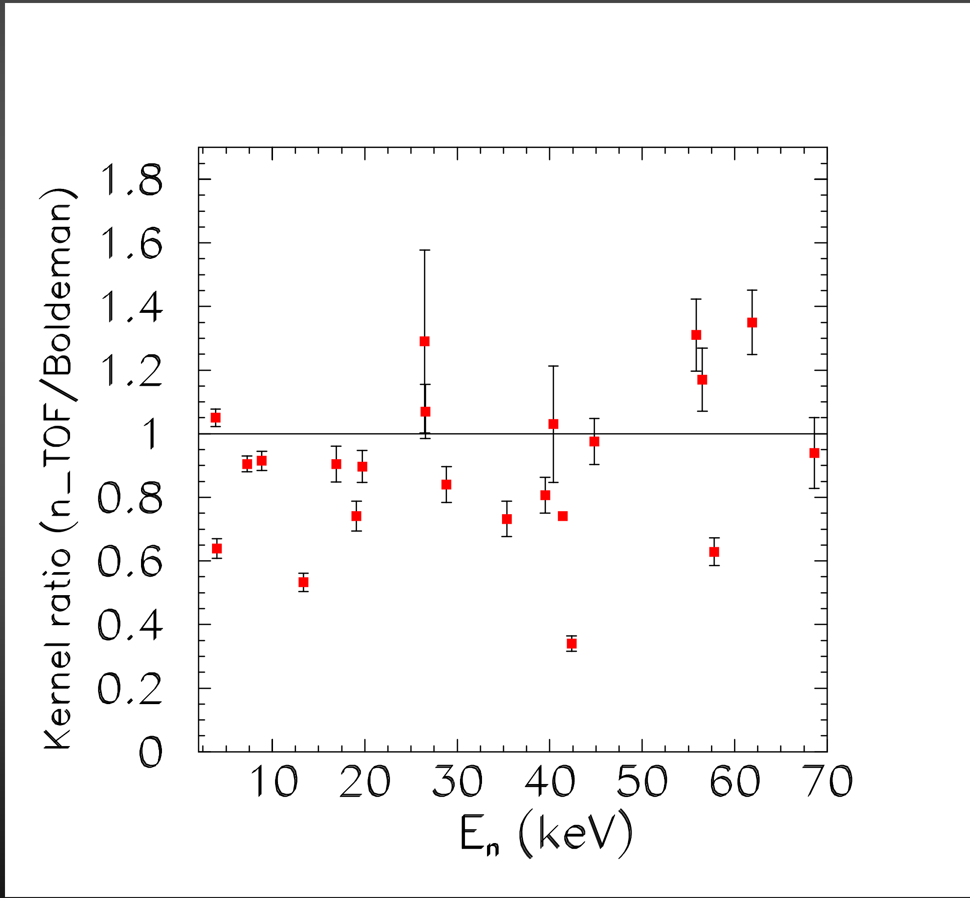
^{232}Th

^{209}Bi

^{237}Np

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

^{90}Zr(n,γ)



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

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

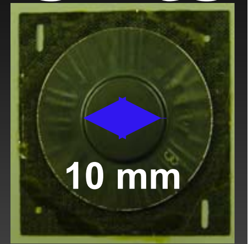
^{232}Th

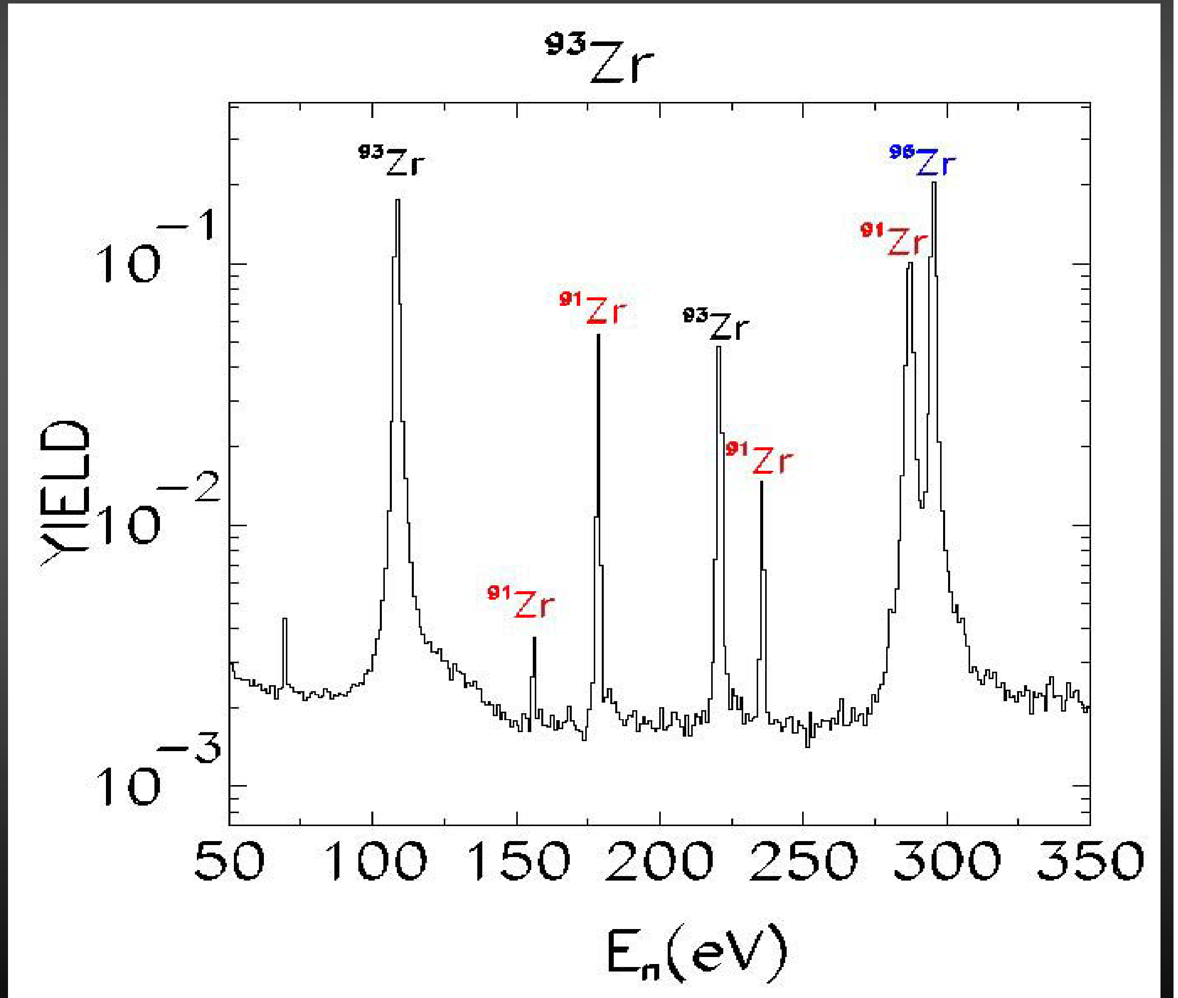
^{209}Bi

^{237}Np

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

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





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

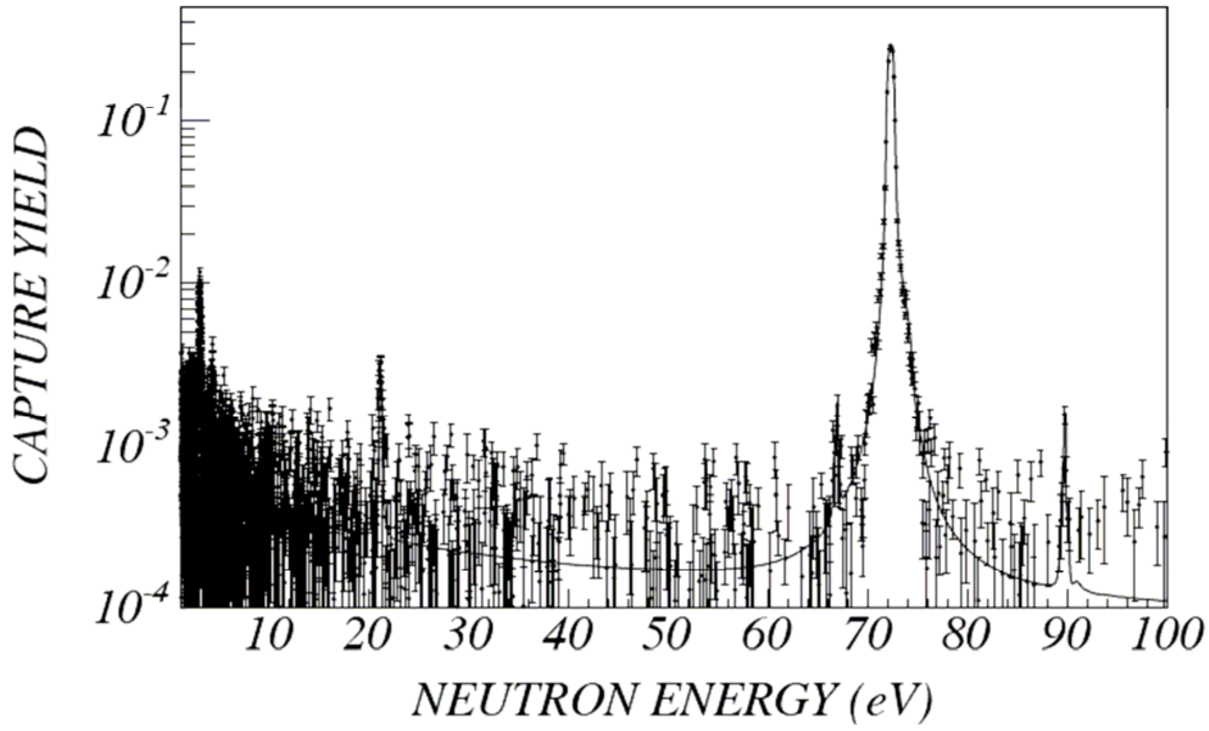
^{209}Bi

^{237}Np

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

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

R Terlizzi, et al. (The n_TOF Collaboration)
CGS12
Notre Dame, IN, USA
AIP Conference Proceedings 819
&
submitted for publication to PRC, October 2006



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

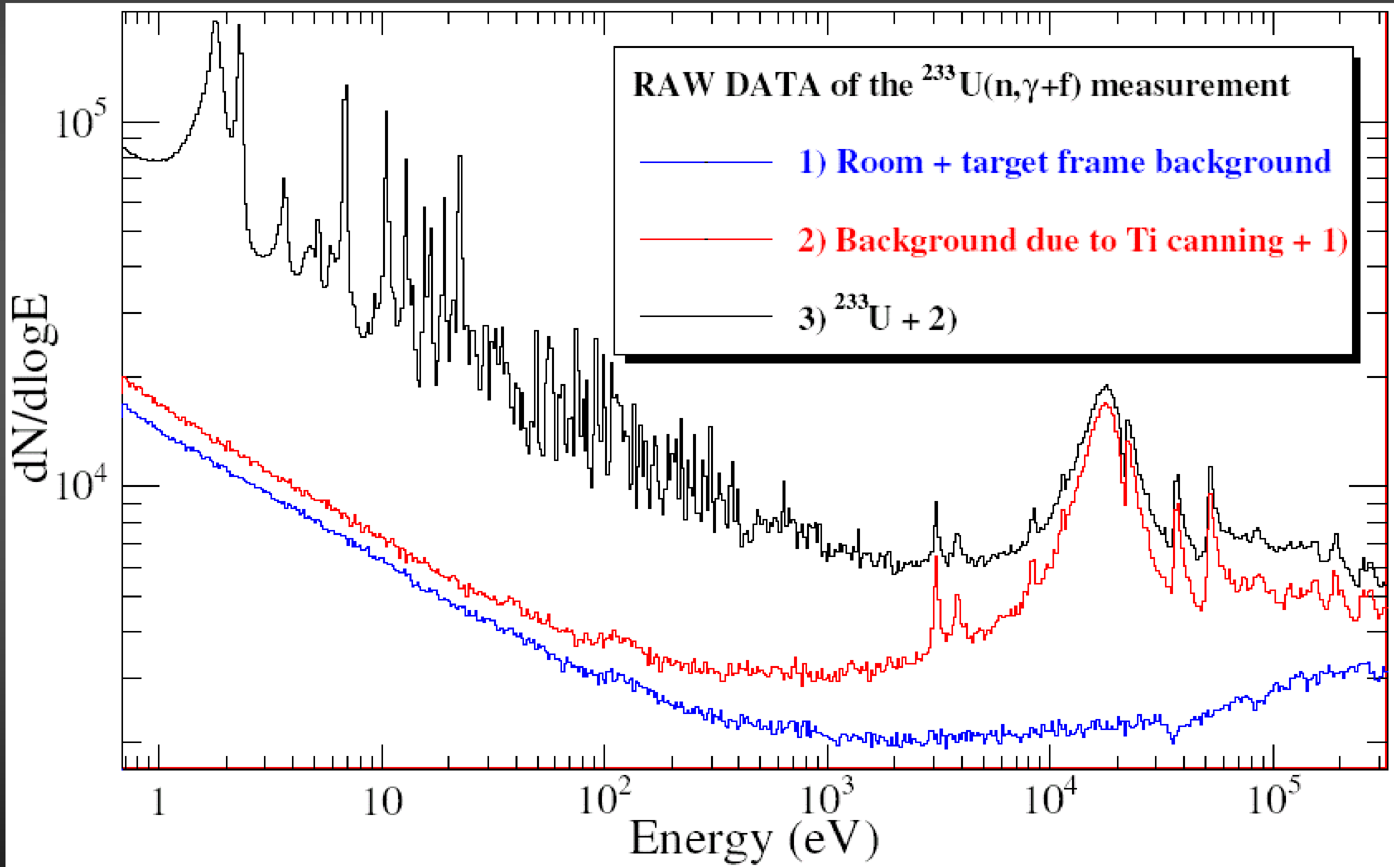
^{209}Bi

^{237}Np

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

^{233}U(n,γ)

