Nuclear Level Density and Photon Strength Function Measurements at n_TOF.

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2nd WORKSHOP on Nuclear Level Density and Gamma Strength Function.

Oslo 11-15 May 2009

OUTLINE

- **n_TOF Collaboration and Facility.**
- How to get fundamental info in **Nuclear Structure.**
- n_TOF-Phase 1: **Results on Nuclear Level Densities.**
- Preliminary Results on **Photon Strength Function** and **Fission**.
- 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]

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

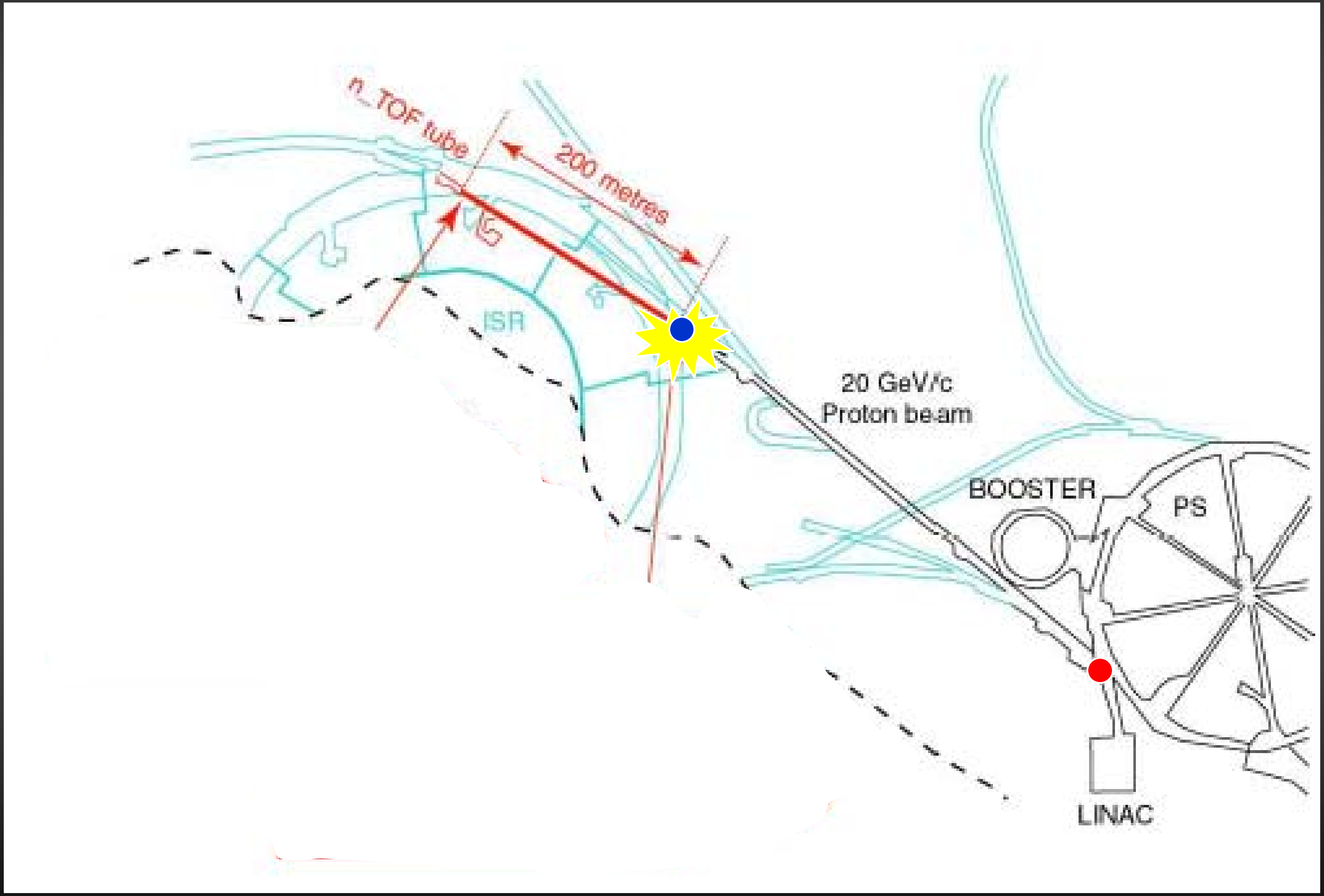
- $^{233,234,235,236,238}U$
- ^{232}Th
- ^{209}Bi
- ^{237}Np
- $^{241,243}Am$, ^{245}Cm

- **n_TOF is a well trained collaboration; so far 18 measurements of capture and fission cross sections.**
- **n_TOF has built several detectors (SiMon, C_6D_6, TAC, PPAC, FIC) and contributed to the commissioning of the neutron beam.**
- Measurements of neutron cross sections relevant for Nuclear Waste Transmutation and related Nuclear Technologies
  - Th/U fuel cycle (capture & fission)
  - Transmutation of MA (capture & fission)
  - Transmutation of FP (capture)
- Cross sections relevant for Nuclear Astrophysics
  - s-process: branchings
  - s-process: presolar grains
  - r-process: Residual Method
- Neutrons as probes for fundamental Nuclear Physics
  - Nuclear level density & n-nucleus interaction
  - Photon Strength Function

The n_TOF facility at CERN

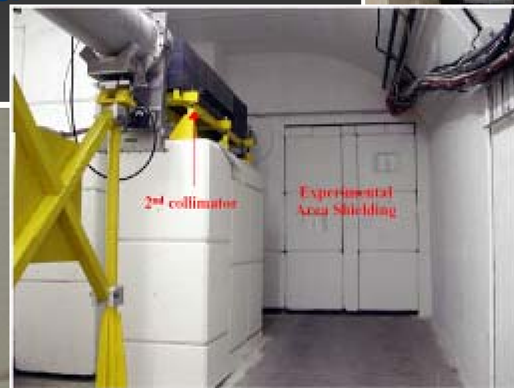
somewhere around here

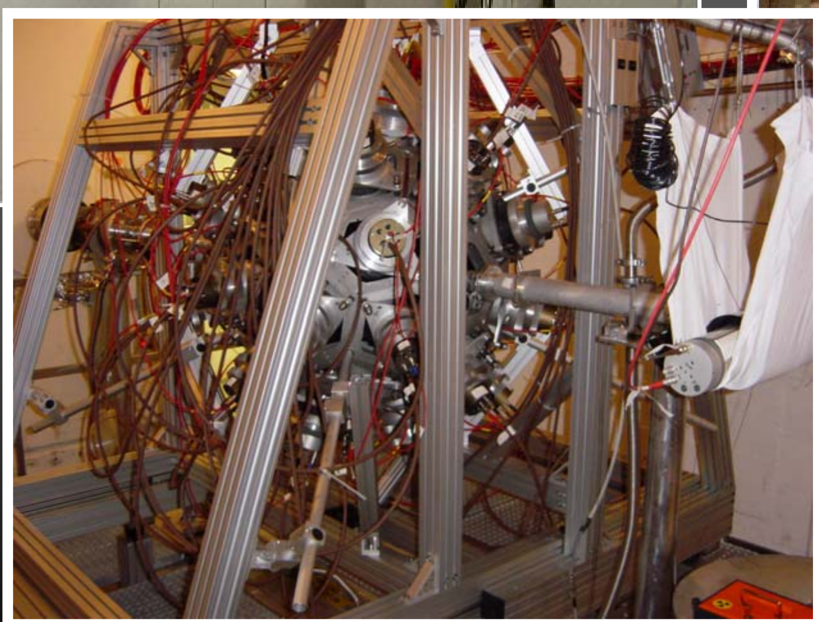
The n_TOF facility at CERN

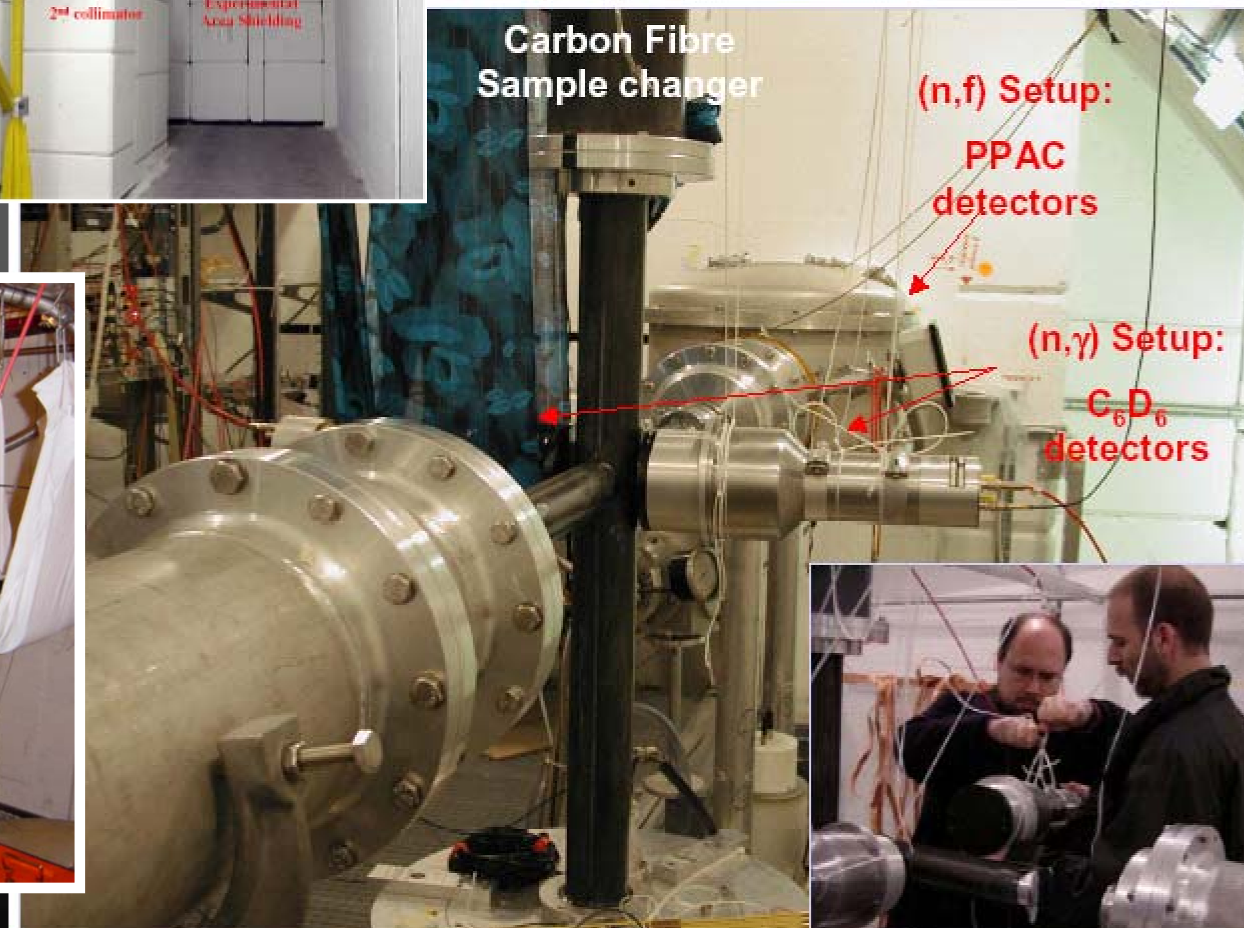


The real world

- n_TOF commissioned in 2001-2002

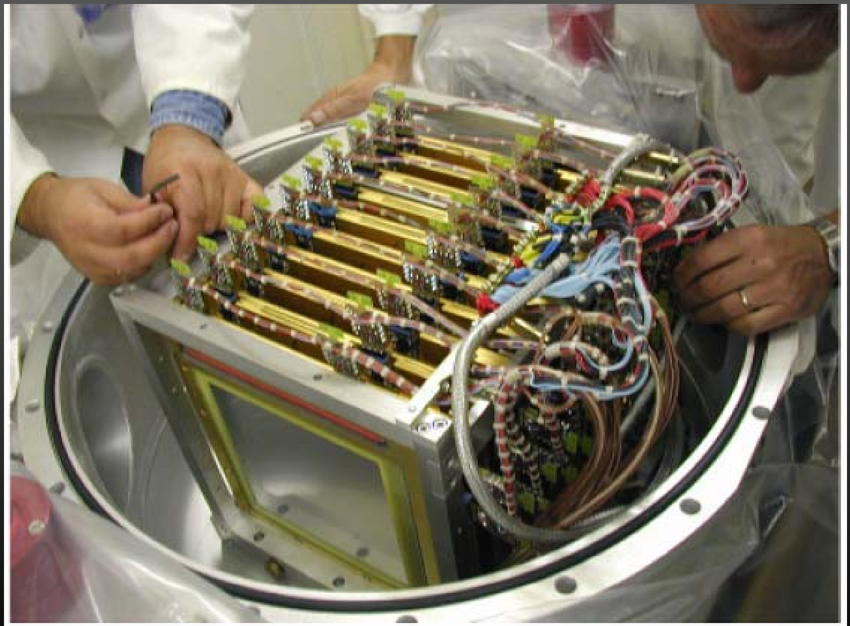


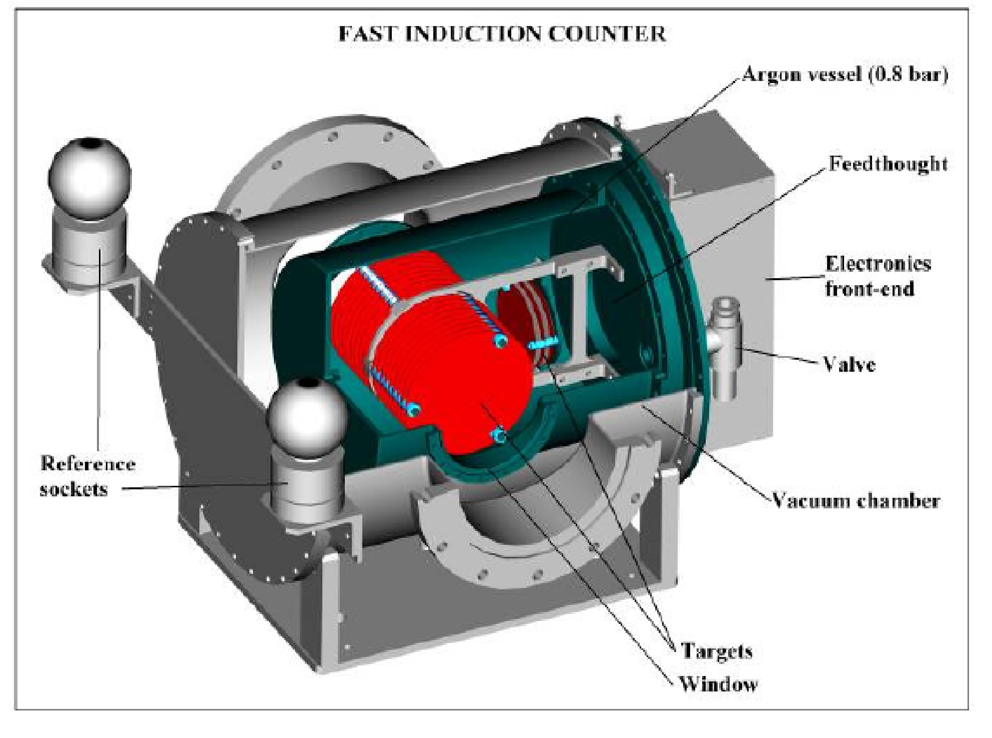




n_TOF fission detectors

- 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





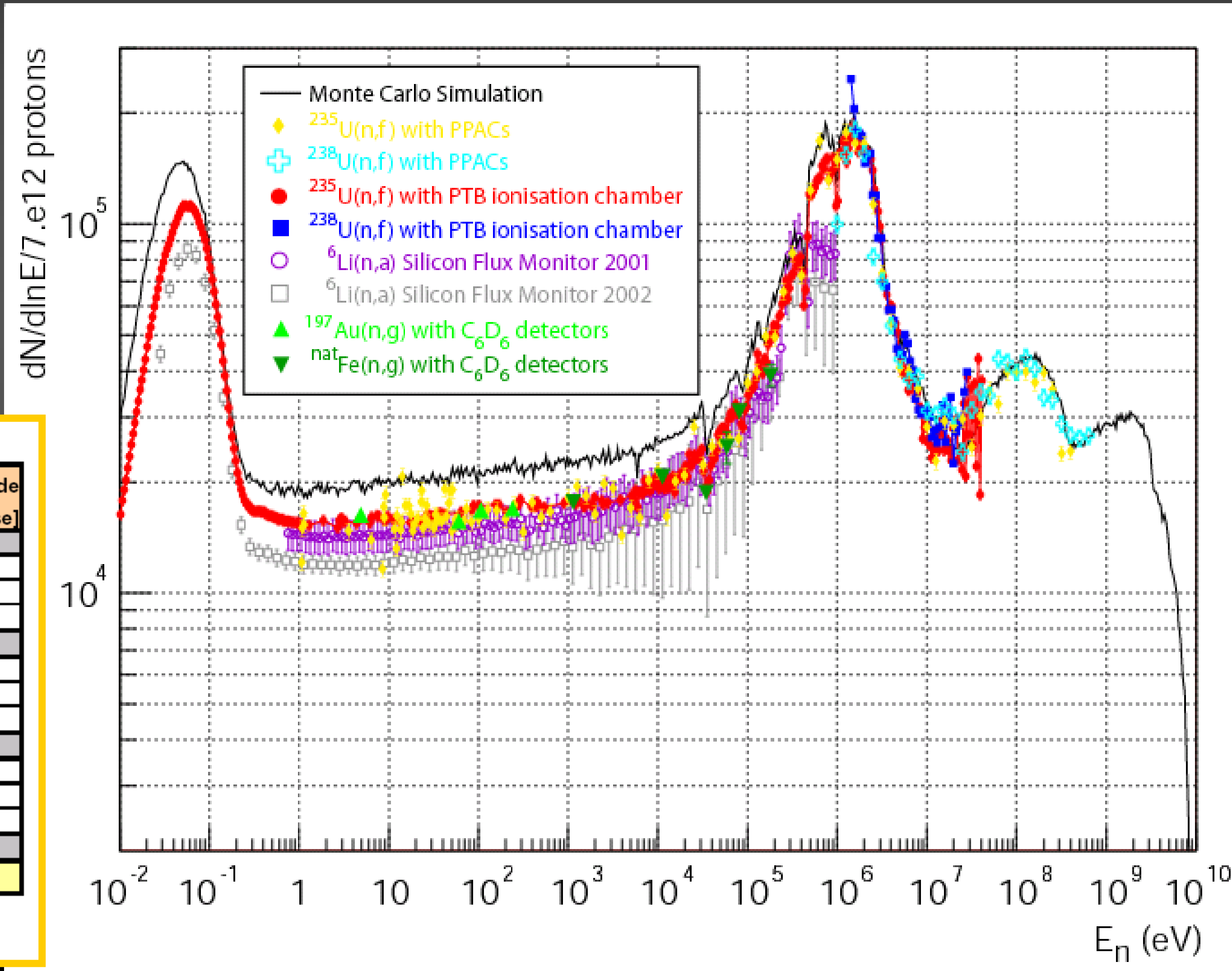
- Gas: Ar (90%) CF_4 (10%)
- Gas pressure : 720 mbar
- Electric field : 600 V/cm
- Gap pitch : 5 mm
- Electrode diameter : 12 cm
- Electrode thickness: 15 μm (Al)
- Deposit thickness : 125 $\mu m/cm^2$
- Backing thickness : 100 μm (Al)
- Window thickness : 125 μm

n_TOF beam characteristics

- the neutron flux for capture

2nd collimator ϕ=1.8 cm (capture mode)

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

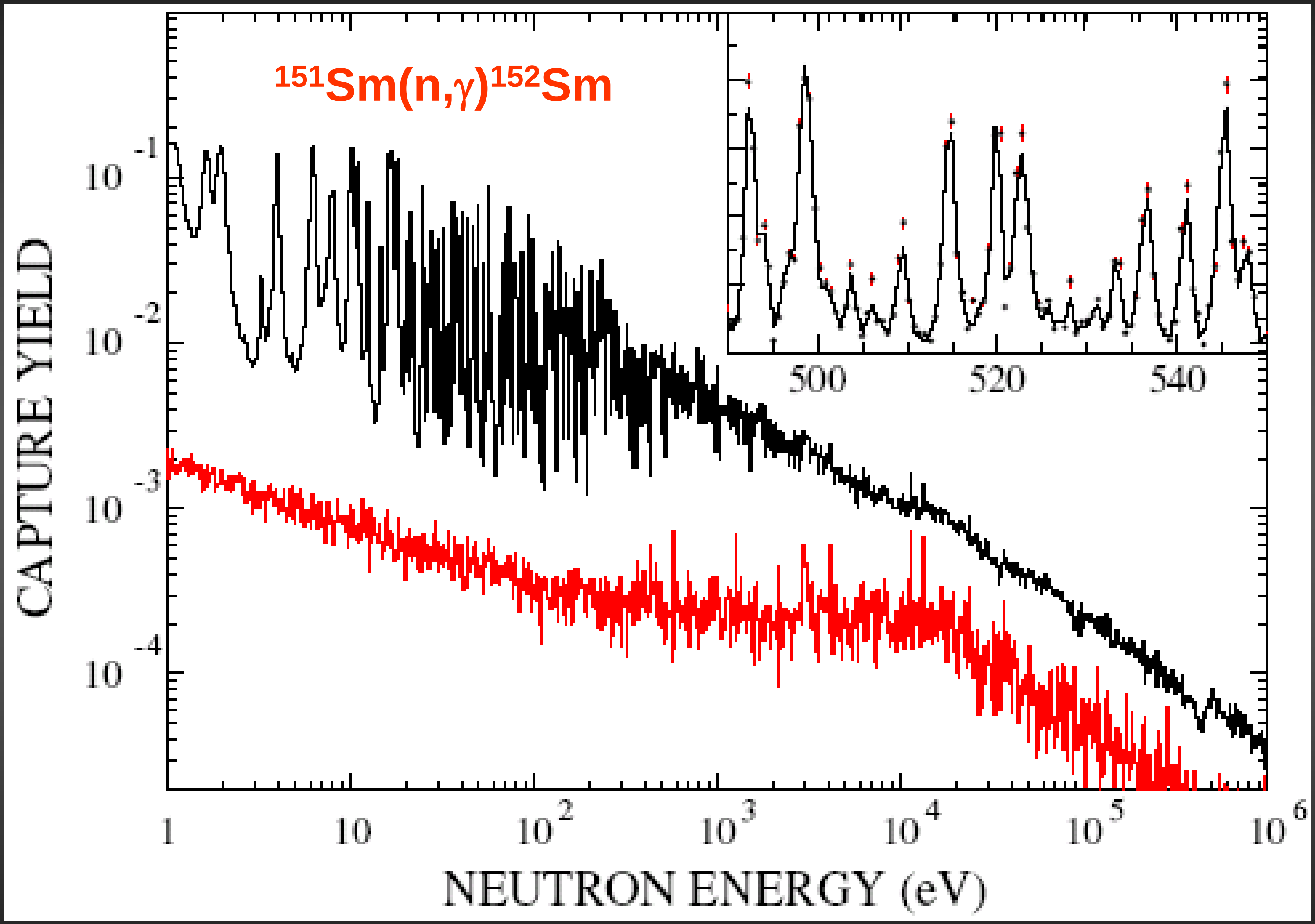


The neutron fluence in EAR-1

Energy range	Uncollimated [n/pulse/cm2]	Capture mode [n/pulse]	Fission mode [n/pulse]
< 1 eV	**2.0E+05**	**3.1E+05**	**2.0E+06**
1 eV - 10 eV	2.7E+04	4.5E+04	2.9E+05
10 eV - 100 eV	2.9E+04	4.7E+04	3.1E+05
100 eV - 1000 eV	3.0E+04	5.1E+04	3.3E+05
1 eV - 1 keV	**8.6E+04**	**1.4E+05**	**9.3E+05**
1 keV - 10 keV	3.2E+04	5.4E+04	3.6E+05
10 keV - 100 keV	3.9E+04	7.1E+04	4.7E+05
100 keV - 1000 keV	1.1E+05	2.3E+05	1.5E+06
1 keV - 1 MeV	**1.8E+05**	**3.5E+05**	**2.3E+06**
1 MeV - 10 MeV	8.3E+04	2.4E+05	1.7E+06
10 MeV - 100 MeV	2.8E+04	7.2E+04	5.1E+05
> 100 MeV	4.4E+04	1.2E+05	5.6E+05
1 MeV - > 100 MeV	**1.6E+05**	**4.4E+05**	**2.7E+06**
Total	**6.2E+05**	**1.2E+06**	**8.0E+06**

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

(n,γ) experiments in RRR



Statistical Analysis

Resonance analysis

E_i , Γ_γ, Γ_n , Γ_f

Statistical analysis

Level spacing $(E_{i+1} - E_i)$: $\mathbf{s_i}$

Reduced neutron width : Γ^0_n

Determination of l and J .

Statistical properties

s : *Wigner*

Γ^0_n : *Porter-Thomas* (P-T) distribution

Γ_γ : *Gaussian*

Statistical parameters

Average level spacing : $<D_0>$

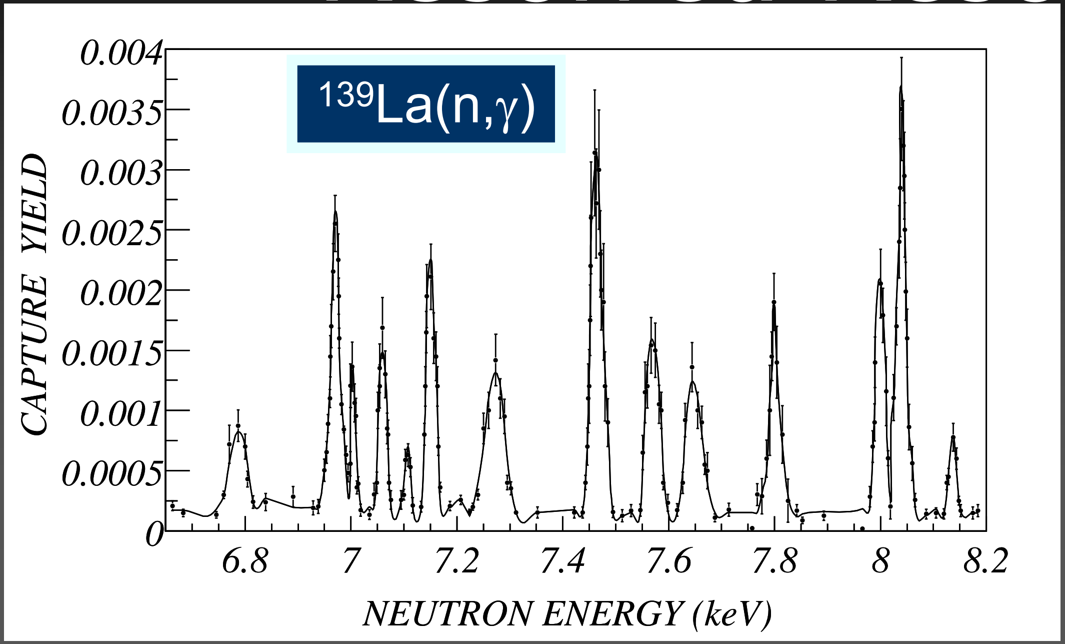
Average radiative width : $<\Gamma_\gamma>$

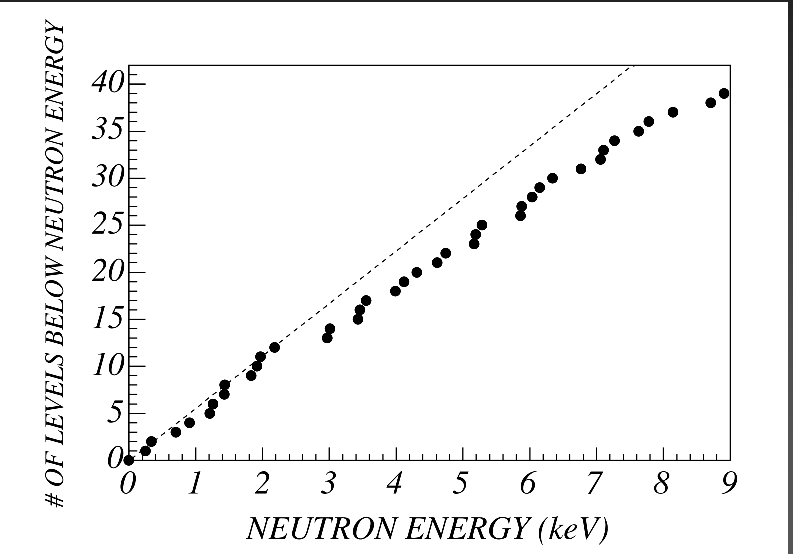
(Average reduced neutron width : $<g\Gamma^0_n>$)

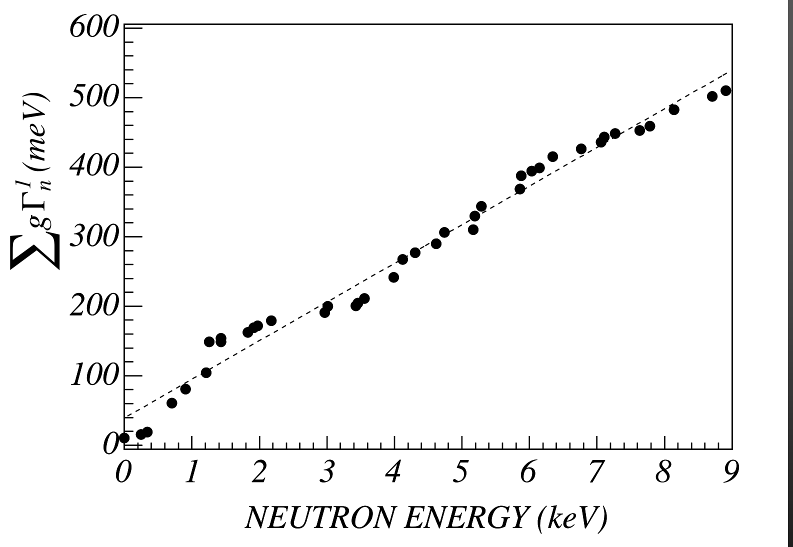
Neutron strength function : $S_0 = \frac{< g\Gamma_n^0 >}{< D_0 >}$

Cross section calculations with statistical model: e.g. Hauser-Feshbach.

Resolved Resonance Region







The data fitted by mean of R-Matrix Code (SAMMY, REFIT)

Provide resonance parameters: E_R, Γ_n, Γ_γ, Γ_f (width) related to XS:

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

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

The optimal fit of the resonances is fundamental for two reasons:

to determine E_R and the average spacing.

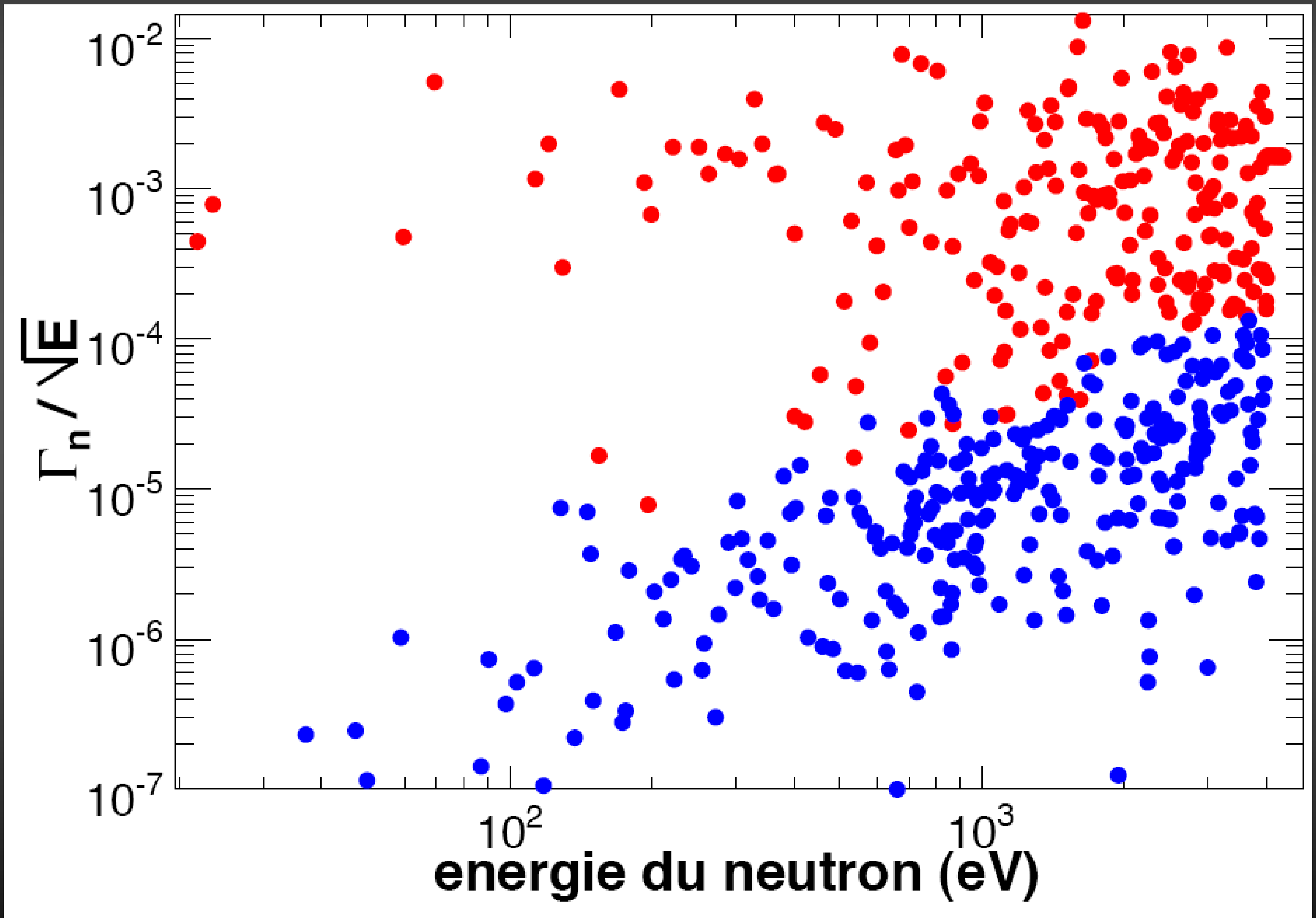
to estimate Γ_n, Γ_γ, Γ_f ,

to determine the l and J and the strength: S_0, S_1 ….

Statistical Analysis: Quantum Numbers

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

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



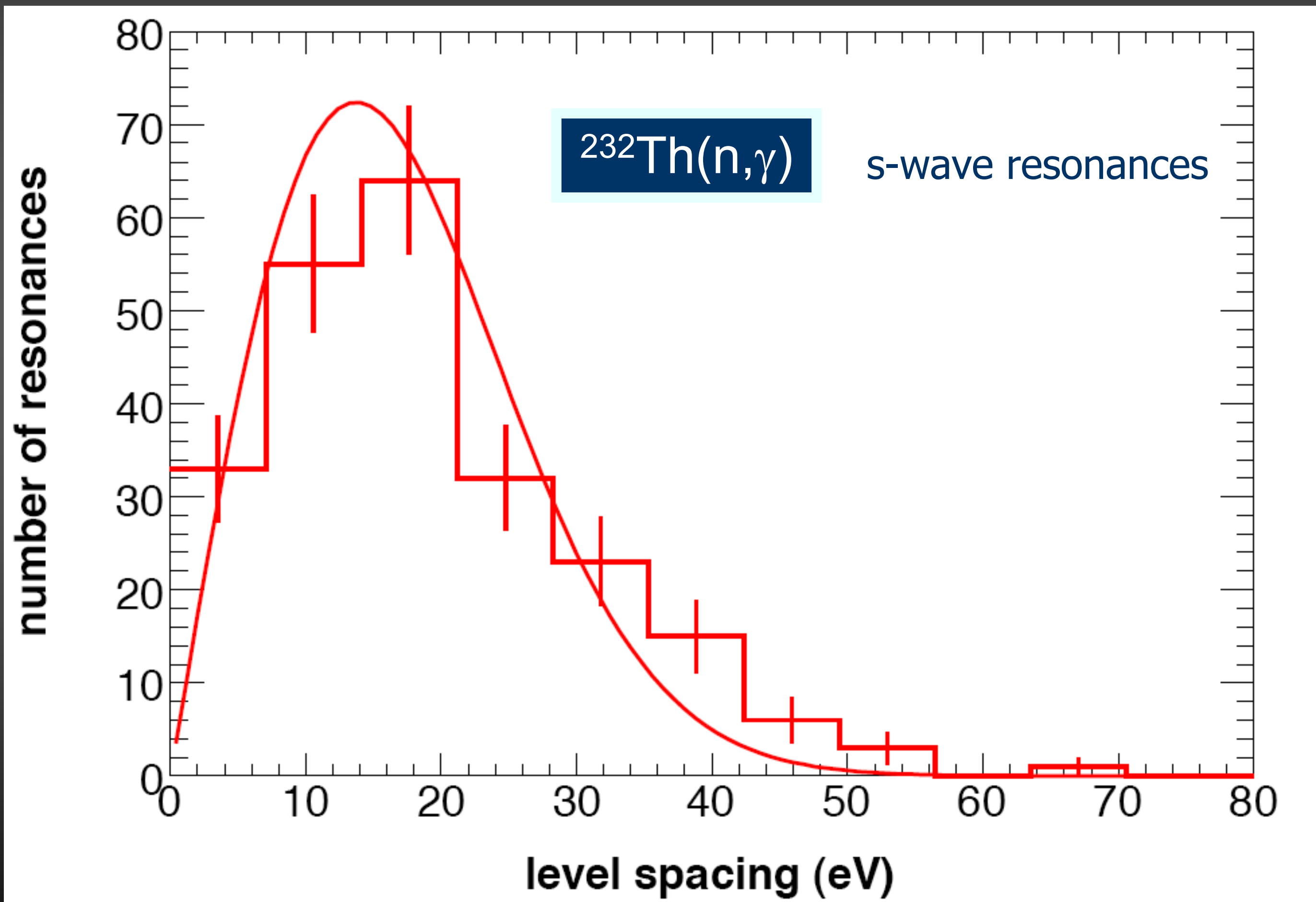
This kind of analysis allows us to determine the s-wave resonance, p-wave resonance etc.. and therefore determine two quantum numbers: *l* and *J*.

Wigner Distribution

$$P(s) = \frac{\pi s}{2} e^{-\frac{\pi s^2}{4}}$$

$$s \equiv \frac{s_i}{\langle D_0 \rangle}$$

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



Distribution of Average Spacing of the Nuclear Levels is directly related to the Gaussian Orthogonal Ensemble.

(Wigner Theory).

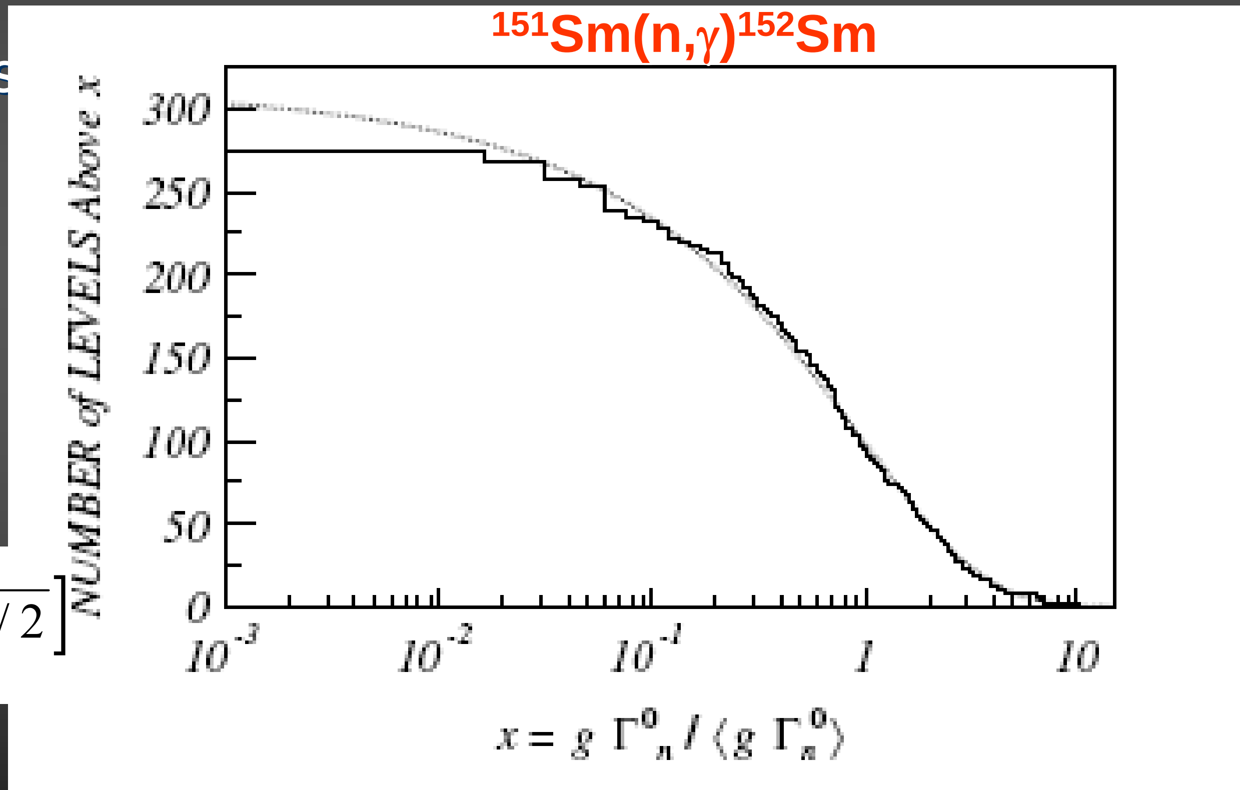
Porter-Thomas Distribution

- Number of Levels Missing related to the reduced neutron width, $\Gamma^0{}_n$.
- $\Gamma^0{}_n$ follows a Porther-Thomas distribution.

$$x \equiv \frac{g\Gamma_n}{\langle g\Gamma_n \rangle}$$

$$f(x) = \frac{1}{\sqrt{2\pi x}} e^{-\frac{x}{2}}$$

$$N(x) = N_0 \int_x^{\infty} f(x')dy = N_0 \left[1 - erf\sqrt{x/2}\right]$$

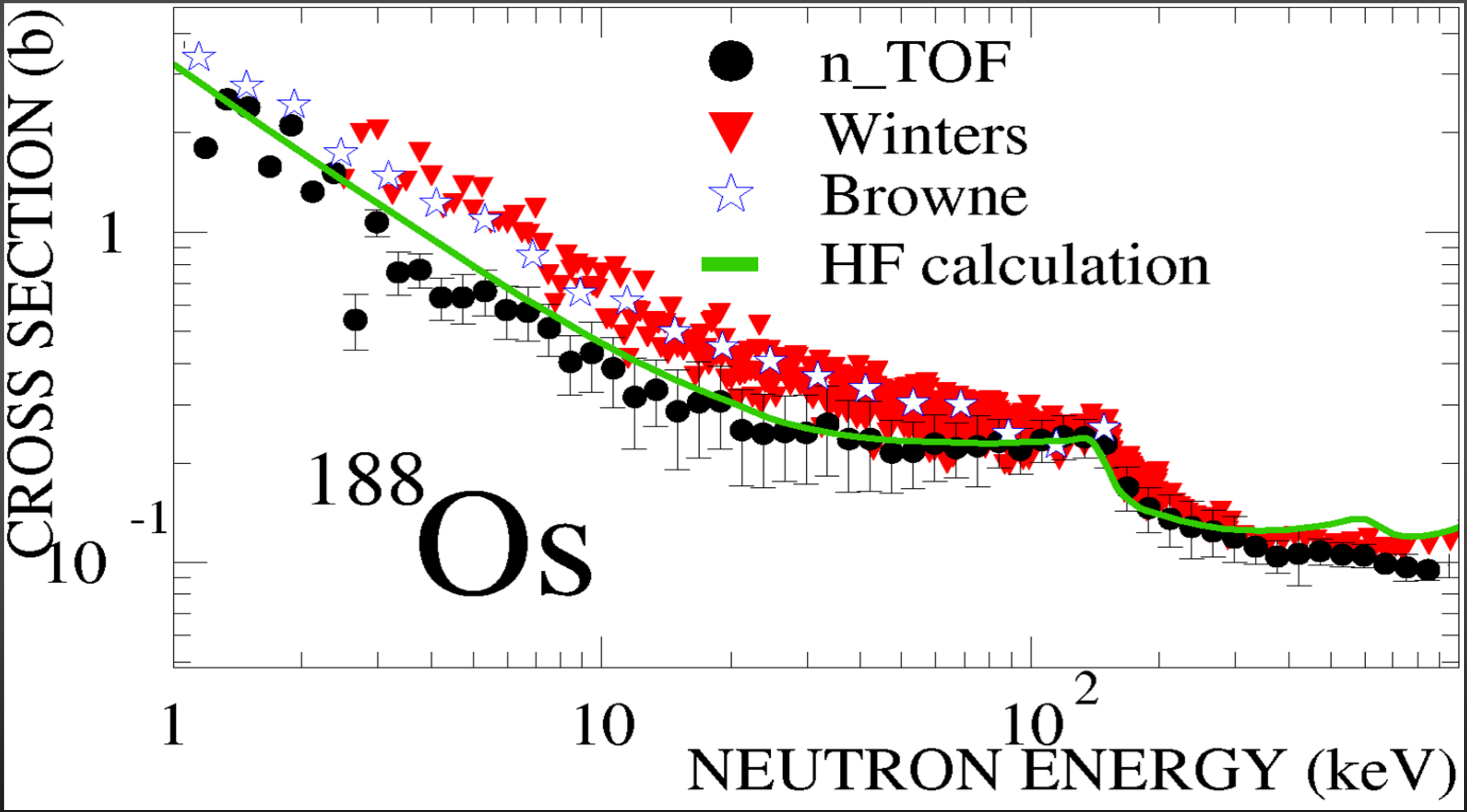


Unresolved Resonance Region

At higher energies (!?) the levels are not resolved.

The levels begin to be missed (Unresolved Resonance Region).

Experimental Difficulties at low energy (< 100 eV) due to Doppler Broadening, at higher energy due to the neutron beam resolution function.



In Statistical Model Calculation important ingredients are the Nuclear Level Density and the Widths.

