Achievements and perspectives for the n_TOF facility at CERN

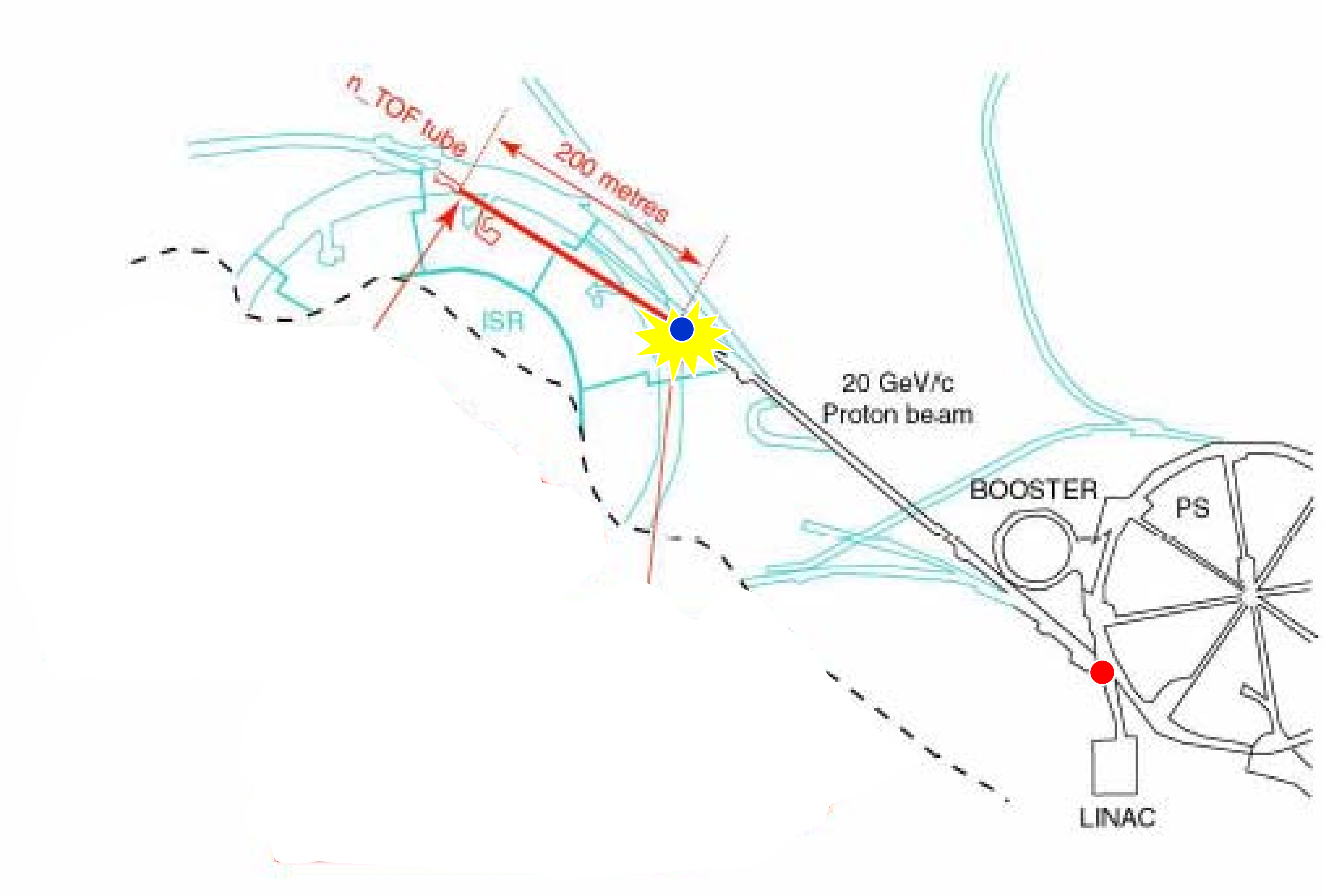
Alberto Mengoni
IAEA , Vienna

- The CERN n_TOF Facility
- Experimental campaigns in 2002-2004: status of the data analysis & results
- n_TOF-Phase 2

The n_TOF facility at CERN

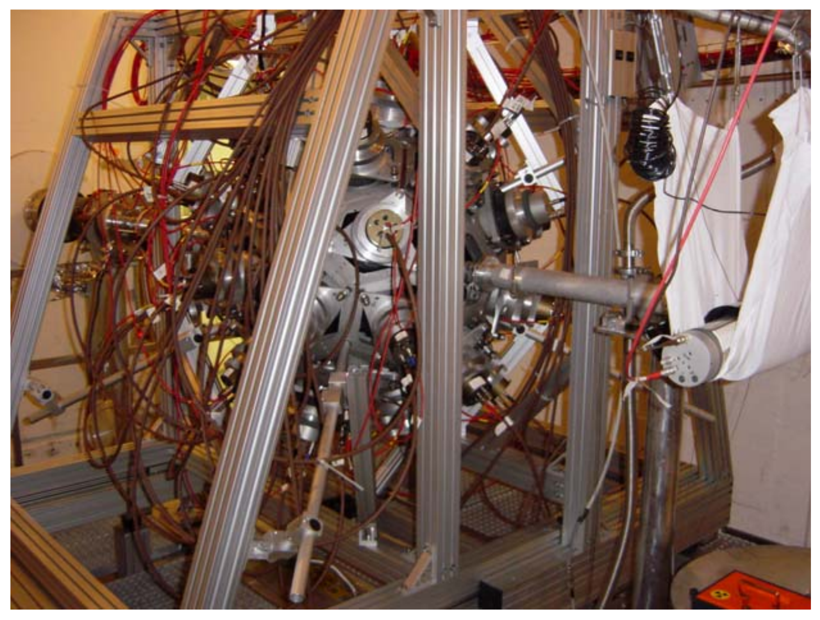
somewhere around here

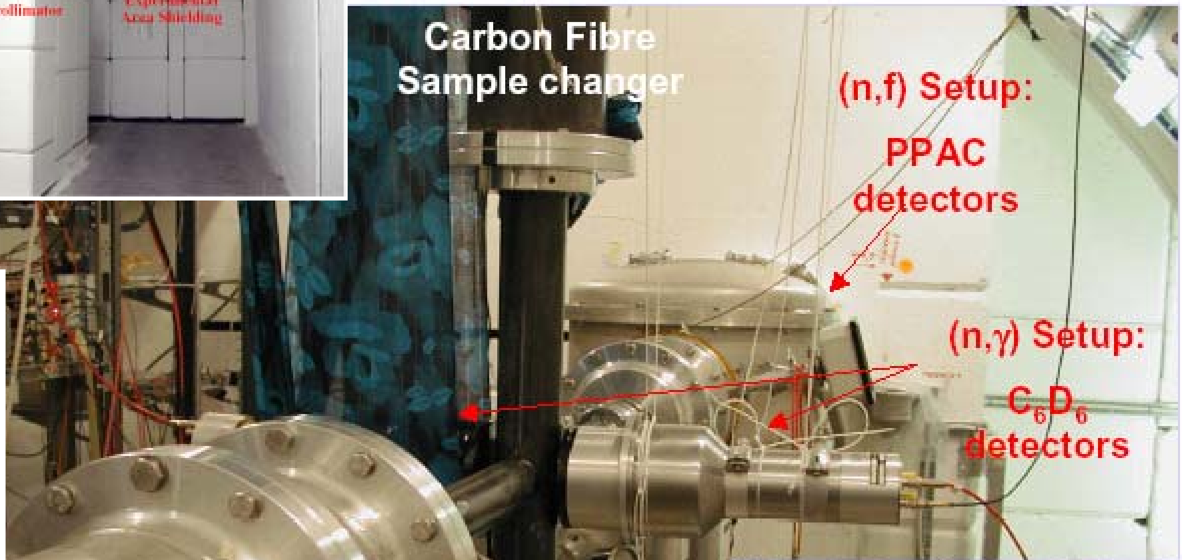
The n_TOF facility at CERN



The real world

- n_TOF commissioned in 2001-2002



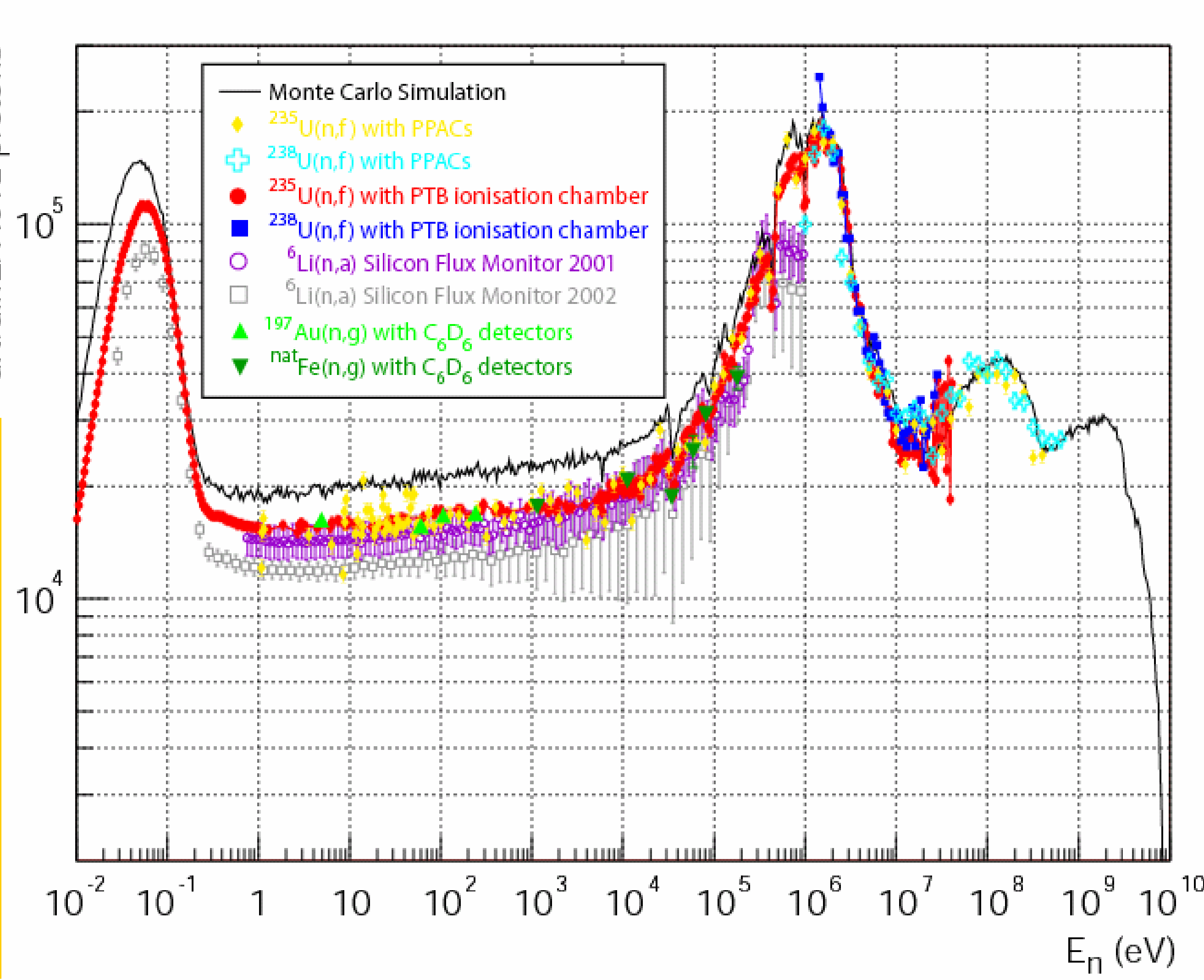


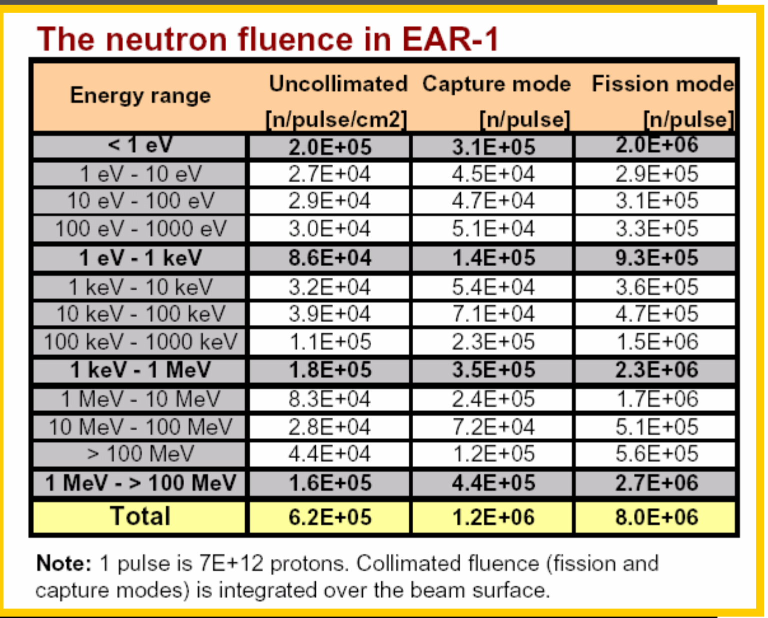
n_TOF beam characteristics

- the neutron flux

2nd collimator ϕ=1.8 cm
(capture mode)

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





The neutron fluence in EAR-1

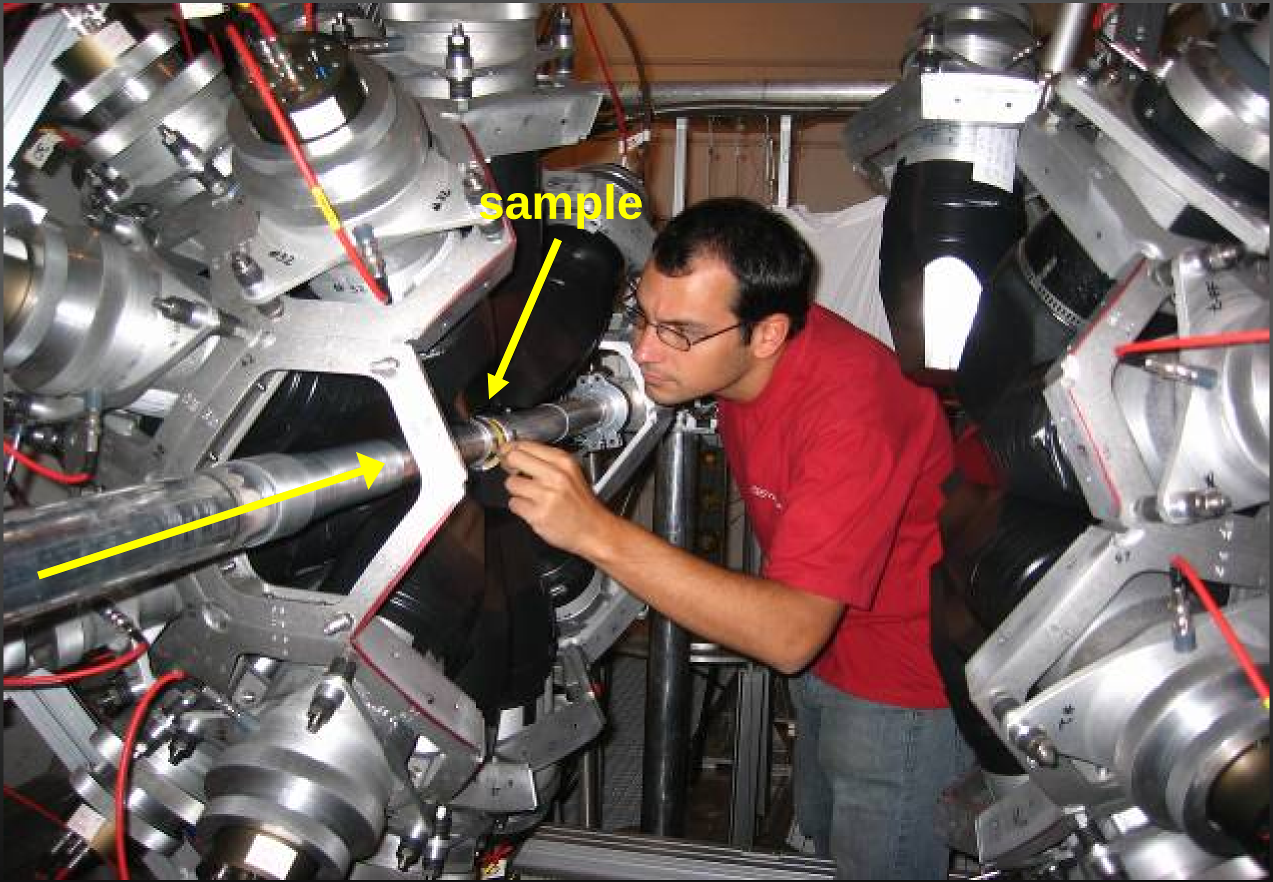
Energy range	Uncollimated [n/pulse/cm2]	Capture mode [n/pulse]	Fission mode [n/pulse]
< 1 eV	**2.0E+05**	**3.1E+05**	**2.0E+06**
1 eV - 10 eV	2.7E+04	4.5E+04	2.9E+05
10 eV - 100 eV	2.9E+04	4.7E+04	3.1E+05
100 eV - 1000 eV	3.0E+04	5.1E+04	3.3E+05
1 eV - 1 keV	**8.6E+04**	**1.4E+05**	**9.3E+05**
1 keV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

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

n_TOF TAC for (n,γ) measurements

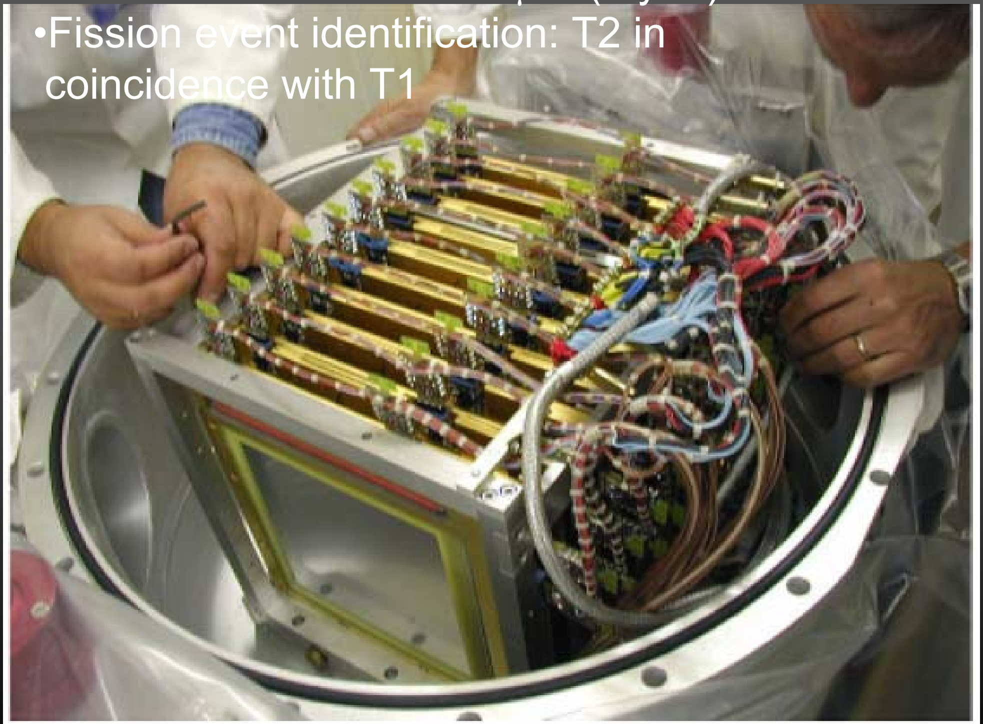
- Structure mounted in April-04
- 4π geometry: end of May-04
- 1.5 month commissioning
- Au(n,γ) & other standards

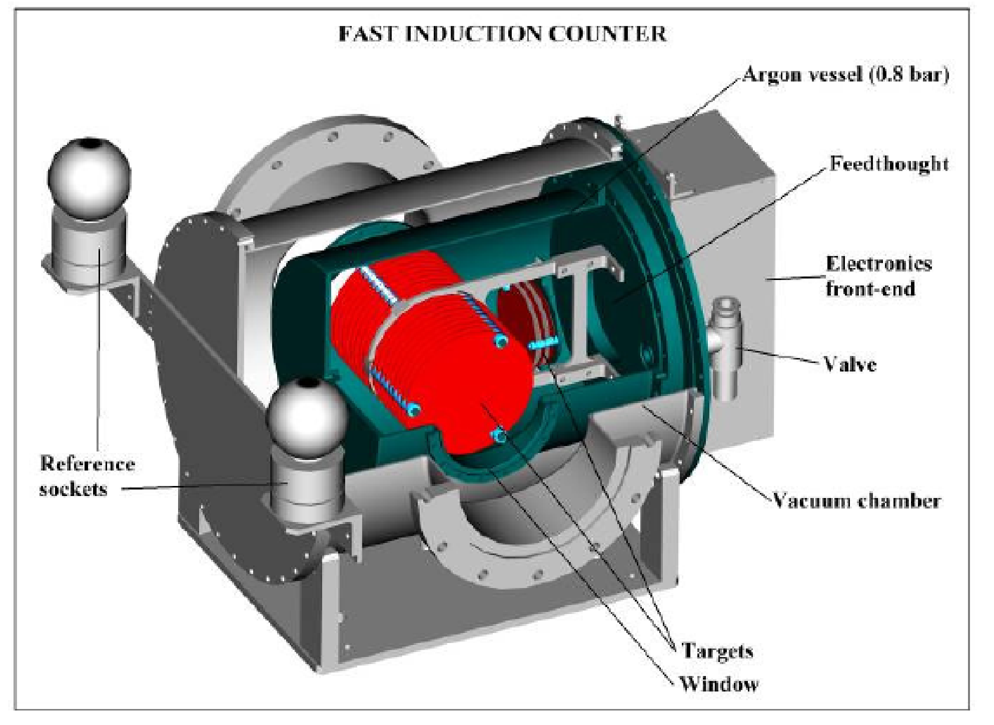
First measurement with a radioactive sample started in August 2004
^{237}Np(n,γ)



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 experiments 2002-4

Capture

^{151}Sm

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

^{232}Th

^{24,25,26}Mg

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

^{139}La

^{186,187,188}Os

^{233,234}U

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

Fission

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

^{232}Th

^{209}Bi

^{237}Np

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

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

n_TOF experiments 2002-4

🟩 **data analysis completed, results published**
🟨 **data analysis completed, paper in preparation**
🟥 **data analysis in progress**

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

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)

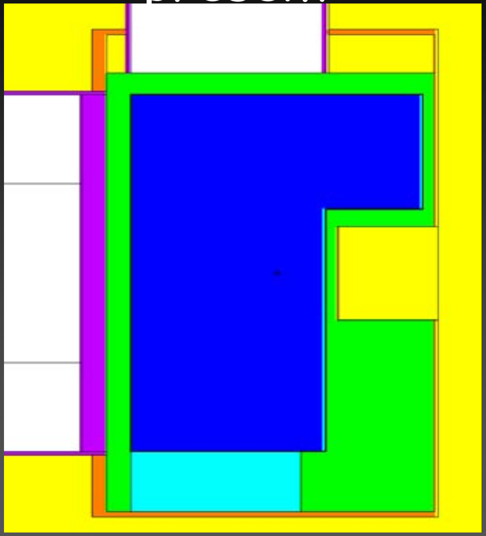
The n_TOF-Ph2 experiments

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

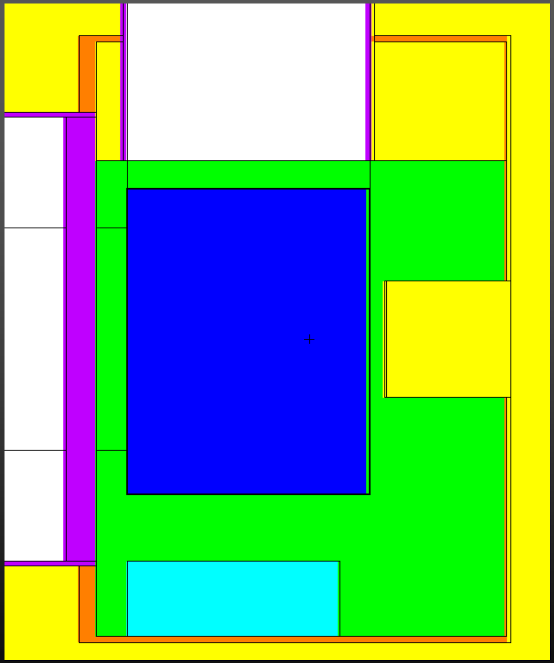
NEW target design

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

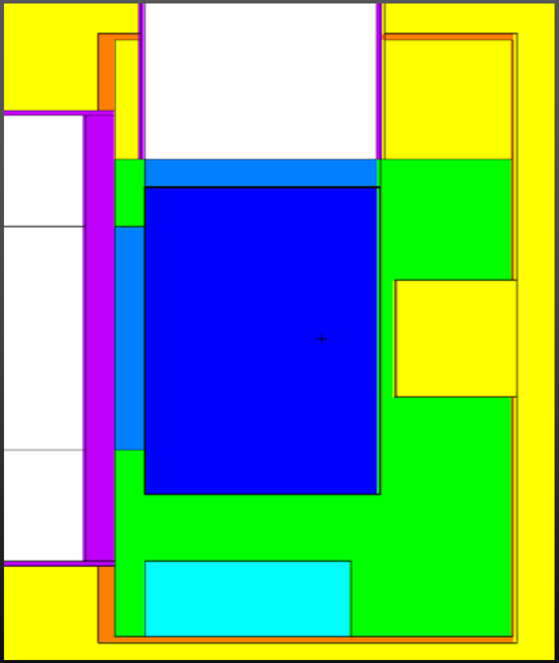
present



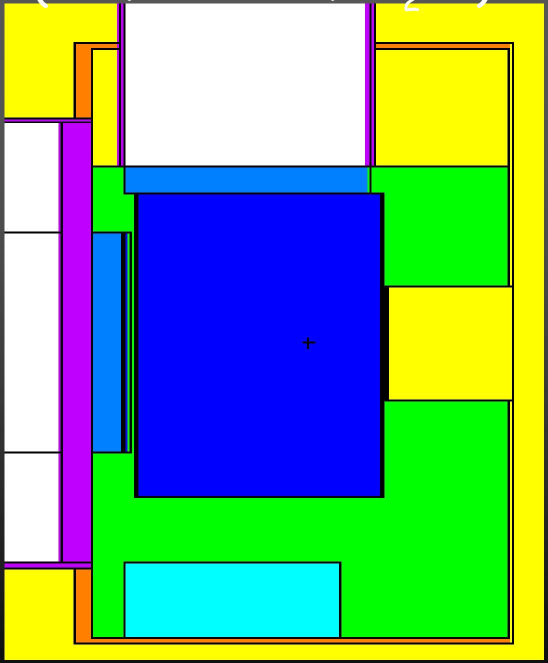
H_2O



D_2O

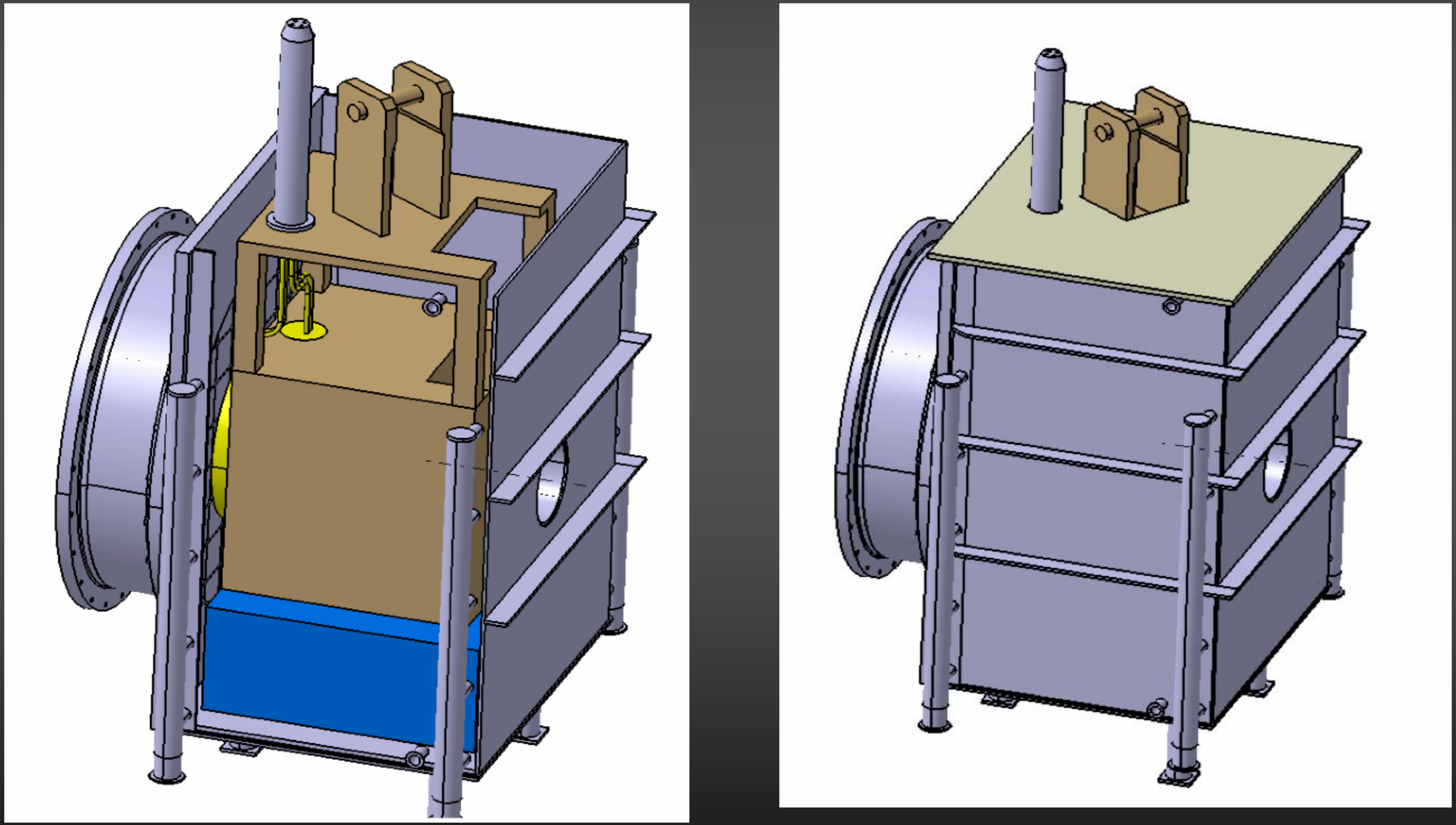


D_2O cooling
(1cm Pb + 1cm H_2O)



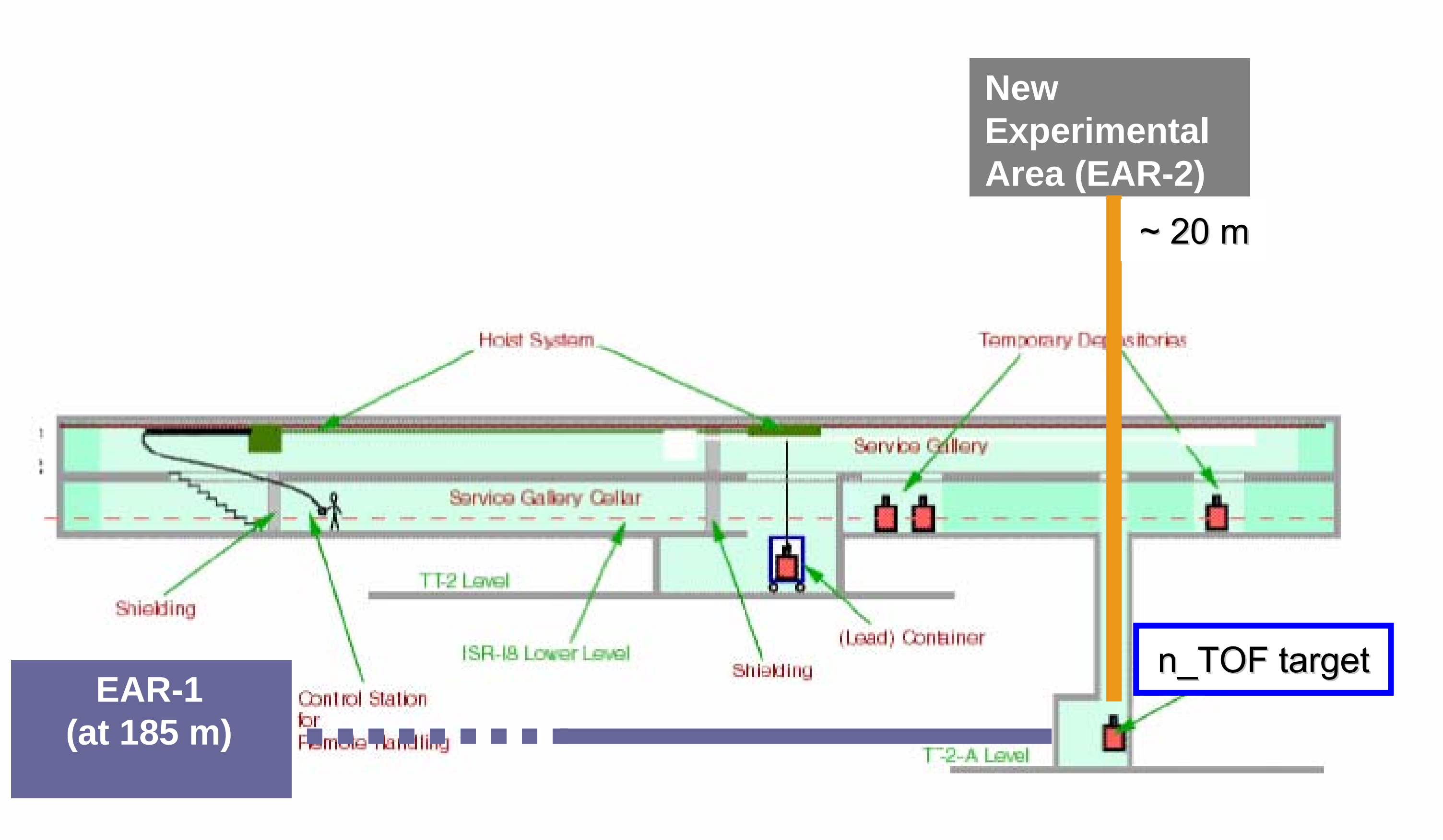
P Cennini, V Vlachoudis, K Tsoulou, et al. (CERN/AB/ATB), October 2006