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



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

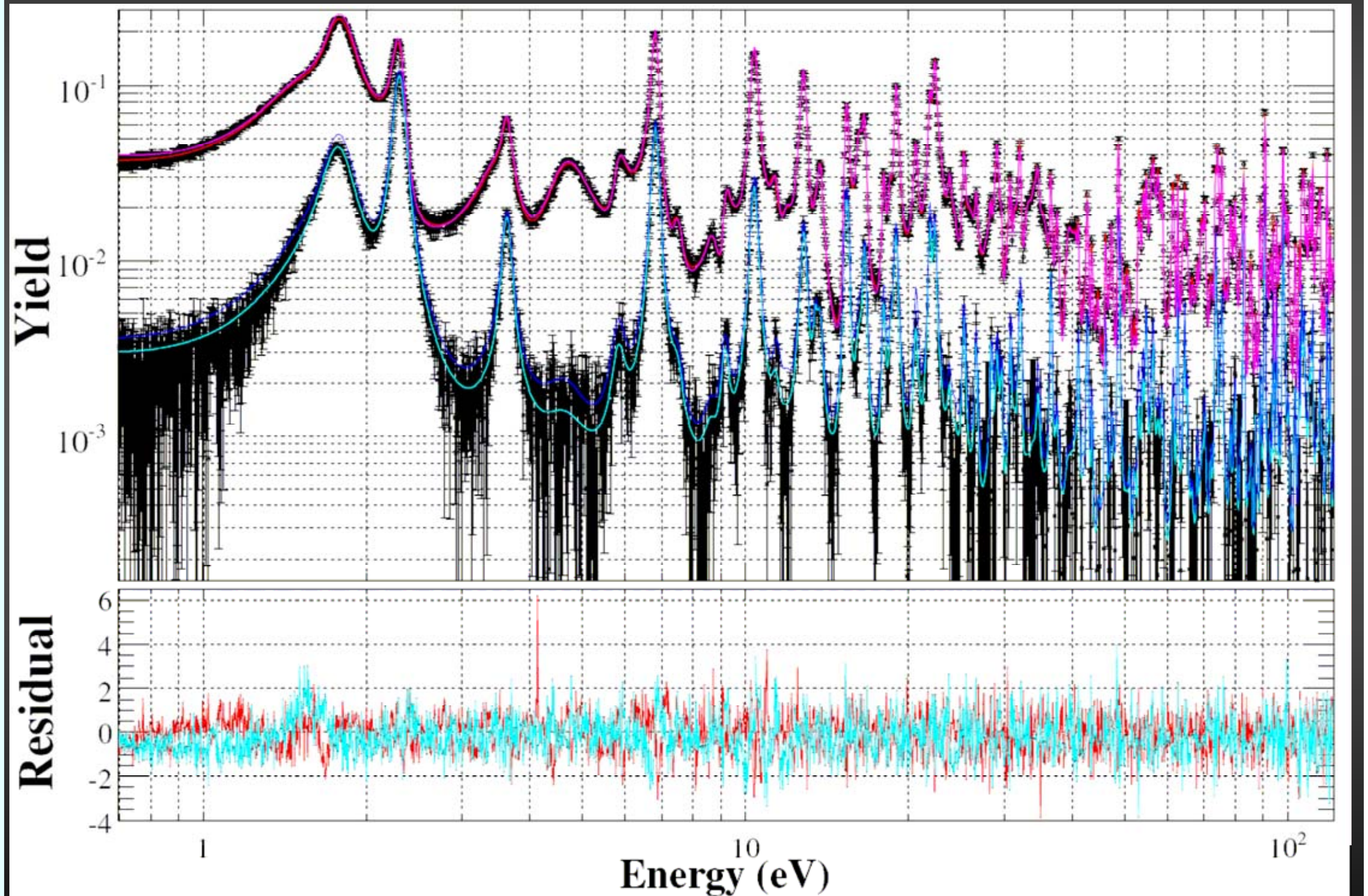
^{209}Bi

^{237}Np

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

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

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

$^{24,25,26}Mg$

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

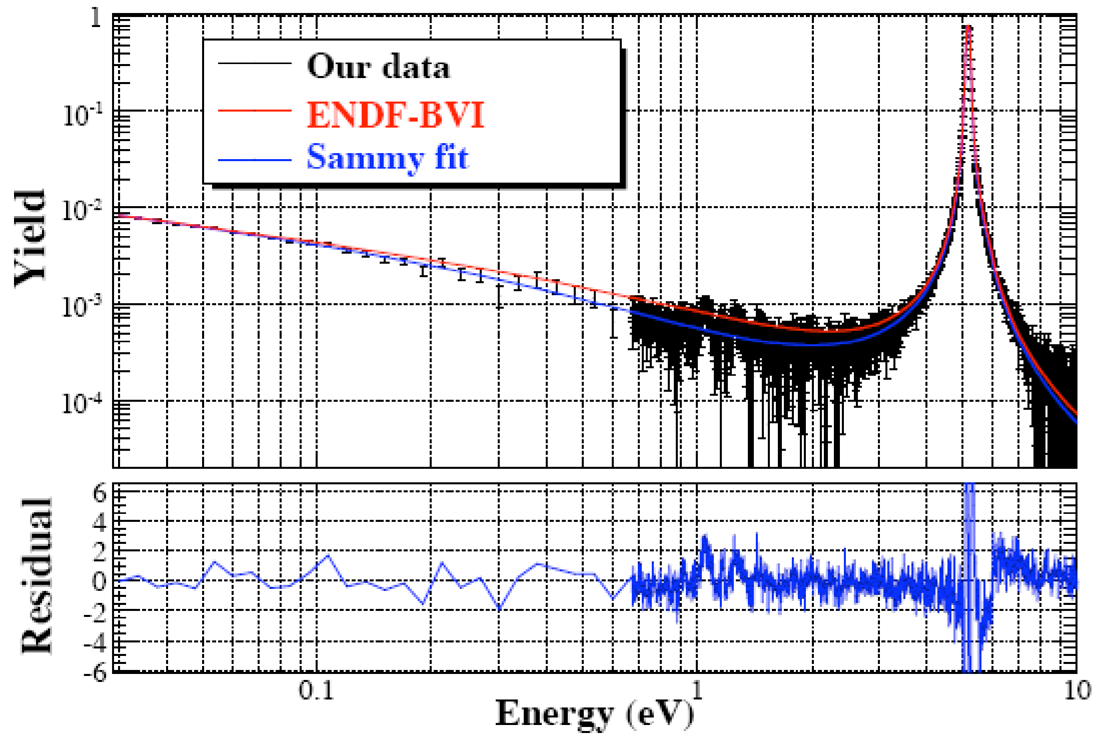
^{237}Np

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

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

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

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



n_TOF TAC in operation

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

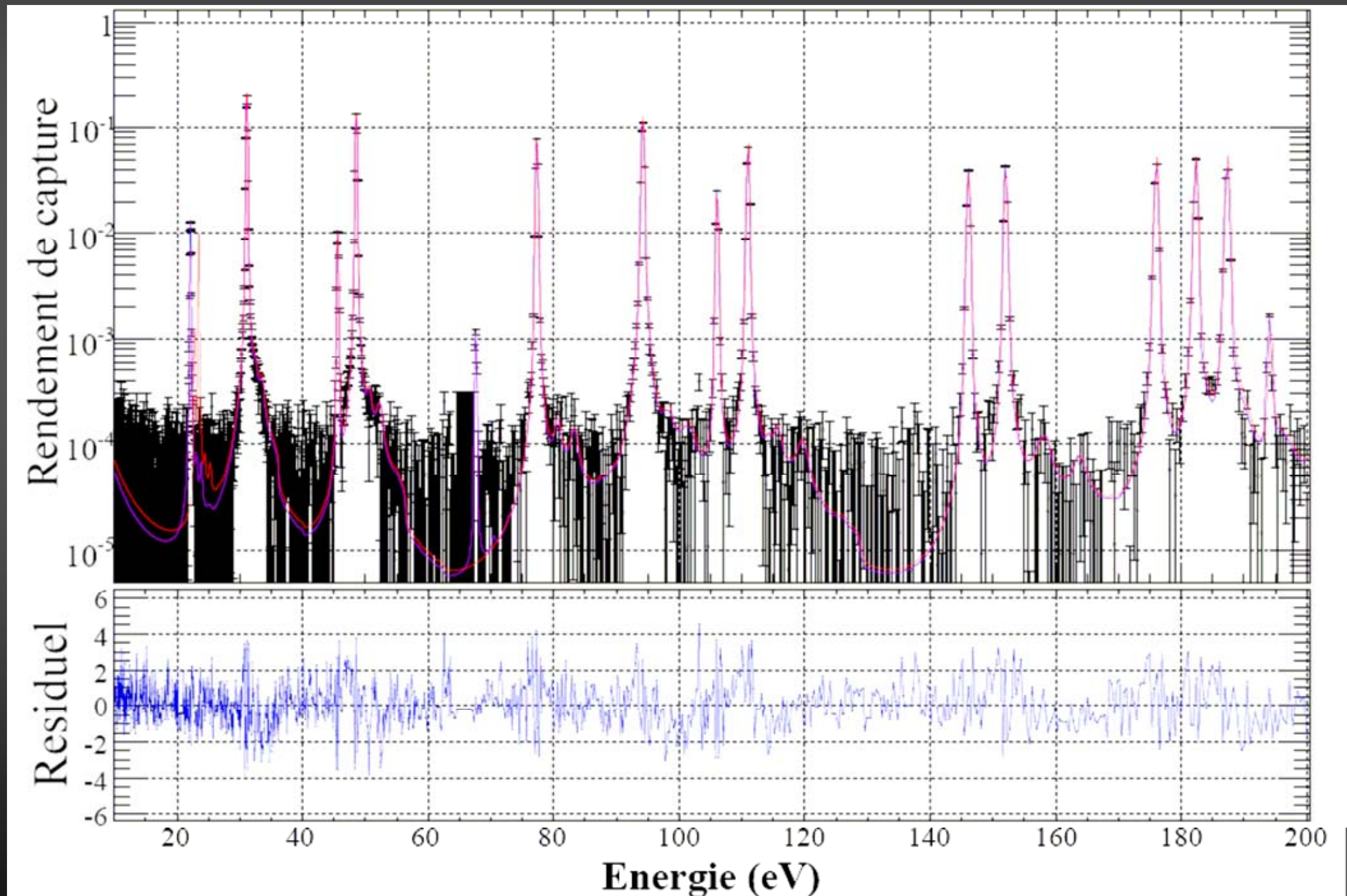
^{209}Bi

^{237}Np

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

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

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$^{233,234}U$

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

Fission

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

^{232}Th

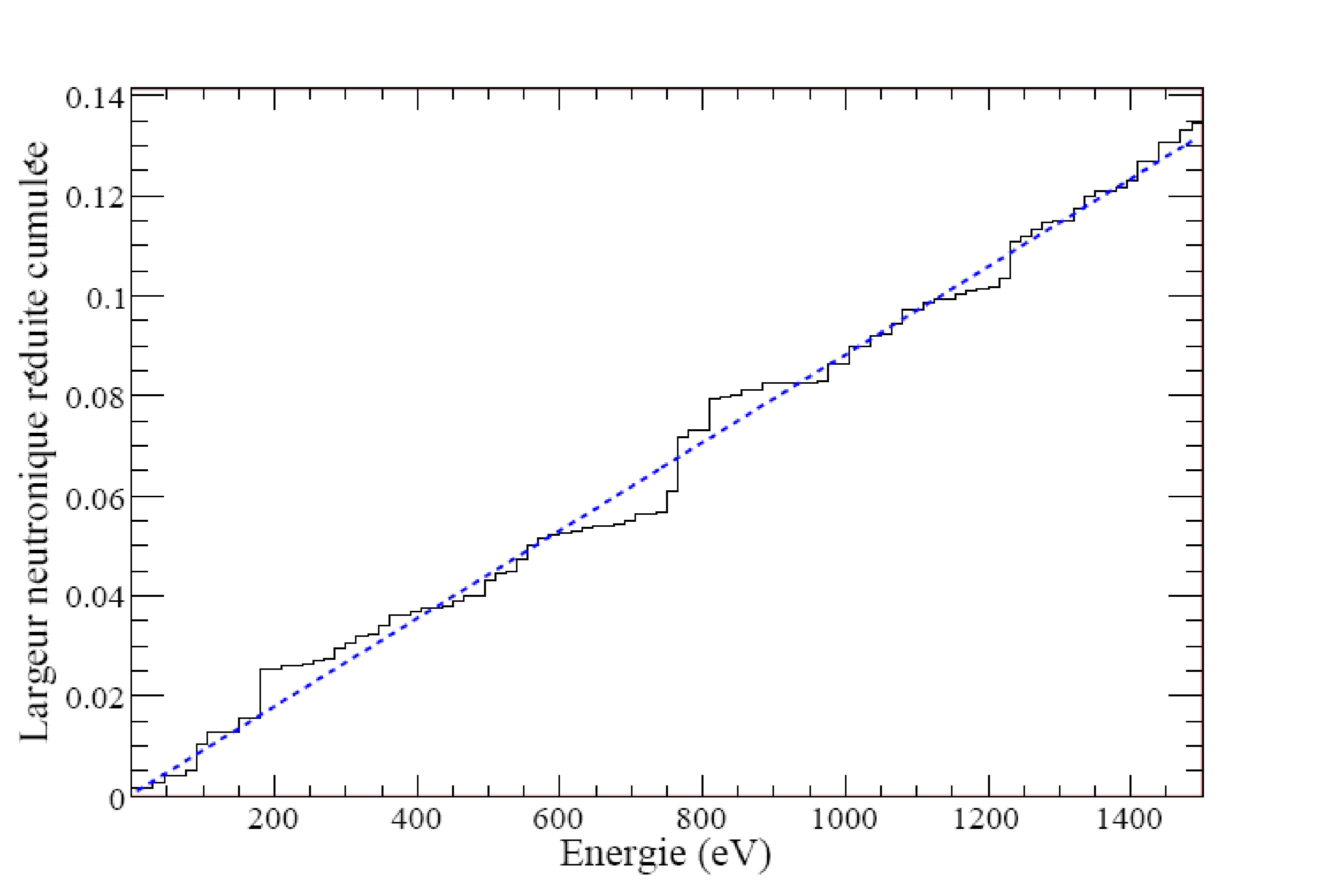
^{209}Bi

^{237}Np

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

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

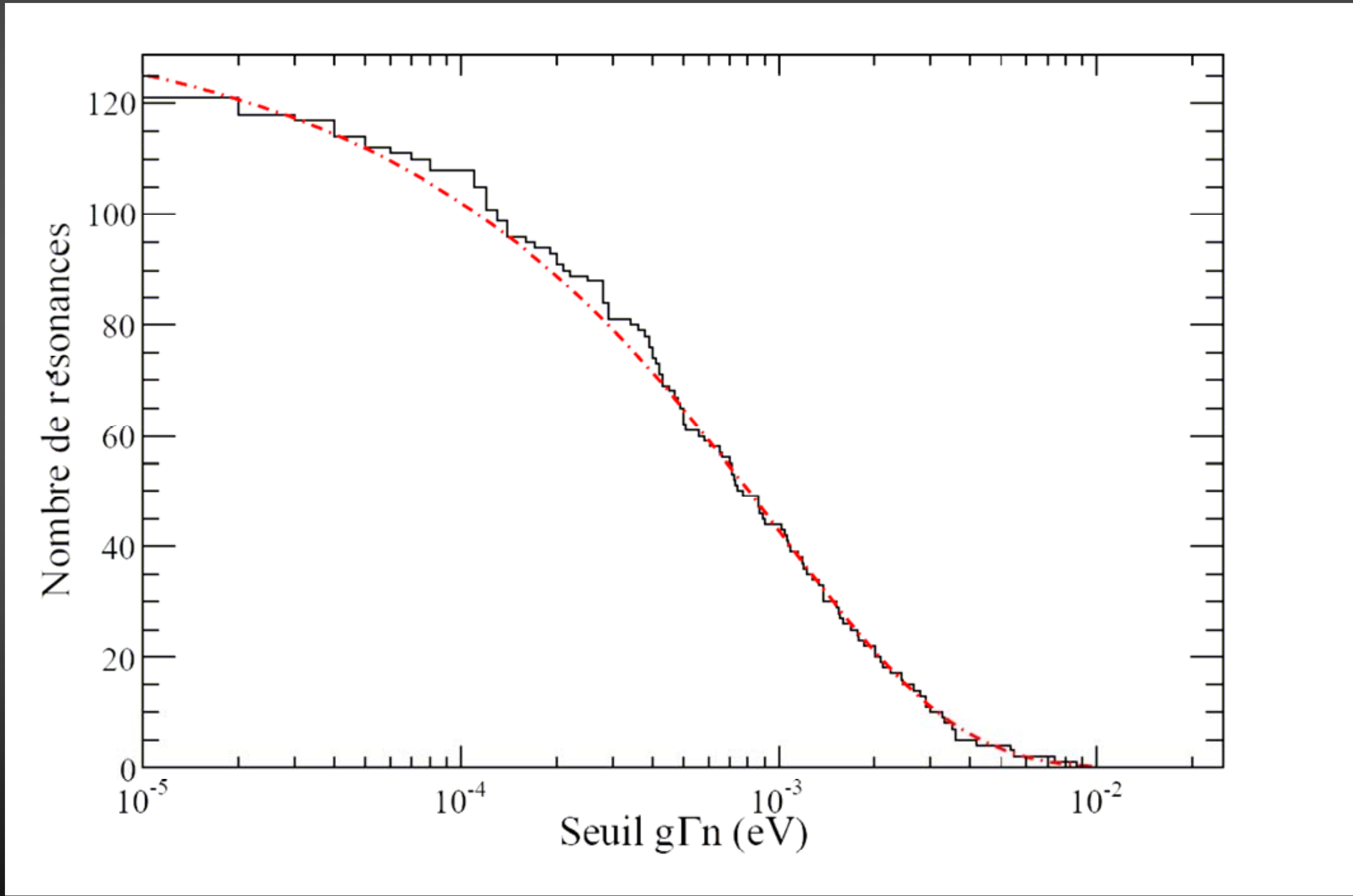
^{209}Bi

^{237}Np

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

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

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

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^{209}Bi

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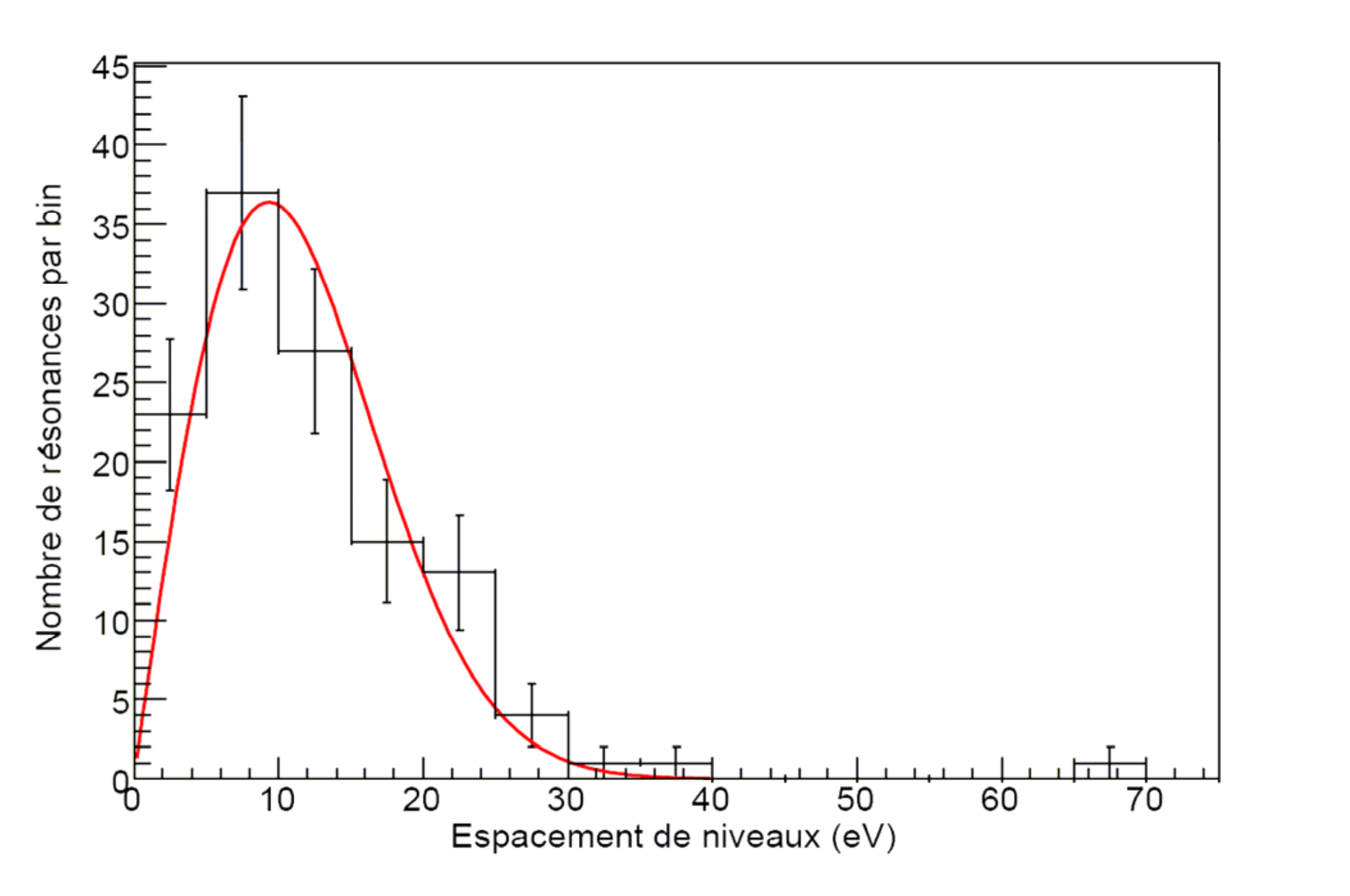
$^{241,243}Am$, ^{245}Cm

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

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



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

^{232}Th

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Fission

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

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^{209}Bi

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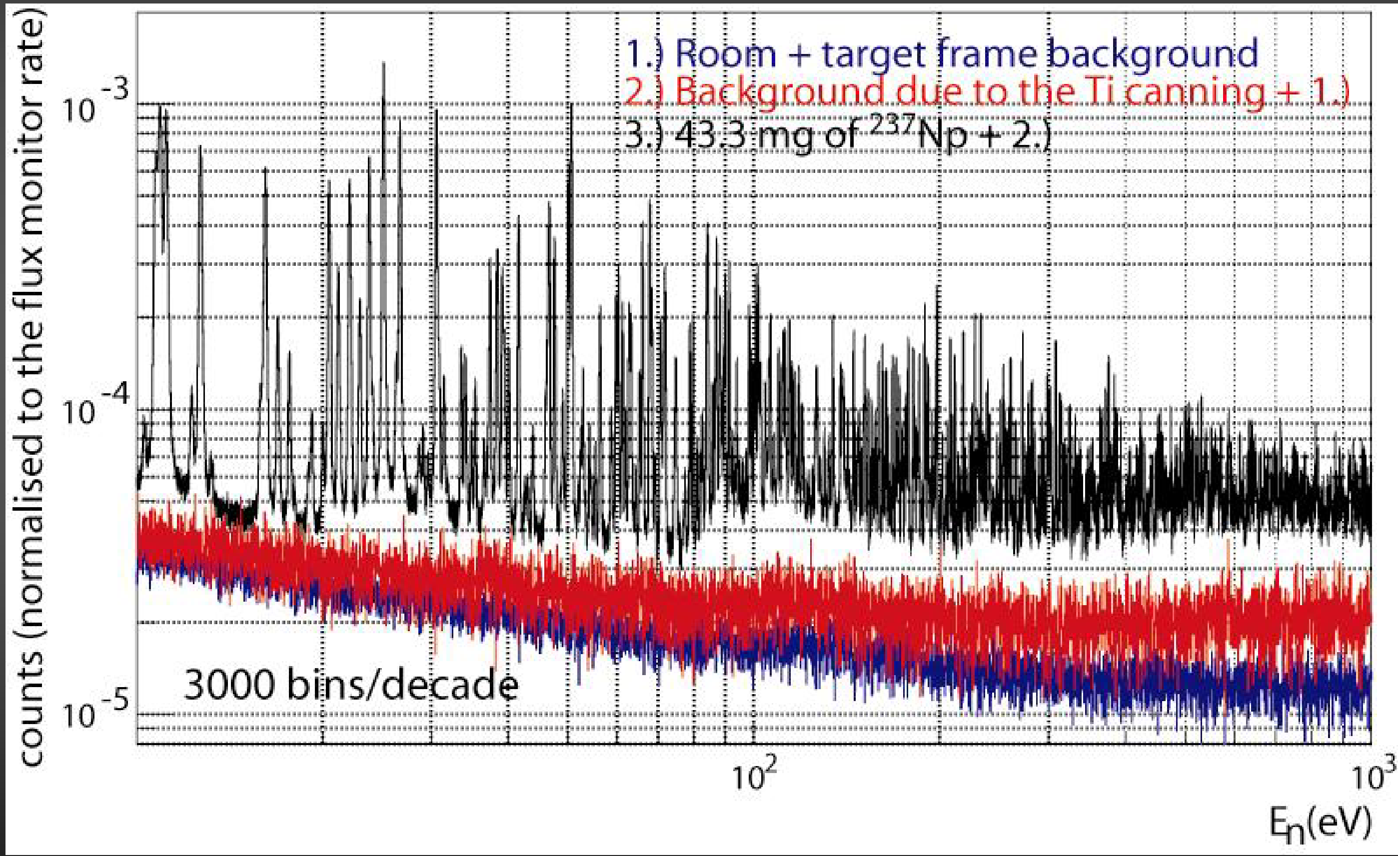

n_TOF TAC in operation

Capture

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^{232}Th

$^{24,25,26}Mg$

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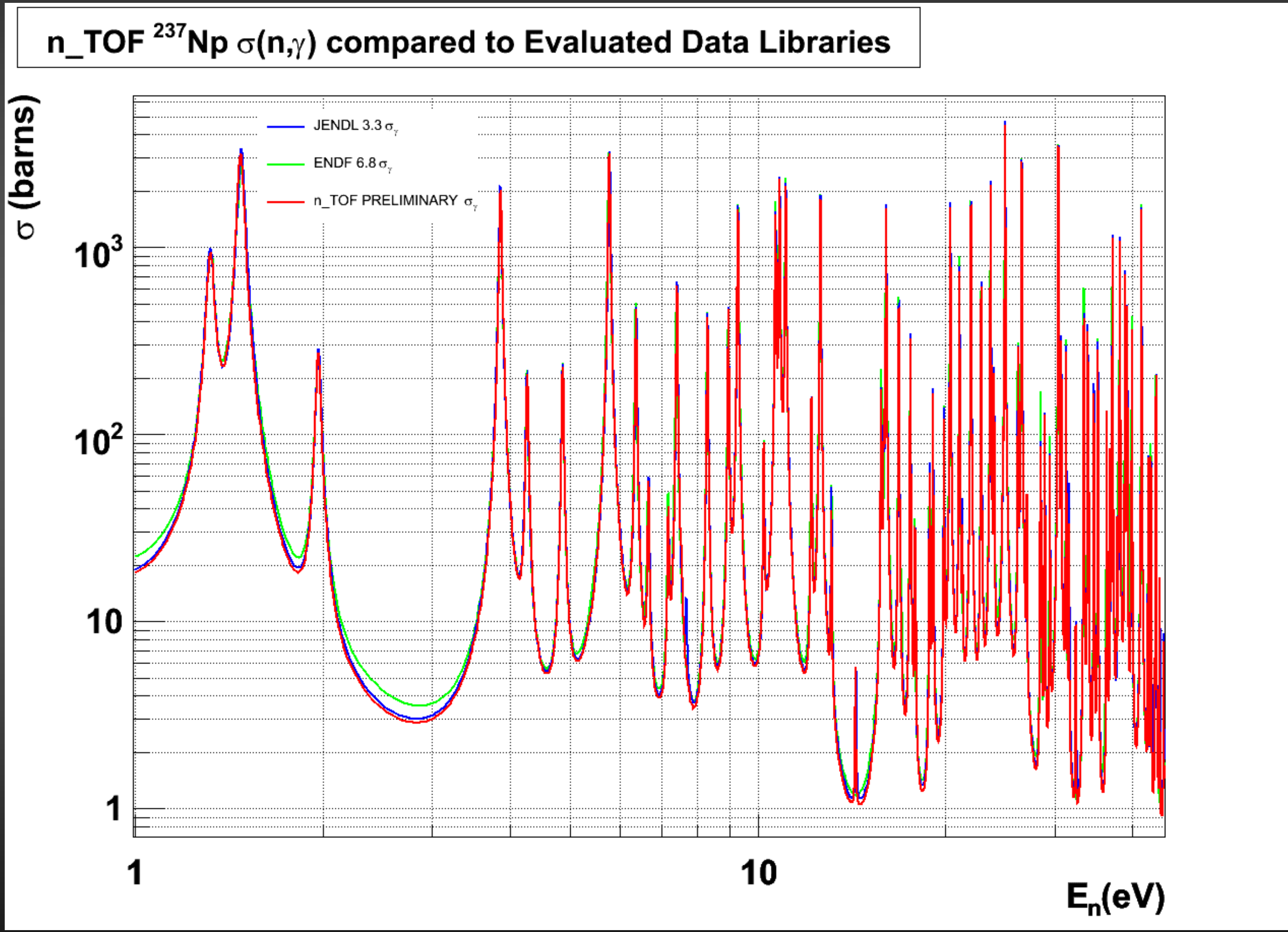
n_TOF experiments

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



n_TOF TAC in operation

n_TOF experiments

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

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^{151}Sm

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

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^{209}Bi

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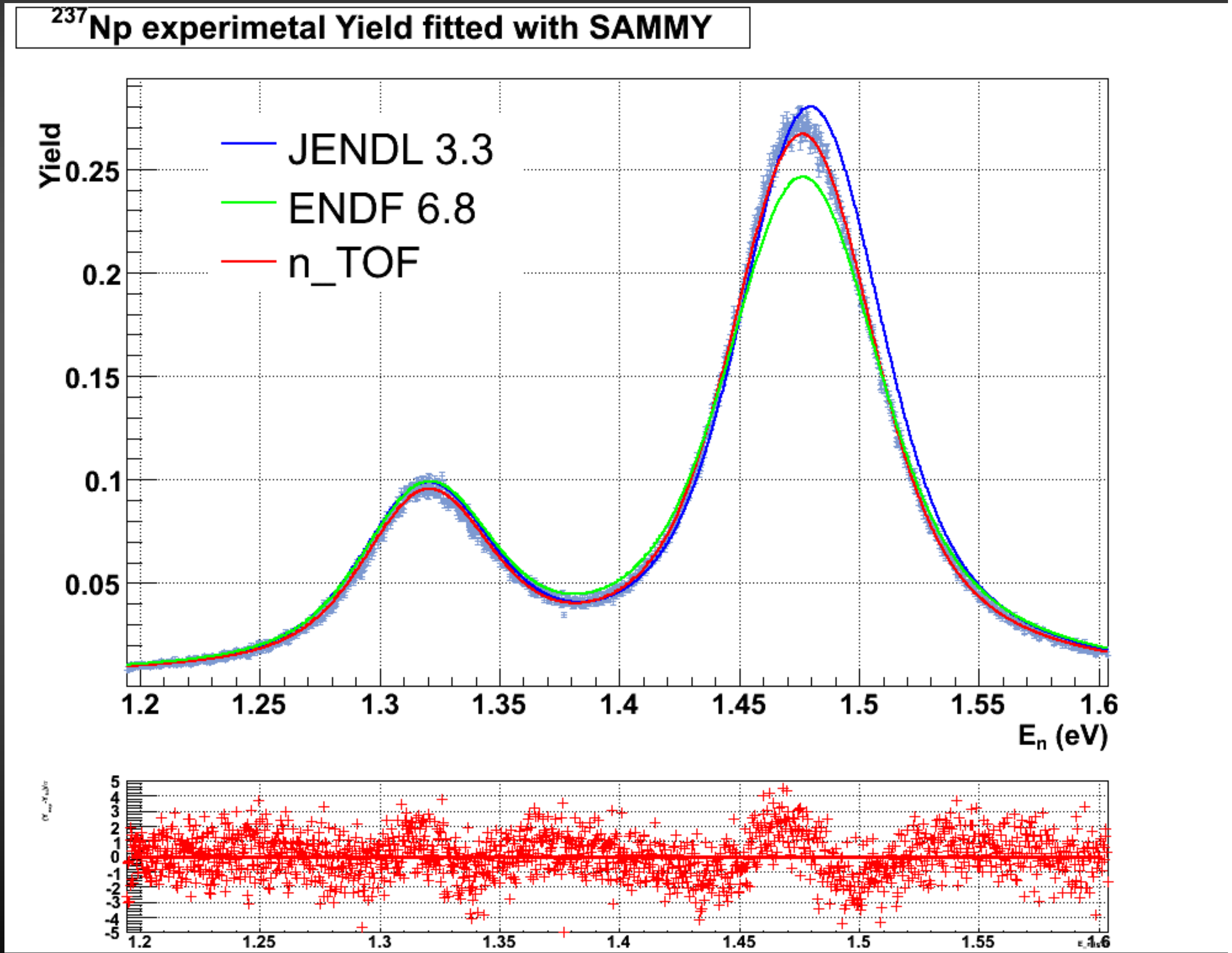
$^{241,243}Am$, ^{245}Cm