Statistical Analysis: Osmium

Number of resonances

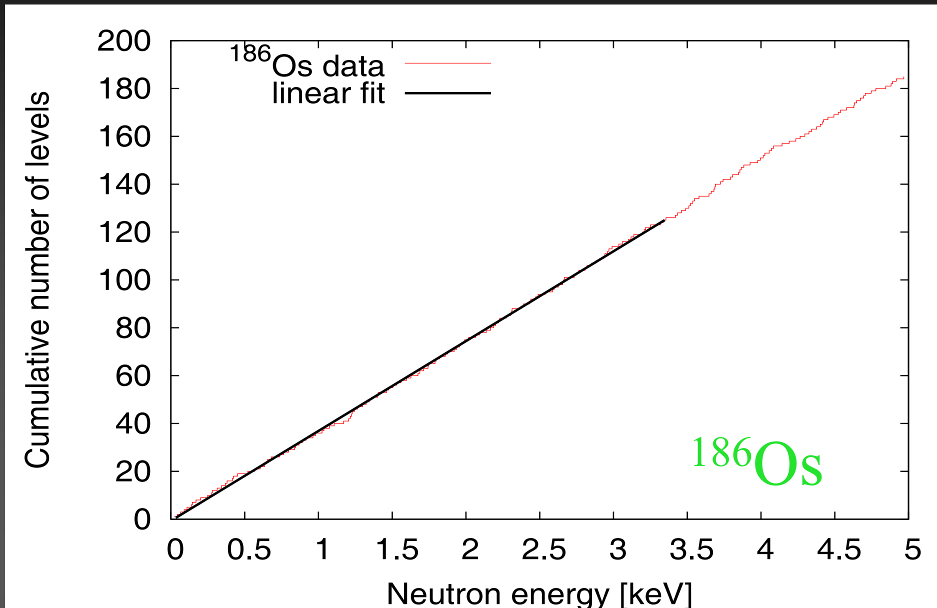
	Resonance analysis	Statistical analysis
	Analyzed, (Emax)	Analyzed, (Emax)
^{186}Os	186, (5.0 keV)	126 , (3.4 keV)
^{187}Os	463, (3.0 keV)	327, (2.0 keV)*
^{188}Os	199, (8.0 keV)	125, (5.0 keV)

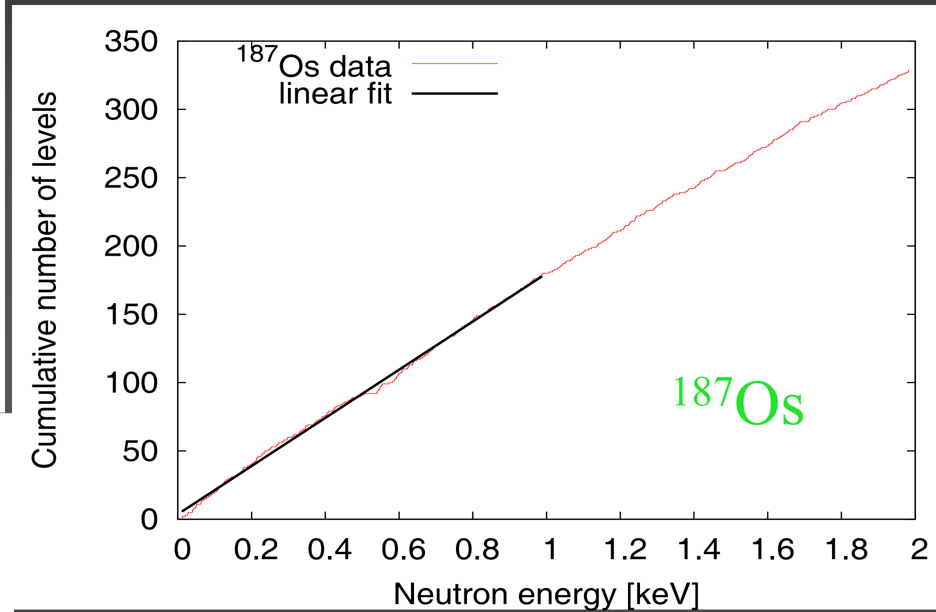
* For $\langle D_0 \rangle$, 179 (1 keV)

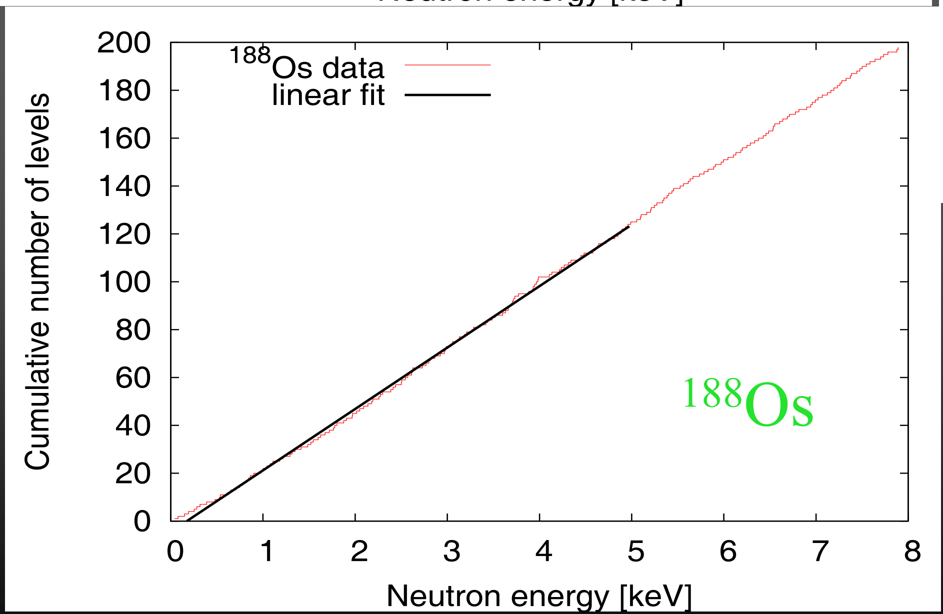
Preliminary data from K. Fuji

Stair case plot

Cumulative number of resonances



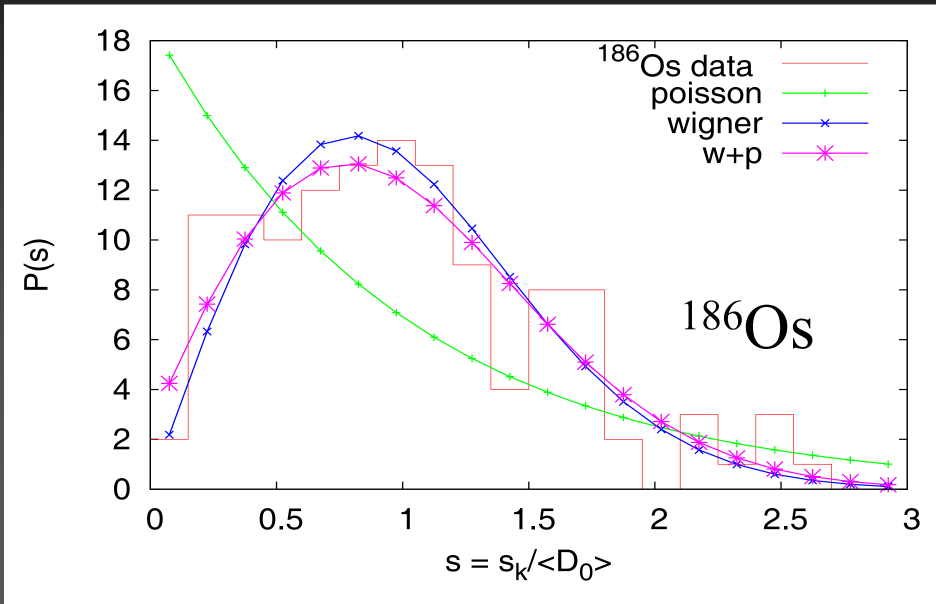


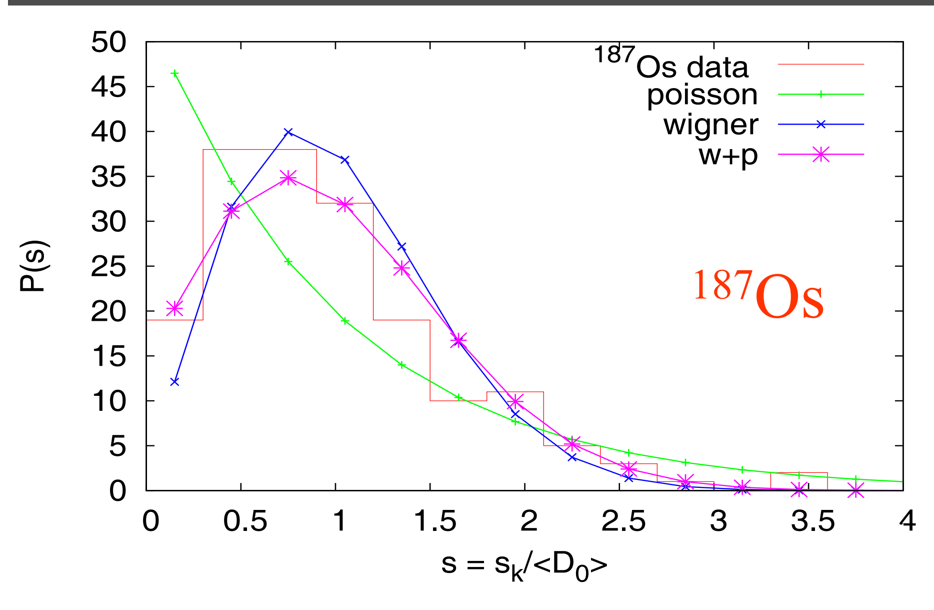


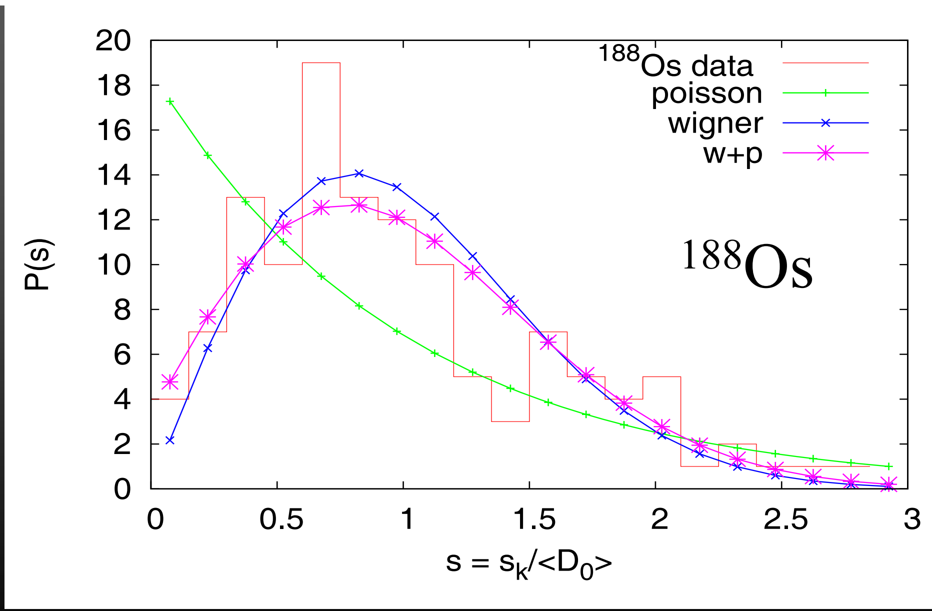
Data, linear fit

Inverse slope → Average level spacing ($\langle D_0 \rangle$)

Level spacing Wigner Distribution



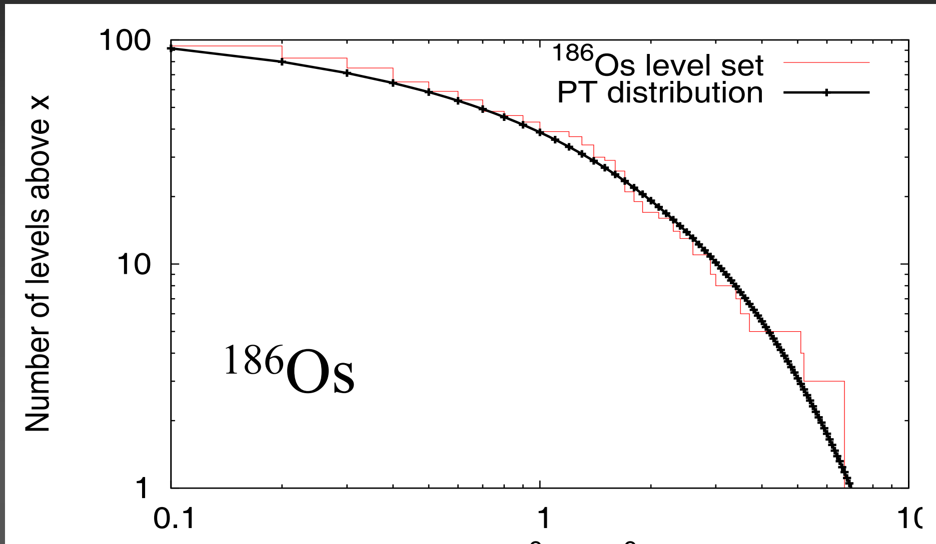


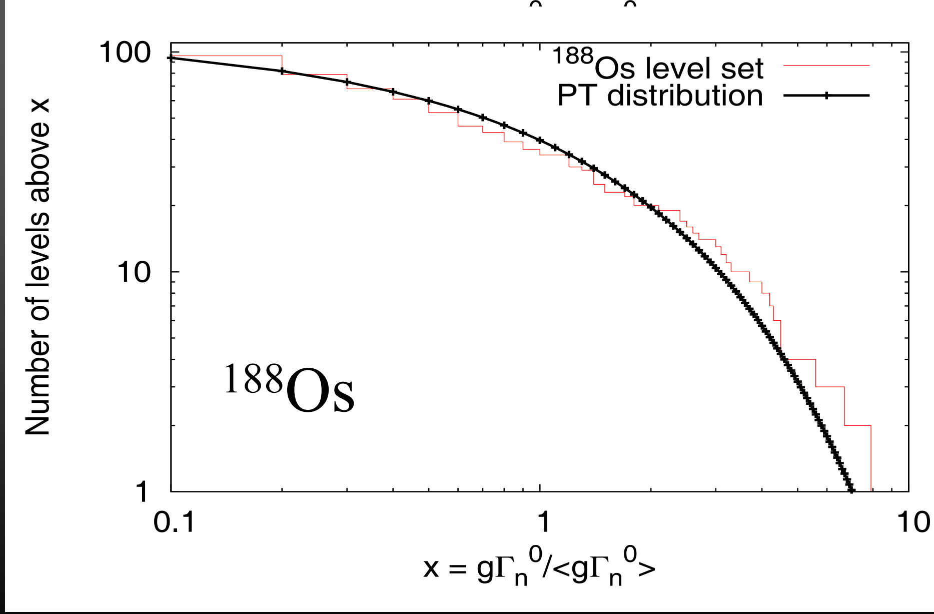


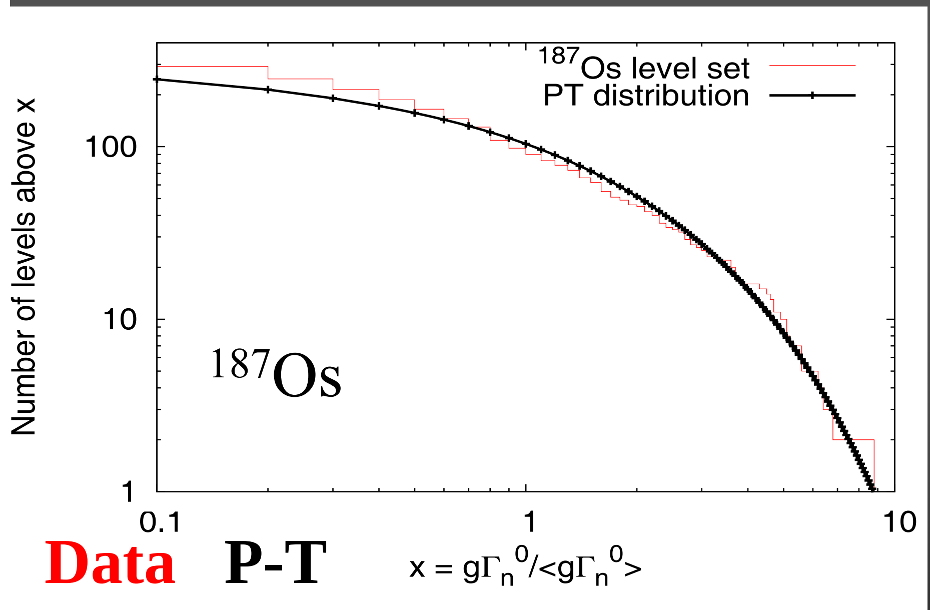
Data, Wigner

Good agreements.

Reduced neutron width ;
P-T distribution (integrated)







Good agreements.

→ Average reduced neutron width $\langle g\Gamma^0 n\rangle$

Statistical parameters

n_TOF

(present analysis)

	D_0[eV]	$<\Gamma^0_\gamma>$ [meV]	$S_0(\times10^{-4})$	$<g\Gamma^0_n>$[meV]
^{186}Os	26.6 ± 1.3	50.0 ± 1.5	2.33 ± 0.32	6.2 ± 0.7
^{187}Os	5.7 ± 0.1	61.0 ± 1.7	3.51 ± 0.29	2.0 ± 0.2
^{188}Os	39.0 ± 0.5	52.0 ± 1.8	2.69 ± 0.36	10.5 ± 1.5

Browne (1981)

Phys.Rev **C23**, 1434

	D_0[eV]	$<\Gamma_\gamma>$ [meV]	$S_0(\times10^{-4})$
^{186}Os	30 ± 2	60 ± 4	2.30 ± 0.32
^{187}Os	4.8 ± 0.2	76 ± 4	3.04 ± 0.35
^{188}Os	40± 2	82 ± 4	2.39 ± 0.36

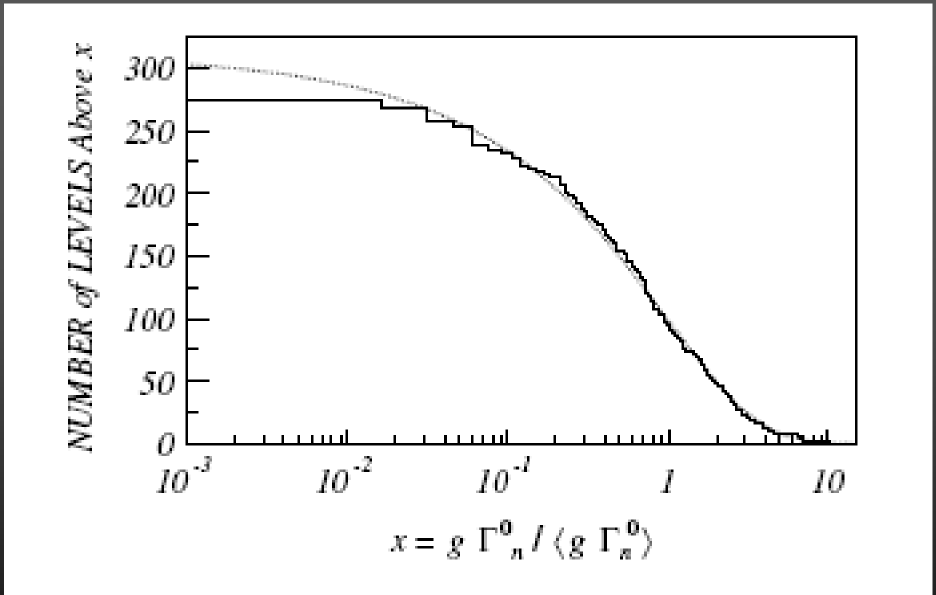
Mughabghab (2006)

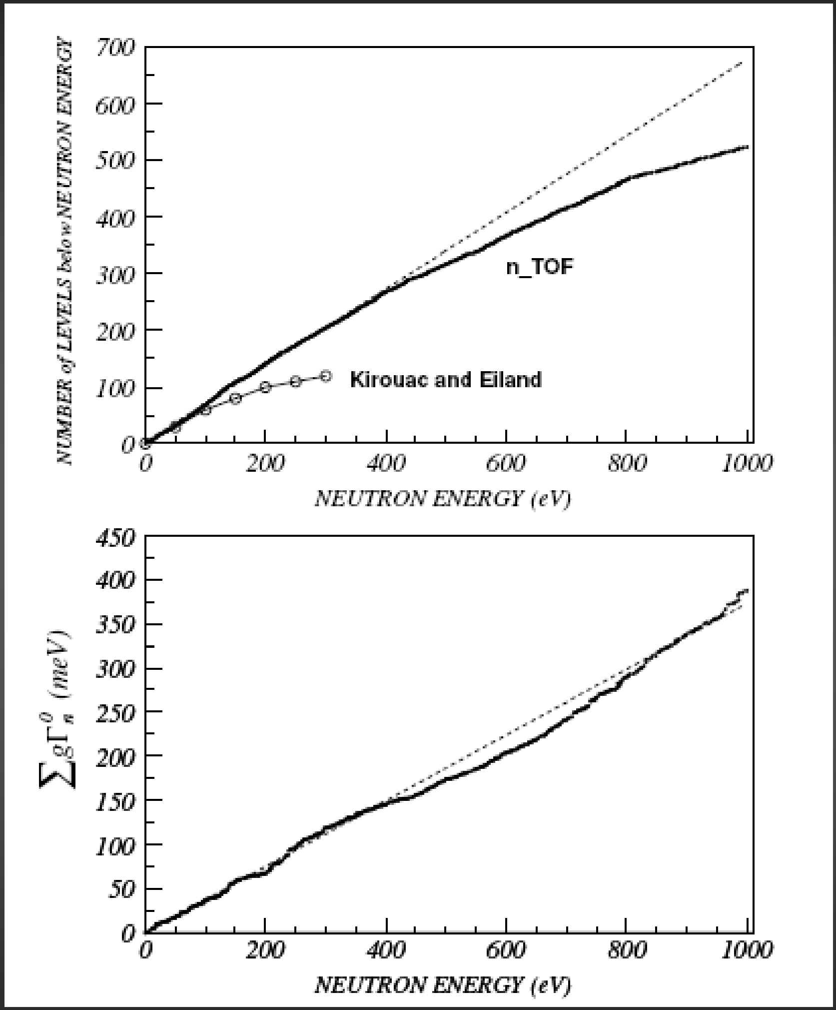
"*Atlas of Neutron resonances*" (Elsevier 2006)

$^{151}Sm(n,\gamma)^{152}Sm$

S. Marrone et al. (The n_TOF Collaboration)
Phys. Rev. C 73 03604 (2006)
All 275 resonances up to 400 eV analyzed.

$\langle D_0 \rangle$ = 1.49 ± 0.07 eV
$\langle S_0 \rangle$ = (3.87 ± 0.33)×10^{-4}
$\langle \Gamma_\gamma \rangle$ = 108 ± 15 meV
R_I = 3575 ± 210 mb





N_0 = 305 ± 6 while we observe at n_TOF 275. No p-wave observed, D_1 is estimated at 0.5 eV

Better estimation respect to previous measurements in the order of 20%.

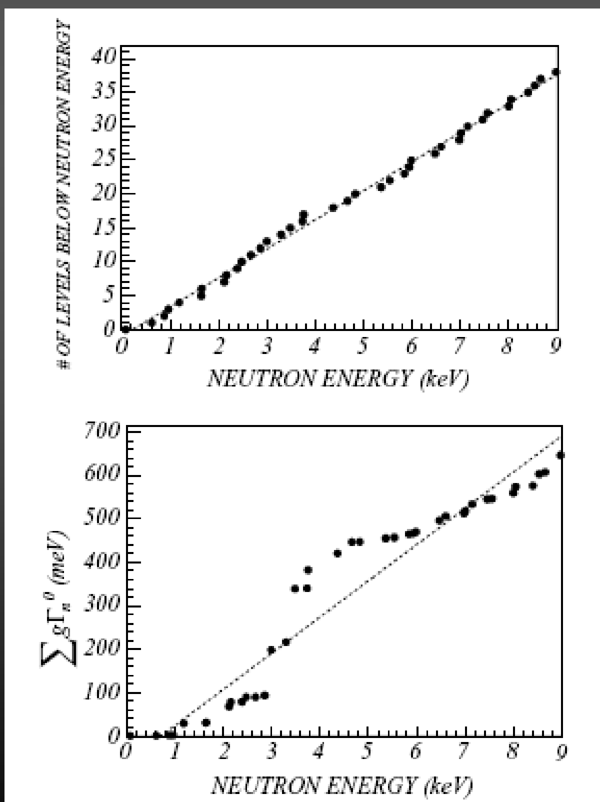
$^{139}La(n,\gamma)^{140}La$

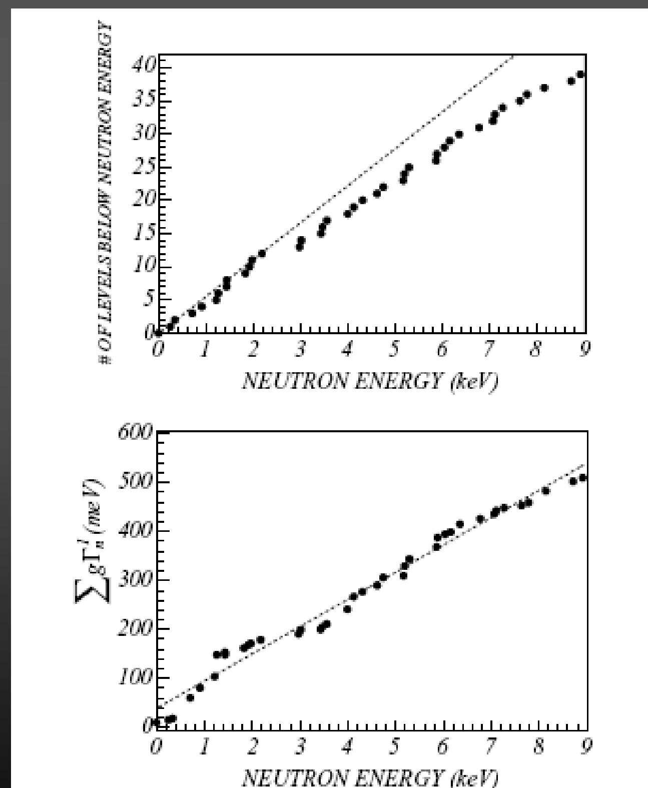
R. Terlizzi et al. (The n_TOF Collaboration)
Phys. Rev. C 75 035807 (2007)

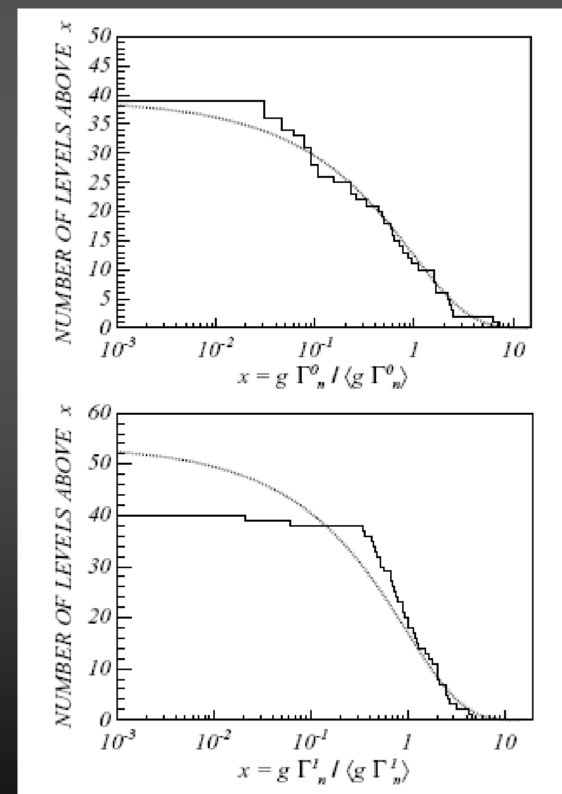
8 new resonances are observed and measured (10% more).

$\langle D_0 \rangle = 252 \pm 22$ eV
$\langle S_0 \rangle = (0.82 \pm 0.05)\times 10^{-4}$
$\langle \Gamma^0_\gamma \rangle = 50.7 \pm 5.4$ meV

$\langle D_1 \rangle < 250$ eV
$\langle S_1 \rangle = (0.55 \pm 0.04)\times 10^{-4}$
$\langle \Gamma^1_\gamma \rangle = 33.6 \pm 6.9$ meV



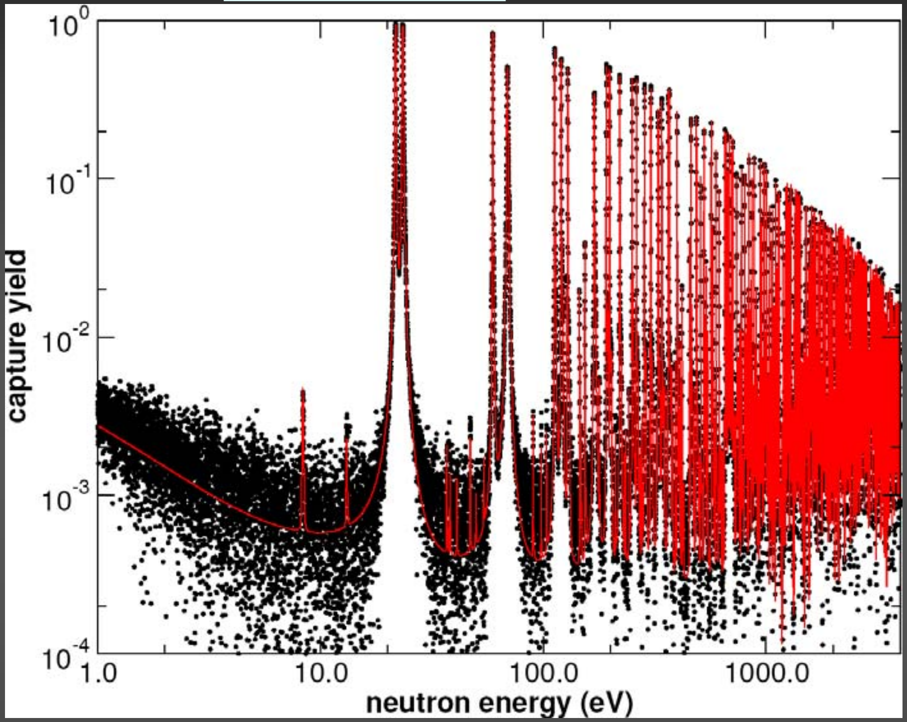




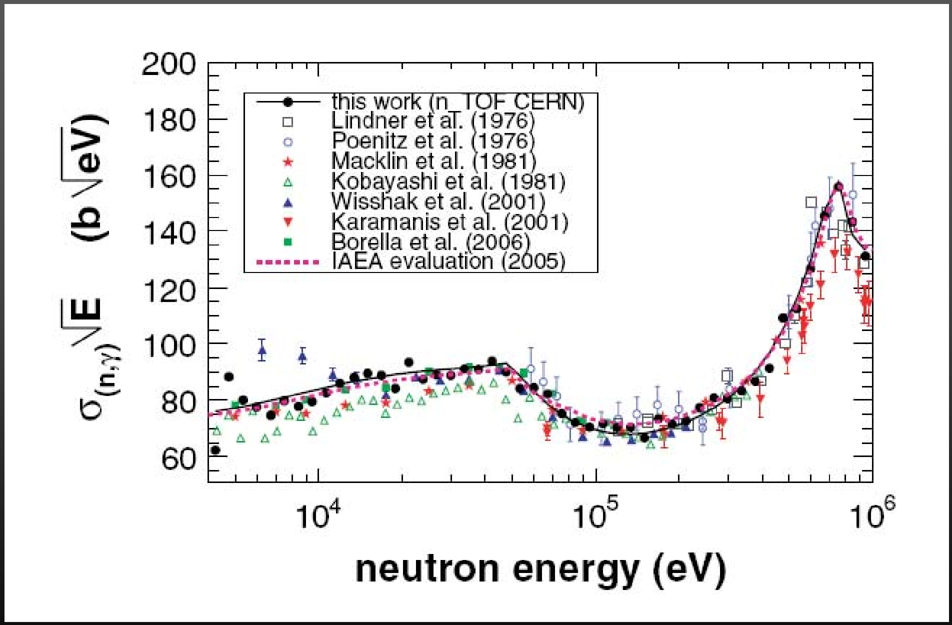
n_TOF experiments

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

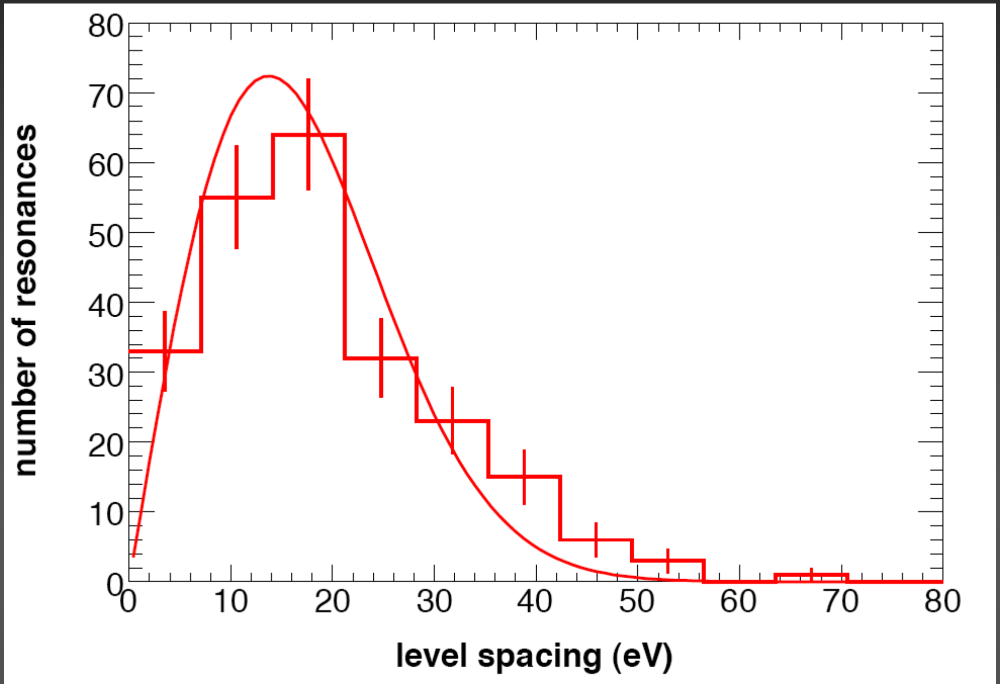
F Gunsing, et al. - The n_TOF Collaboration
ND2004 Conference, Santa Fe, NM – Sept. 2004
&
G Aerts et al. (The n_TOF Collaboration)
Phys. Rev. C 73 (2006)



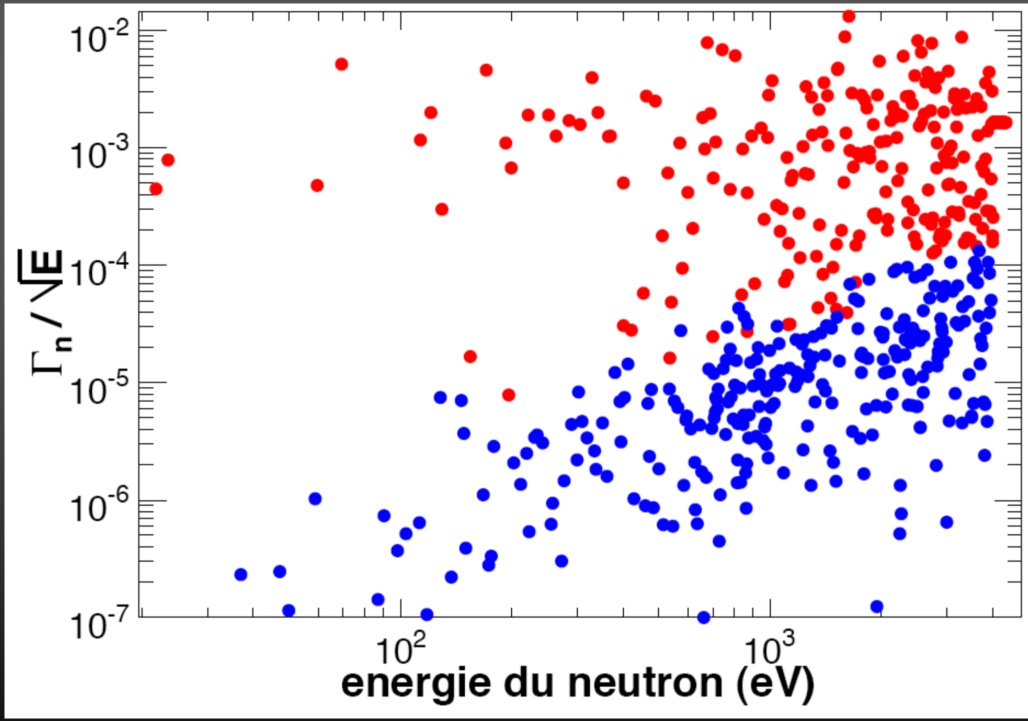
- Very large neutron energy range.
- High resolution power of the neutron resonances.
- Very interesting implications in Nuclear Astrophysics. (Th/U and Th/Eu chronometers).



$^{232}Th(n,\gamma)^{233}Th$



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

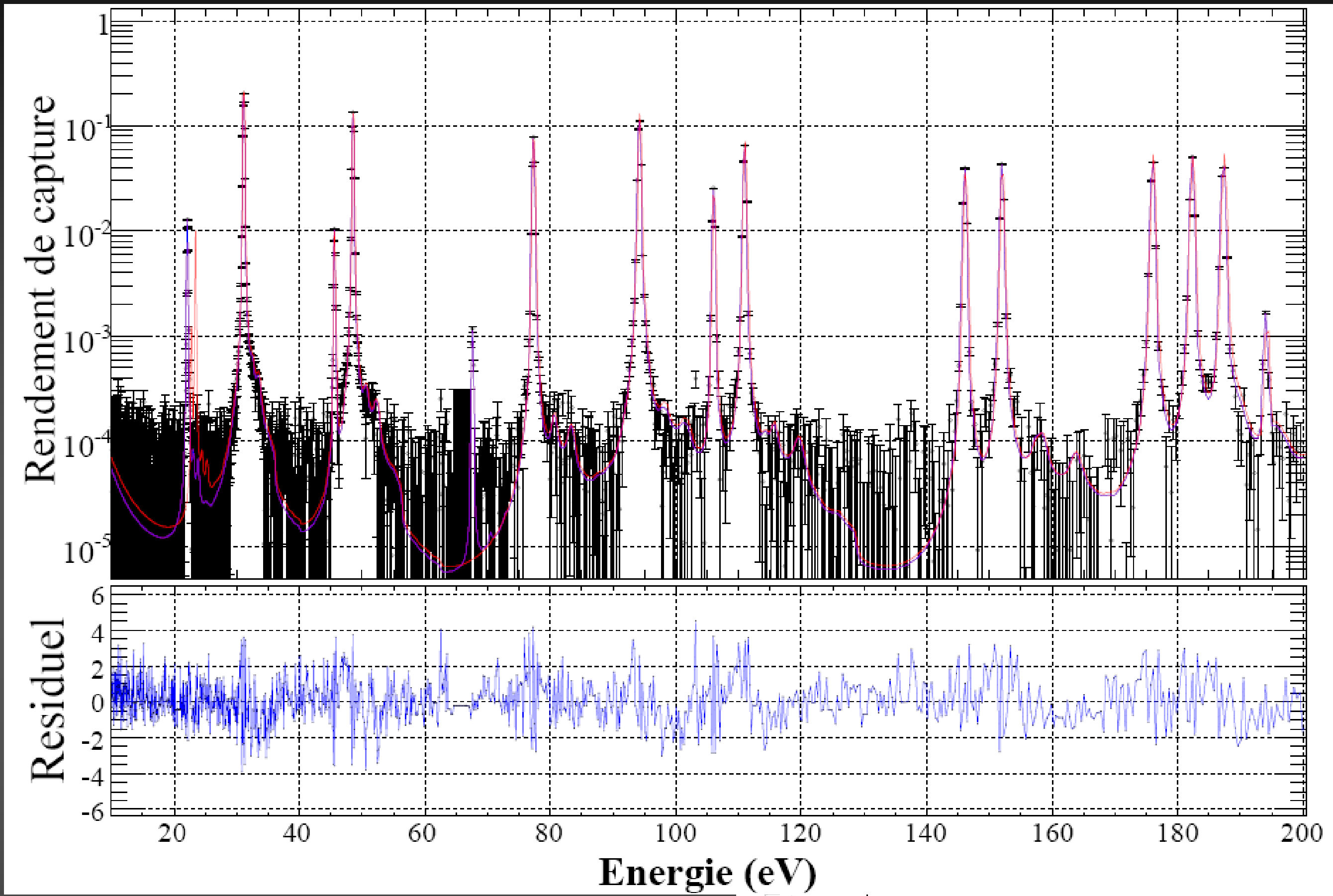


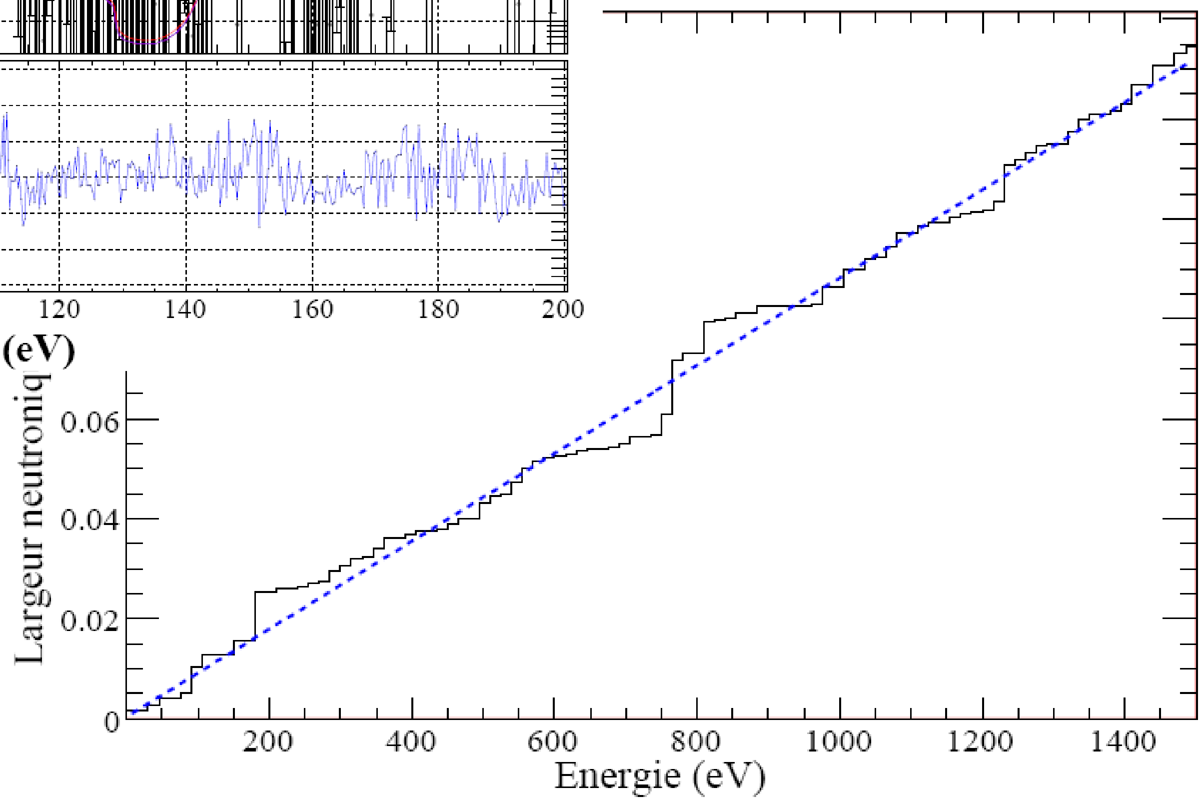
Almost 250 s-wave resonances under analysis up to 3 keV.

Much more for p-wave.

$^{234}U(n,\gamma)^{235}U$

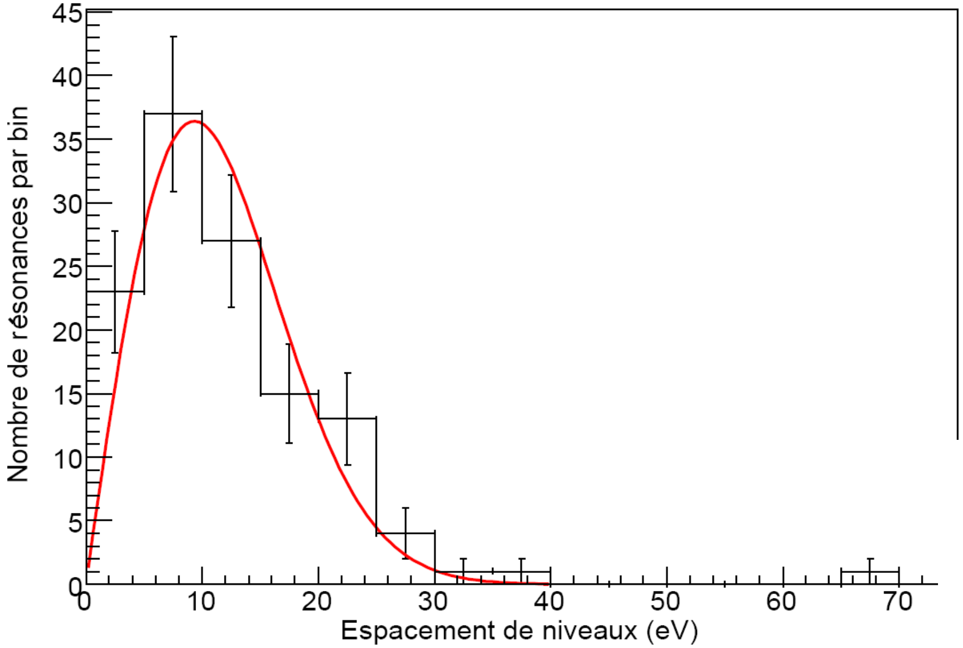
W Dridi, E Berthoumieux, et al.
(The n_TOF Collaboration)
PHYSOR-2006, Vancouver,
September 2006
full paper in preparation





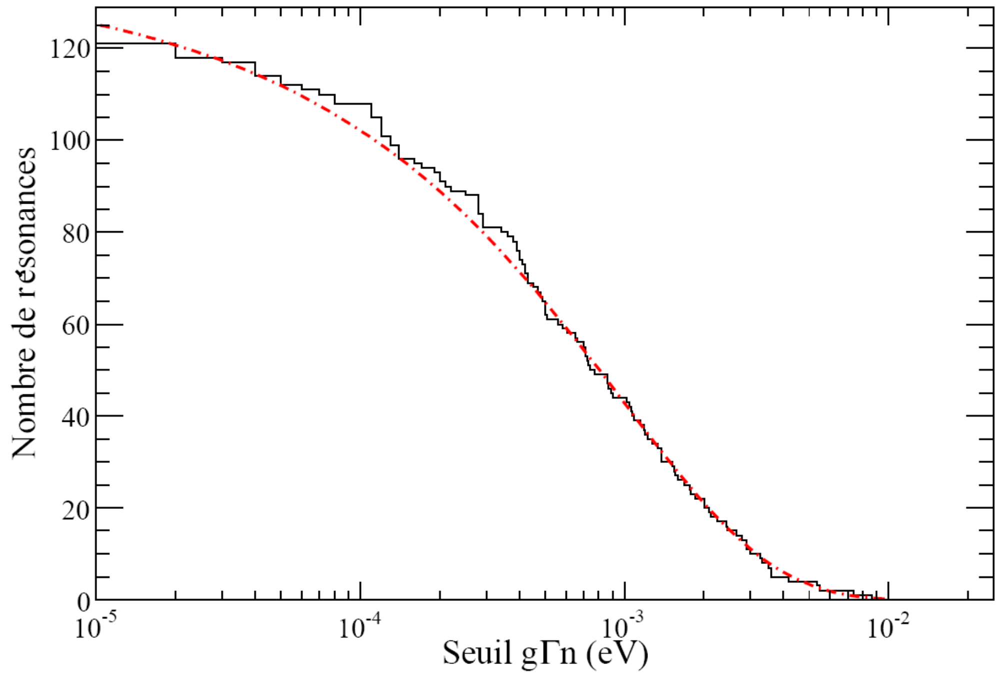
n_TOF TAC in operation

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



More than 120 resonances are under analysis.