NEW: target design proposal



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

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

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

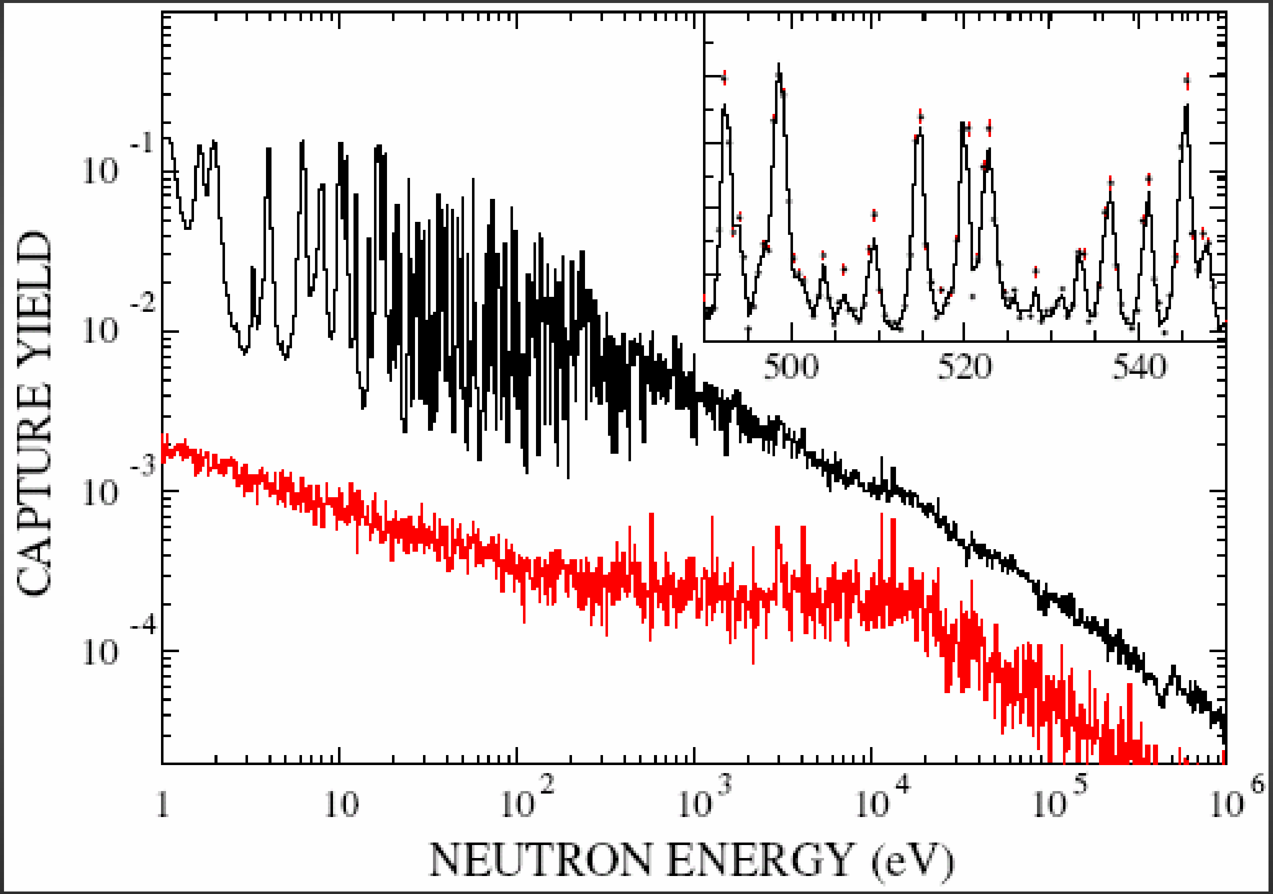
^{232}Th

^{209}Bi

^{237}Np

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

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



MACS-30 = 3100 ± 160 mb

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

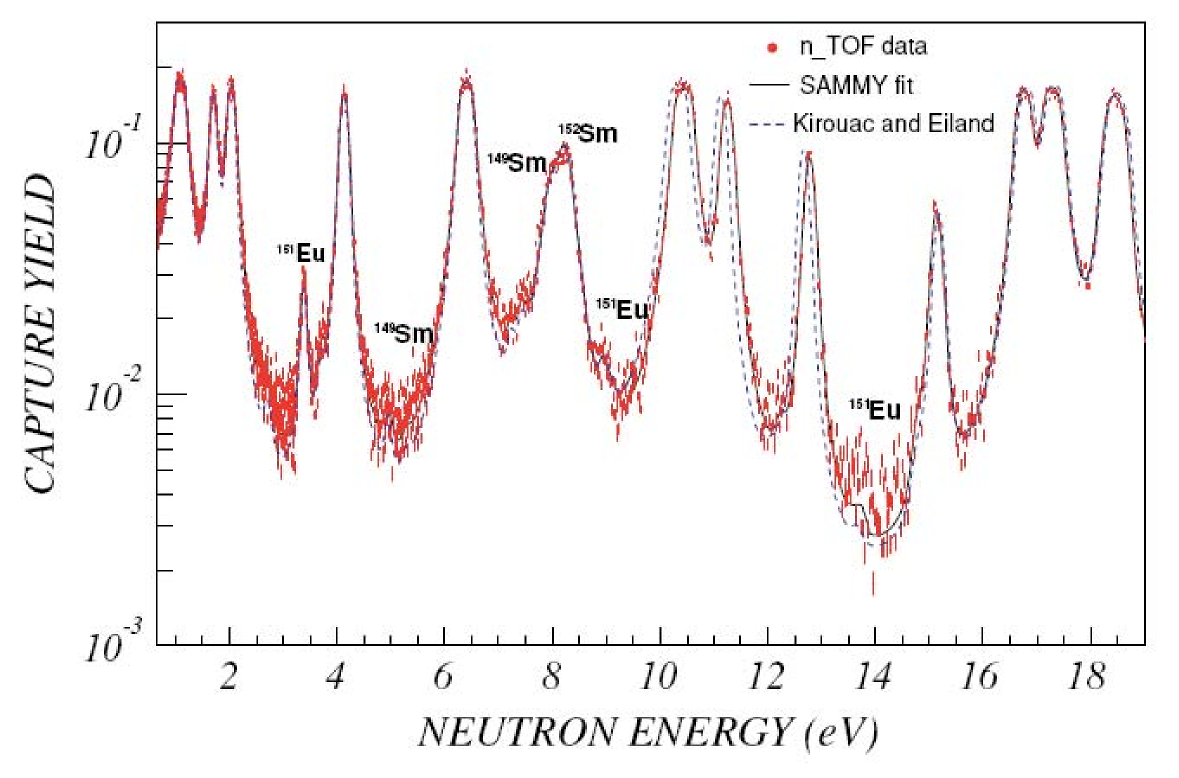
^{232}Th

^{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 experiments

Capture

$^{151}\mathrm{Sm}$

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

$^{232}\mathrm{Th}$

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

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

$^{139}\mathrm{La}$

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

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

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

Fission

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

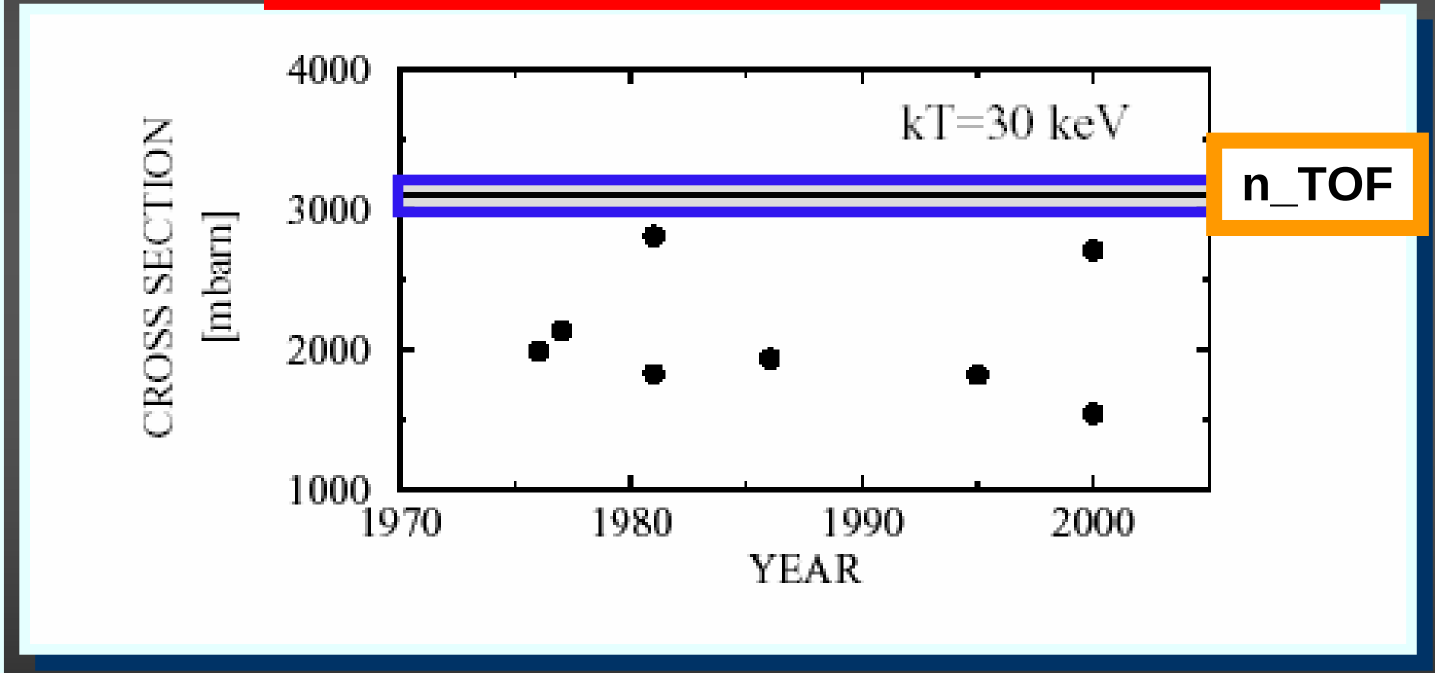
$^{232}\mathrm{Th}$

$^{209}\mathrm{Bi}$

$^{237}\mathrm{Np}$

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

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)



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

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)

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

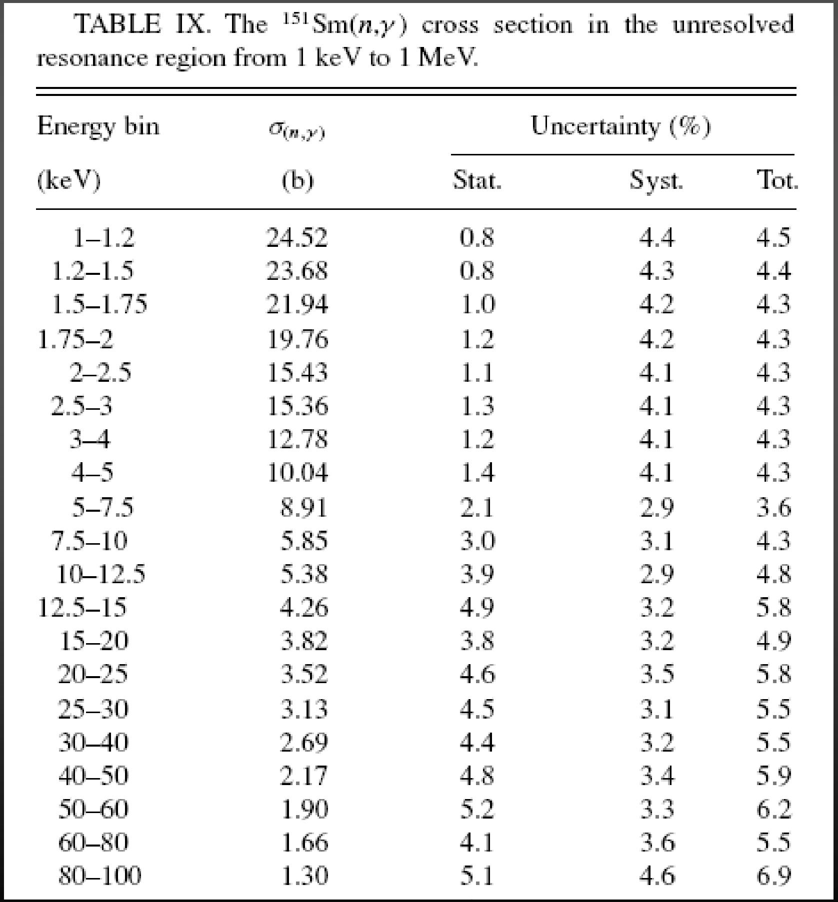


TABLE IX. The ^{151}Sm(n,γ) cross section in the unresolved resonance region from 1 keV to 1 MeV.

Energy bin	$\sigma_{(n,\gamma)}$	Uncertainty (%)		
(keV)	(b)	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

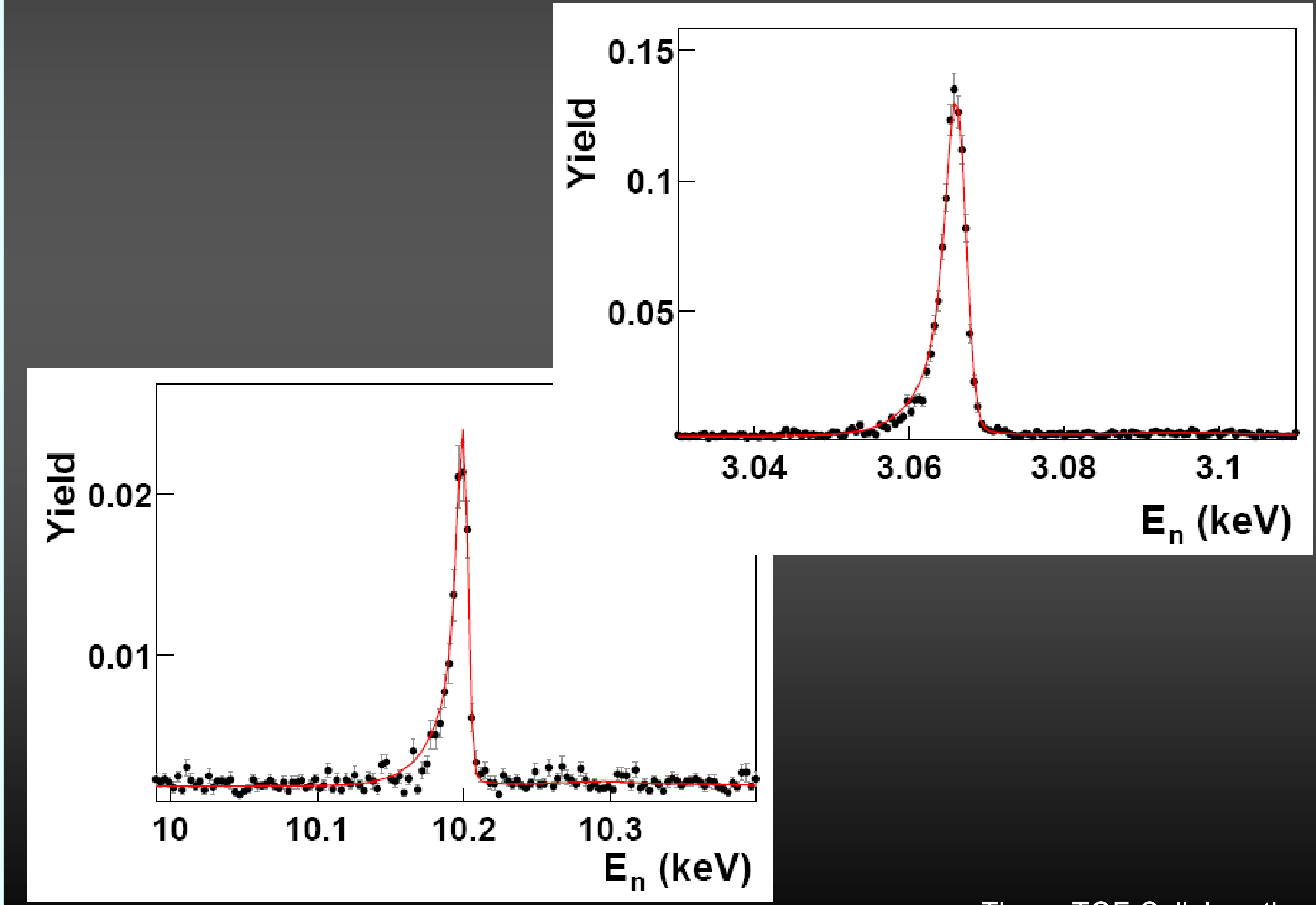
^{209}Bi

^{237}Np

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

^{207}Pb(n,γ)

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



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

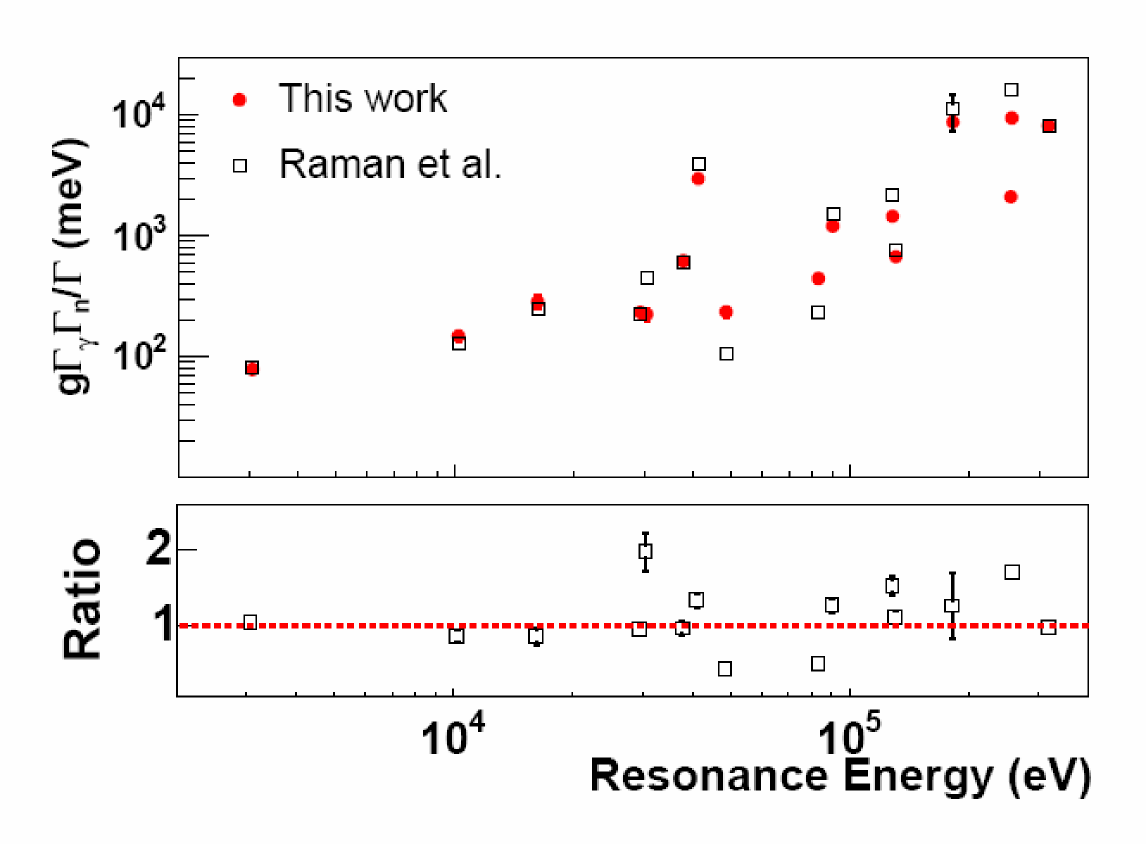
^{209}Bi

^{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)



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)

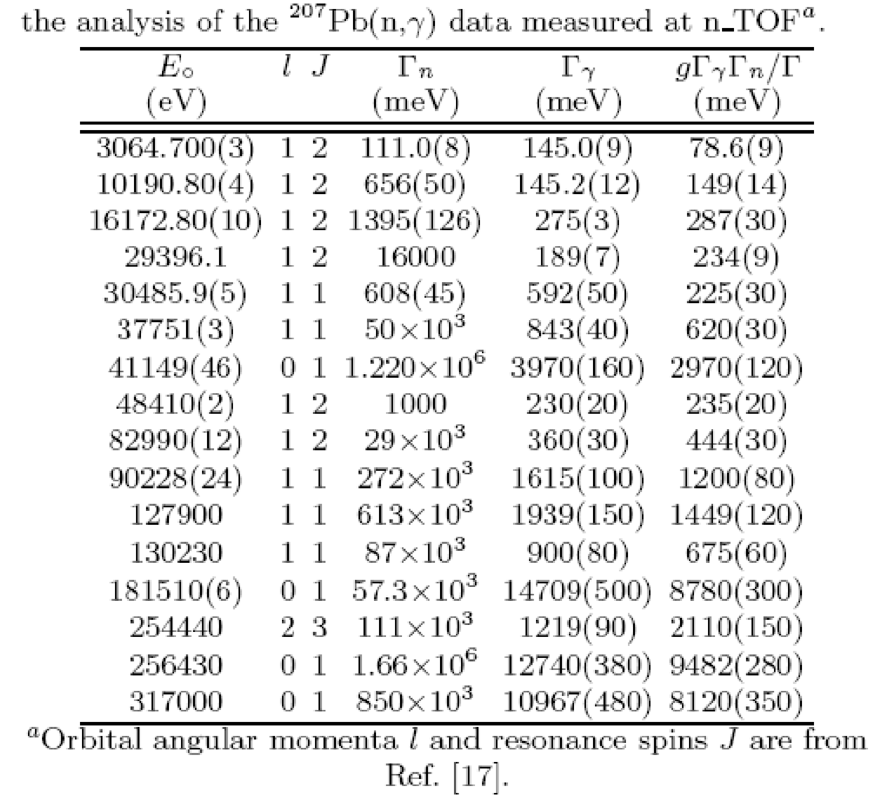


TABLE II: Resonance parameters and radiative kernels from the analysis of the ^{207}Pb(n,γ) data measured at n_TOF[a].

$E_\circ$ (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

Capture

^{151}Sm

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

^{232}Th

^{24,25,26}Mg

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

^{139}La

^{186,187,188}Os

^{233,234}U

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

Fission

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

^{232}Th

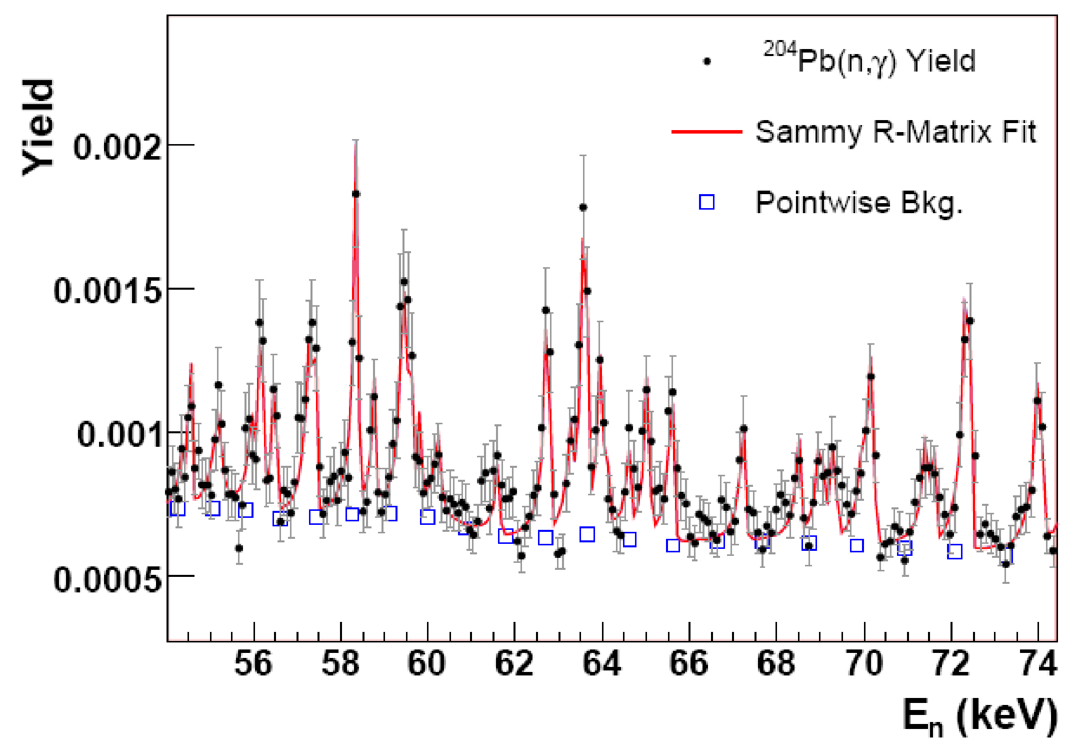
^{209}Bi

^{237}Np

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

^{204}Pb(n,γ)

C Domingo-Pardo, et al. - The n_TOF Collaboration
ND2004 Conference, Santa Fe, NM – Sept. 2004
&
submitted for publication to PRC, October 2006



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

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

^{204}Pb(n,γ)

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

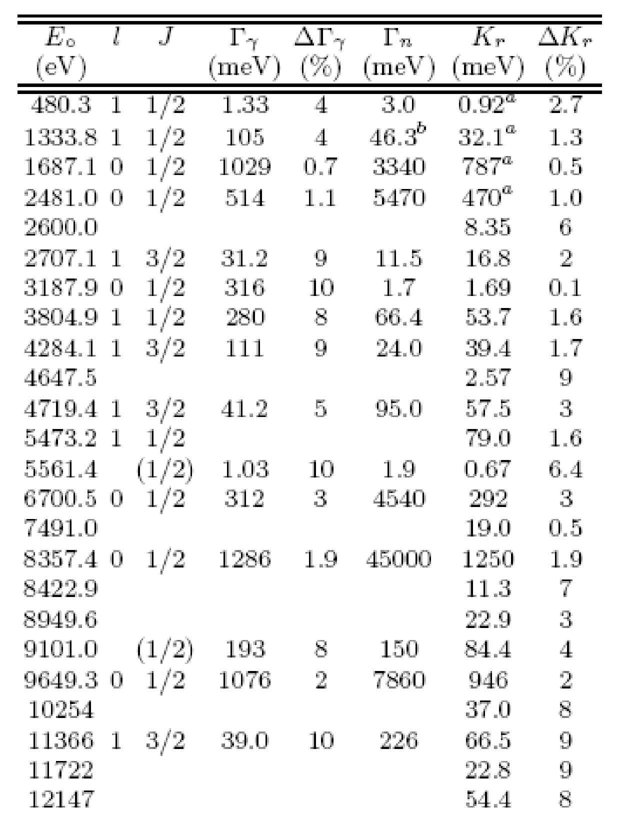
^{233,234,235,236,238}U

^{232}Th

^{209}Bi

^{237}Np

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



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

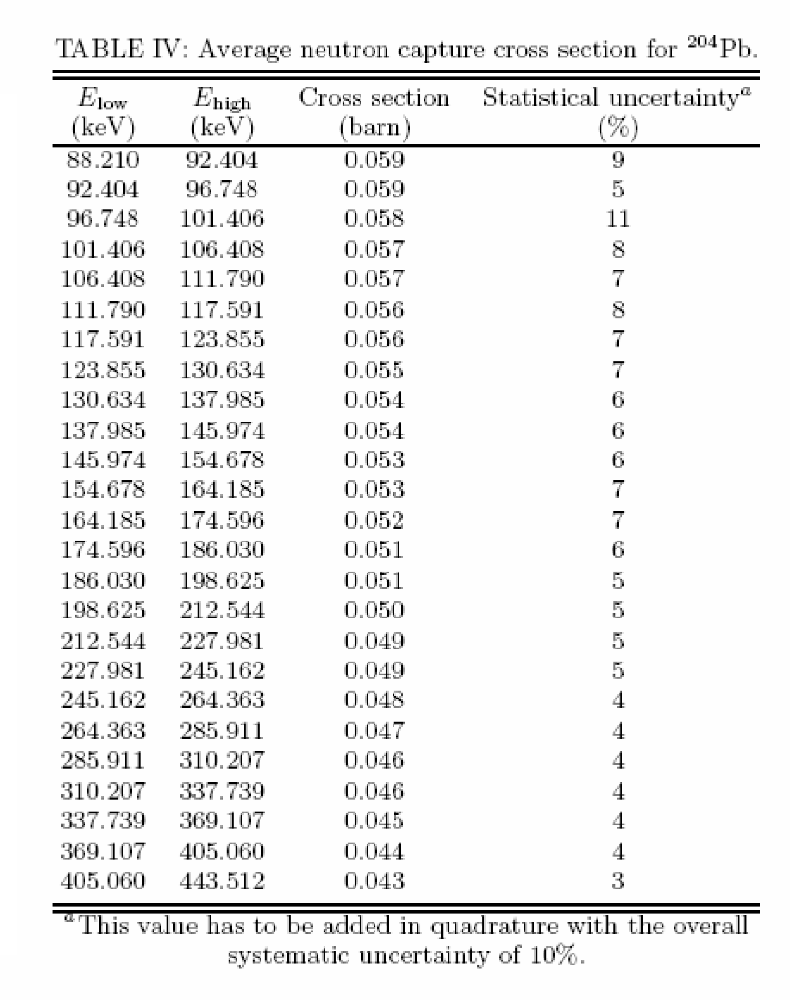


TABLE IV: Average neutron capture cross section for ^{204}Pb.

$E_{\rm low}$ (keV)	$E_{\rm high}$ (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

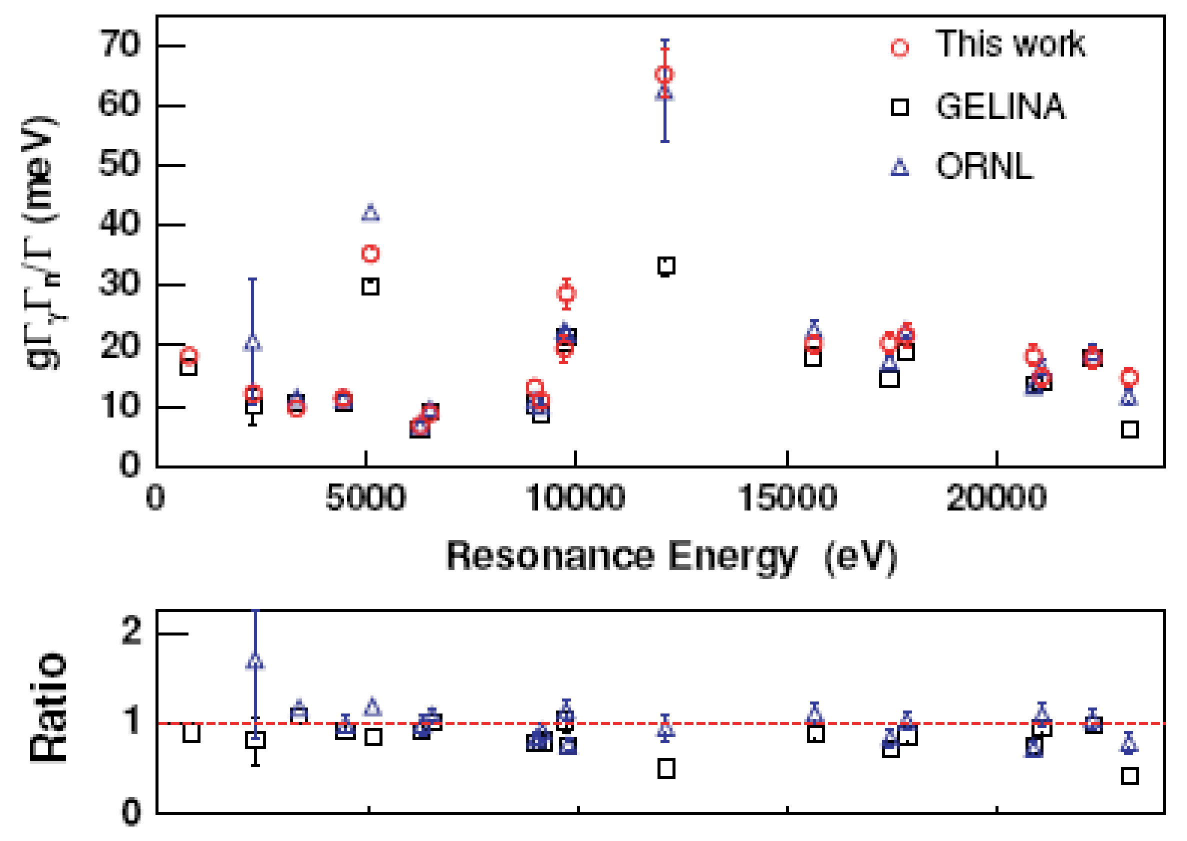
^{209}Bi

^{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

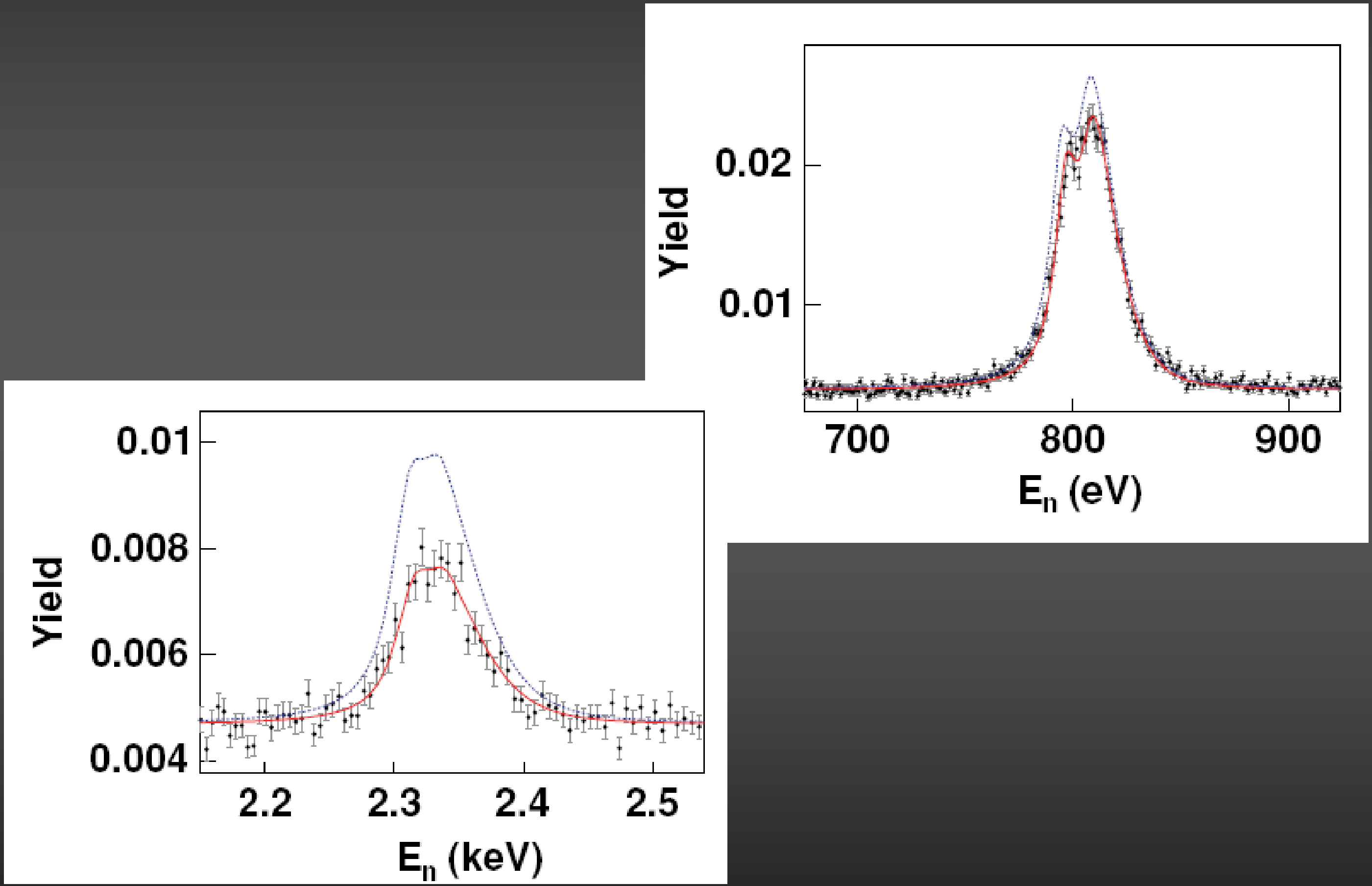
^{209}Bi

^{237}Np

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

^{209}Bi(n,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

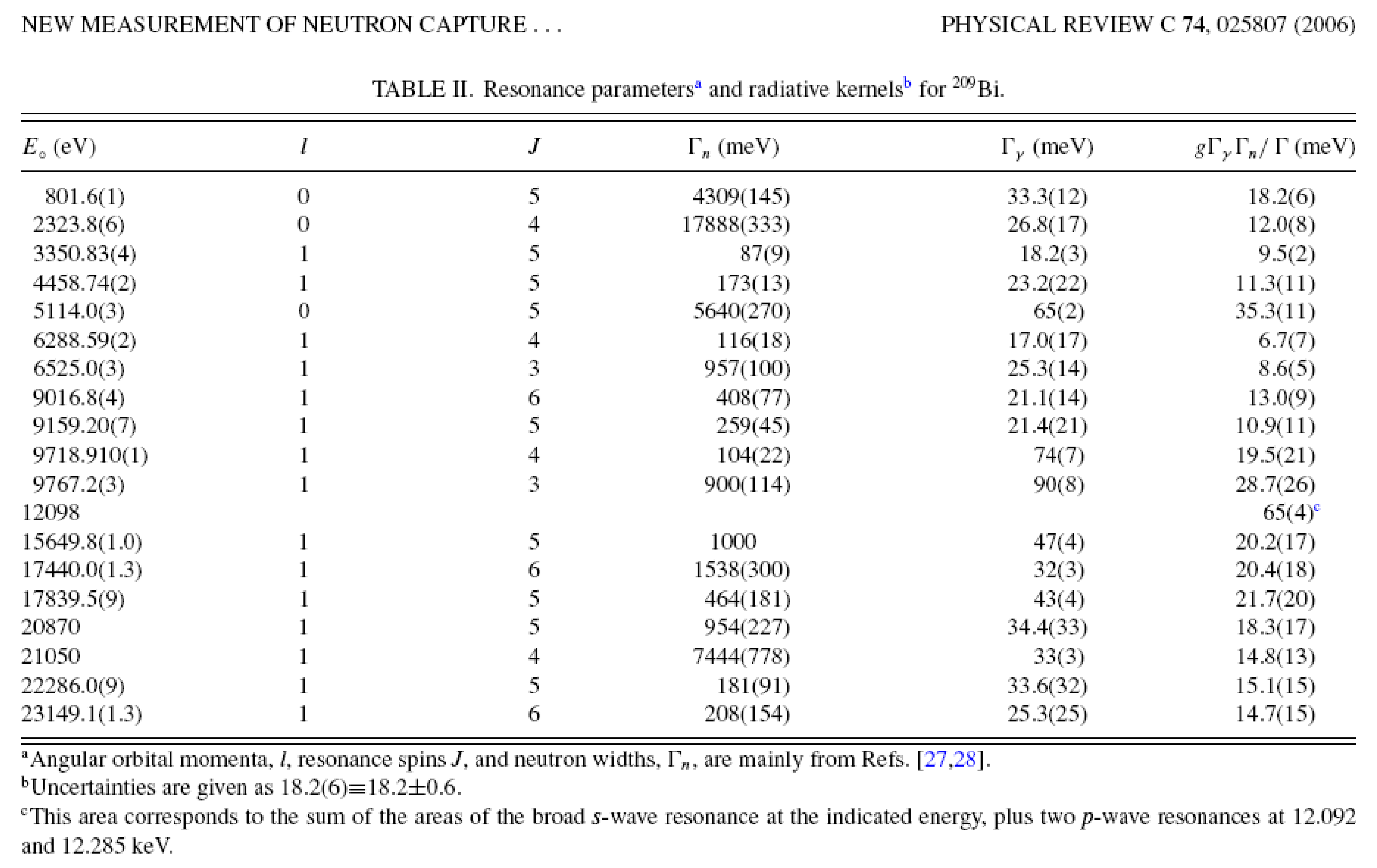
^{209}Bi

^{237}Np

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

^{209}Bi(n,γ)

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

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

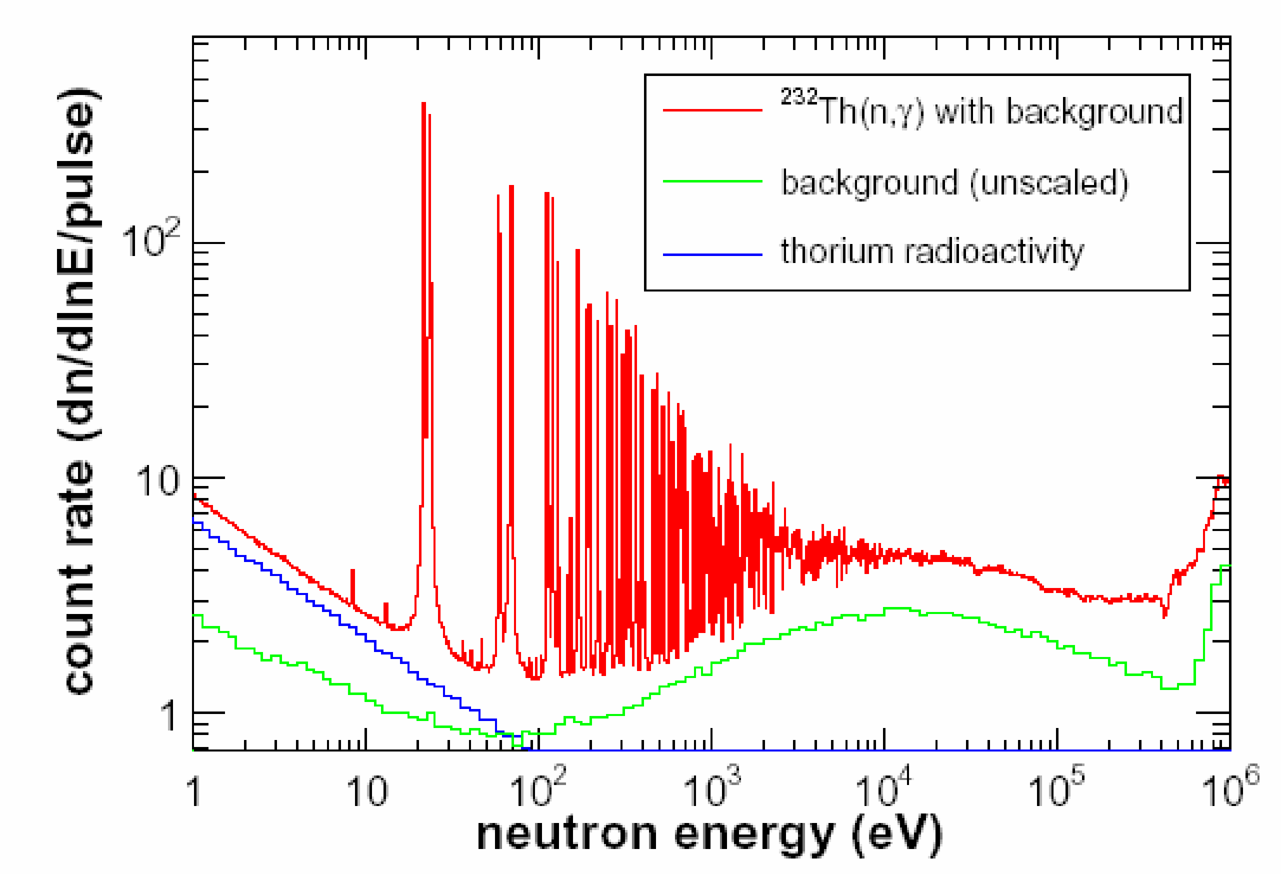
^{209}Bi

^{237}Np

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

^{232}Th(n,γ)

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

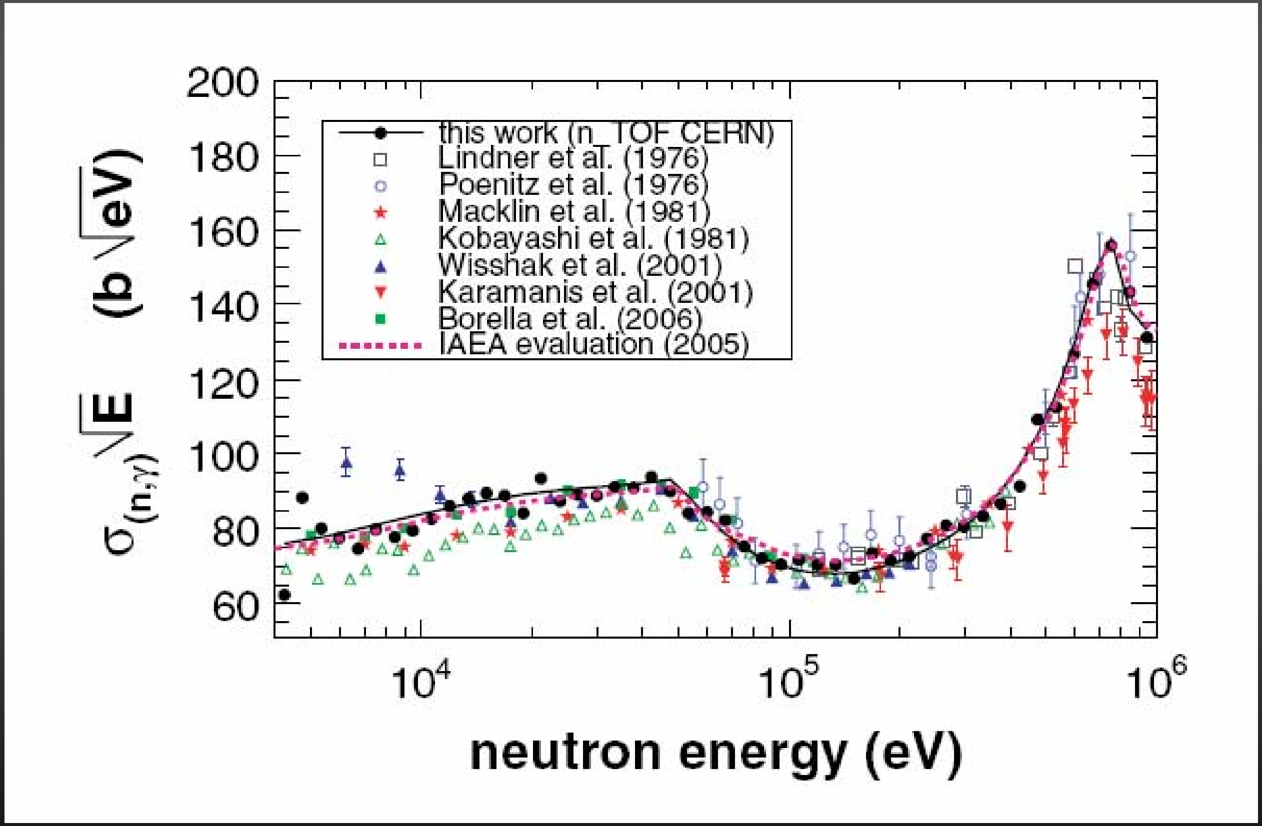
^{209}Bi

^{237}Np

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

^{232}Th(n,γ)

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)



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,γ)

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)

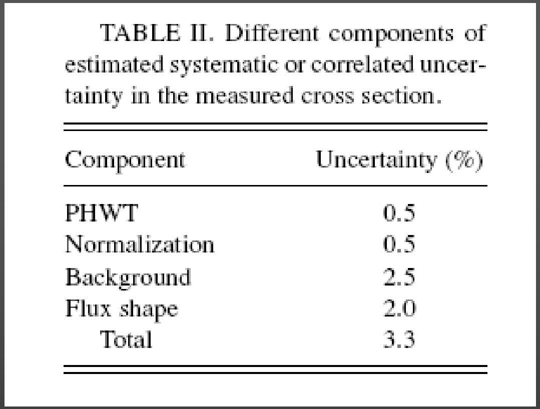
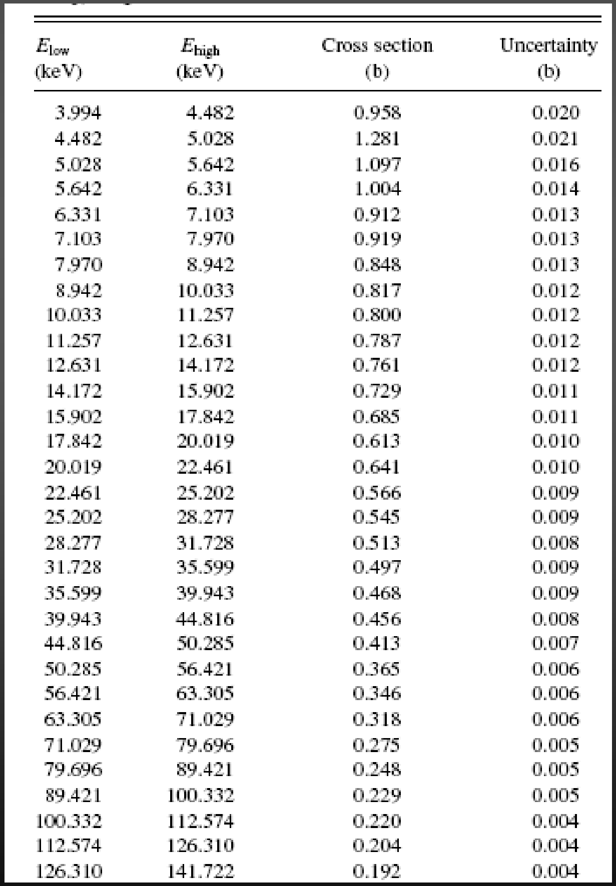


TABLE II. Different components of estimated systematic or correlated uncertainty in the measured cross section.