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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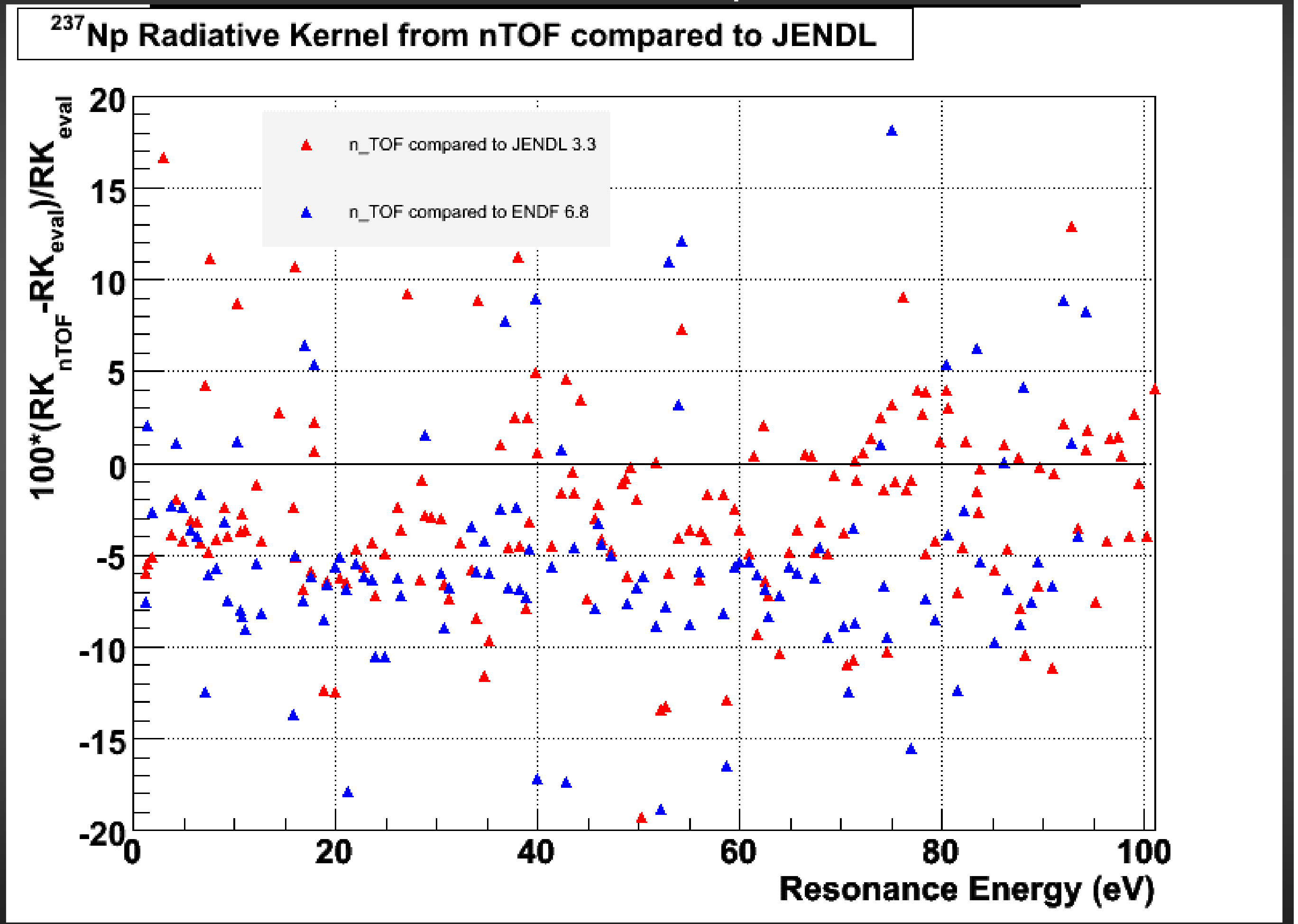
^{209}Bi

^{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

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

^{139}La

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^{233,234}U

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

Fission

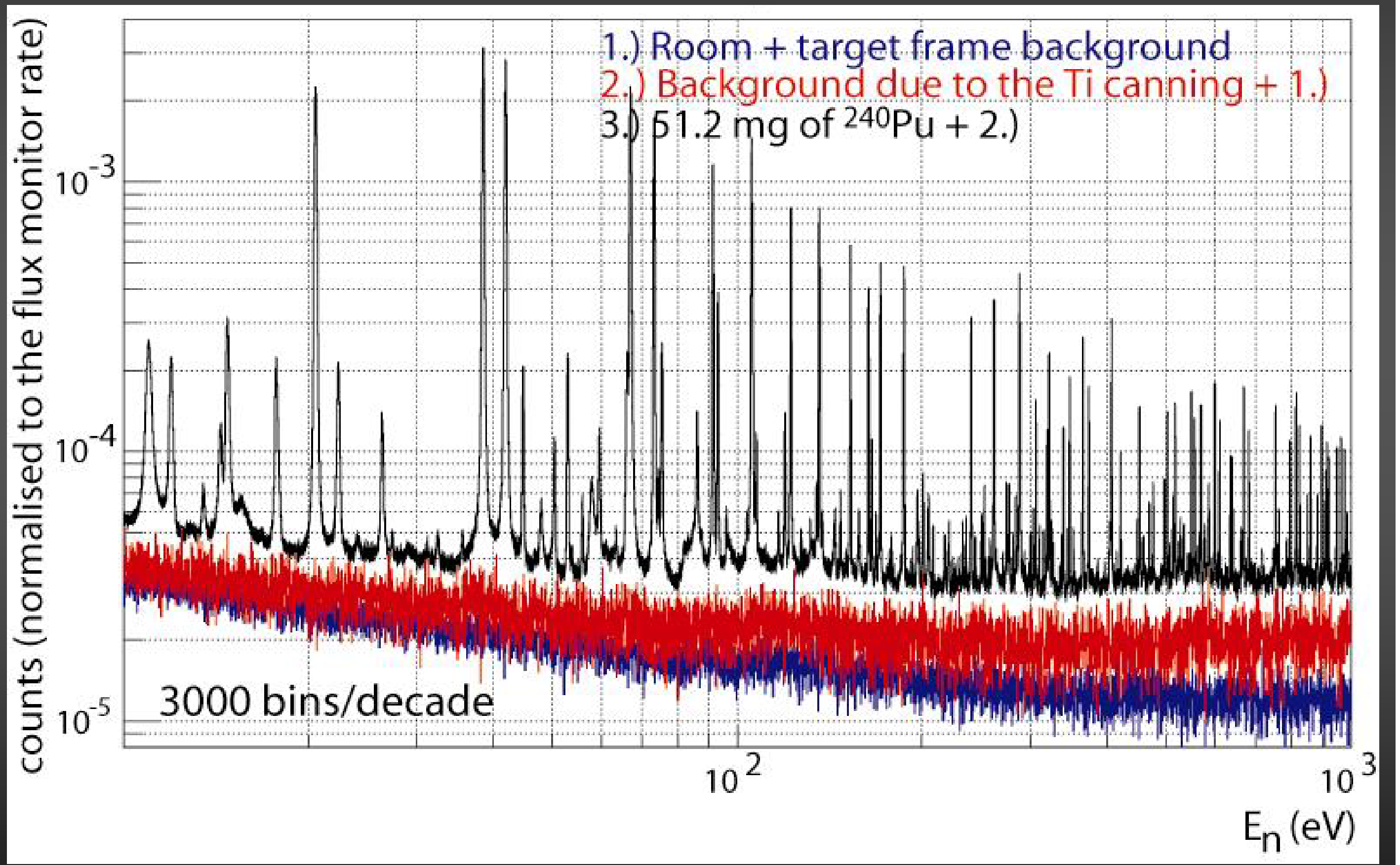
^{233,234,235,236,238}U

^{232}Th

^{209}Bi

^{237}Np

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



n_TOF TAC in operation

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}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

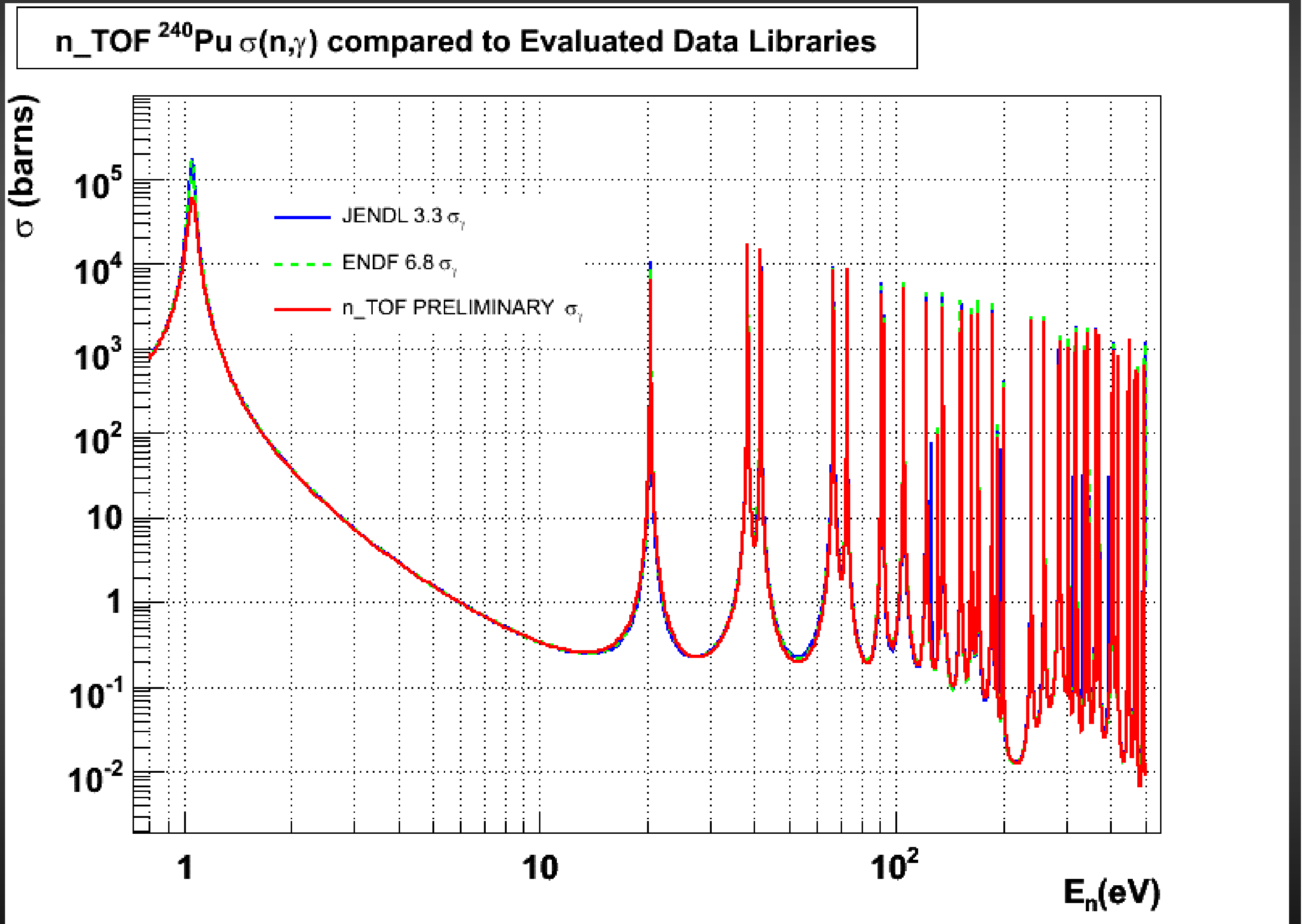
^{233,234,235,236,238}U

^{232}Th

^{209}Bi

^{237}Np

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



n_TOF TAC in operation

n_TOF experiments

Capture

^{151}Sm

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

^{232}Th

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$^{233,234}U$

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

Fission

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

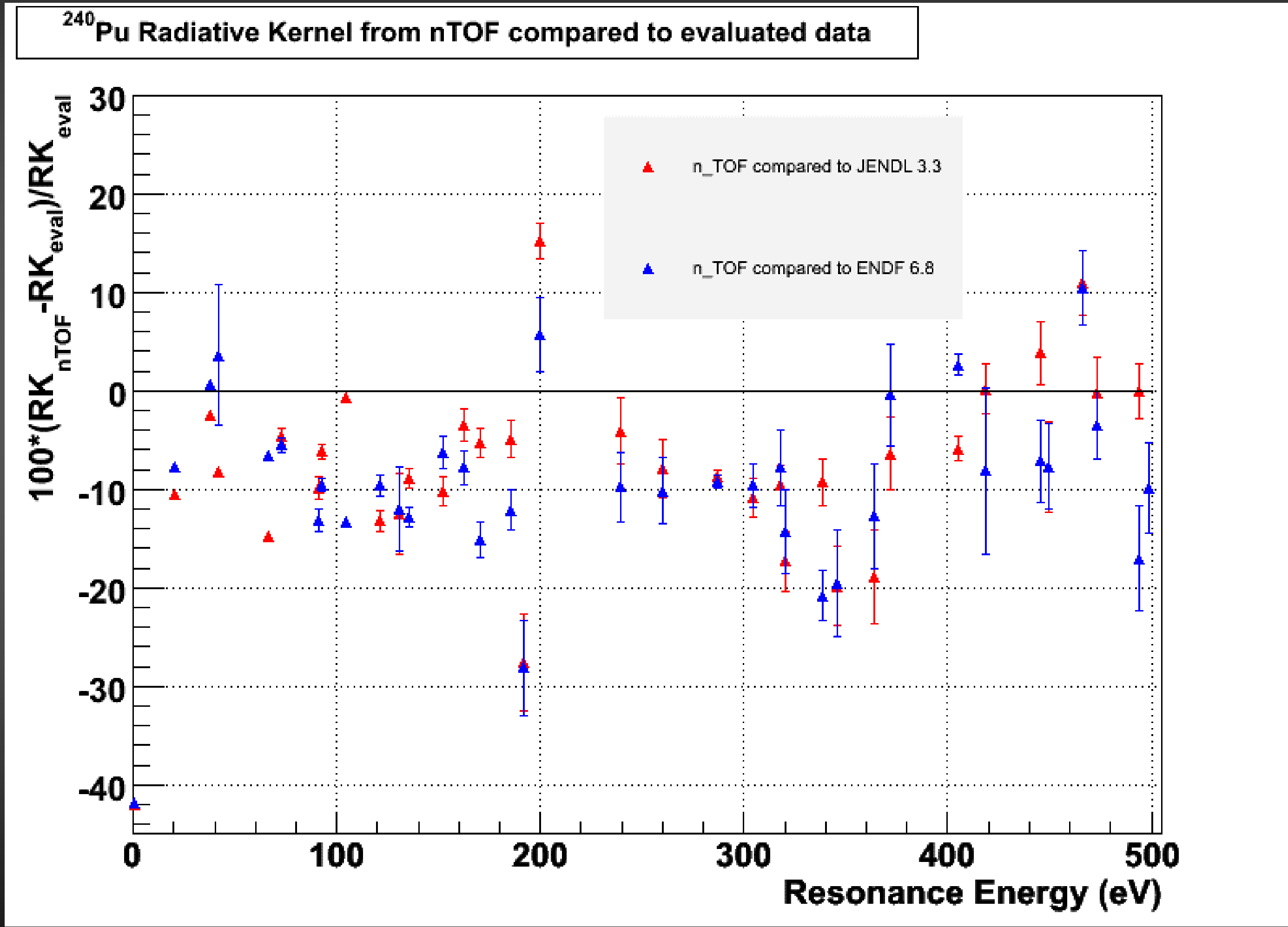
^{232}Th

^{209}Bi

^{237}Np

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

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}.

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

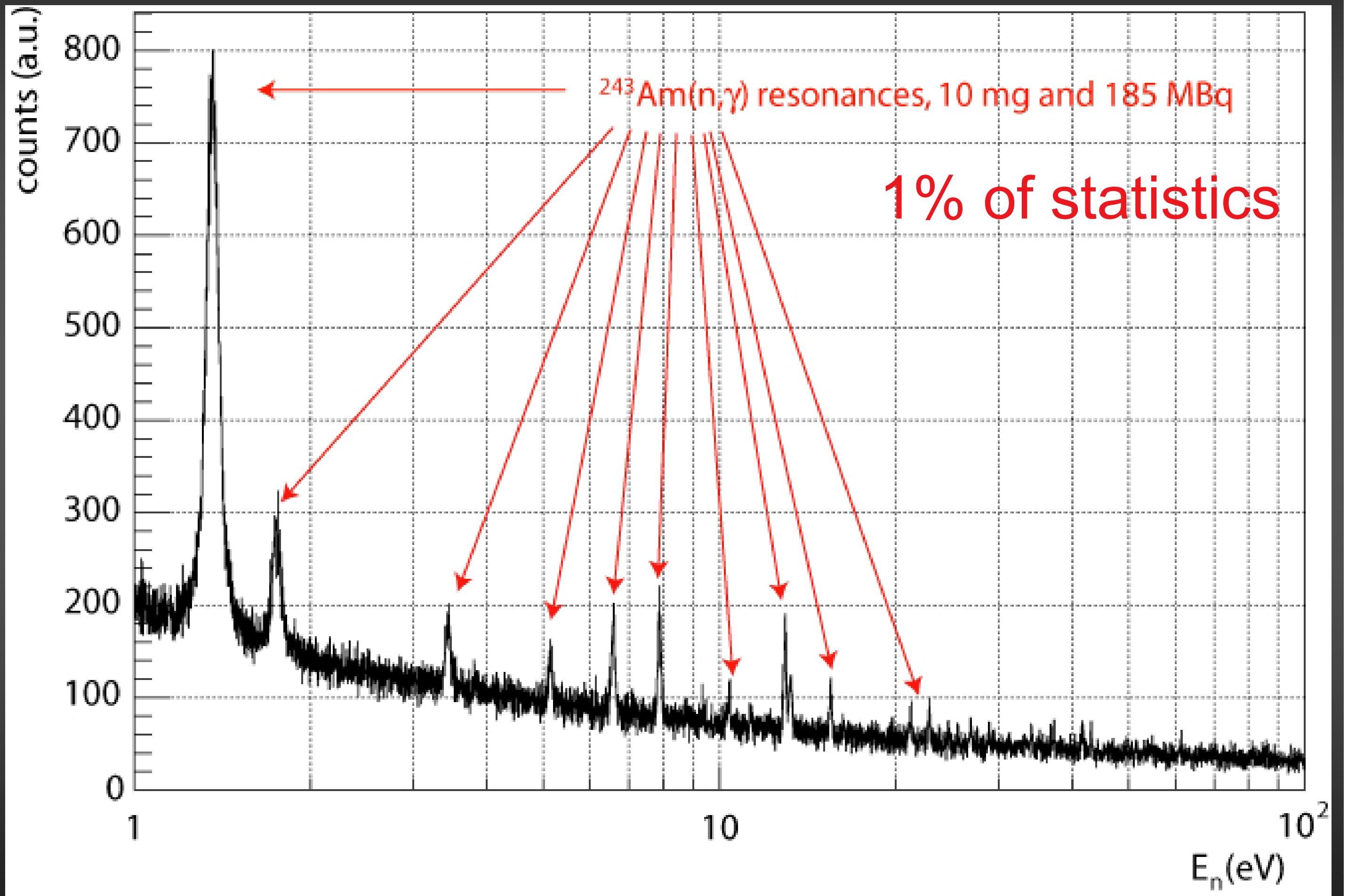
^{209}Bi

^{237}Np

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

n_TOF experiments

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



n_TOF TAC in operation

n_TOF experiments

Capture

^{151}Sm

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

^{232}Th

$^{24,25,26}Mg$

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

Fission

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

^{232}Th

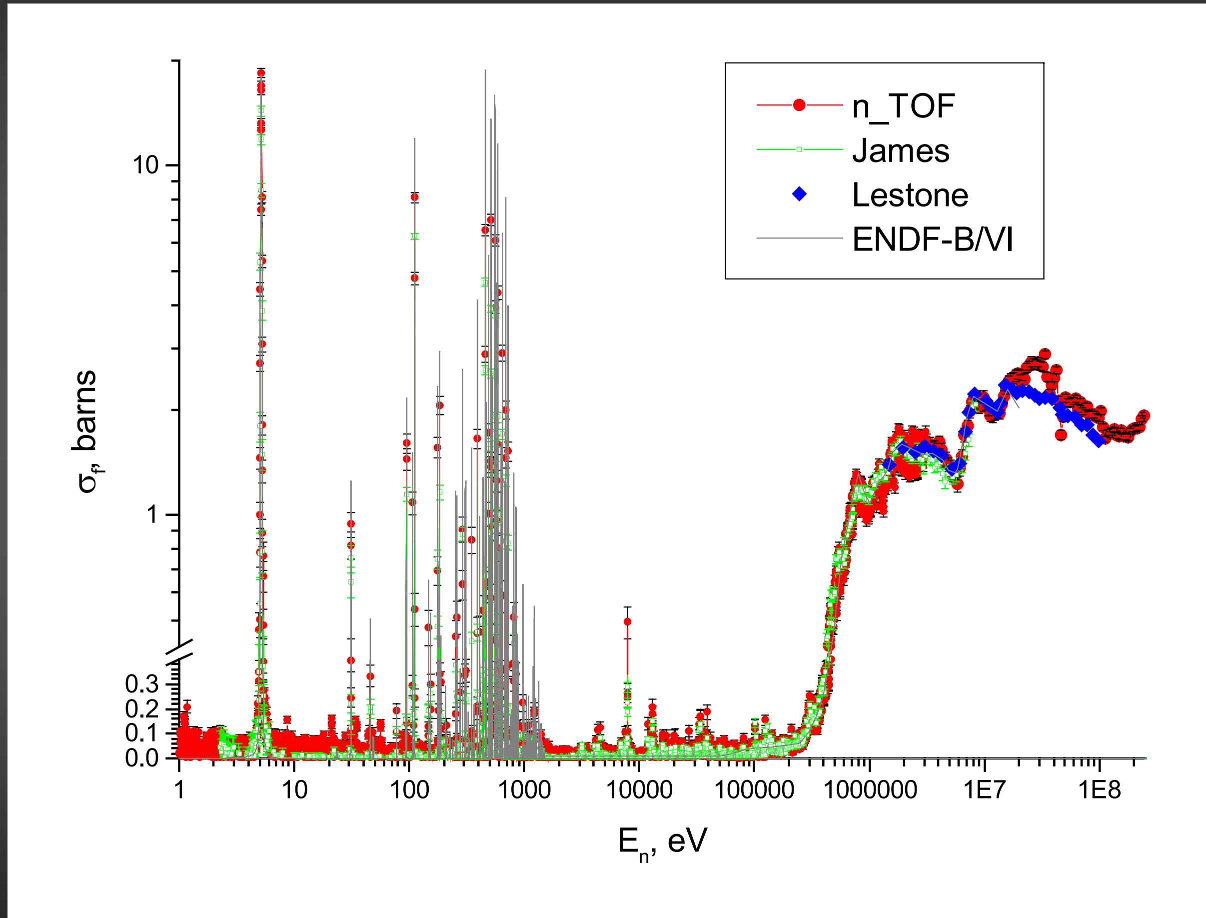
^{209}Bi

^{237}Np

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

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

PPACs & FIC-0 (2003)



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

n_TOF experiments

PPACs & FIC-0 (2003)