The preliminary results indicate that there is a good agreement with Wigner and P-T distribtuions.

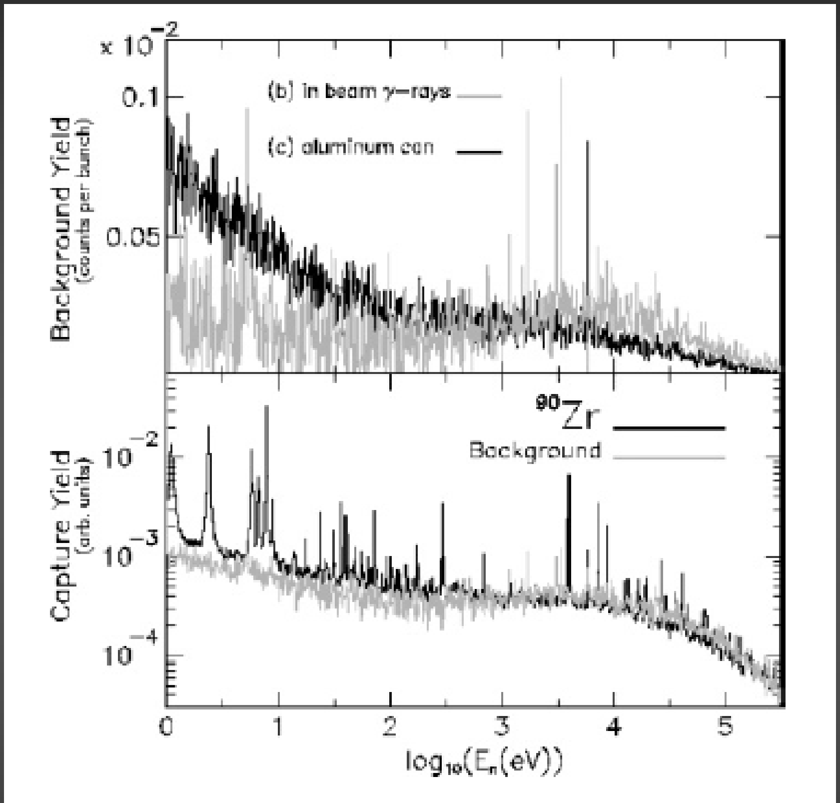


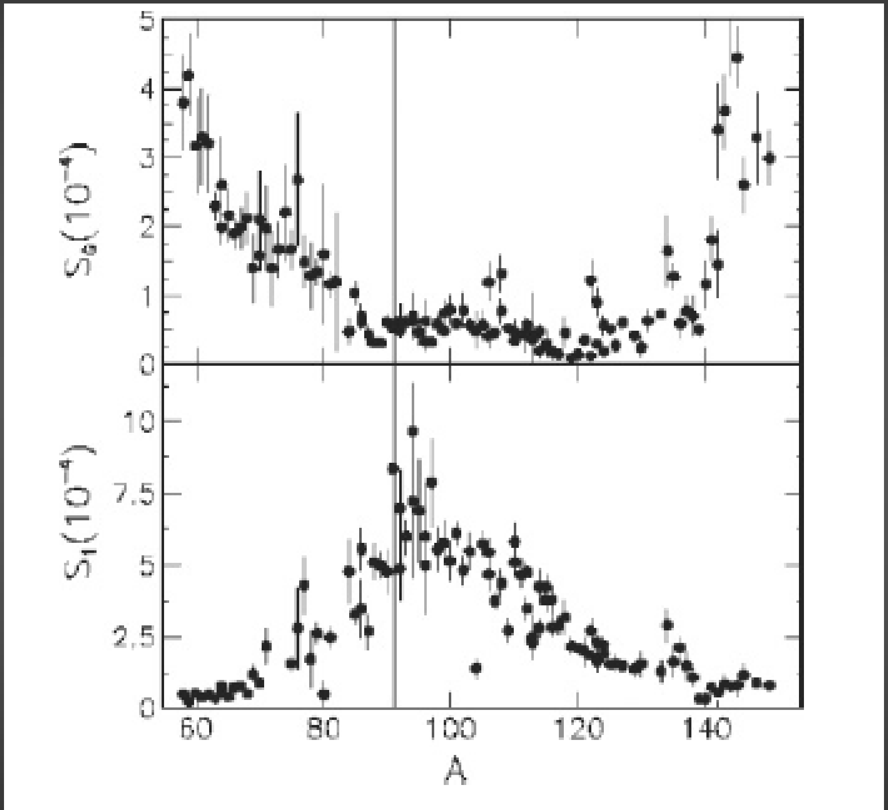
TAC in operation

Zr isotopes: $^{90,91,92}Zr$

$^{90}Zr(n,\gamma)91Zr$

G. Tagliente, et al. (The n_TOF Collaboration)
2 papers published in Phys. Rev. C 77, 78 (2008-2009)
1 under submission.





Neutron magic nucleus (n=50 ^{90}Zr).
Very low neutron sensitivity of capture γ-ray detection systems & high resolution.

Summary for Zr

- Level density low betwen 519 and 4315 eV.
- Between 10% and 50% new resonances detected for those isotopes.
- Signficant difference in nuclear level density.
- A systematic difference in area of the resonance (lower) with respect to past.

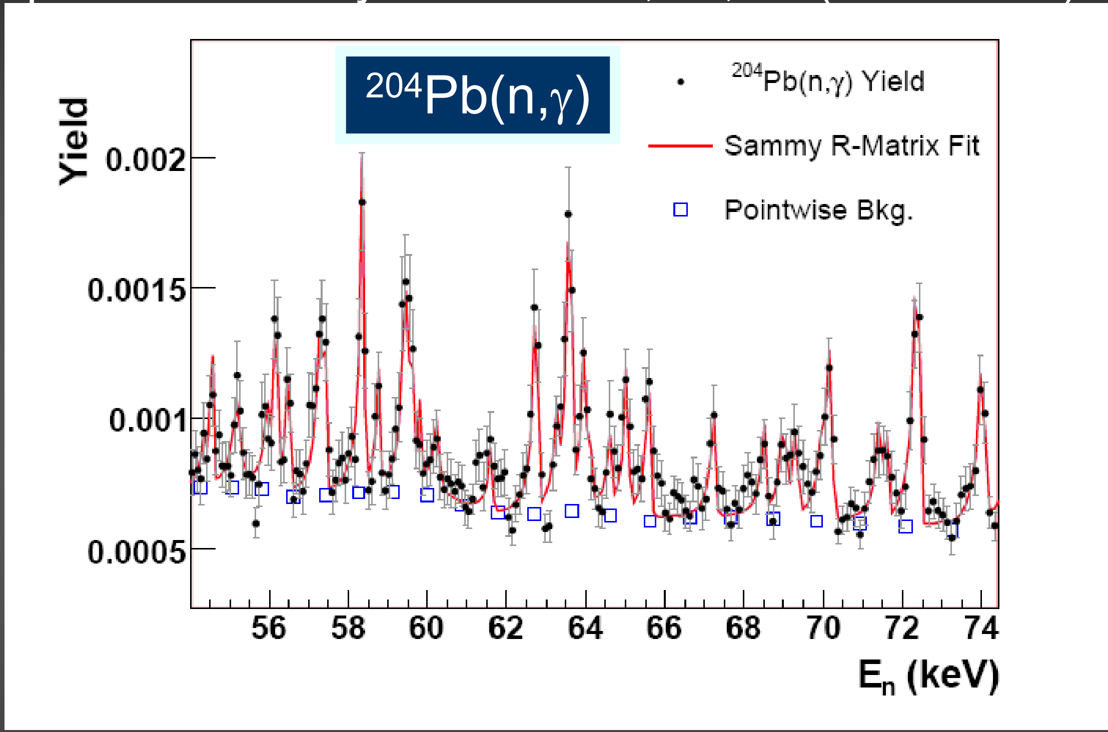
$^{204,206,207}Pb$ and ^{209}Bi

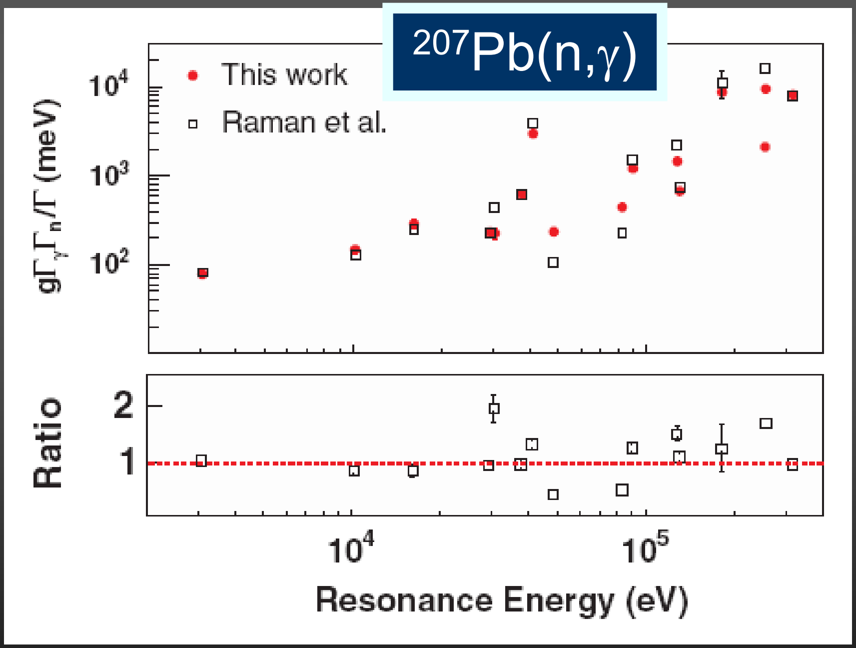
Very large energy neutron region to detect the neutron levels.

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)
4 papers published in Phys. Rev. C **74**, 76, 77 (2006-2007)



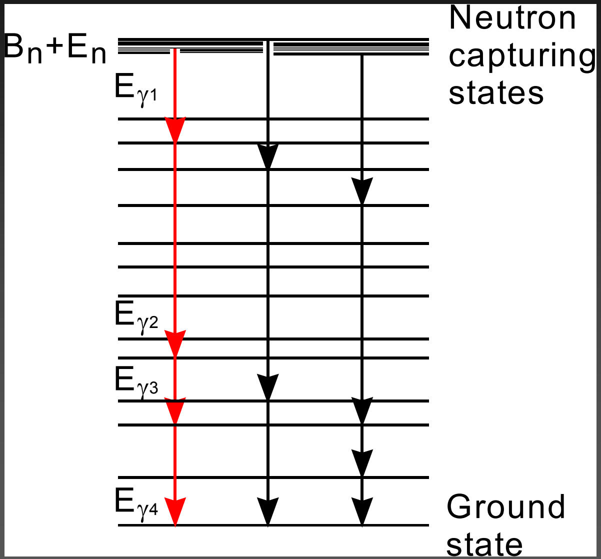


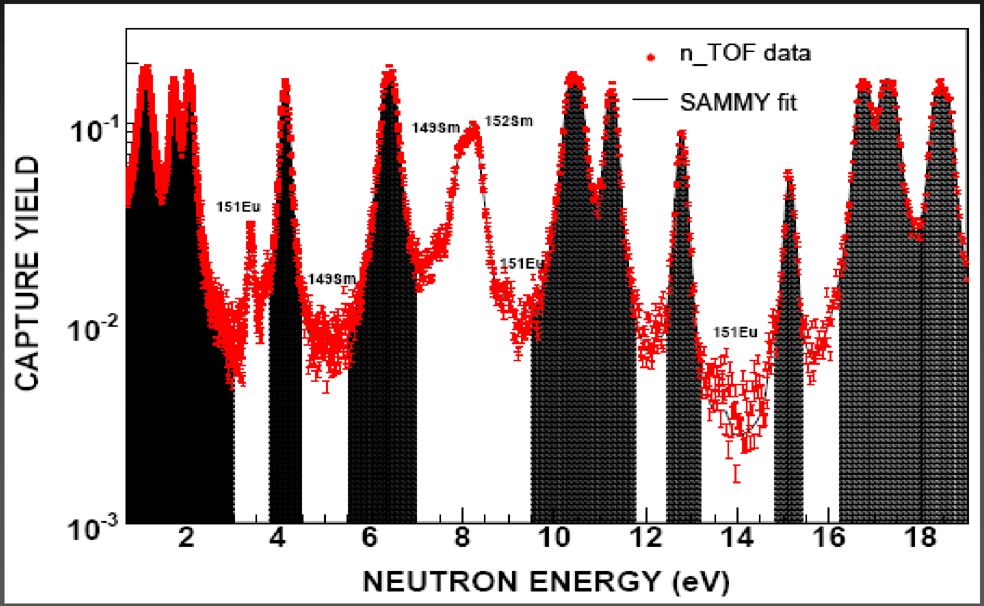
Very low neutron sensitivity of capture γ-ray detection systems & high resolution

Summary for Pb-Bi

- $^{204,206,207}Pb$ and ^{209}Bi.
- 4 new resonances detected for ^{204}Pb
- Any signficant difference in nuclear level density.
- A systematic difference in neutron and gamma widths lower with respect to past, while is in agreement with Geel data.

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 for C6D6:

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

Disadvantages for C6D6:

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

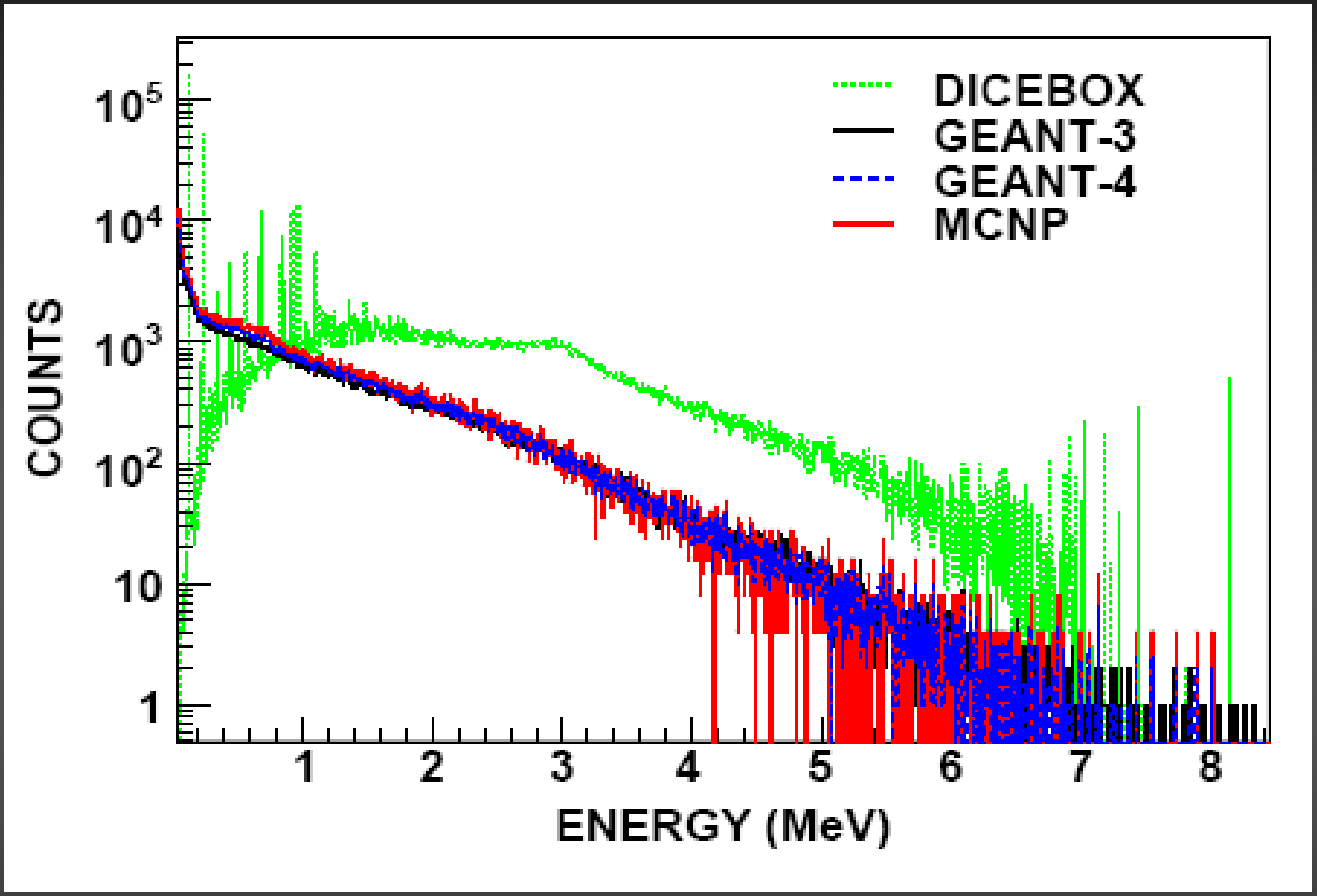
Proposed solution: filter model predictions through detector's response

Monte Carlo Simulations

The idea is to simulate both the cascade generation (DICEBOX) and using three different Monte Carlo codes:

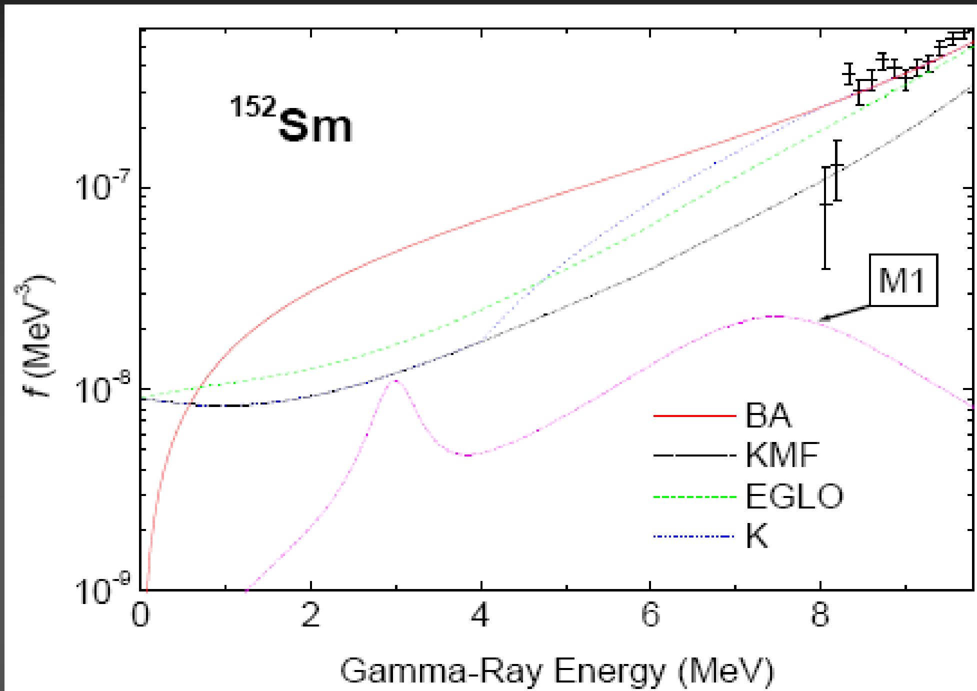
- MCNP-X
- GEANT 3.21
- GEANT 4

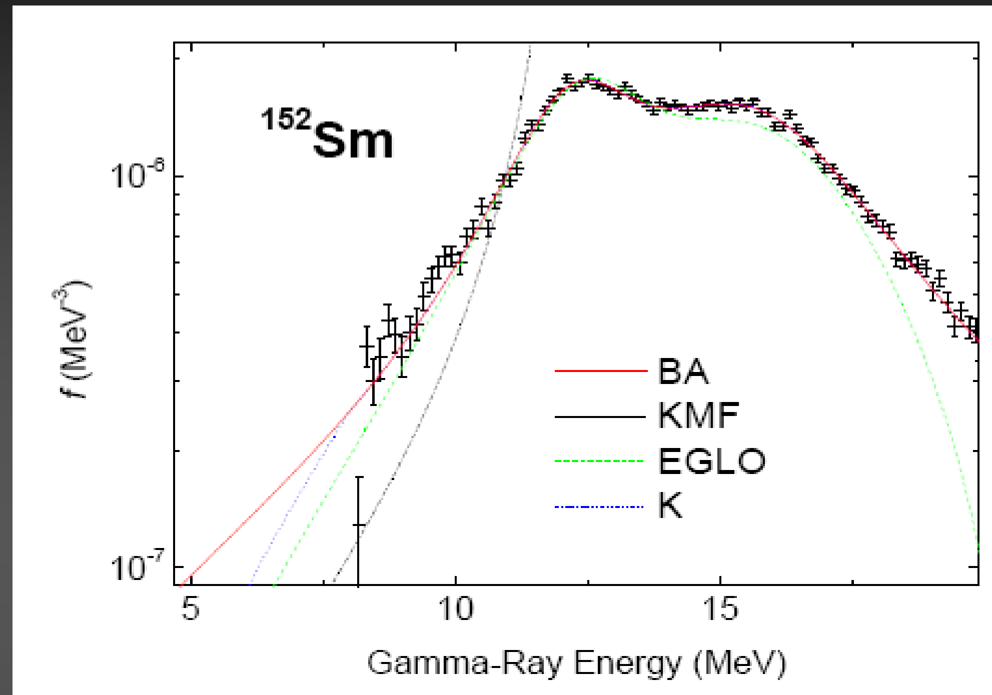
Accurate implementation of the materials and detailed geometry of experimental apparatus



- 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

Models of Photon Strength Function





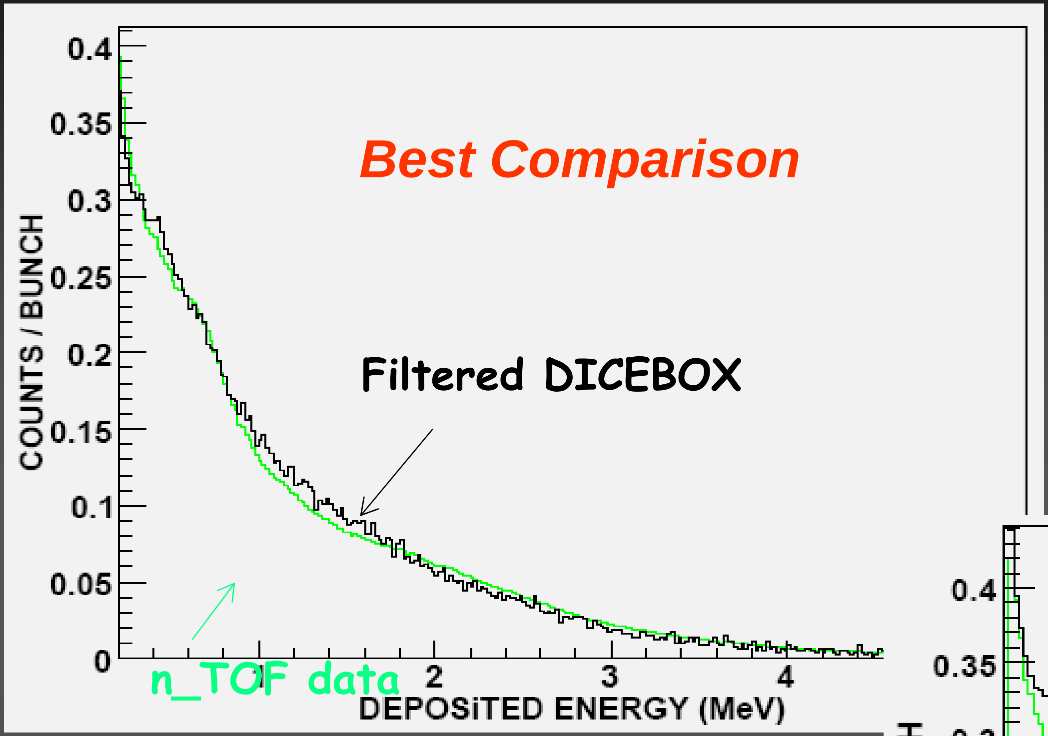
Photon Strength Function are proportional to the γ-ray cross section on nuclei.

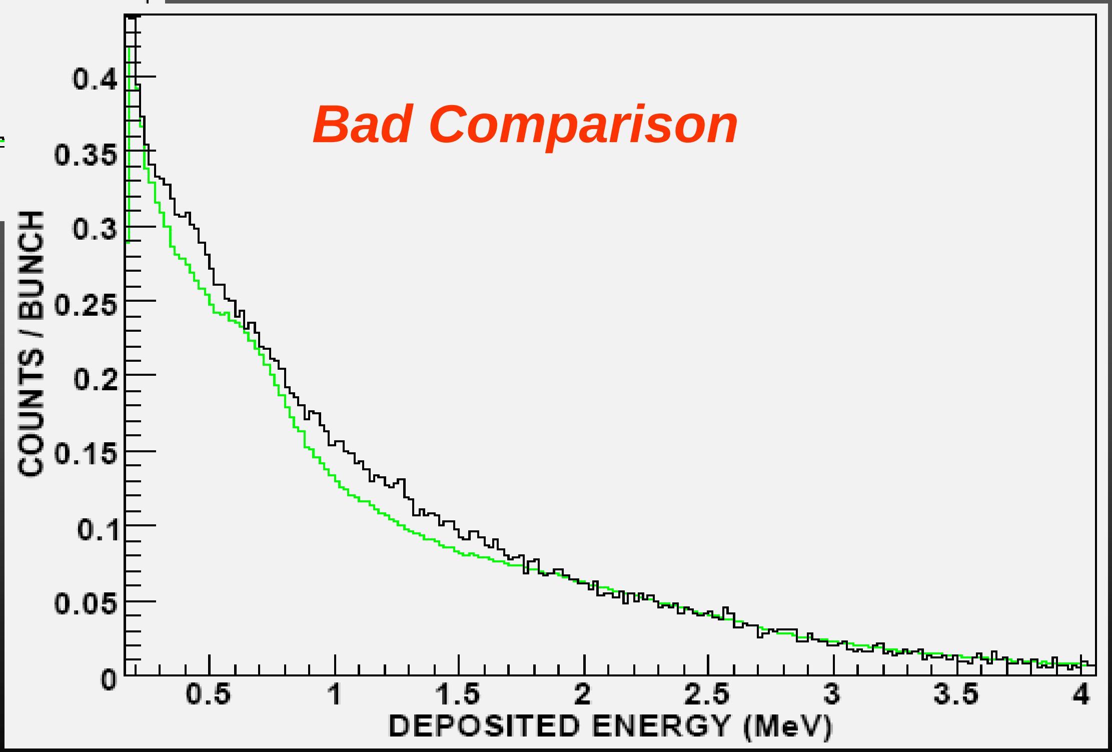
Several Models are under study: BA, KMF, EGLO, K.

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

Also Nuclear Level Density Models can be checked but in this case there are two main choices: Back-shifted Fermi Gas and Constant Temperature.

Comparison with the Experimental Data



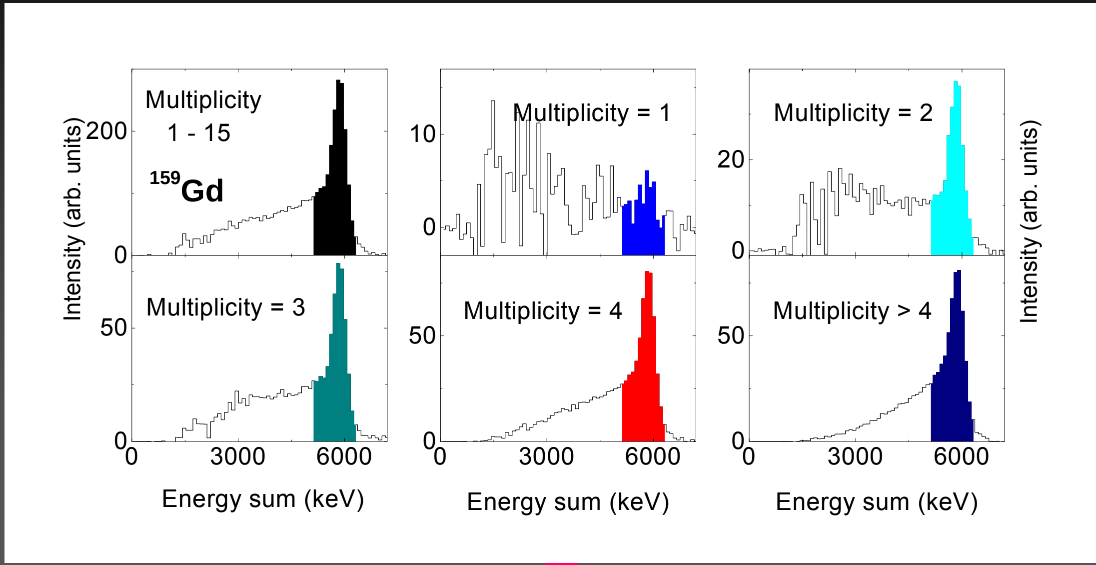


A more accurate comparison (and conclusion) requires fixing some uncertainties in the MC filtering code.

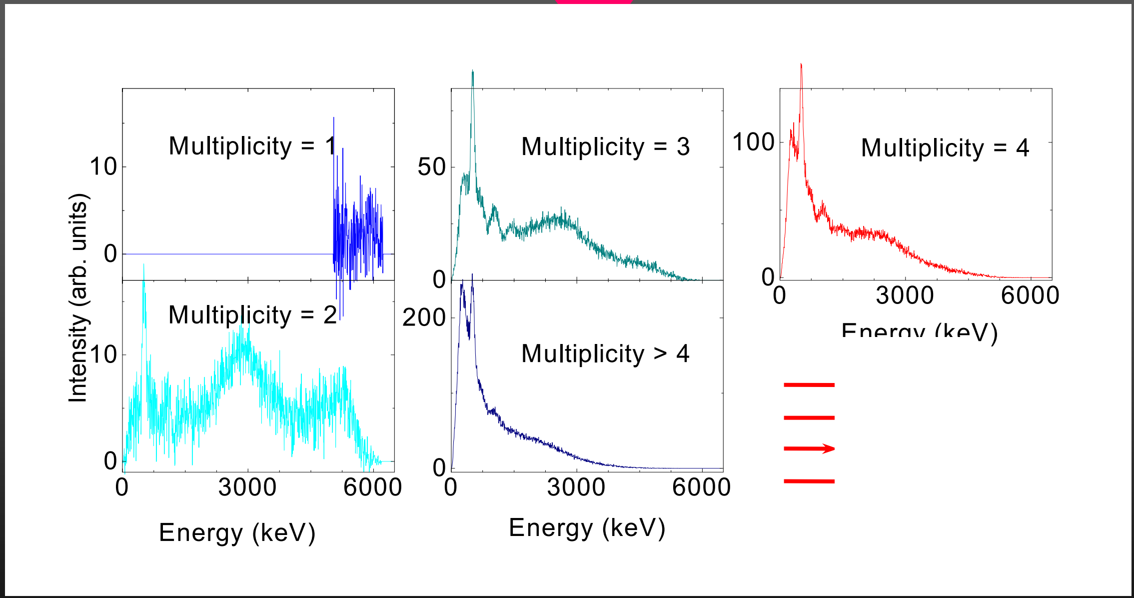
Photon Strength Function in TAC

Advantages

- The multiplicity studies.
- The angular distribution studies
- Higher statistics
- Better Energy Resolution.

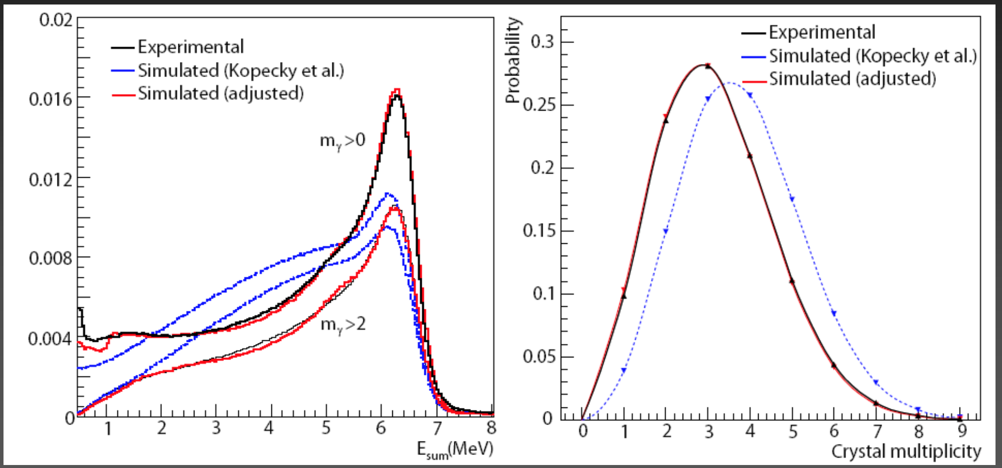


DICEBOX Simulation of decay must be combined with MC simulation of detector



Experimental Results

$^{196}Au(n,\gamma)$



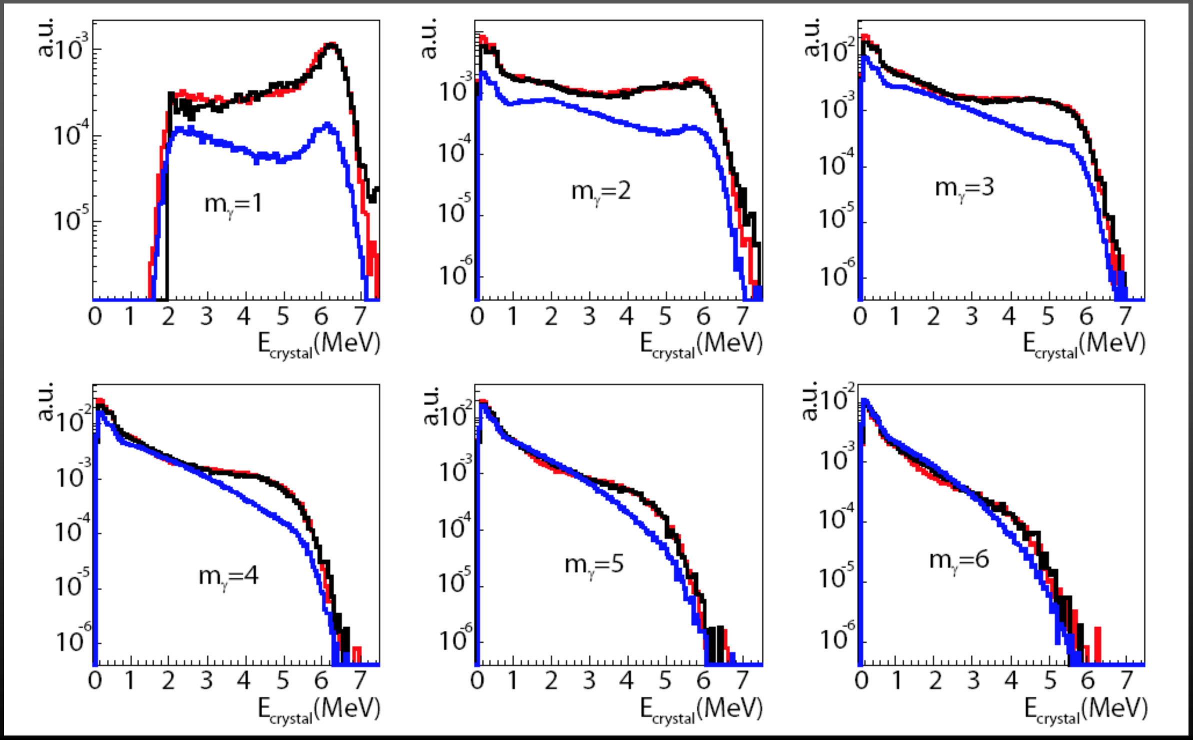
Data are in black.

SImulations with Kopecky model in blue.

Simulations with modified Kopecky model in red

The modified model has to fit all the different kind of data.

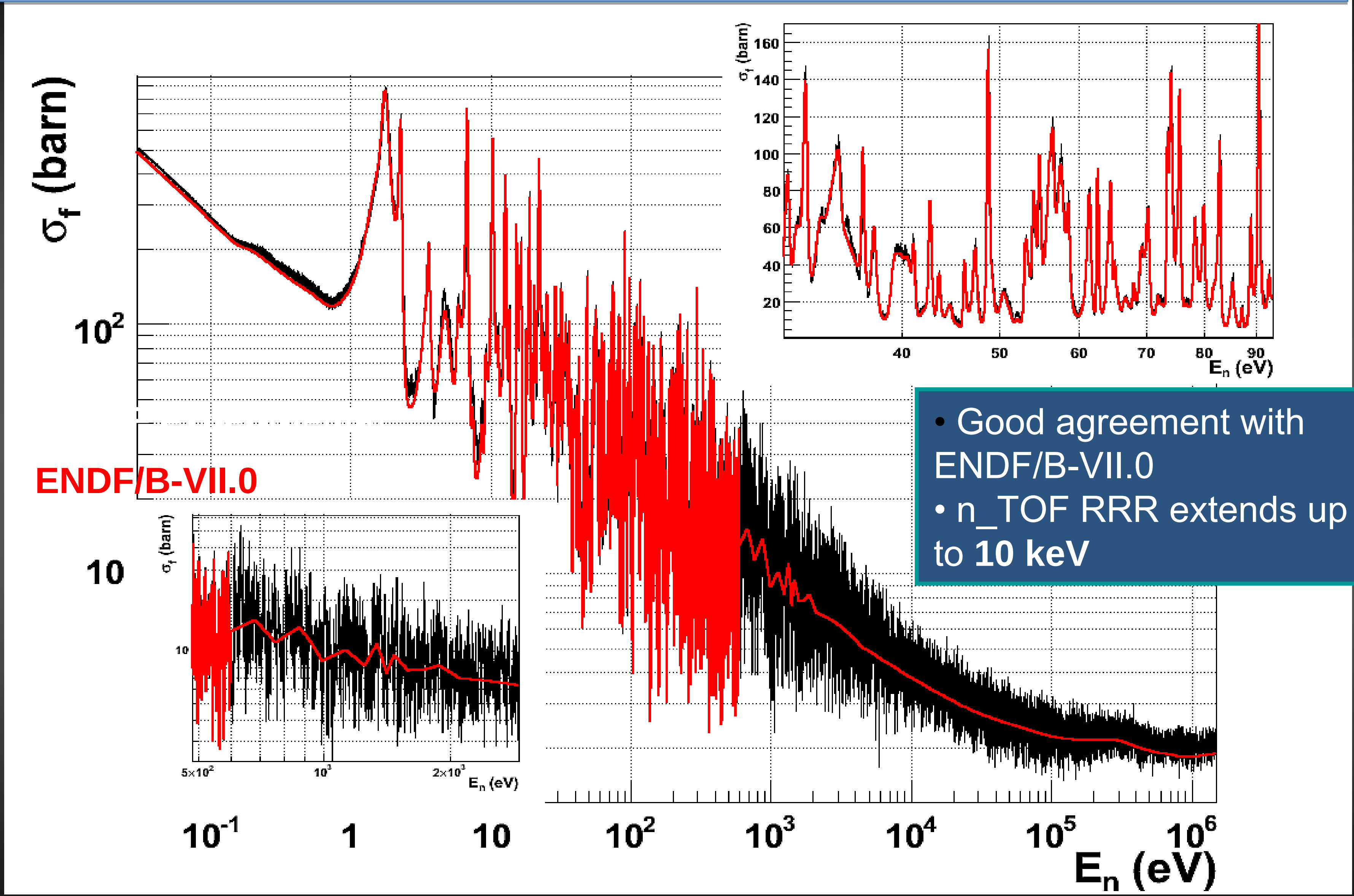
Angular distribution studies are in progress,



C. Guerrero et al., Proceedings of Workshop on Photon Strength Function, Prague 17-20 January 2007.

^{233}U(n,f) cross section – results (comparison with evaluated data)

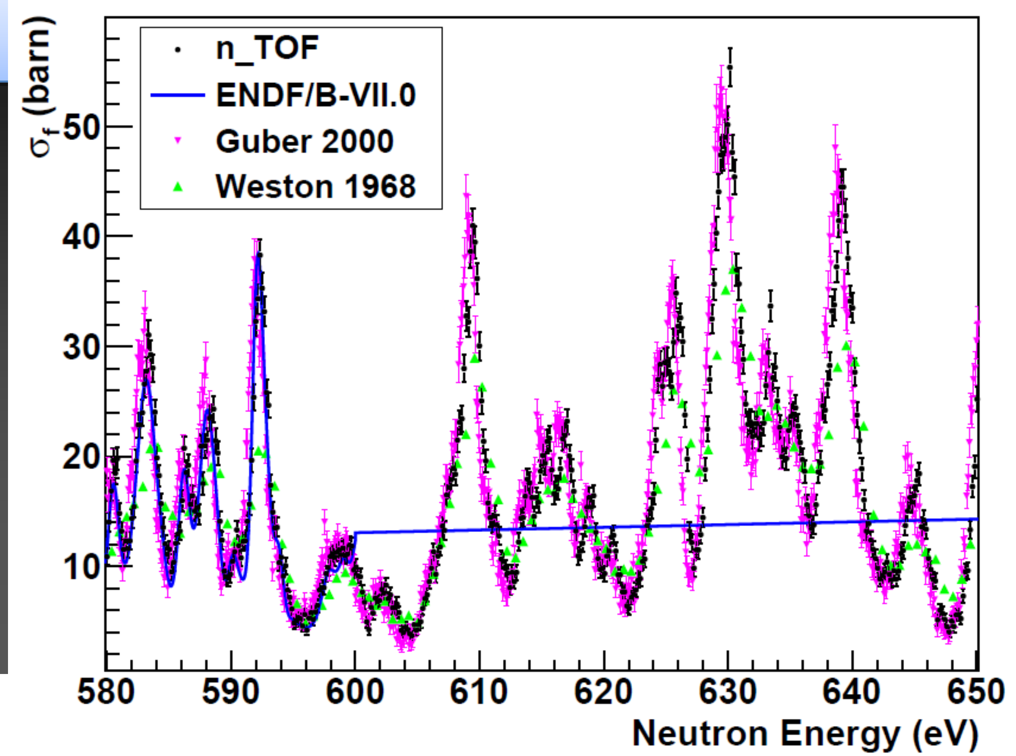
6000 bin/decade



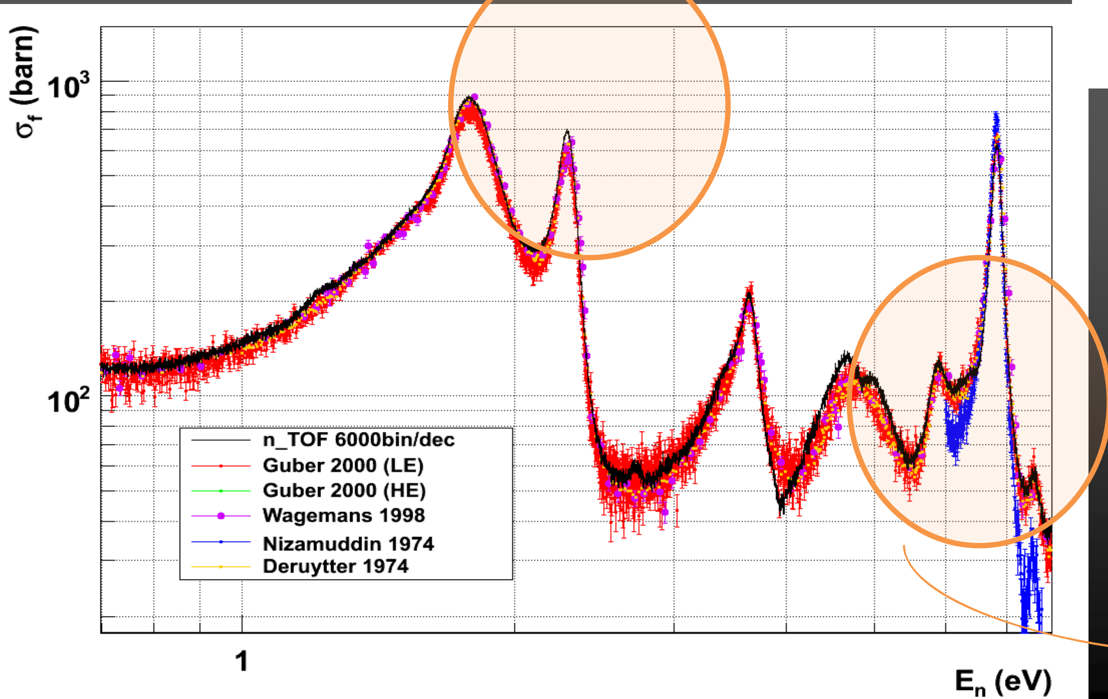
- Good agreement with ENDF/B-VII.0
- n_TOF RRR extends up to **10 keV**

Uncertainty in the order of 6%

FISSION DATA: SAMMY Analysis

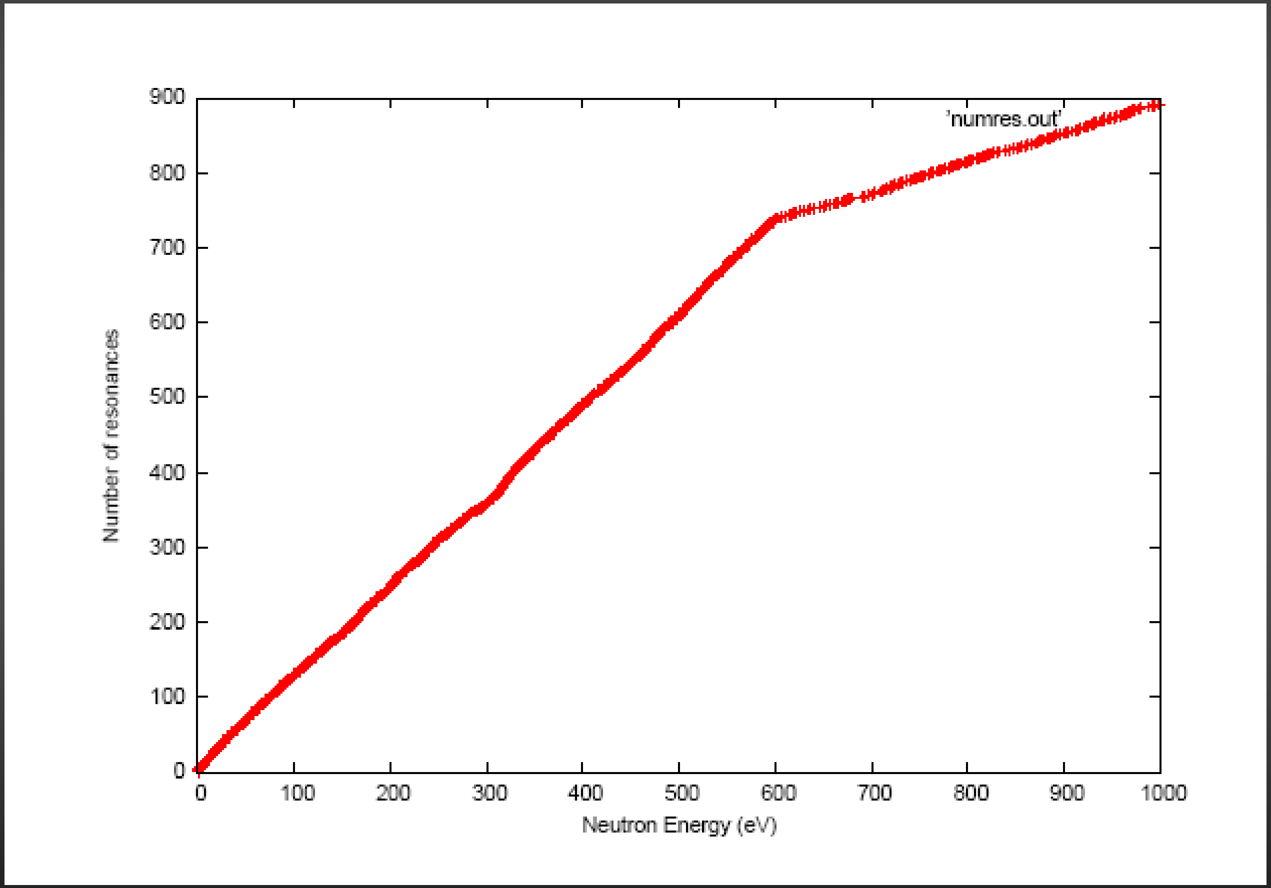


Good agreement observed between n_TOF and previous experimental data (although with lower resolution)



Due to some inconsistencies between $^{235}U(n,f)$ experimental values and ENDF/B-VII.0, the agreement is not good between 3.5 eV and 5.5 eV (will be corrected by a flux smoothing procedure)

Evaluated Resonance File



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

stefano.marrone@ba.infn.it

Summary & Conclusions

- n_TOF is a world leading facility for the accurate measurements of neutron cross sections.
- Several targets already analyzed and the results are published;
- Significant differences in the measurements of Nuclear Level Density at the Neutron Binding Energy especially for low Z and radioactive sample.
- Preliminary results coming from Fission data and Photon Strength Function are also extracted.
- Large Plan of measurements in EAR-1:

- restarted the activities in 2008 with the commissioning of the new target
- In few days the n_TOF beam will run again @ CERN.