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

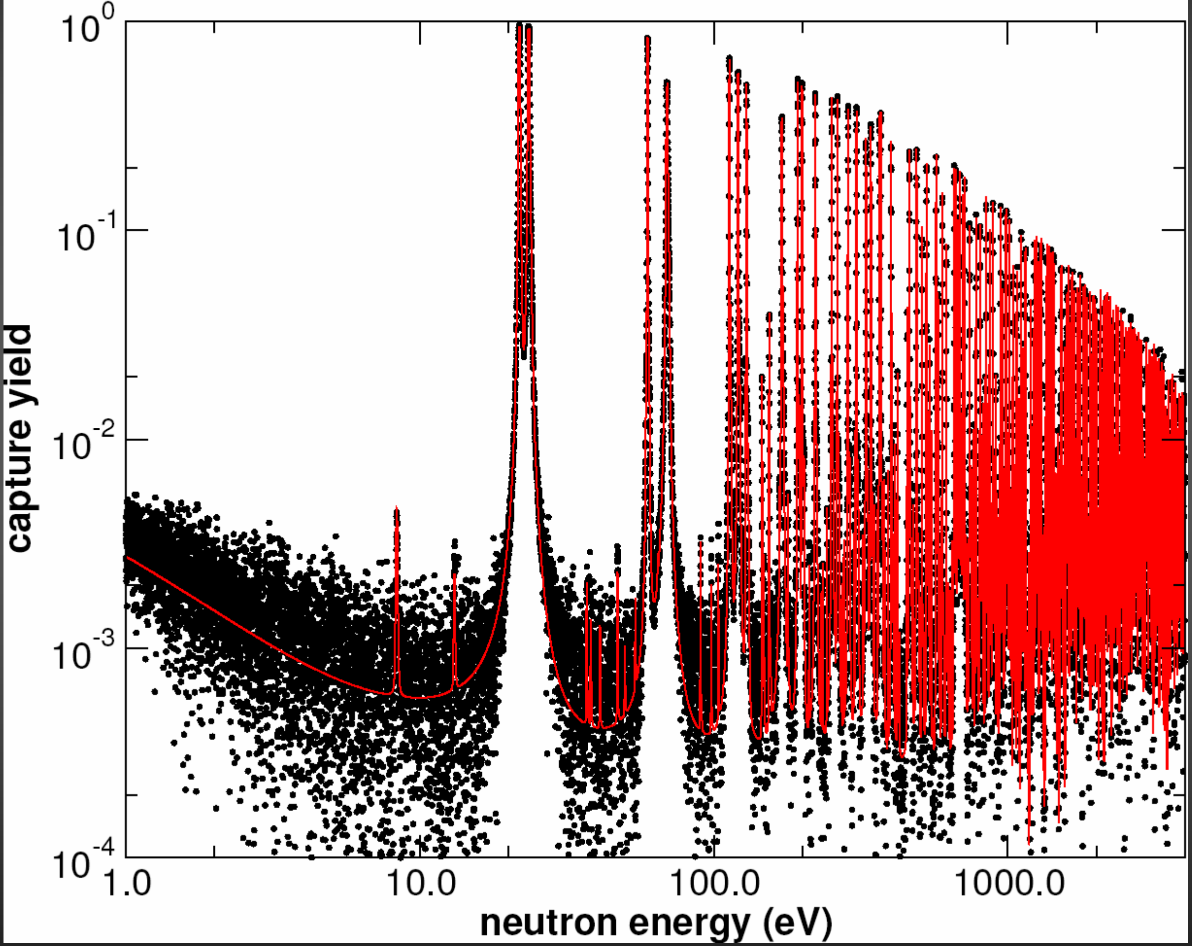
^{209}Bi

^{237}Np

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

^{232}Th(n,γ)

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

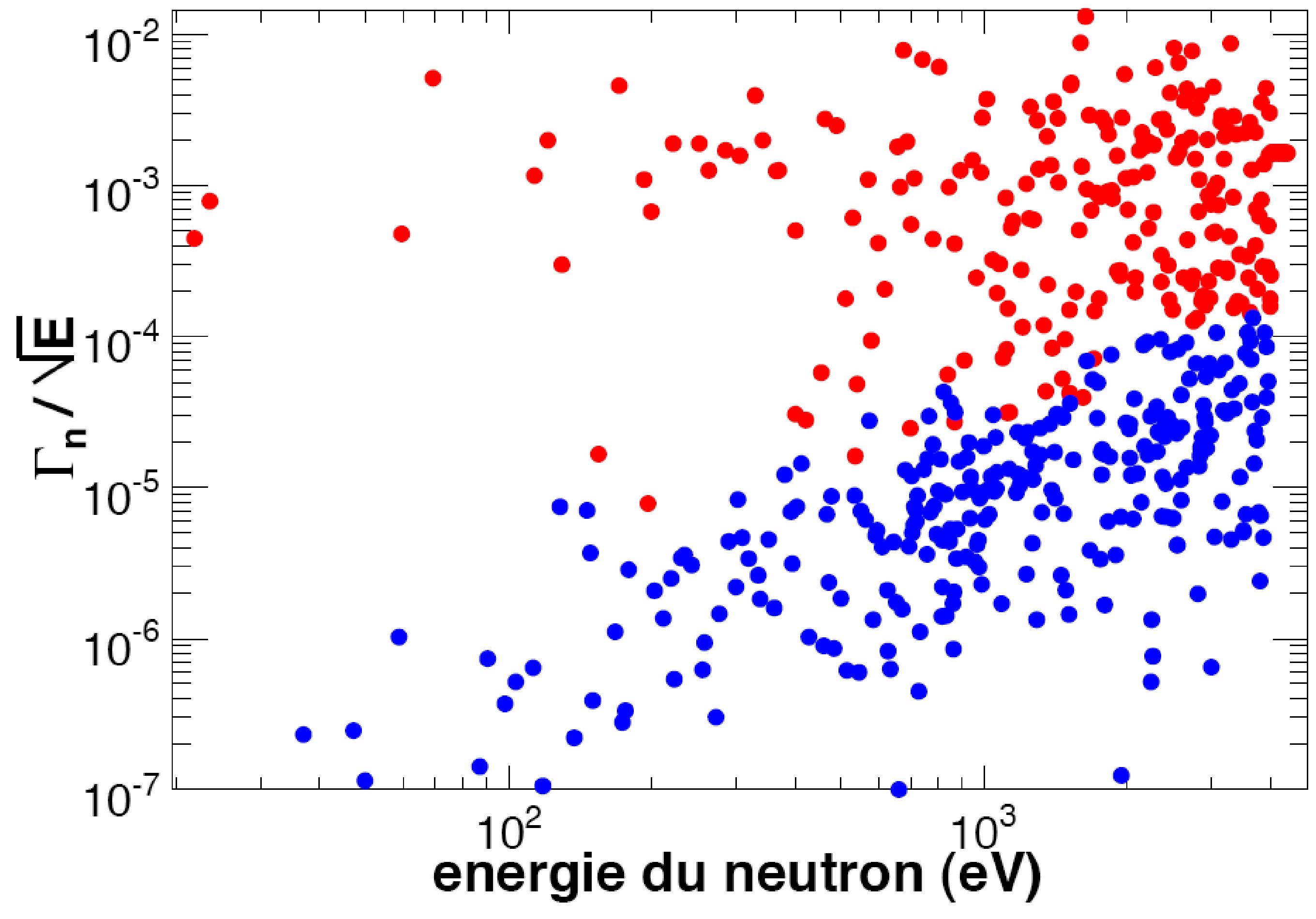
^{209}Bi

^{237}Np

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

^{232}Th(n,γ)

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

^{233,234}U

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

Fission

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

^{232}Th

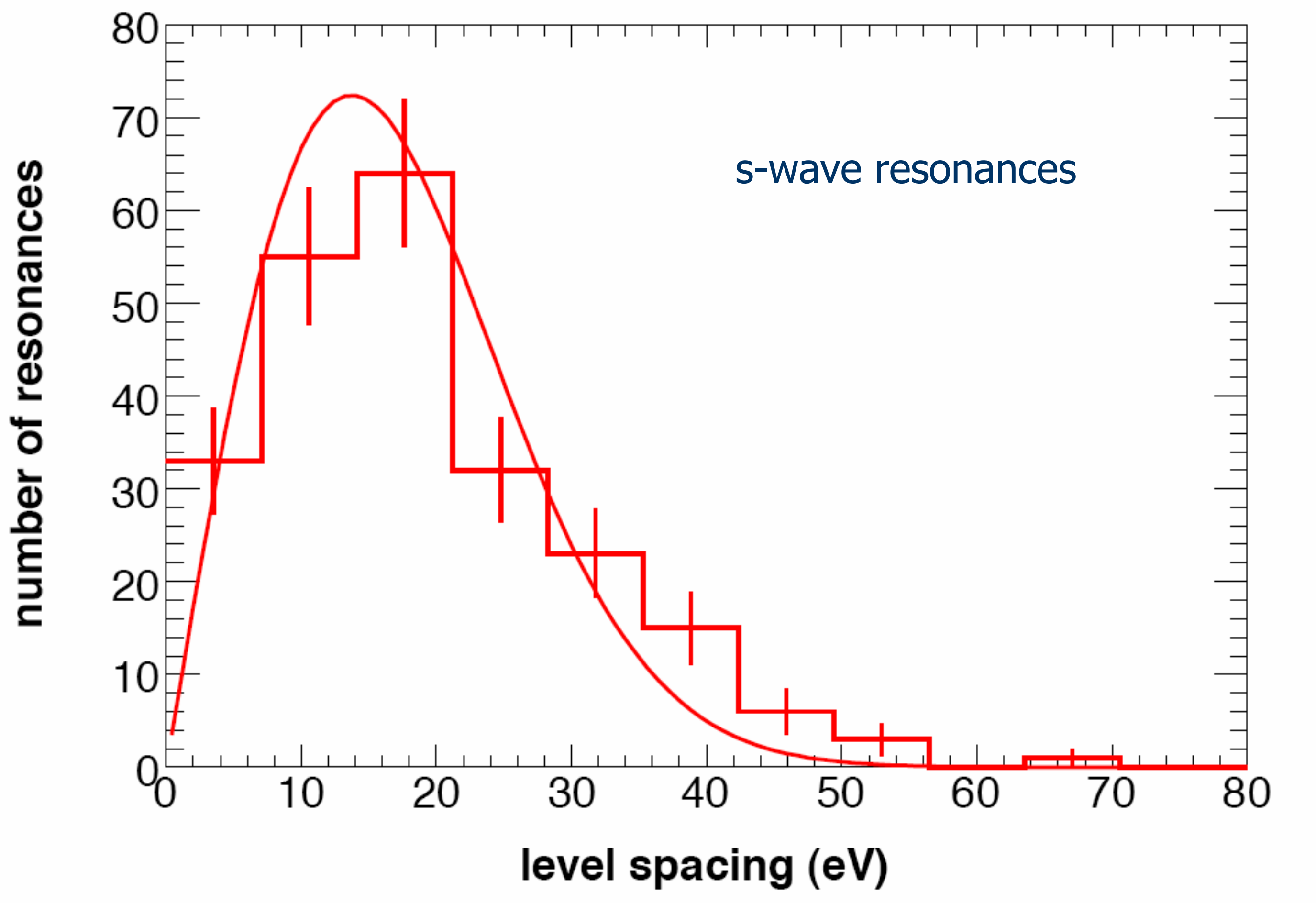
^{209}Bi

^{237}Np

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

^{232}Th(n,γ)

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

^{233,234}U

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

Fission

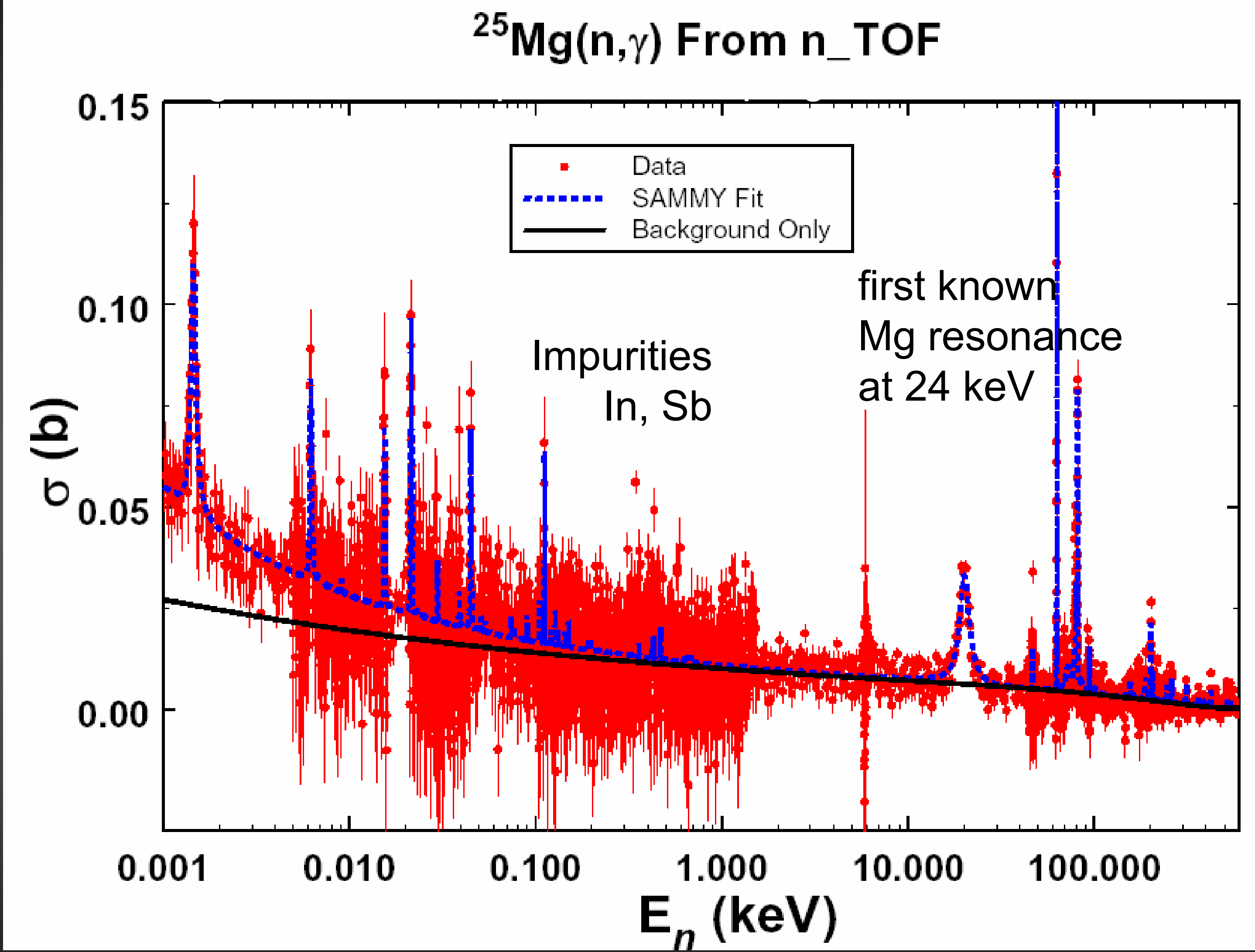
^{233,234,235,236,238}U

^{232}Th

^{209}Bi

^{237}Np

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



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

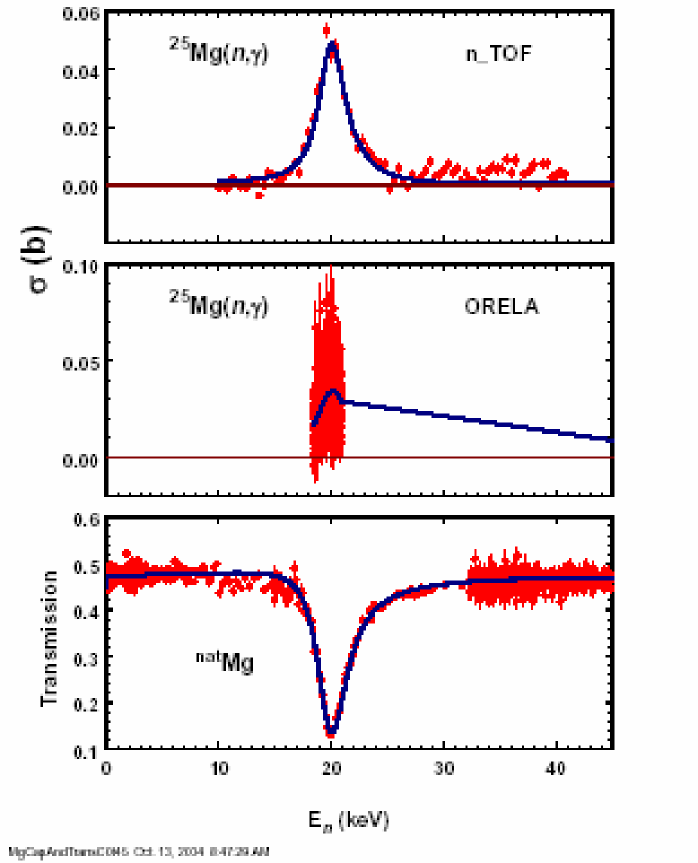
^{233,234,235,236,238}U

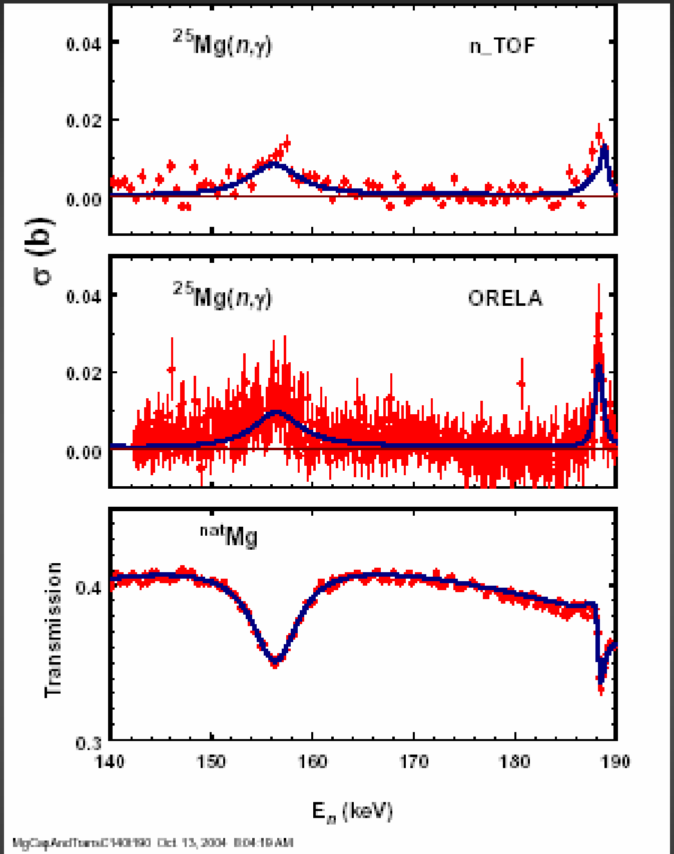
^{232}Th

^{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

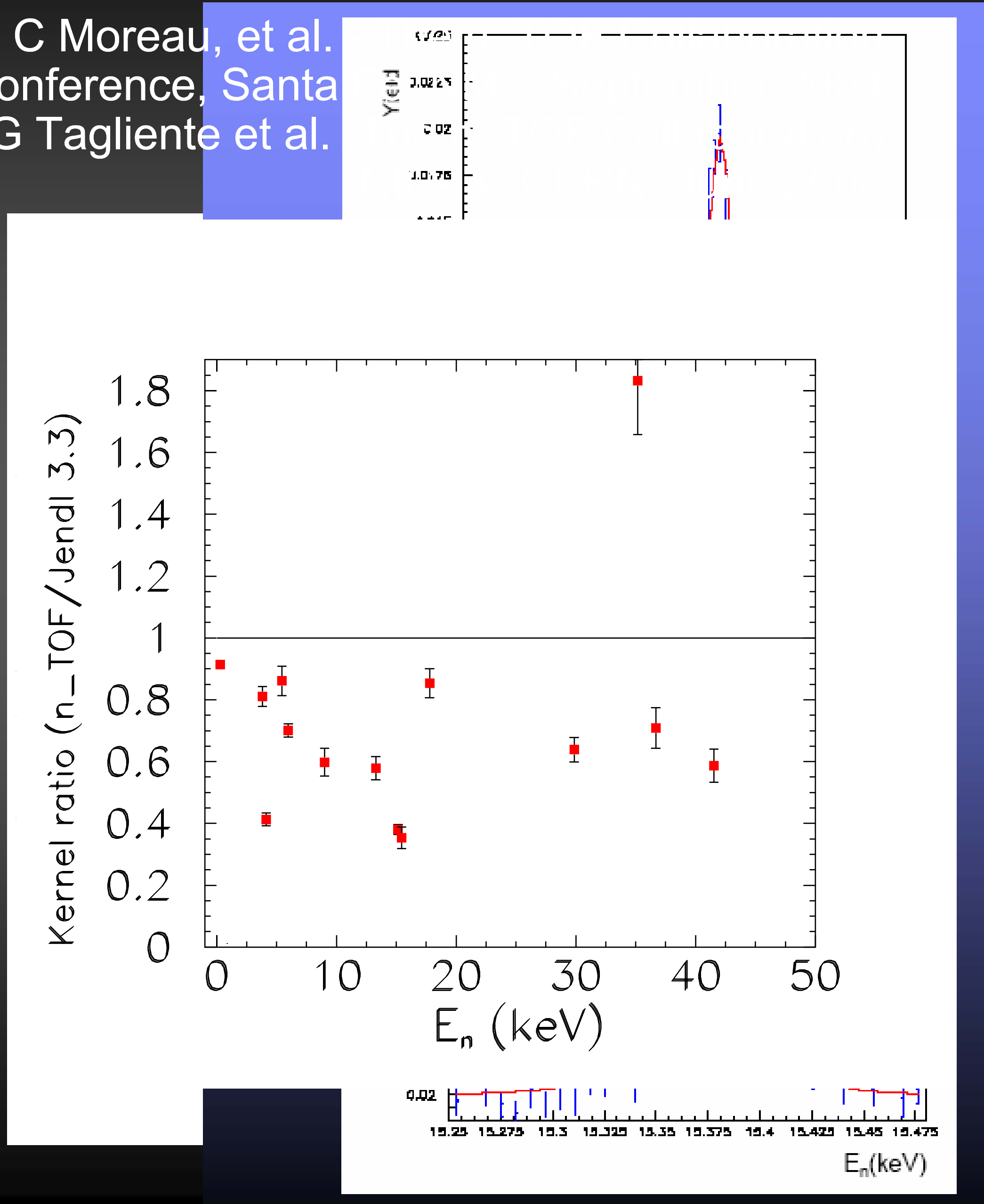
^{237}Np

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

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

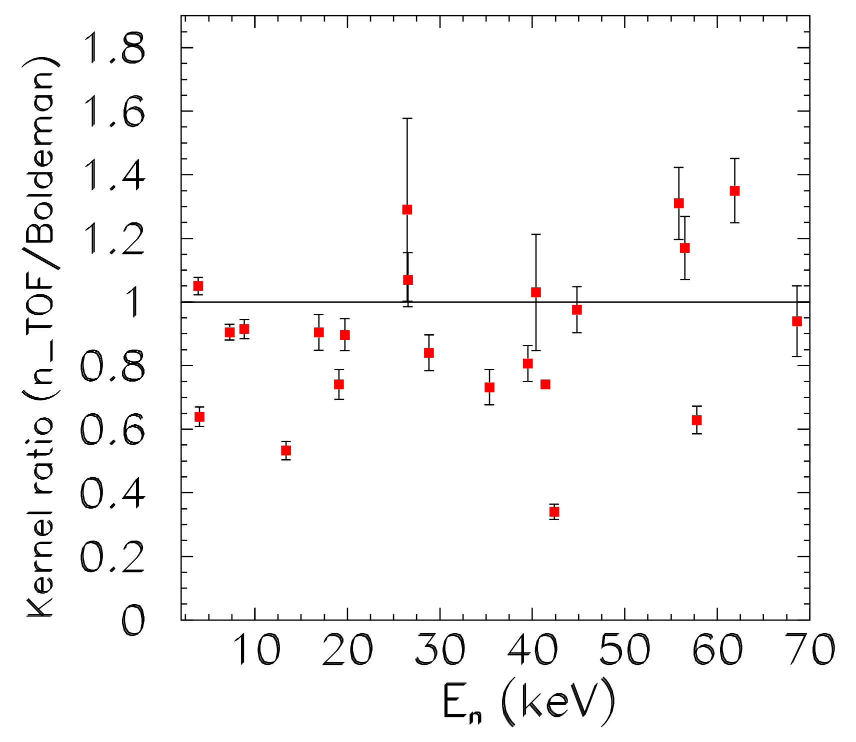
^{209}Bi

^{237}Np

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

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

^{90}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

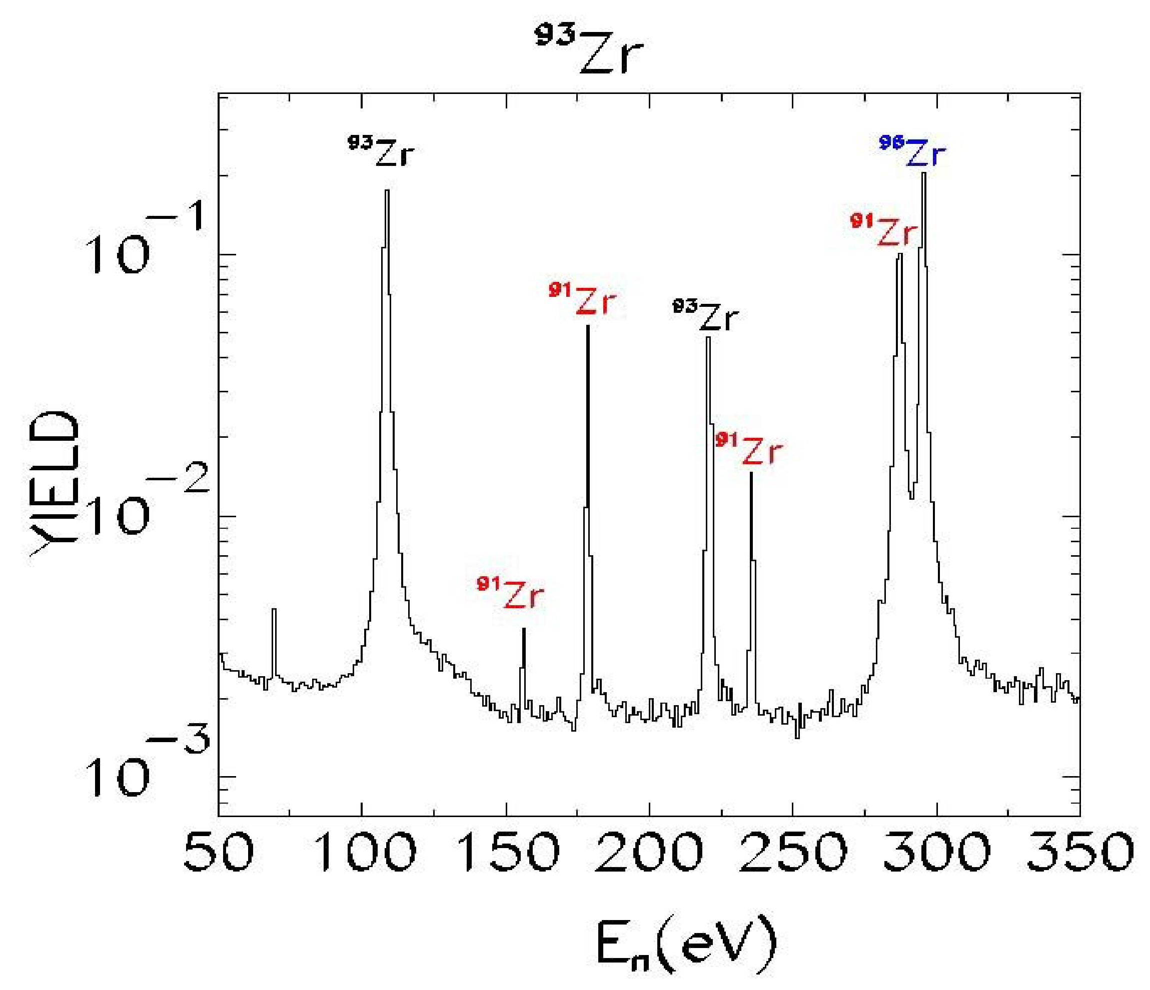
^{232}Th

^{209}Bi

^{237}Np

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

^{93}Zr(n,γ): 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

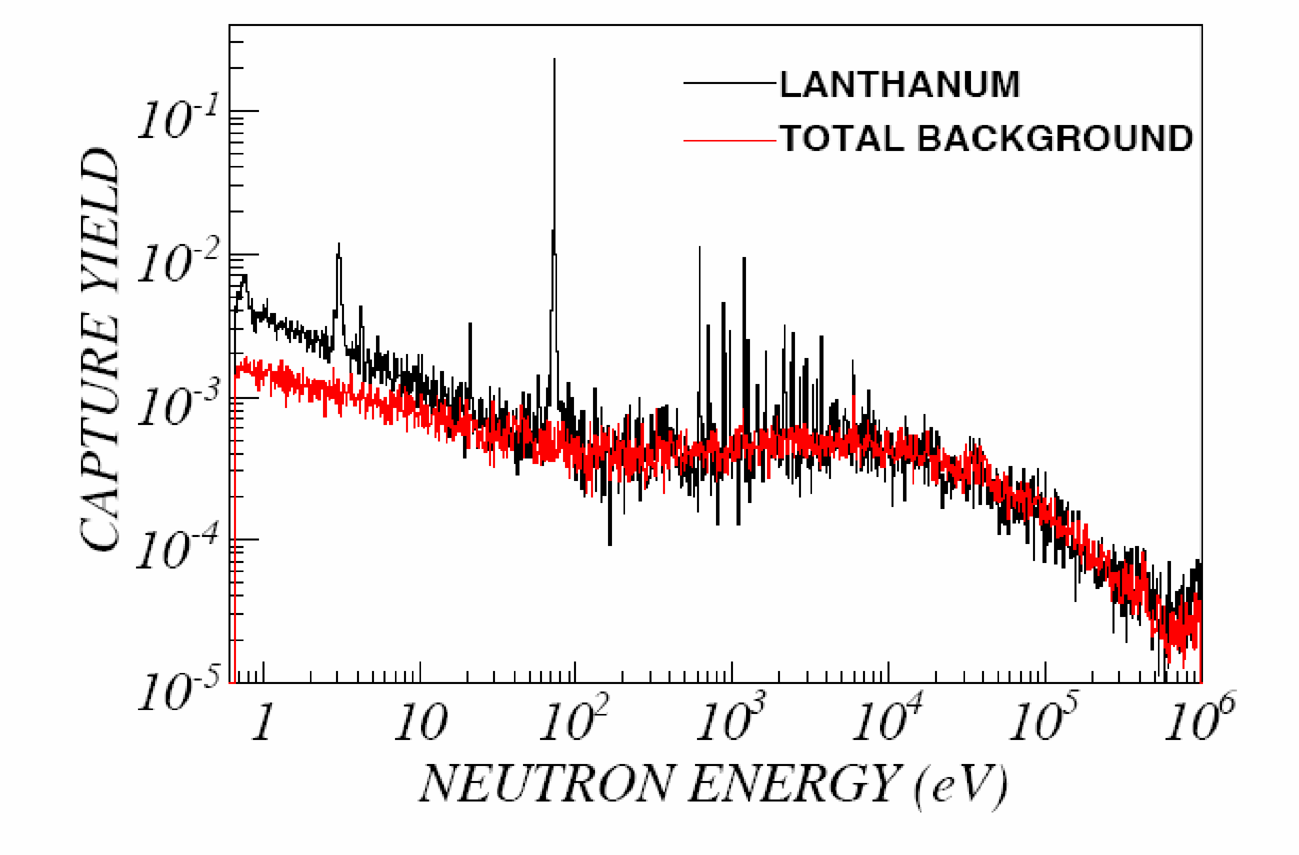
^{209}Bi

^{237}Np

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

^{139}La(n,γ)

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



Capture

^{151}Sm

^{204,206,207,208}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

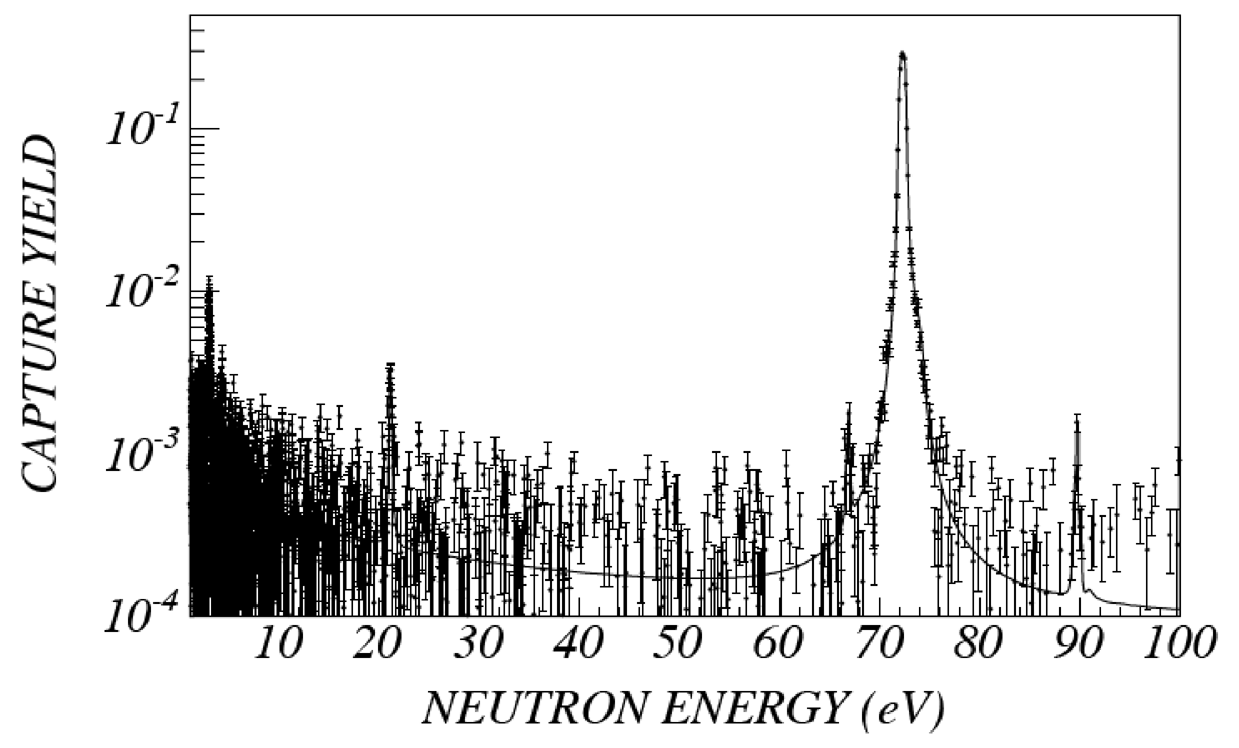
^{237}Np

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

n_TOF experiments

^{139}La(n,γ)