Capture

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

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

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Fission

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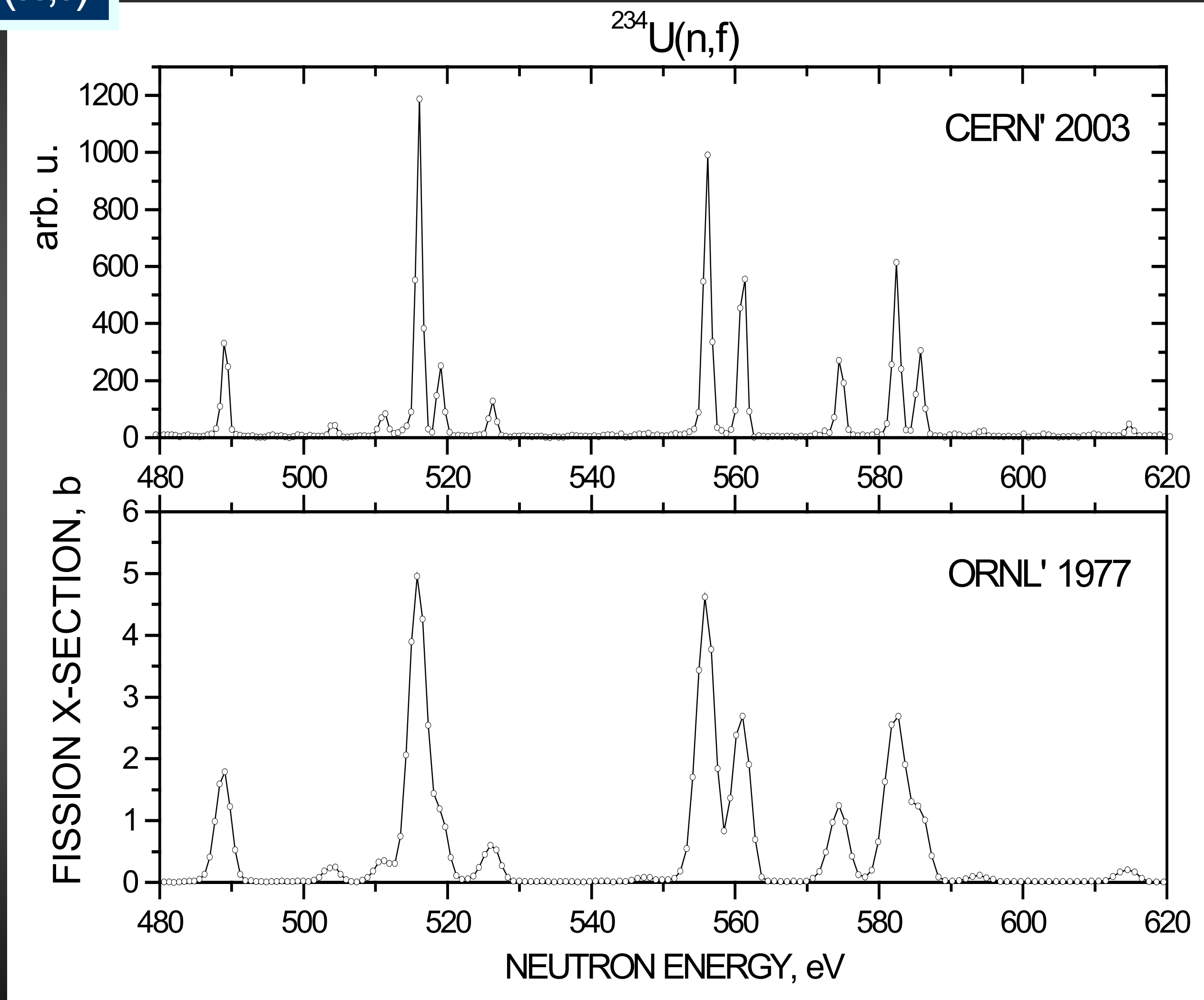
^{232}Th

^{209}Bi

^{237}Np

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

^{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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Fission

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^{232}Th

^{209}Bi

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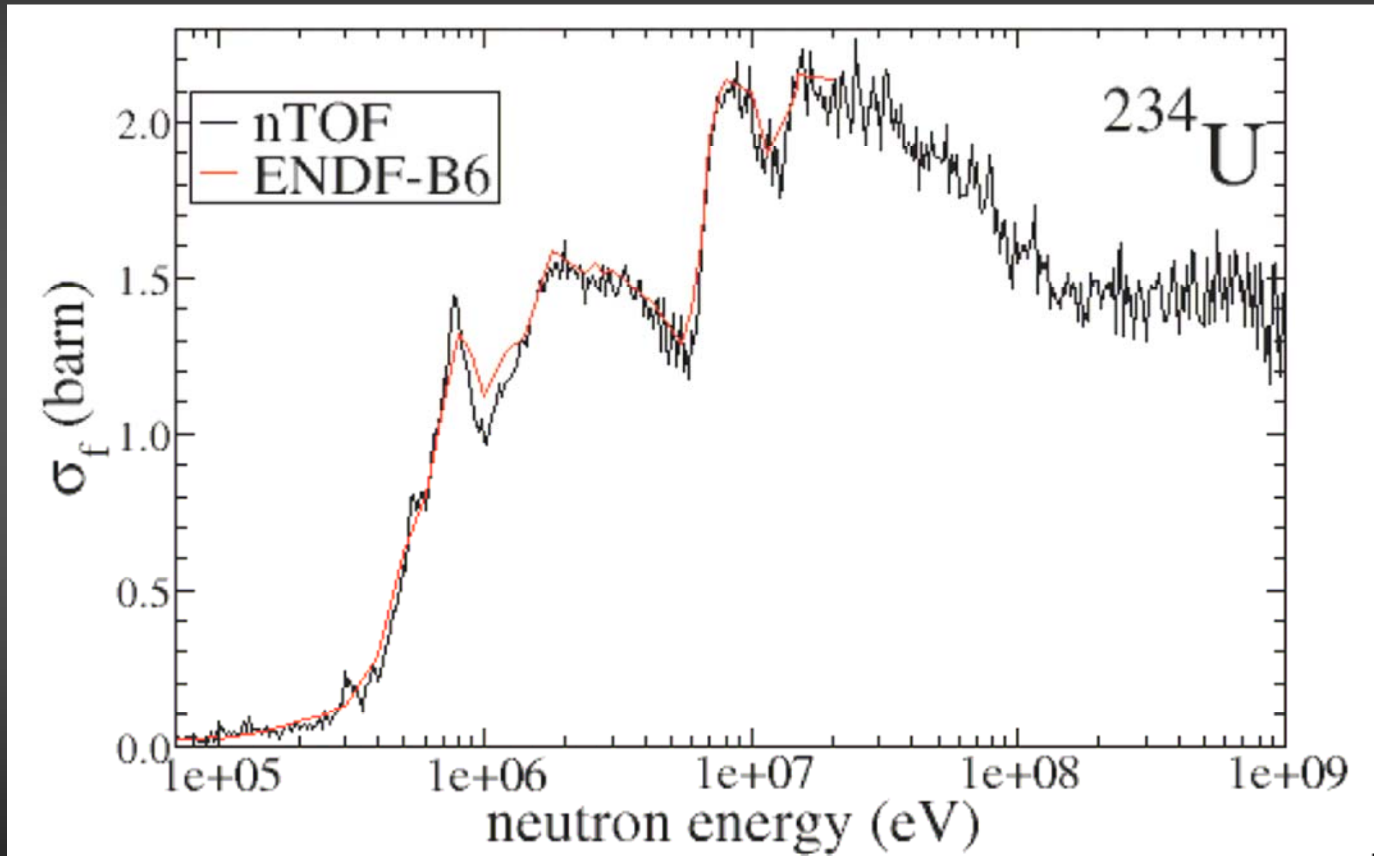
$^{234}U(n,f)$



High-resolution data up to high(er) energies

n_TOF experiments

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$^{186,187,188}Os$

$^{233,234}U$

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

Fission

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

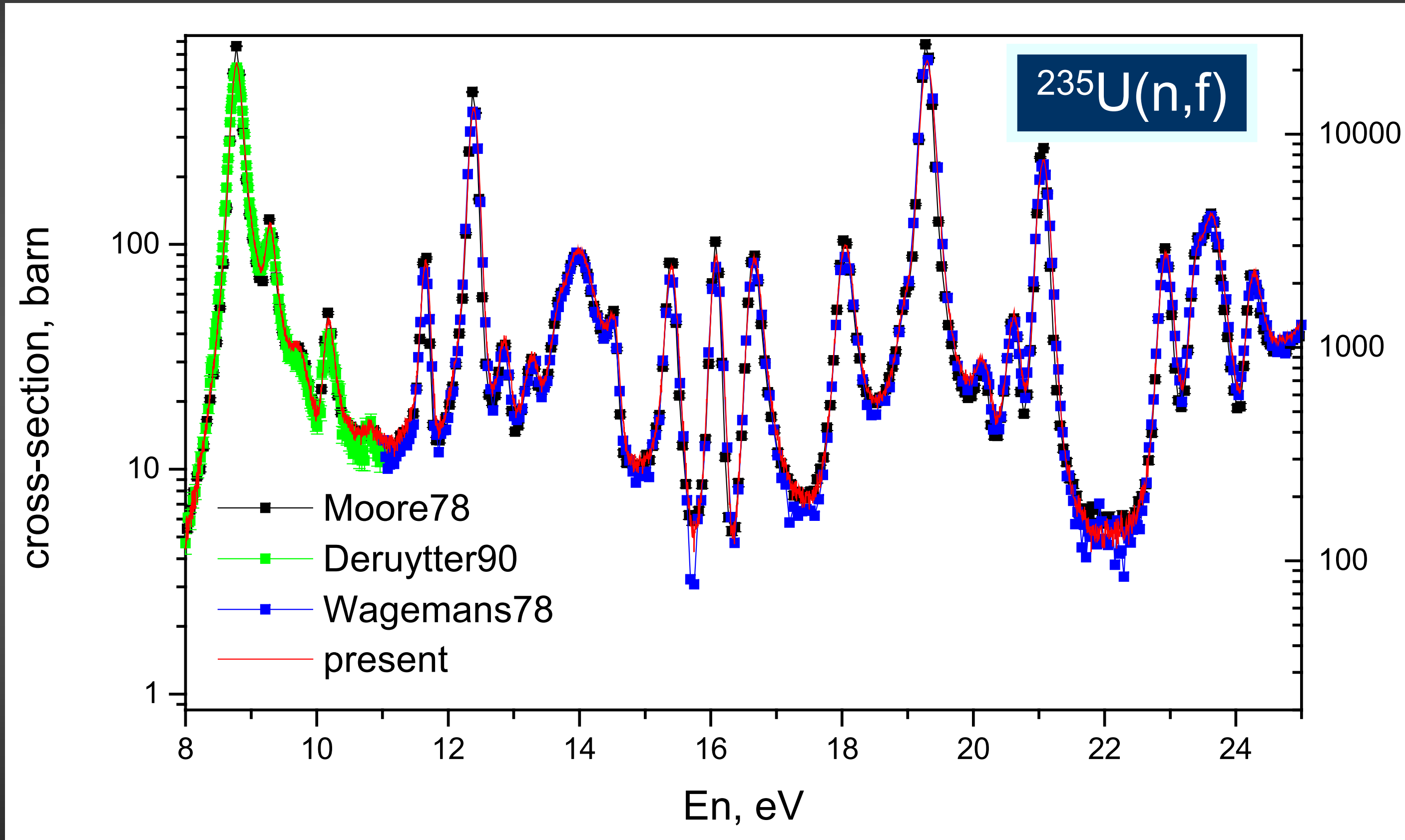
^{232}Th

^{209}Bi

^{237}Np

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

FIC-0 (2003)