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n_TOF experiments 2002-4

- data analysis completed, results published (green)
- data analysis completed, paper in preparation (yellow)
- data analysis in progress (red)

Capture

- ^{151}Sm (green)
- $^{204,206,207,208}Pb$ (green), ^{209}Bi (green)
- ^{232}Th (green)
- $^{24,25,26}Mg$ (red)
- $^{90,91,92,94,96}Zr$ (yellow), ^{93}Zr (red)
- ^{139}La (green)
- $^{186,187,188}Os$ (yellow)
- $^{233,234}U$ (yellow)
- ^{237}Np, ^{240}Pu (yellow), ^{243}Am (red)

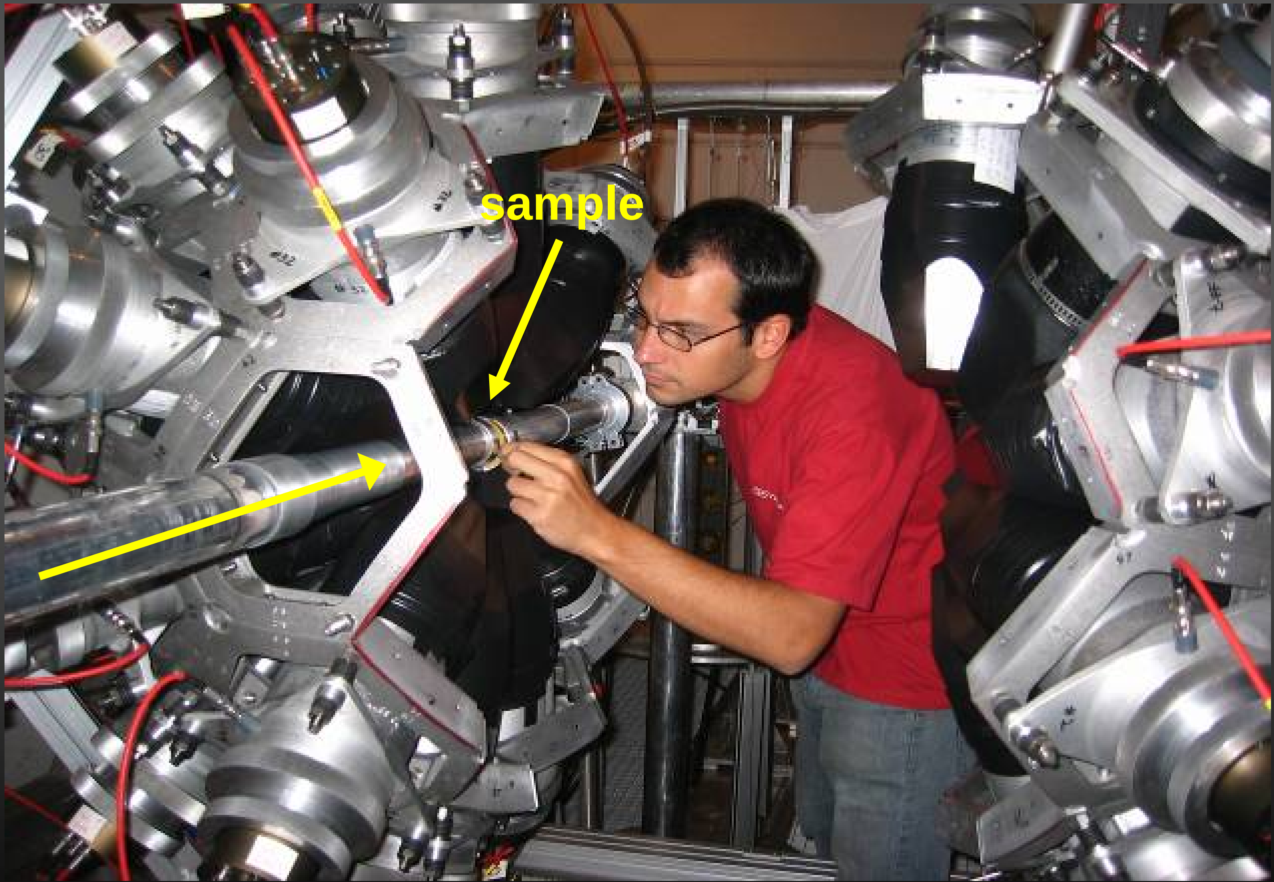
Fission

- $^{233,234,235,236,238}U$
- ^{232}Th
- ^{209}Bi
- ^{237}Np
- $^{241,243}Am$, ^{245}Cm

n_TOF TAC for (n,γ) measurements

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

First measurement with a radioactive sample started in August 2004
^{237}Np(n,γ)

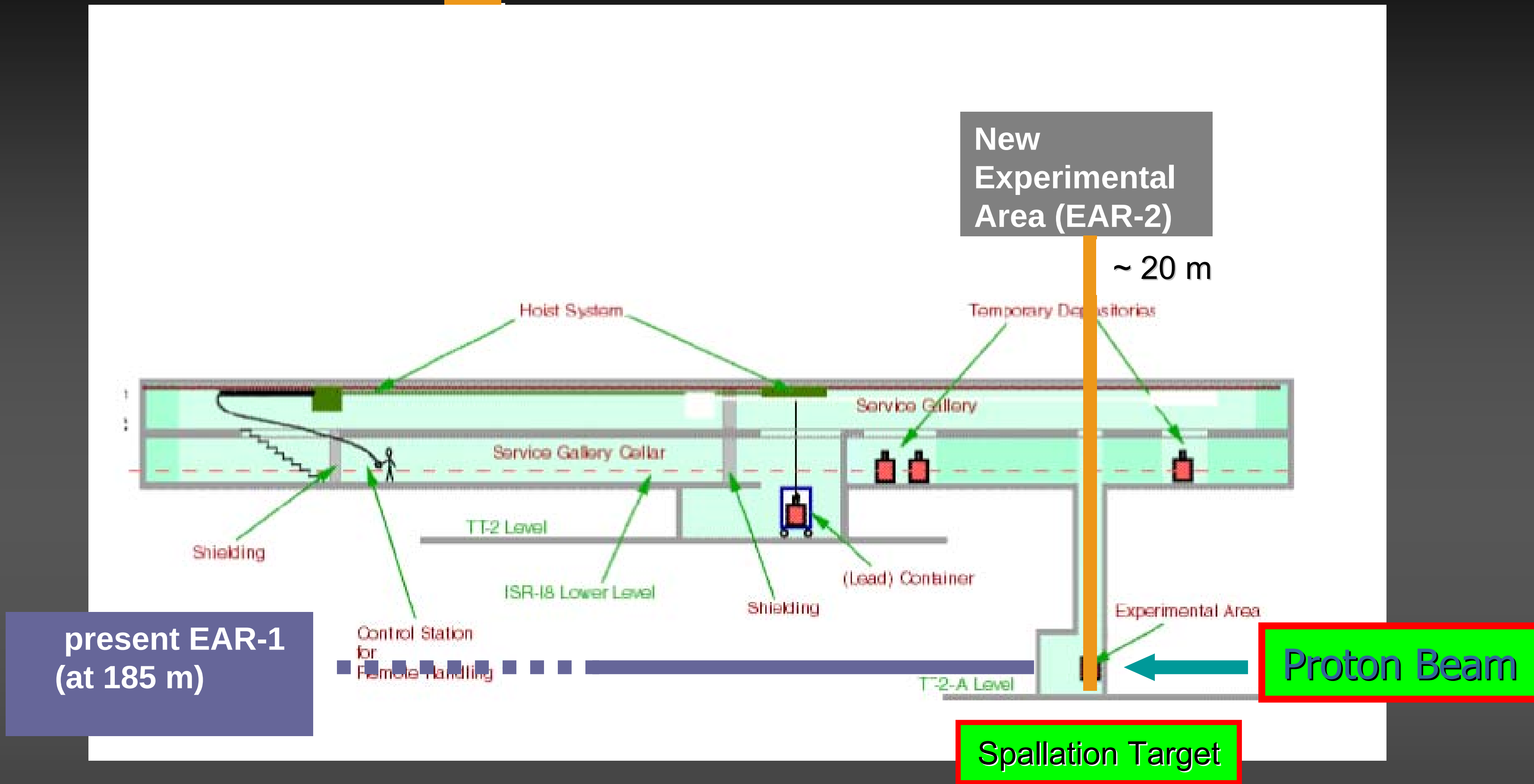


The n_TOF-Ph2 experiments

Fission measurements	
MA	ADS, high-burnup, GEN-IV reactors
^{235}U(n,f) with p(n,p')	new ^{235}U(n,f) cross section standard
^{234}U(n,f)	study of vibrational resonances at the fission barrier

Other measurements	
^{147}Sm(n,α), ^{67}Zn(n,α), ^{99}Ru(n,α) ^{58}Ni(n,p), other (n,lcp)	p-process studies gas production in structural materials
Al, V, Cr, Zr, Th, ^{238}U(n,lcp)	structural and fuel material for ADS and other advanced nuclear reactors
He, Ne, Ar, Xe	low-energy nuclear recoils (development of gas detectors)
n+D_2	neutron-neutron scattering length

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 CROSS SECTION SAMPLES**)

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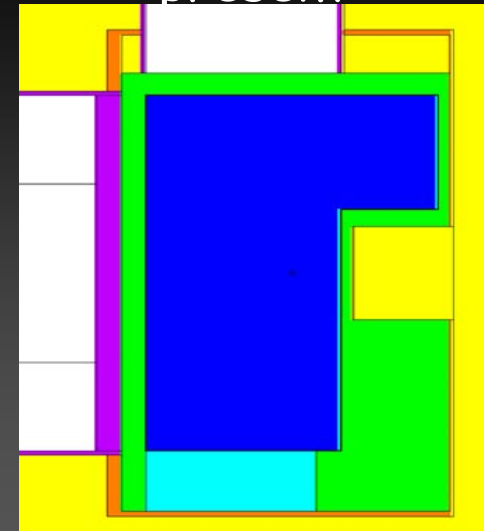
The n_TOF-Ph2 experiments

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)

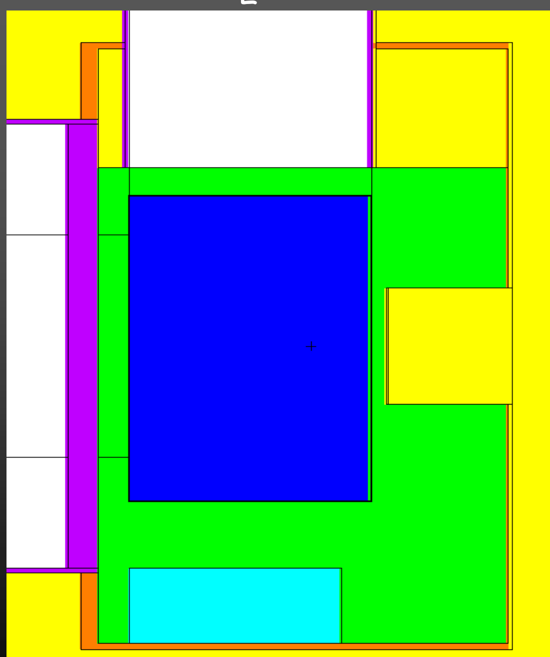
NEW target design

present

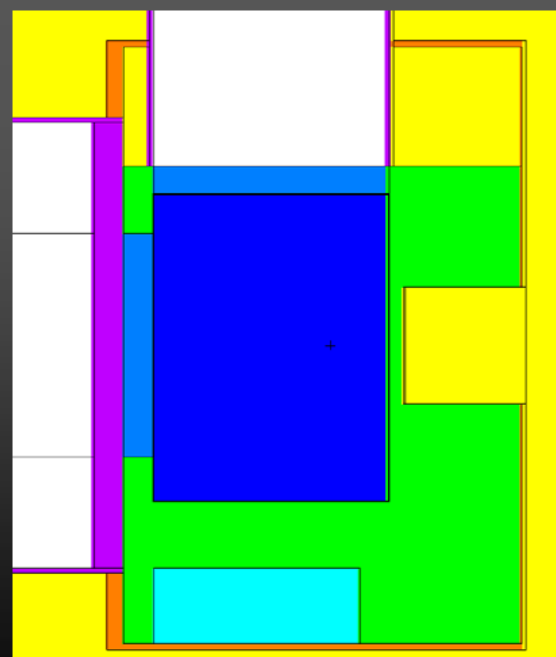


xz-squared target (40x40x55) with 5cm-thick cylinder moderator containers

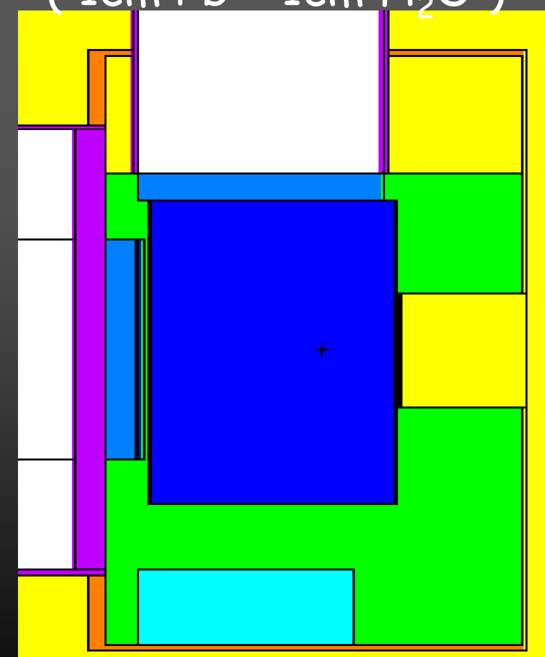
H_2O



D_2O

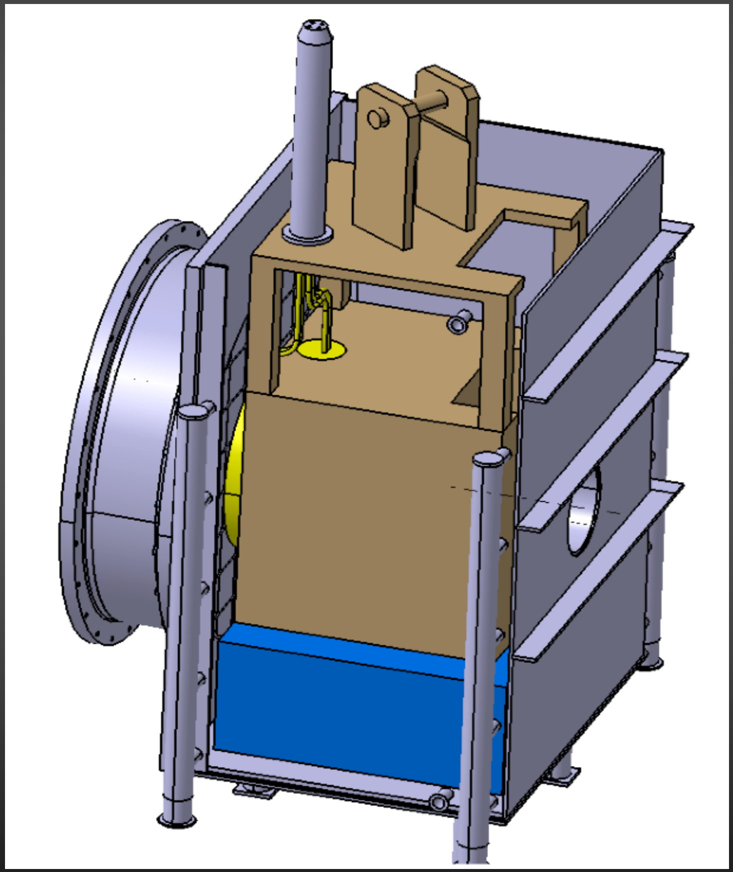


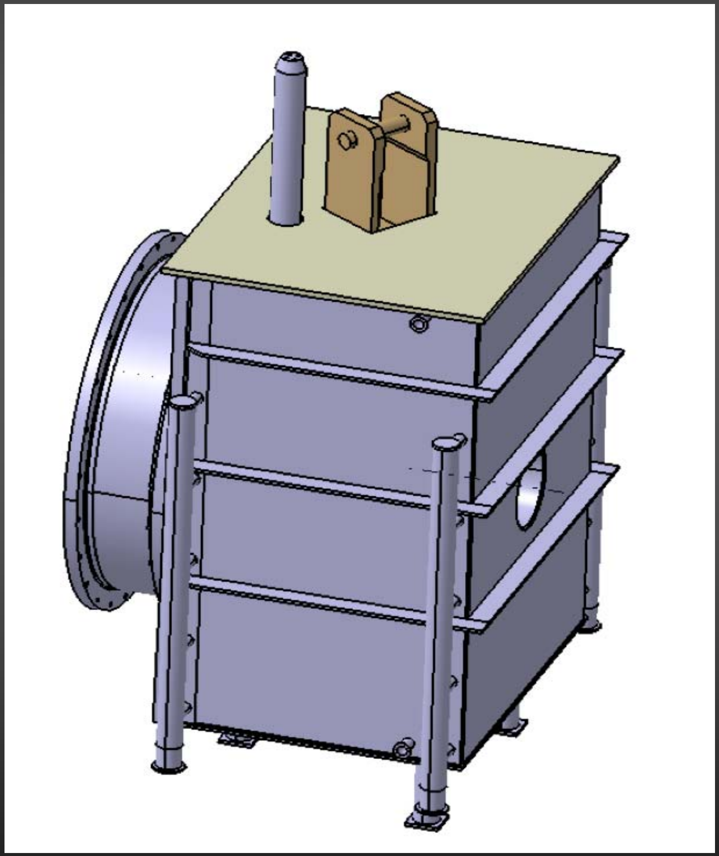
D_2O cooling
(1cm Pb + 1cm H_2O)



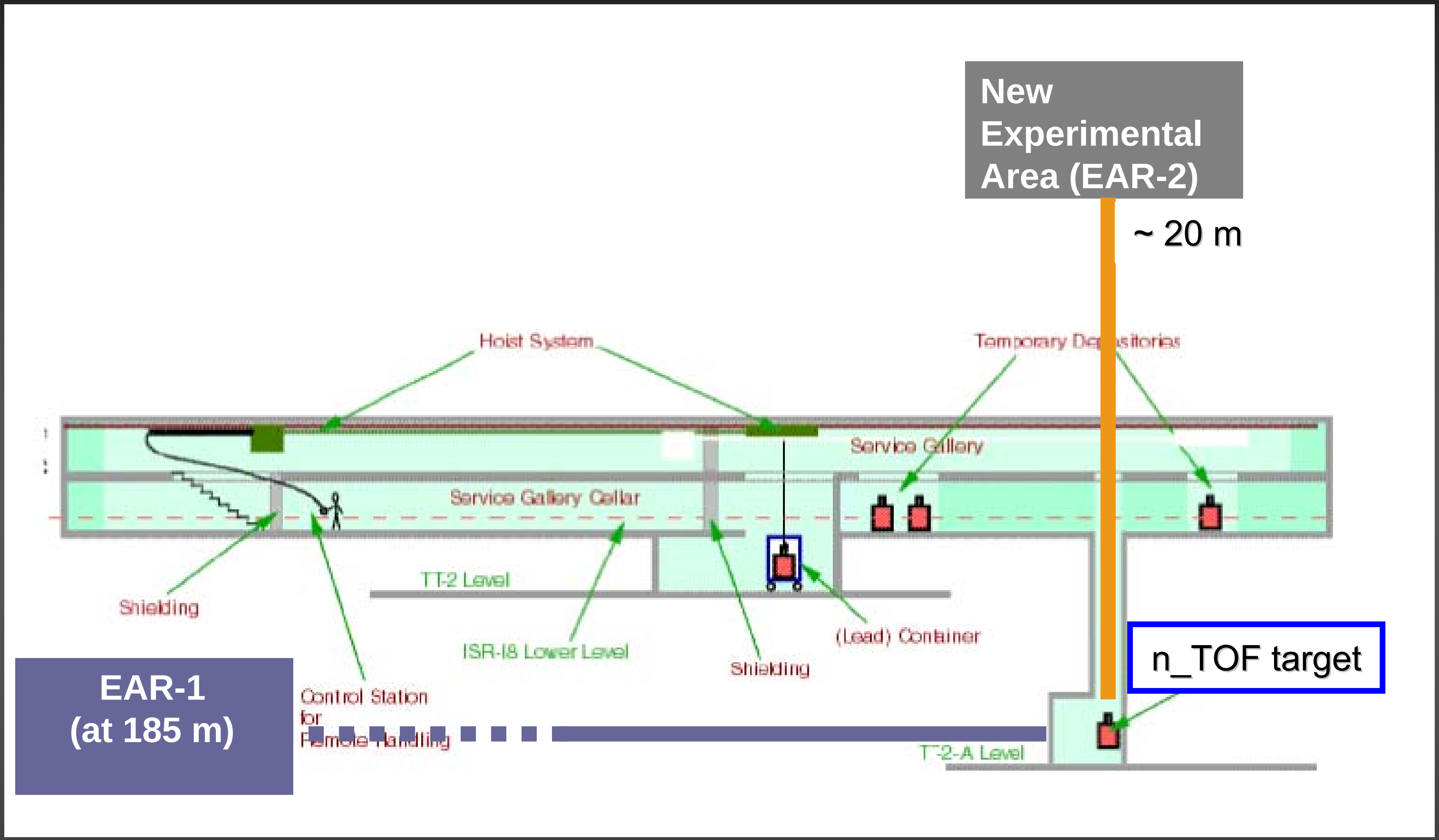
P Cennini, V Vlachoudis, K Tsoulou, et al. (CERN/AB/ATB), October 2006

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.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

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

^{232}Th

^{209}Bi

^{237}Np

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

^{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

C Domingo-Pardo, et al. - The n_TOF Collaboration
ND2004 Conference, Santa Fe, NM – Sept. 2004
&
submitted for publication to PRC, October 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

^{204}Pb(n,γ)

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

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

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

n_TOF experiments

Capture

^{151}Sm

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

^{232}Th

^{24,25,26}Mg

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

^{139}La

^{186,187,188}Os

^{233,234}U

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

Fission

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

^{232}Th

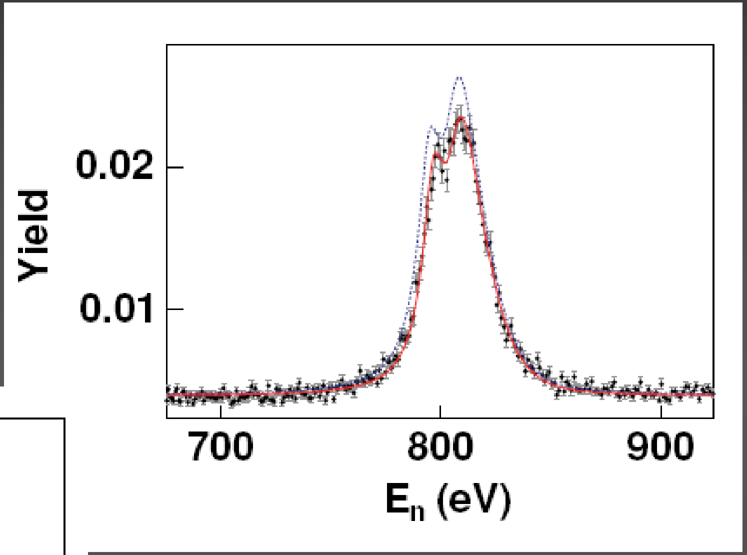
^{209}Bi

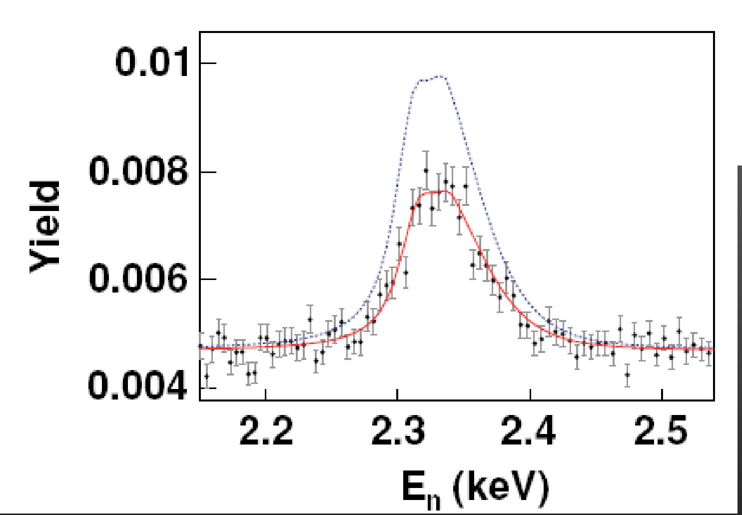
^{237}Np

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

^{209}Bi(n,γ)