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

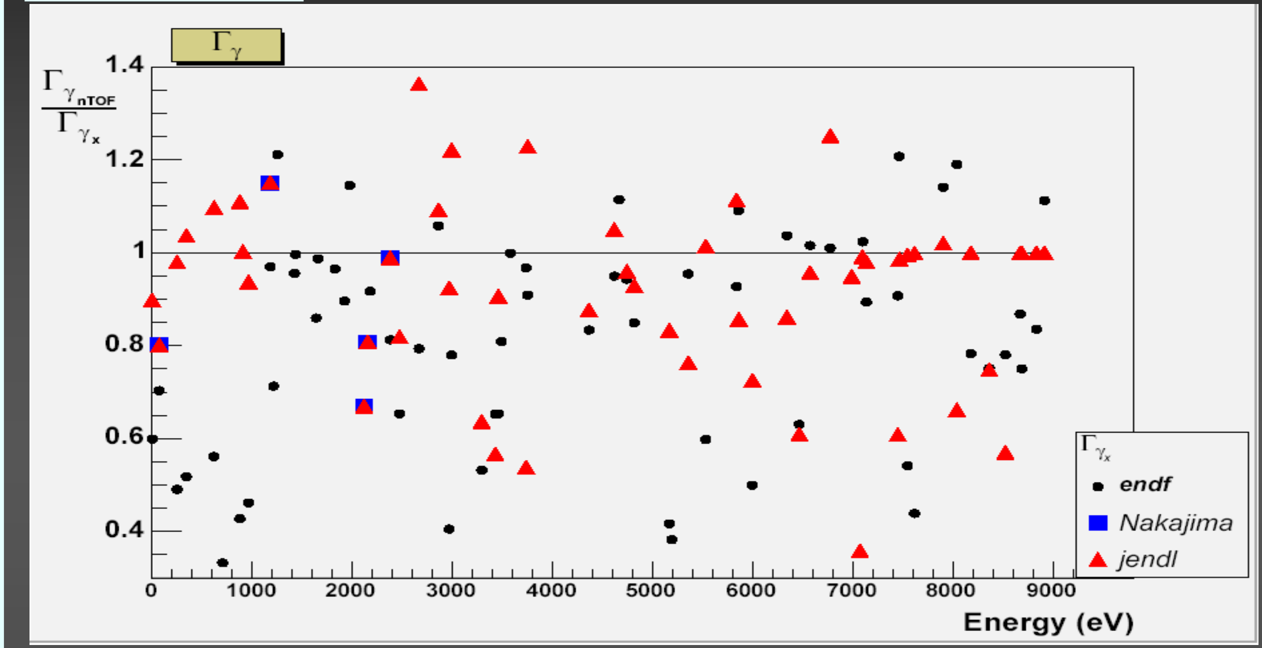
^{232}Th

^{209}Bi

^{237}Np

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

^{139}La(n,γ)



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

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

The n_TOF Collaboration

n_TOF experiments

Capture

^{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

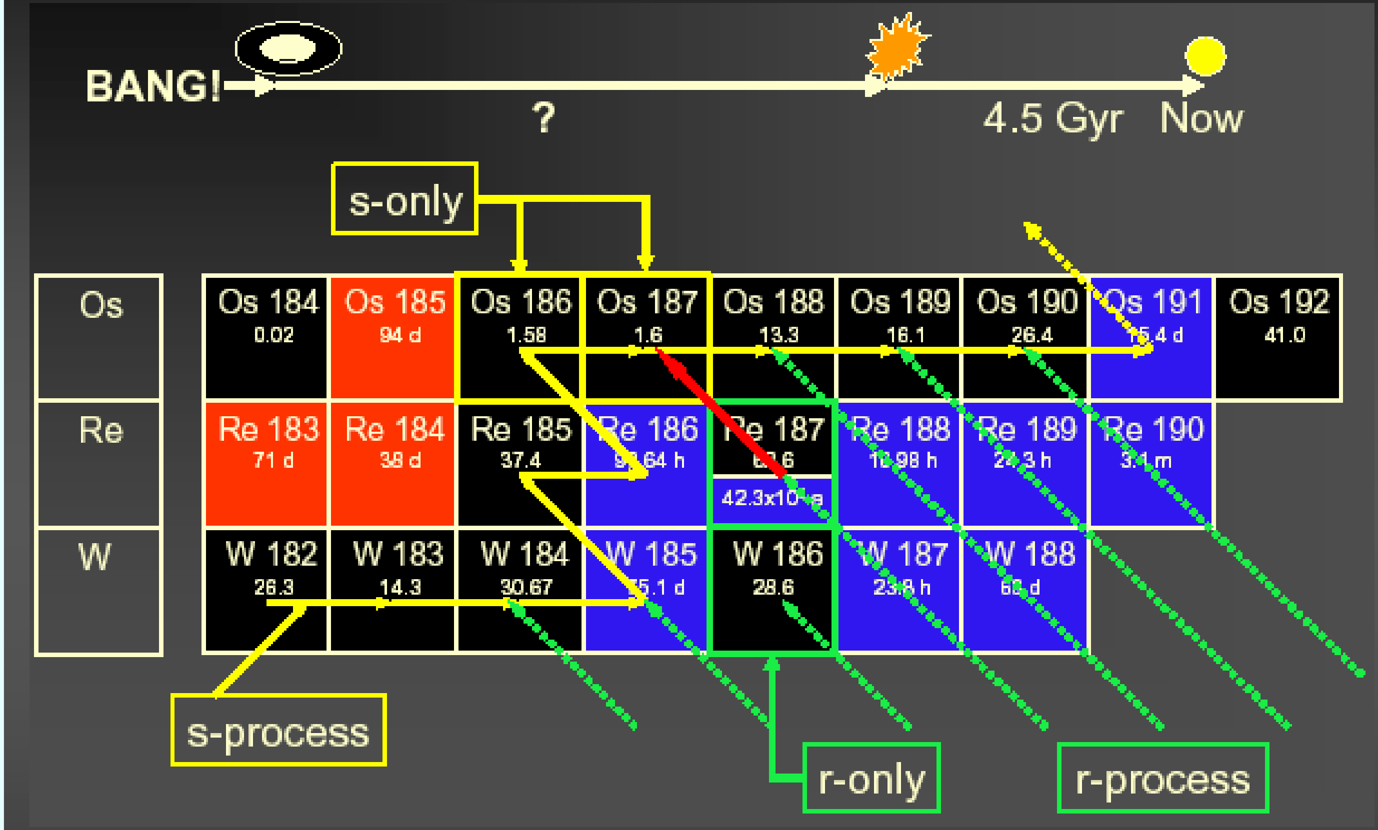
^{233,234,235,236,238}U

^{232}Th

^{209}Bi

^{237}Np

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



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

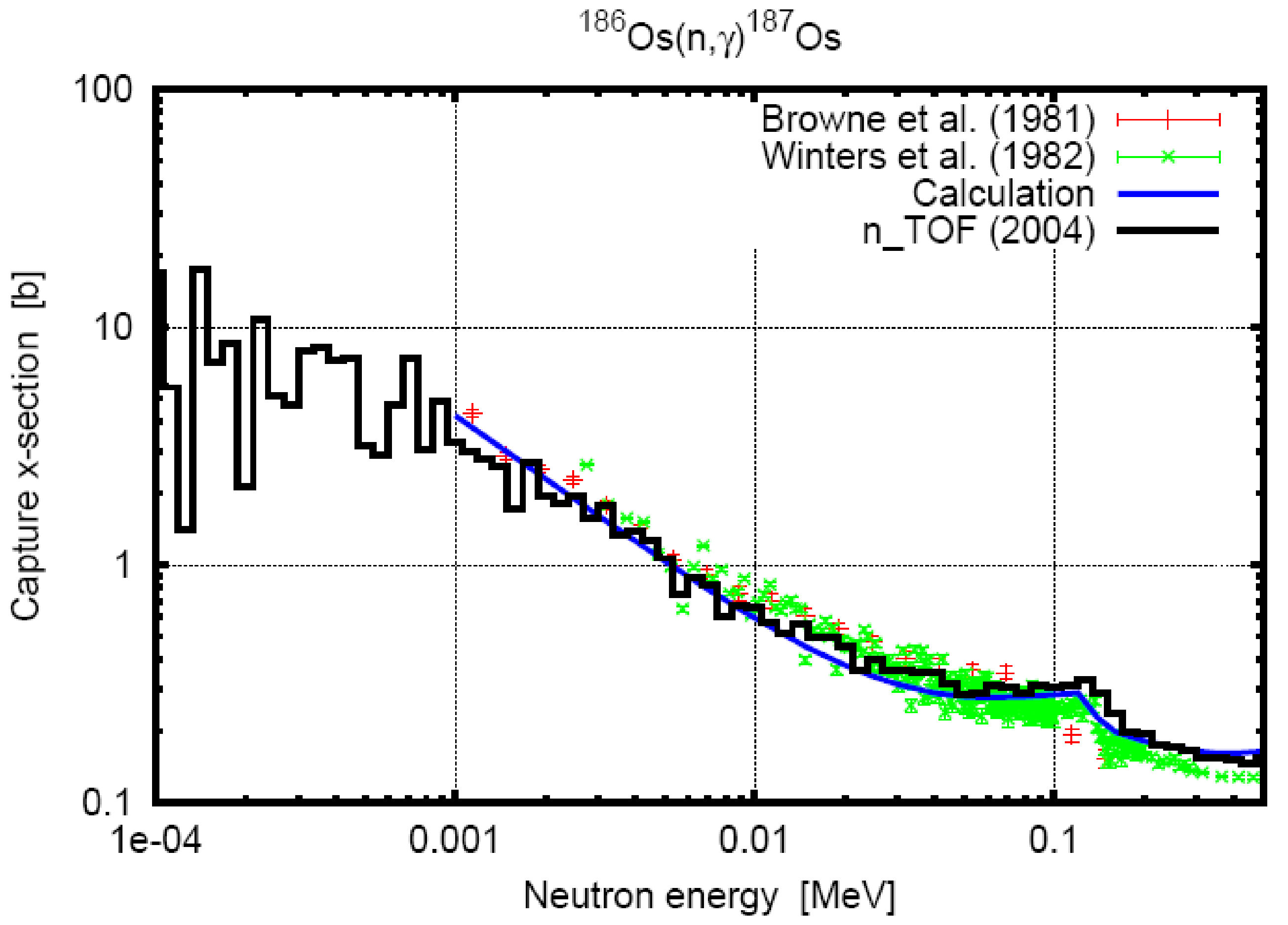
^{209}Bi

^{237}Np

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

M Mosconi, *et al.* – (The n_TOF Collaboration)
NIC-IX, CERN, Geneva – June 2006
analysis completed - paper in preparation

MACS-30	
BrB81	438 ± 30 mb
WiM82	418 ± 16 mb
n_TOF	384 ± 17 mb



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

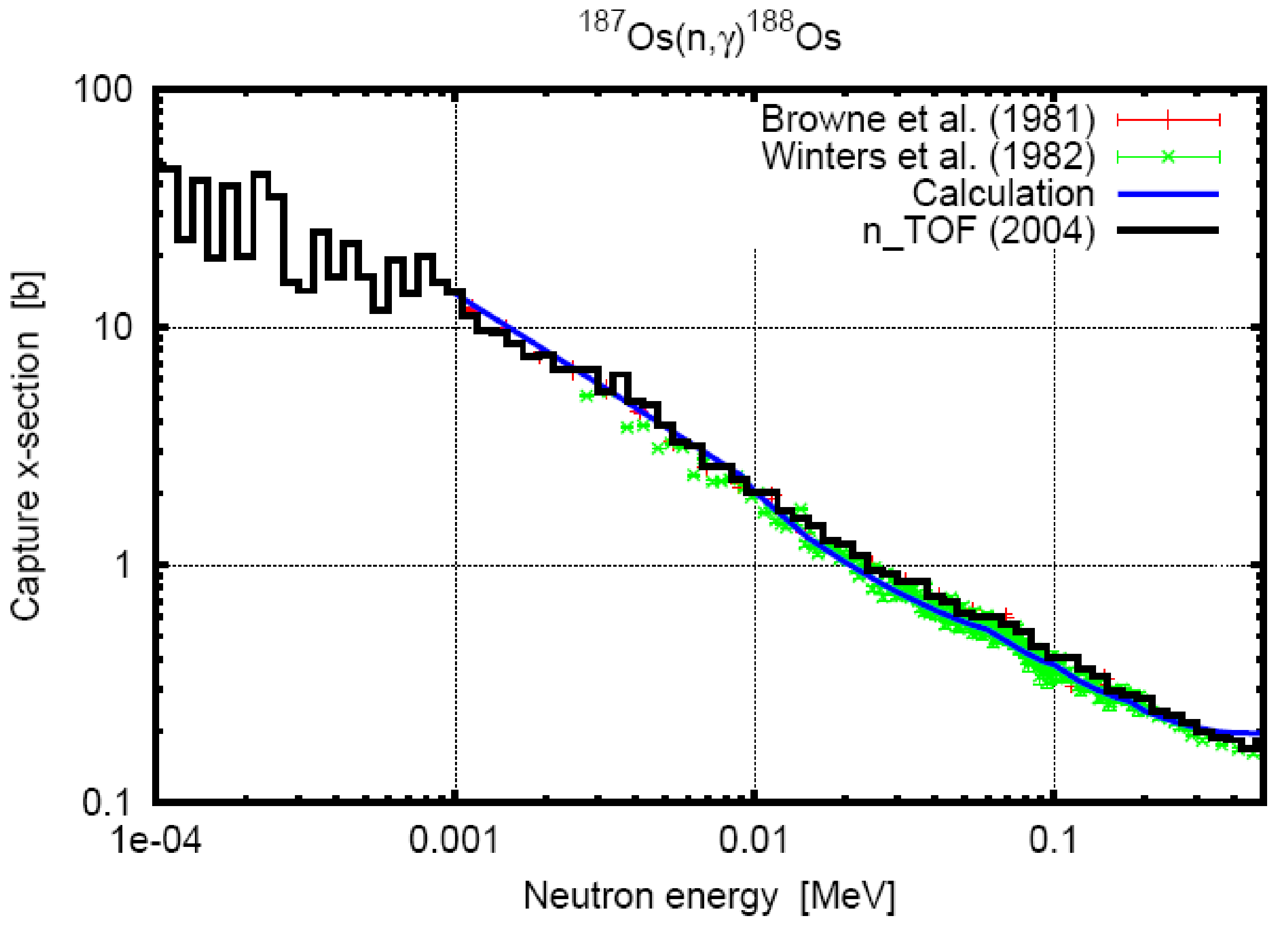
^{209}Bi

^{237}Np

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

M Mosconi, *et al.* – (The n_TOF Collaboration)
NIC-IX, CERN, Geneva – June 2006
analysis completed - paper in preparation

MACS-30	
BrB81	919 ± 28 mb
WiM82	874 ± 28 mb
n_TOF	940 ± 18 mb



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

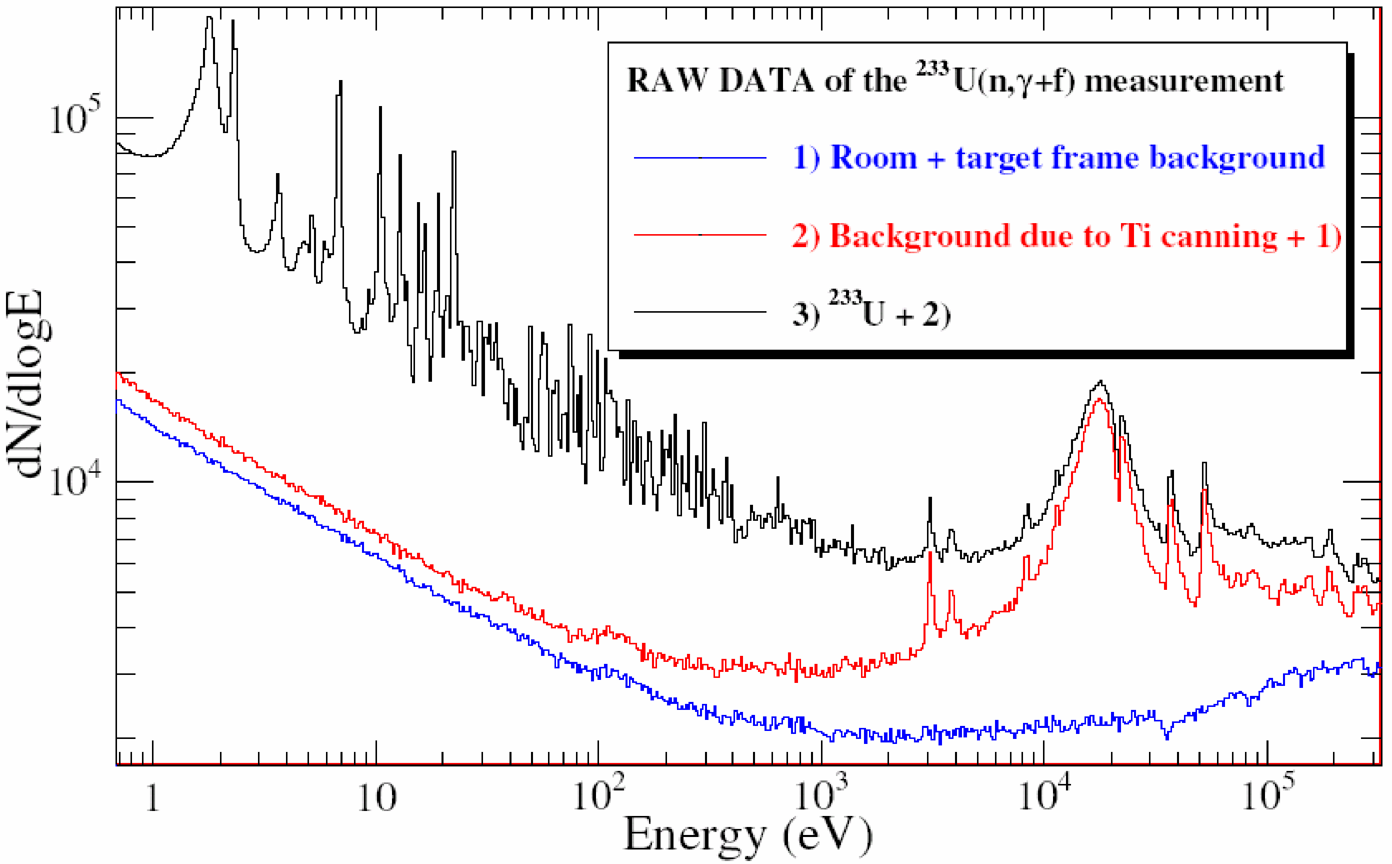
^{209}Bi

^{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

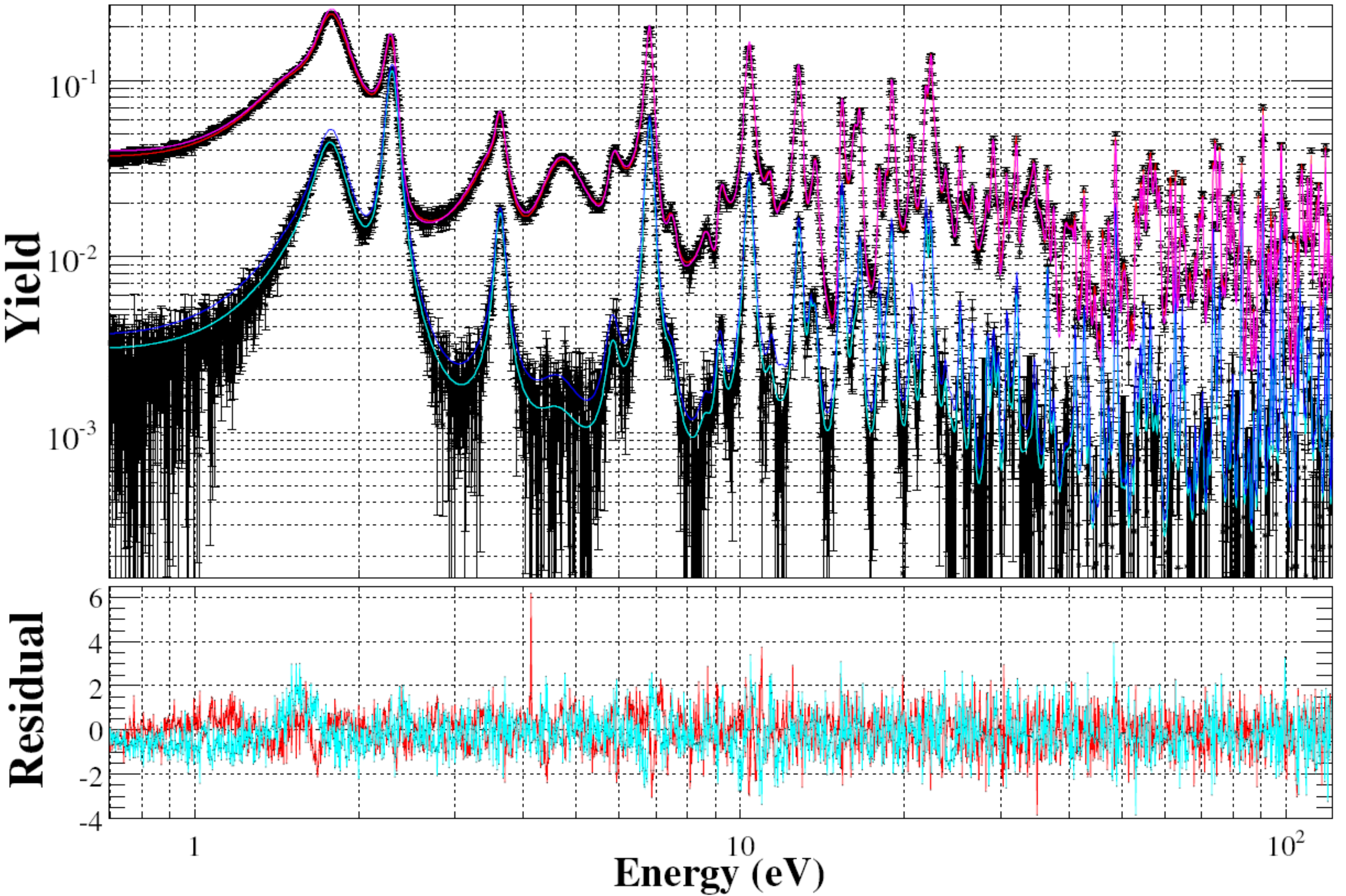
^{209}Bi

^{237}Np

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

^{233}U(n,γ)

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



n_TOF TAC in operation: capture & fission discrimination

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

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

^{234}U(n,γ)

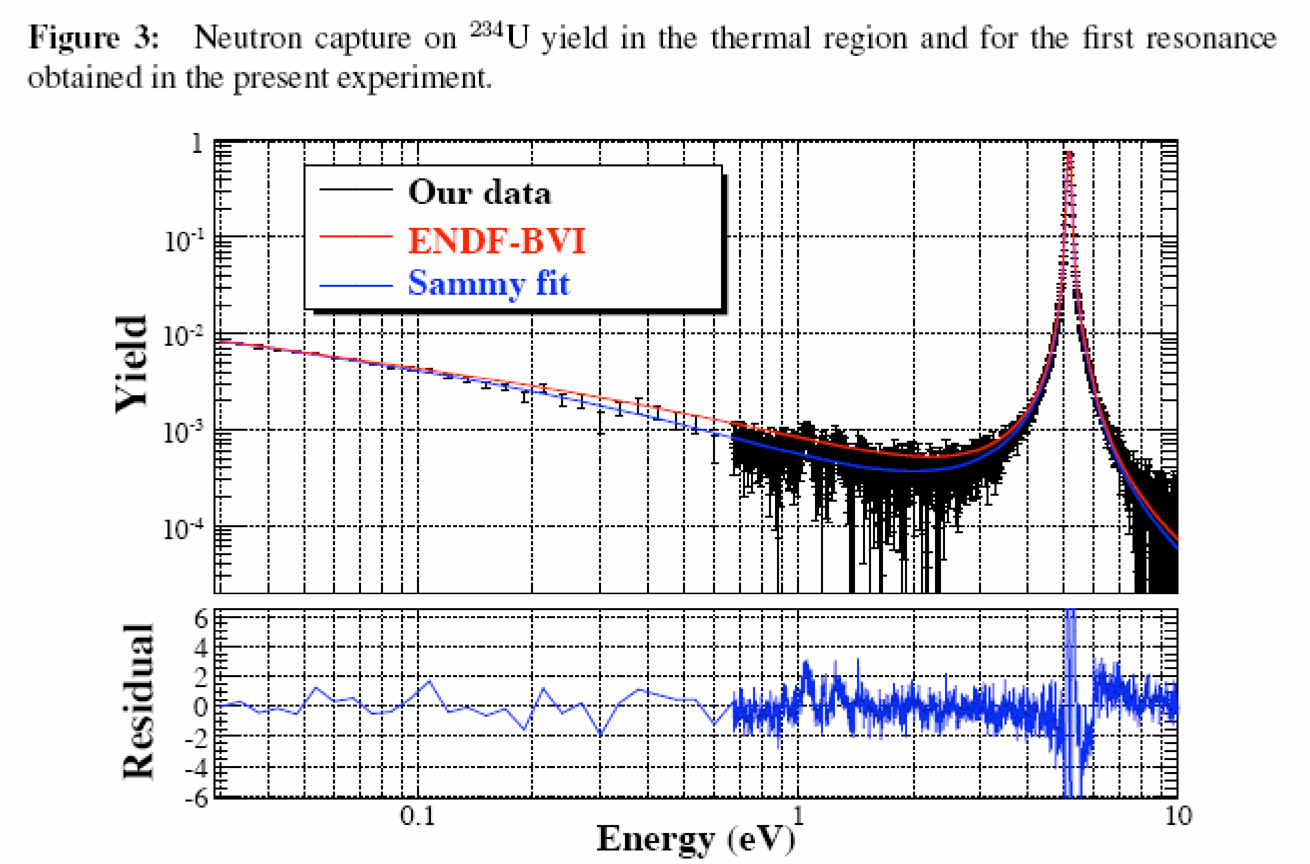


Figure 3: Neutron capture on ^{234}U yield in the thermal region and for the first resonance obtained in the present experiment.

n_TOF TAC in operation

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

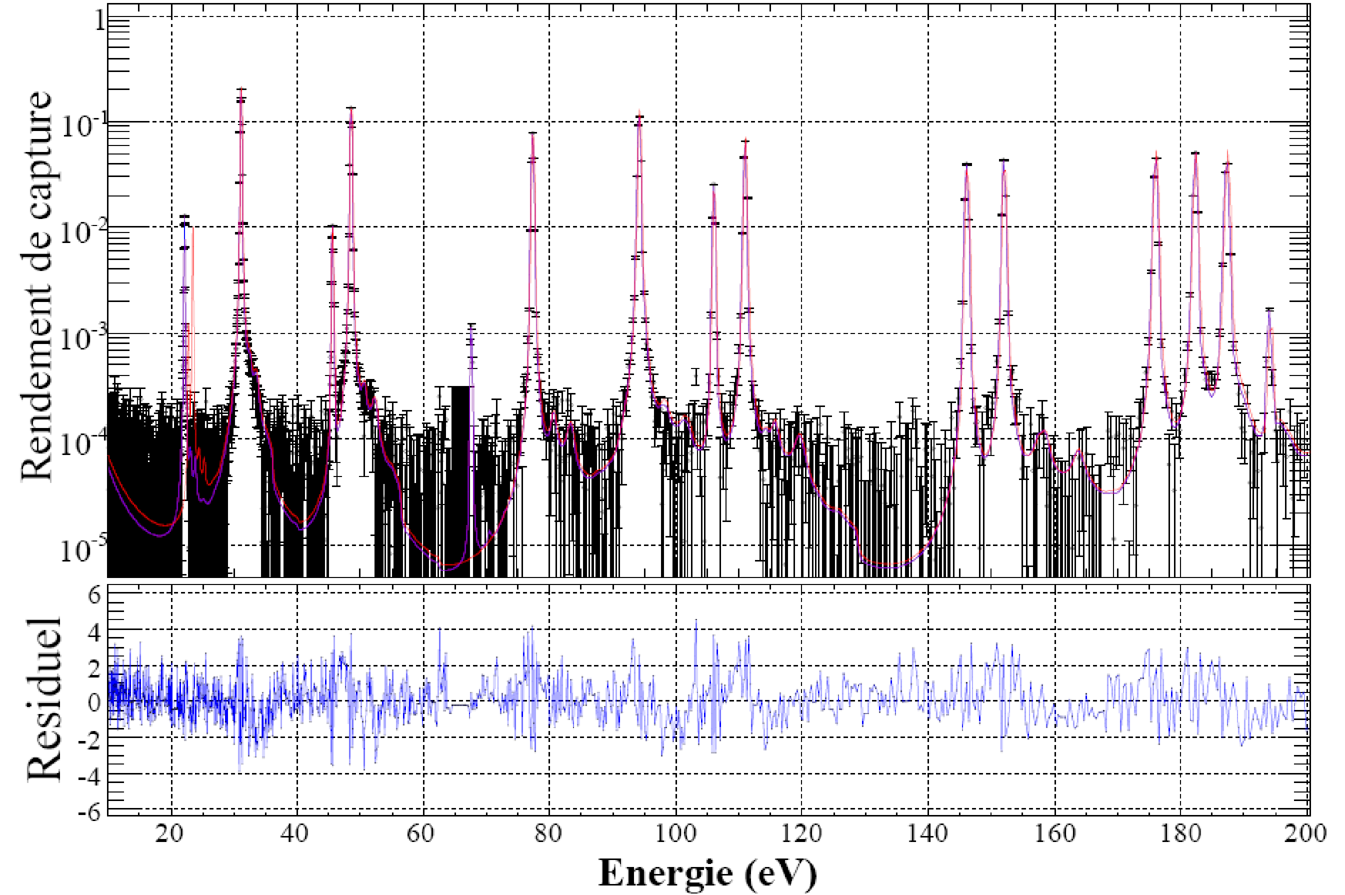
^{209}Bi

^{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,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

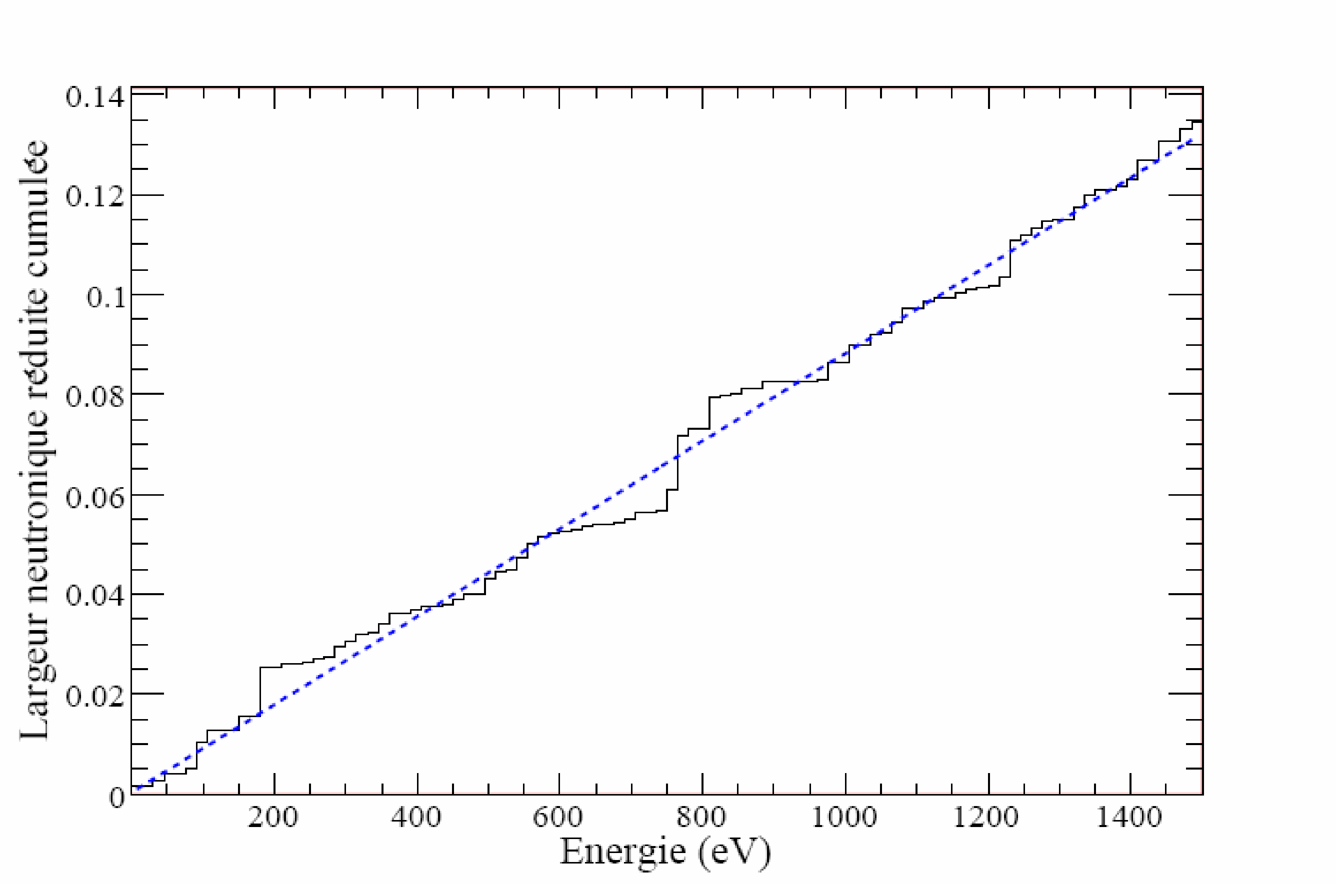
^{209}Bi

^{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,γ)



n_TOF TAC in operation

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

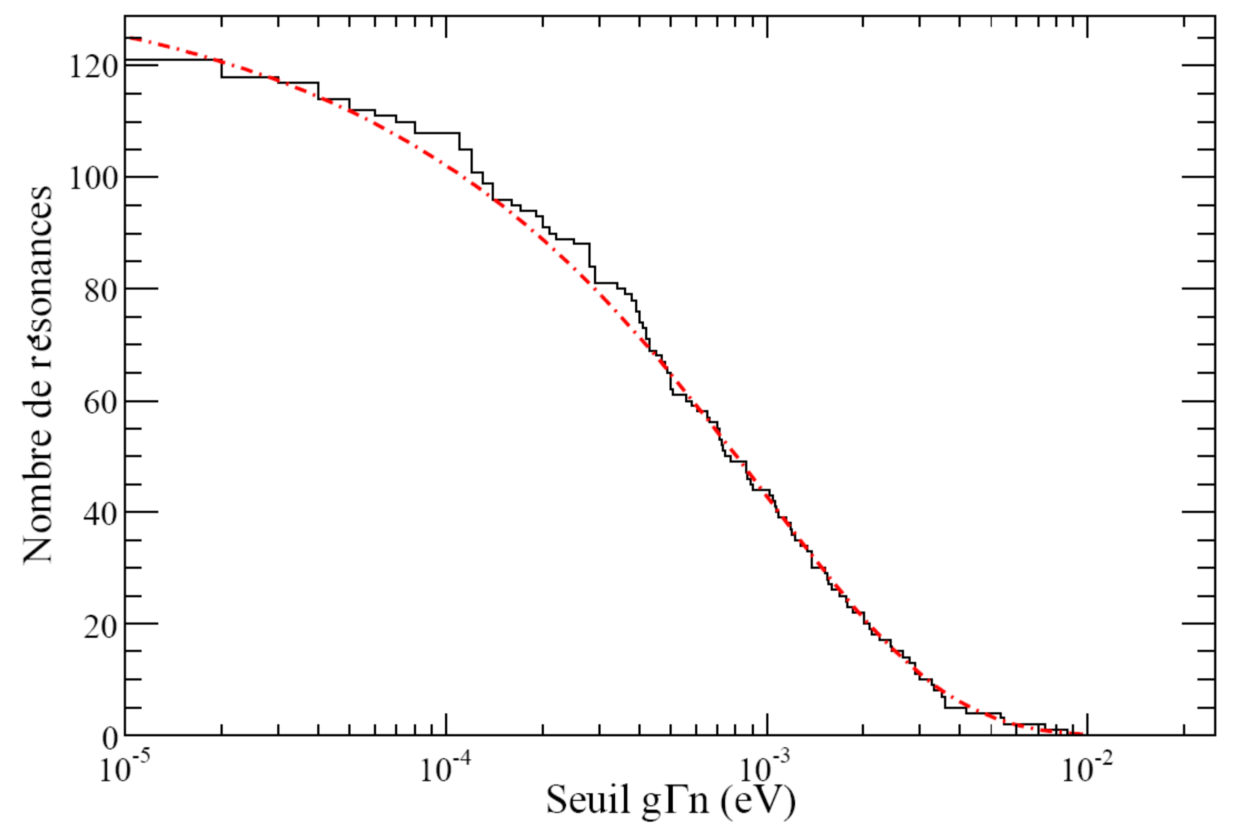
^{209}Bi

^{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,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