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

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

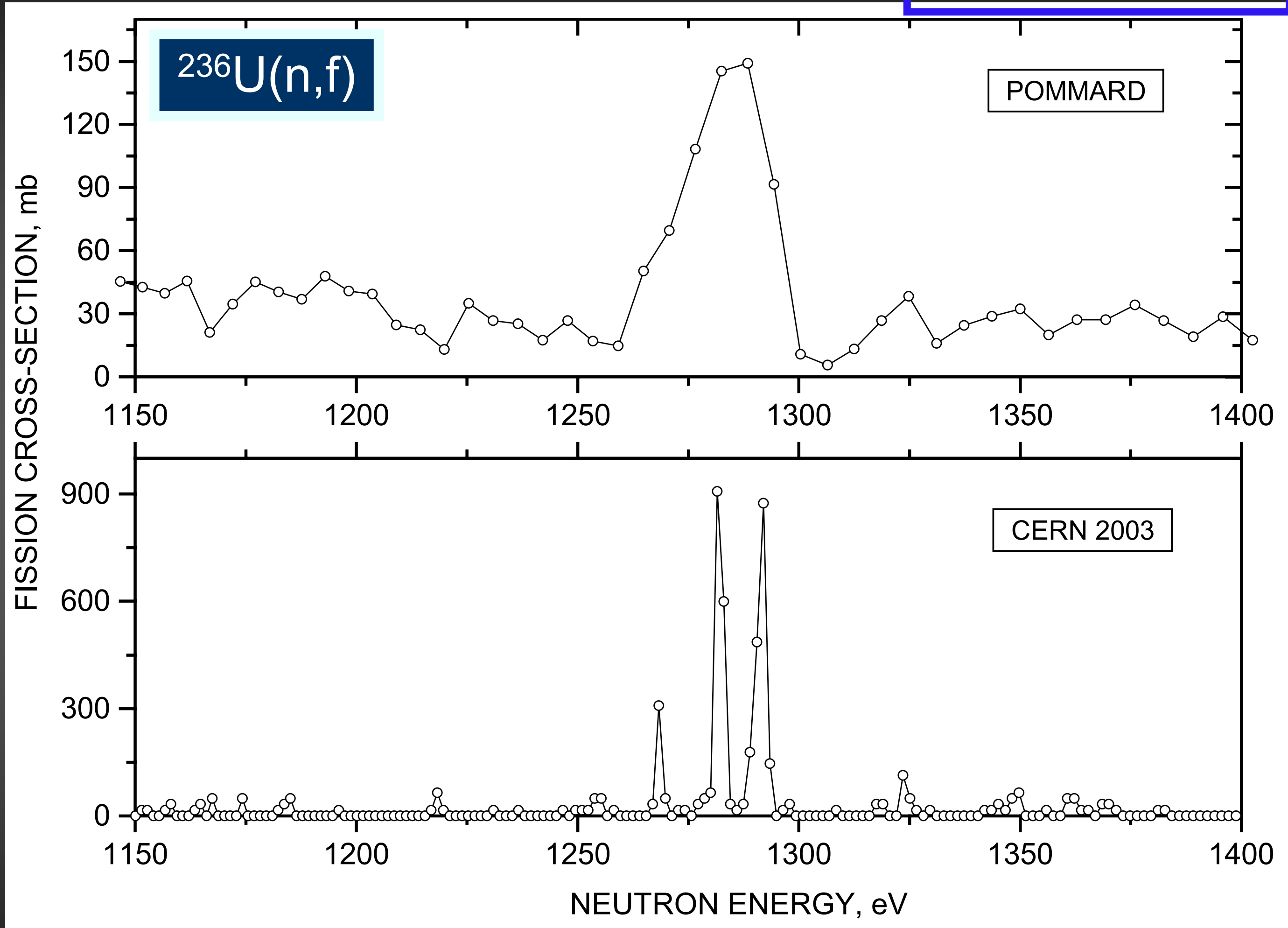
$^{233,234,235,236,238}U$

^{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

^{139}La

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$^{233,234}U$

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

Fission

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

^{232}Th

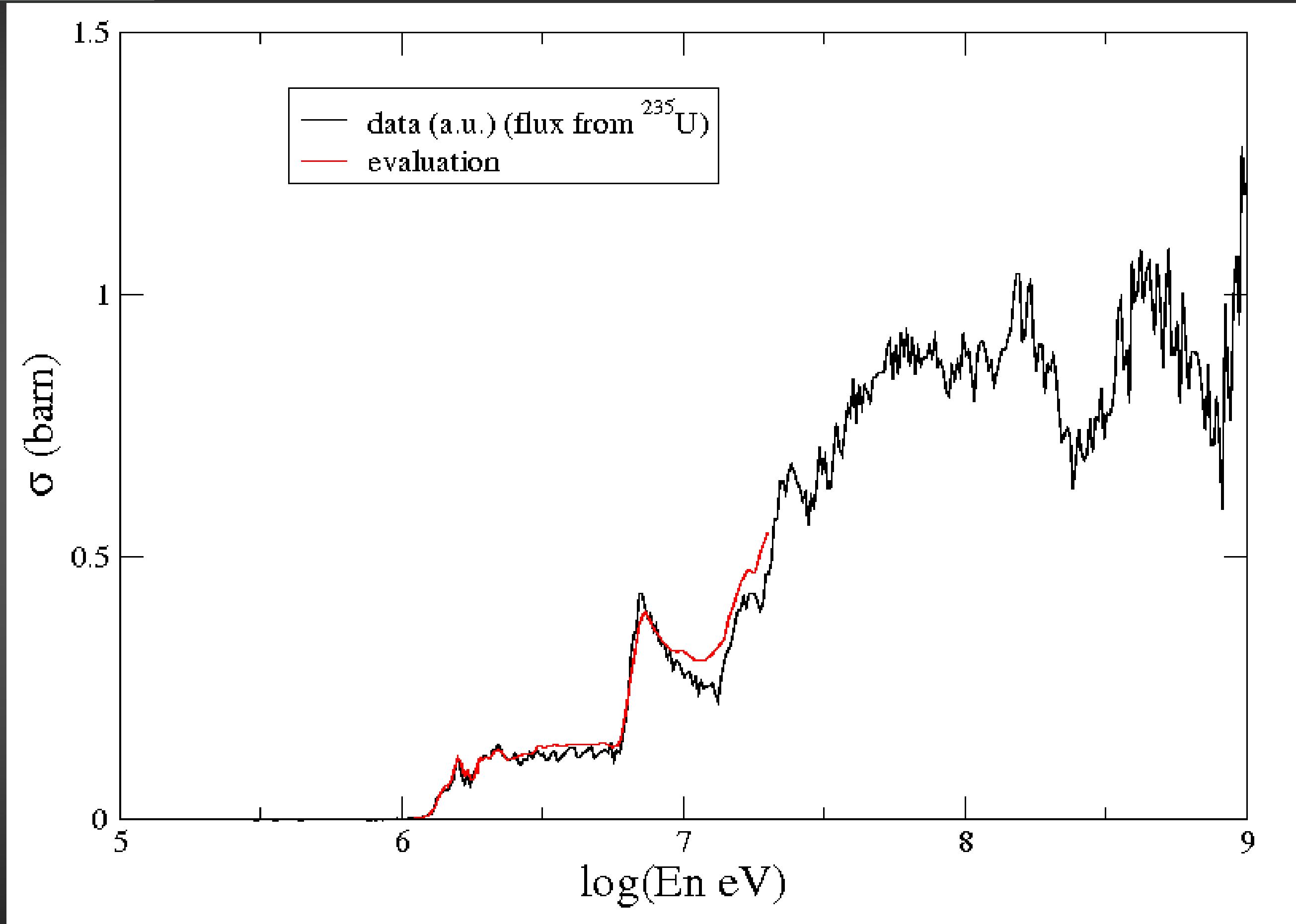
^{209}Bi

^{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

The n_TOF Collaboration

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

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

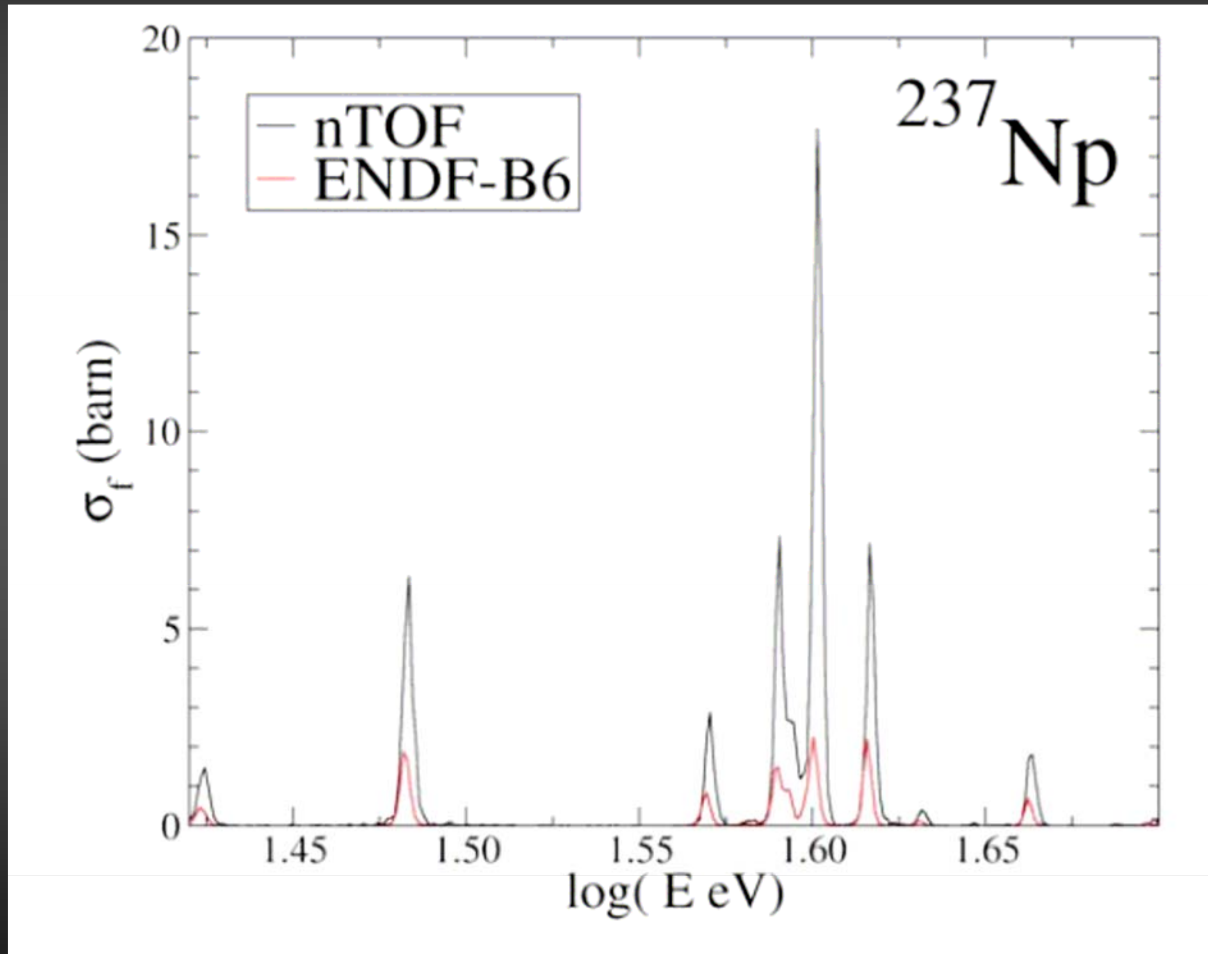
^{232}Th

^{209}Bi

^{237}Np

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

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



Higher fission x-section in the sub-threshold region

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

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

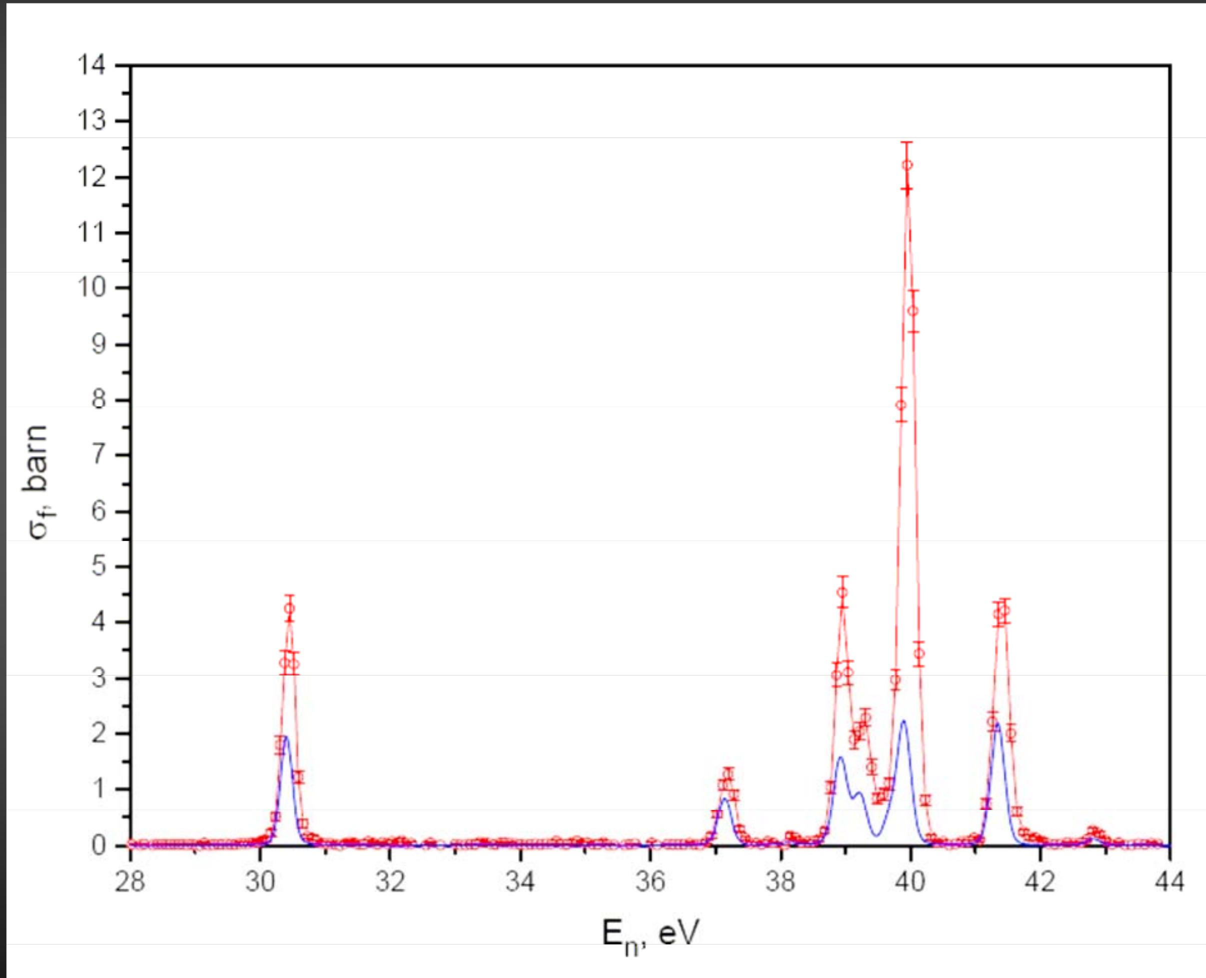
^{232}Th

^{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

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

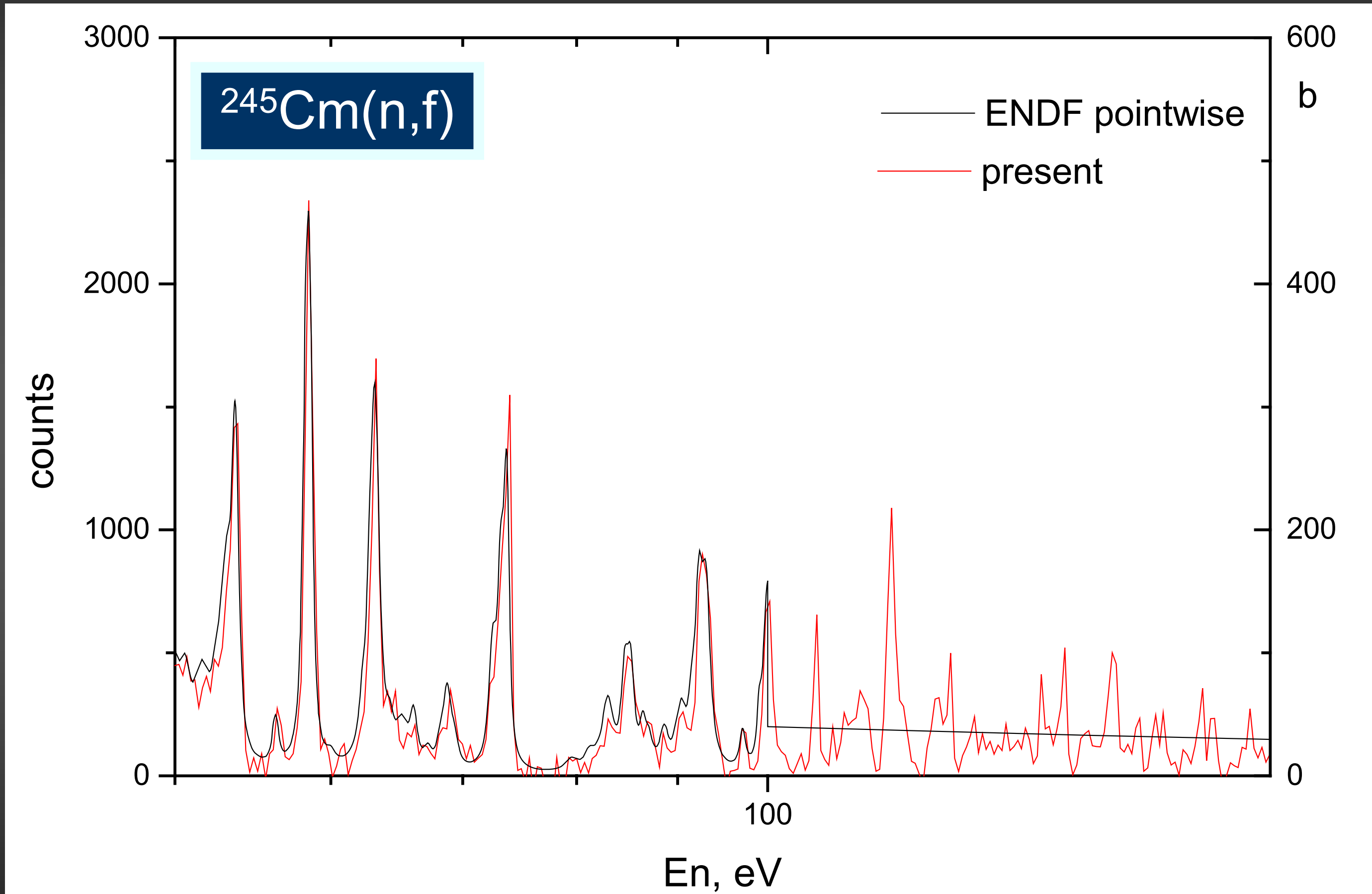
^{232}Th

^{209}Bi

^{237}Np

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

FIC-1 (2003)



High-resolution data up to high(er) energies

The n_TOF Collaboration

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

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

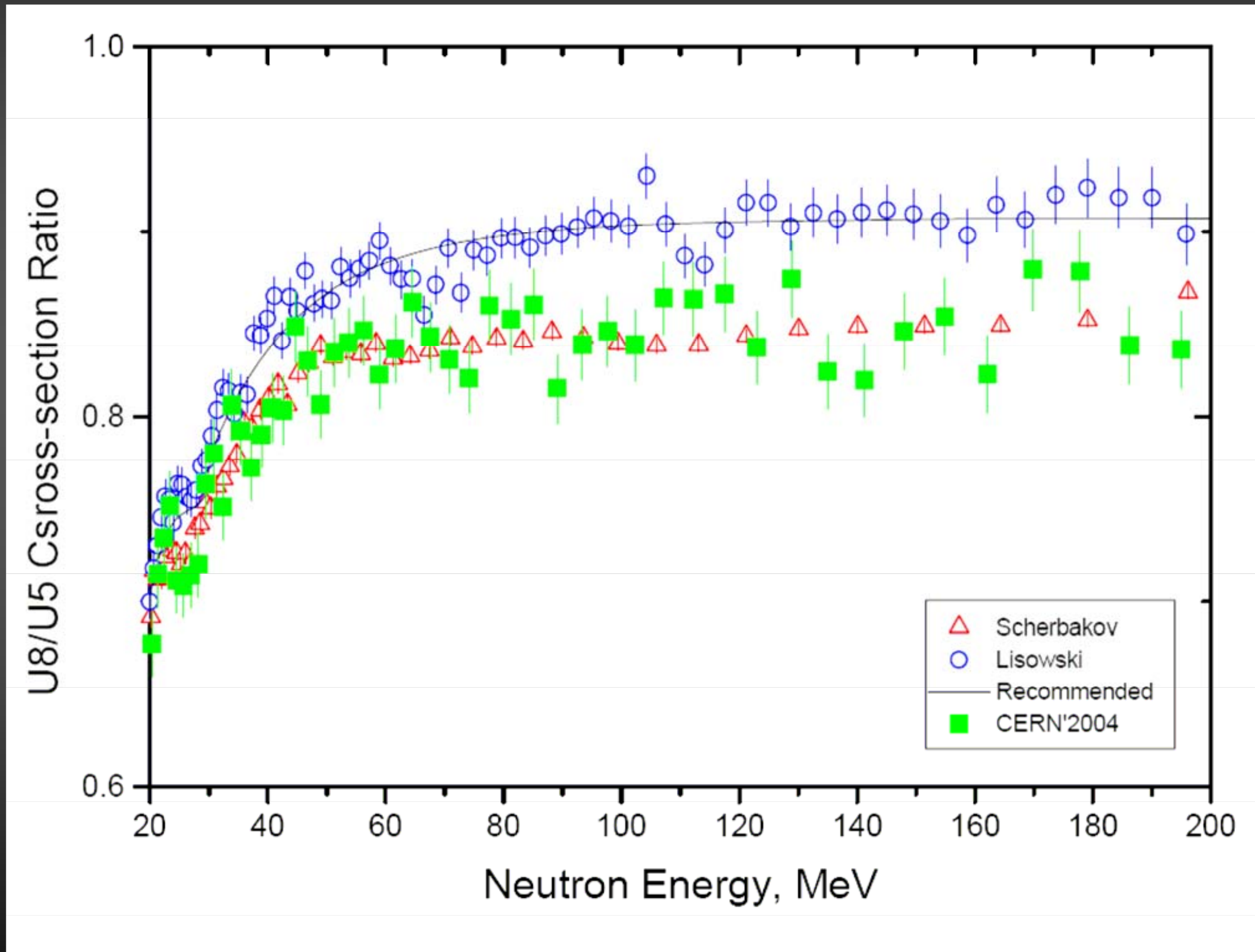
^{232}Th

^{209}Bi

^{237}Np

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

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



15% lower U8/U5 ratio at high energies

back

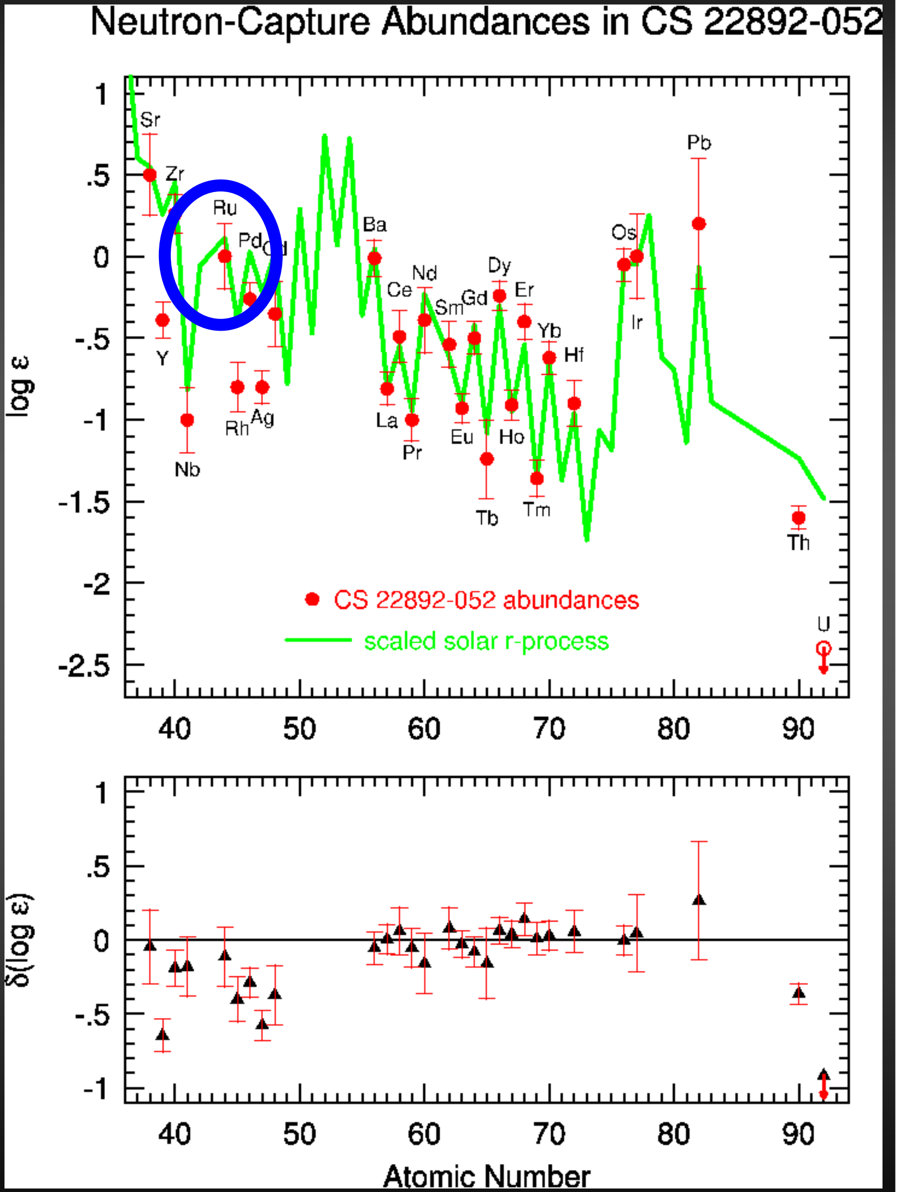
Capture studies: Mo, Ru and Pd

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.

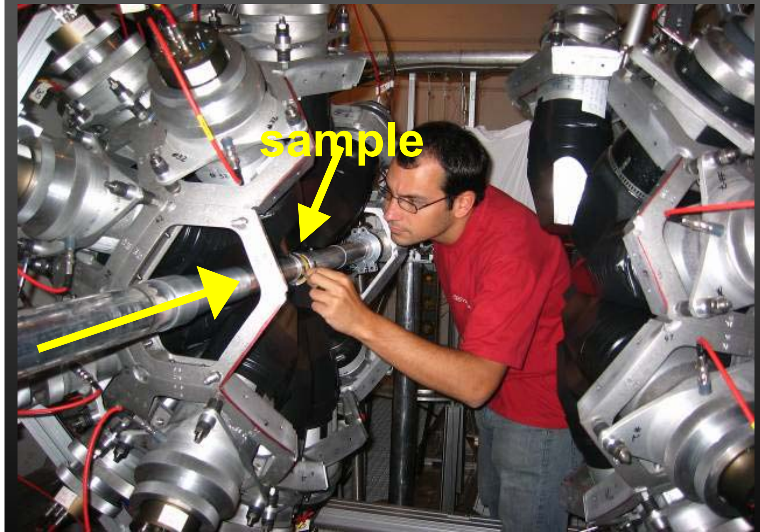
$$N_r = N_{solar} - N_s$$

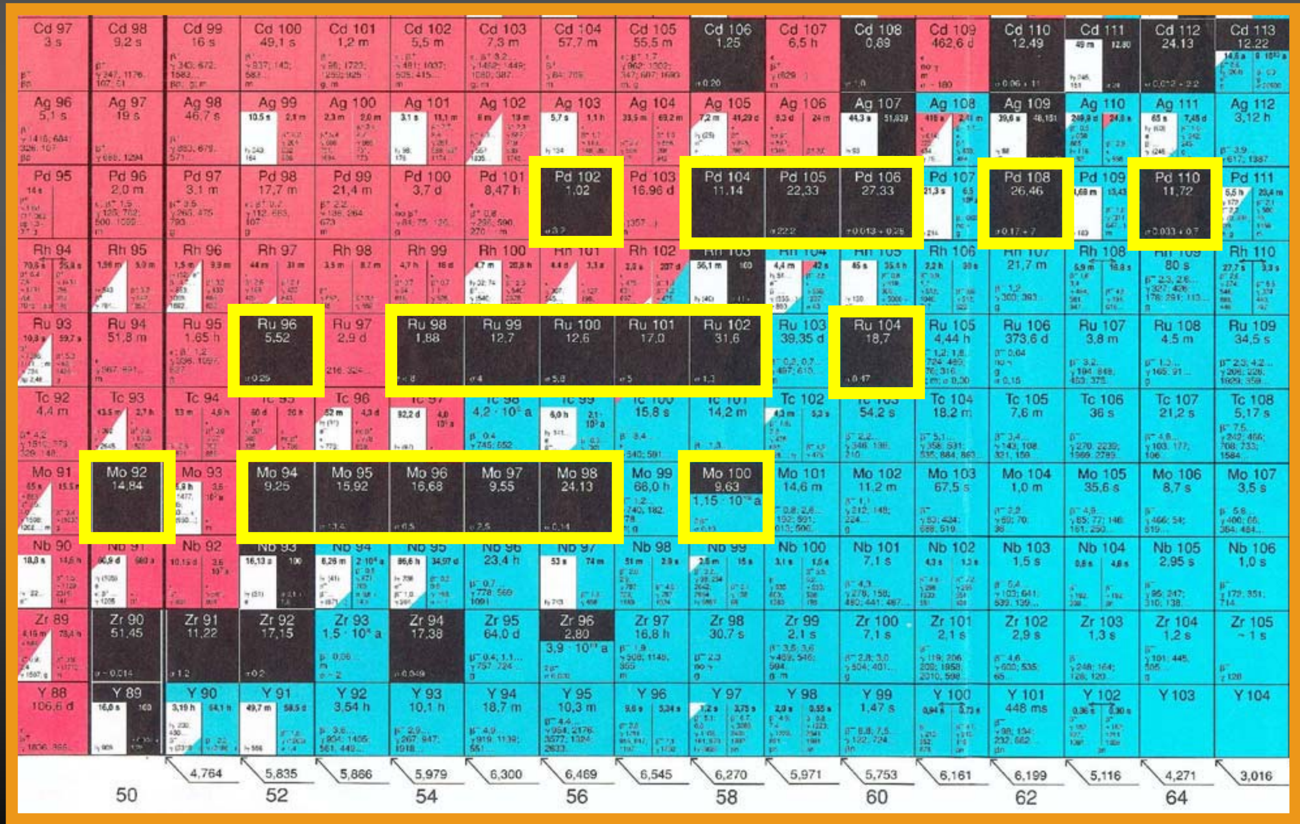


Capture studies: Mo, Ru and Pd

- Setup: The n_TOF TAC in EAR-1
  (a few cases with C_6D_6 if larger neutron scattering)
- All samples are stable and non-hazardous
- Metal samples preferable (oxides acceptable)

Estimated # of protons
20 x 5×10^{16} = $\mathbf{10^{18}}$





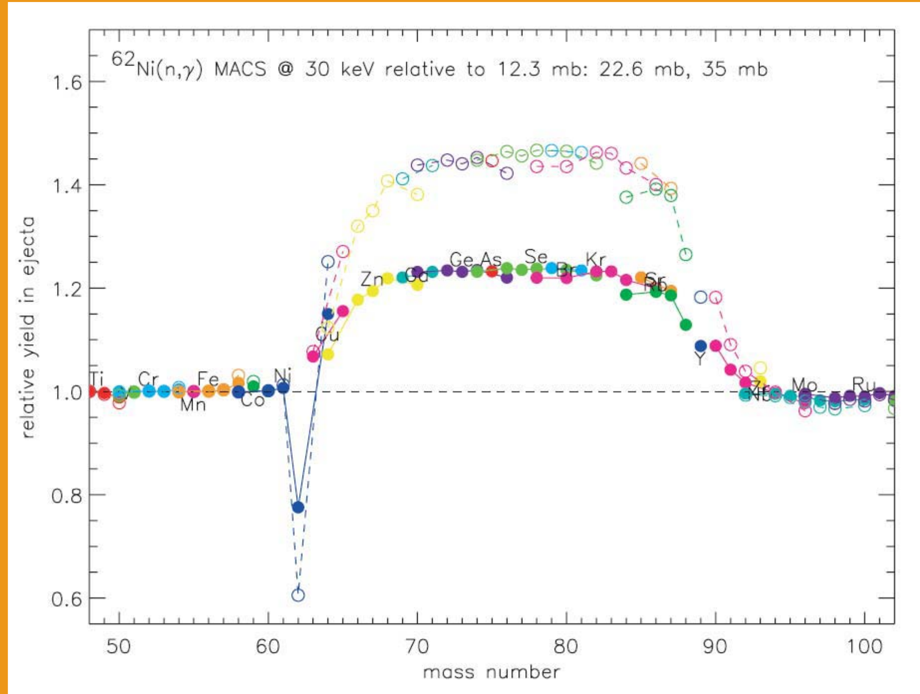
Capture studies: Fe, Ni, Zn, and Se

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.

