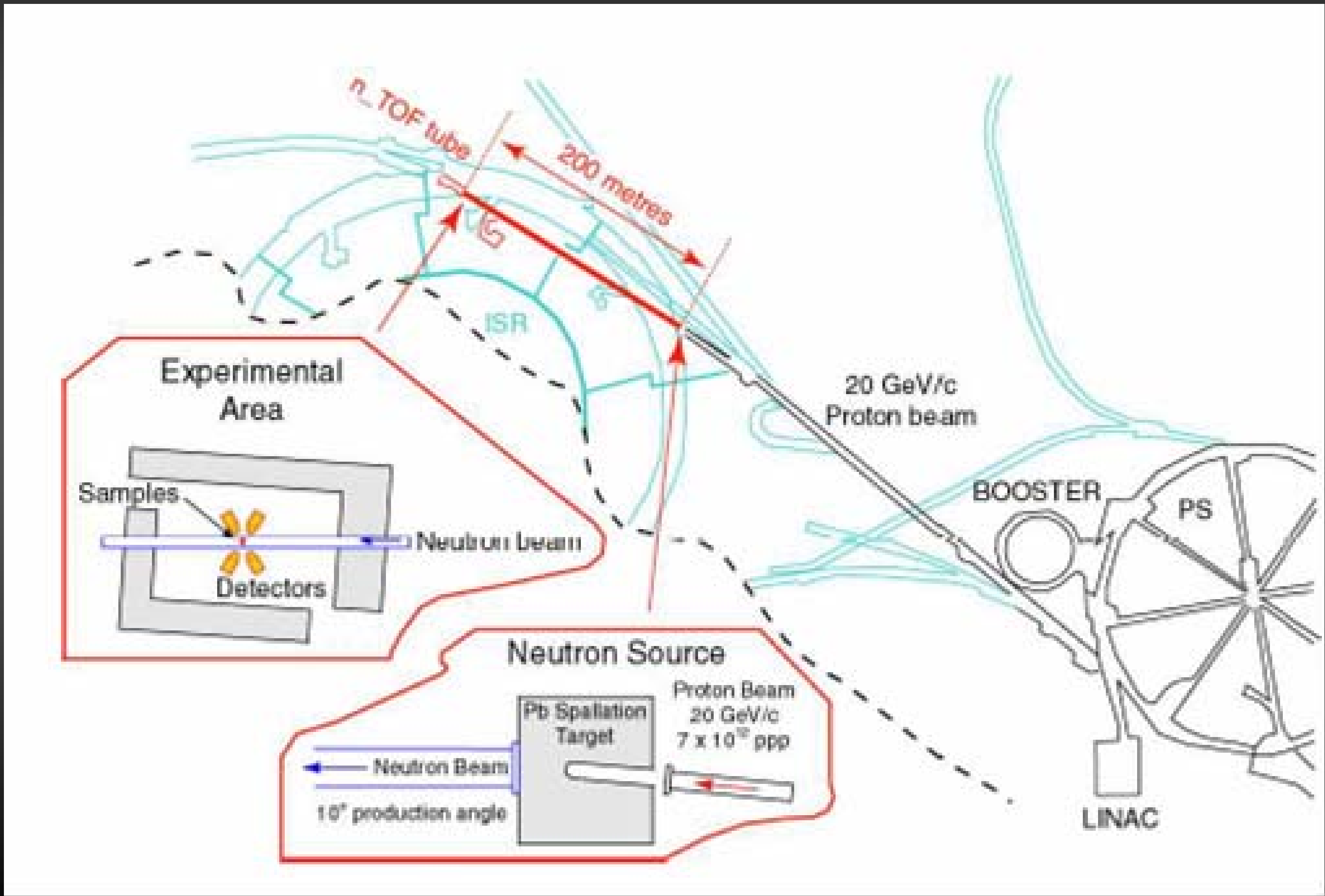
The Future of/at n_TOF

The physics case and the related proposal for measurements at n_TOF for 2006 and beyond