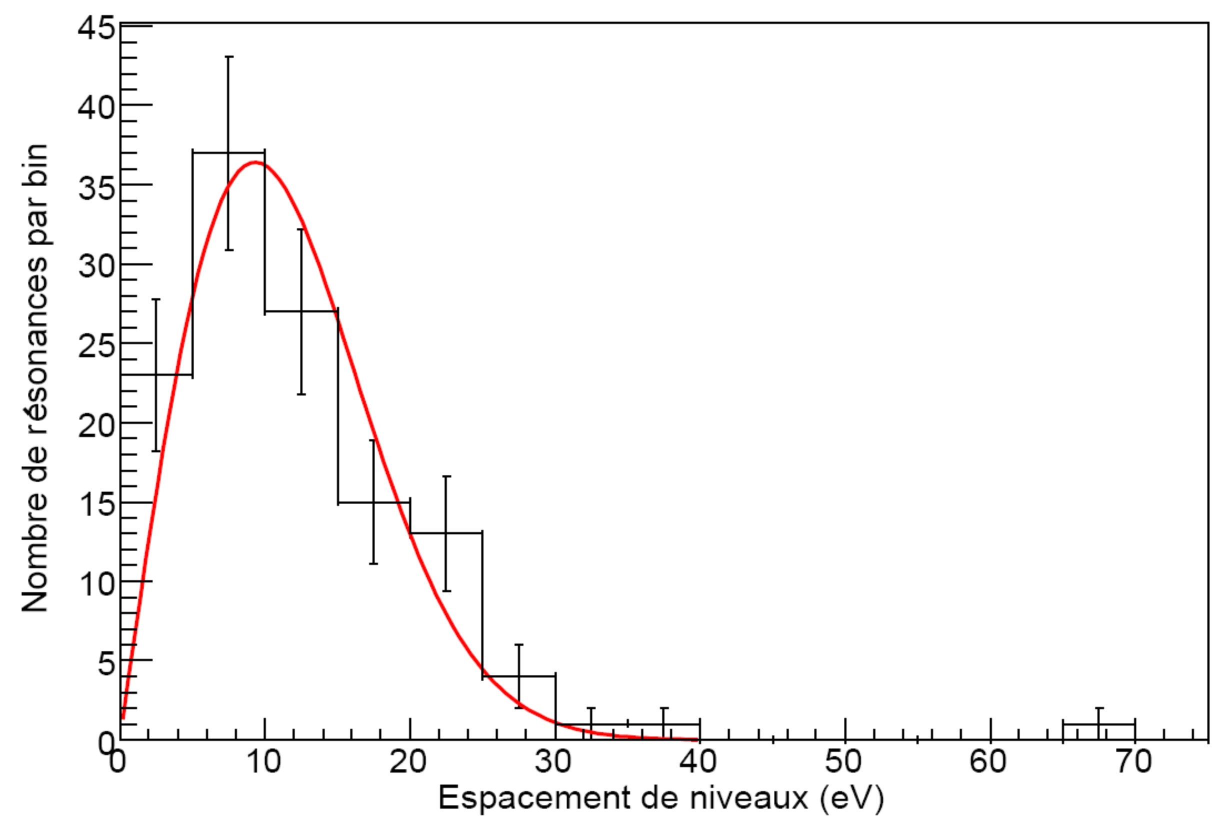
^{209}Bi

^{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,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

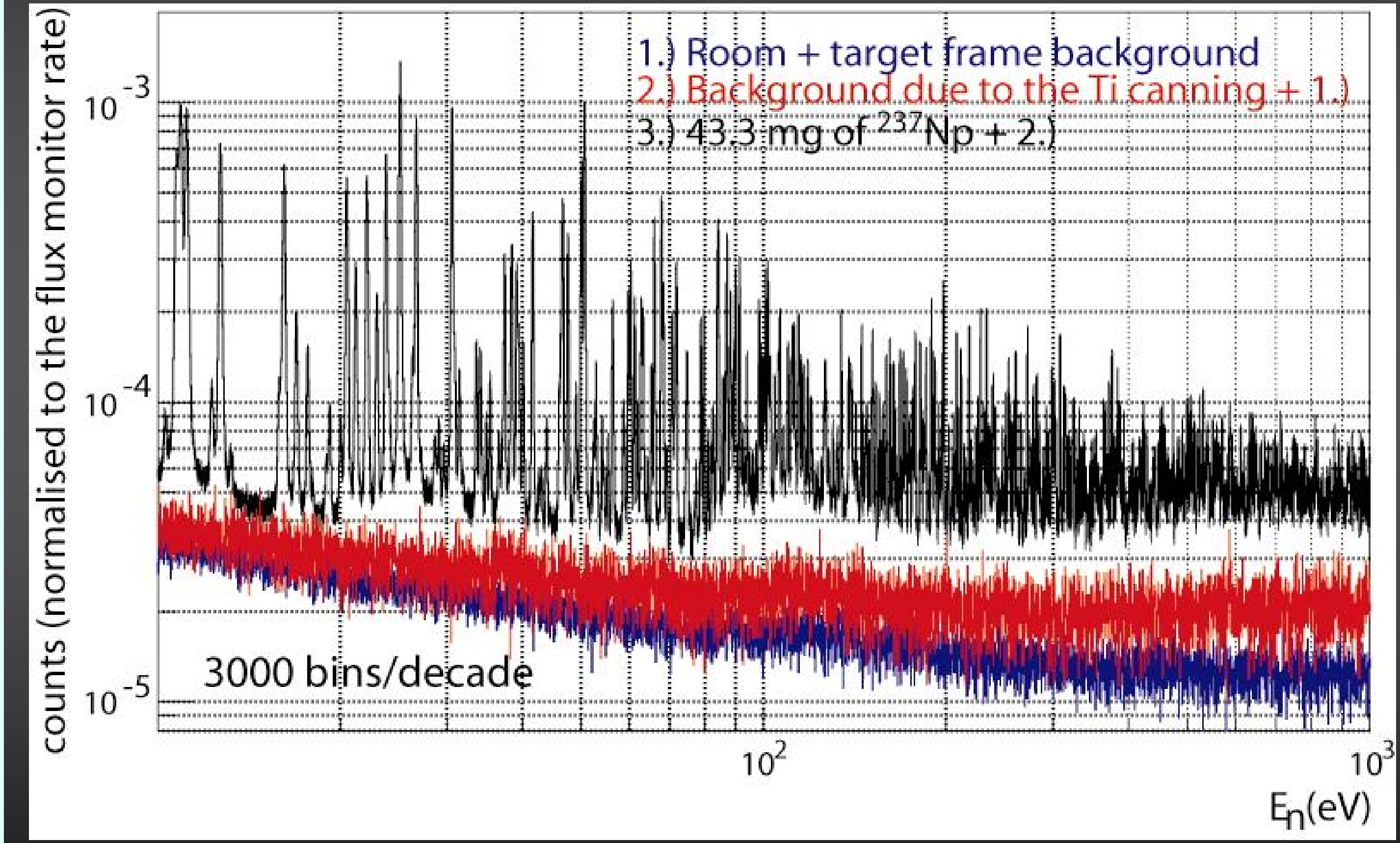
^{232}Th

^{209}Bi

^{237}Np

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

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

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

^{139}La

^{186,187,188}Os

^{233,234}U

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

Fission

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

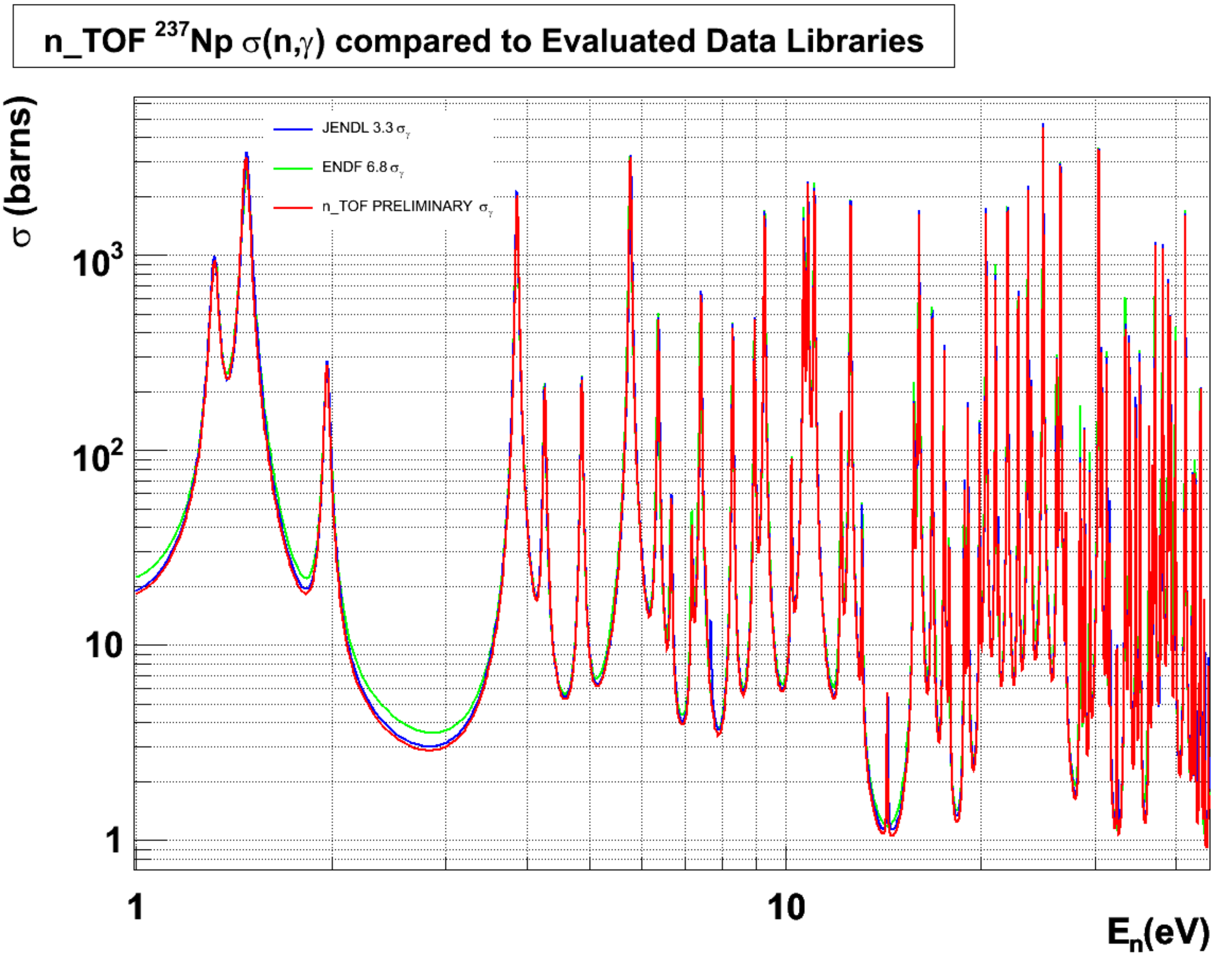
^{232}Th

^{209}Bi

^{237}Np

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

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



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

n_TOF TAC in operation

n_TOF experiments

Capture

^{151}Sm

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

^{232}Th

^{24,25,26}Mg

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

^{139}La

^{186,187,188}Os

^{233,234}U

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

Fission

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

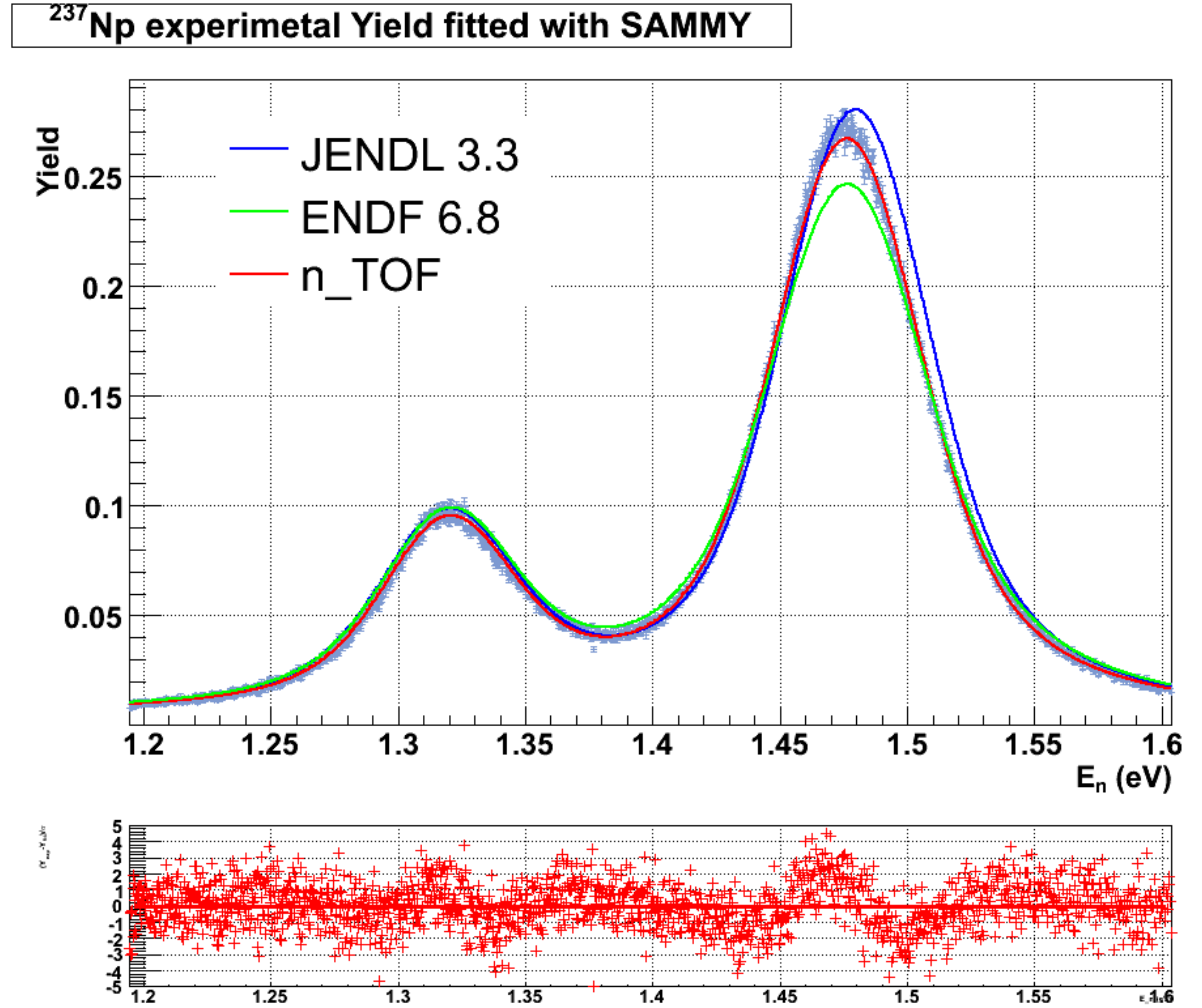
^{232}Th

^{209}Bi

^{237}Np

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

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



^{237}Np experimetal Yield fitted with SAMMY

n_TOF experiments

Capture

^{151}Sm

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

^{232}Th

^{24,25,26}Mg

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

^{139}La

^{186,187,188}Os

^{233,234}U

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

Fission

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

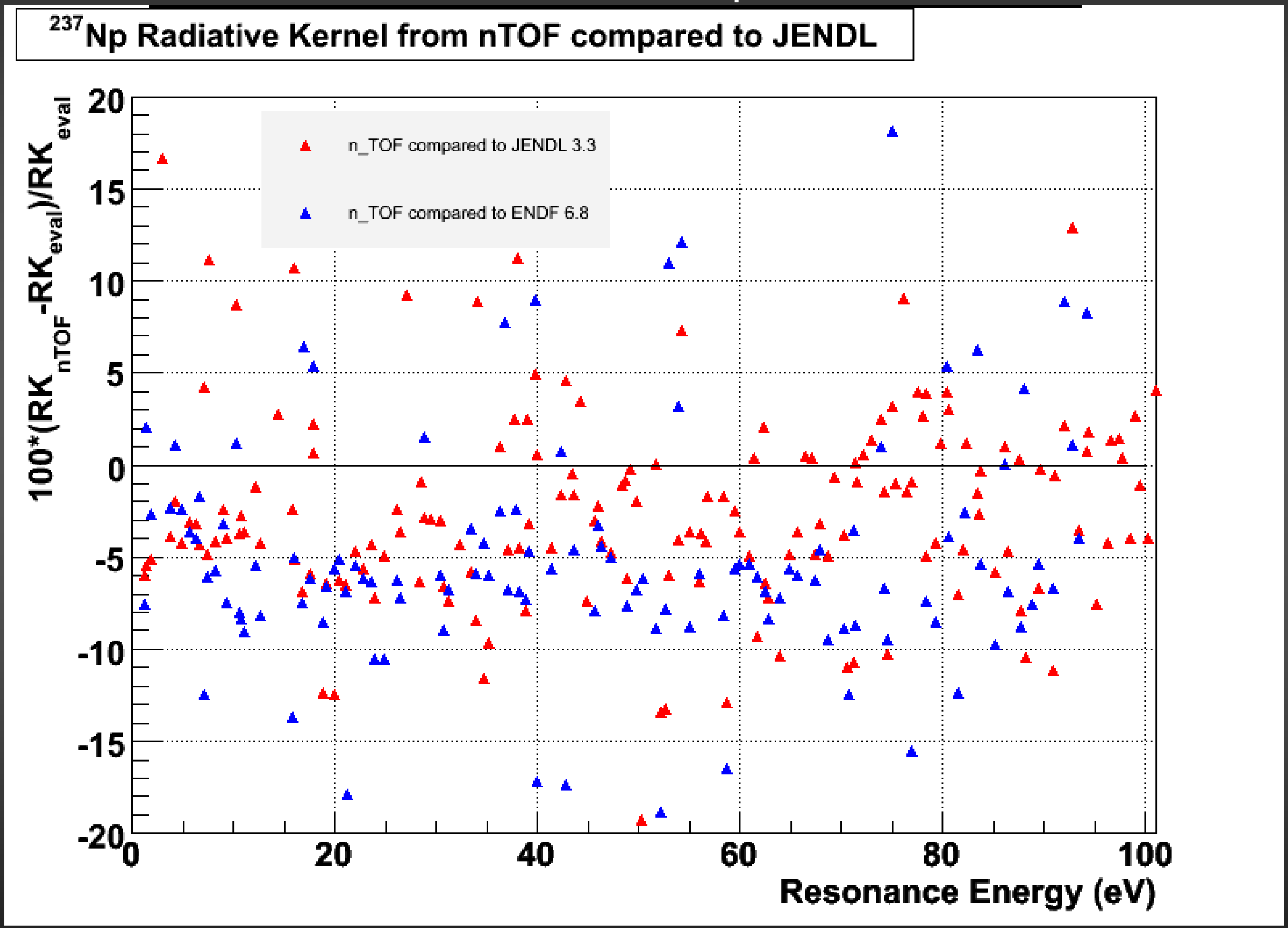
^{232}Th

^{209}Bi

^{237}Np

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

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



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

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

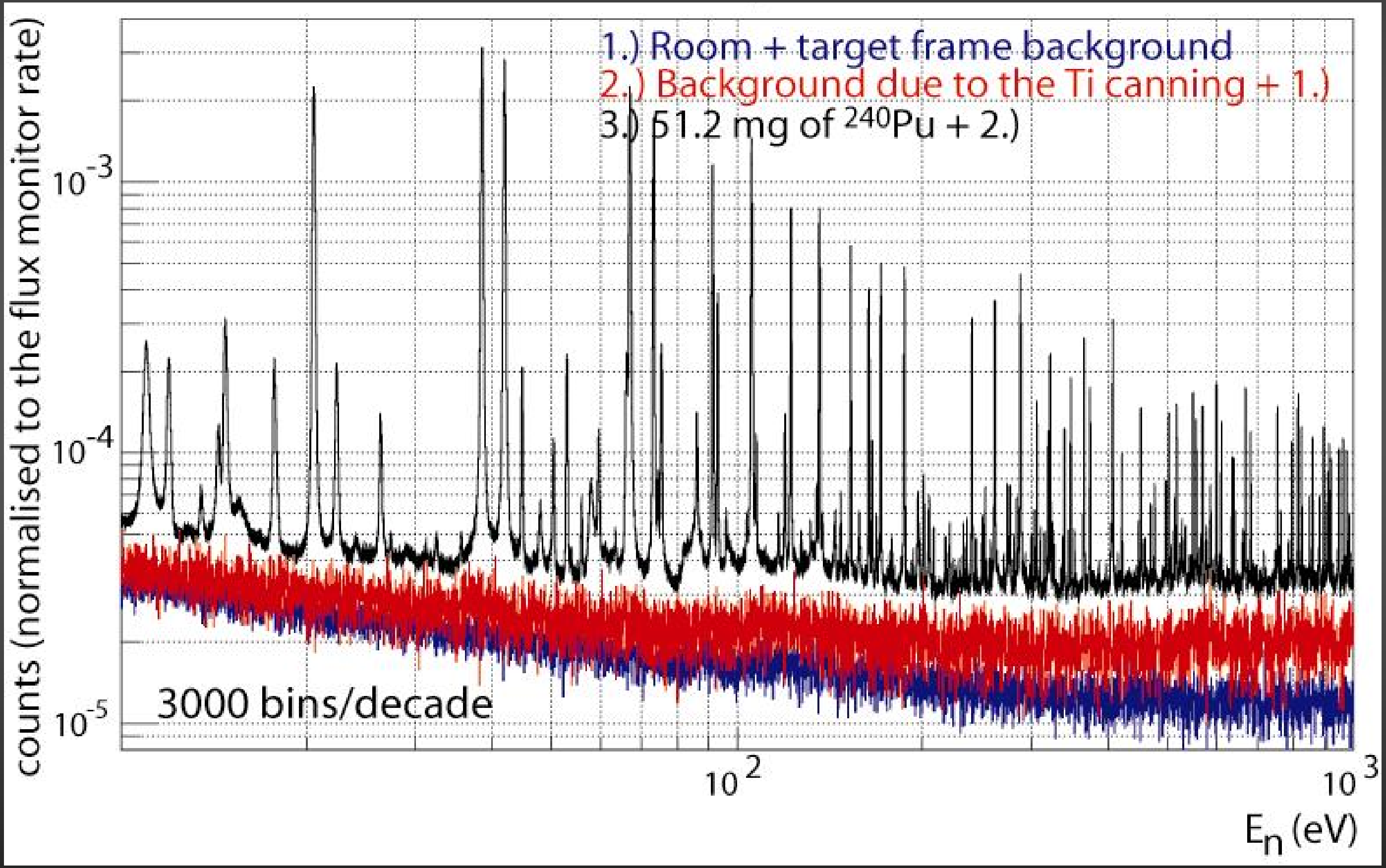
^{209}Bi

^{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

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

^{139}La

^{186,187,188}Os

^{233,234}U

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

Fission

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

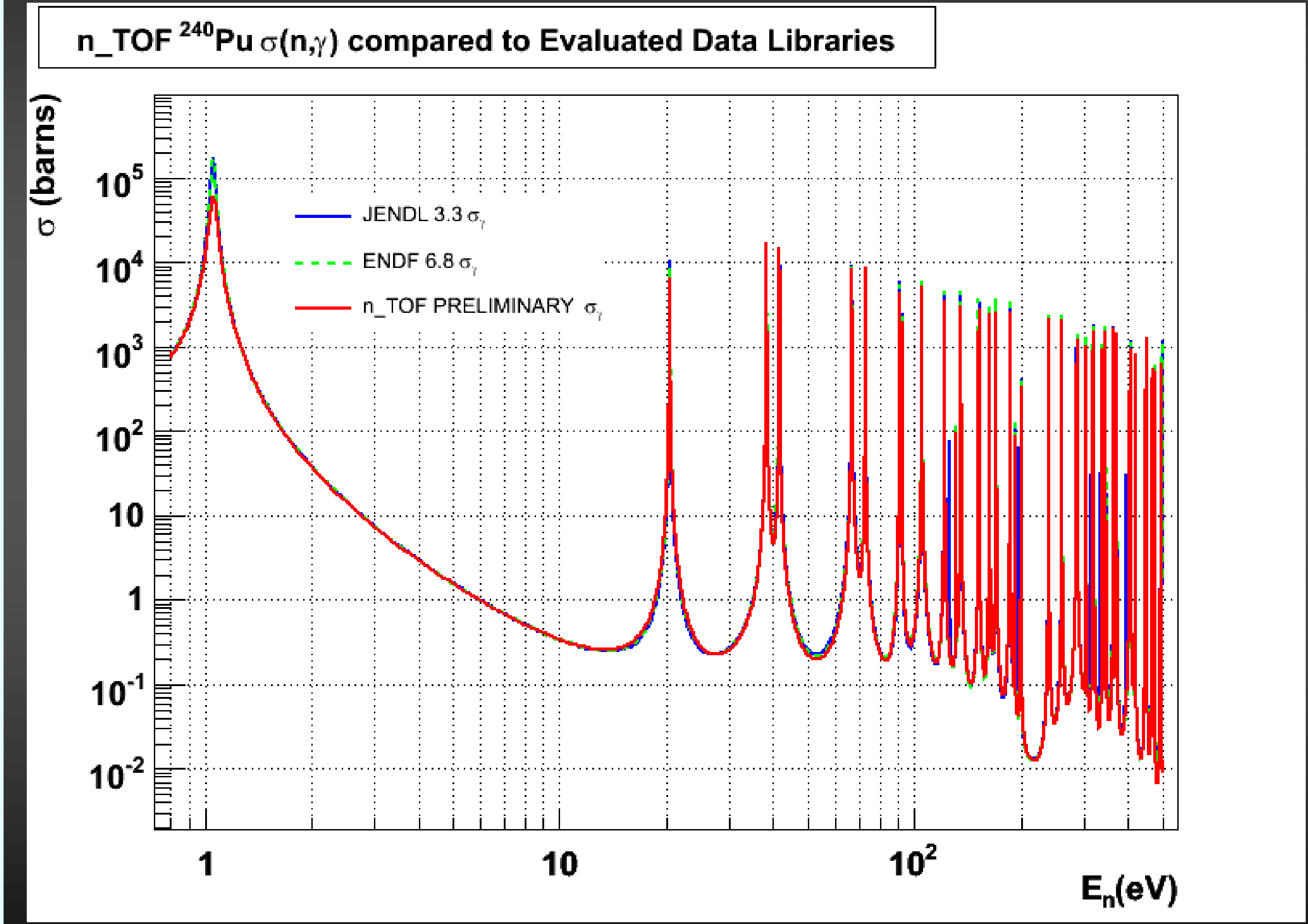
^{232}Th

^{209}Bi

^{237}Np

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

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



n_TOF TAC in operation

n_TOF experiments

Capture

^{151}Sm

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

^{232}Th

^{24,25,26}Mg

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

^{139}La

^{186,187,188}Os

^{233,234}U

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

Fission

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

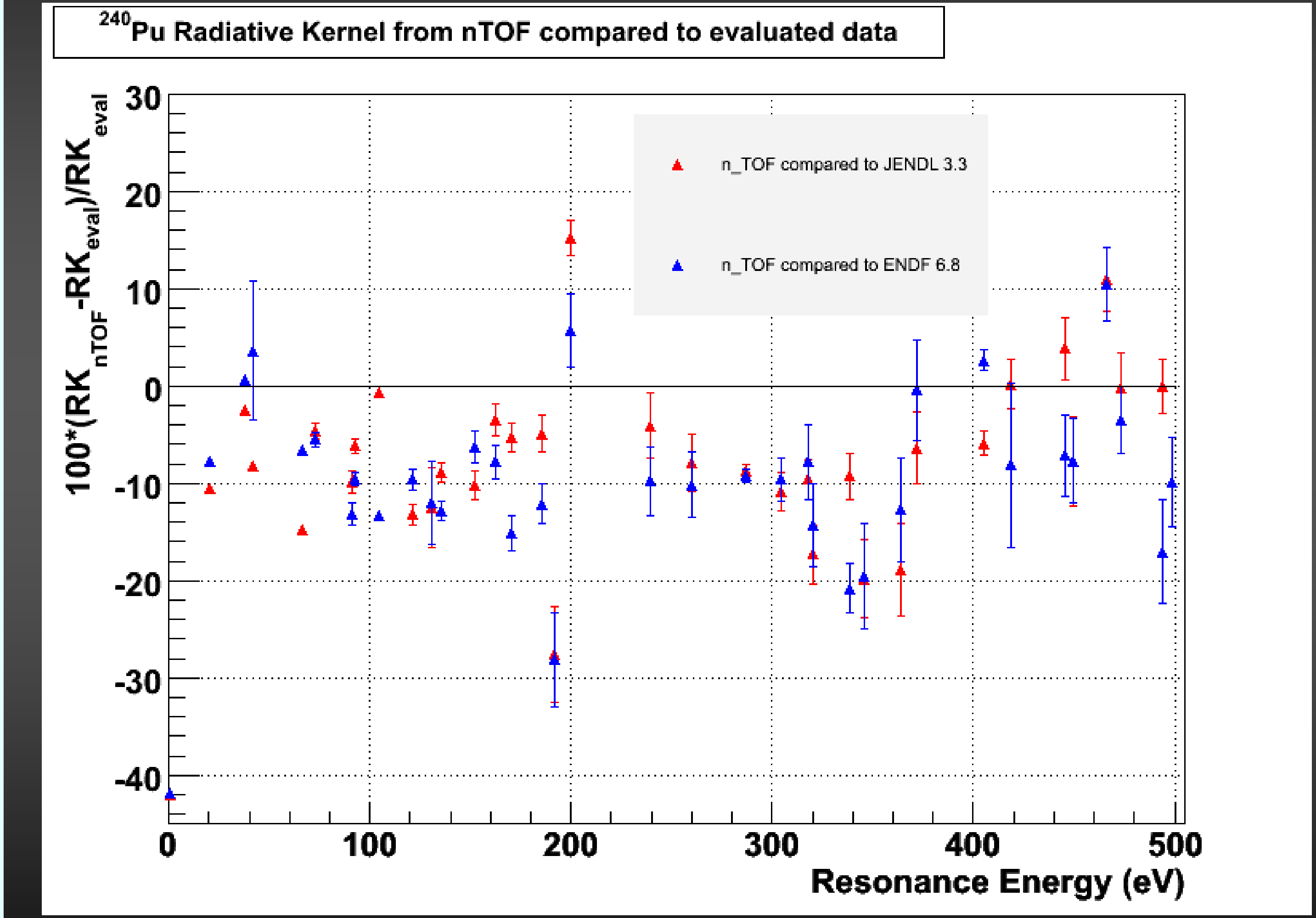
^{232}Th

^{209}Bi

^{237}Np

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

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



RK_{n_TOF} is on average 9% smaller than RK_{JENDL} and 7% smaller than RK_{ENDF}.

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

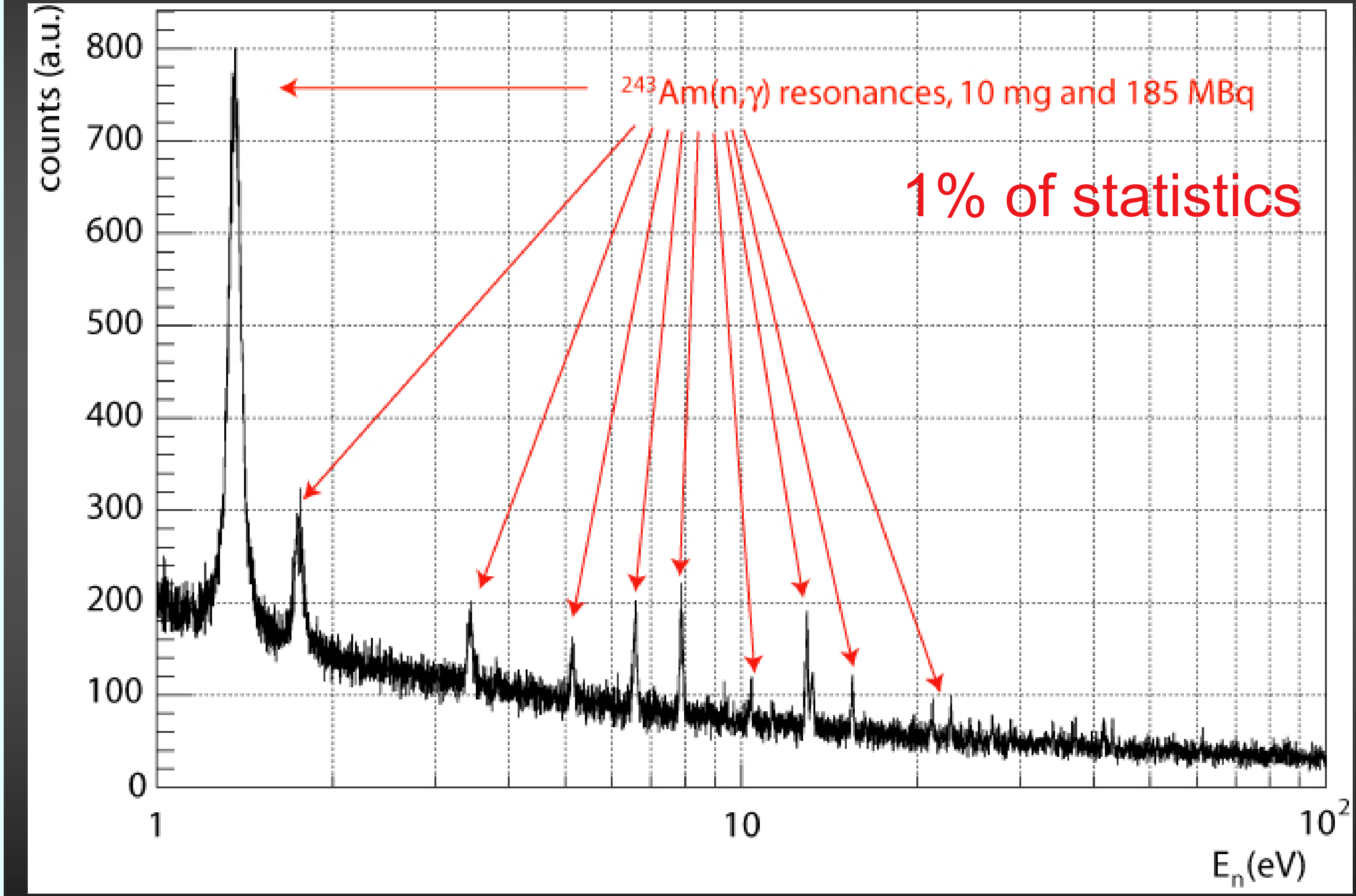
^{232}Th

^{209}Bi

^{237}Np

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

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



^{243}Am(n,γ) resonances, 10 mg and 185 MBq

1% of statistics

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

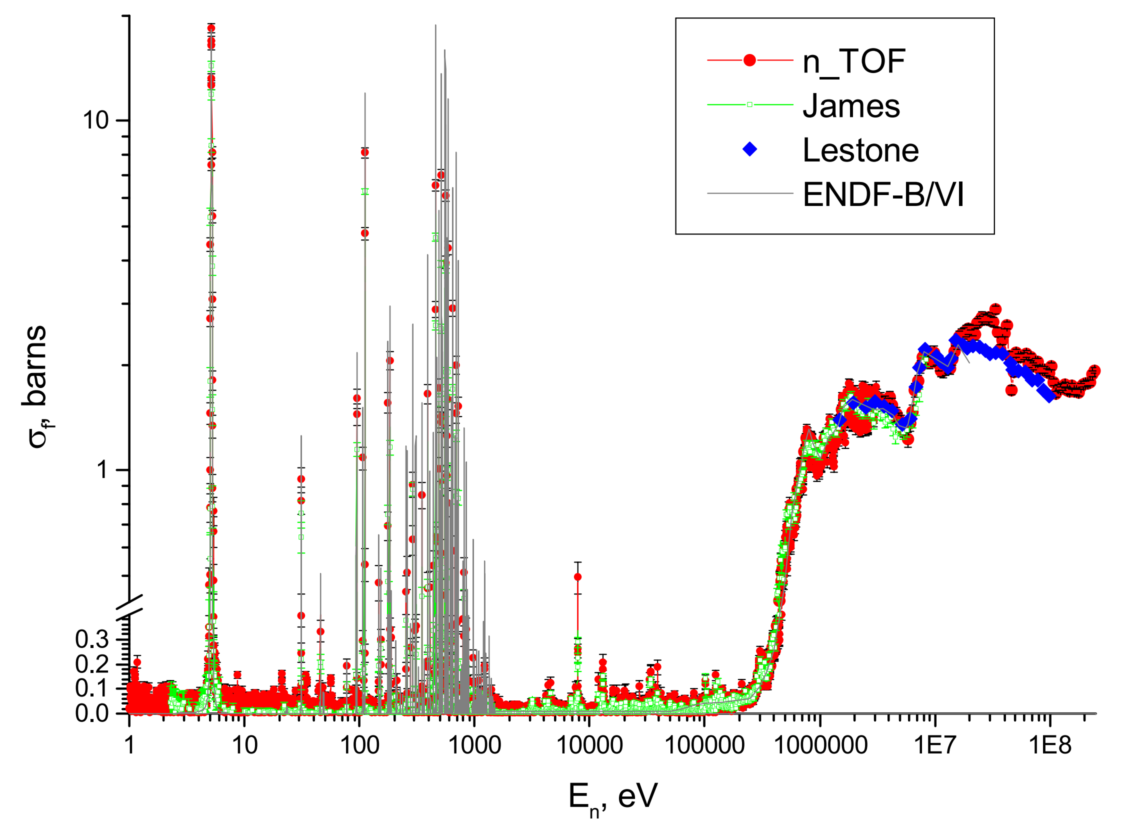
^{209}Bi

^{237}Np

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

^{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

^{151}Sm

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

^{232}Th

^{24,25,26}Mg

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

^{139}La

^{186,187,188}Os

^{233,234}U

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

Fission

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

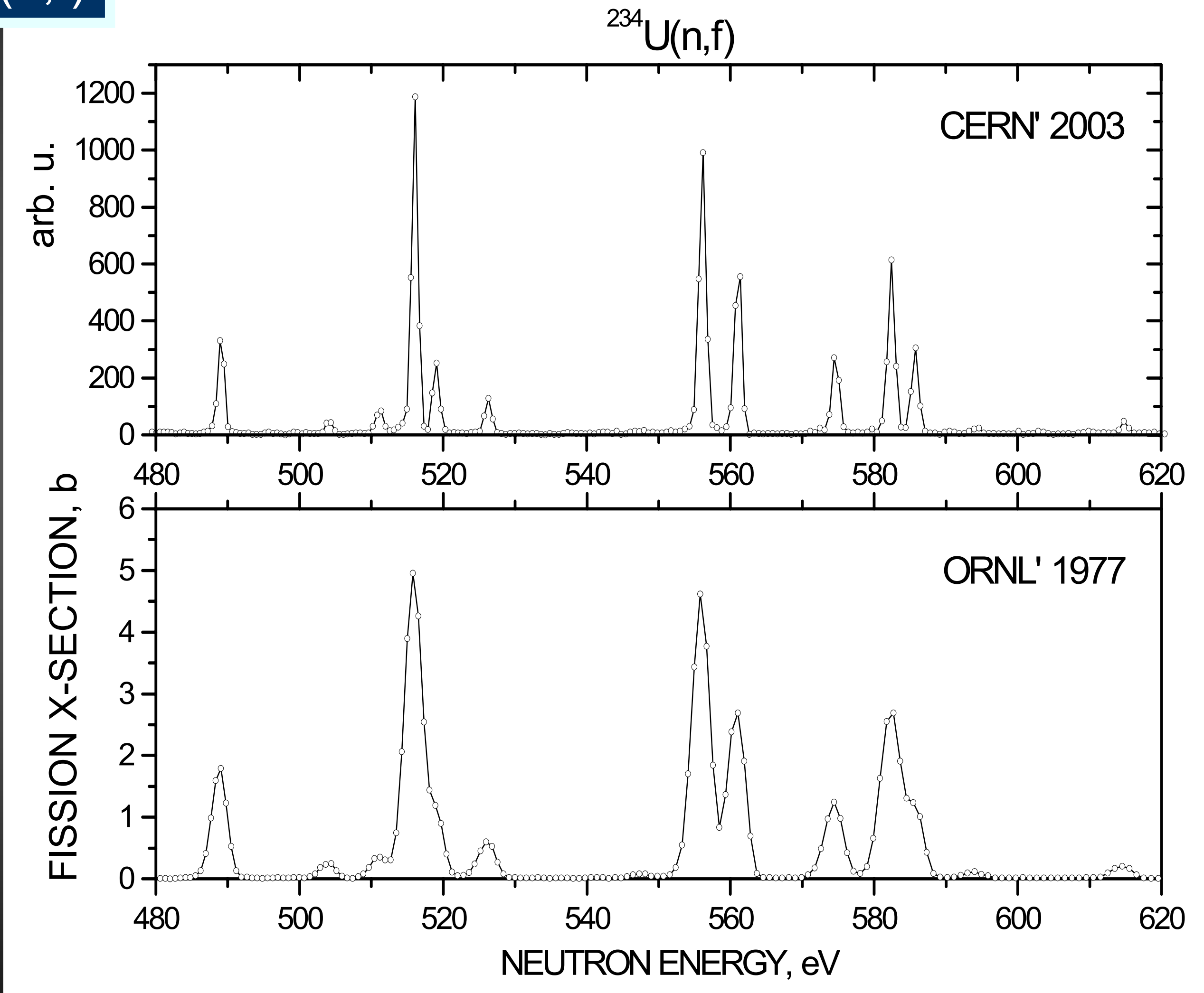
^{232}Th

^{209}Bi

^{237}Np

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

^{234}U(n,f)