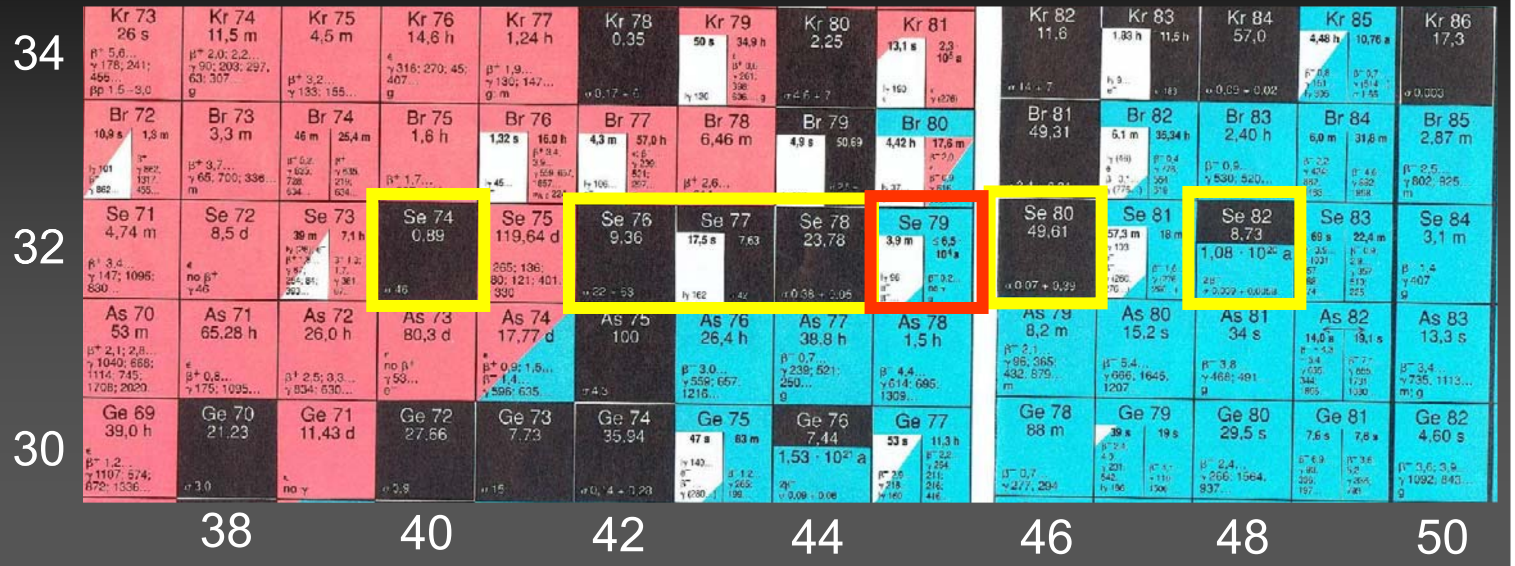
• s-process efficiency due to bottleneck cross sections (Example: ^{62}Ni)



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

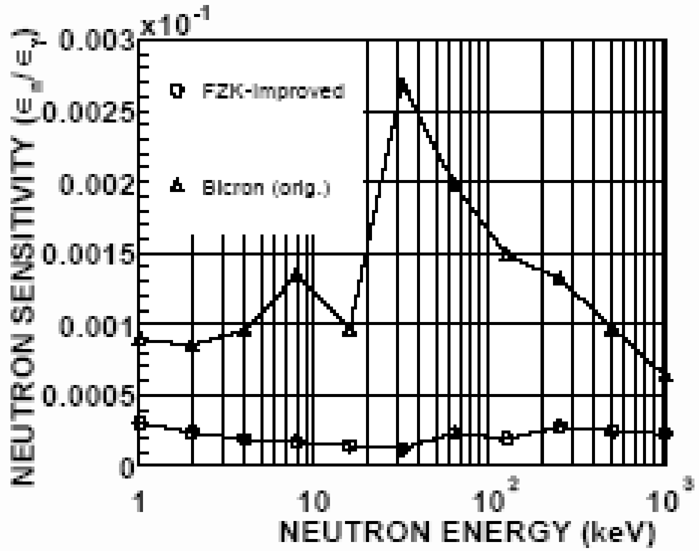


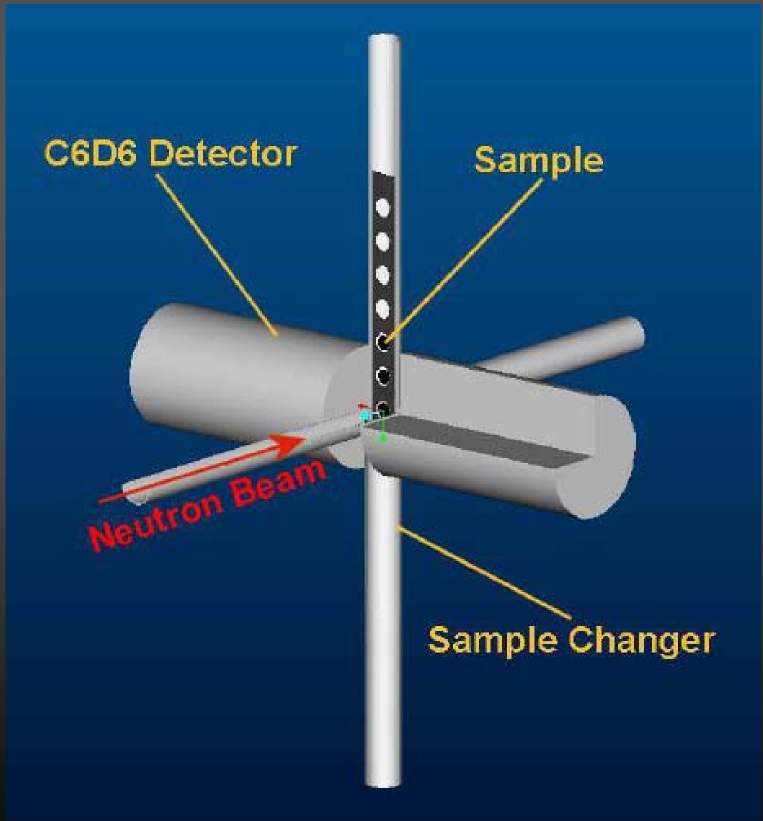
The ^{79}Se case

- s-process branching: neutron density & temperature conditions for the weak component.
- $t_{1/2} < 6.5 \times 10^4$ yr

Capture studies: Fe, Ni, Zn, and Se

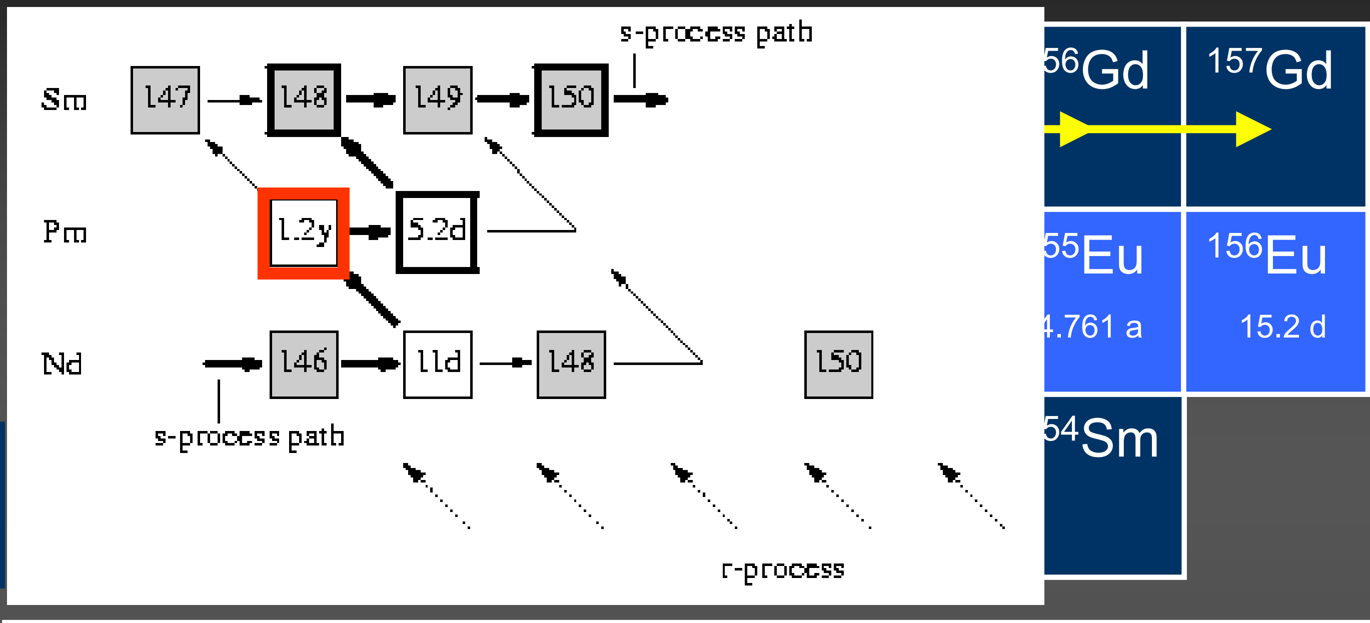
- Setup: C_6D_6 in EAR-1
- All samples are stable(*) and non-hazardous
- Metal samples preferable (oxides acceptable)





(*) except ^{79}Se

Capture studies: A ≈ 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!)

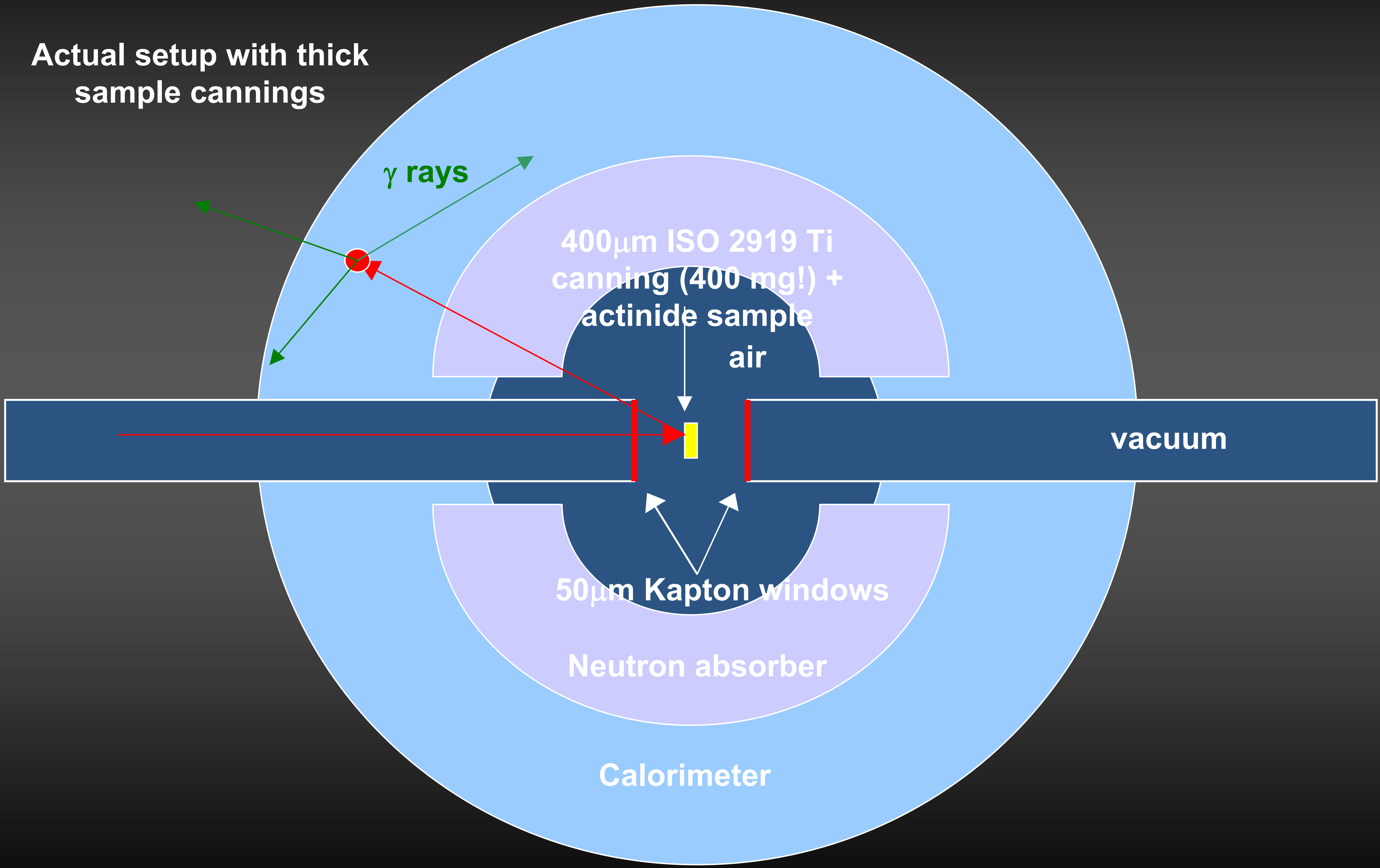
Capture studies: actinides

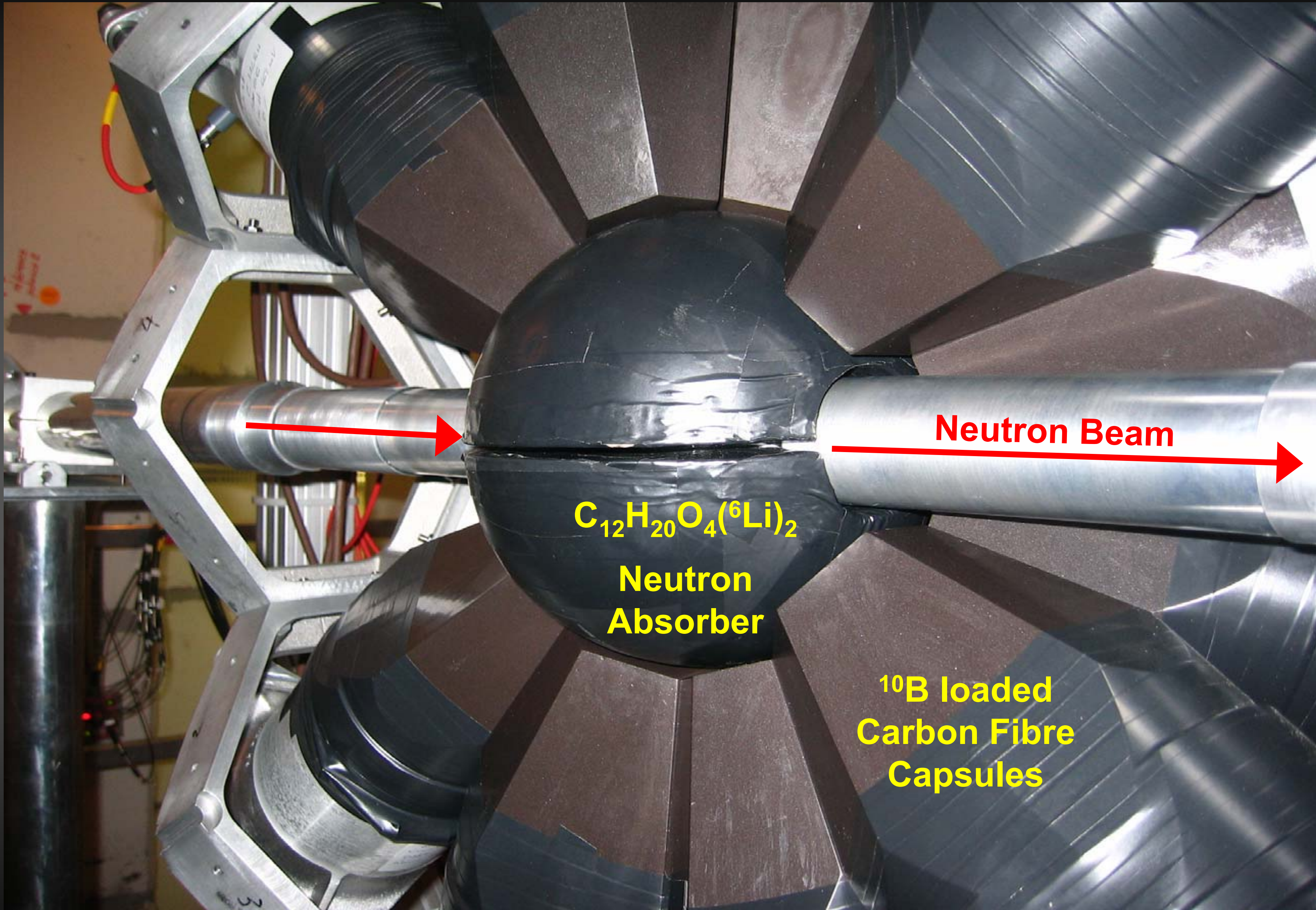
Neutron cross section measurements for nuclear waste transmutation and advanced nuclear technologies

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

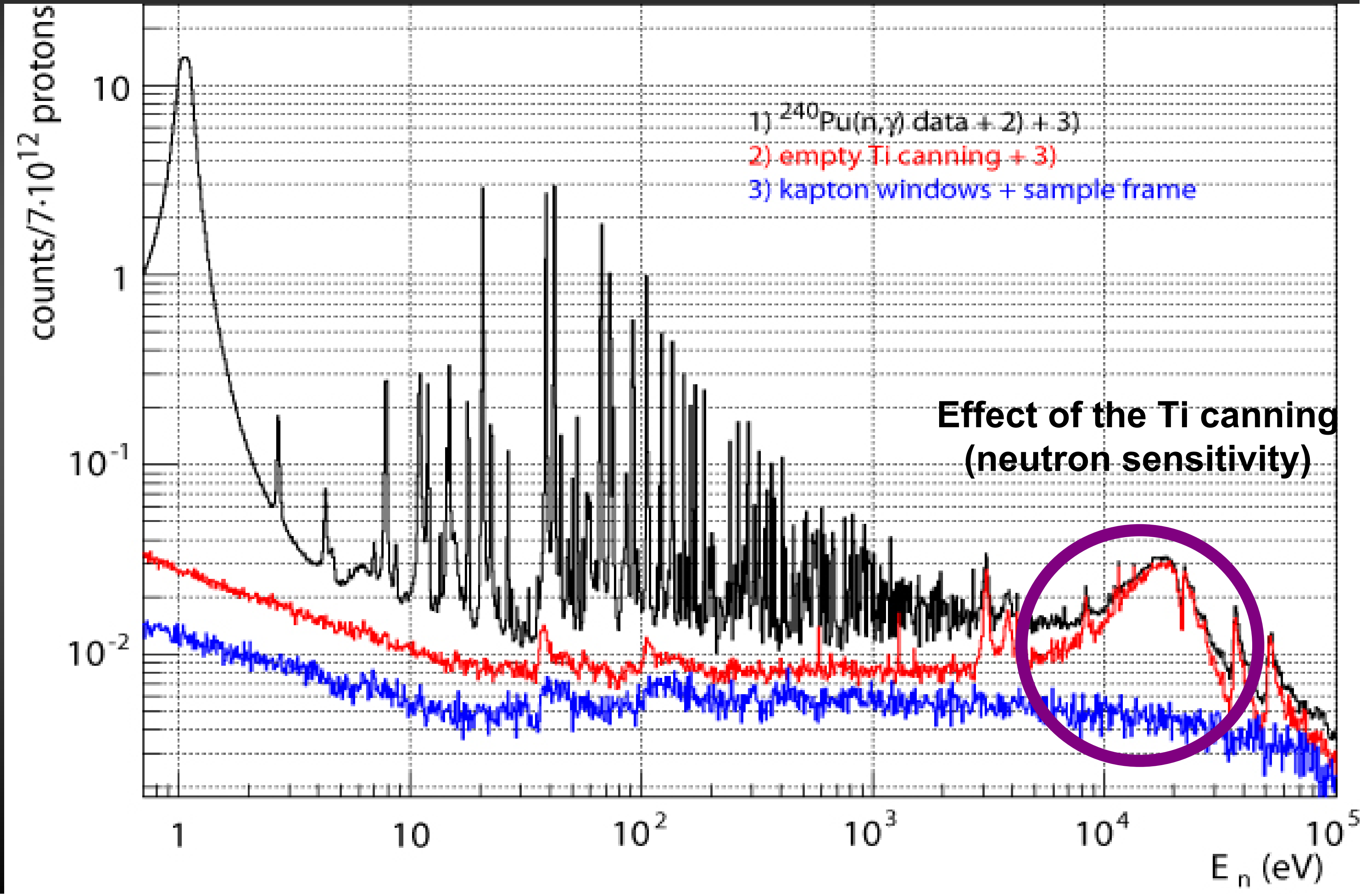
All measurements can be done in EAR-1 (except ^{241}Am and ^{233}Pa)

Capture studies: actual TAC setup

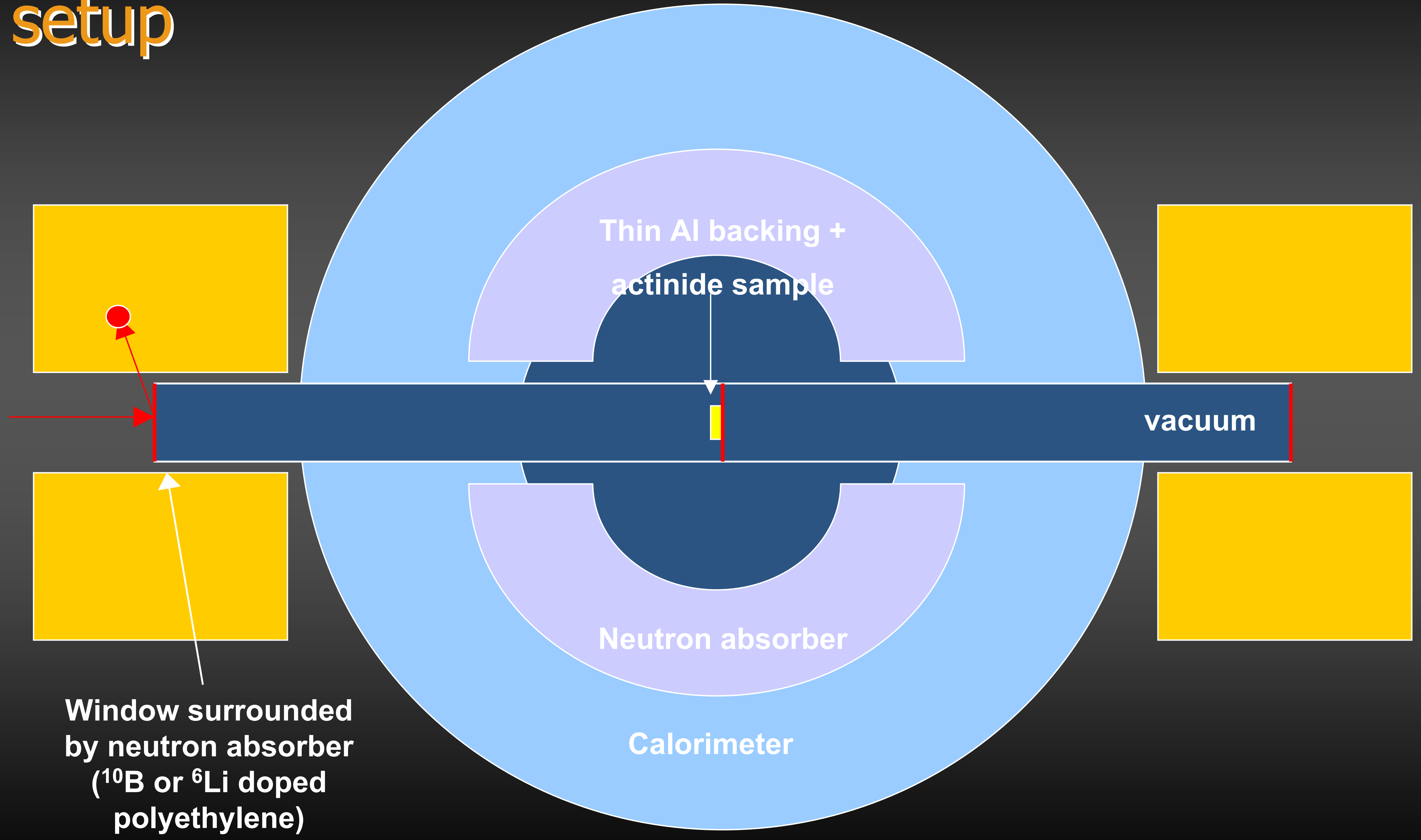



Neutron Beam
$C_{12}H_{20}O_4(^6Li)_2$
Neutron Absorber
^{10}B loaded Carbon Fibre Capsules