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





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

n_TOF experiments

Capture

^{151}Sm

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

^{232}Th

$^{24,25,26}Mg$

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

^{139}La

$^{186,187,188}Os$

$^{233,234}U$

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

Fission

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

^{232}Th

^{209}Bi

^{237}Np

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

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

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

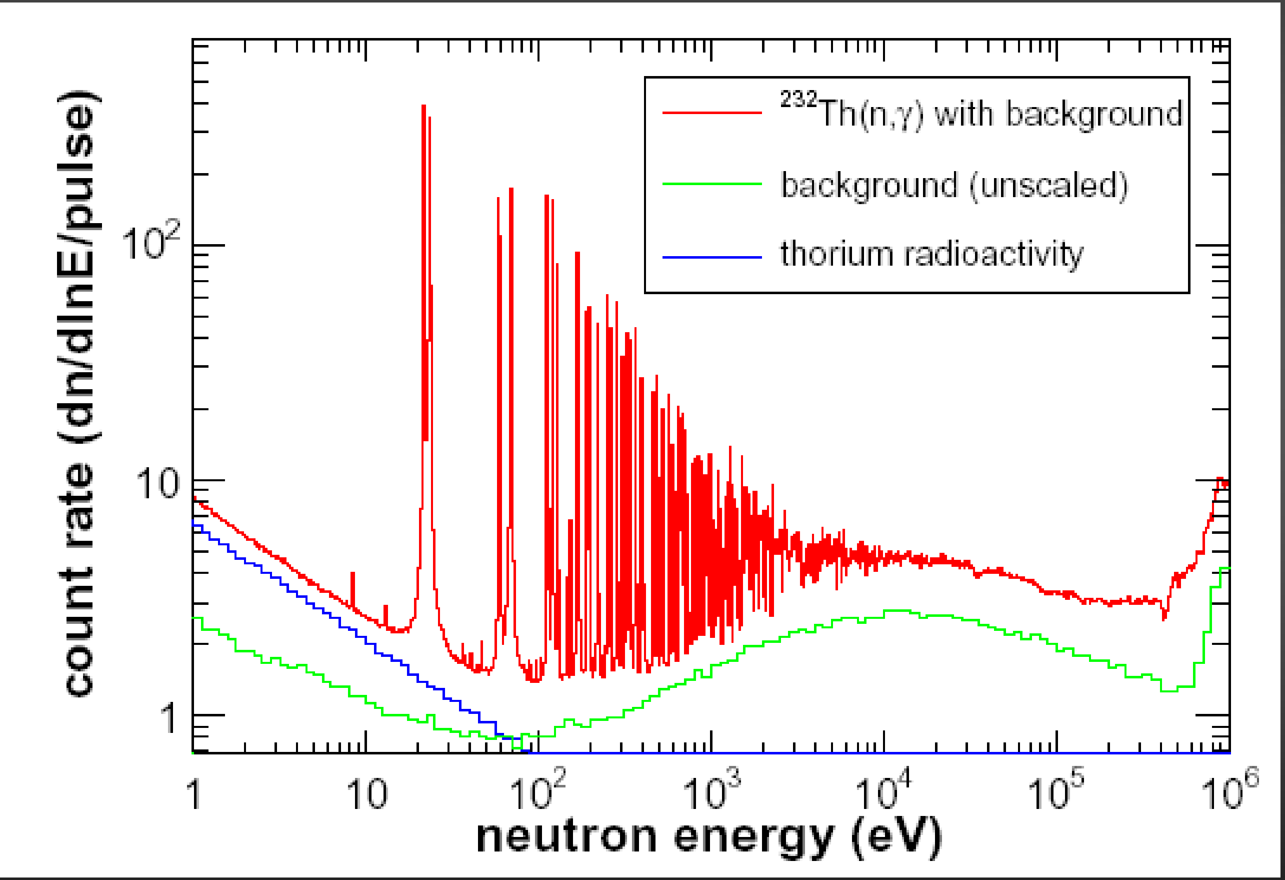
^{209}Bi

^{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



Low PS duty-cycle favours meaasurements on radiactive samples

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

$^{24,25,26}Mg$

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^{139}La

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

Fission

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

^{232}Th

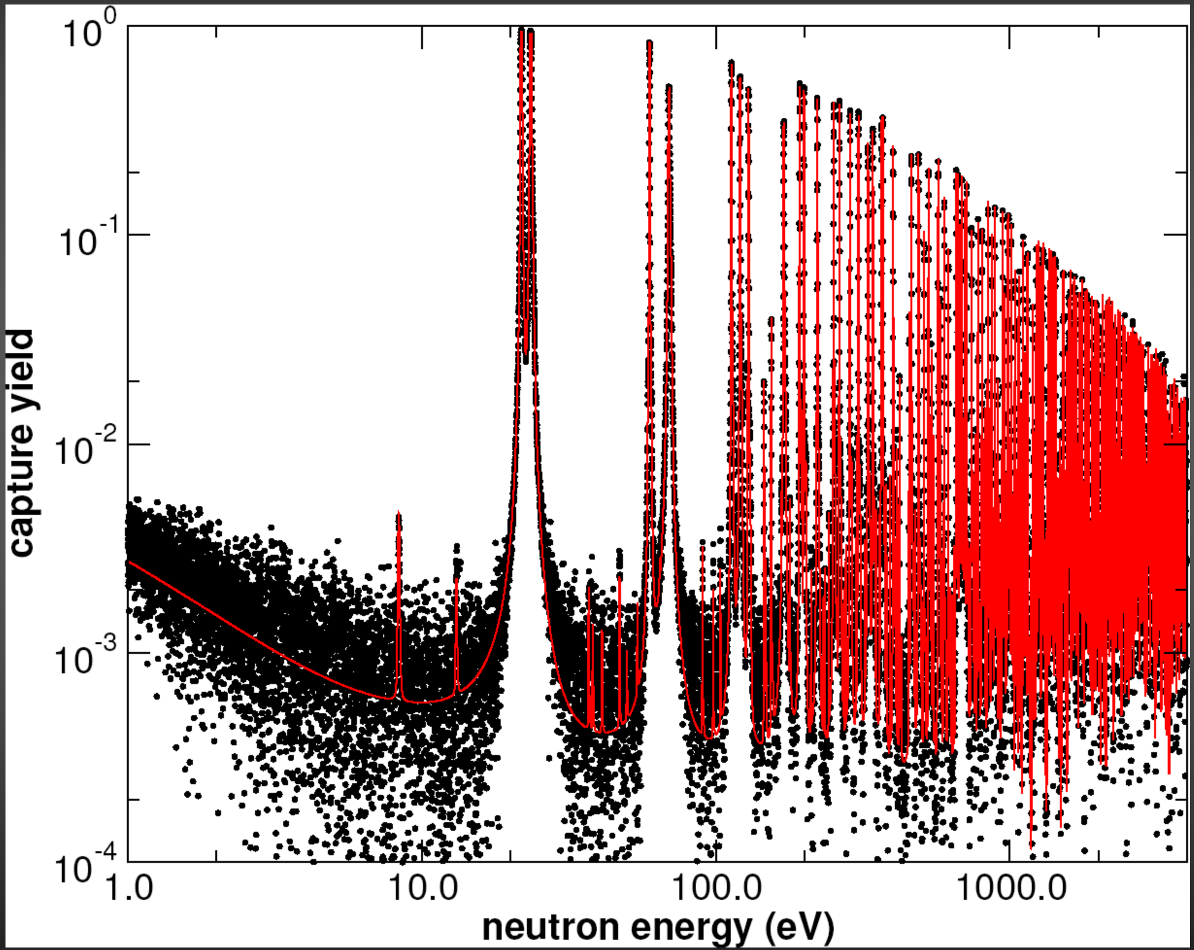
^{209}Bi

^{237}Np

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

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

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

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

Fission

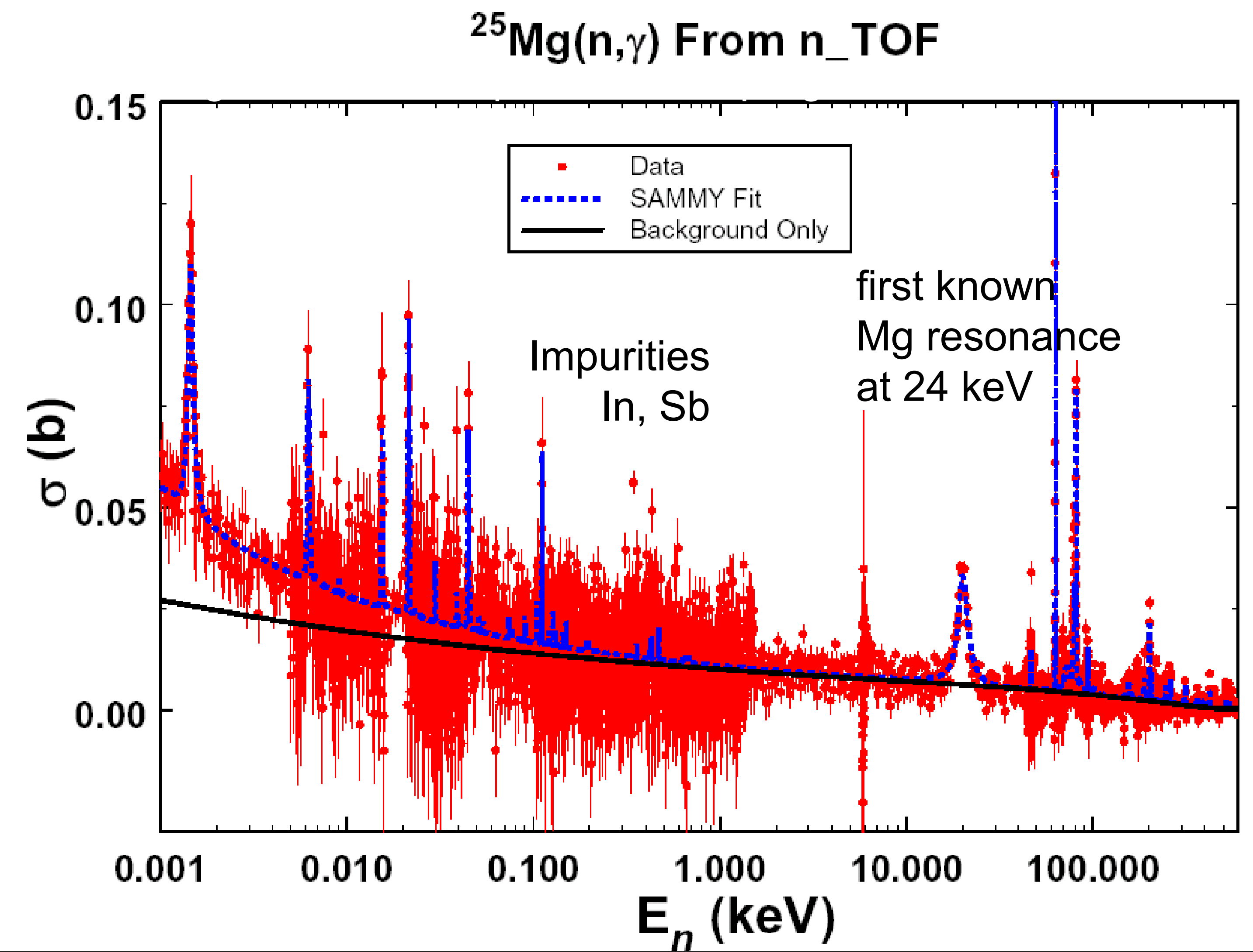
$^{233,234,235,236,238}U$

^{232}Th

^{209}Bi

^{237}Np

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



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

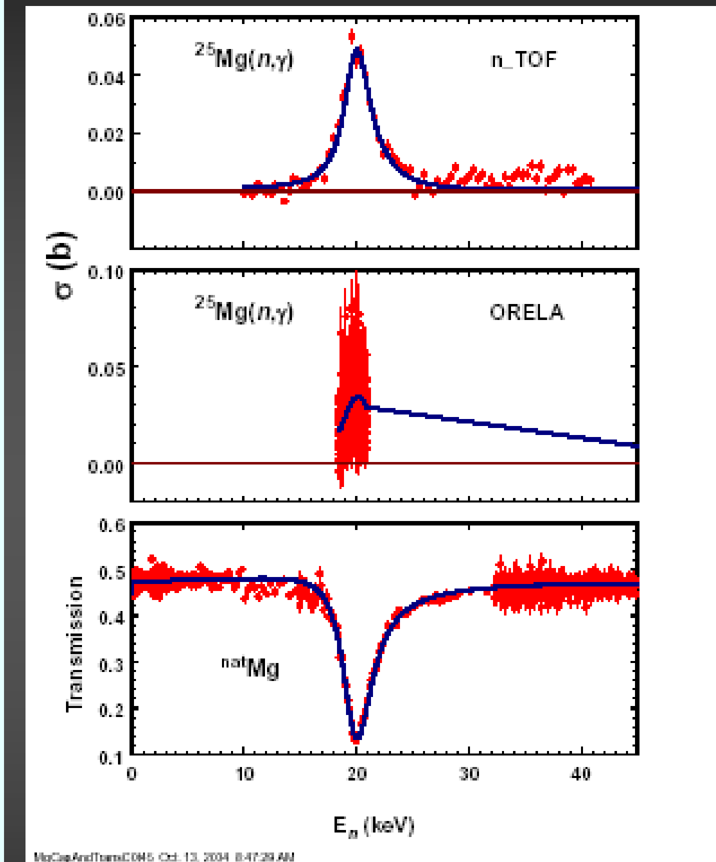
^{233,234,235,236,238}U

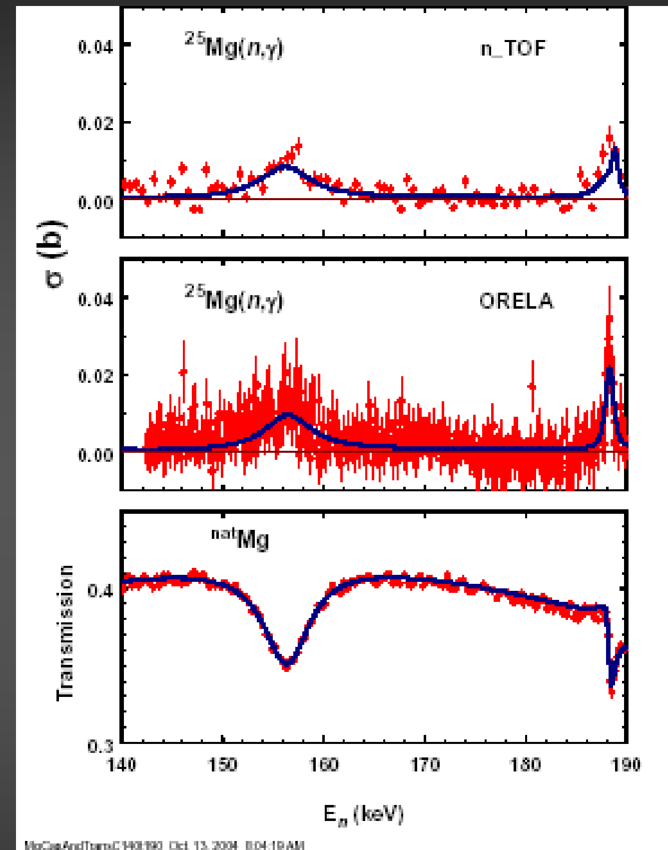
^{232}Th

^{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

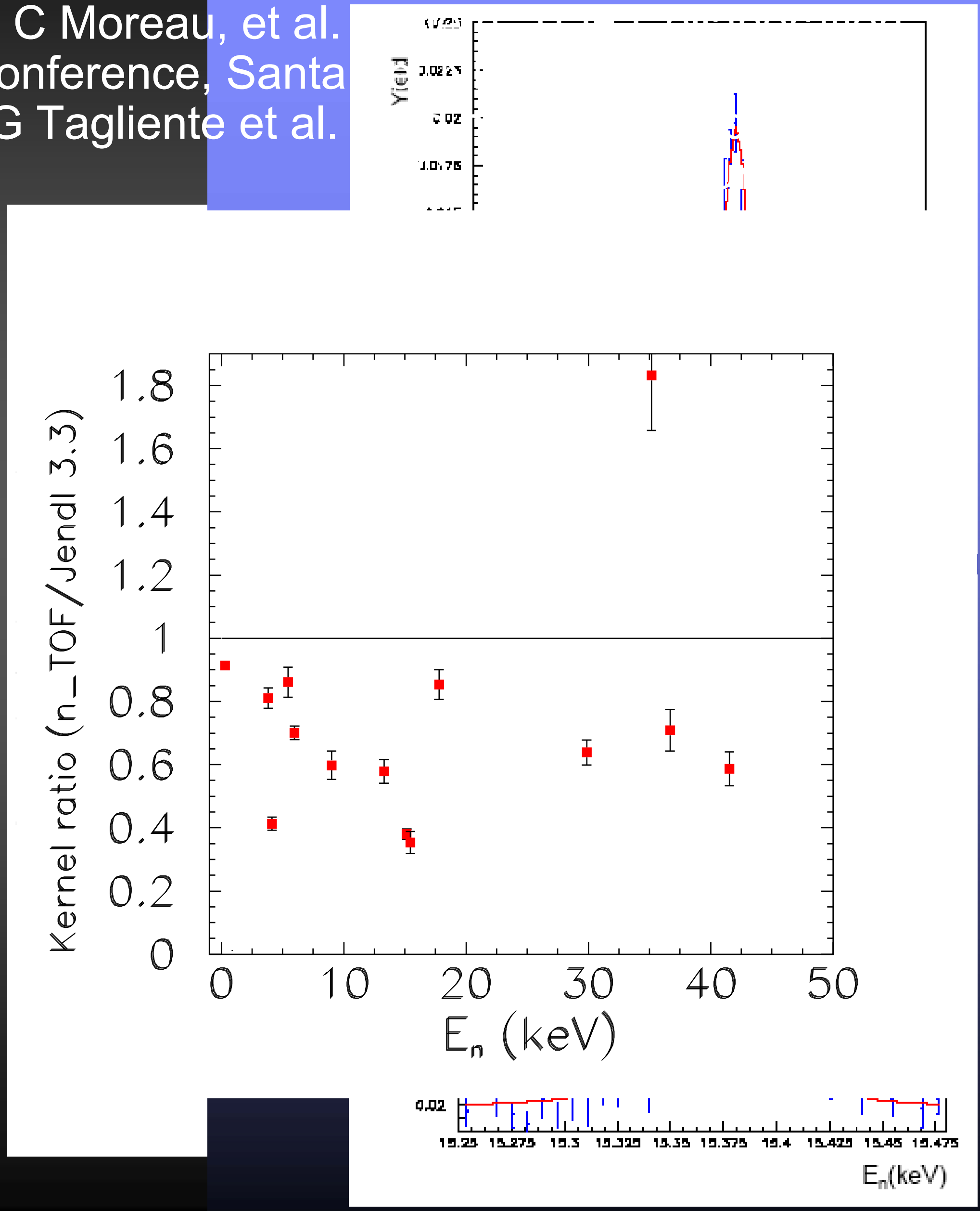
^{237}Np

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

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

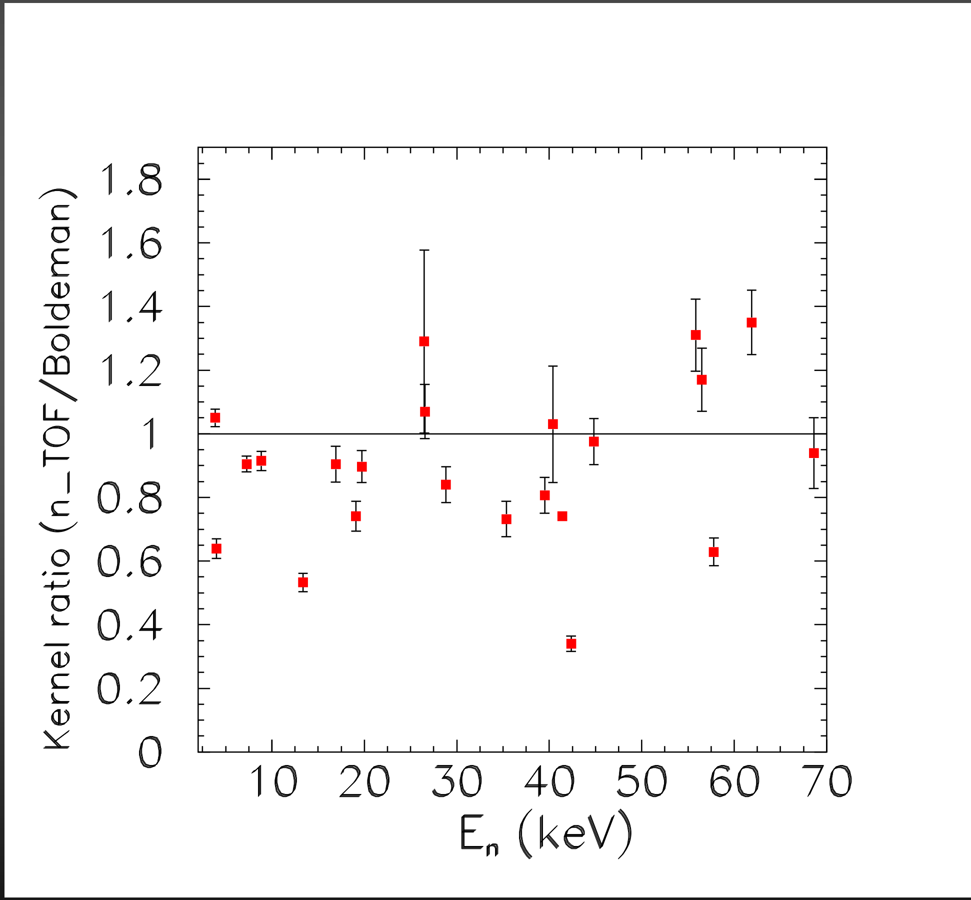
^{232}Th

^{209}Bi

^{237}Np

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

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



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

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

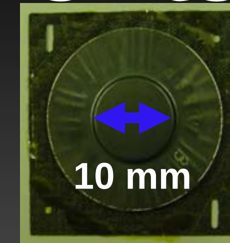
^{232}Th

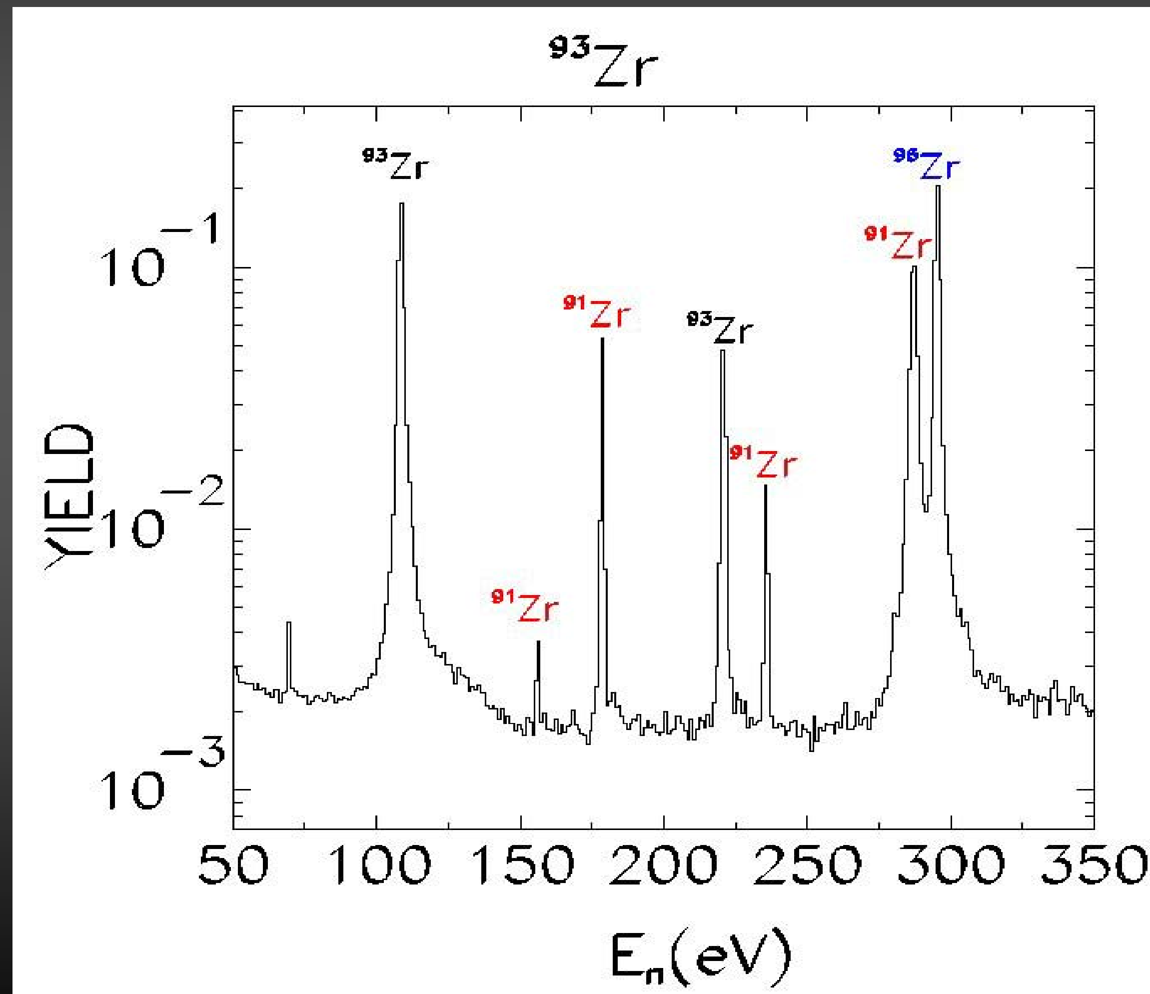
^{209}Bi

^{237}Np

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

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

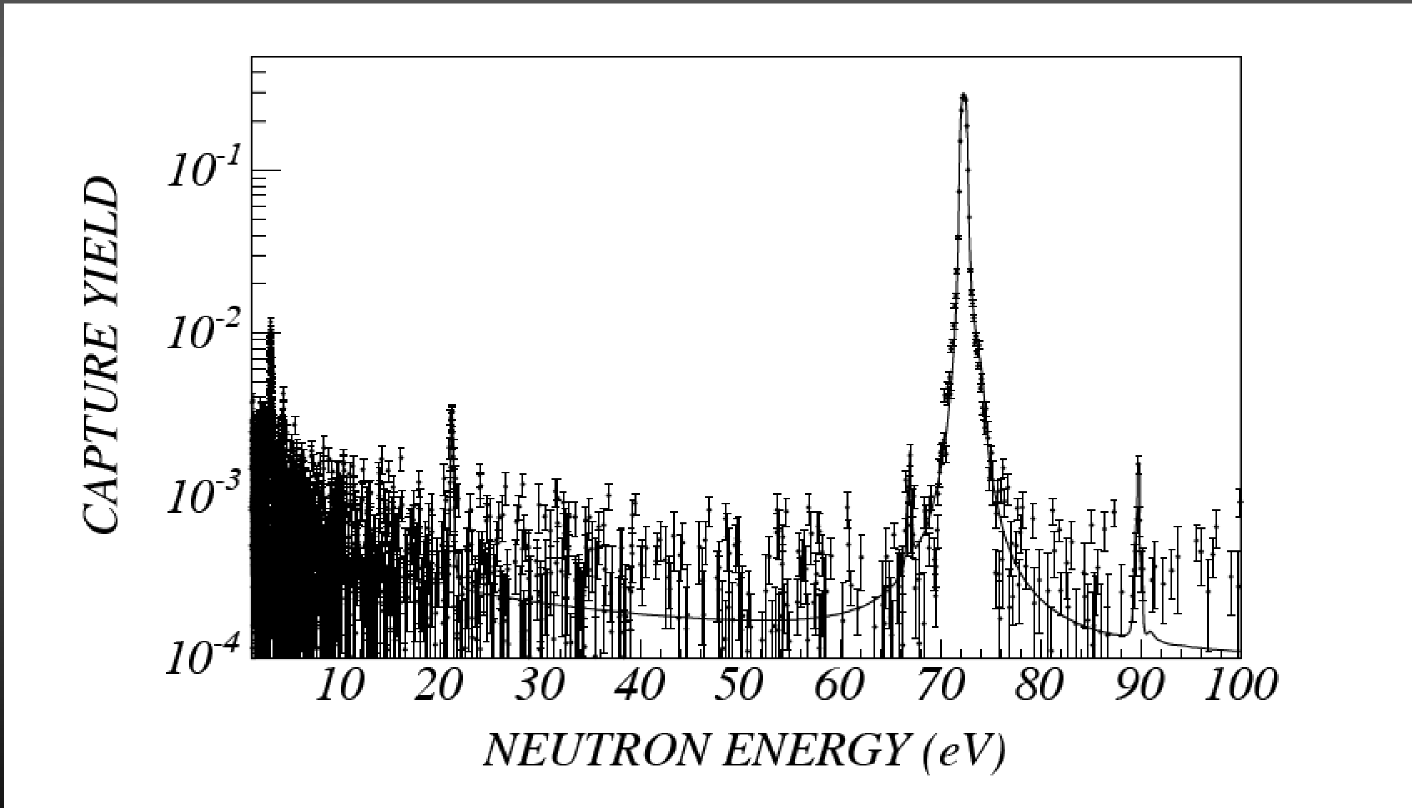
^{209}Bi

^{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

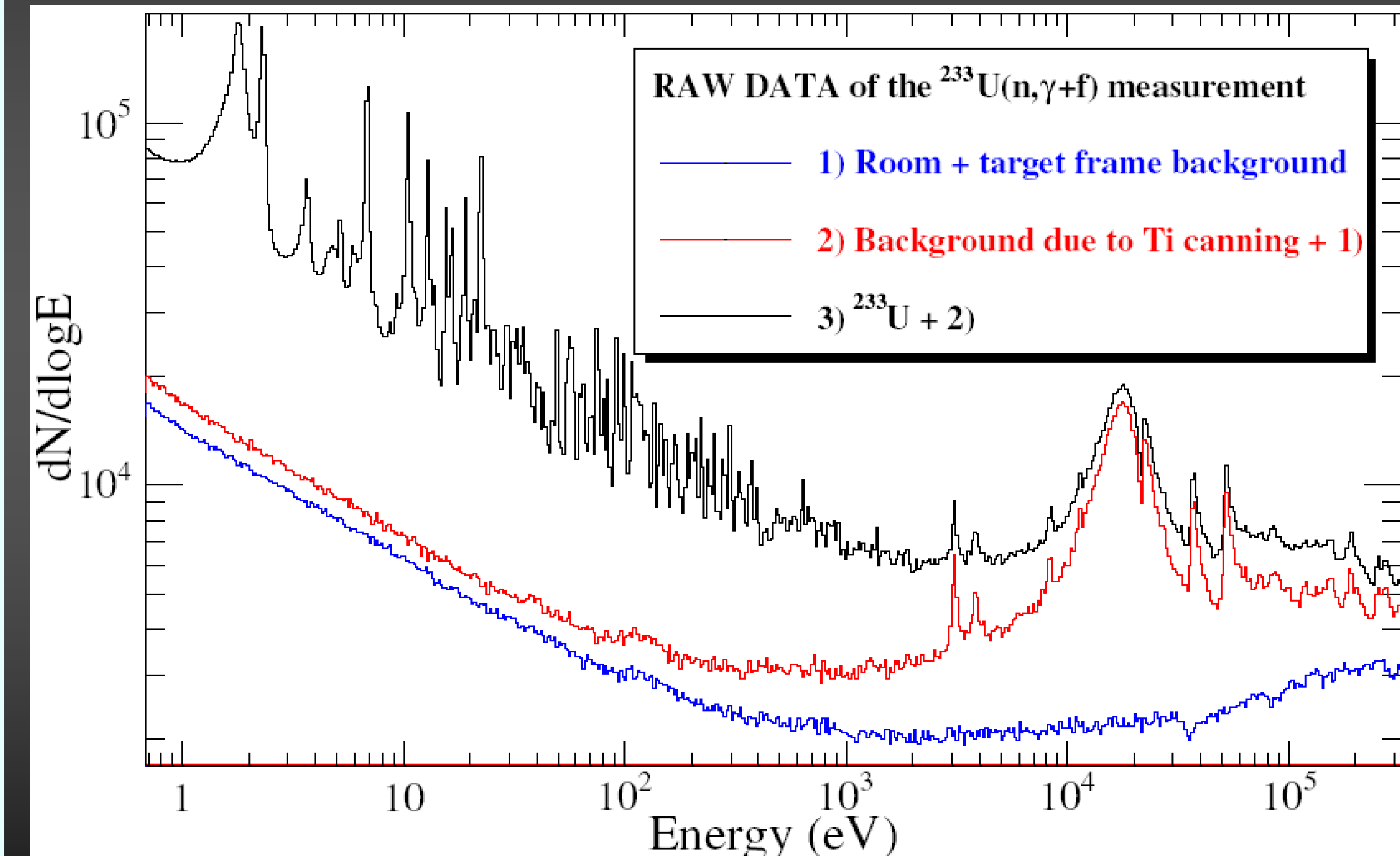
^{209}Bi

^{237}Np

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

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

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

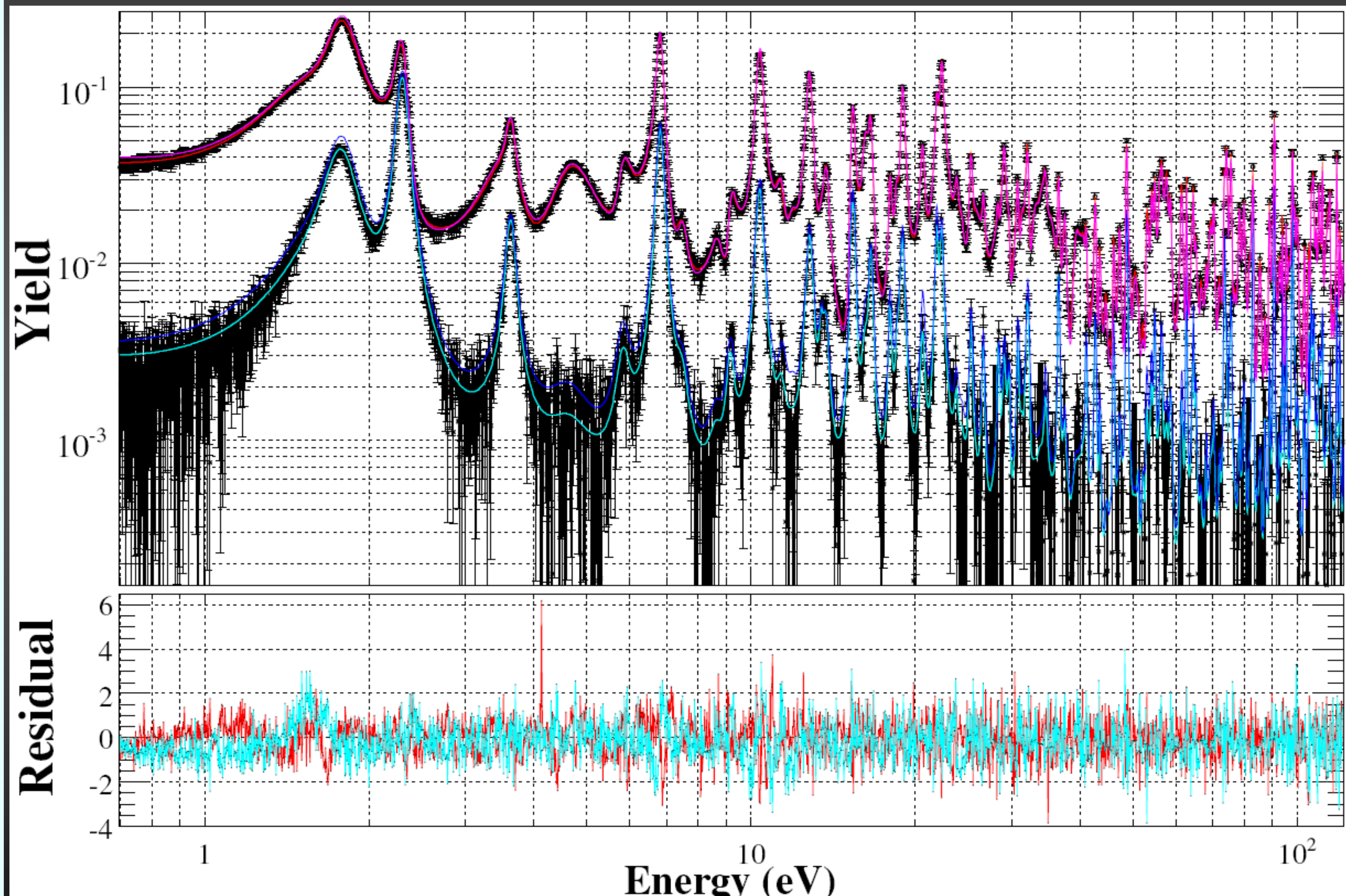
^{209}Bi

^{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

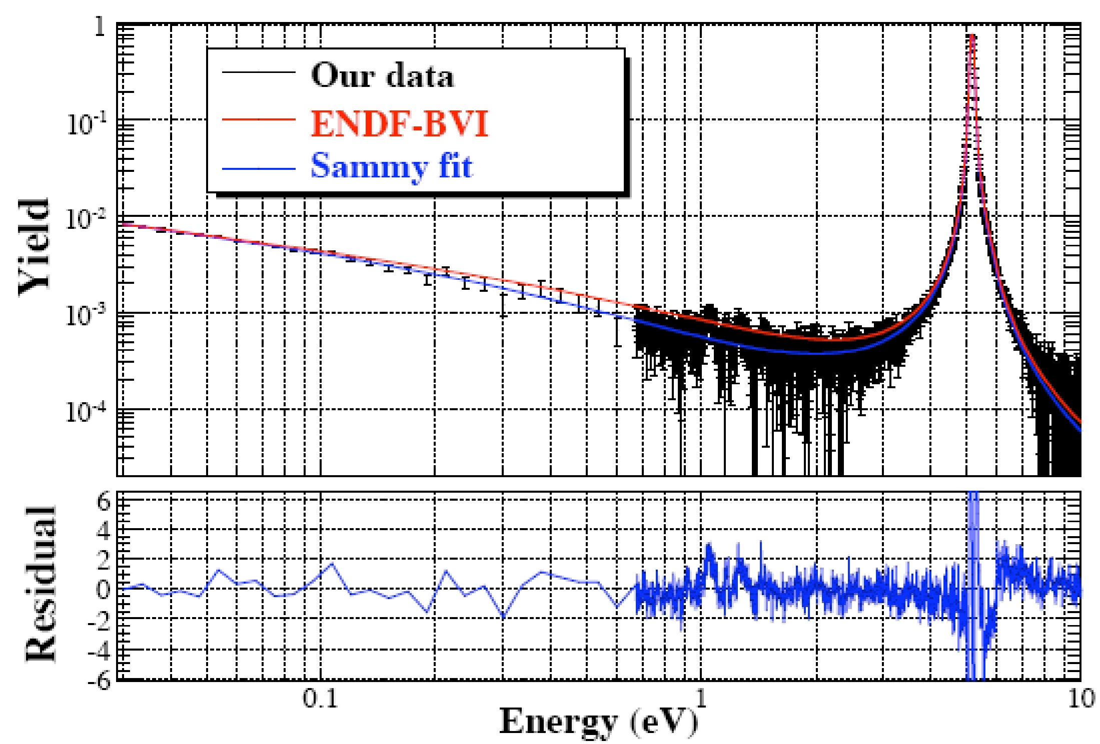
^{237}Np

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

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

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

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



n_TOF TAC in operation

n_TOF experiments

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

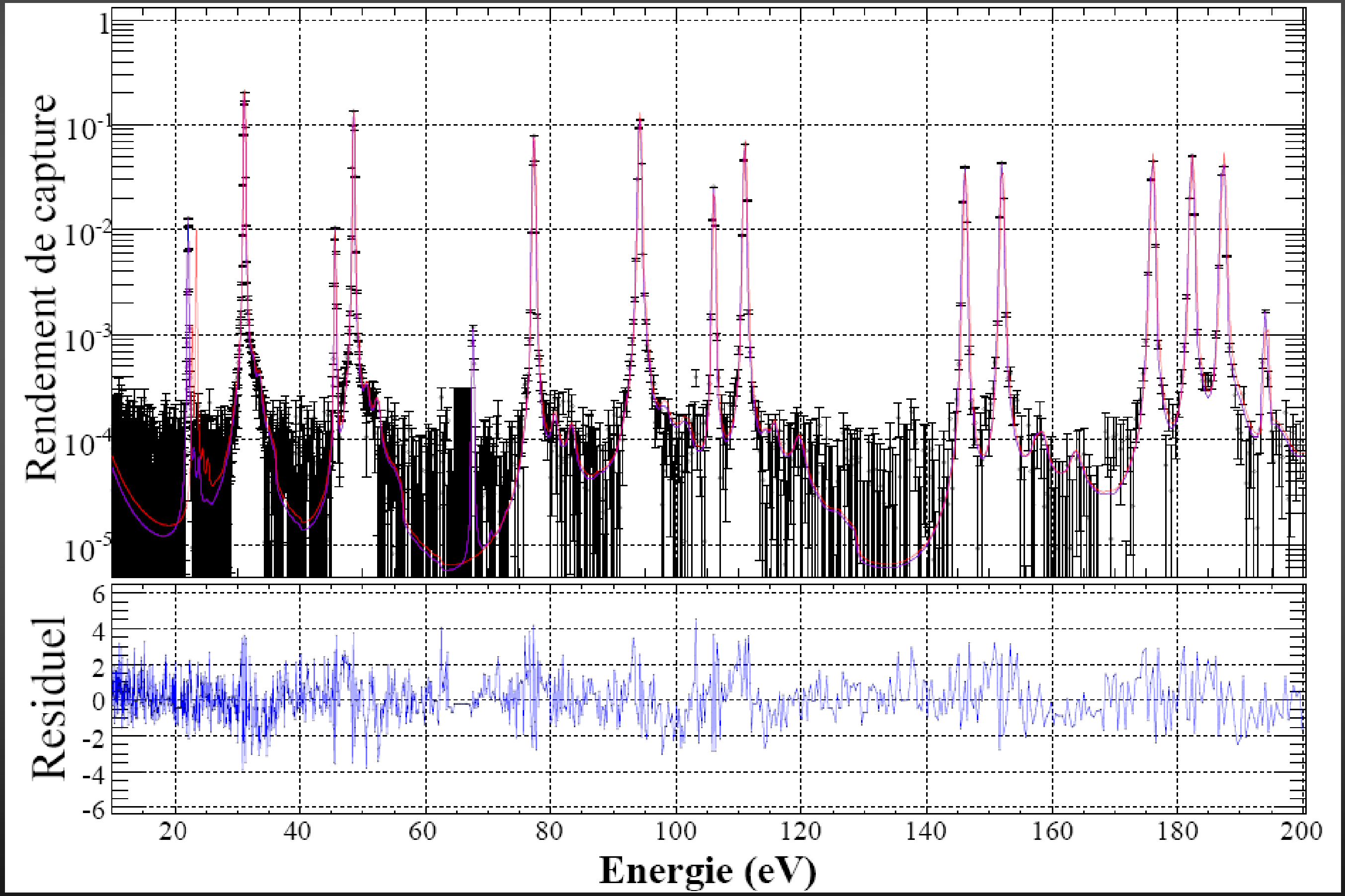
^{209}Bi

^{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

$^{186,187,188}Os$

$^{233,234}U$

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

Fission

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

^{232}Th

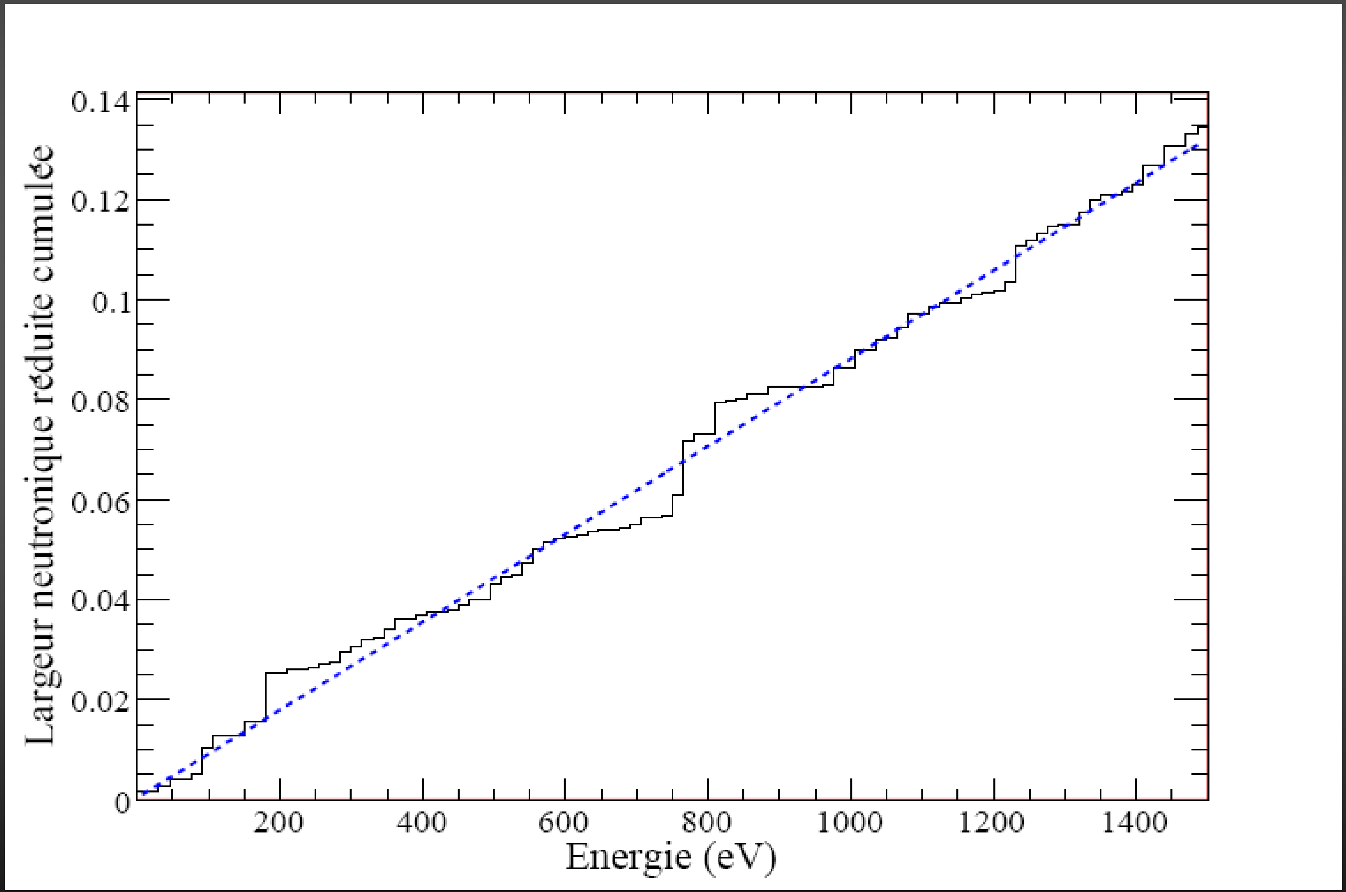
^{209}Bi

^{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

^{186,187,188}Os

^{233,234}U

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

Fission

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

^{232}Th

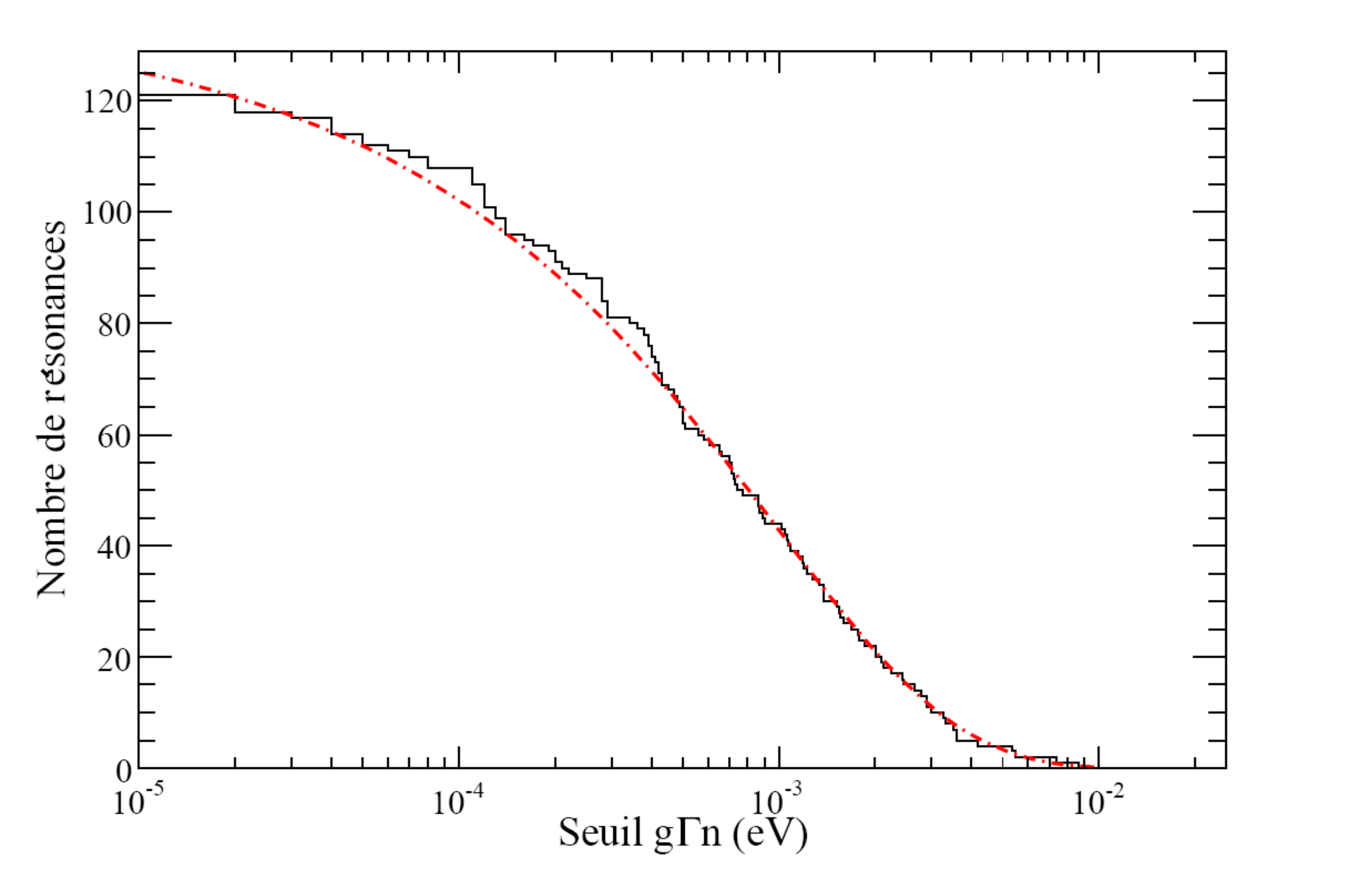
^{209}Bi

^{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,γ)



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

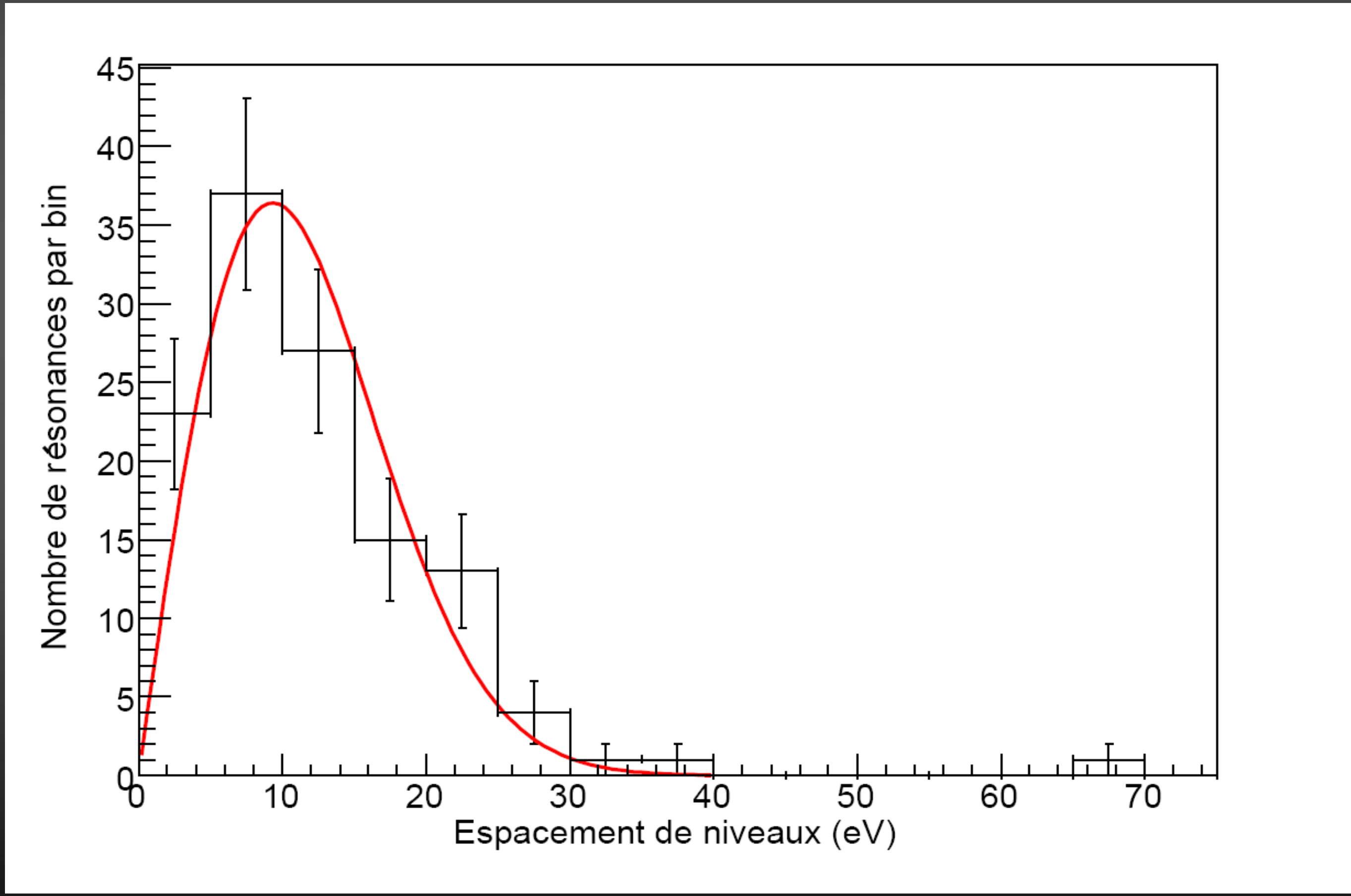
^{209}Bi

^{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

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

Capture

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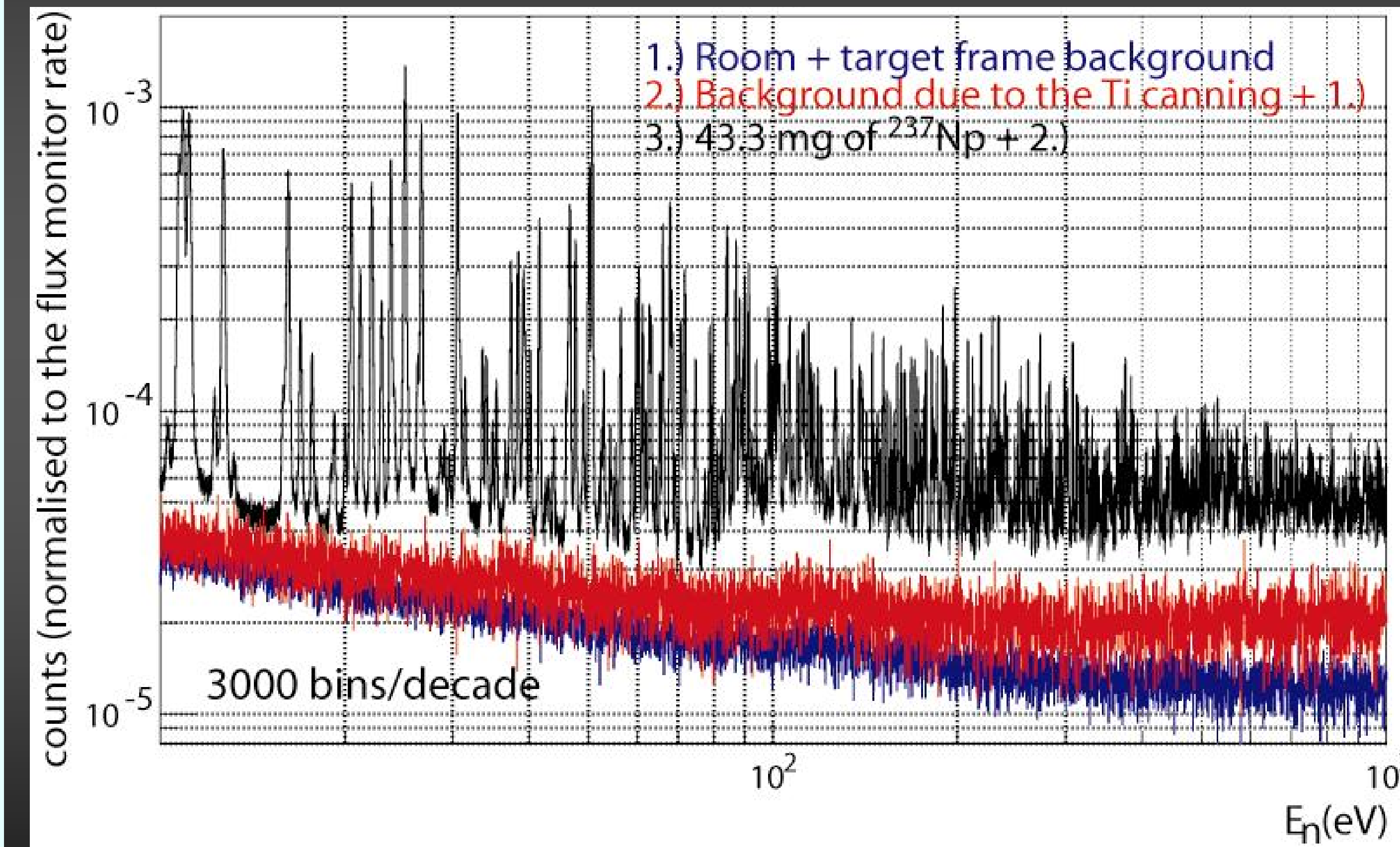

n_TOF TAC in operation

n_TOF experiments

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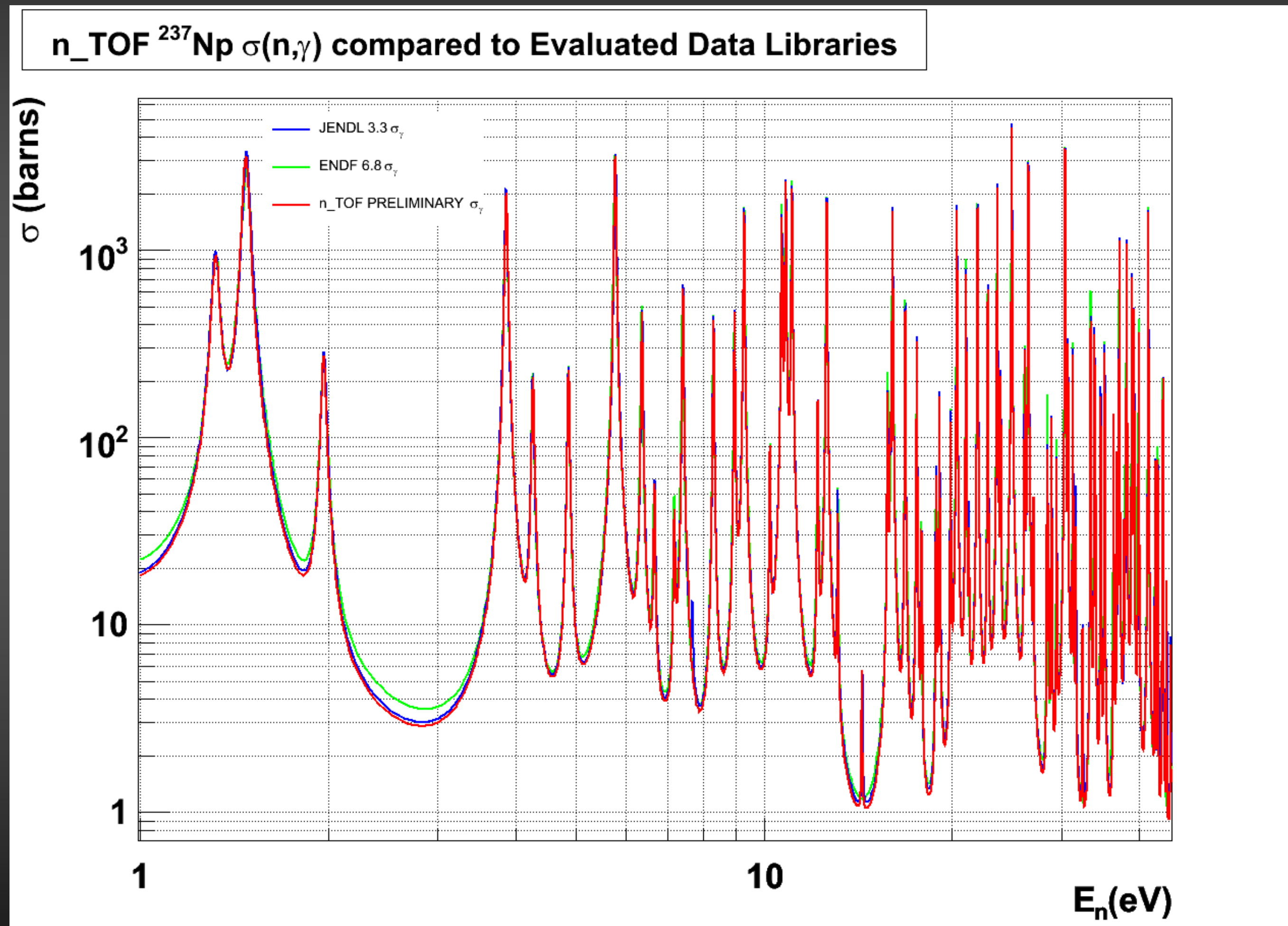
C Guerero, D Cano-Ott, et al. - The n_TOF Collaboration
PHYSOR 2006, Vancouver, September 2006