High-resolution data up to high(er) energies

The n_TOF Collaboration

n_TOF experiments

PPACs & FIC-0 (2003)

Capture

^{151}Sm

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

^{232}Th

^{24,25,26}Mg

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

^{139}La

^{186,187,188}Os

^{233,234}U

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

Fission

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

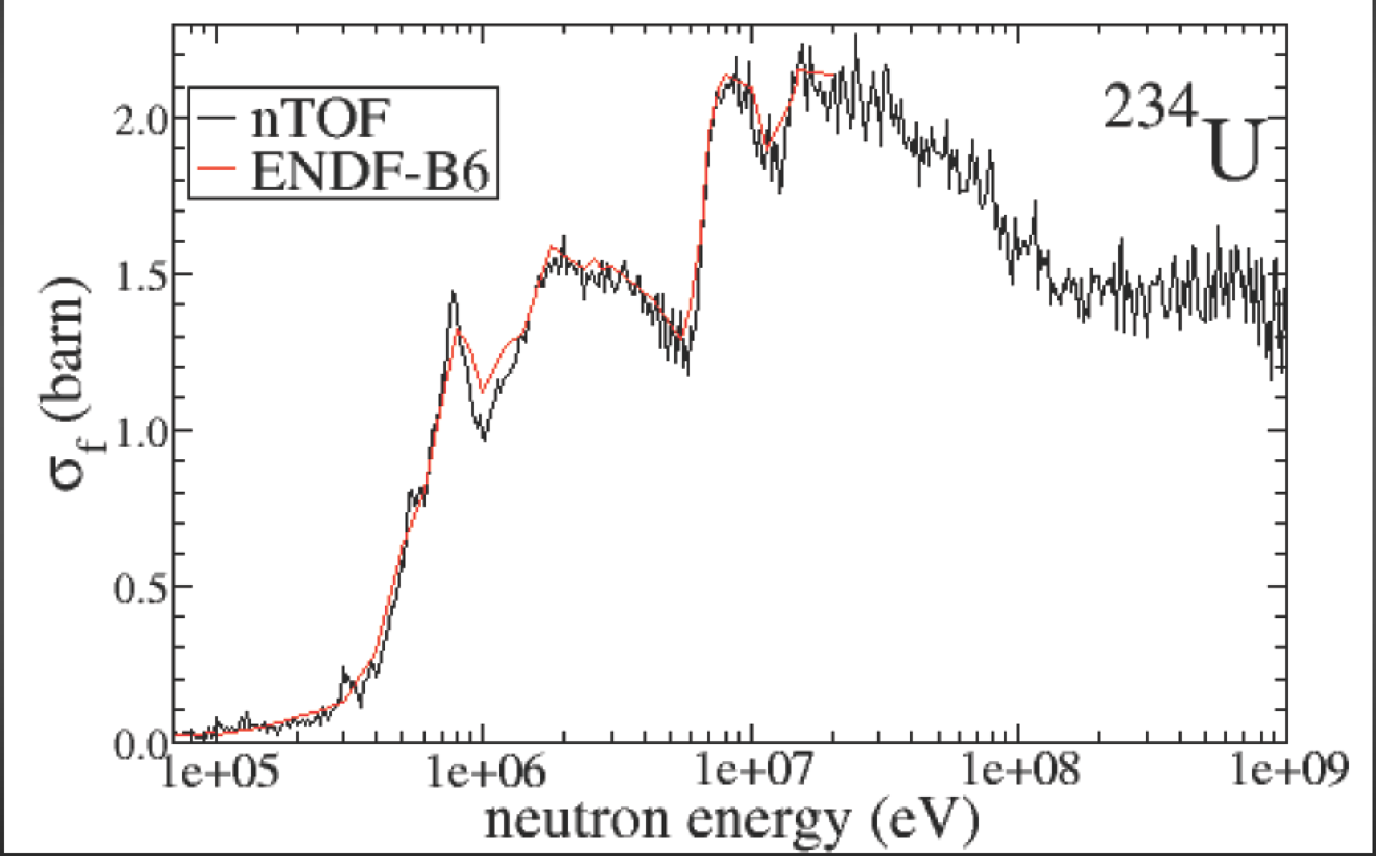
^{232}Th

^{209}Bi

^{237}Np

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

^{234}U(n,f)



High-resolution data up to high(er) energies

n_TOF experiments

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

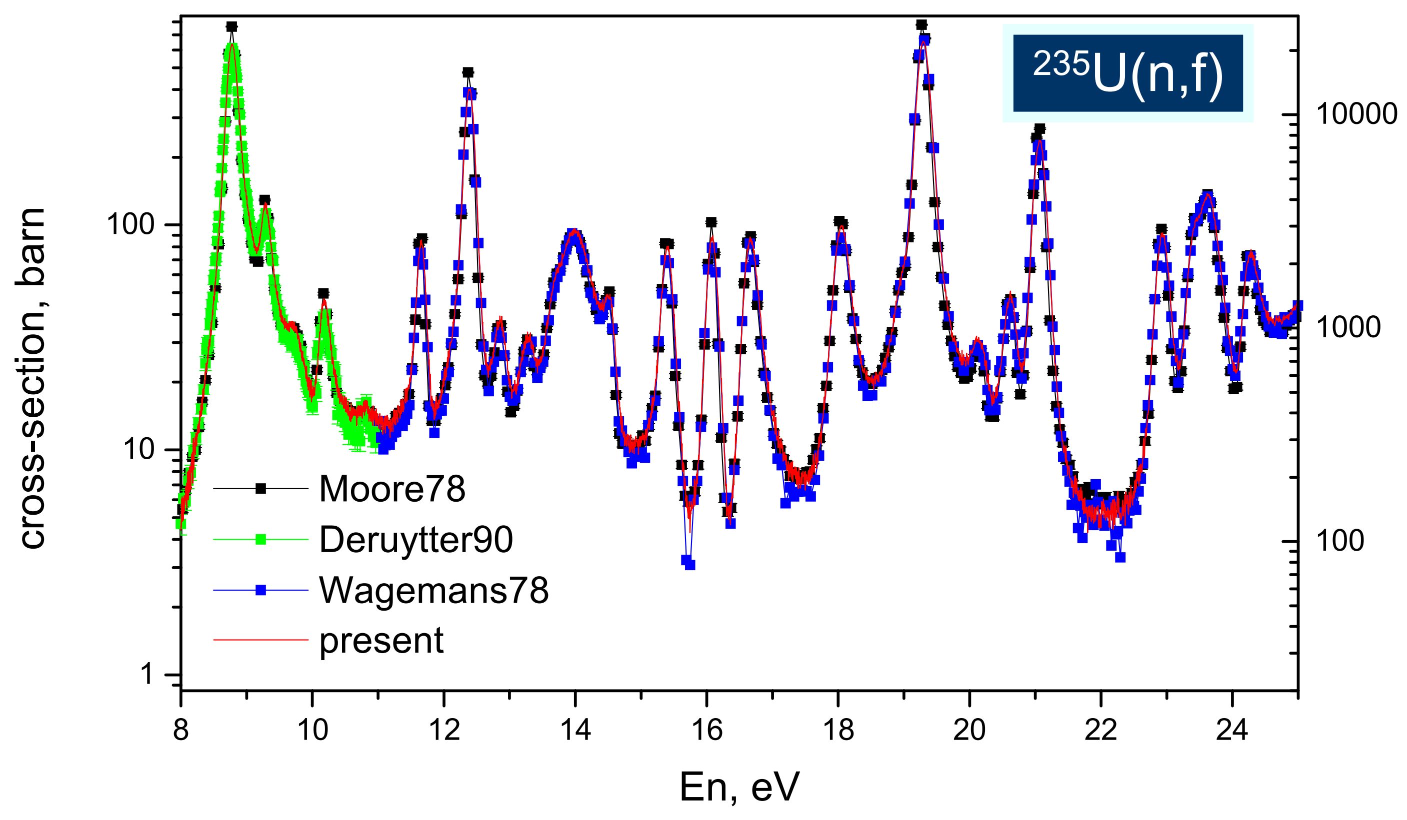
^{232}Th

^{209}Bi

^{237}Np

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

FIC-0 (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

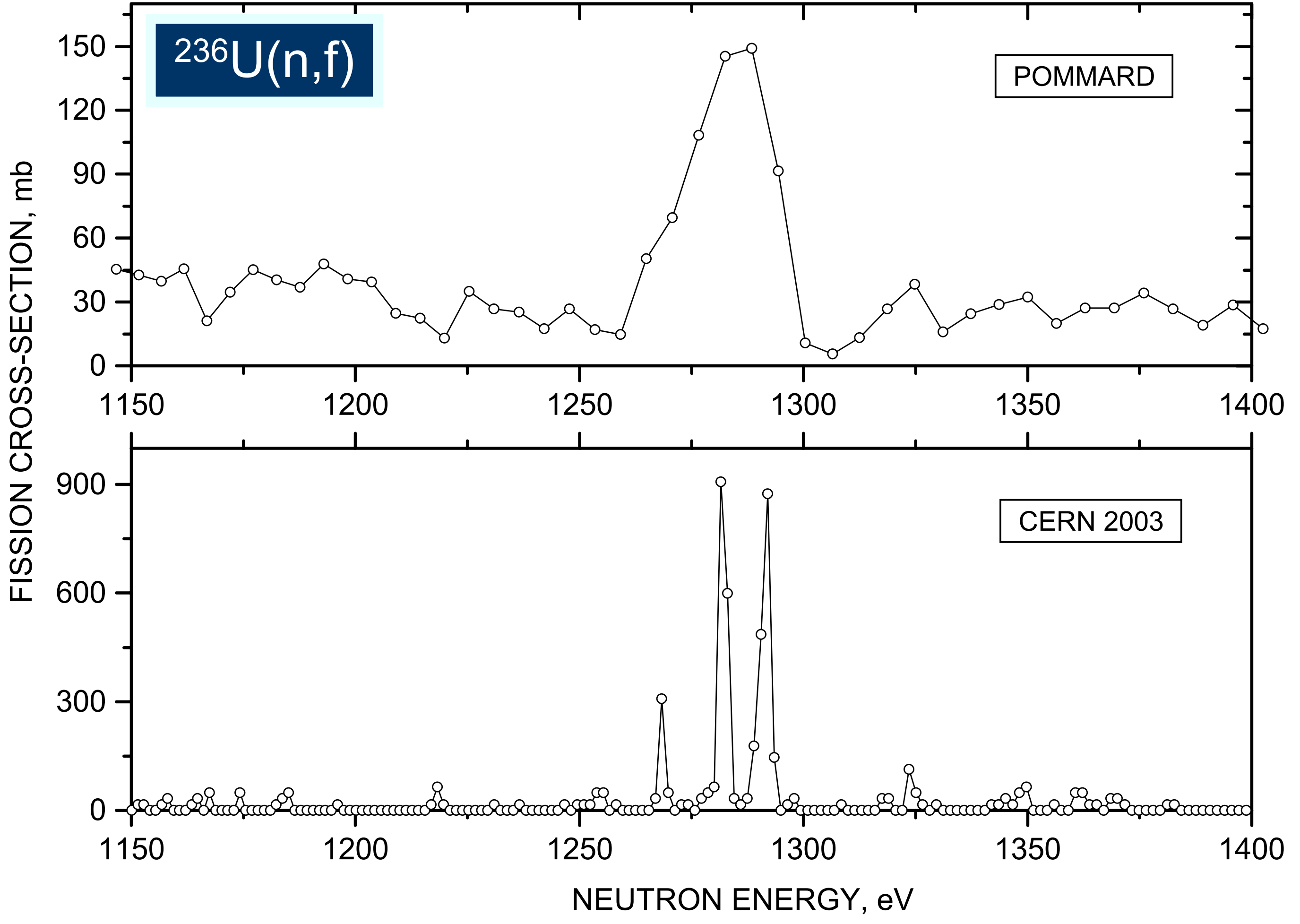
^{232}Th

^{209}Bi

^{237}Np

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

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

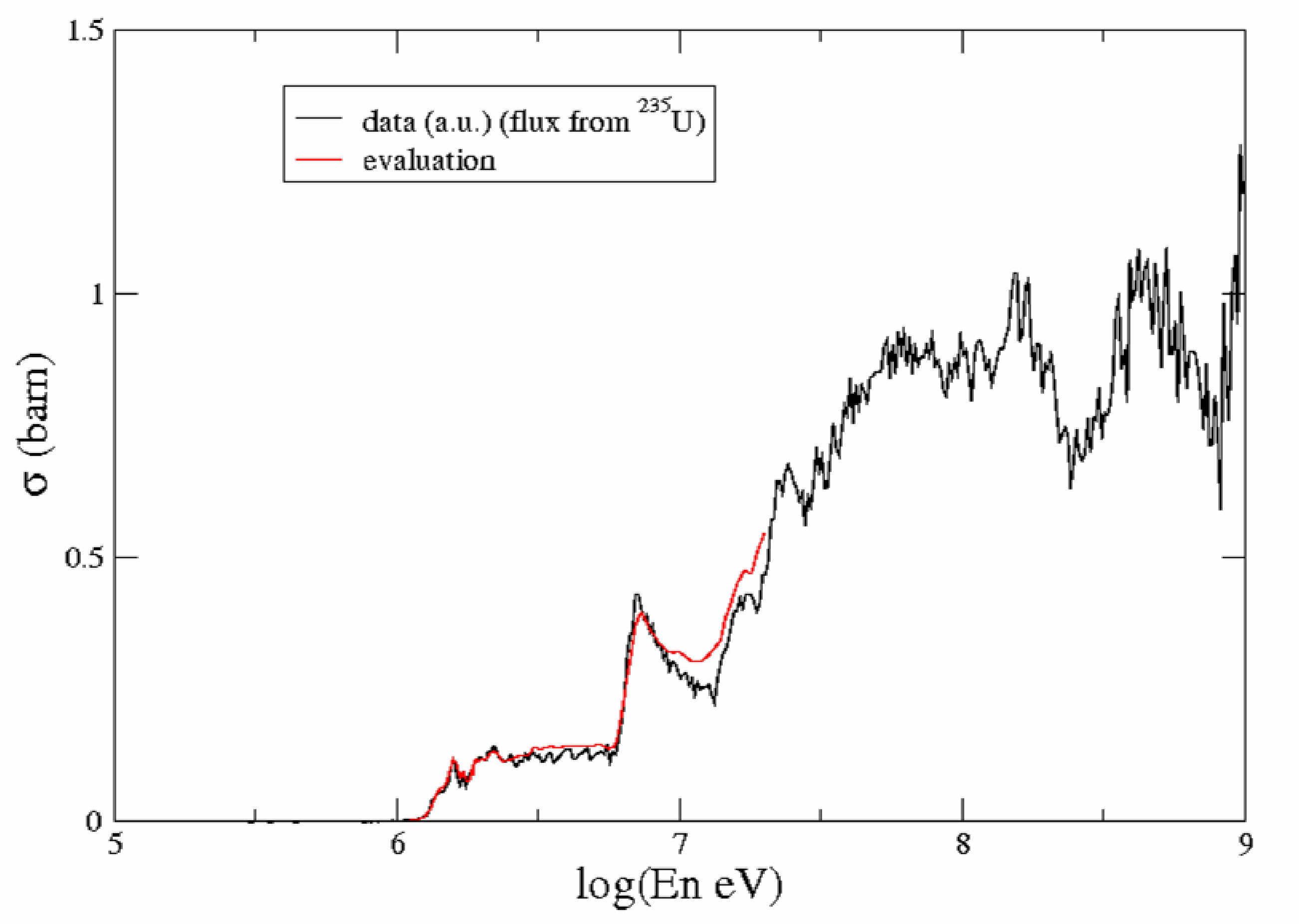
^{209}Bi

^{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

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

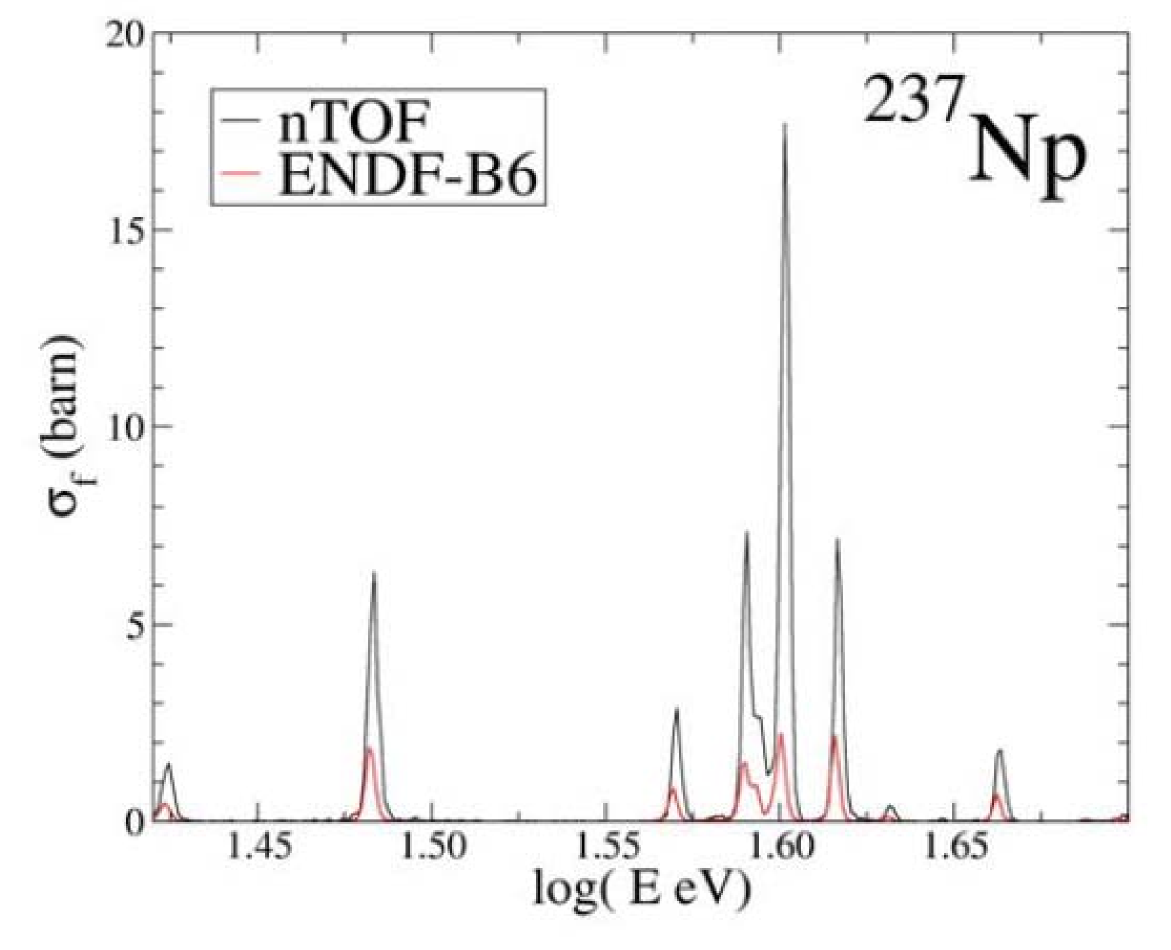
^{232}Th

^{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

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

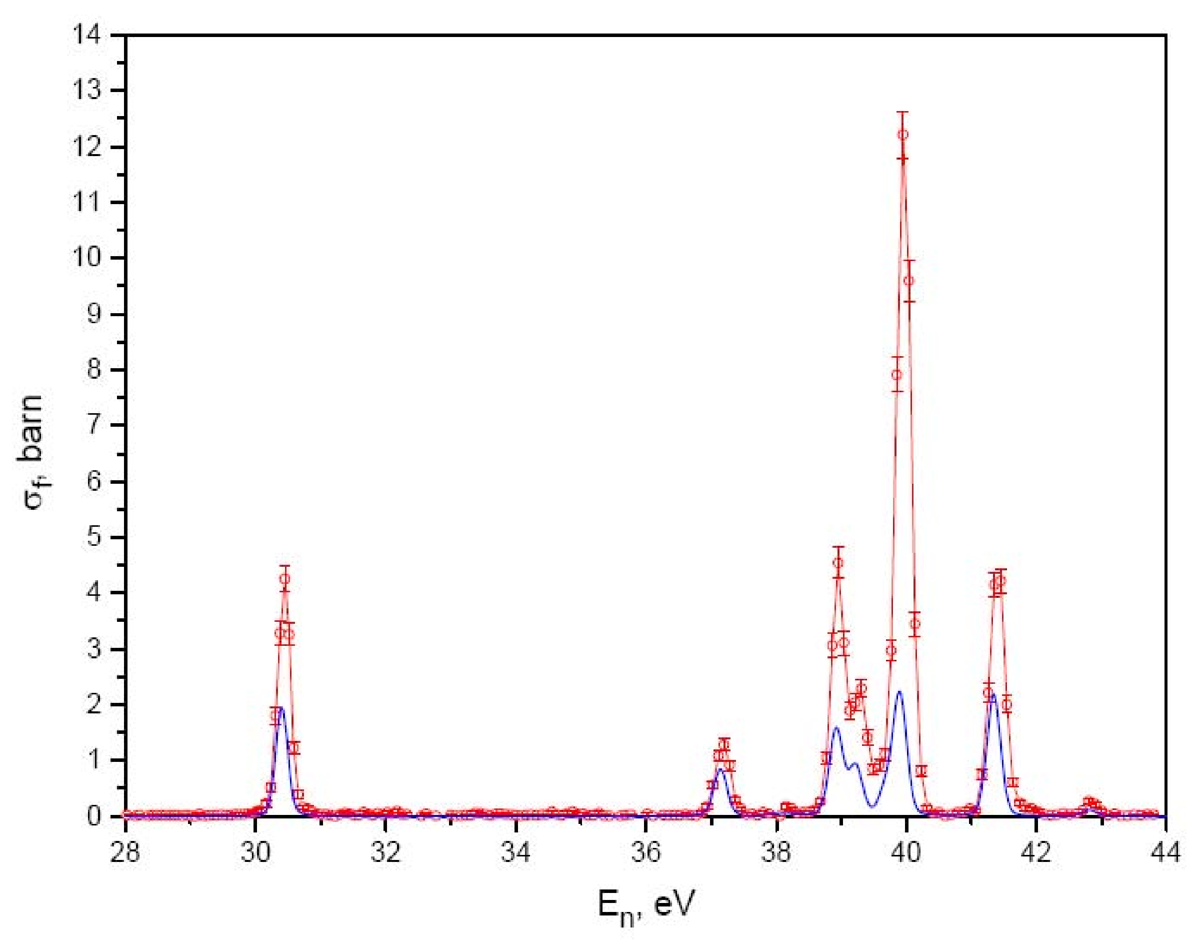
^{209}Bi

^{237}Np

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

^{237}Np(n,f)

PPACs (2003)



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

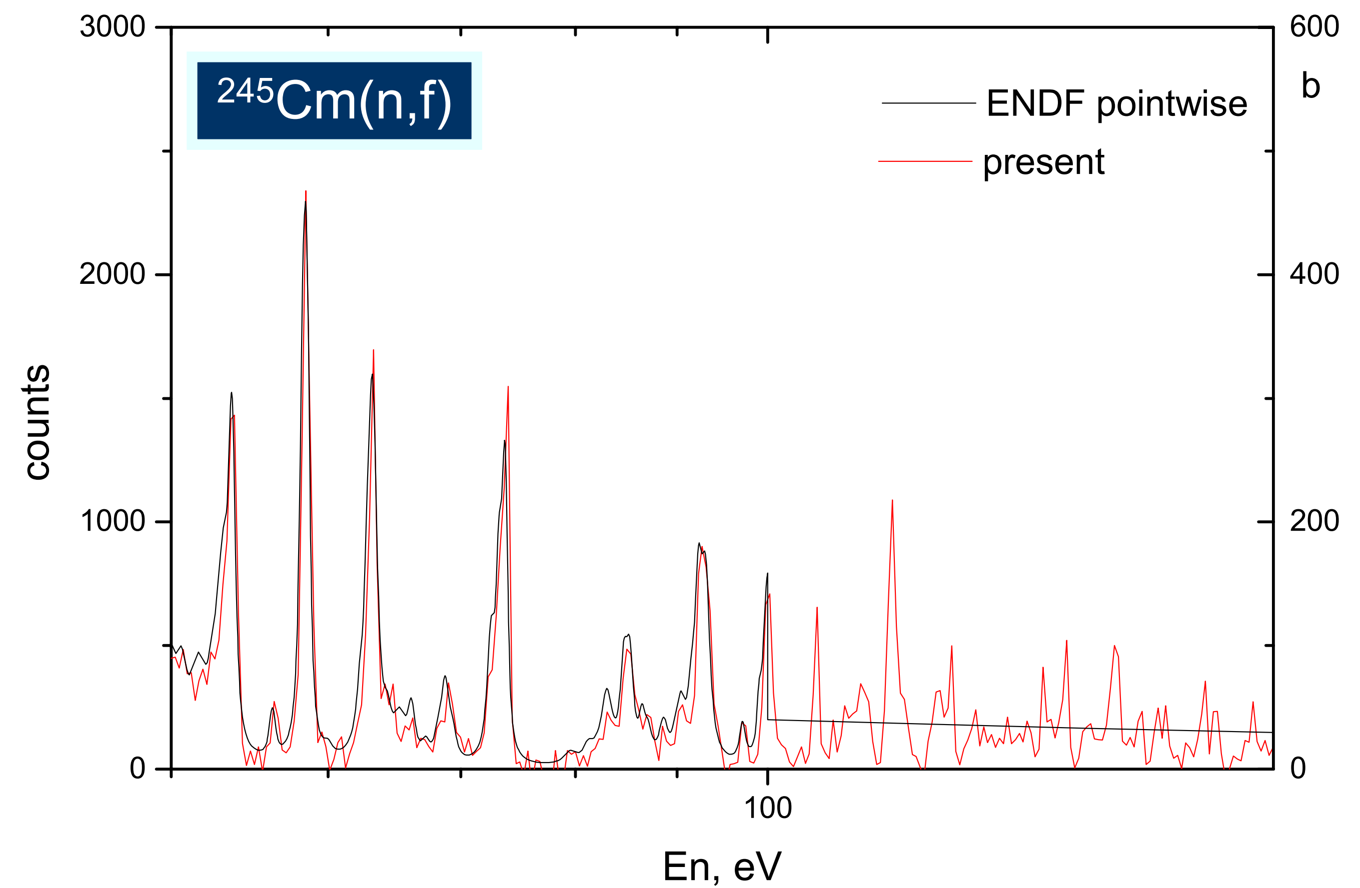
^{232}Th

^{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

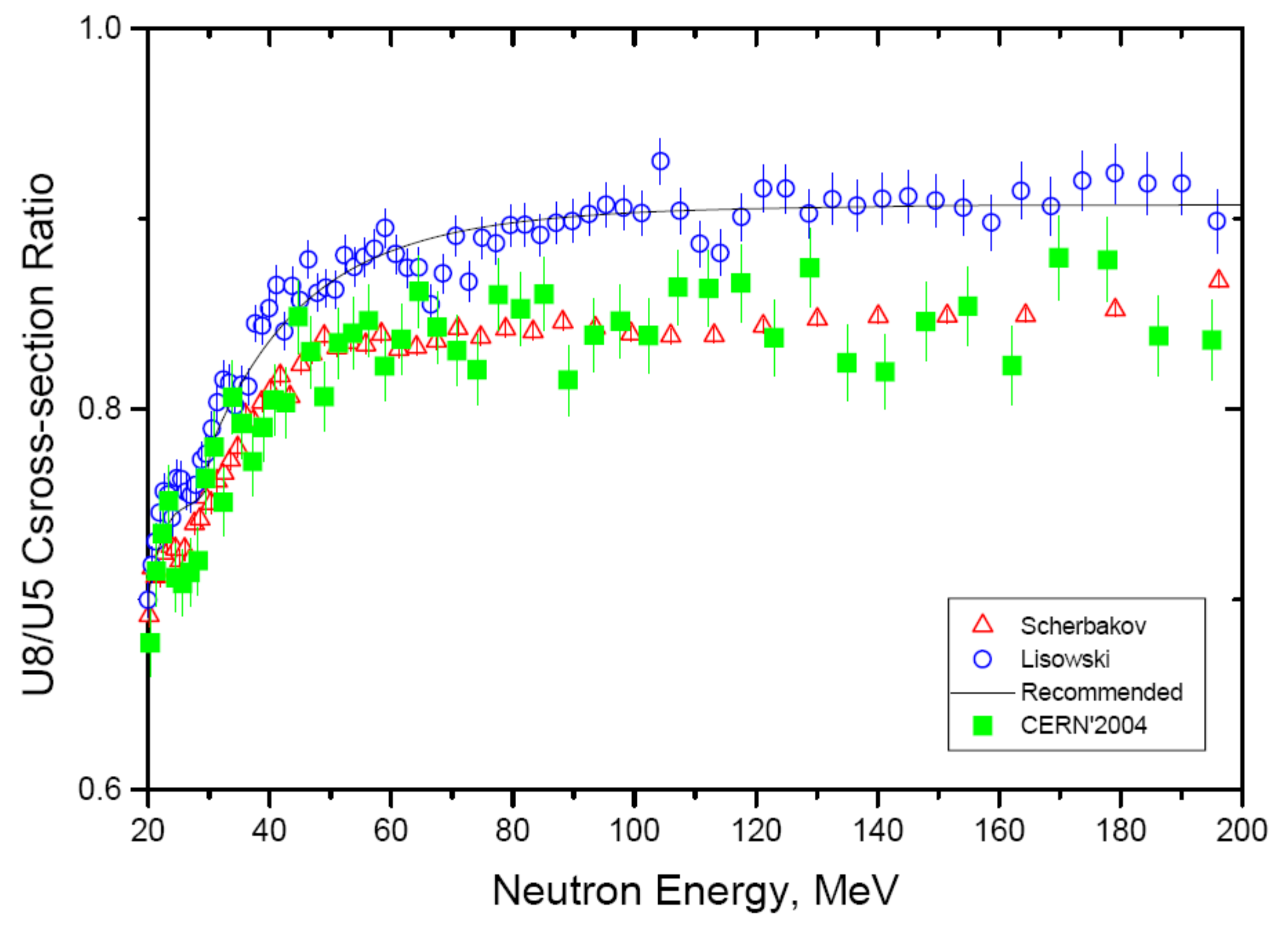
^{232}Th

^{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

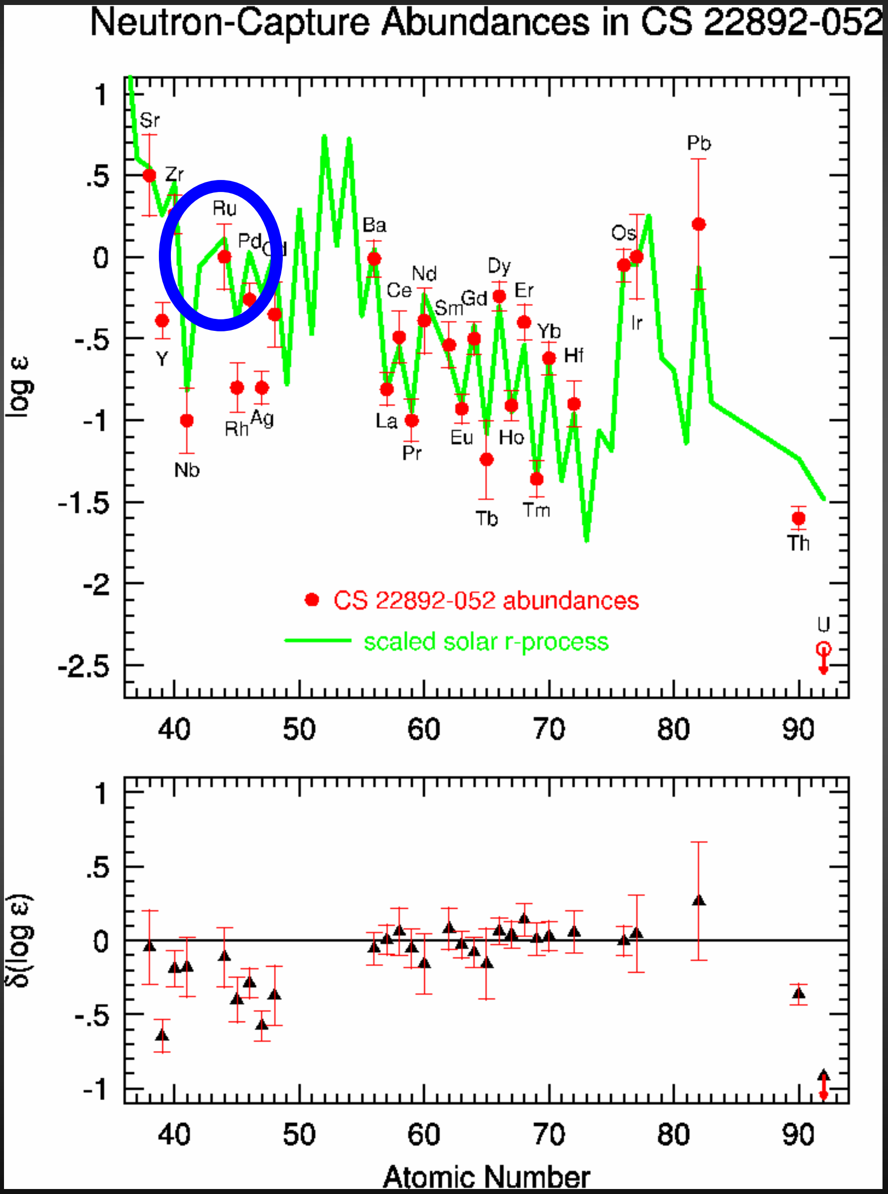
Capture studies: Mo, Ru and Pd

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.