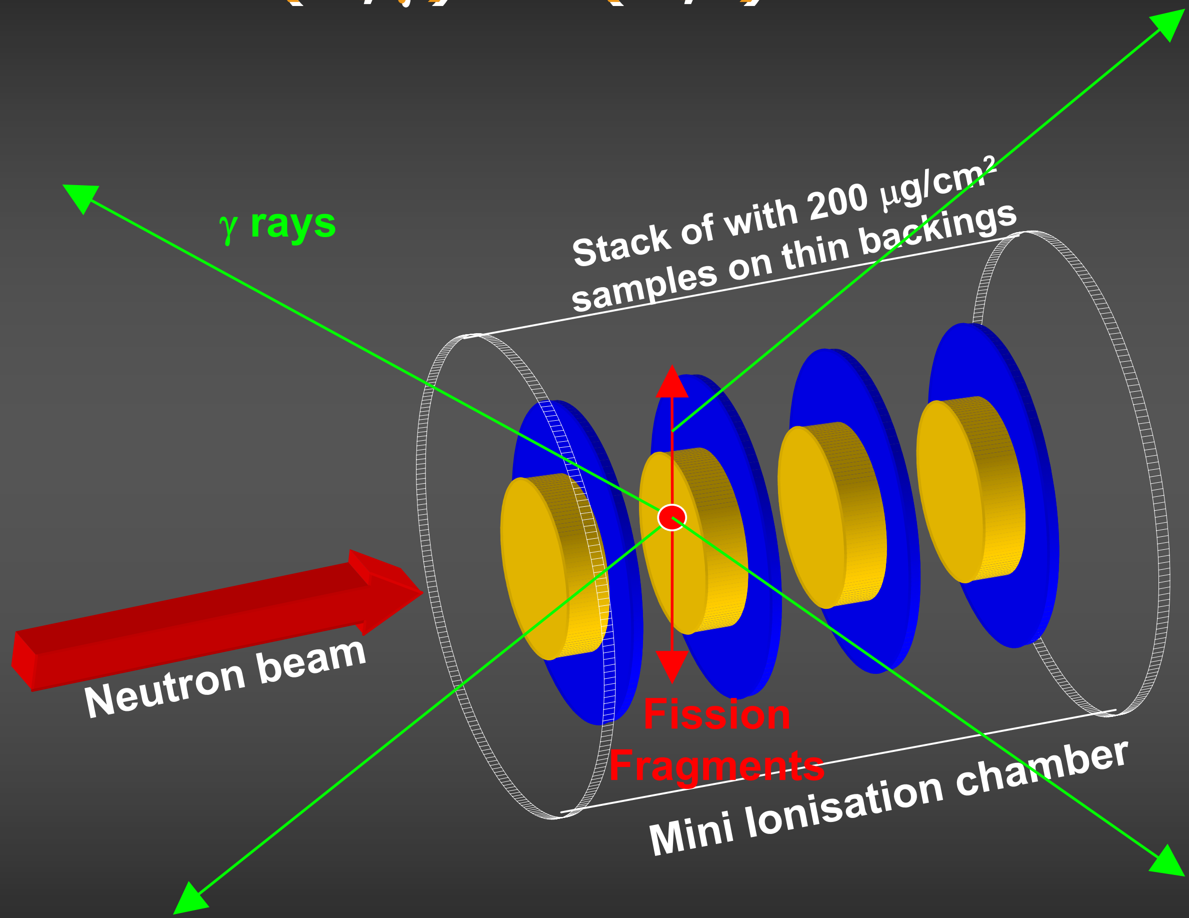
Capture studies: actual TAC setup



Capture studies: Low neutron sensitivity setup



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



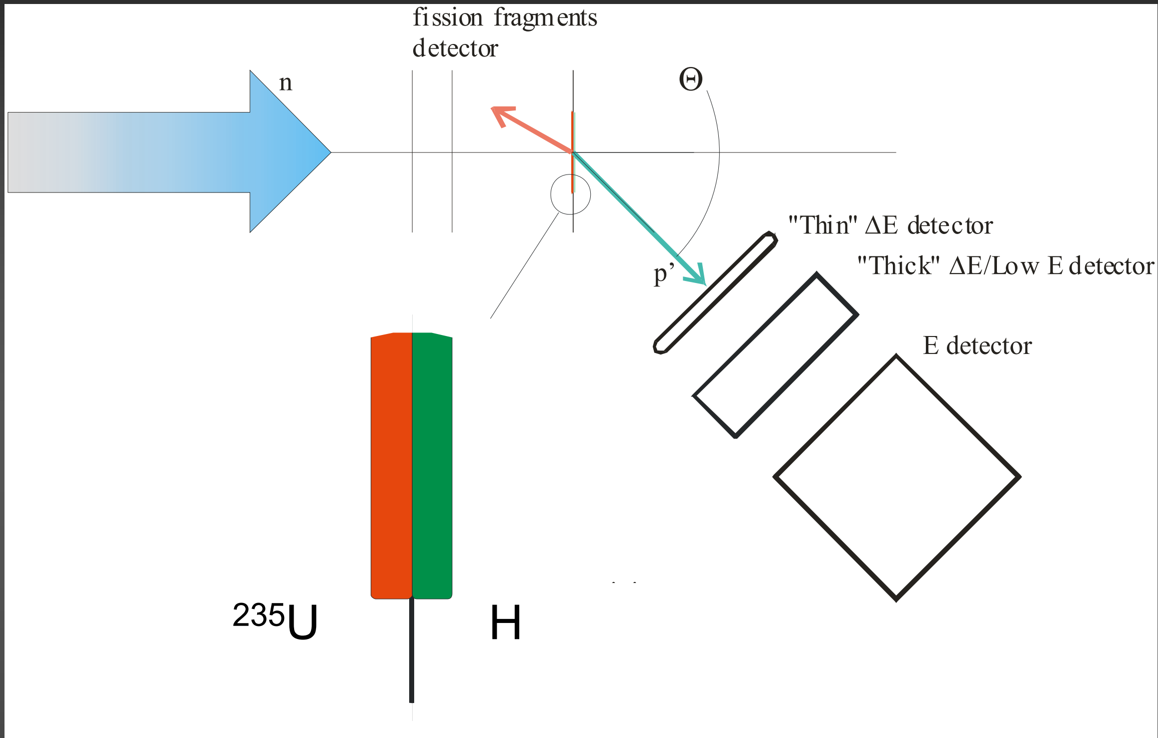
<< back

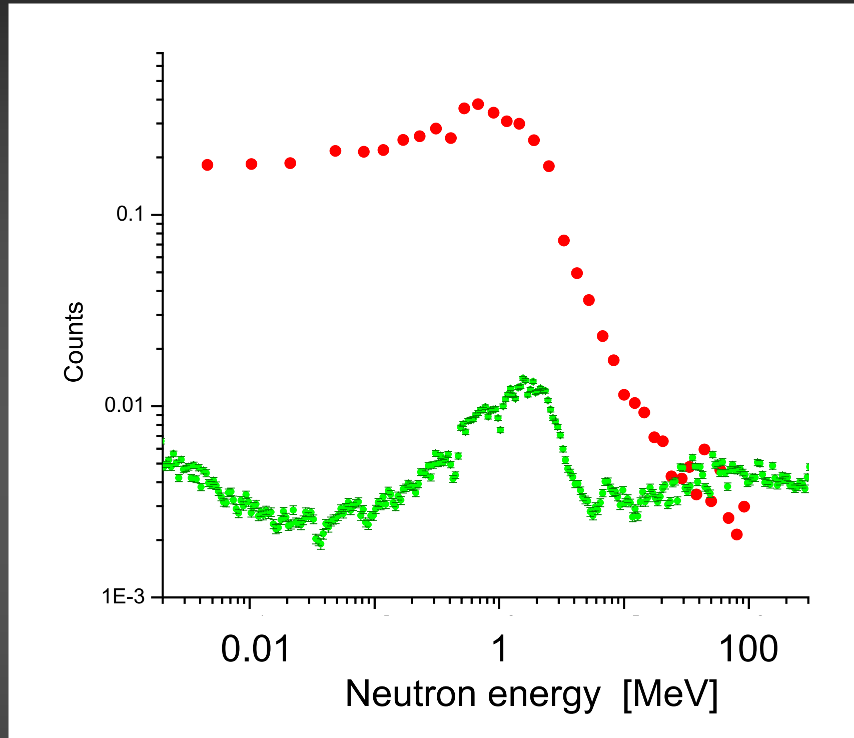
Measurement of capture cross sections of fissile materials (veto) and measurement of the (n,γ)/(n,f) ratio.

Fission studies

Fission studies

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



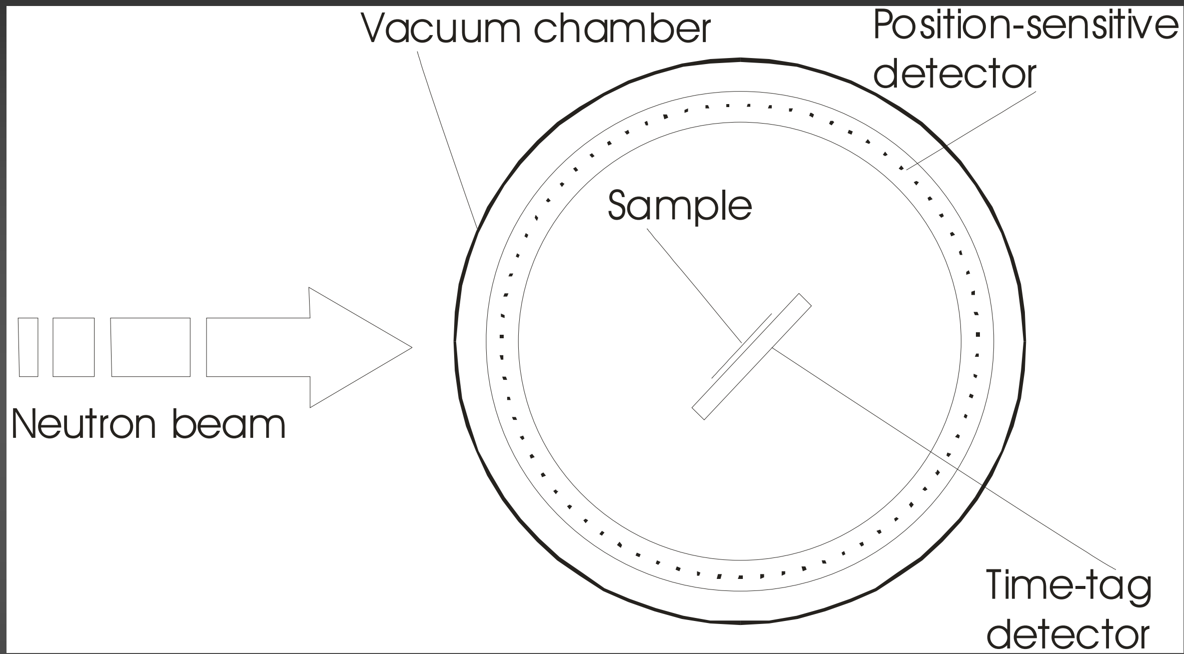


Beam	capture mode (2 mm Ø)
Scattering angle	30°
Target thickness	250 μg/cm^2
Detector radius	20 mm
Target-to-detector distance	250 mm

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

Fission studies

FF distributions in vibrational resonances



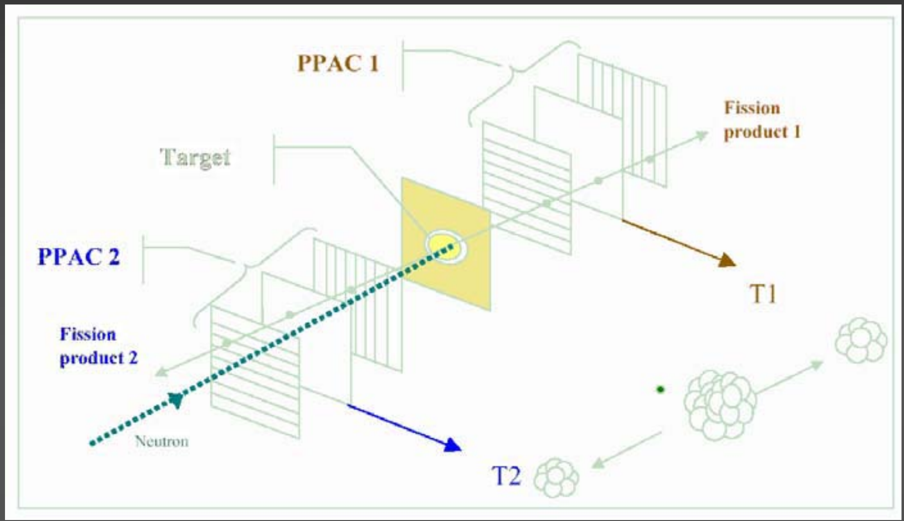
Principles:

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

<< back

Fission studies

cross sections with PPAC detectors: present setup



Measurements:

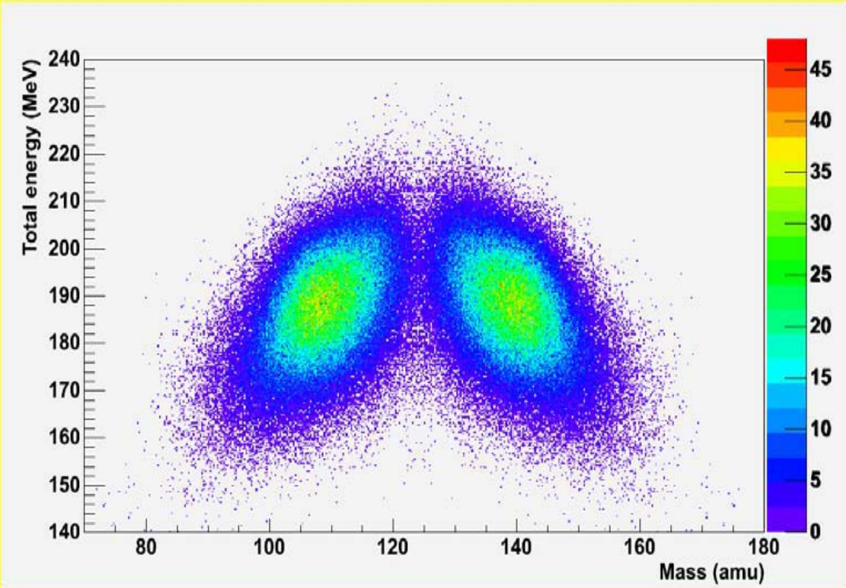
- ^{231}Pa(n,f)
- Fission fragments angular distributions (45° tilted targets) for ^{232}Th, ^{238}U and other low-activity actinides

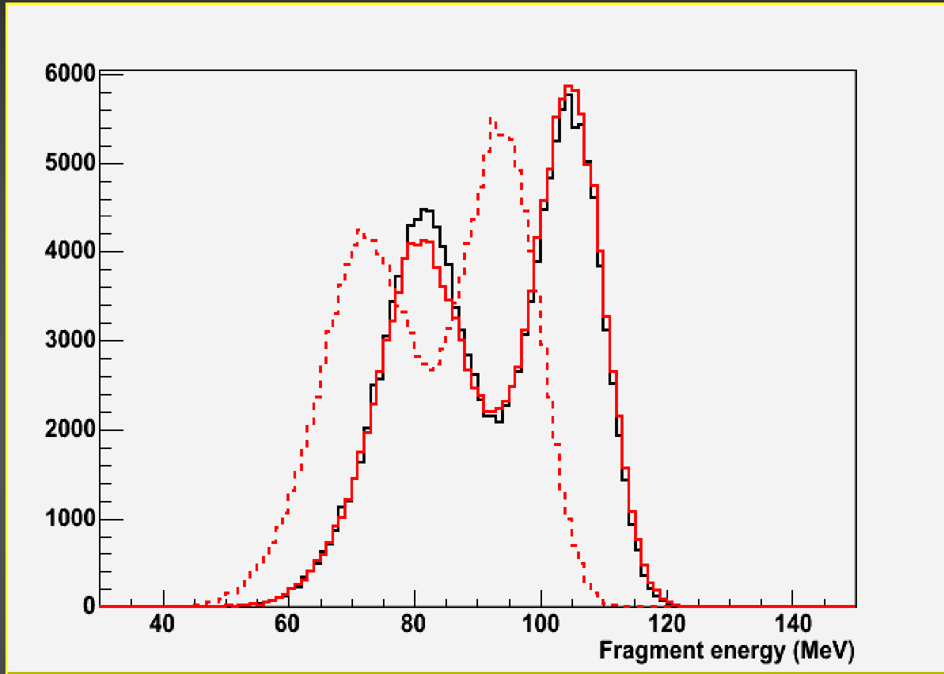
EAR-2 boost:

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

<< back

Fission studies
with twin ionization chamber





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

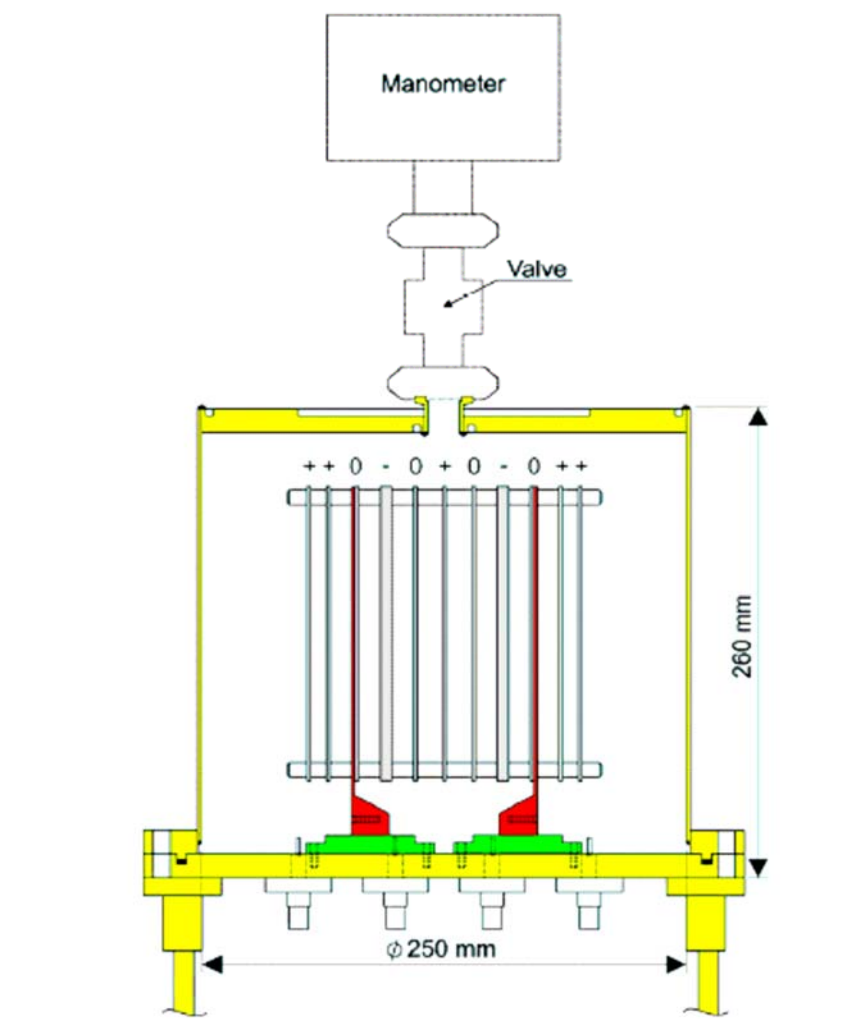
Measurements:

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

<< back

(n,p), (n,α) & (n,lcp) measurements

1. CIC: compensated ion chamber already tested at n_TOF



For n_TOF-Ph2:

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

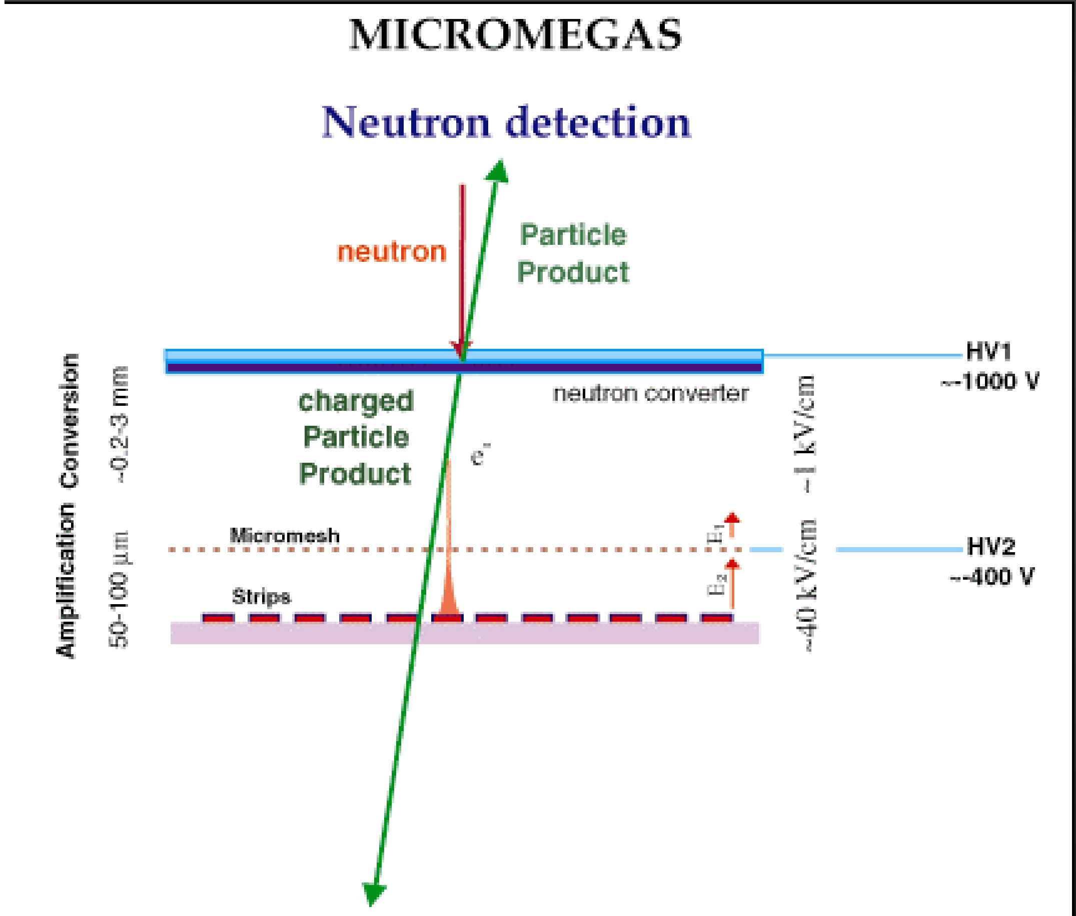
Measurements:

• ^{147}Sm(n,α) (tune up experiment)
• ^{6}LiF target for calibration

EAR-2 boost:
• approx 100 times the ORELA count rate expected
• ^{67}Zn and ^{99}Ru (n,α) measurements

(n,p), (n,α) & (n,lcp) measurements

2. MICROMEGAS
already used for measurements of nuclear recoils at n_TOF



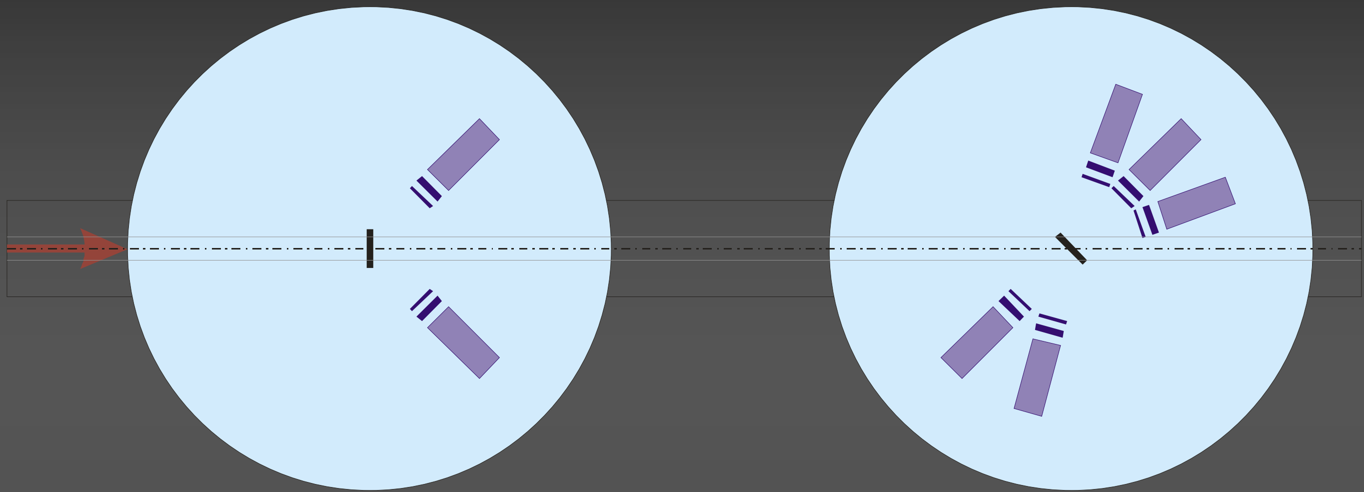
For n_TOF-Ph2:

- converter replaced by sample
- expected count rate: 1 reaction/pulse (σ=200 mb, Ø=5cm, 1μm thick)

<< back

(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, α, 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 x 10^{18} protons/sample in fission mode

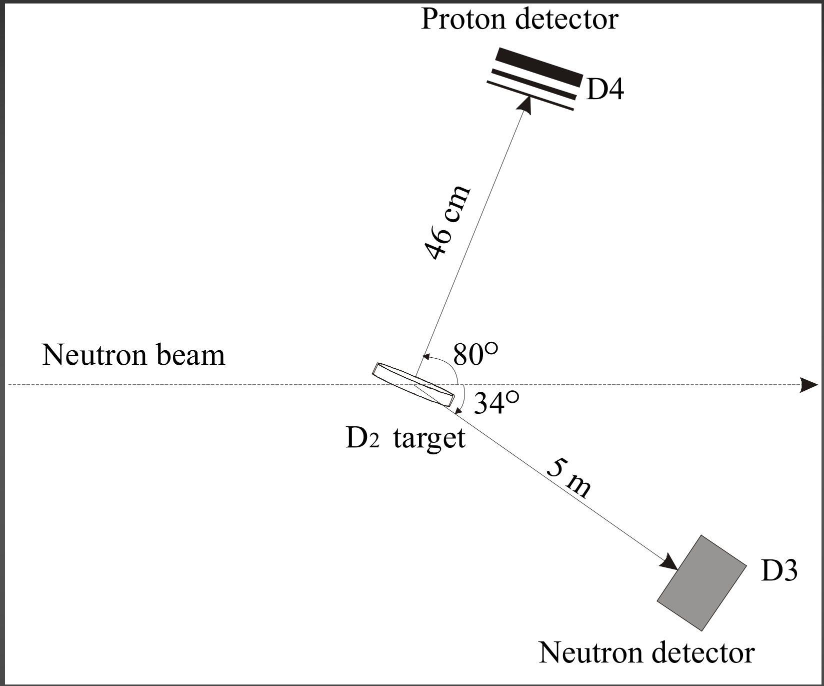
<< back

Neutron scattering reactions

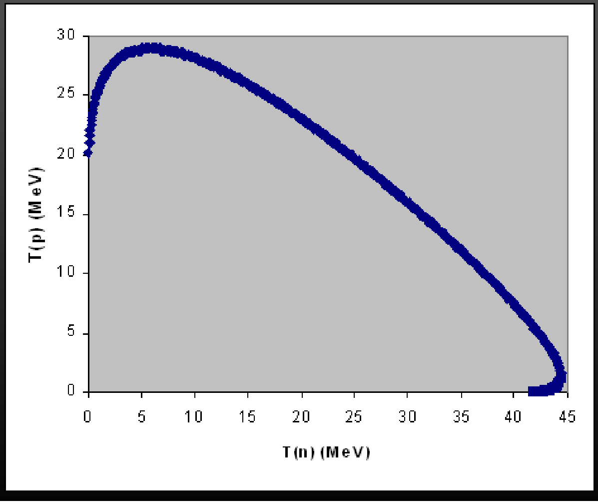
Direct n + n scattering experiment not feasible!