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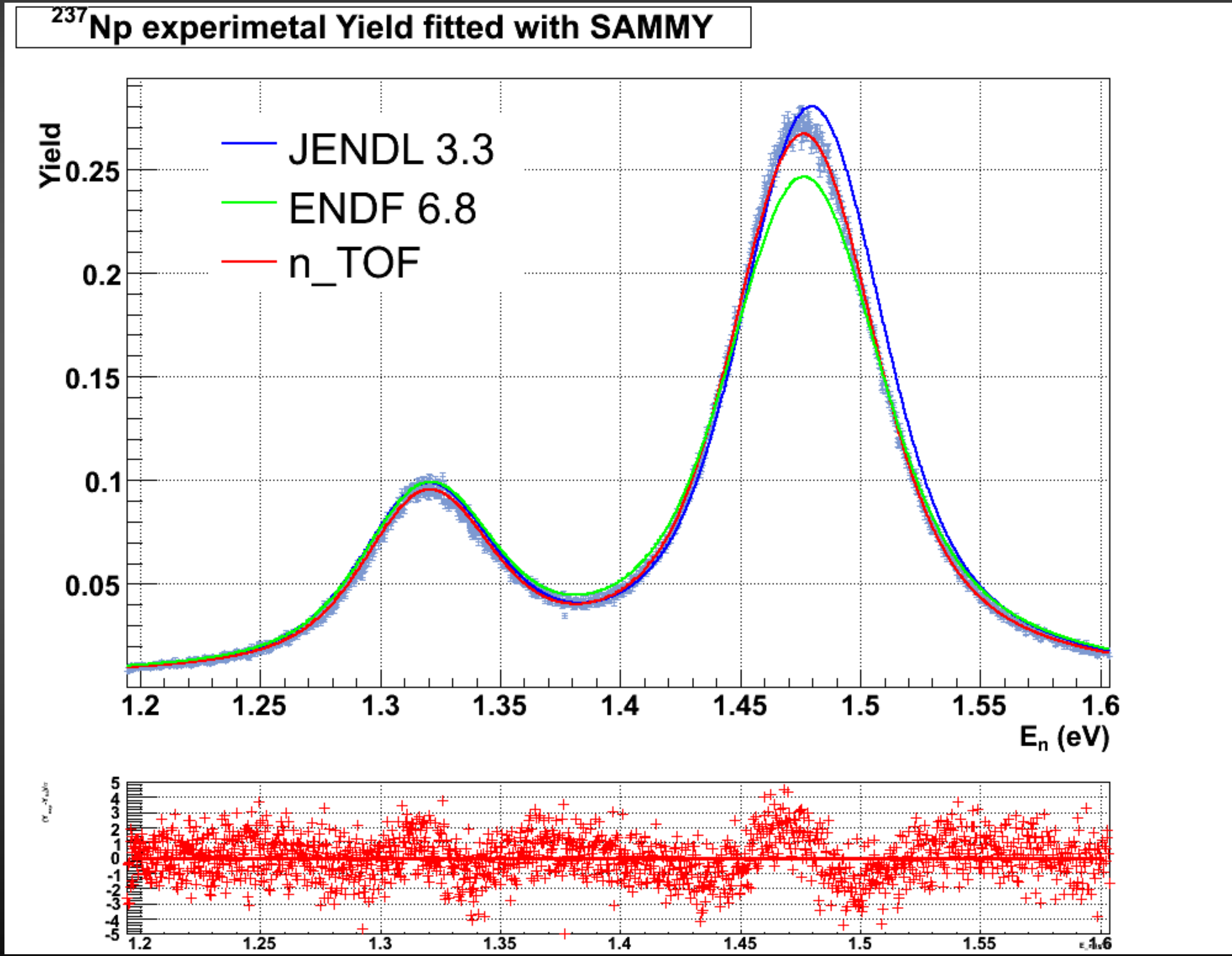
C Guerero, D Cano-Ott, et al. - The n_TOF Collaboration
PHYSOR 2006, Vancouver, September 2006



n_TOF experiments

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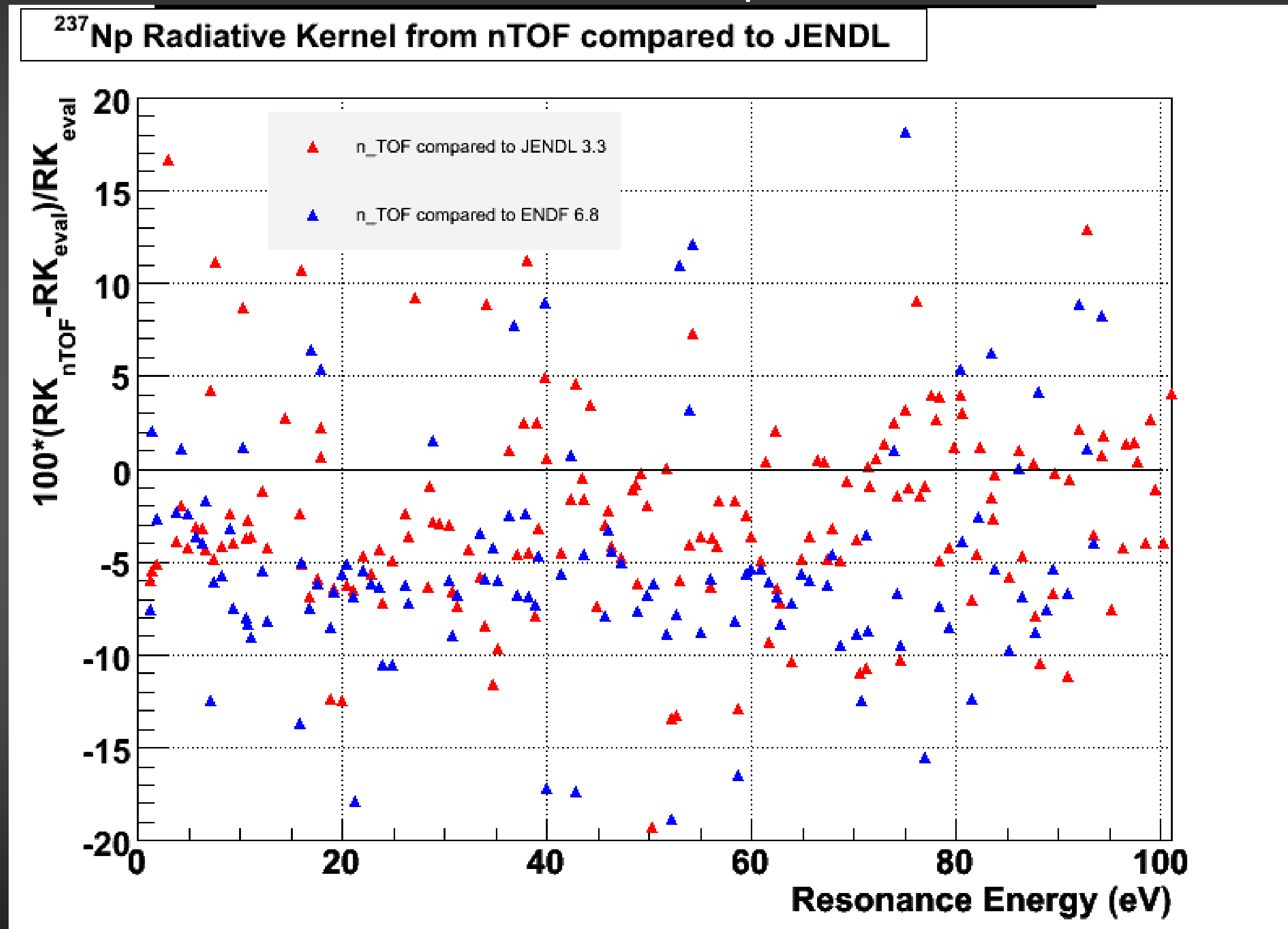
C Guerero, D Cano-Ott, et al. - The n_TOF Collaboration
PHYSOR 2006, Vancouver, September 2006



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

n_TOF experiments

Capture

^{151}Sm

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

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$^{186,187,188}Os$

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

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^{209}Bi

^{237}Np

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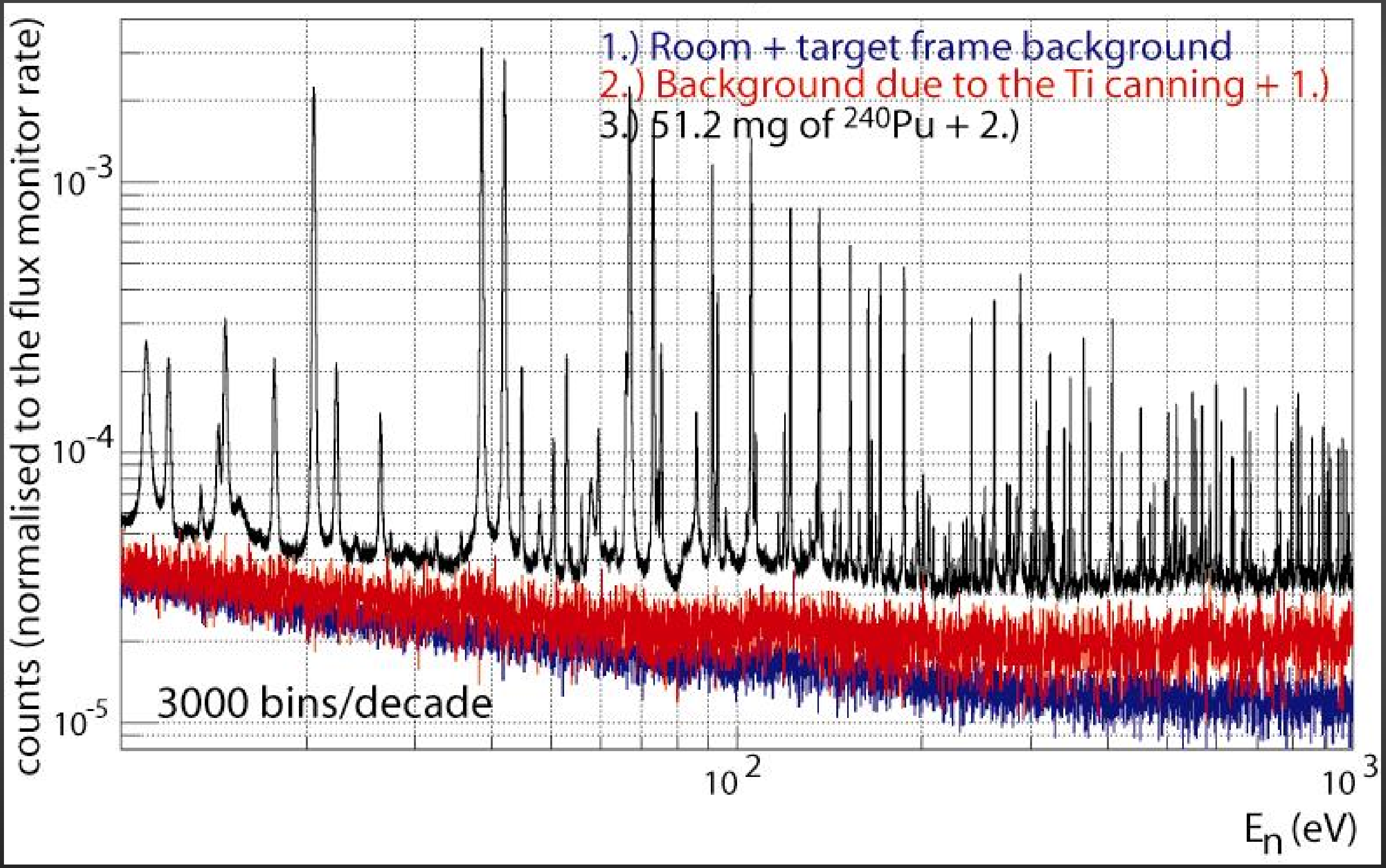
D Cano-Ott, et al. - The n_TOF Collaboration
ND2004 Conference, Santa Fe, NM – Sept. 2004



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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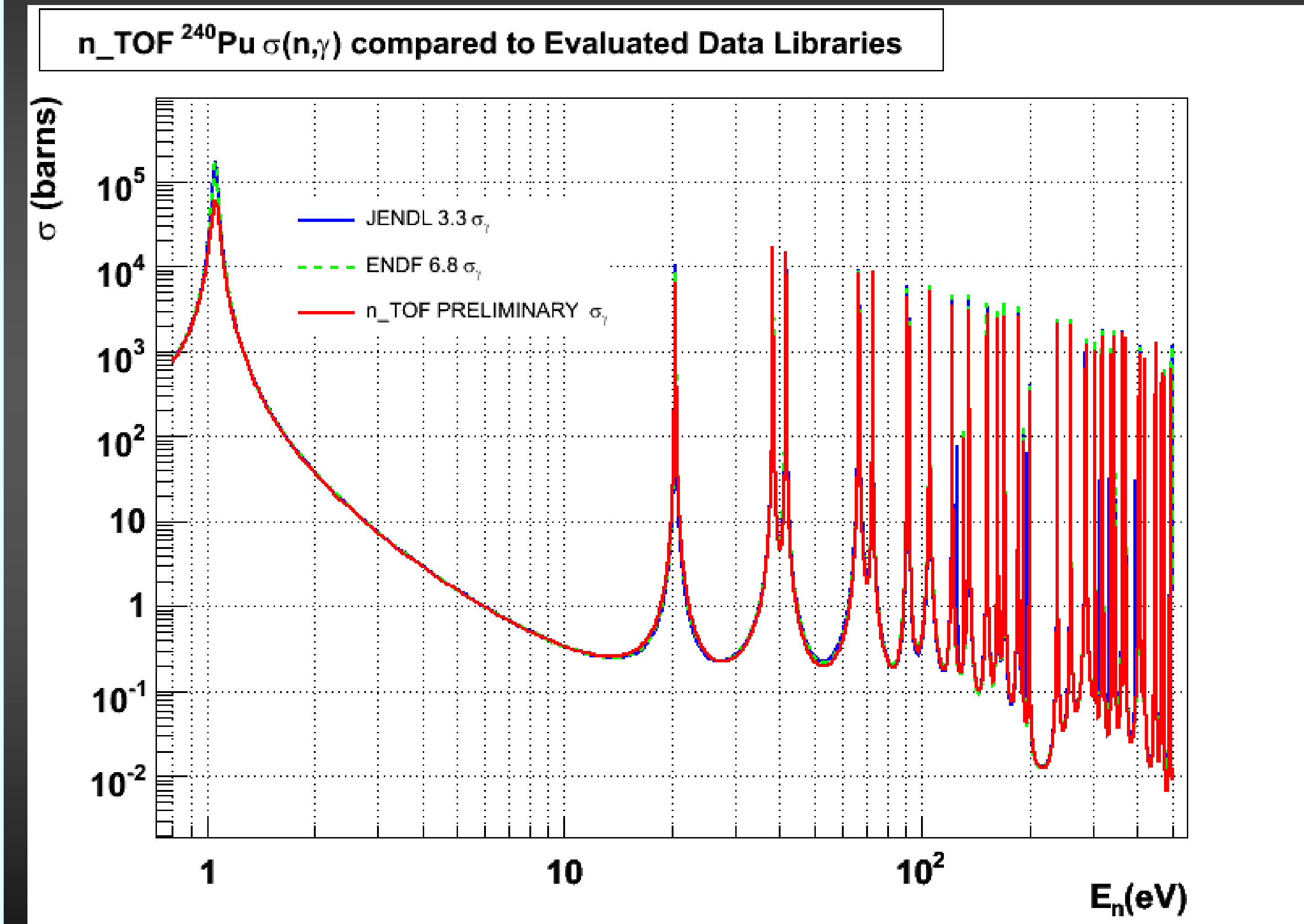

n_TOF TAC in operation

n_TOF experiments

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

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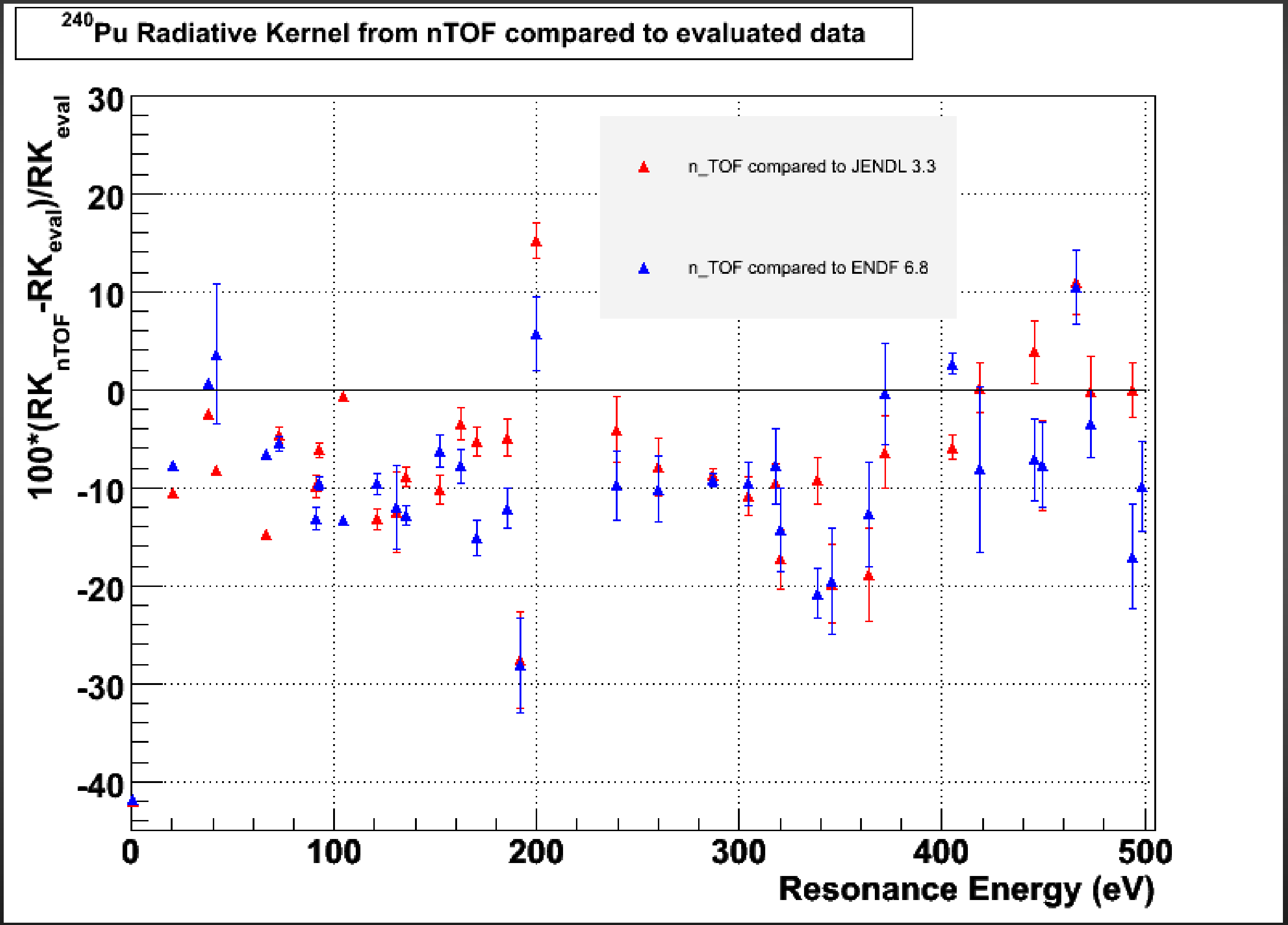
^{237}Np

^{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}.

n_TOF experiments

Capture

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

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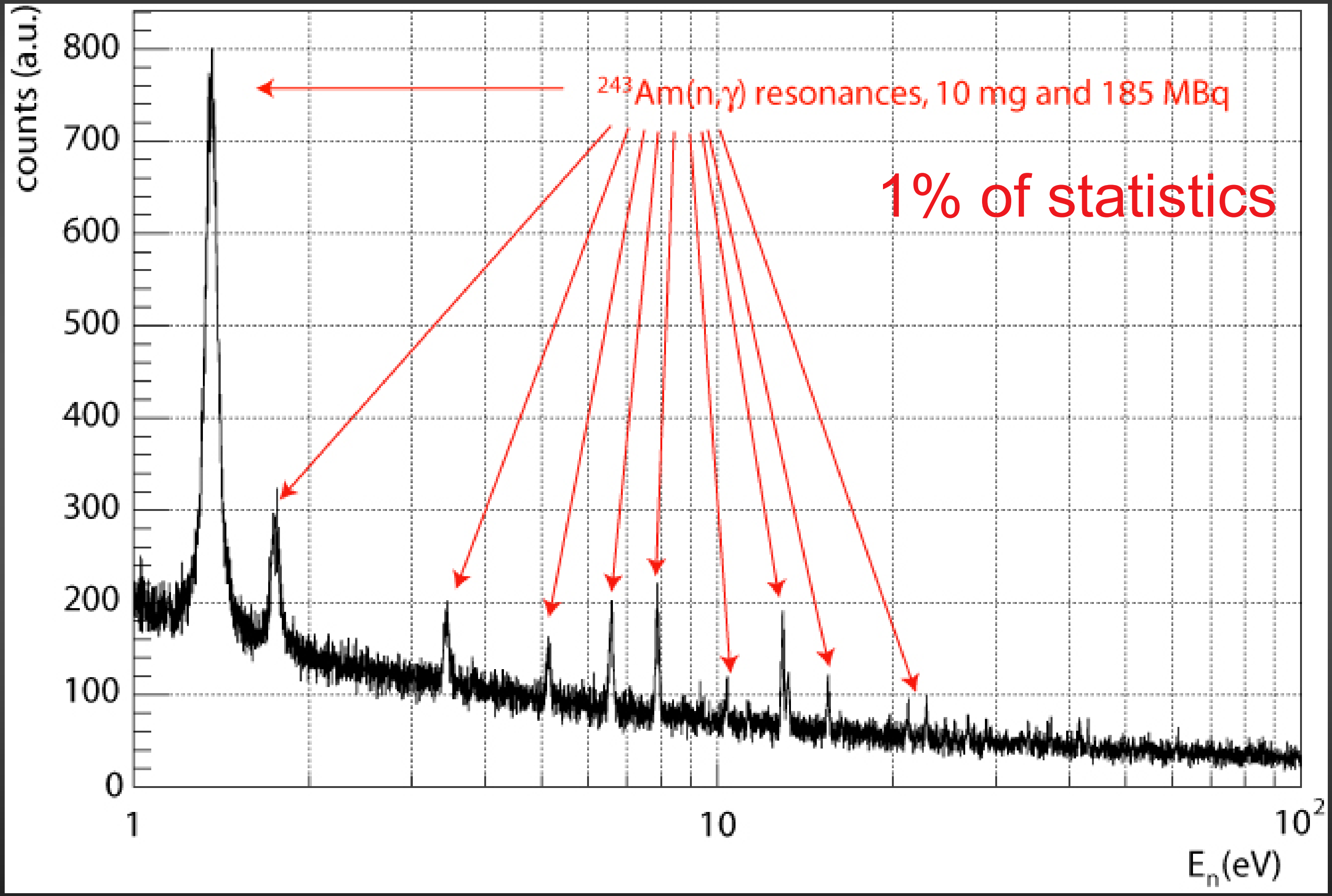
$^{241,243}Am$, ^{245}Cm

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



n_TOF TAC in operation

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^{232}Th

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Fission

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^{232}Th

^{209}Bi

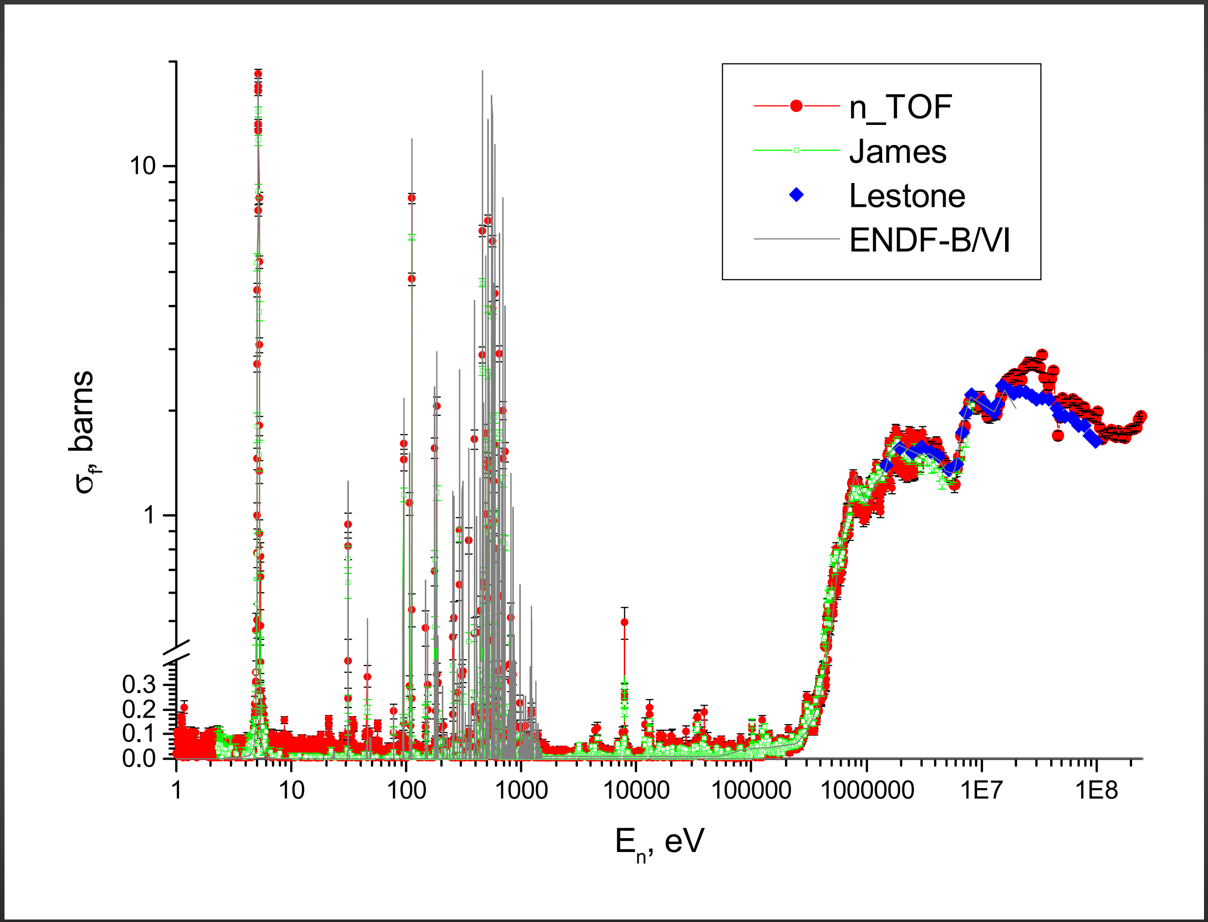
^{237}Np

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

n_TOF experiments

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

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)

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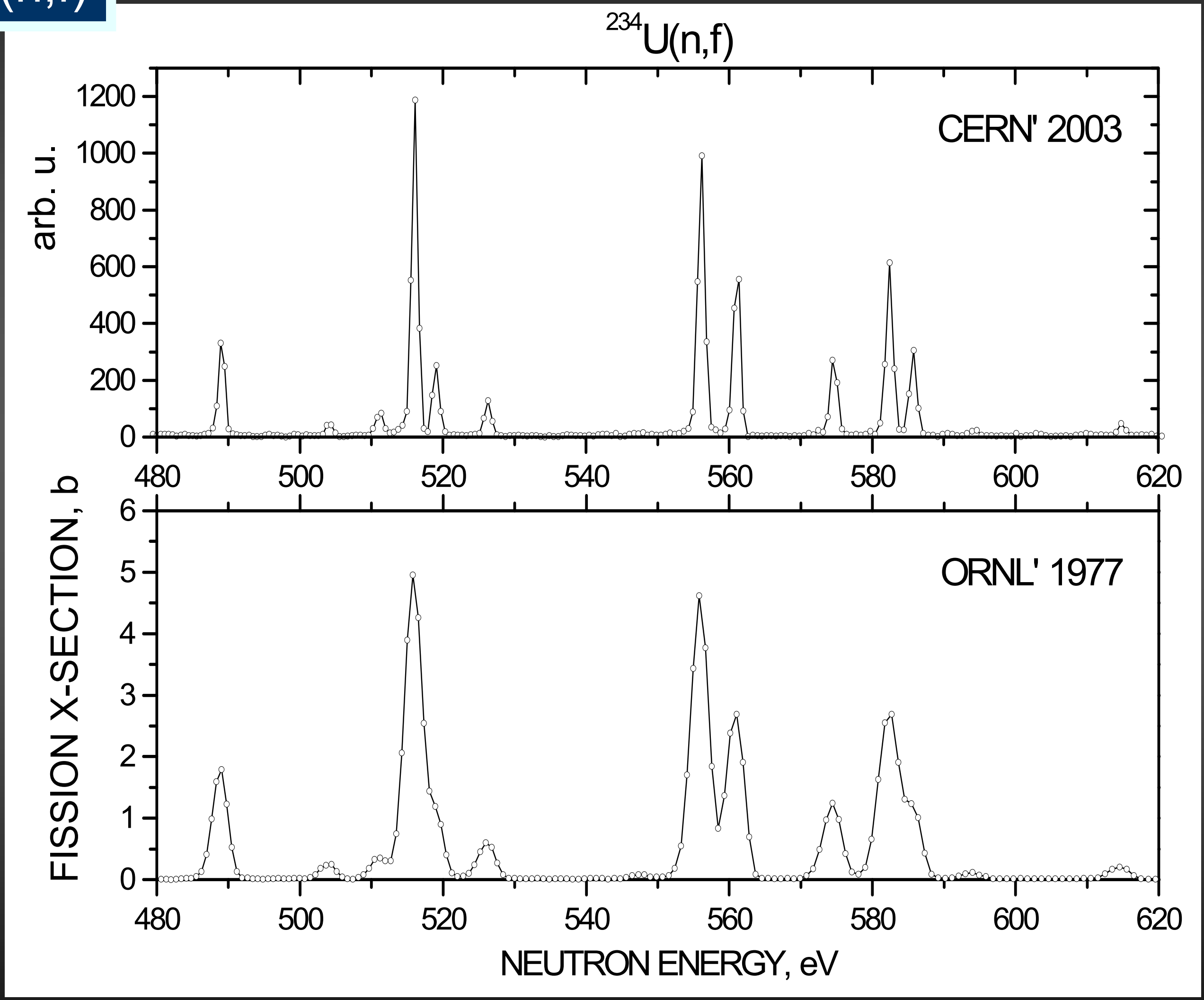
^{232}Th

^{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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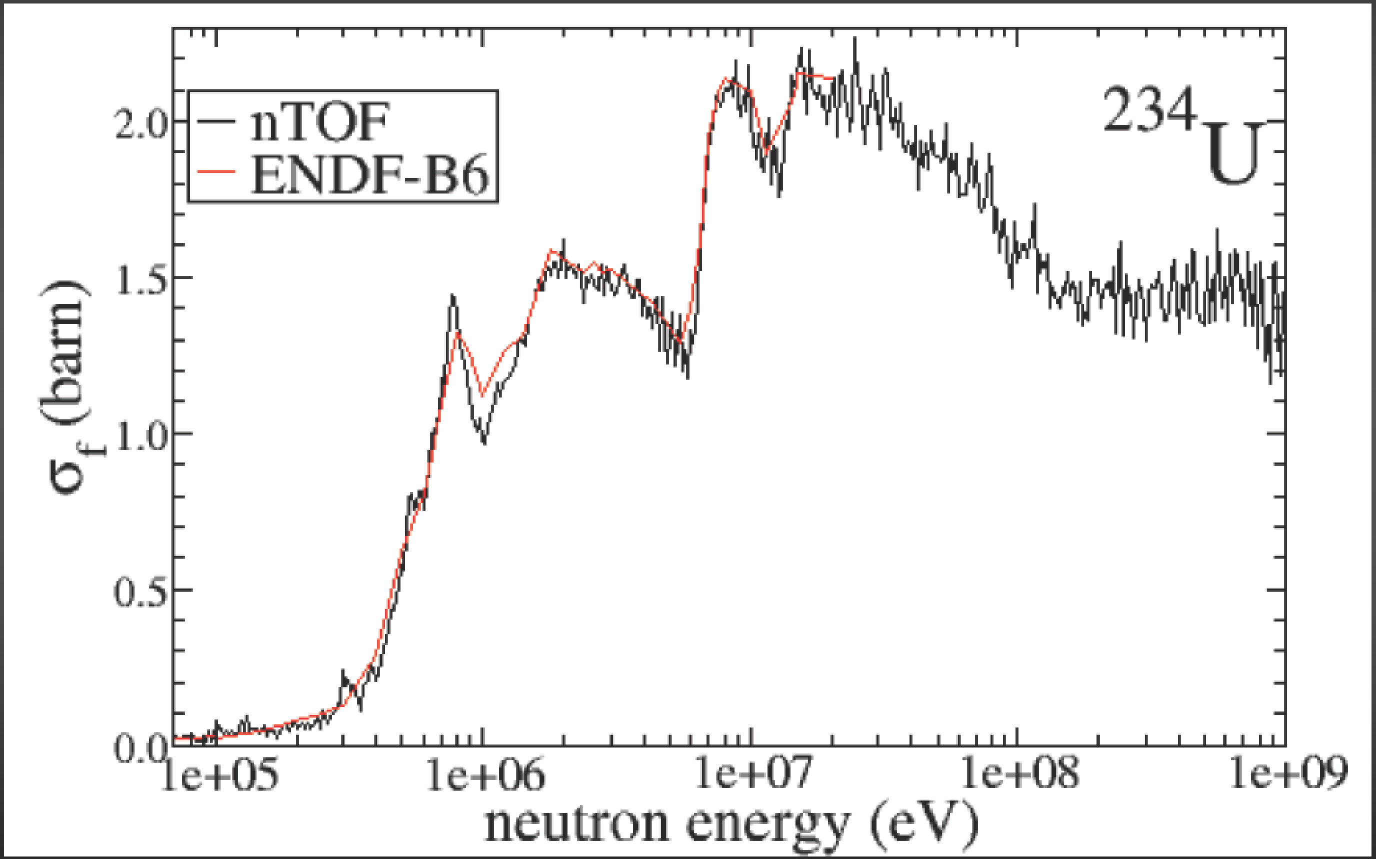

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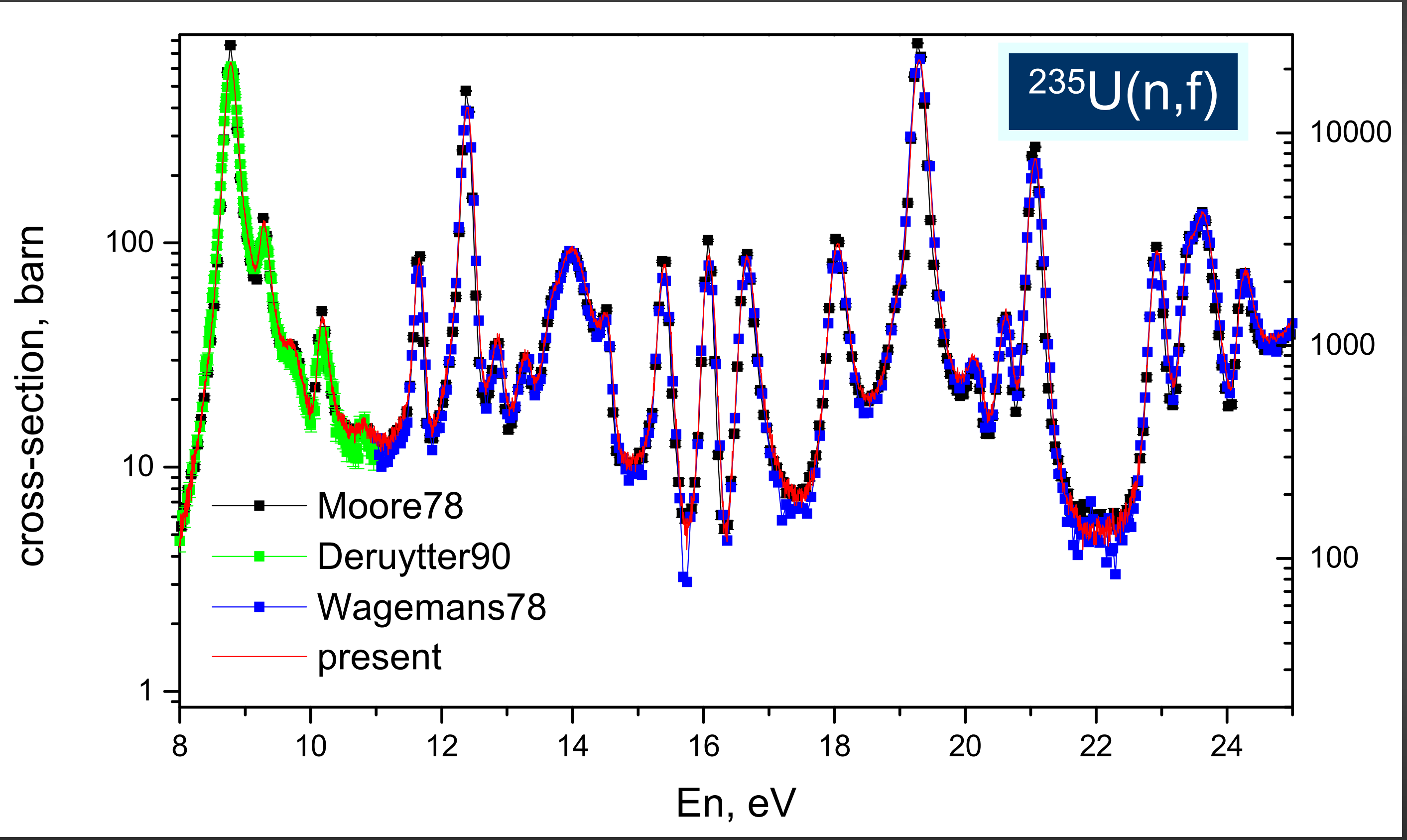
FIC-0 (2003)



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

n_TOF experiments

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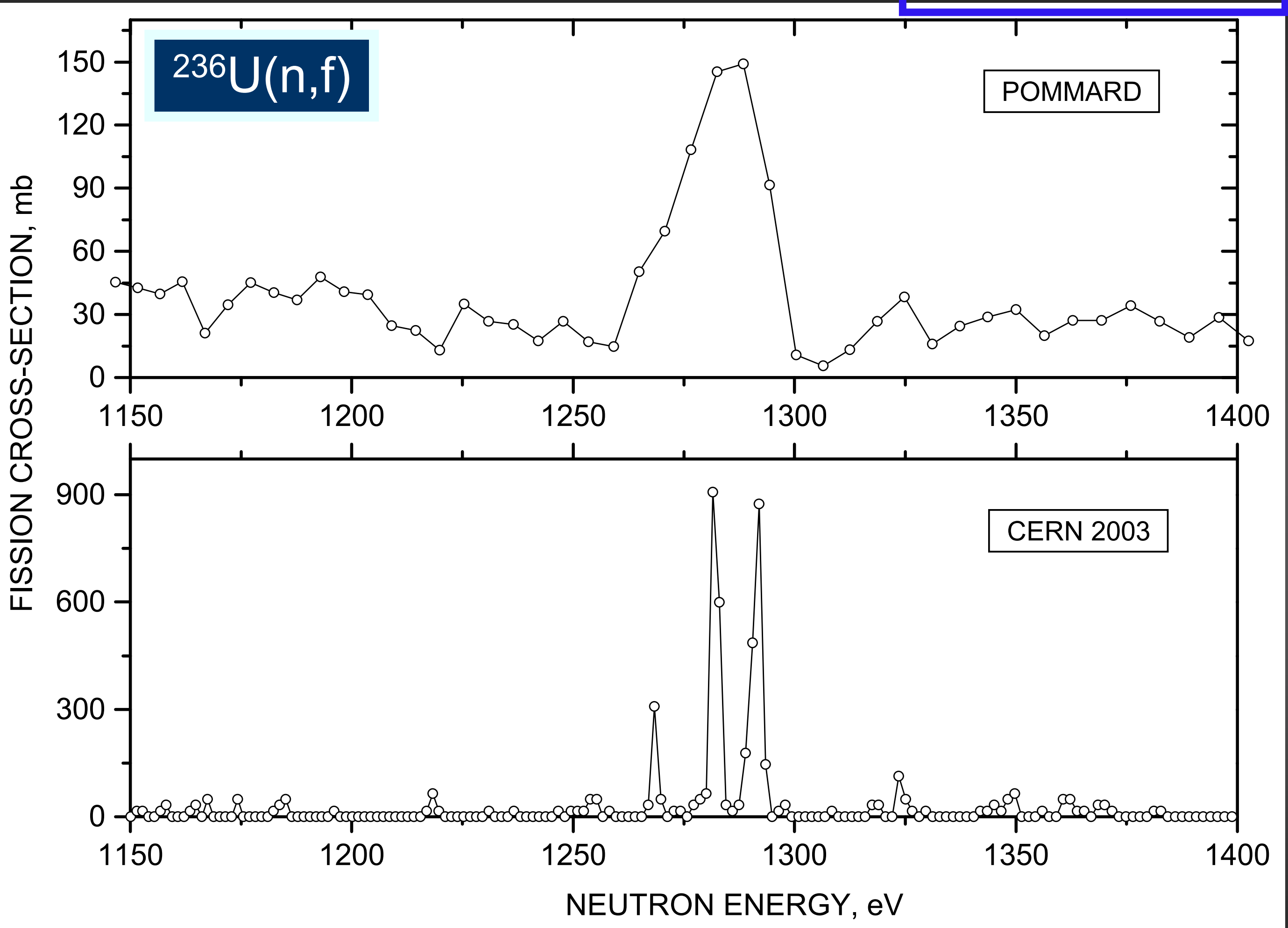
^{232}Th

^{209}Bi

^{237}Np

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

FIC-1 (2003)



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

^{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

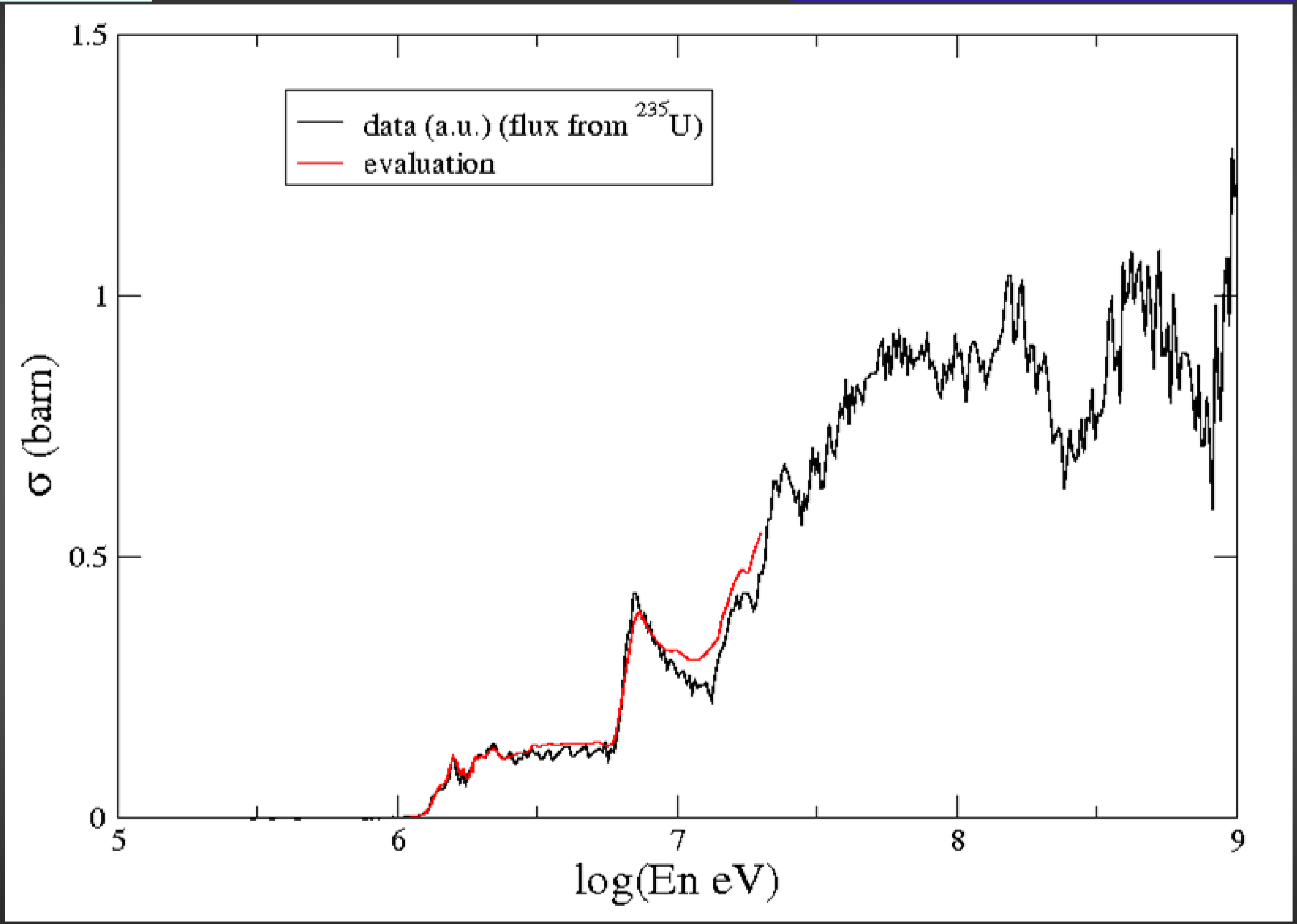
^{209}Bi

^{237}Np

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

^{232}Th(n,f)

PPAC detectors



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

n_TOF experiments

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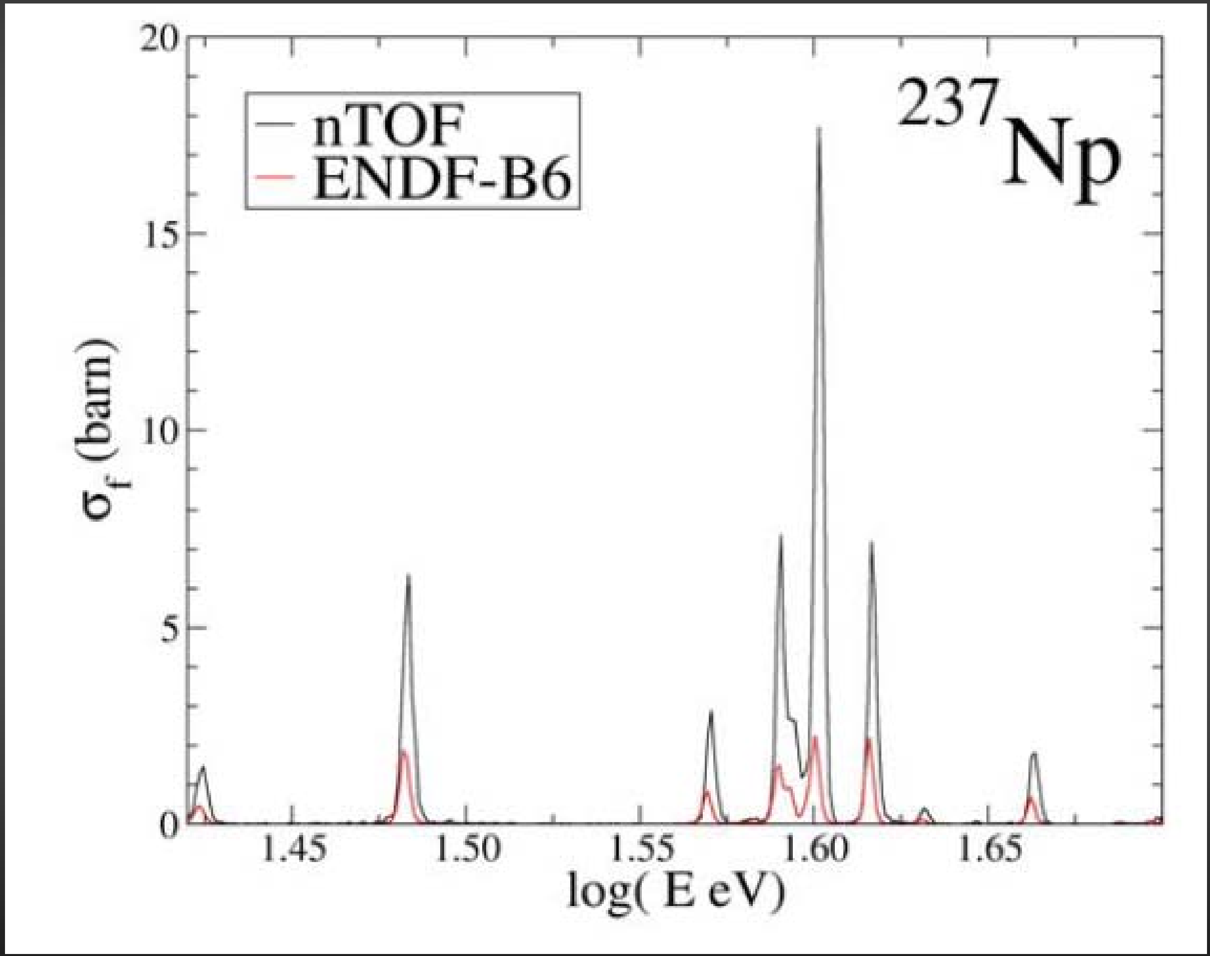
^{237}Np