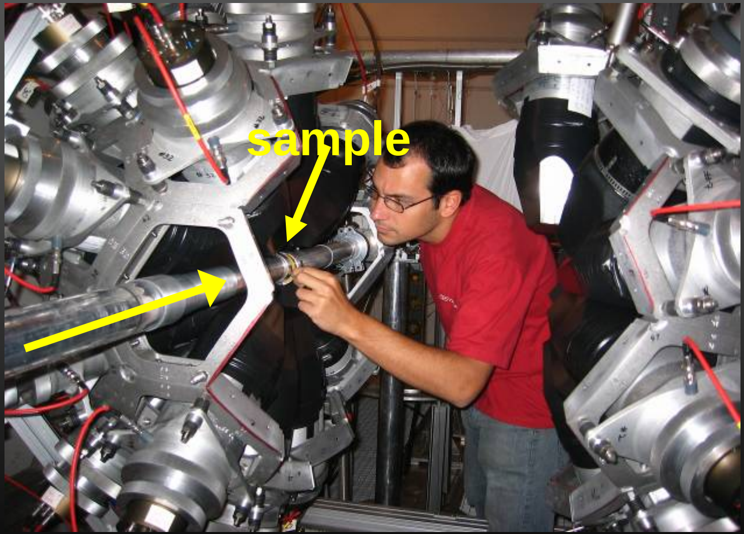
$$N_r = N_{solar} - N_s$$

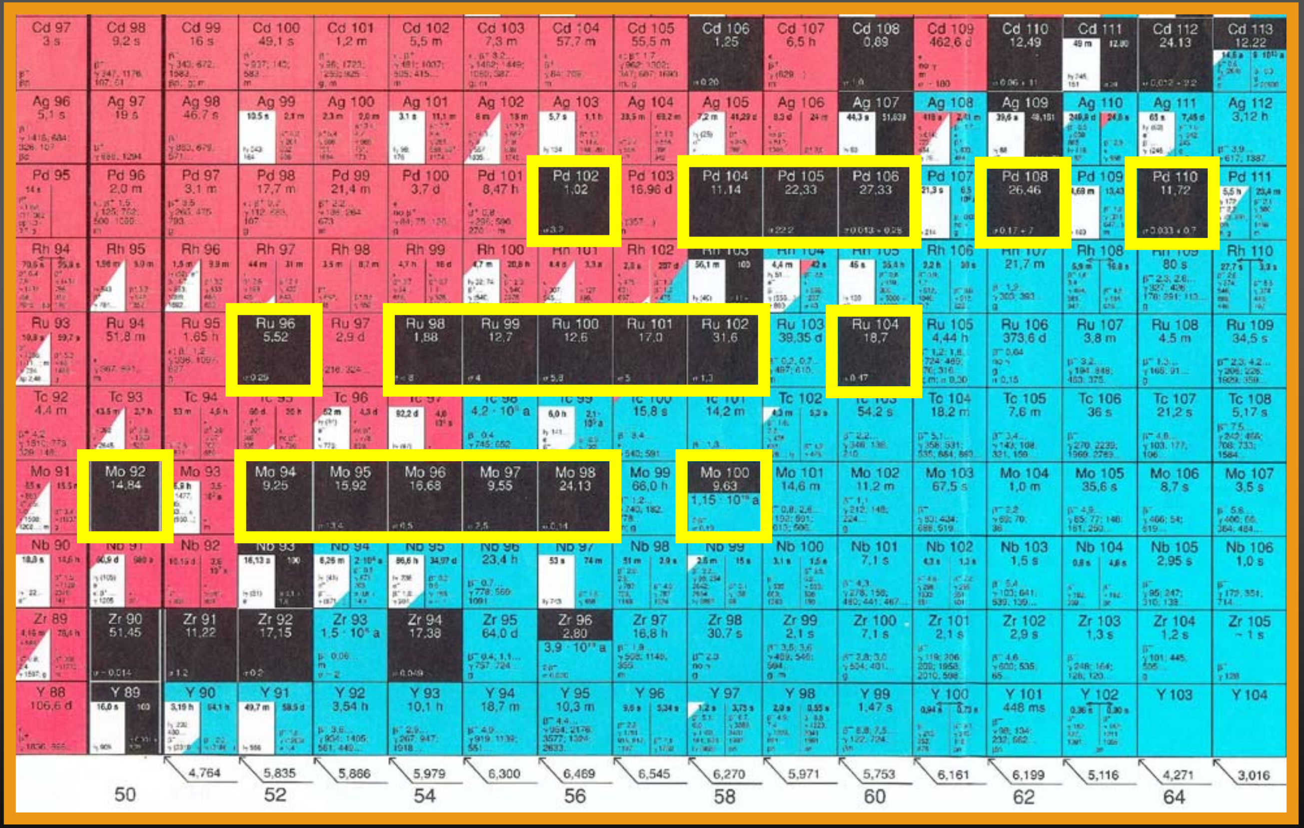


Capture studies: Mo, Ru and Pd

- 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 $5x10^{16}$ = **10^{18}**



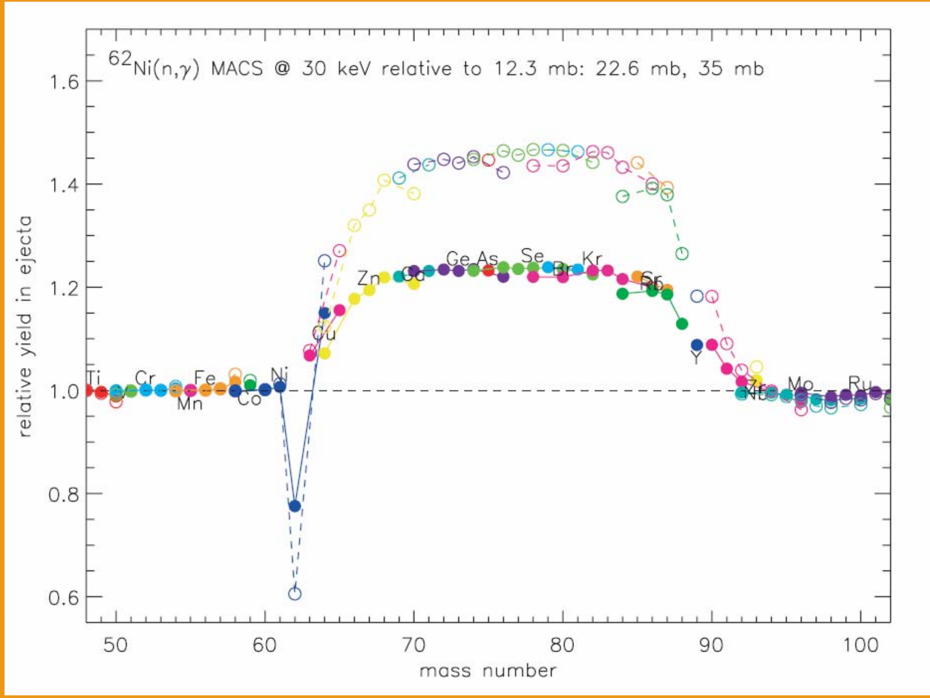


Cd 97 3 s	Cd 98 9,2 s	Cd 99 16 s	Cd 100 49,1 s	Cd 101 1,2 m	Cd 102 5,5 m	Cd 103 7,3 m	Cd 104 57,7 m	Cd 105 55,5 m	Cd 106 1,25	Cd 107 6,5 h	Cd 108 0,89	Cd 109 462,6 d	Cd 110 12,49	Cd 111 49 m 12,80	Cd 112 24.13	Cd 113 12.22
Ag 96 5,1 s	Ag 97 19 s	Ag 98 46,7 s	Ag 99 10,5 s 2,1 m	Ag 100 2,3 m 2,0 m	Ag 101 3,1 s 11,1 m	Ag 102 8 m 13 m	Ag 103 5,7 s 1,1 h	Ag 104 33,5 m 69,2 m	Ag 105 7,2 m 41,29 d	Ag 106 8,3 d 24 m	Ag 107 44,3 s 51,839	Ag 108 418 a 2,41 m	Ag 109 39,6 s 48,161	Ag 110 249,8 d 24,6 s	Ag 111 65 s 7,45 d	Ag 112 3,12 h
Pd 95 14 s	Pd 96 2,0 m	Pd 97 3,1 m	Pd 98 17,7 m	Pd 99 21,4 m	Pd 100 3,7 d	Pd 101 8,47 h	Pd 102 1,02	Pd 103 16,96 d	Pd 104 11,14	Pd 105 22,33	Pd 106 27,33	Pd 107 21,3 s	Pd 108 26,46	Pd 109 4,69 m 13,43	Pd 110 11,72	Pd 111 5,5 h 23,4 m
Rh 94 70,6 s 25,8 s	Rh 95 1,96 m 5,0 m	Rh 96 1,5 m 9,9 m	Rh 97 44 m 31 m	Rh 98 3,5 m 8,7 m	Rh 99 4,7 h 16 d	Rh 100 4,7 m 20,8 h	Rh 101 4,4 d 3,3 a	Rh 102 2,9 a 207 d	Rh 103 56,1 m 100	Rh 104 4,4 m 42 s	Rh 105 45 s 35,4 h	Rh 106 2,2 h 30 s	Rh 107 21,7 m	Rh 108 5,9 m 16,8 s	Rh 109 80 s	Rh 110 27,7 s 3,3 s
Ru 93 10,8 s 59,7 s	Ru 94 51,8 m	Ru 95 1,65 h	Ru 96 5,52	Ru 97 2,9 d	Ru 98 1,88	Ru 99 12,7	Ru 100 12,6	Ru 101 17,0	Ru 102 31,6	Ru 103 39,35 d	Ru 104 18,7	Ru 105 4,44 h	Ru 106 373,6 d	Ru 107 3,8 m	Ru 108 4,5 m	Ru 109 34,5 s
Tc 92 4,4 m	Tc 93 43,5 m 2,7 h	Tc 94 53 m 4,9 h	Tc 95 60 d 20 h	Tc 96 52 m 4,3 d	Tc 97 92,2 d	Tc 98 $4,2 \cdot 10^6$ a	Tc 99 6,0 h	Tc 100 15,8 s	Tc 101 14,2 m	Tc 102 4,3 m 5,3 s	Tc 103 54,2 s	Tc 104 18,2 m	Tc 105 7,6 m	Tc 106 36 s	Tc 107 21,2 s	Tc 108 5,17 s
Mo 91 65 s 15,5 m	Mo 92 14,84	Mo 93 6,9 h	Mo 94 9,25	Mo 95 15,92	Mo 96 16,68	Mo 97 9,55	Mo 98 24,13	Mo 99 66,0 h	Mo 100 9,63 $1,15 \cdot 10^{19}$ a	Mo 101 14,6 m	Mo 102 11,2 m	Mo 103 67,5 s	Mo 104 1,0 m	Mo 105 35,6 s	Mo 106 8,7 s	Mo 107 3,5 s
Nb 90 18,8 s 14,6 h	Nb 91 60,9 d 680 a	Nb 92 10,15 d	Nb 93 16,13 a 100	Nb 94 6,26 m	Nb 95 86,6 h 34,97 d	Nb 96 23,4 h	Nb 97 53 s 74 m	Nb 98 51 m 2,9 s	Nb 99 2,6 m 15 s	Nb 100 3,1 s 1,5 s	Nb 101 7,1 s	Nb 102 4,3 s 1,3 s	Nb 103 1,5 s	Nb 104 0,9 s 4,8 s	Nb 105 2,95 s	Nb 106 1,0 s
Zr 89 4,18 m 78,4 h	Zr 90 51,45	Zr 91 11,22	Zr 92 17,15	Zr 93 $1,5 \cdot 10^6$ a	Zr 94 17,38	Zr 95 64,0 d	Zr 96 2,80 $3,9 \cdot 10^{19}$ a	Zr 97 16,8 h	Zr 98 30,7 s	Zr 99 2,1 s	Zr 100 7,1 s	Zr 101 2,1 s	Zr 102 2,9 s	Zr 103 1,3 s	Zr 104 1,2 s	Zr 105 ~1 s
Y 88 106,6 d	Y 89 16,0 s 100	Y 90 3,19 h 64,1 h	Y 91 49,7 m 58,5 d	Y 92 3,54 h	Y 93 10,1 h	Y 94 18,7 m	Y 95 10,3 m	Y 96 9,6 s 5,34 s	Y 97 1,2 s 3,75 s	Y 98 2,0 s 0,55 s	Y 99 1,47 s	Y 100 0,94 s 0,73 s	Y 101 448 ms	Y 102 0,36 s 0,30 s	Y 103	Y 104
		4,764	5,835	5,866	5,979	6,300	6,469	6,545	6,270	5,971	5,753	6,161	6,199	5,116	4,271	3,016
	50		52		54		56		58		60		62		64	

Capture studies: Fe, Ni, Zn, and Se

Motivations:

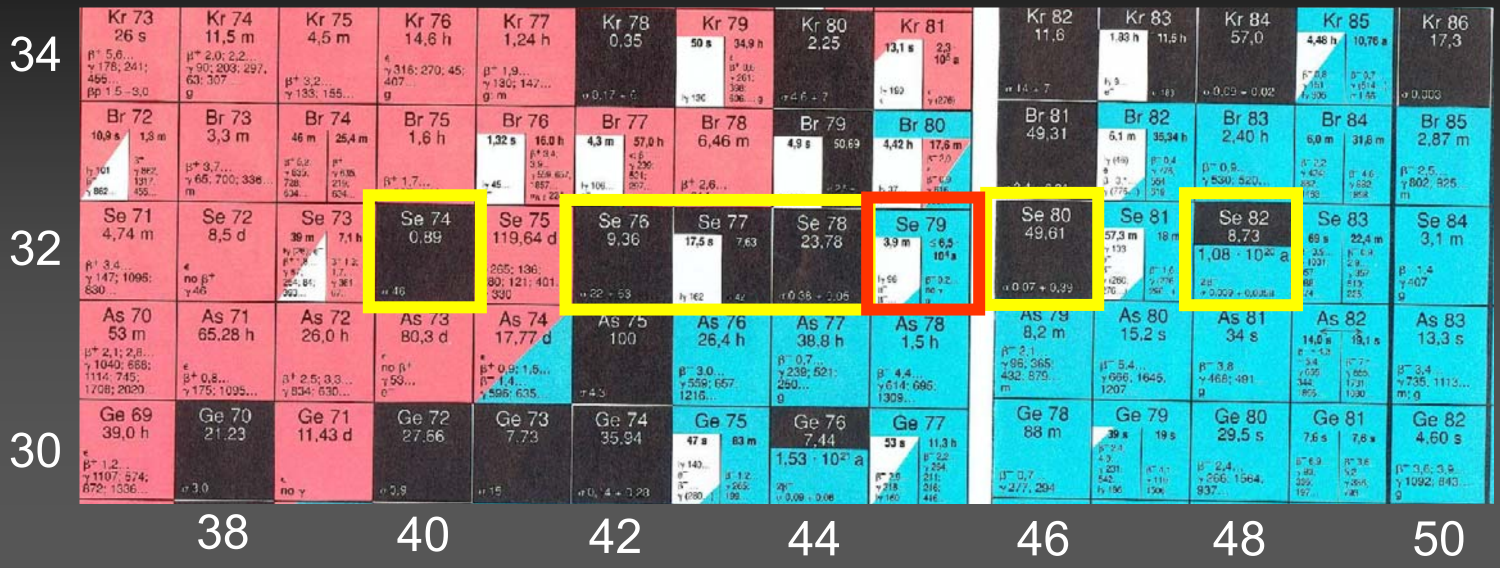
- Study of the weak s-process component (nucleosynthesis up to A ~ 90)
- Contribution of massive stars (core He-burning phase) to the s-process nucleosynthesis.
- s-process efficiency due to bottleneck cross sections (Example: ^{62}Ni)



In addition:

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

Capture studies: Fe, Ni, Zn, and Se

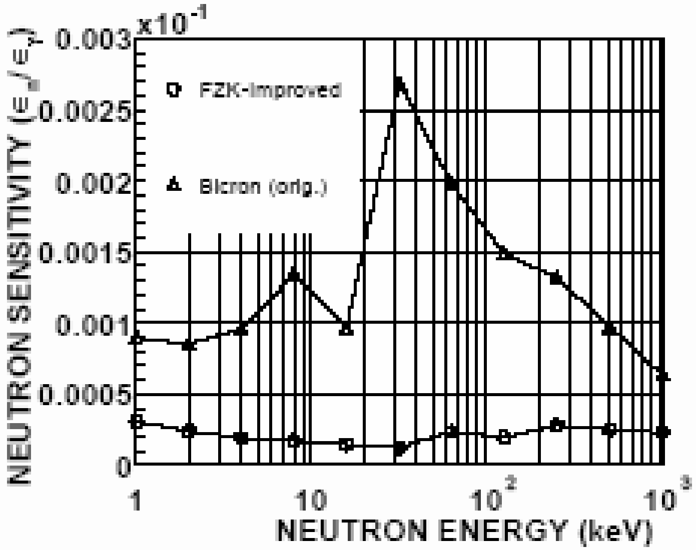


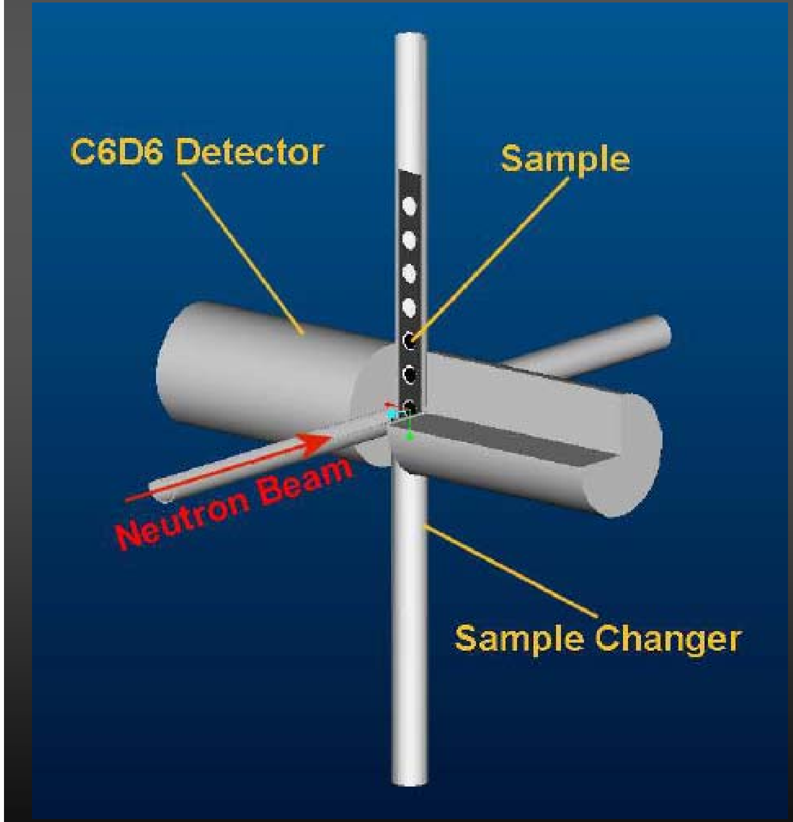
The ^{79}Se case

- 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)

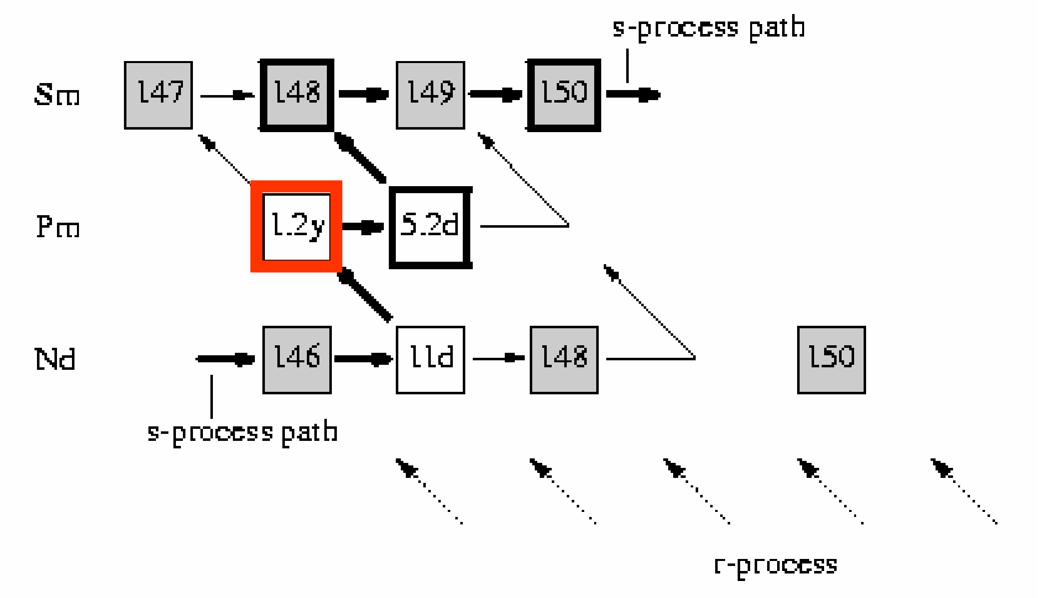




(*) except ^{79}Se

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

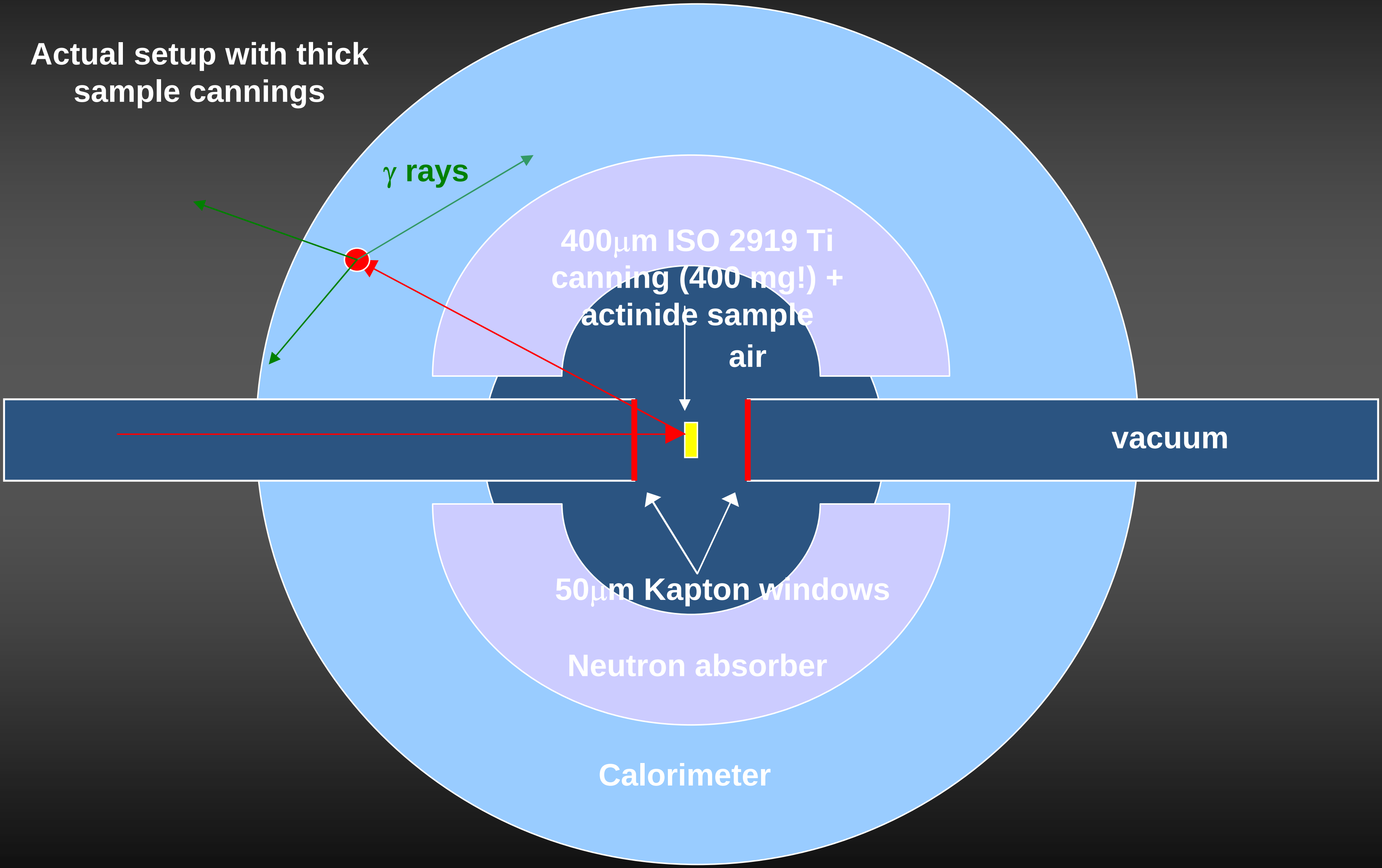
Neutron cross section measurements for nuclear waste transmutation and advanced nuclear technologies

^{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



γ **rays**

400μm ISO 2919 Ti canning (400 mg!) + actinide sample

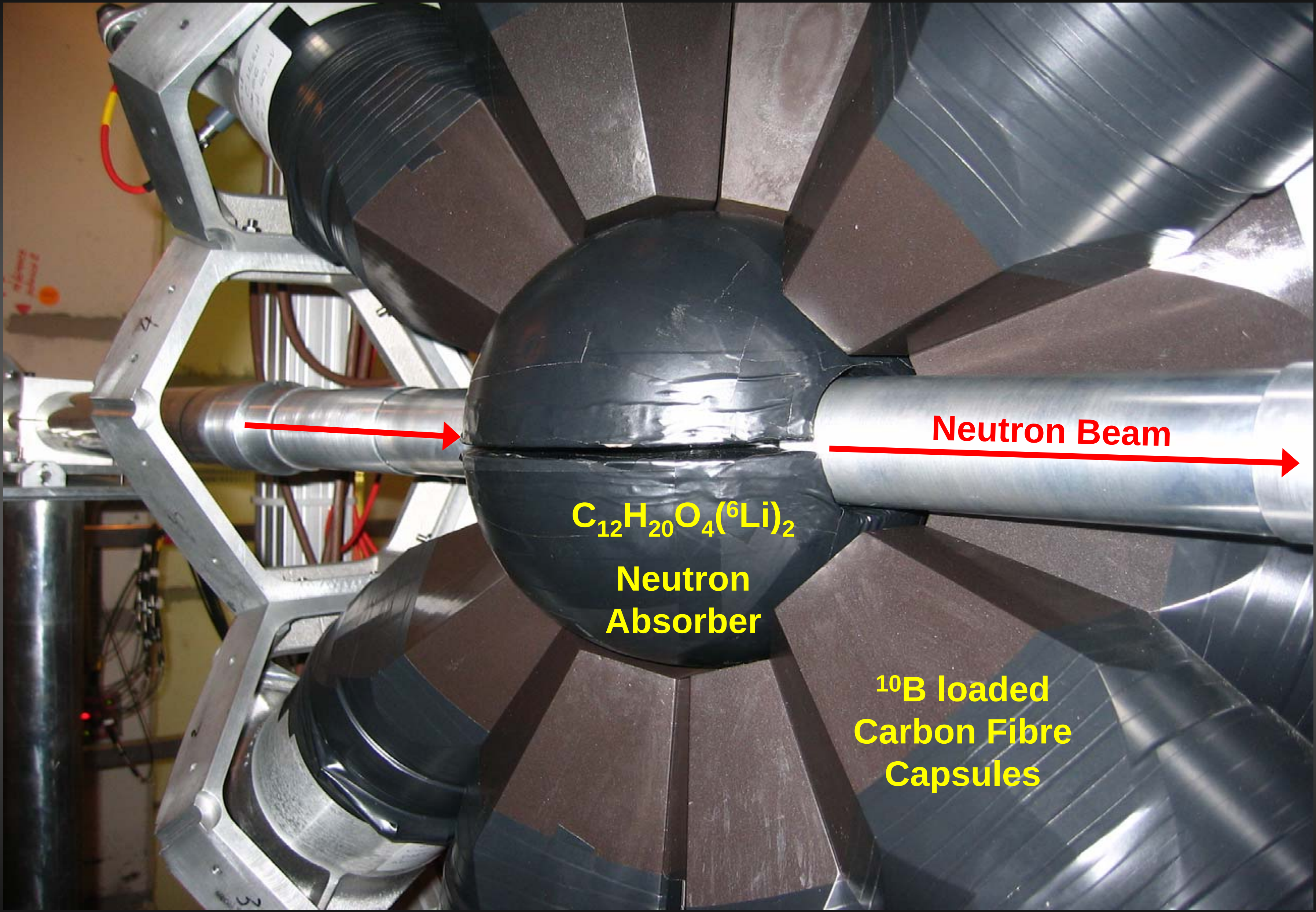
air

vacuum

50μm Kapton windows

Neutron absorber

Calorimeter



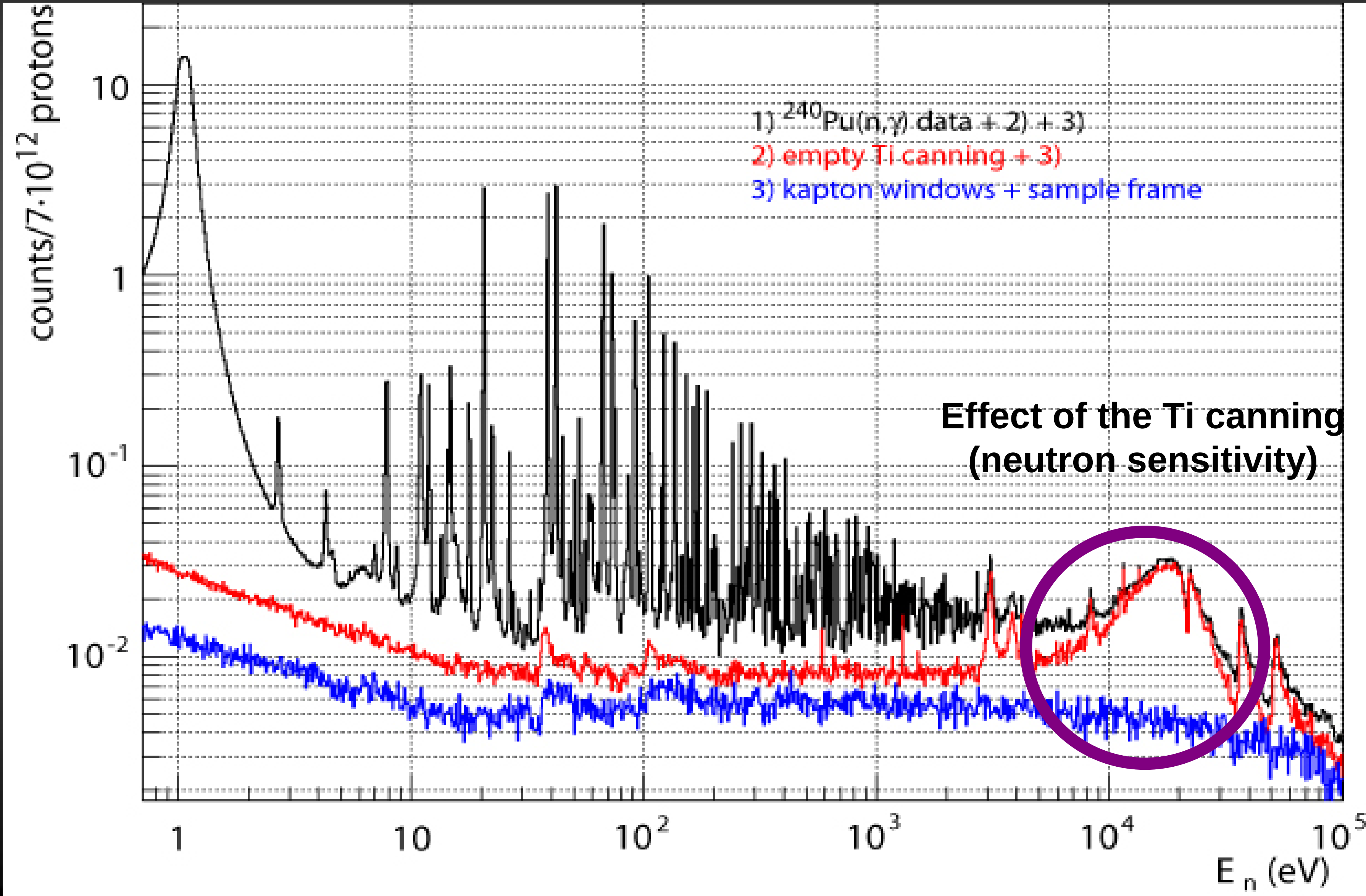
Neutron Beam

$C_{12}H_{20}O_4(^6Li)_2$

Neutron Absorber

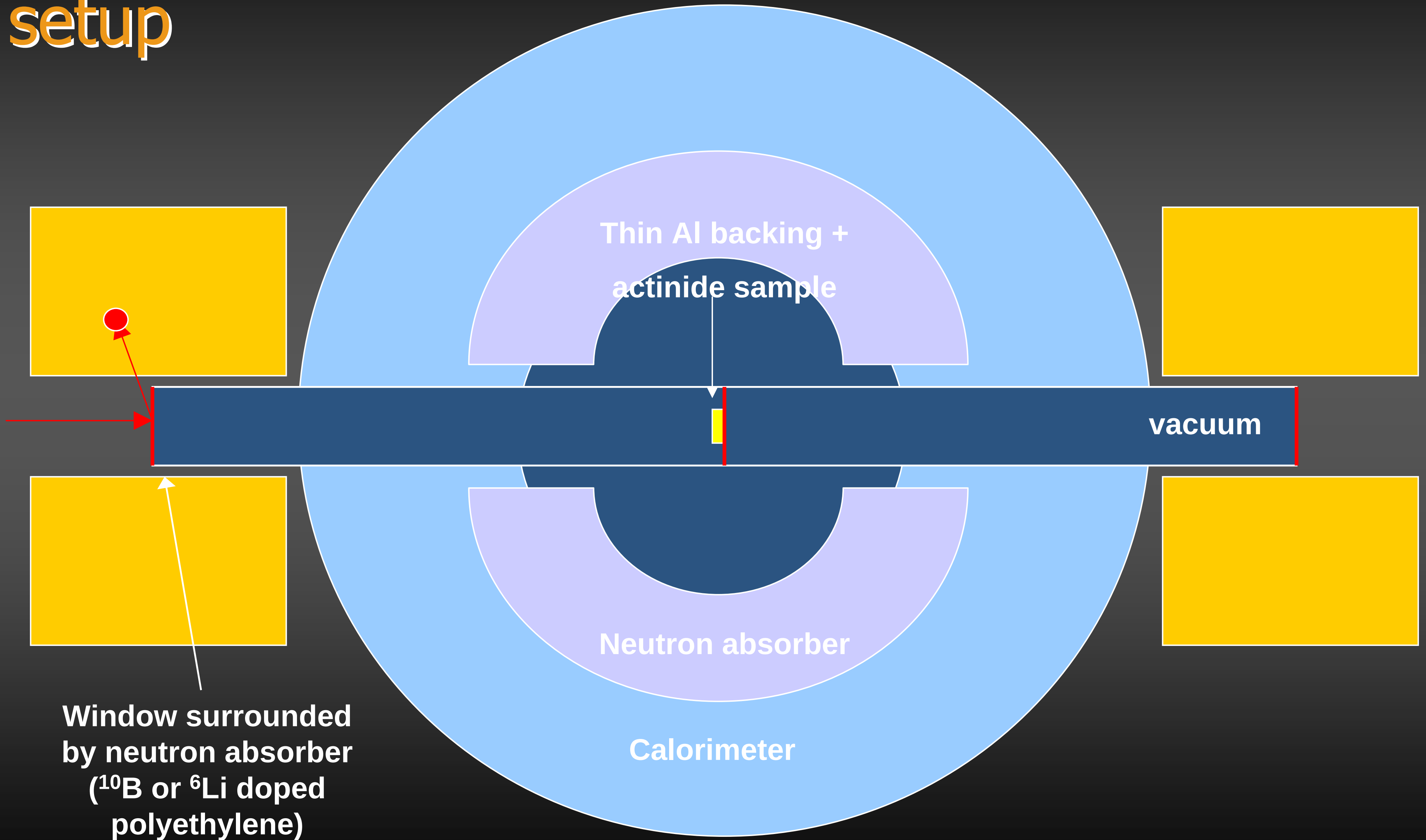
^{10}B loaded Carbon Fibre Capsules

Capture studies: actual TAC setup



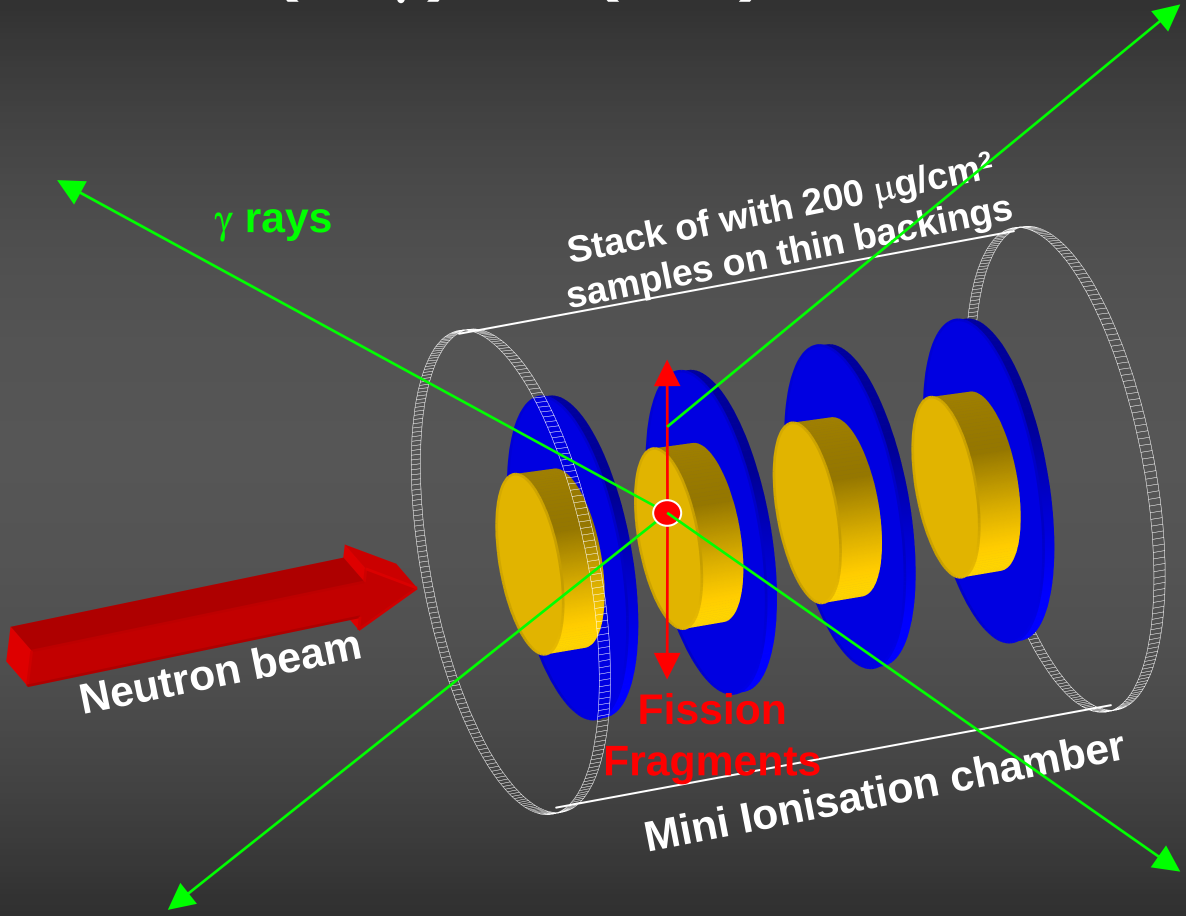
Effect of the Ti canning (neutron sensitivity)

Capture studies: Low neutron sensitivity setup



Window surrounded by neutron absorber (^{10}B or ^{6}Li doped polyethylene)

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



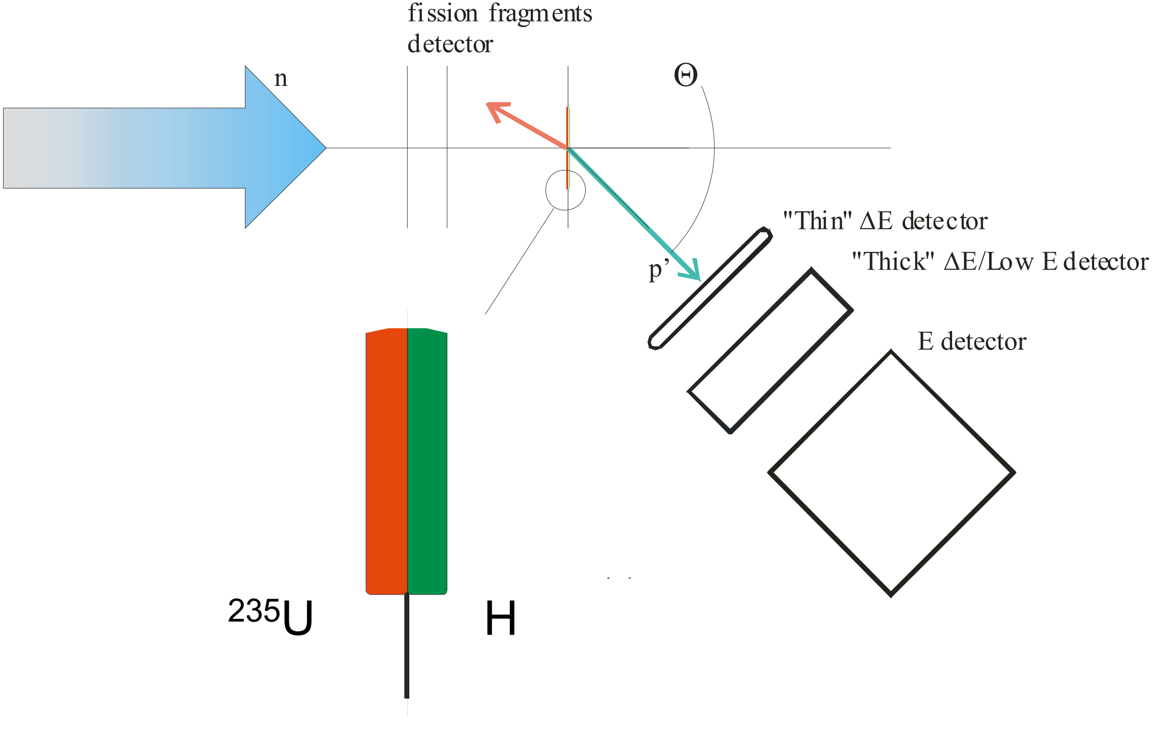
<< back

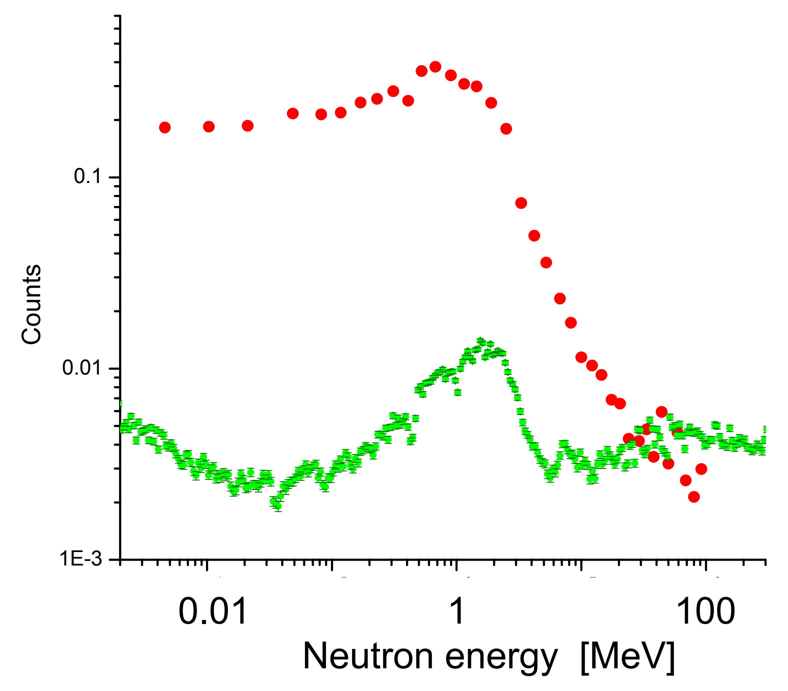
Measurement of capture cross sections of fissile materials (veto) and measurement of the (n,γ)/(n,f) ratio.