A Mengoni
IAEA, Vienna

- the CERN n_TOF Facility
- the physics case for the activities at n_TOF
- plan for measurements in Phase-2
- opportunities with a new, shorter flight-path: EAR-2

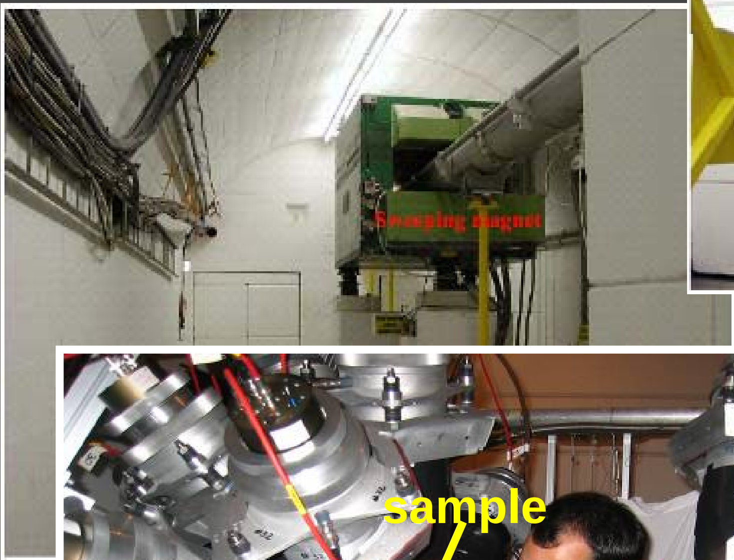
The n_TOF facility at CERN

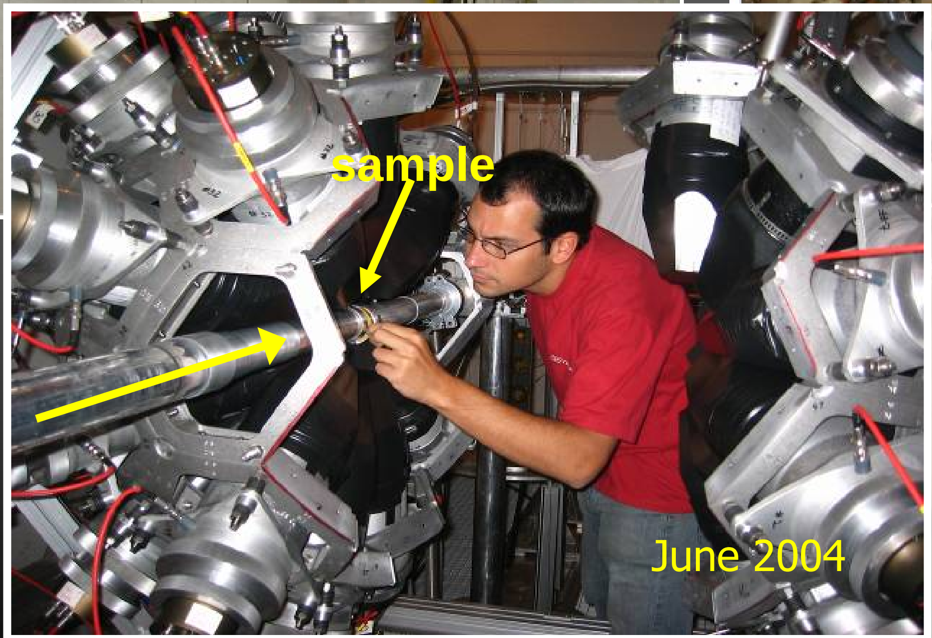