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

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

FIC-0 (2003)



Higher fission x-section in the sub-threshold region

n_TOF experiments

Capture

^{151}Sm

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$^{186,187,188}Os$

$^{233,234}U$

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

Fission

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

^{232}Th

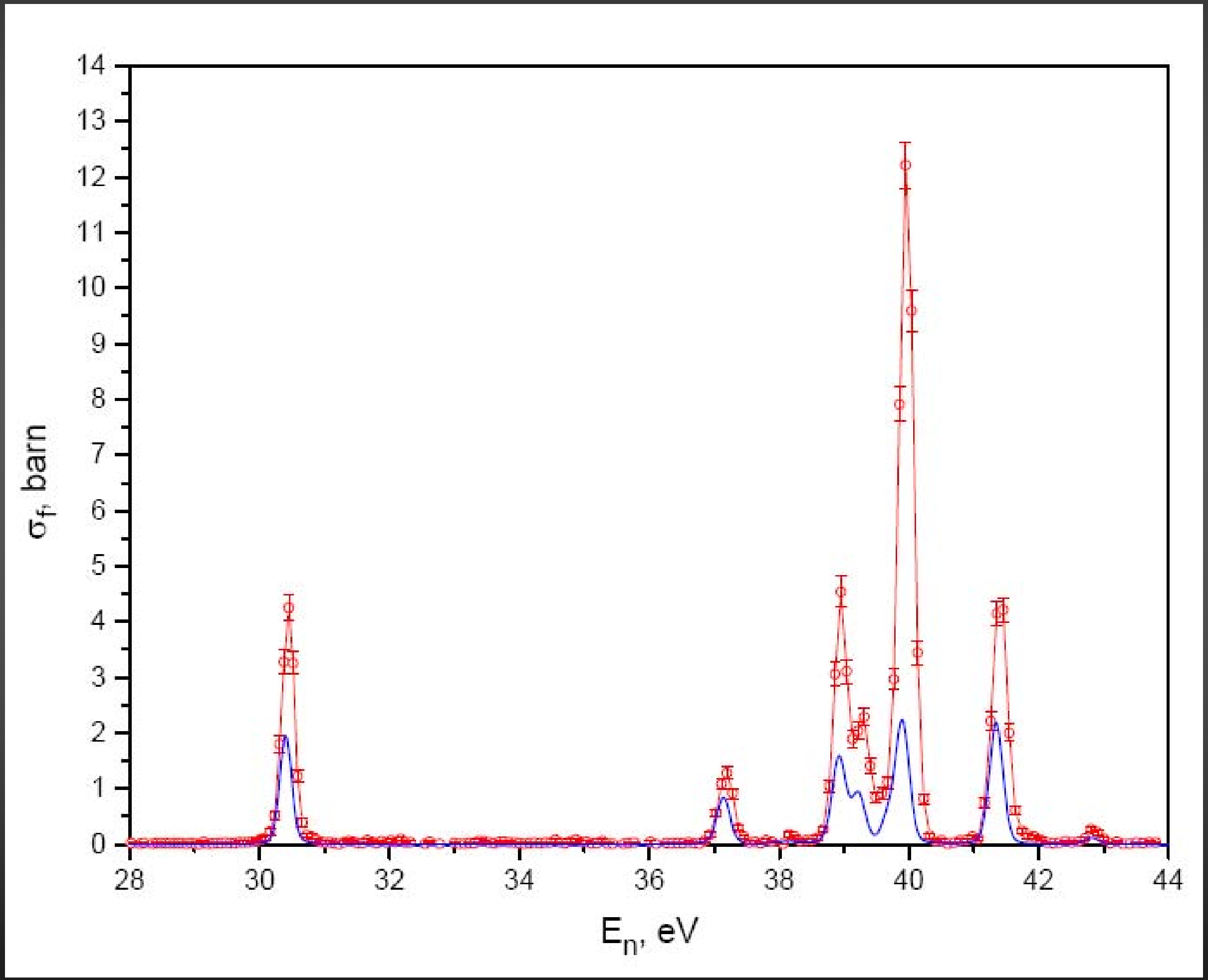
^{209}Bi

^{237}Np

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

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

PPACs (2003)



Higher fission x-section in the sub-threshold region

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

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

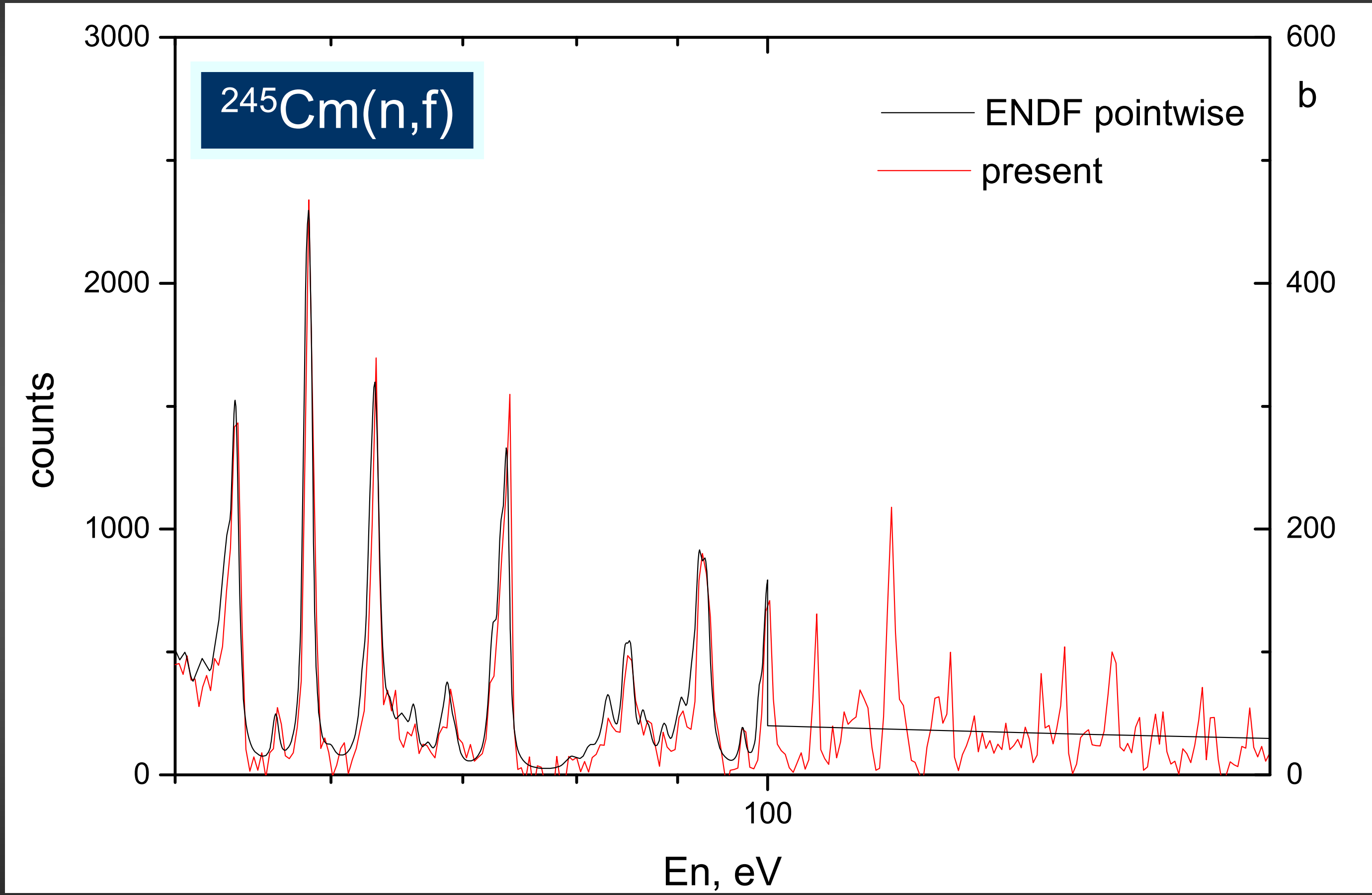
^{232}Th

^{209}Bi

^{237}Np

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

FIC-1 (2003)



High-resolution data up to high(er) energies

n_TOF experiments

FIC-0 (2003)

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

Fission

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

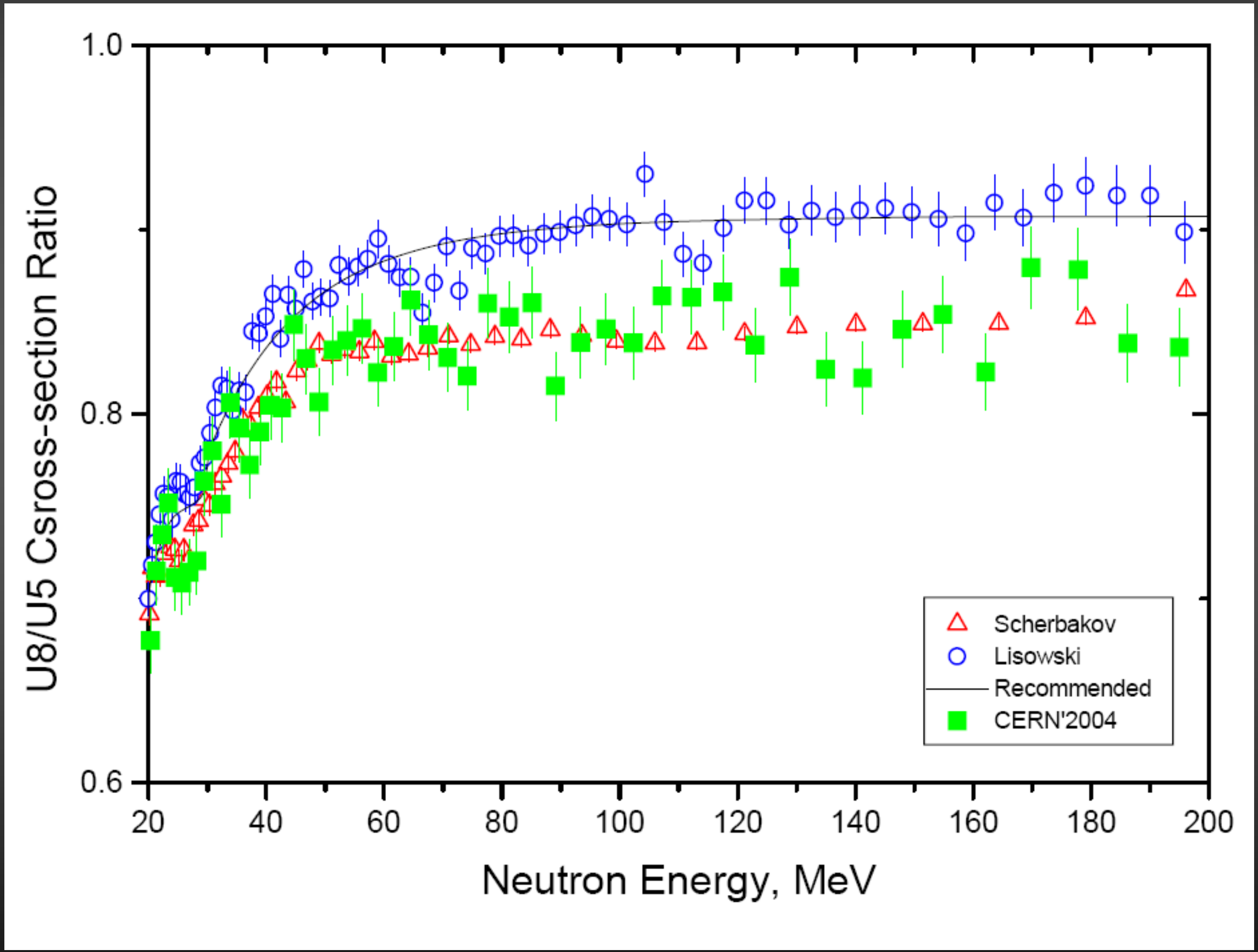
^{232}Th

^{209}Bi

^{237}Np

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

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



15% lower U8/U5 ratio at high energies

back

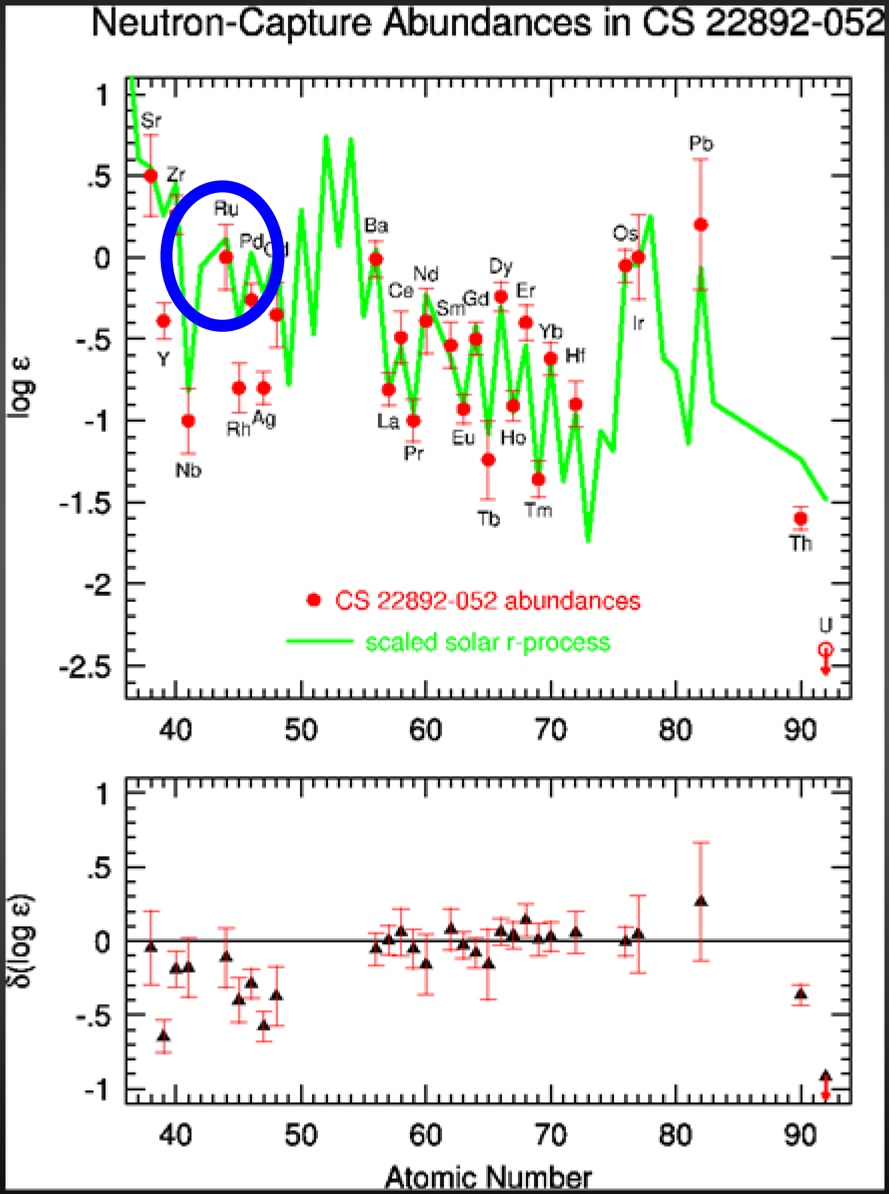
Capture studies: Mo, Ru and Pd

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.

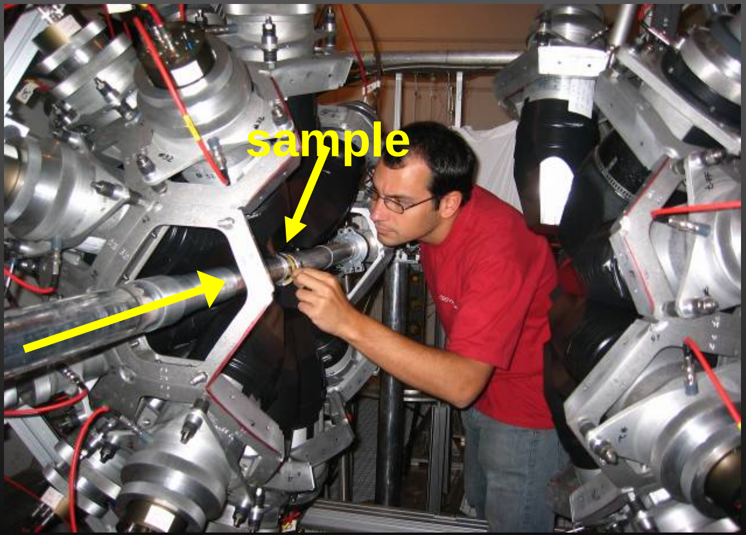
$$N_r = N_{solar} - N_s$$

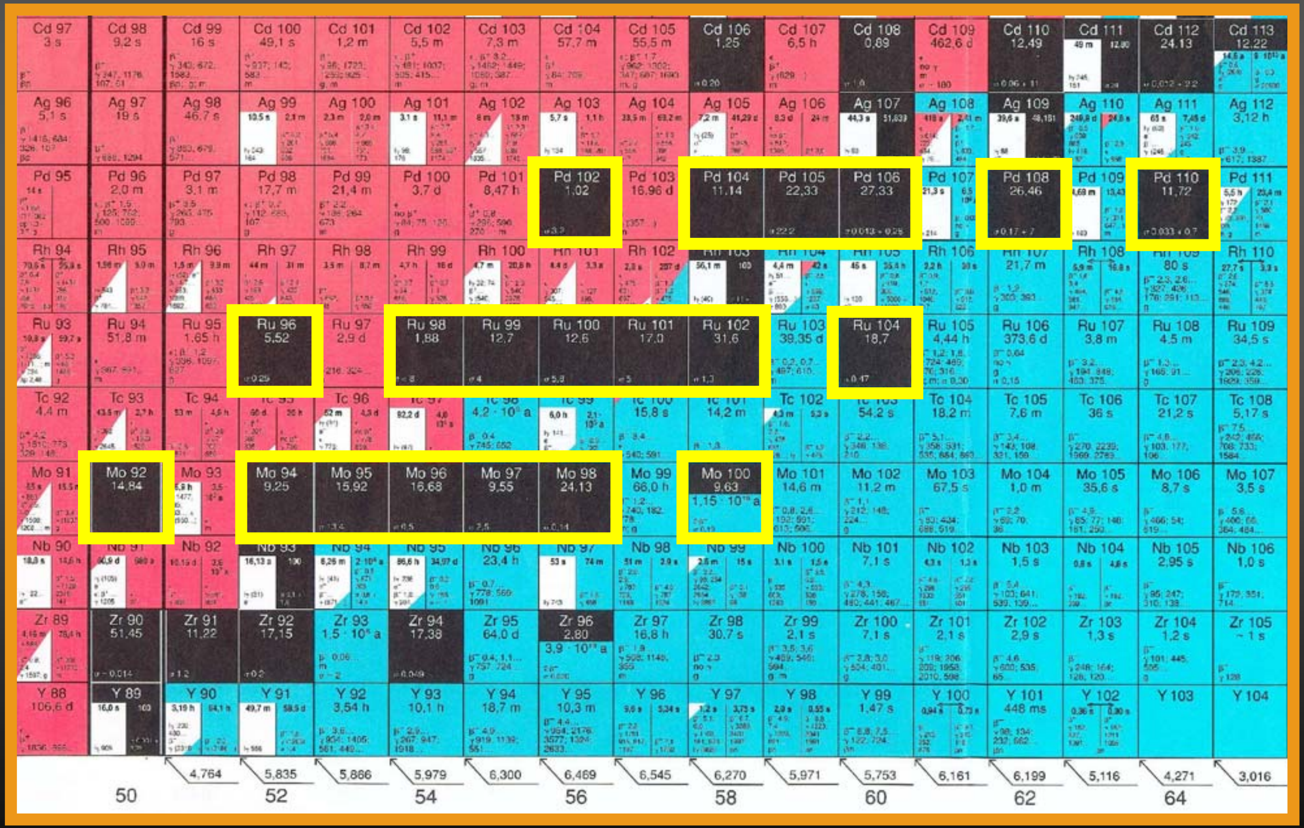


Capture studies: Mo, Ru and Pd

- 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} = **10^{18}**

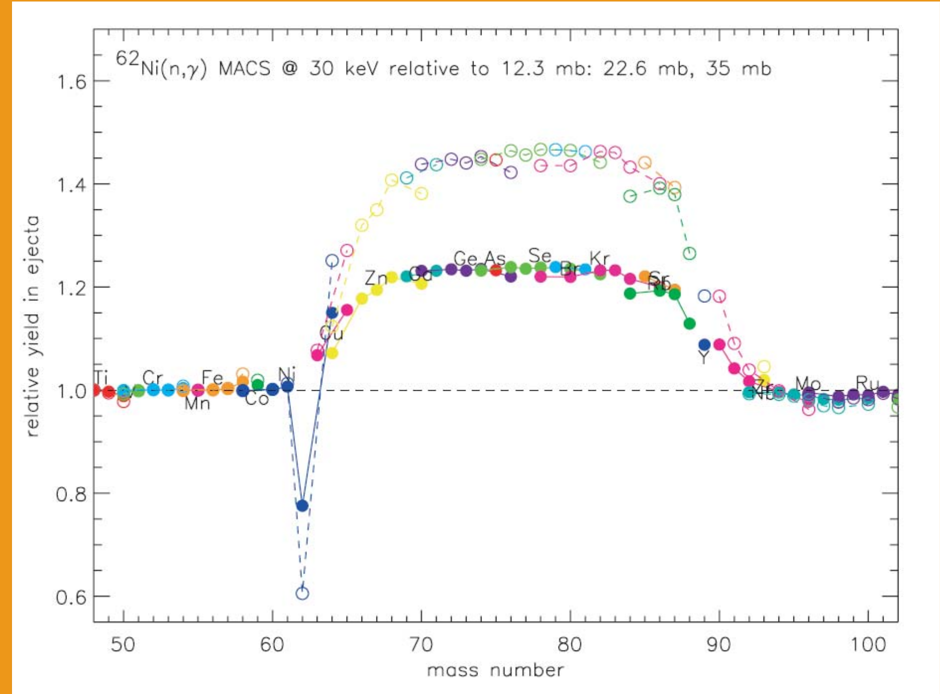




Capture studies: Fe, Ni, Zn, and Se

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.

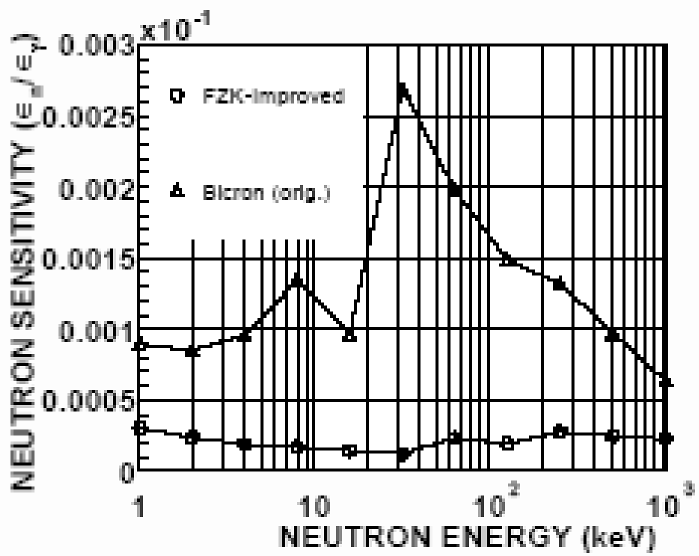
Capture studies: Fe, Ni, Zn, and Se

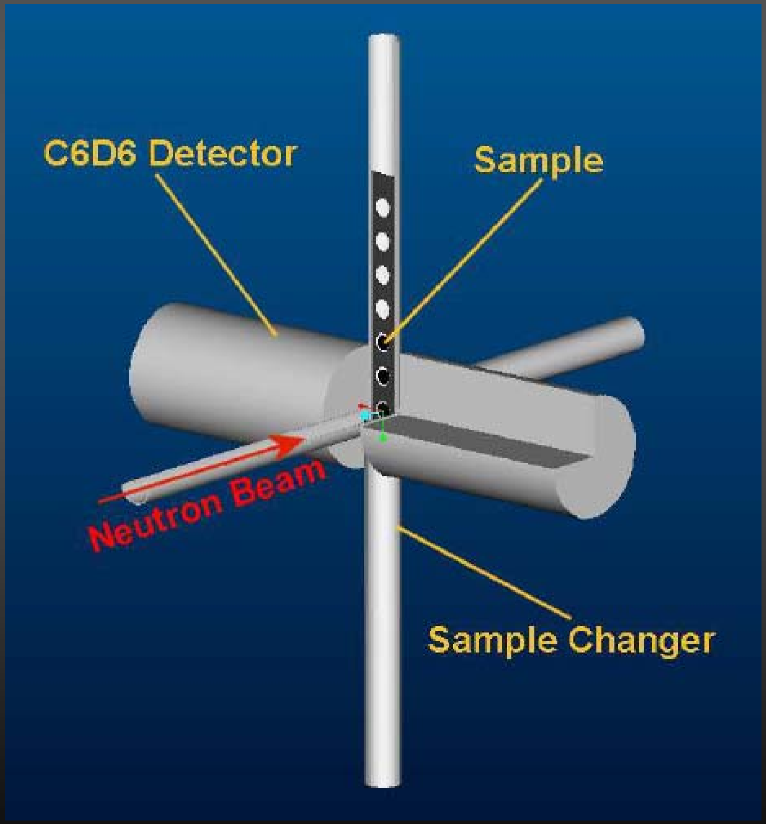
The ^{79}Se case

- 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)

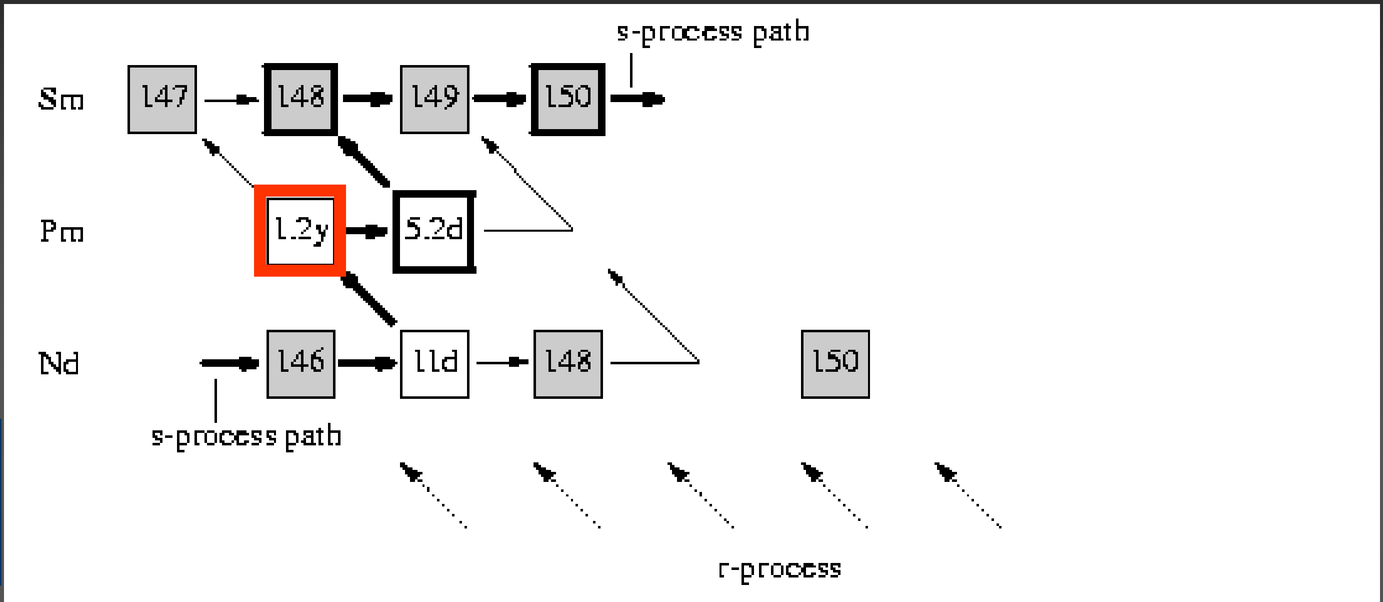




(*) except ^{79}Se

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

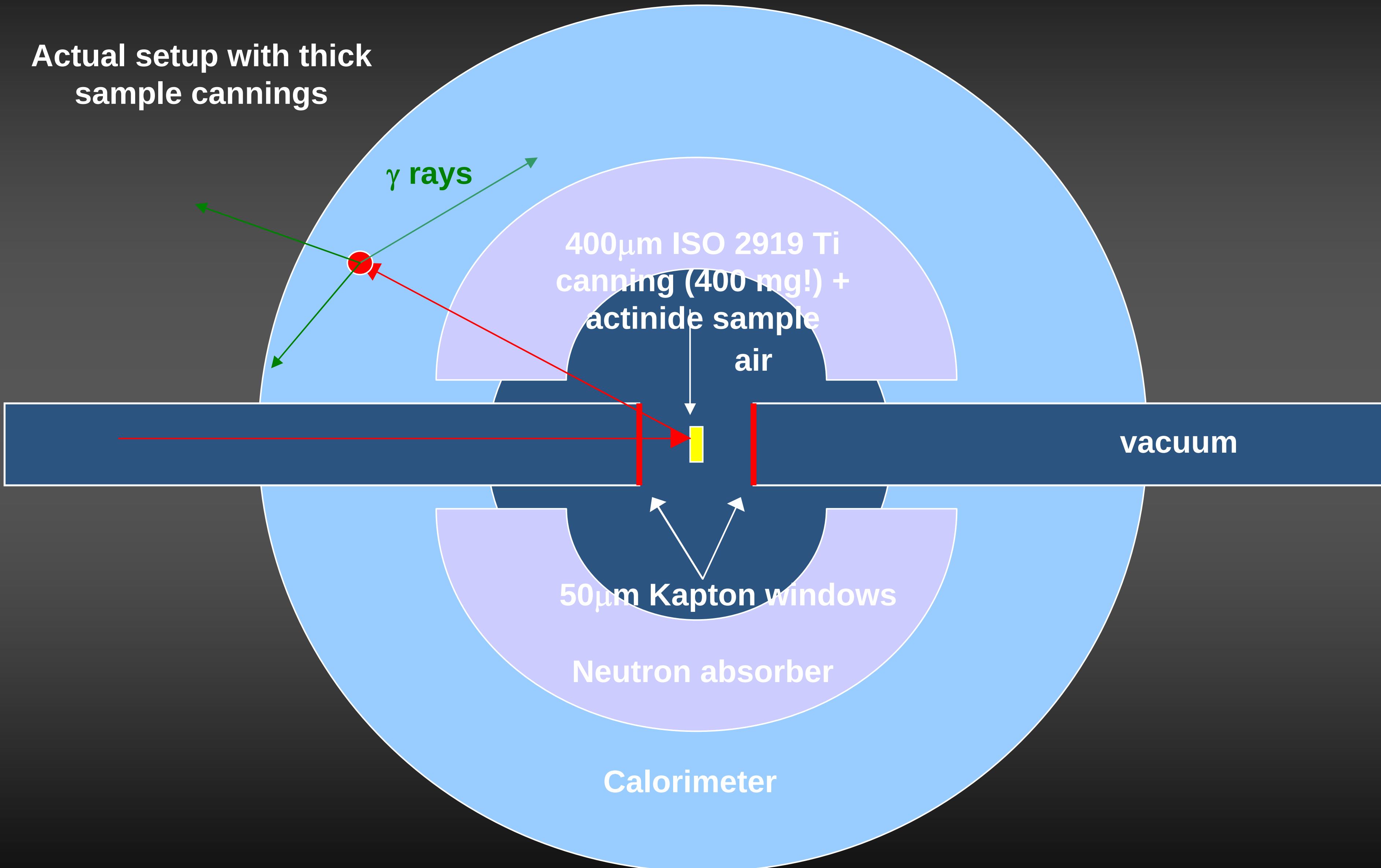
Neutron cross section measurements for nuclear waste transmutation and advanced nuclear technologies

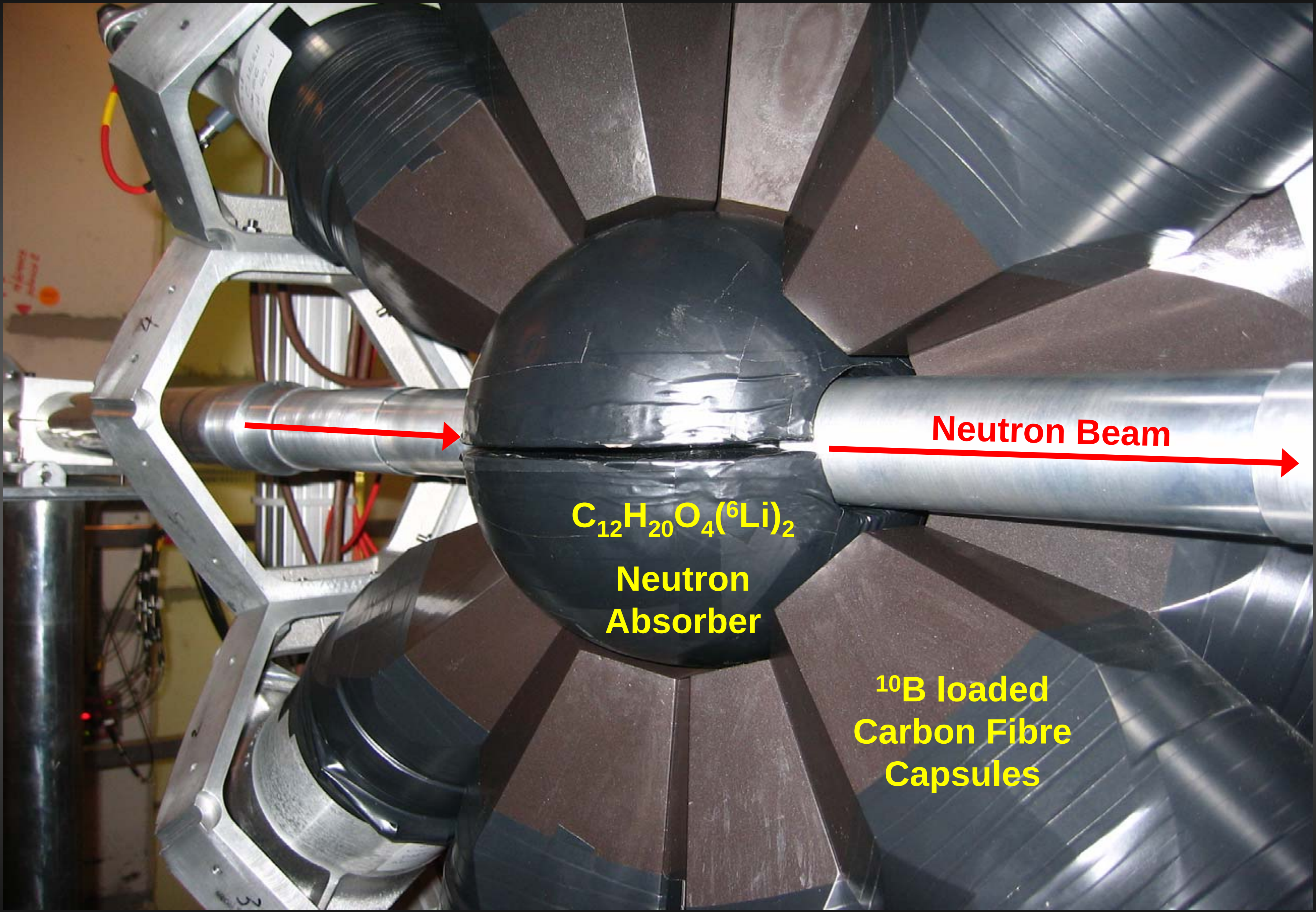
$^{241,243}Am$	The most important neutron poison in the fuels proposed for transmutation scenarios. Build up of Cm isotopes.
$^{239,240,242}Pu$	(n,γ) and (n,f) with active canning. Build up of Am and Cm isotopes.
^{245}Cm	No data available.
$^{235,238}U$	Improvement of standard cross sections.
^{232}Th,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

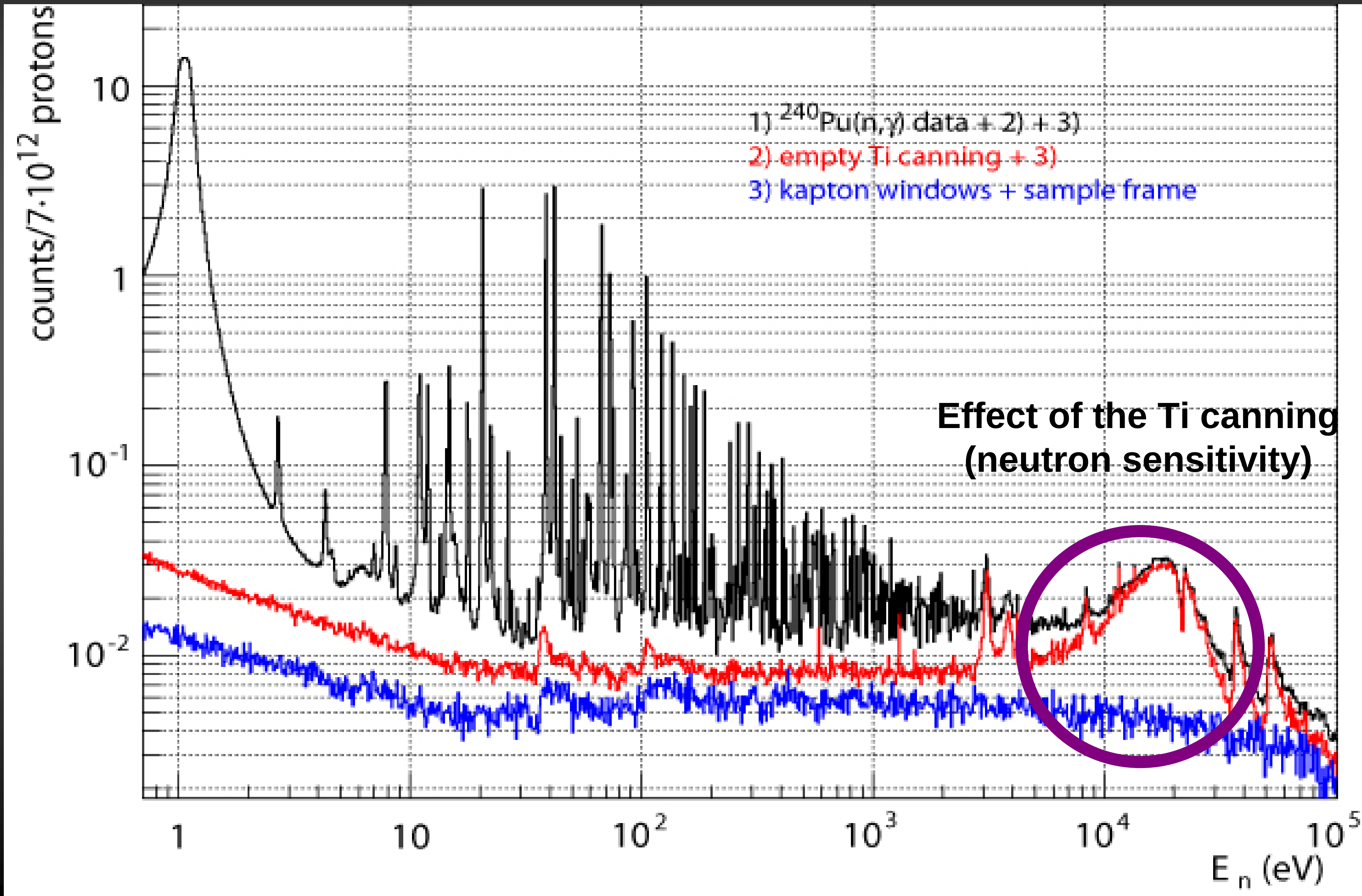
Capture studies: actual TAC setup

Actual setup with thick sample cannings

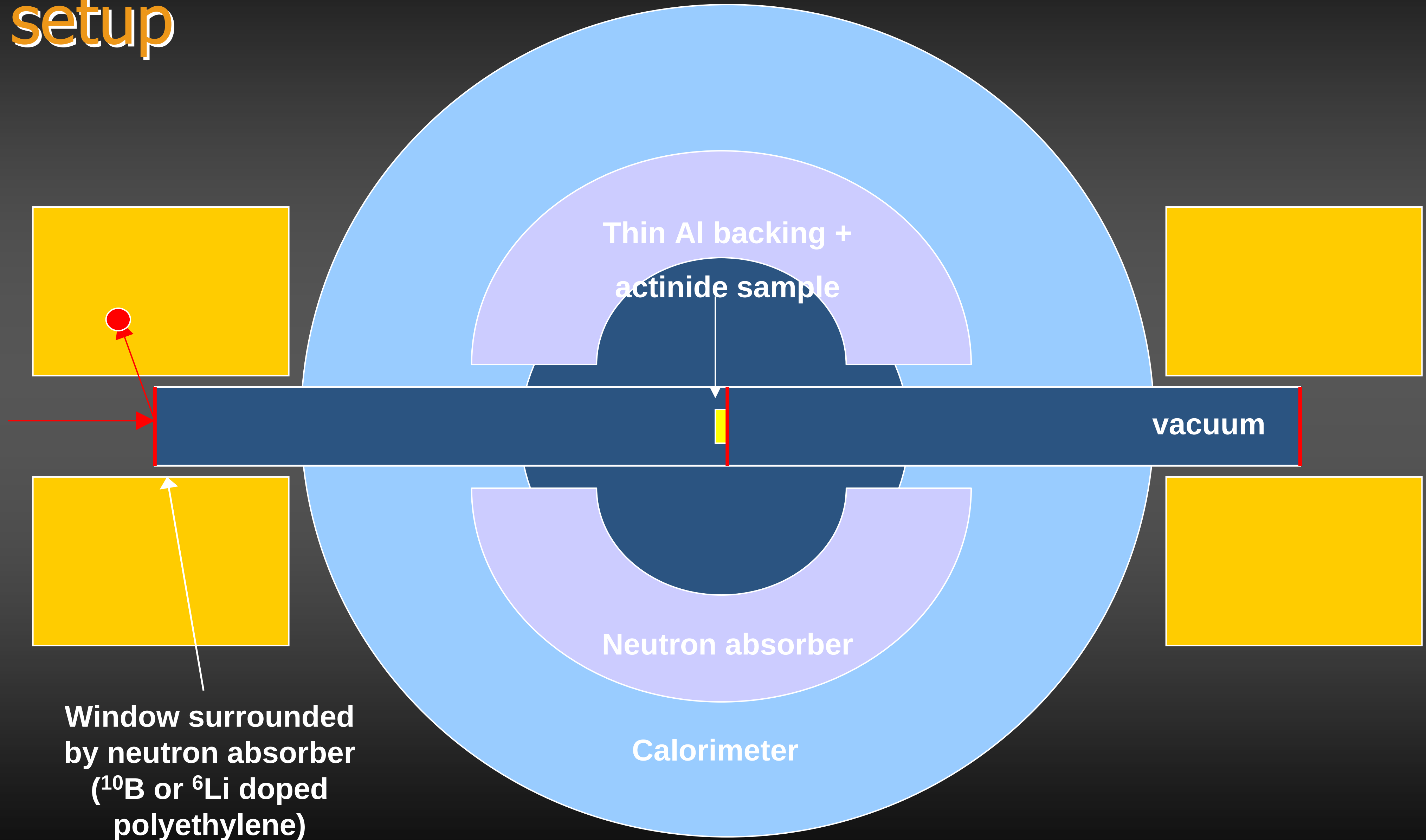



Neutron Beam
$C_{12}H_{20}O_4(^6Li)_2$
Neutron
Absorber
^{10}B loaded
Carbon Fibre
Capsules