Fission studies

Fission studies

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



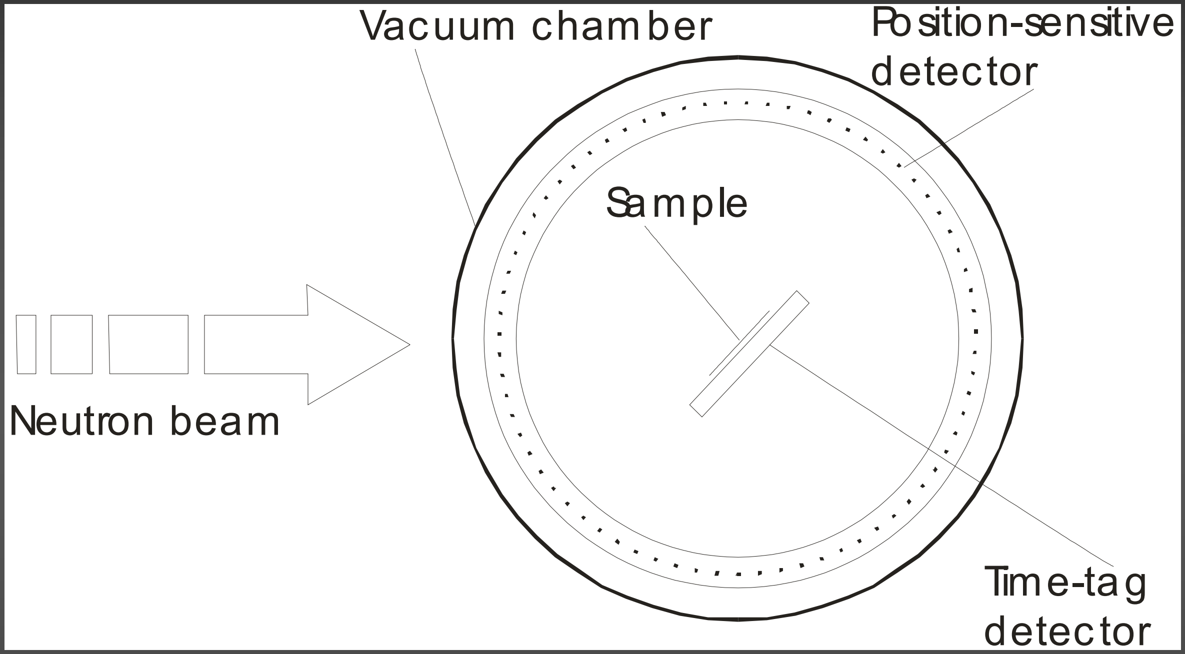


Beam	capture mode (2 mm Ø)
Scattering angle	30°
Target thickness	250 μg/cm^2
Detector radius	20 mm
Target-to-detector distance	250 mm

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

Fission studies

FF distributions in vibrational resonances



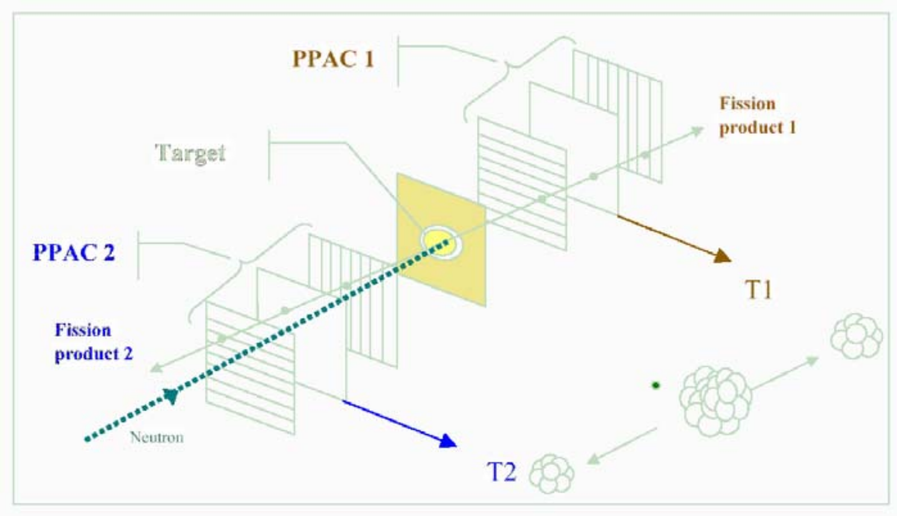
Principles:

- 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

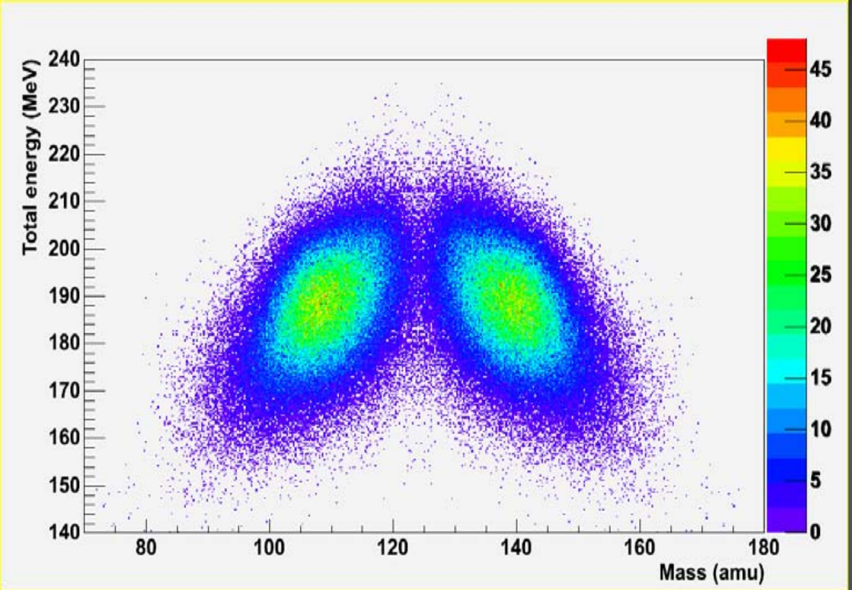
EAR-2 boost:

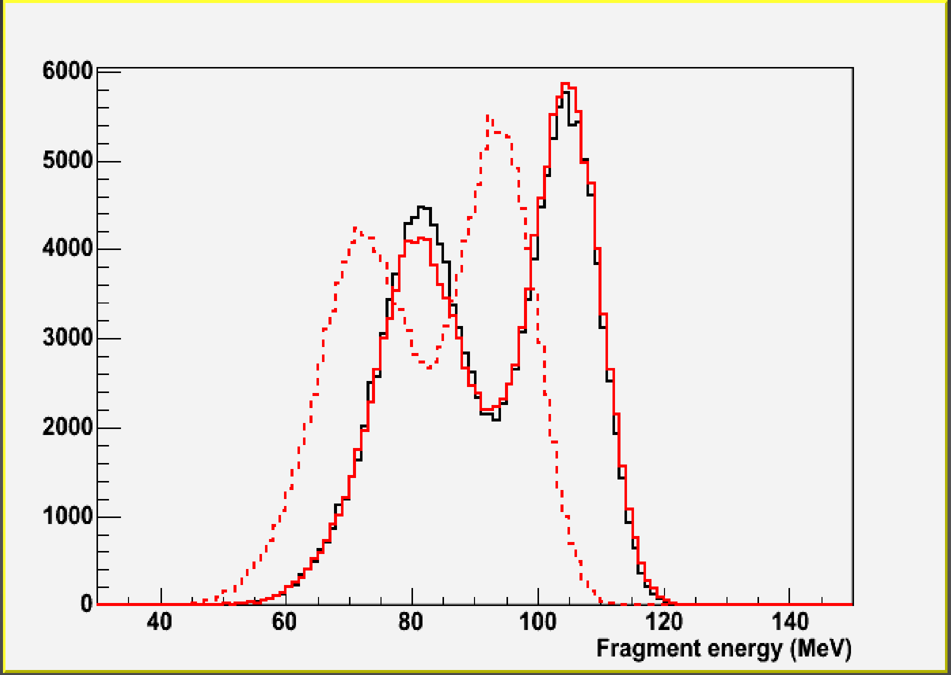
- measurements of ^{241,243}Am (in class-A lab)
- measurements of ^{241}Pu and ^{244}Cm (in class-A lab)

<< back

Fission studies

with twin ionization chamber





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

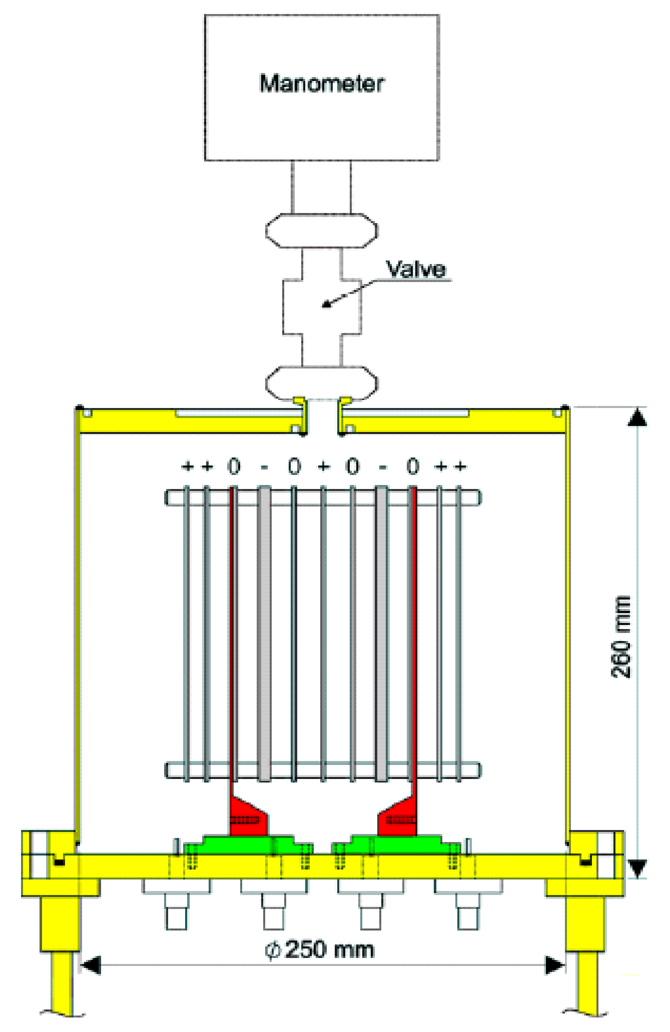
Measurements:

- 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:

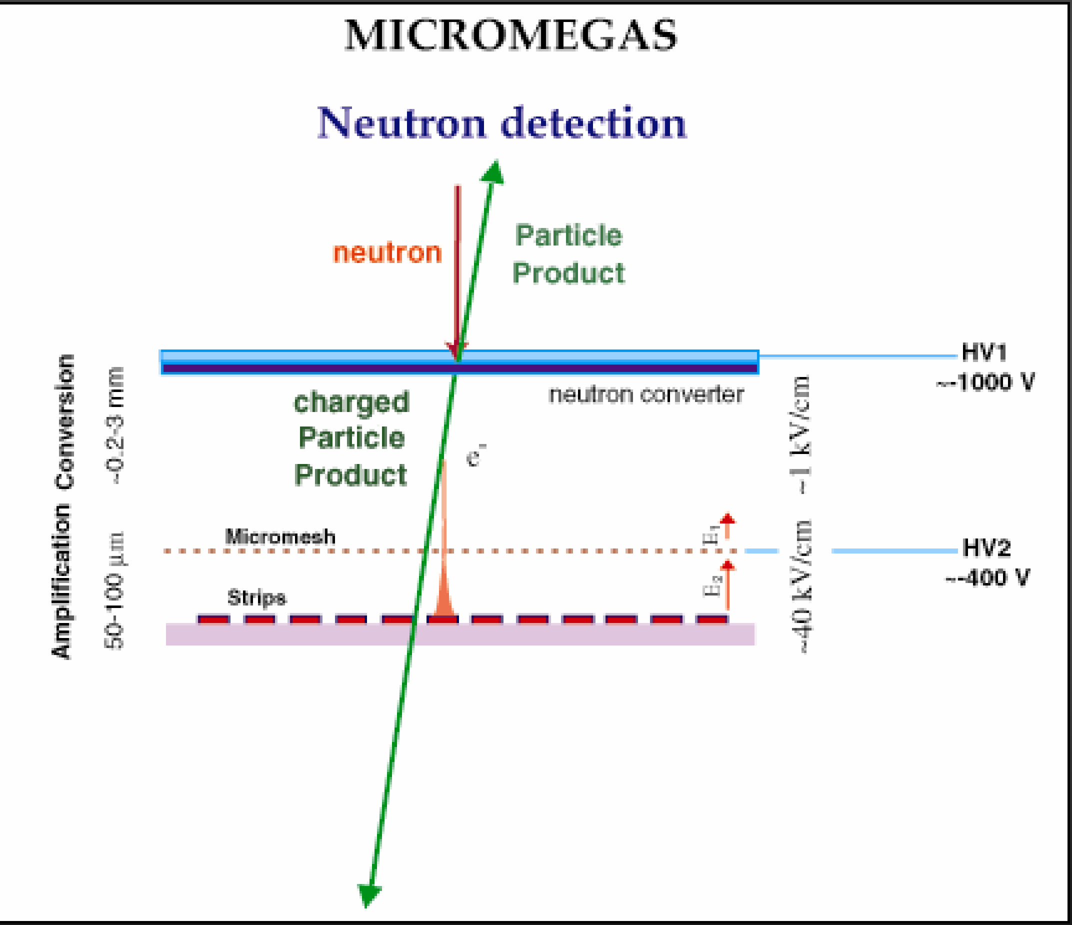
- ^{147}Sm(n,α) (tune up experiment)
- ^{6}LiF target for calibration

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



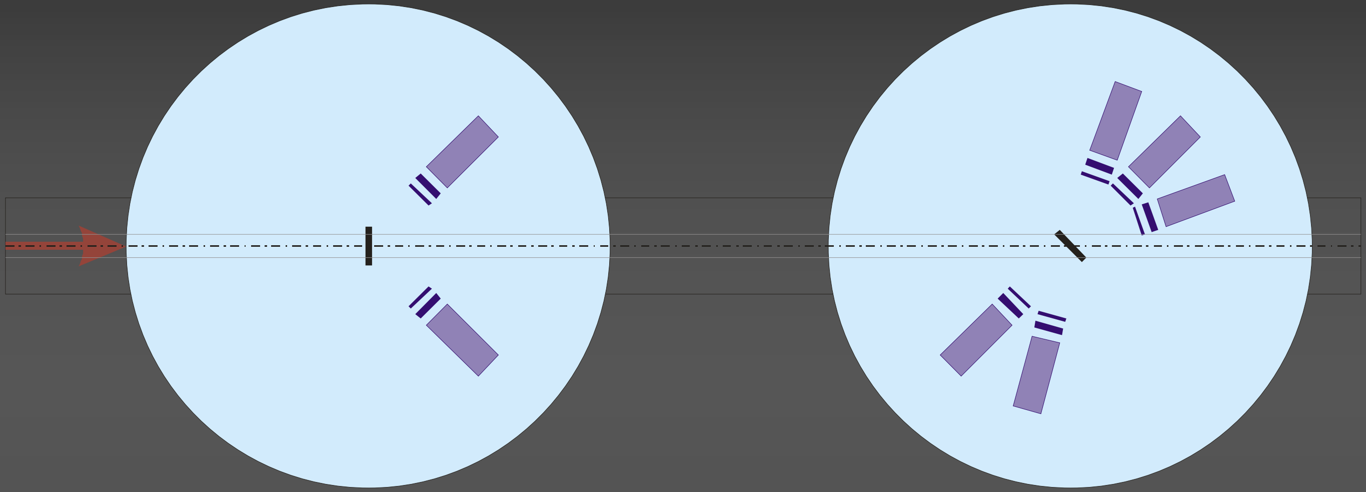
For n_TOF-Ph2:

- 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

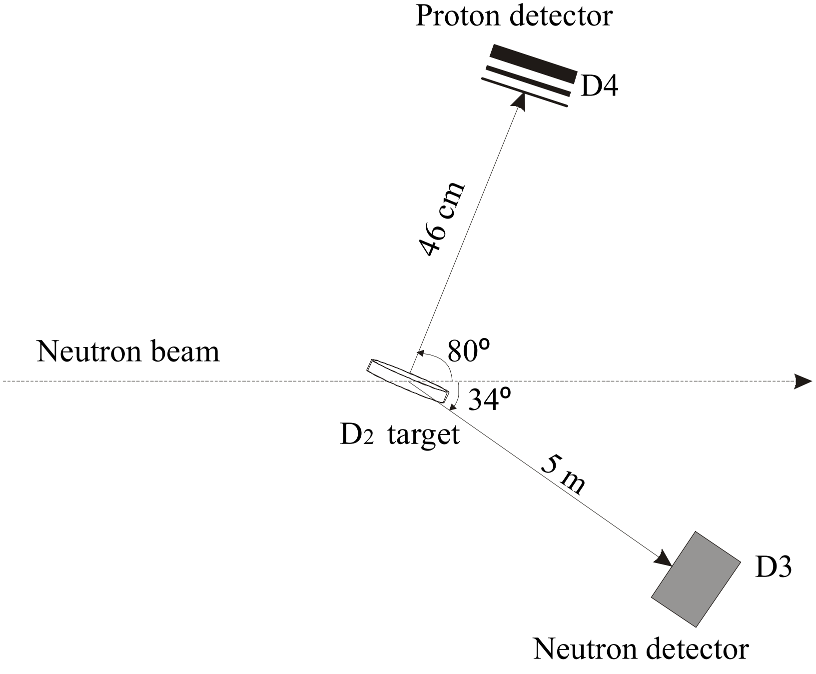
<< back

Neutron scattering reactions

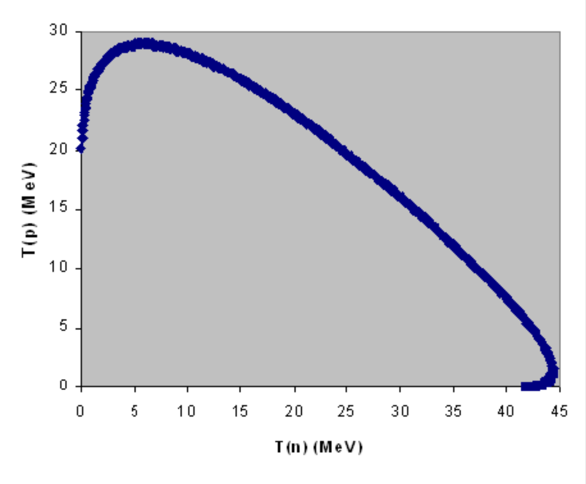
Direct n + n scattering experiment not feasible!

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

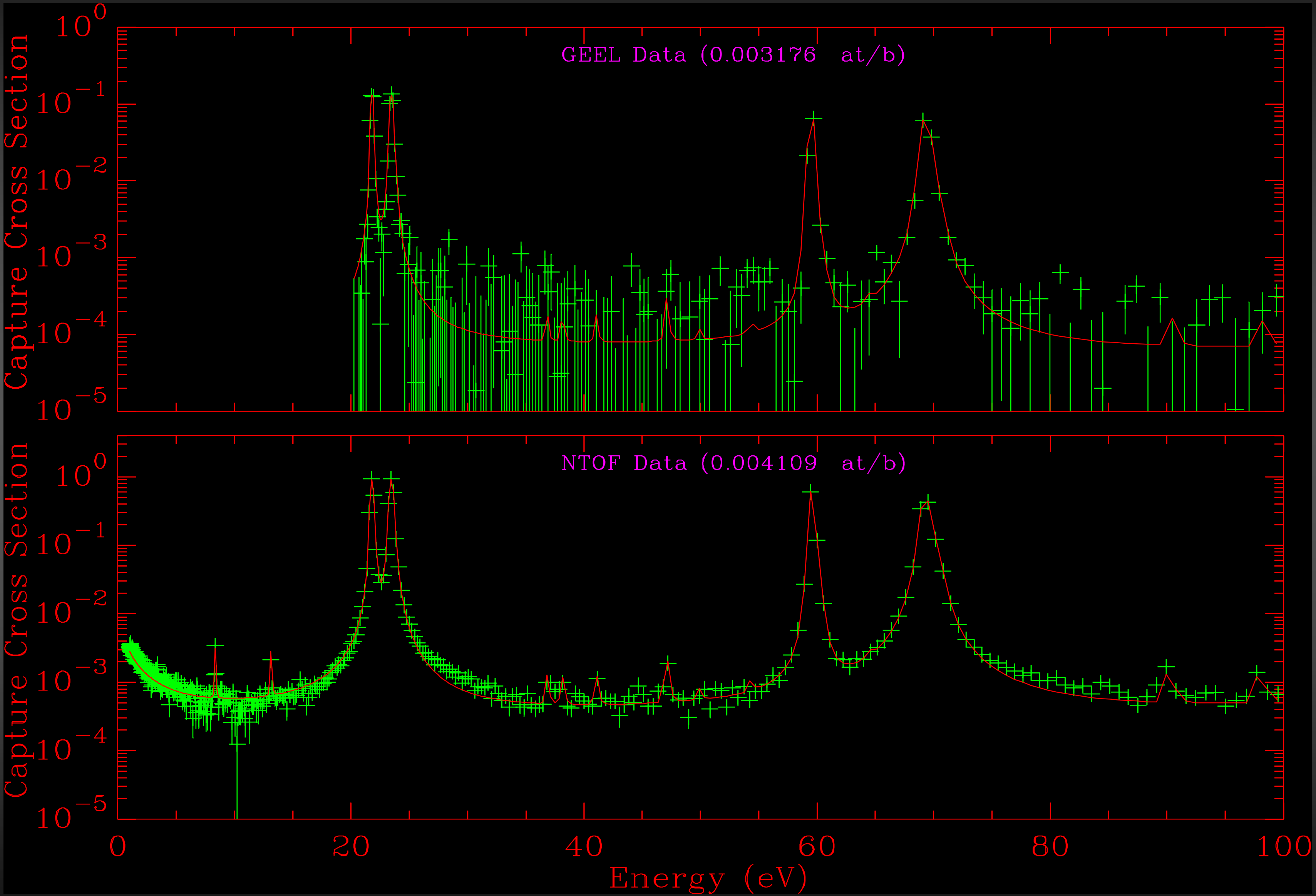


Kiematic locus of the $n + {}^2H \rightarrow n + p + n$ reaction for:
E_n = 50 MeV
$\Theta_n = 20°, \Phi_n = 0°$
$\Theta_p = 50°, \Phi_p = 180°$

<< back

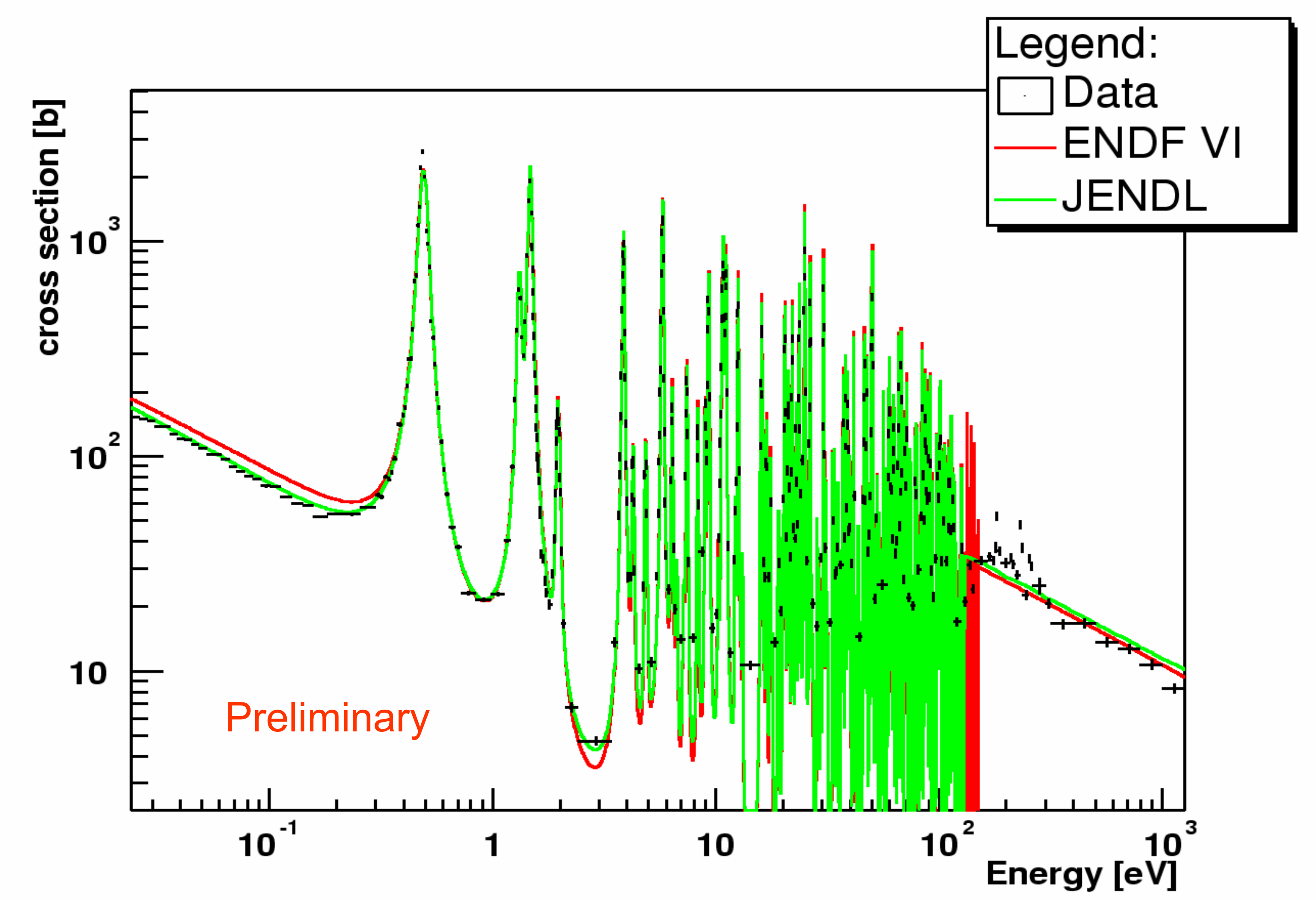
<< back

^{232}Th(n,γ): n_TOF & GELINA



Source: L Leal, IAEA CRP meeting, December 2004

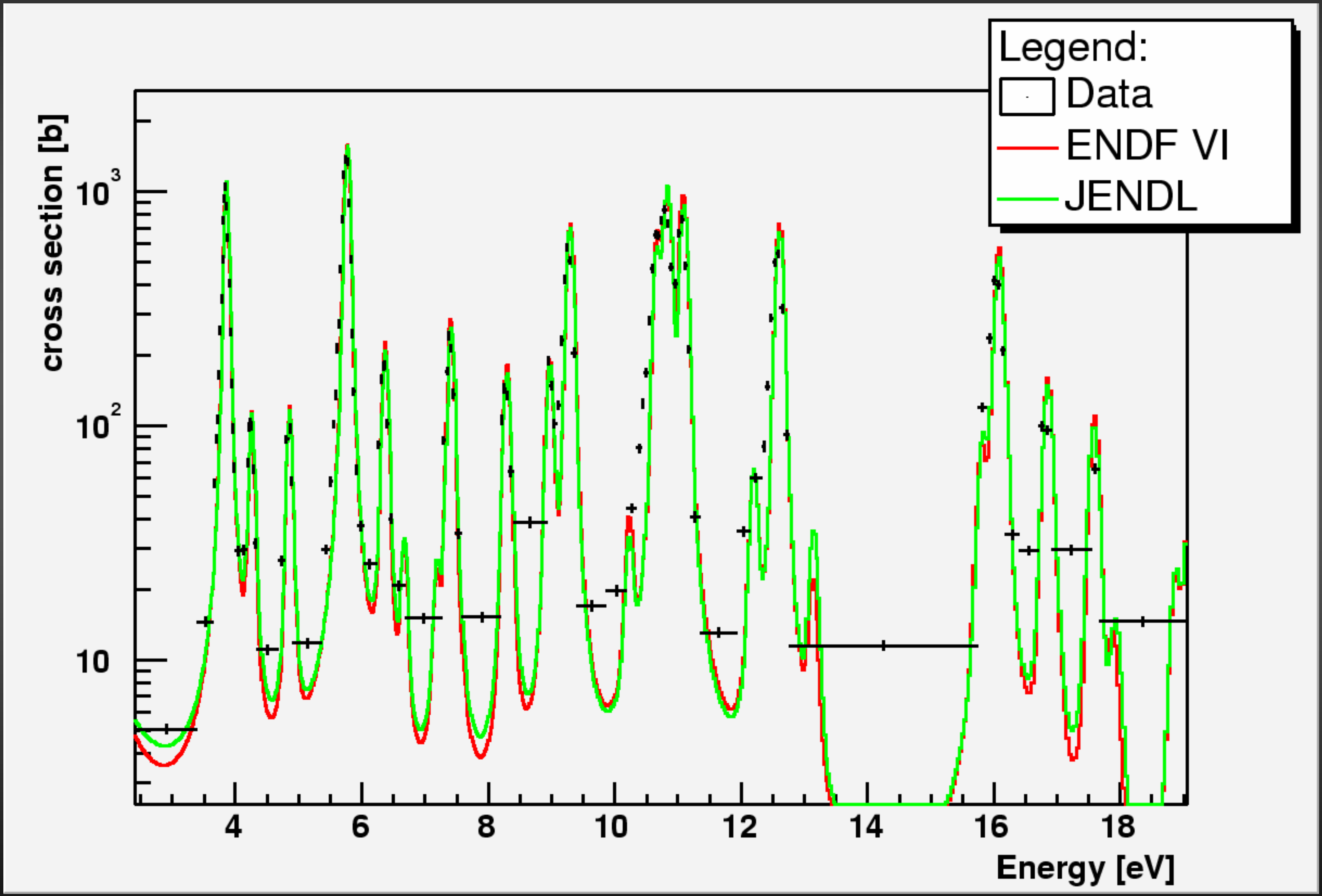
$^{237}Np(n,\gamma)$ at LANSCE



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

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

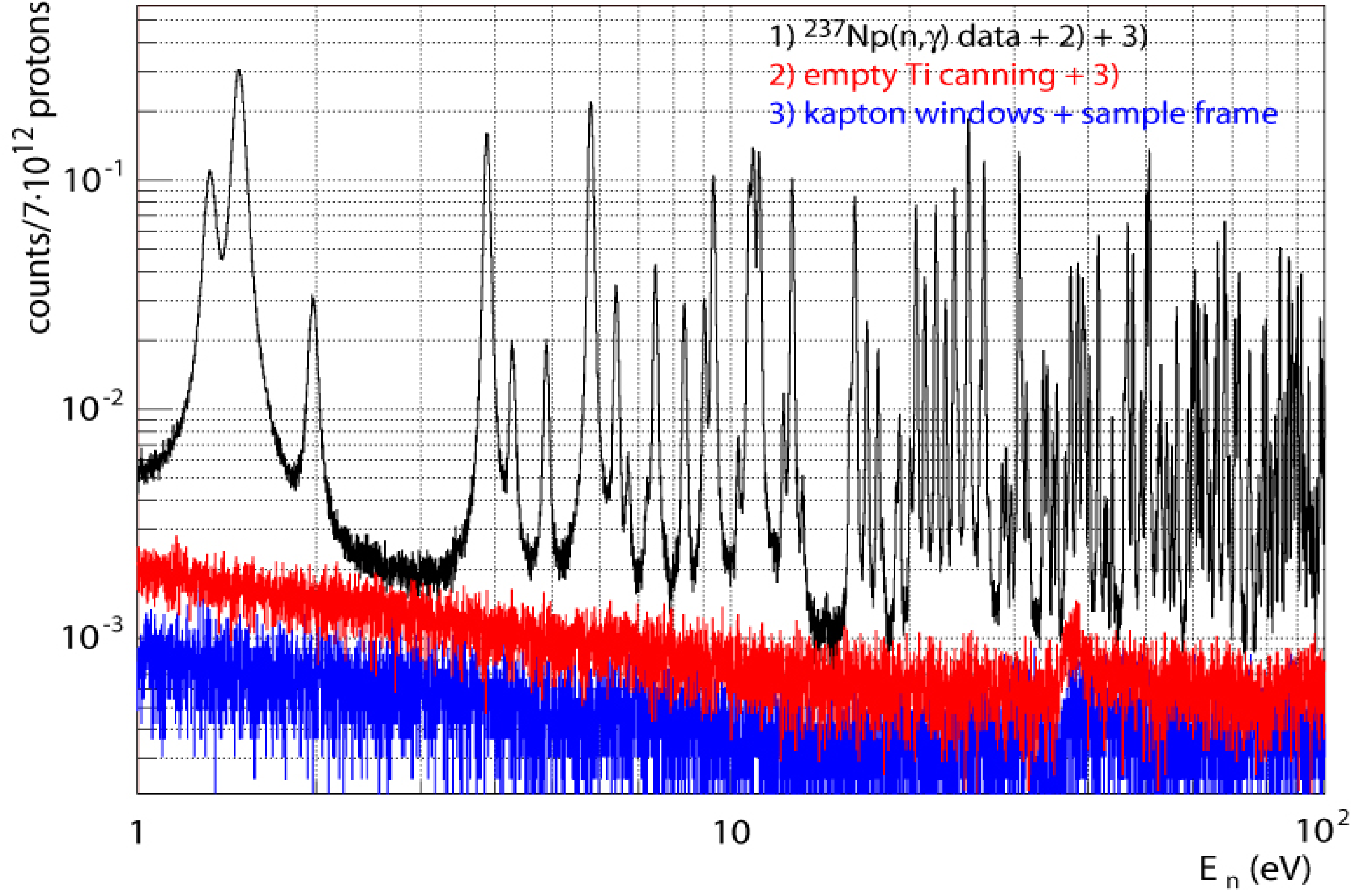
$^{237}Np(n,\gamma)$ at LANSCE



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

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

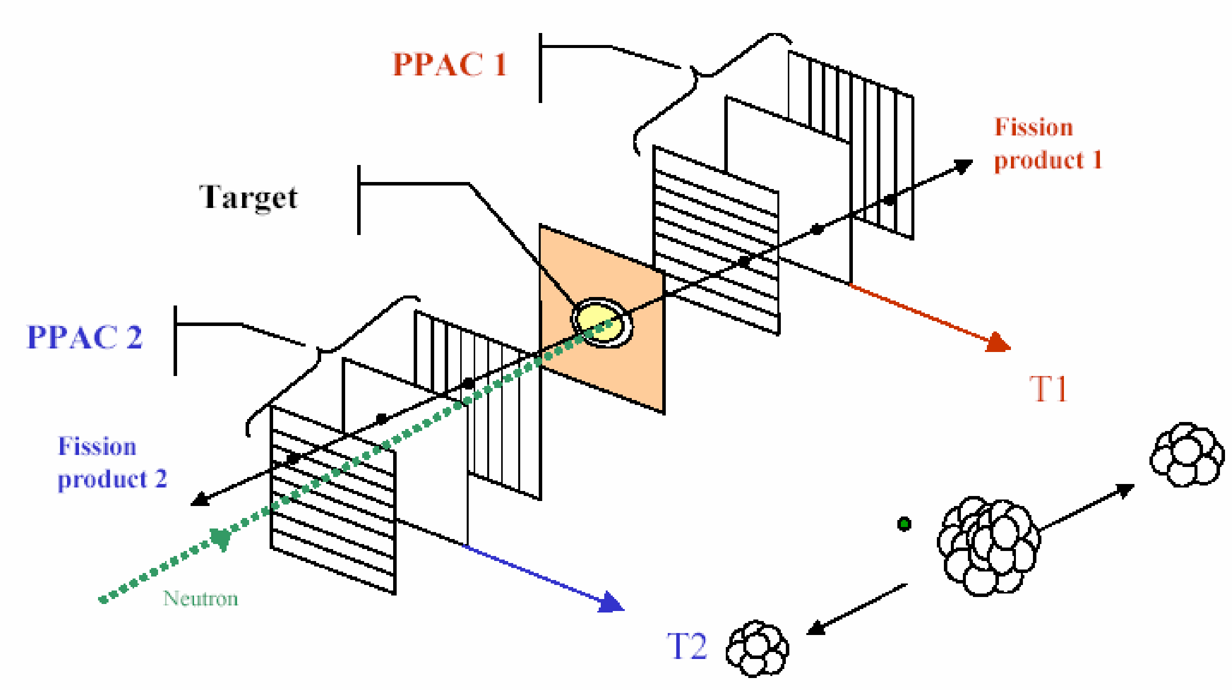
^{237}Np(n,γ) at n_TOF

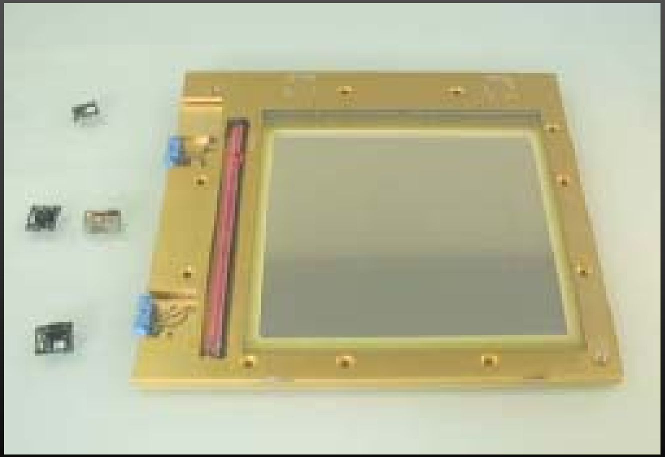


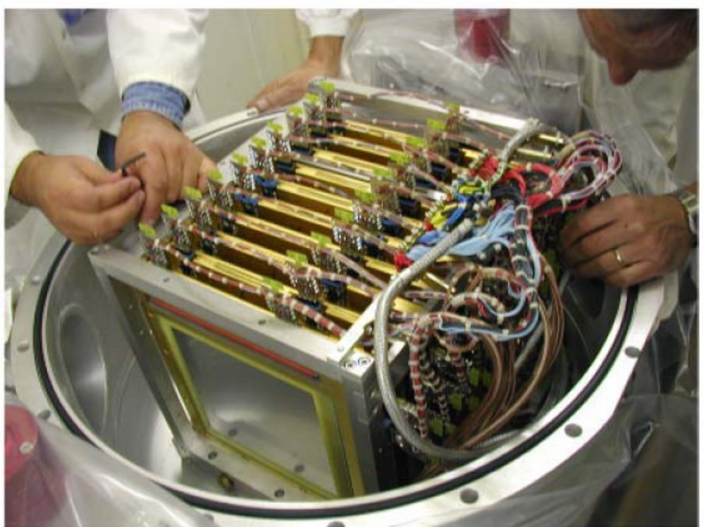
< back

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 μg/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!

alberto.mengoni@cern.ch