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

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



Neutron incident energy 30 – 75 MeV in 2.5 MeV bins

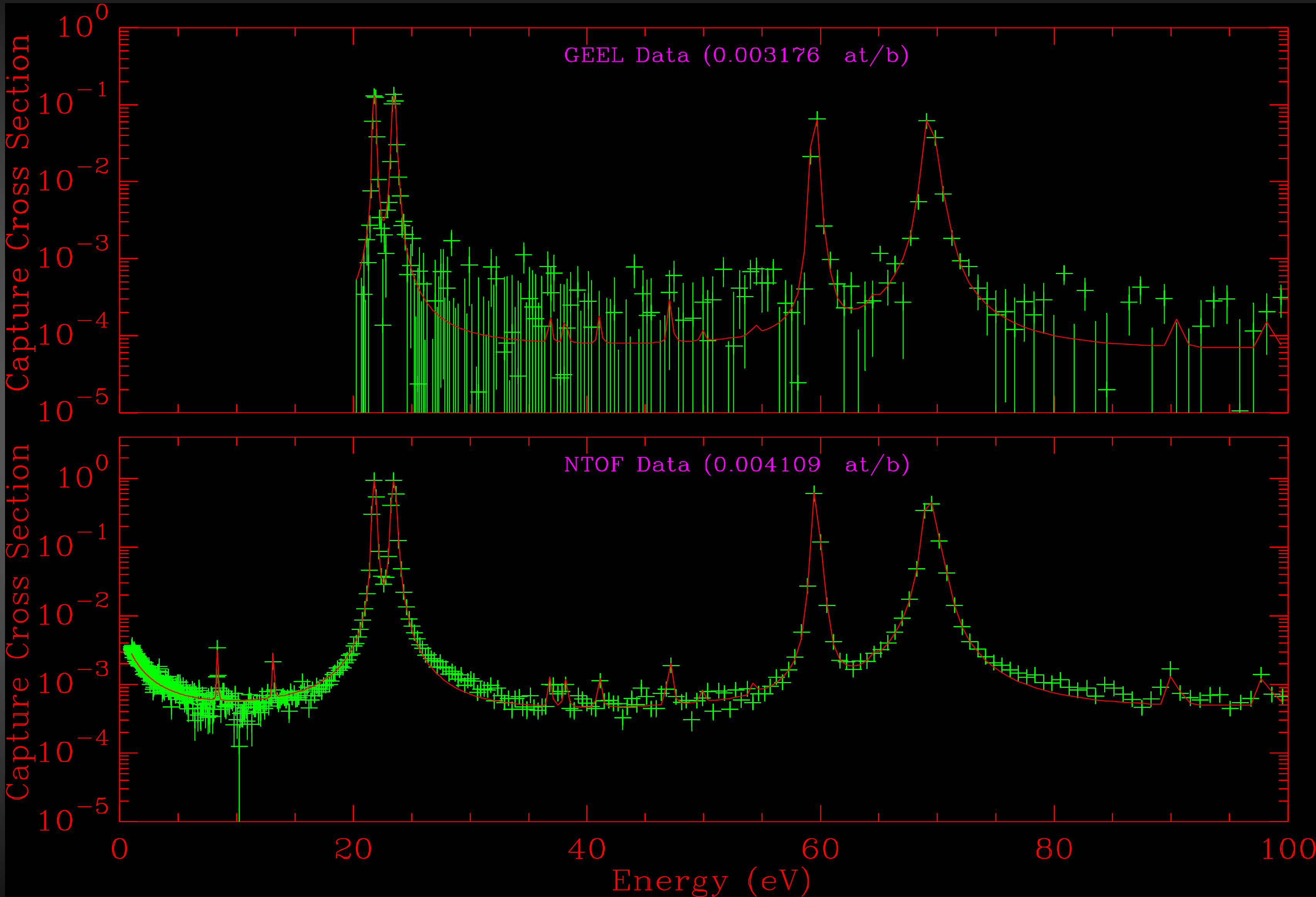


Kiematic locus of the $n + {}^2H \rightarrow n + p + n$ reaction for:
E_n = 50 MeV
$\Theta_n = 20^\circ$, $\Phi_n = 0^\circ$
$\Theta_p = 50^\circ$, $\Phi_p = 180^\circ$

<< back

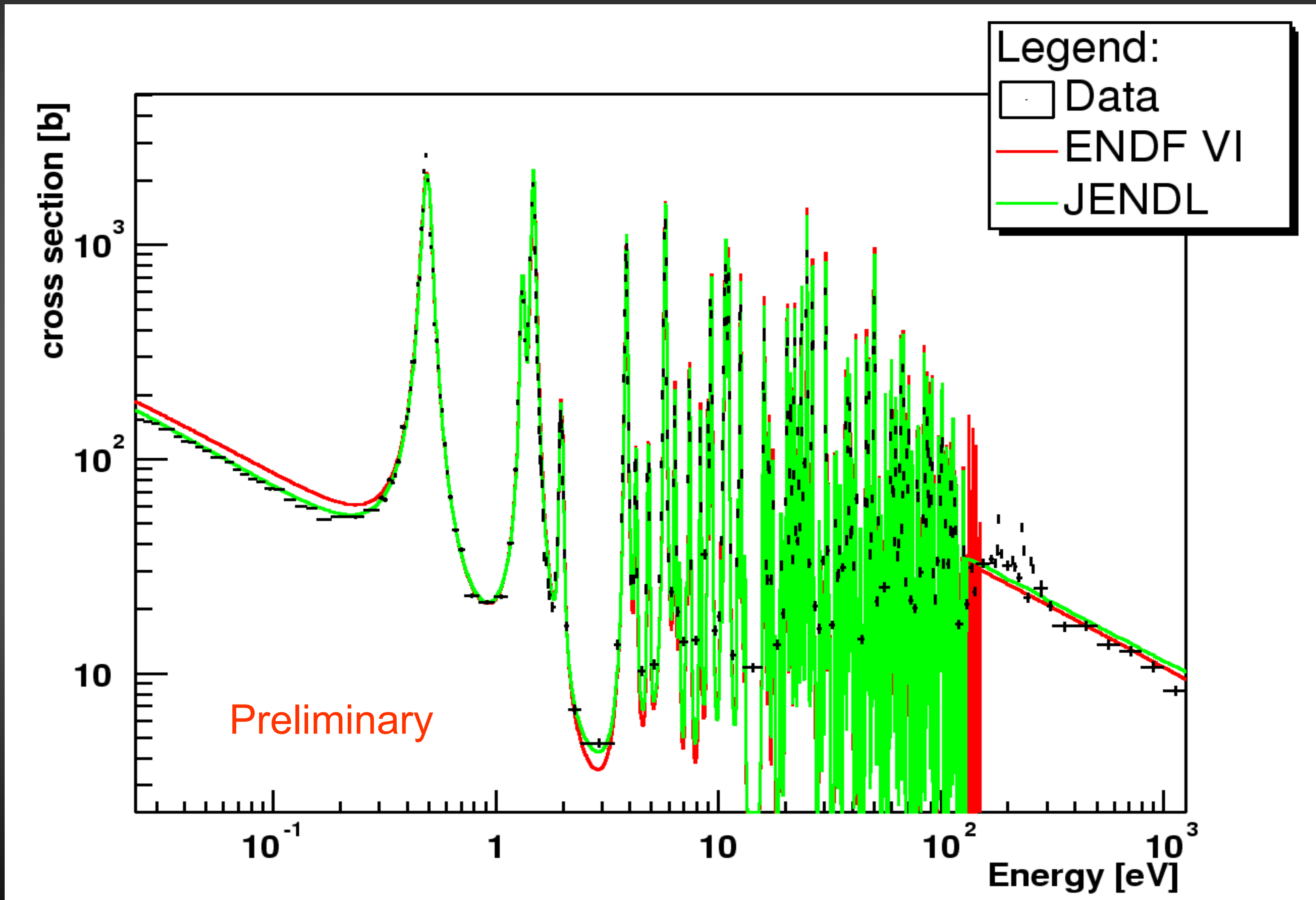
<< back

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



Source: L Leal, IAEA CRP meeting, December 2004

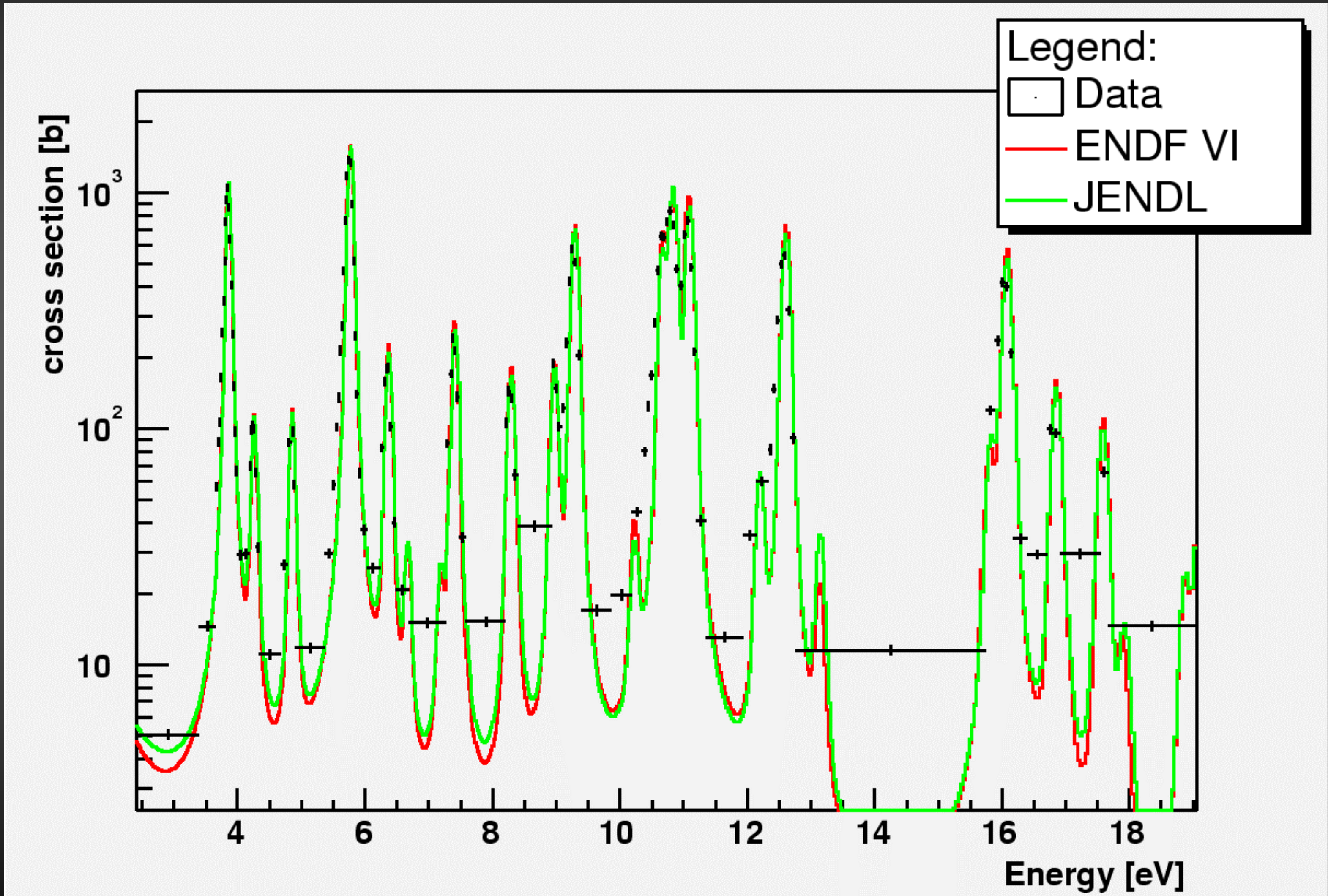
$^{237}Np(n,\gamma)$ at LANSCE



(Analysis by E.I. Esch and R. Reifarth)

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

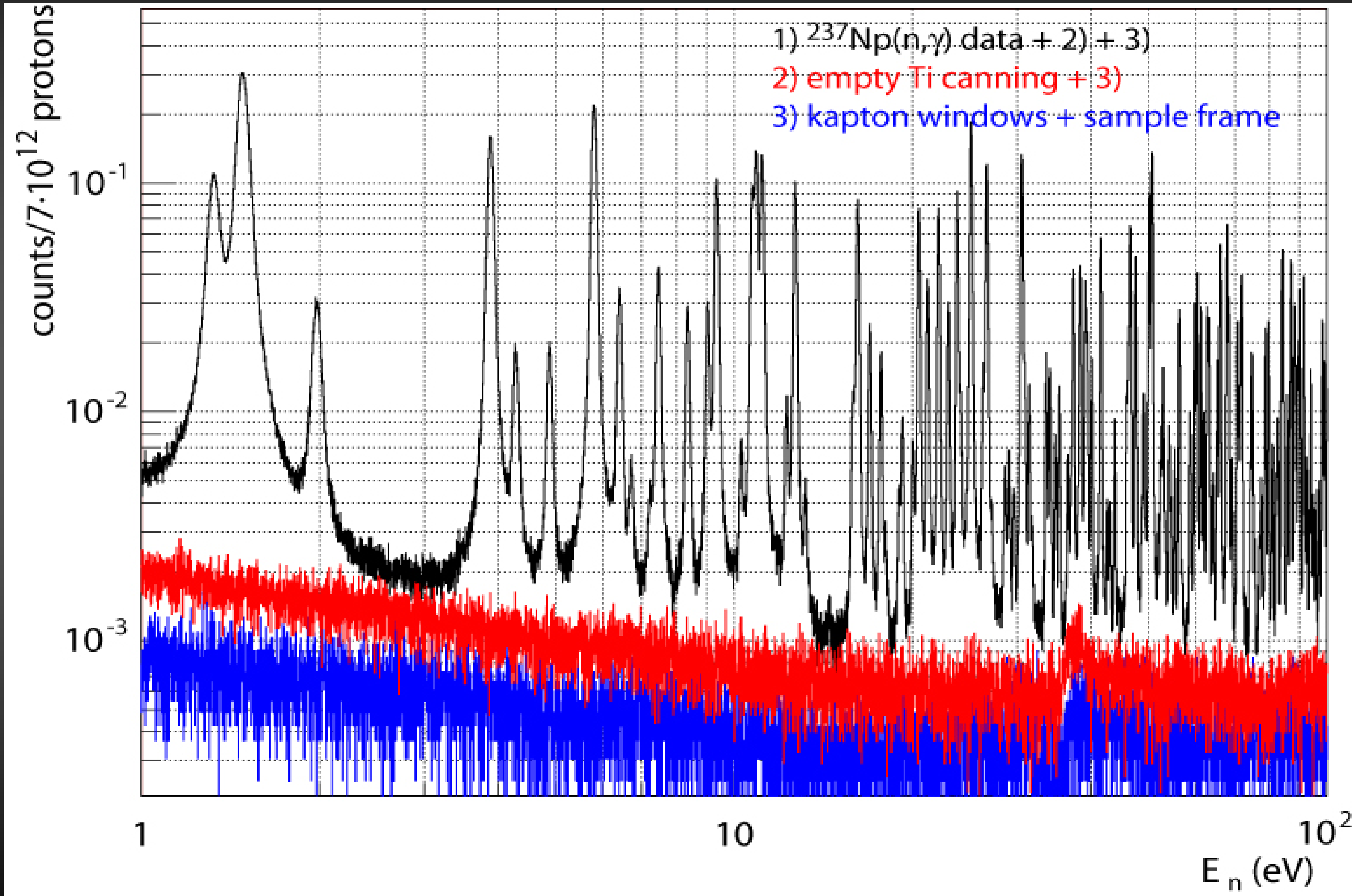
$^{237}Np(n,\gamma)$ at LANSCE



(Analysis by E.I. Esch and R. Reifarth)

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

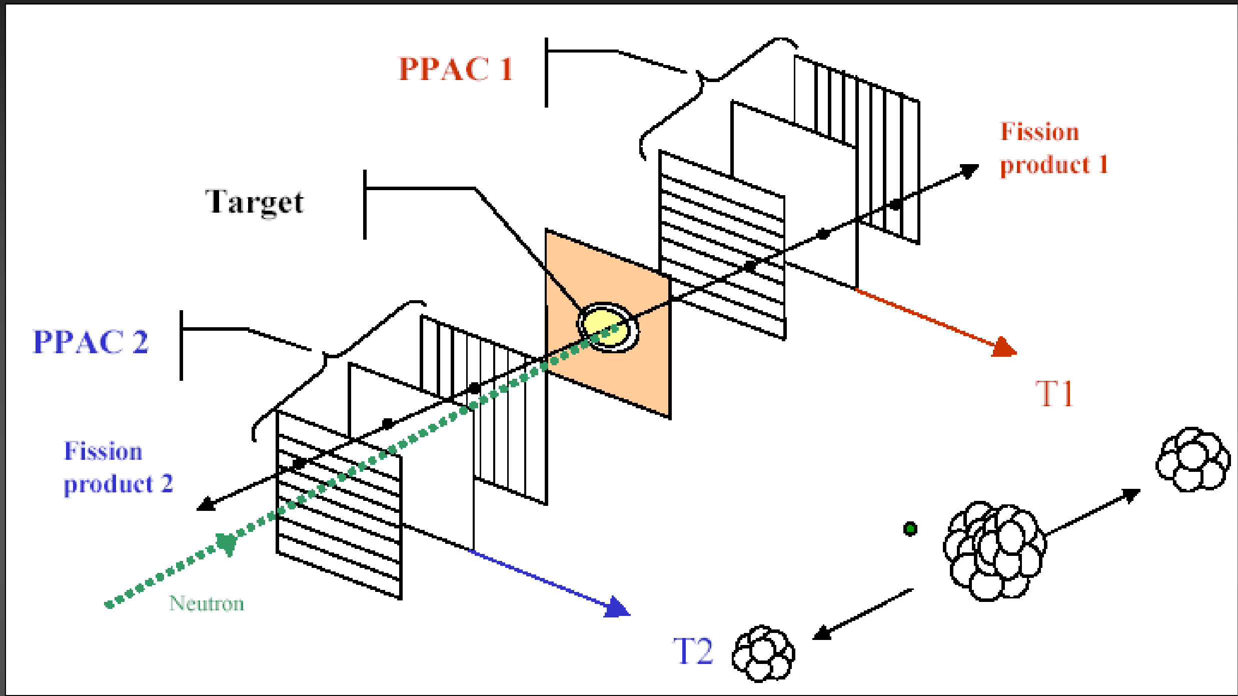
$^{237}Np(n,\gamma)$ at n_TOF

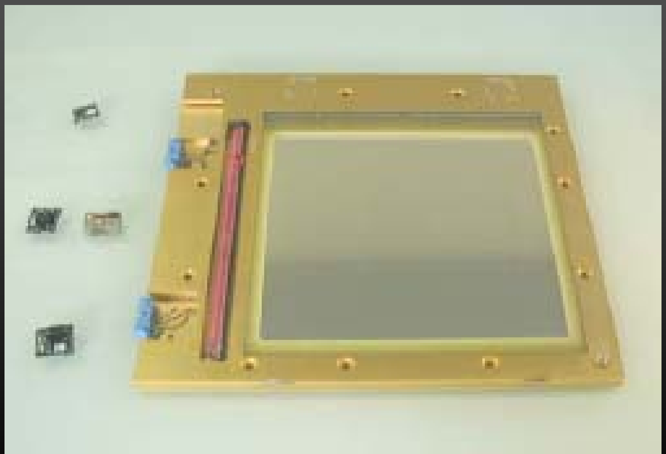


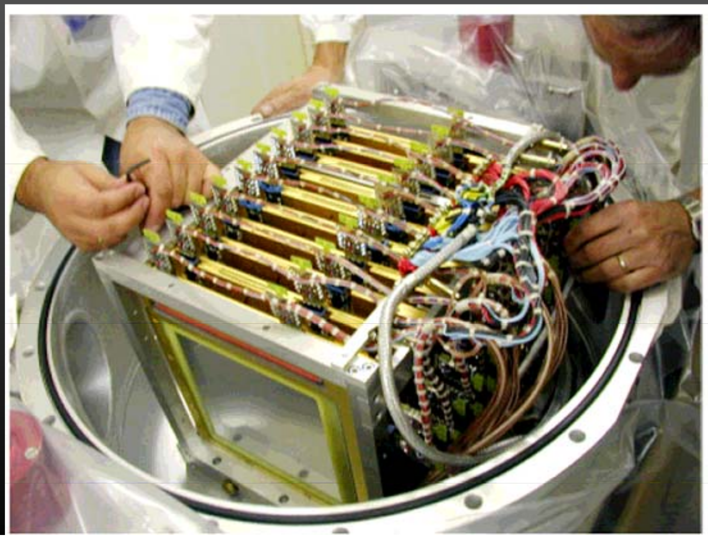
< back

Parallel Plate Avalache Counters (PPACs)

- 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 $\mu g/cm^2$
- Backing thickness : 0.1 μm (Al)
- : 1.5 μm (Mylar)
- Fission event identification: T2 in coincidence with T1







IN2P3 (IPN Orsay)

- position-sensitive!

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