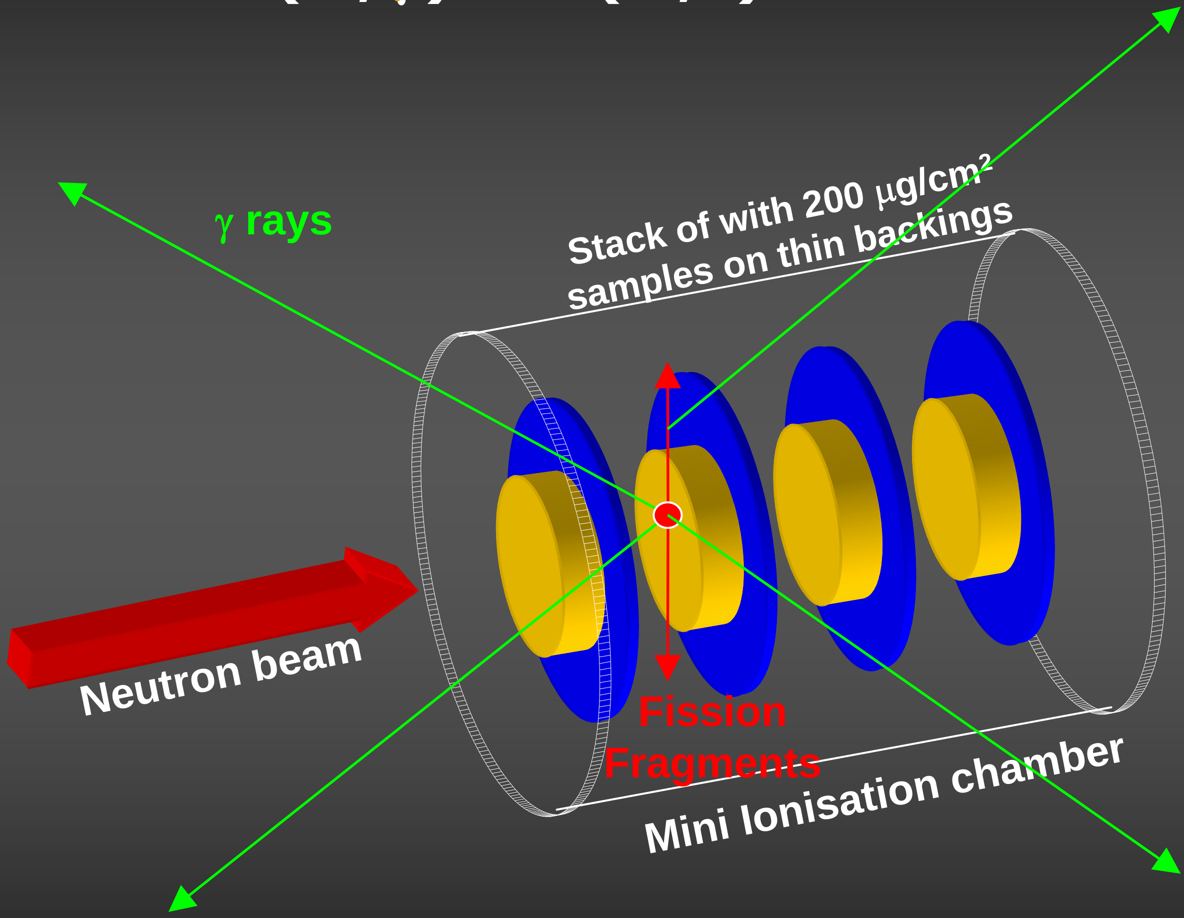
Capture studies: actual TAC setup



Capture studies: Low neutron sensitivity setup



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



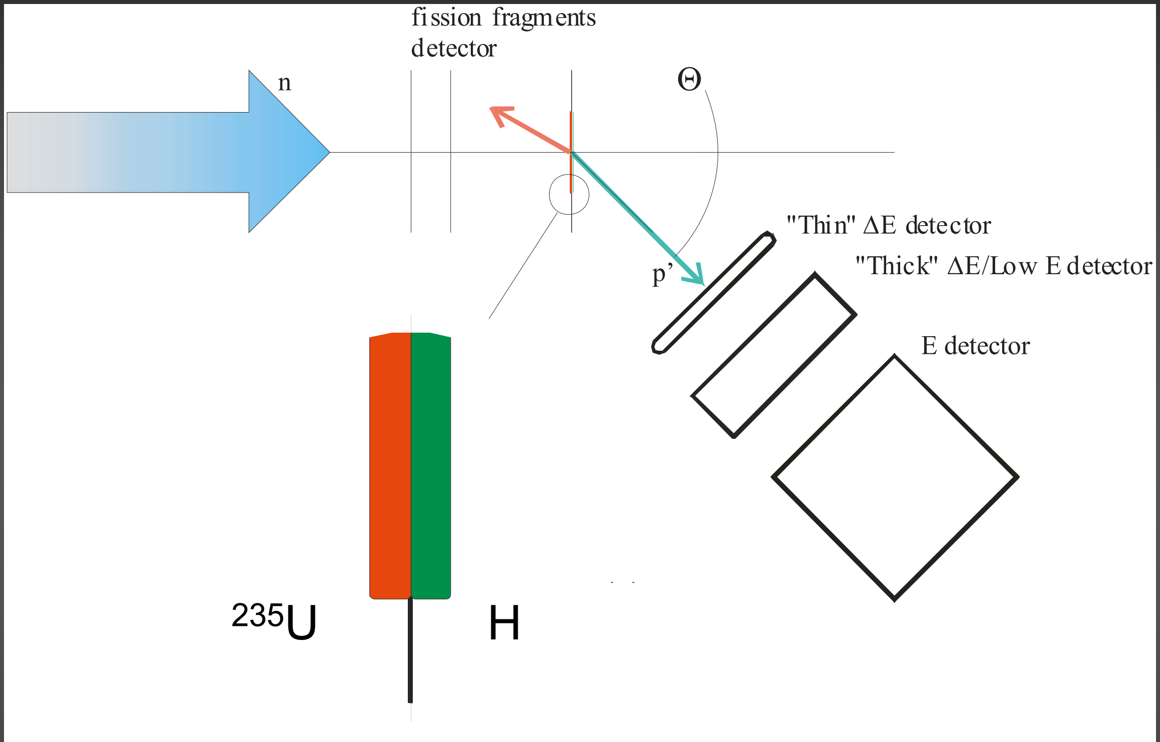
<< back

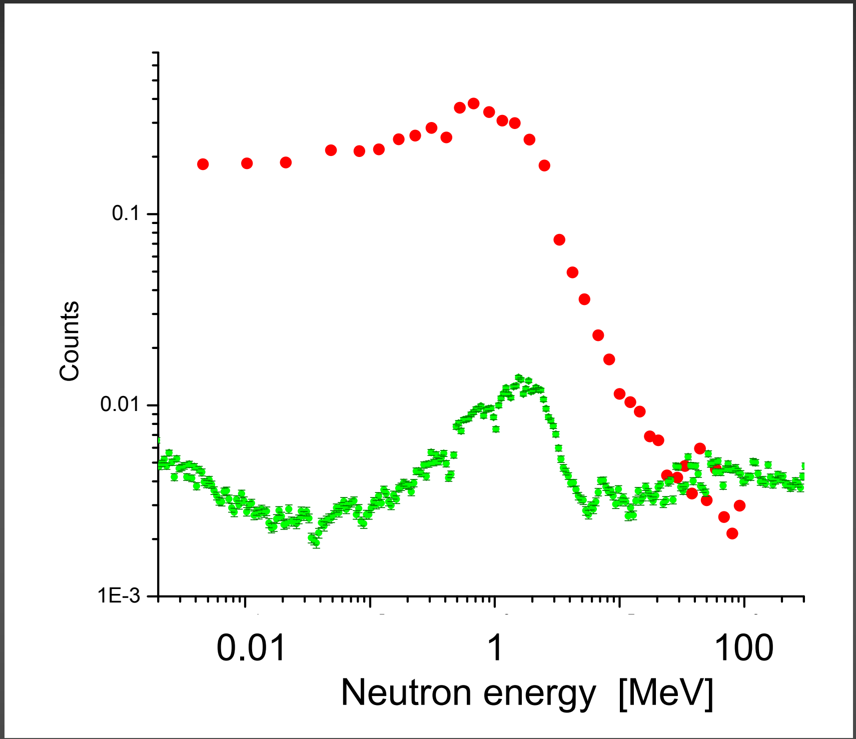
Measurement of capture cross sections of fissile materials (veto) and measurement of the (n,γ)/(n,f) ratio.

Fission studies

Fission studies

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



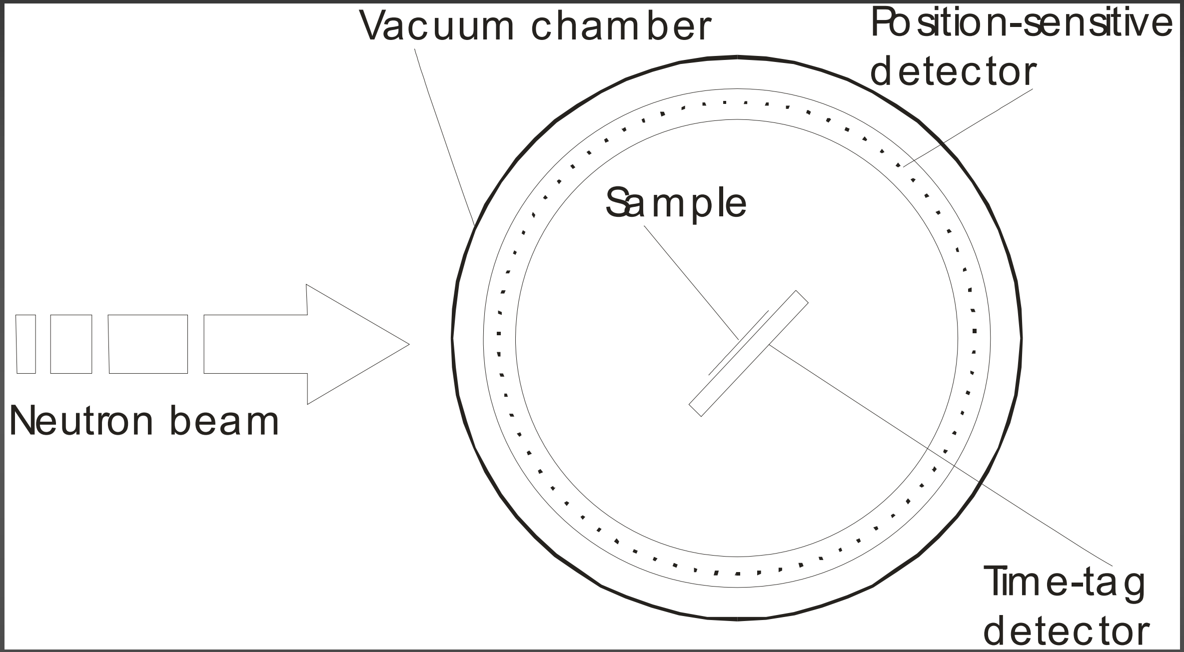


Beam	capture mode (2 mm Ø)
Scattering angle	30°
Target thickness	250 $\mu g/cm^2$
Detector radius	20 mm
Target-to-detector distance	250 mm

(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)

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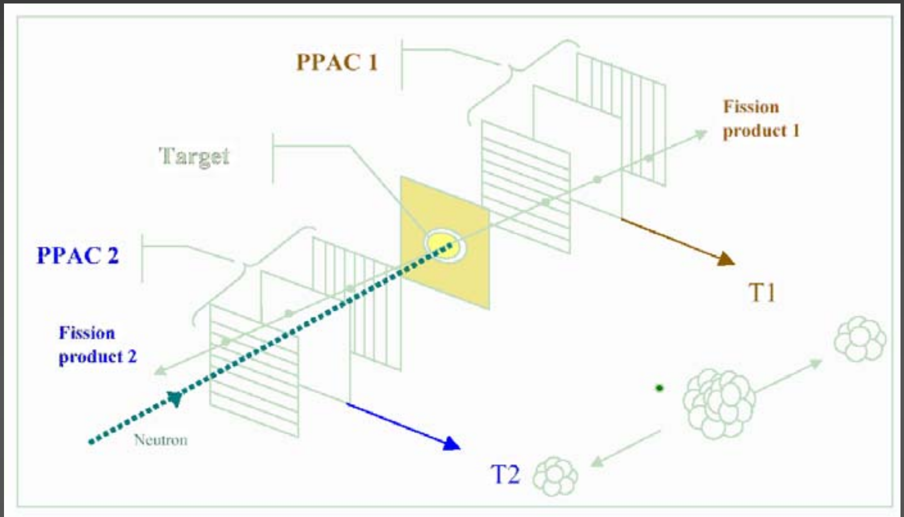
Fission studies
cross sections with PPAC detectors: present setup



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)

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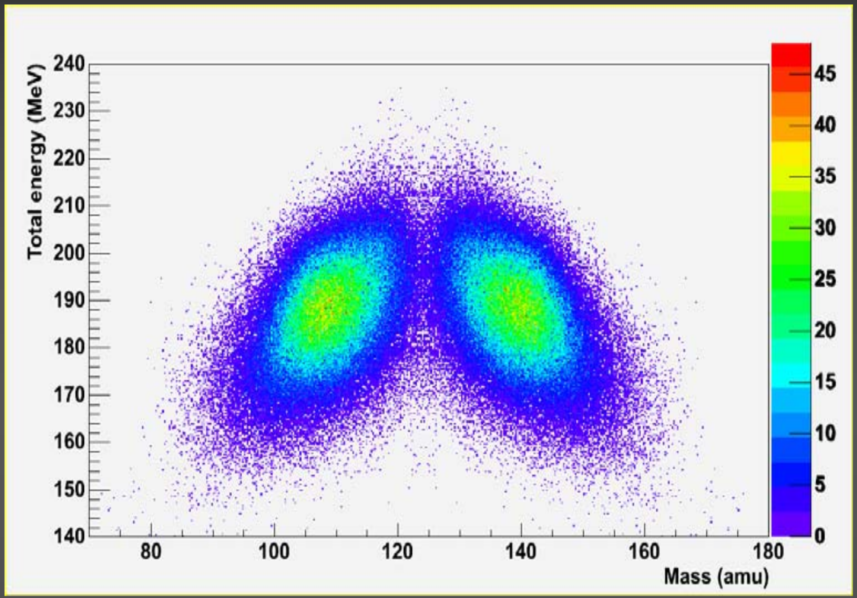
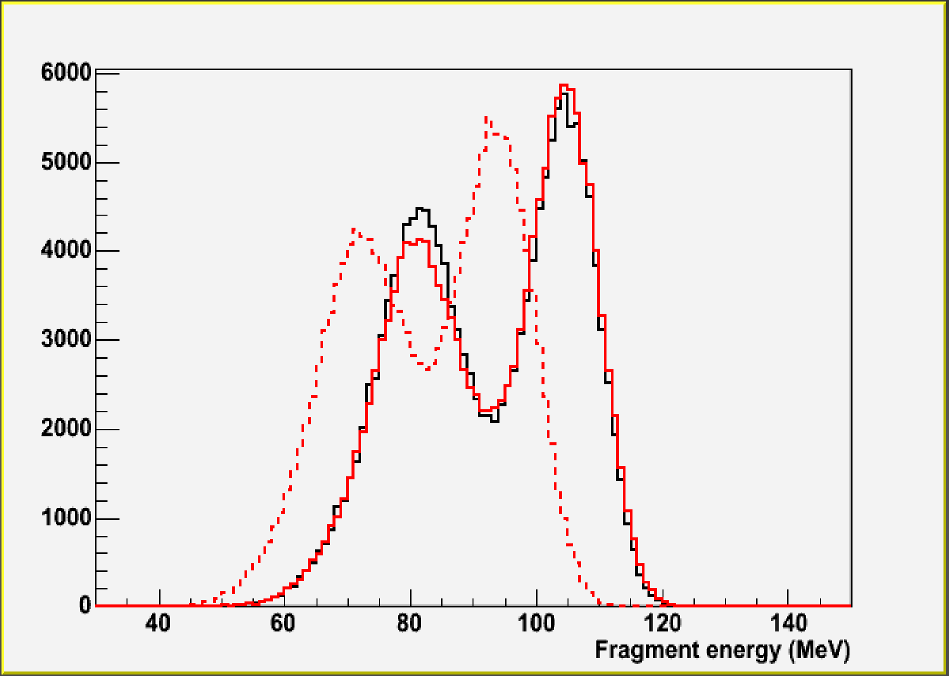
Fission studies
with twin ionization chamber





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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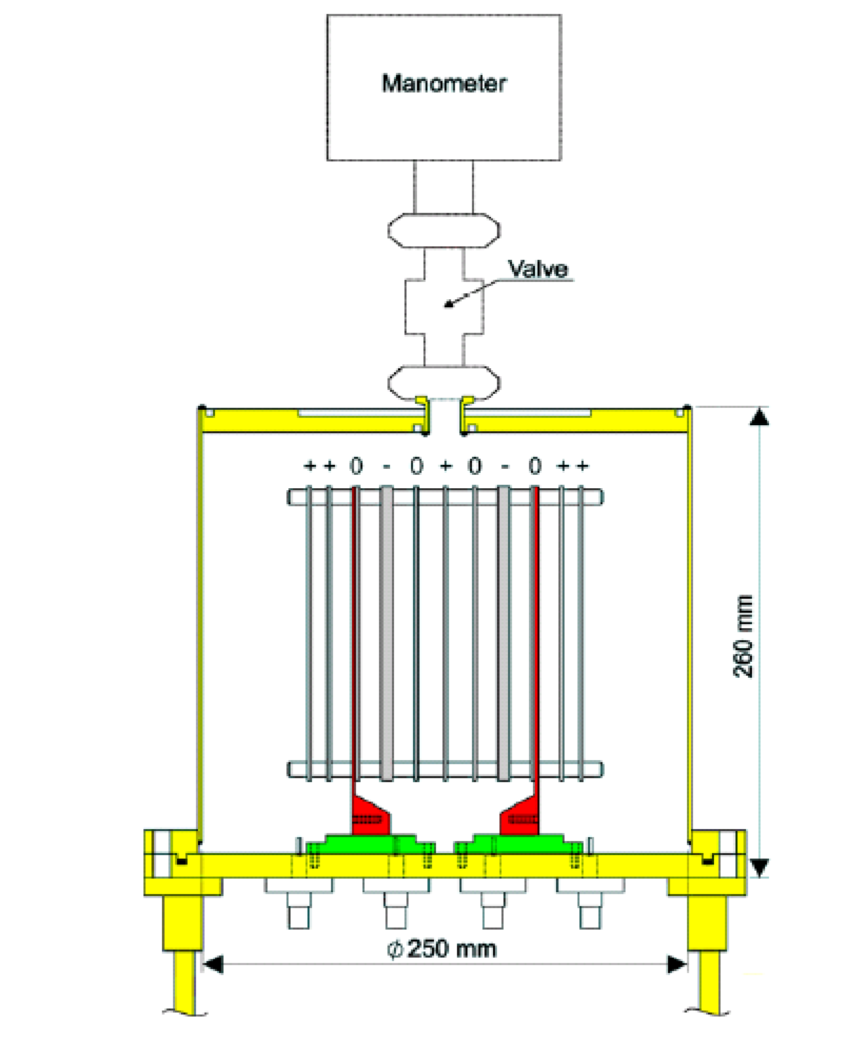
(n,p), (n,α) & (n,lcp) measurements

1. CIC: compensated ion chamber already tested at n_TOF



For n_TOF-Ph2:

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

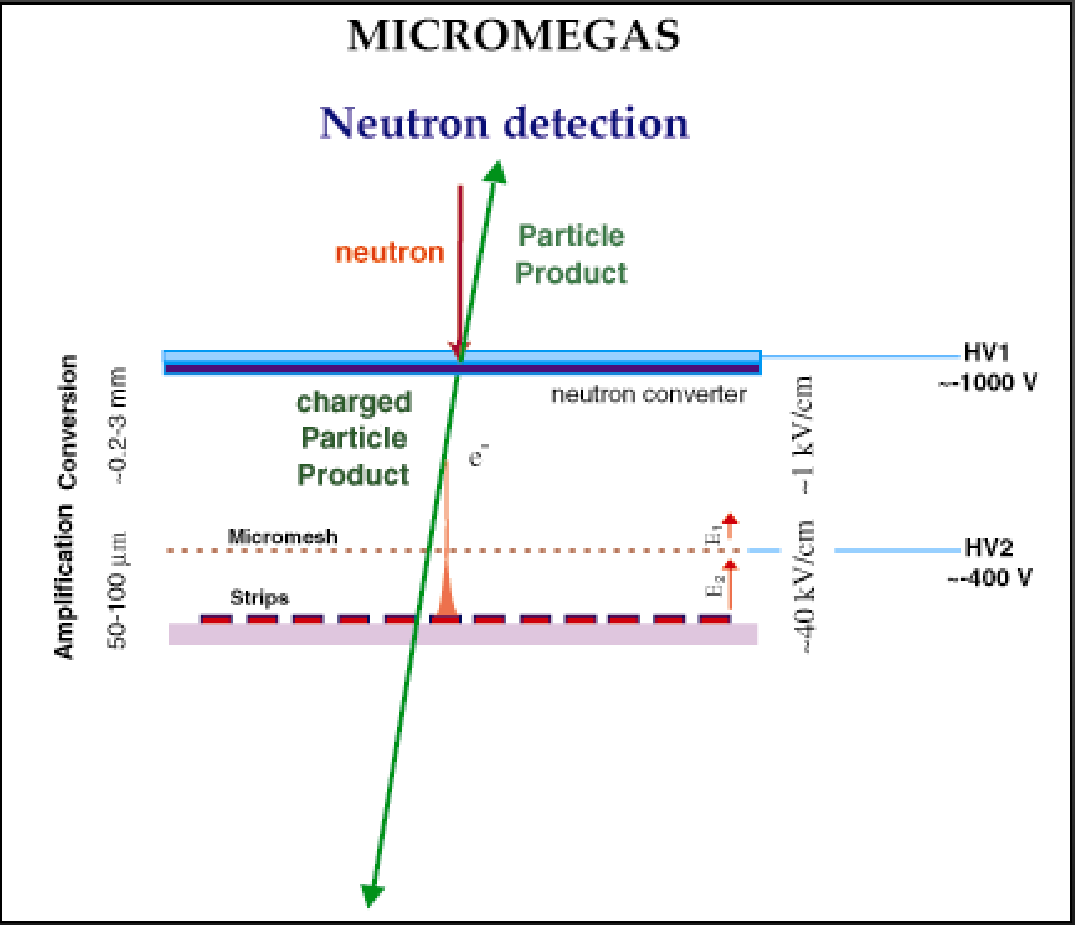
Measurements:

• ^{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)

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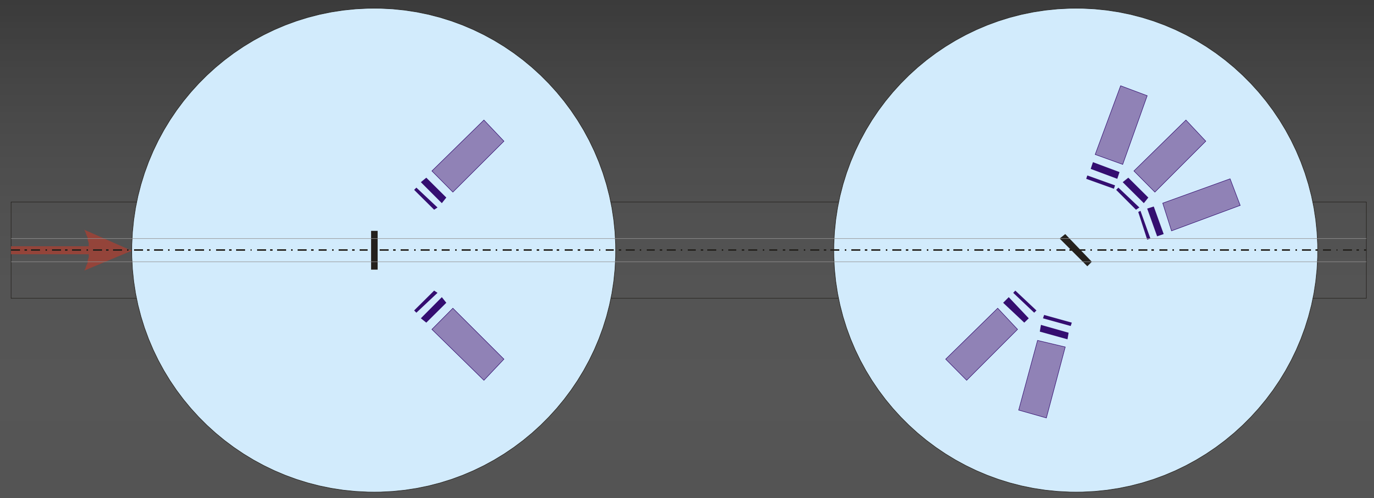
(n,p), (n,α) & (n,lcp) measurements

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

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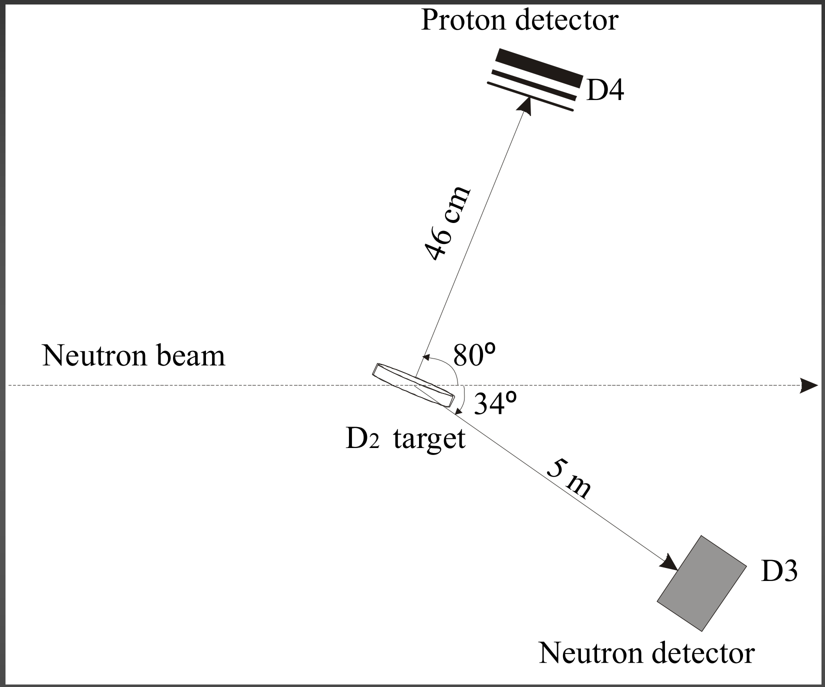
Neutron scattering reactions

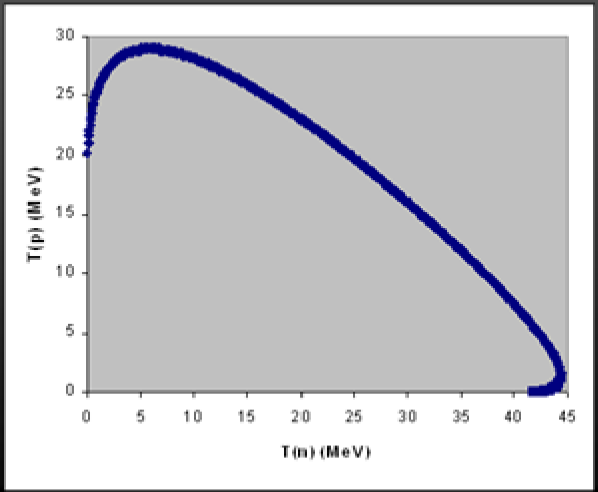
Direct n + n scattering experiment not feasible!

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
$\Theta_n = 20°, \Phi_n = 0°$
$\Theta_p = 50°, \Phi_p = 180°$

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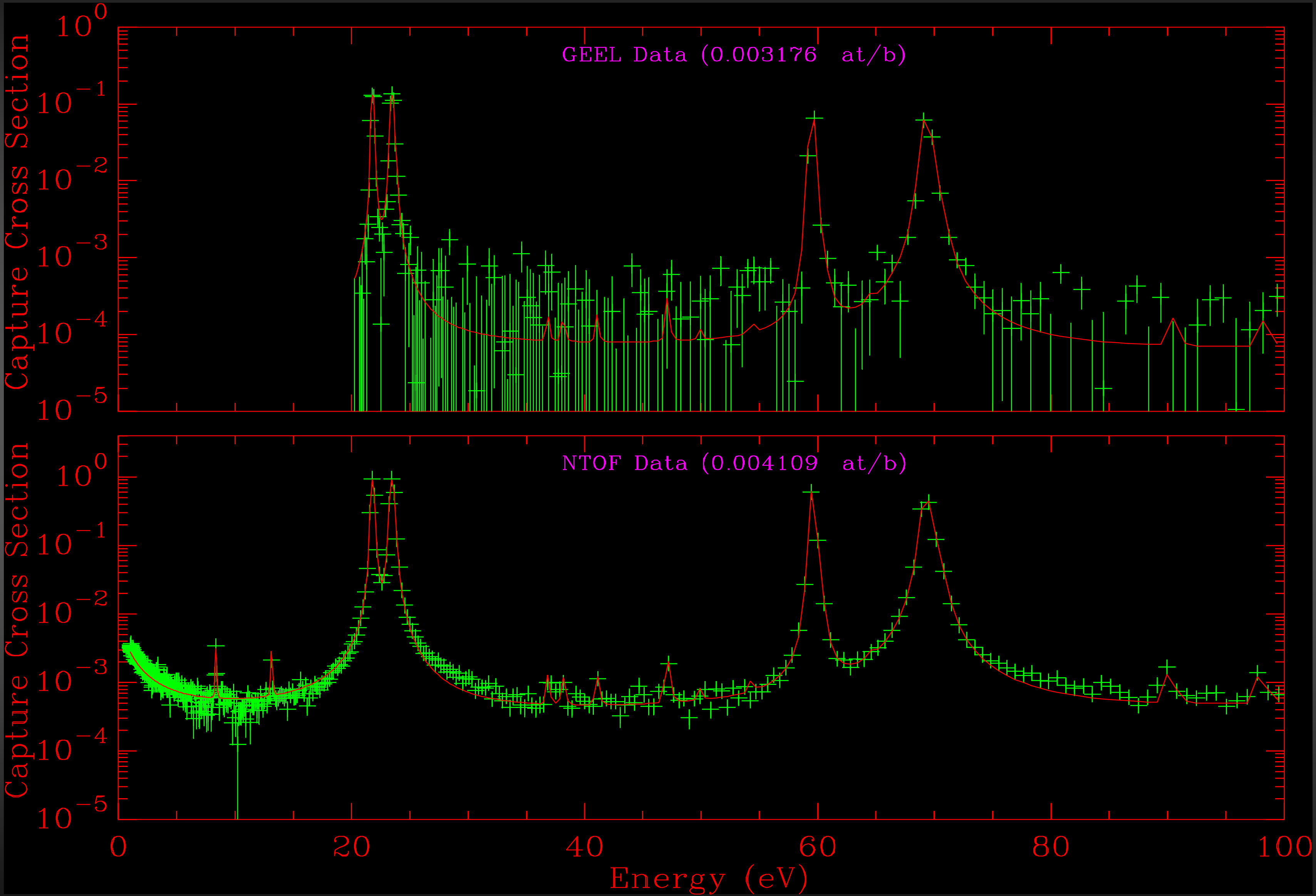
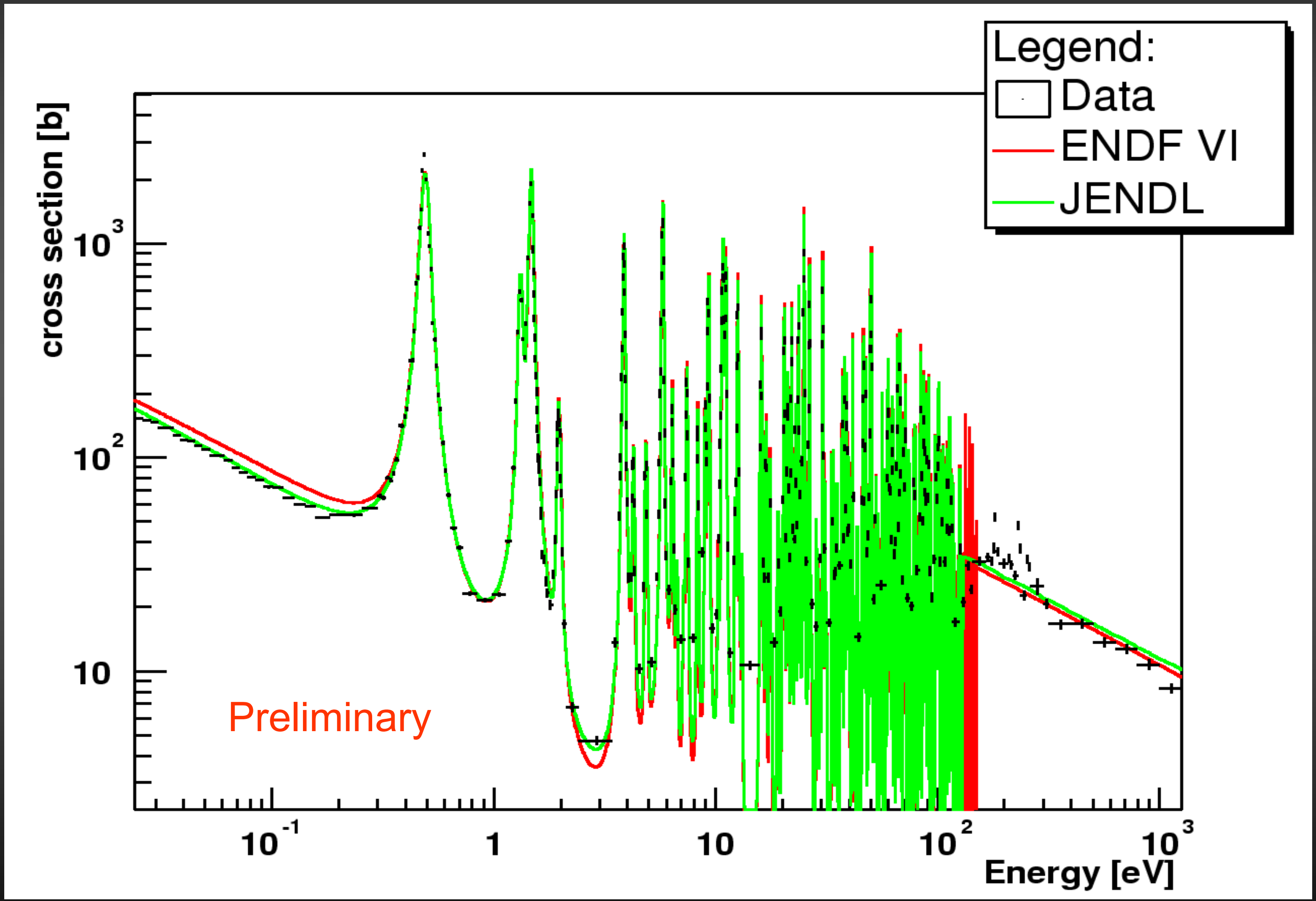
$^{232}Th(n,\gamma)$: n_TOF & GELINA



Source: L Leal, IAEA CRP meeting, December 2004

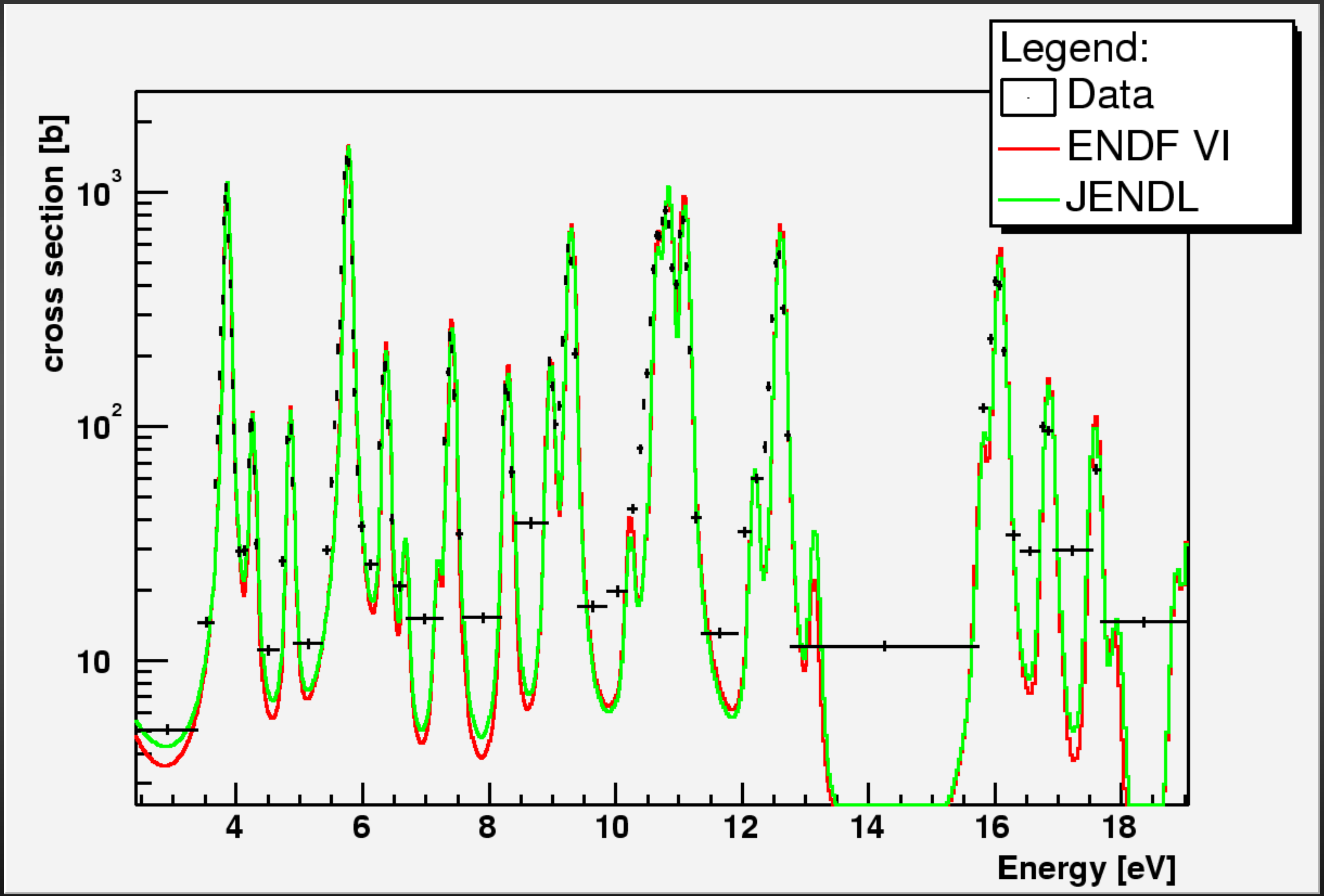
$^{237}Np(n,\gamma)$ at LANSCE



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

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

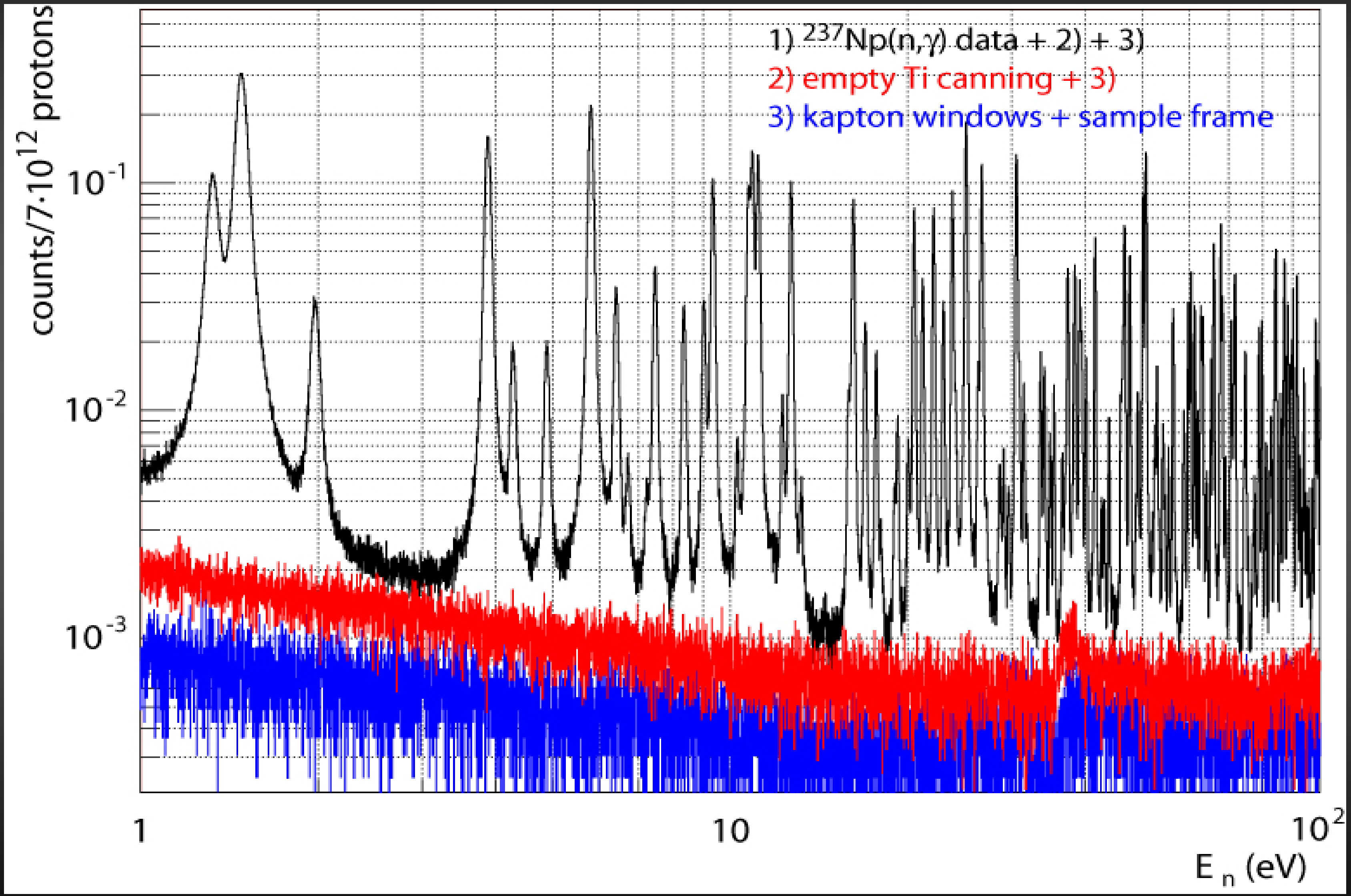
$^{237}Np(n,\gamma)$ at LANSCE



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

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

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



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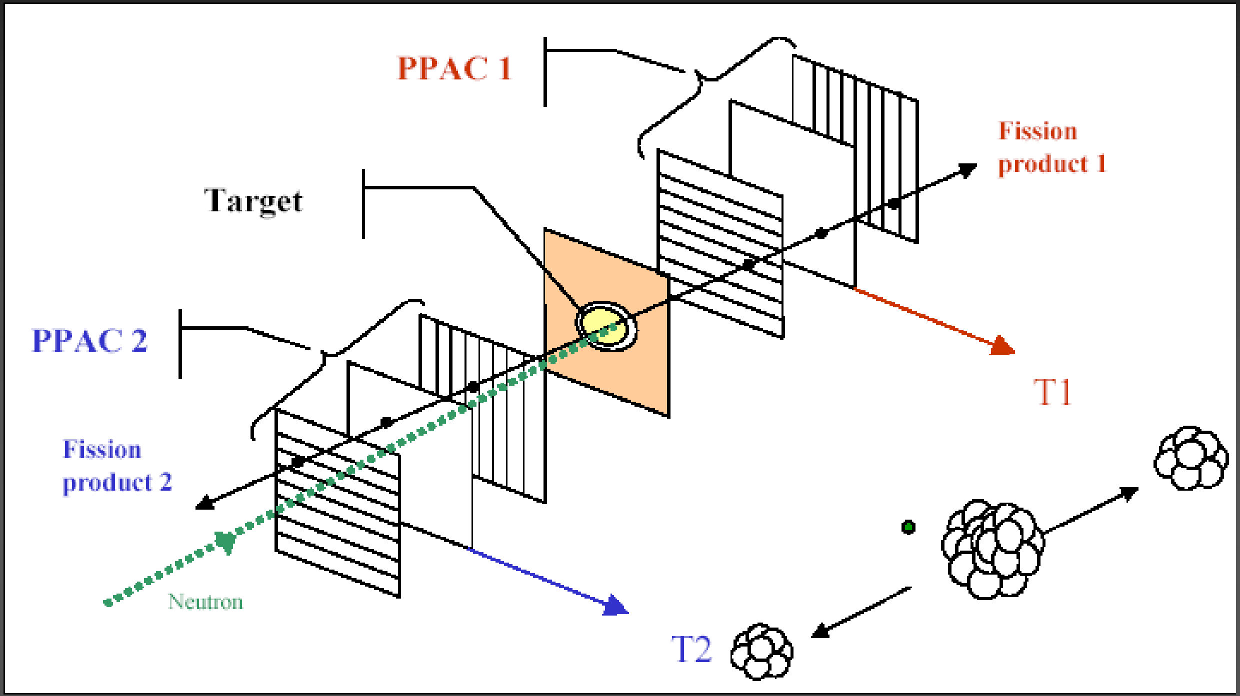
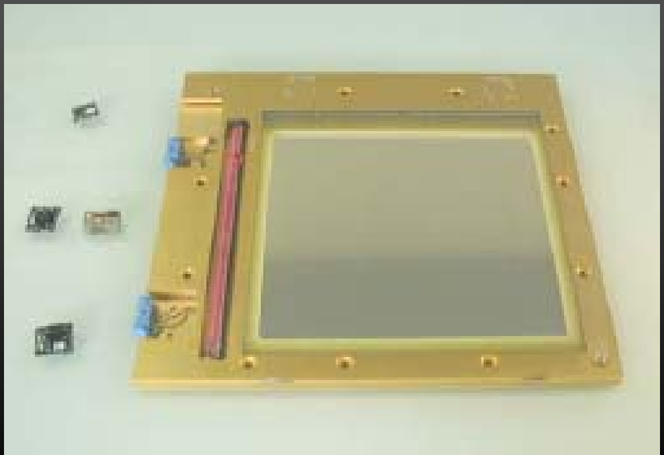
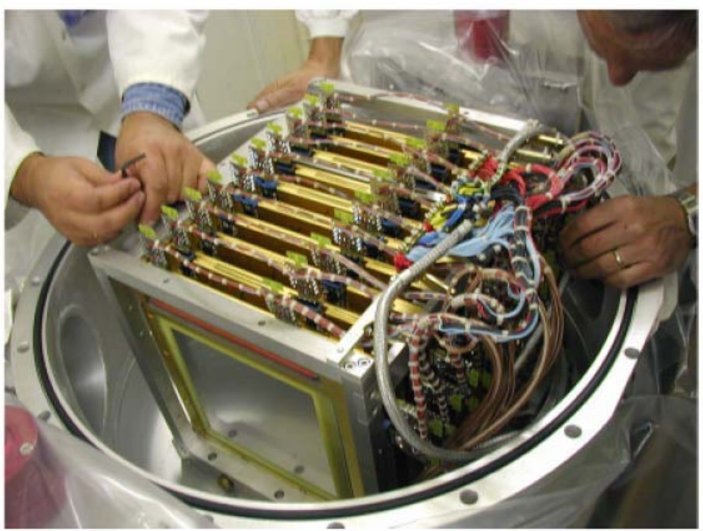
Parallel Plate Avalache Counters (PPACs)

- 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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