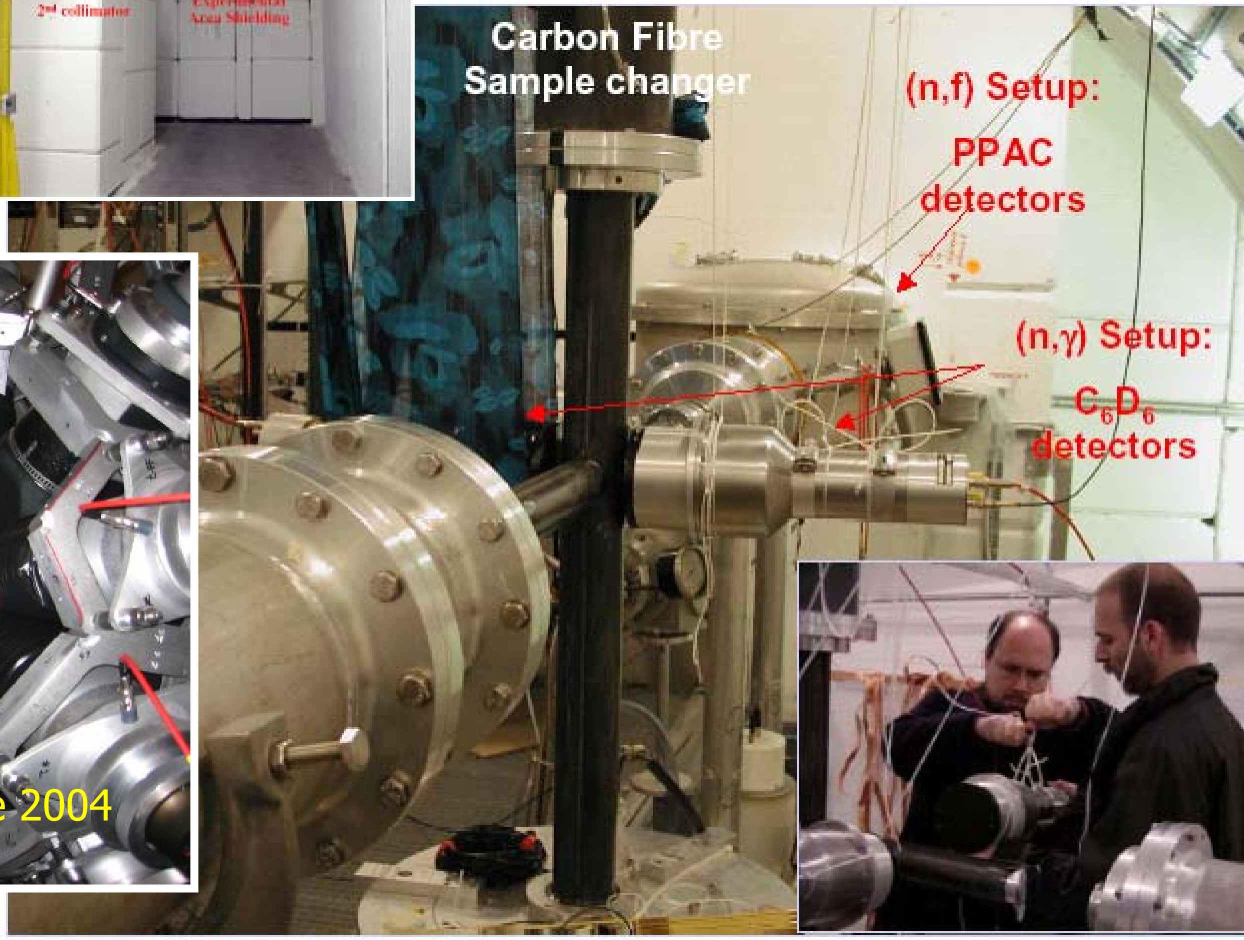
www.cern.ch/n_TOF

n_TOF

- n_TOF commissioned in 2002







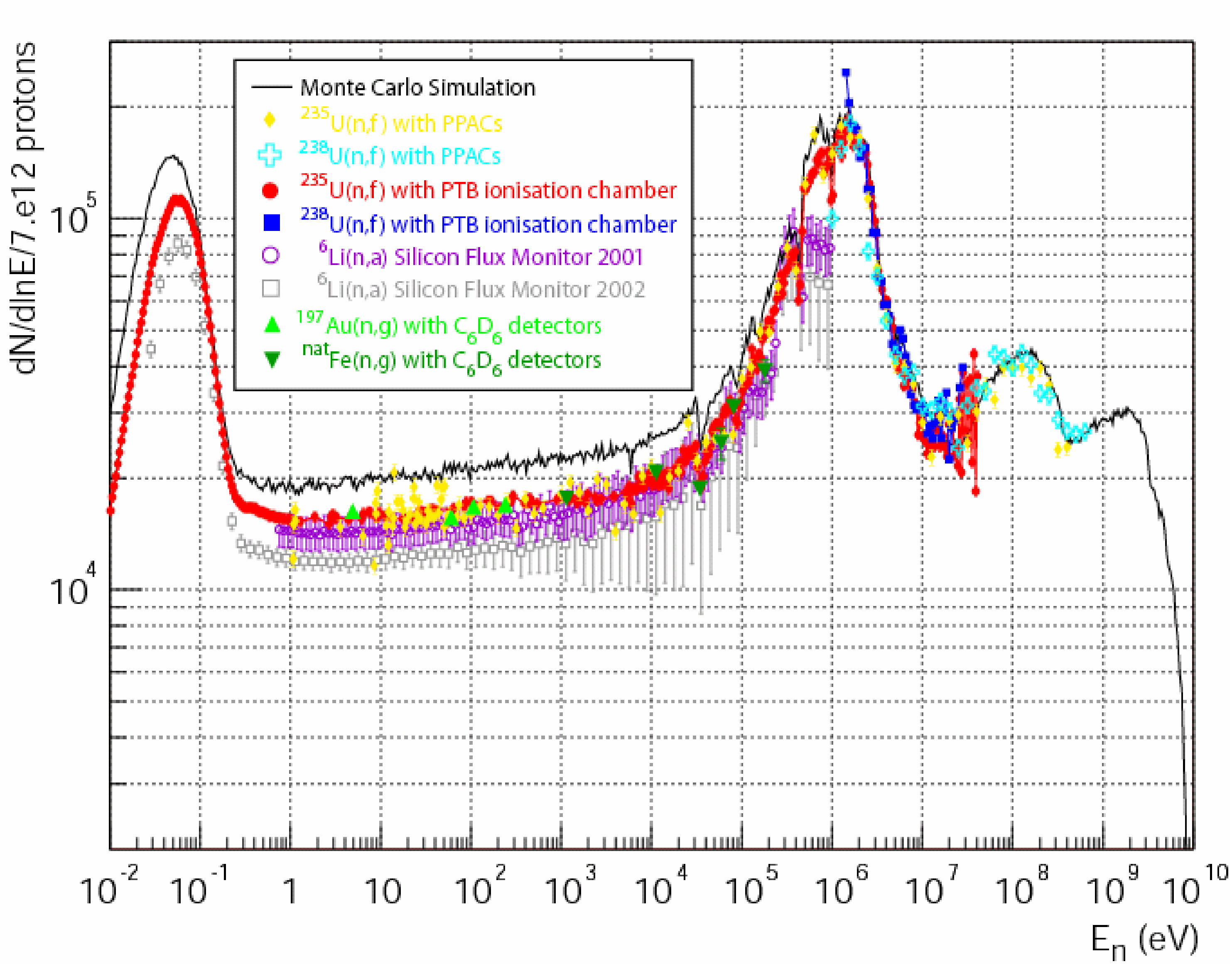
n_TOF basic parameters

proton beam momentum	20 GeV/c
intensity (dedicated mode)	7 x 10^{12} protons/pulse
repetition frequency	1 pulse/2.4s
pulse width	6 ns (rms)
n/p	300
lead target dimensions	80x80x60 cm^3
cooling & moderation material	H_2O
moderator thickness in the exit face	5 cm
neutron beam dimension in EAR-1 (capture mode)	2 cm (FWHM)

The neutron flux

2nd collimator ϕ=1.8 cm

Neutron Energy	ΔE/E
1 ev	3.0×10^{-4}
30 keV	1.1×10^{-3}
1 MeV	4.2×10^{-3}
100 MeV	2.1×10^{-2}

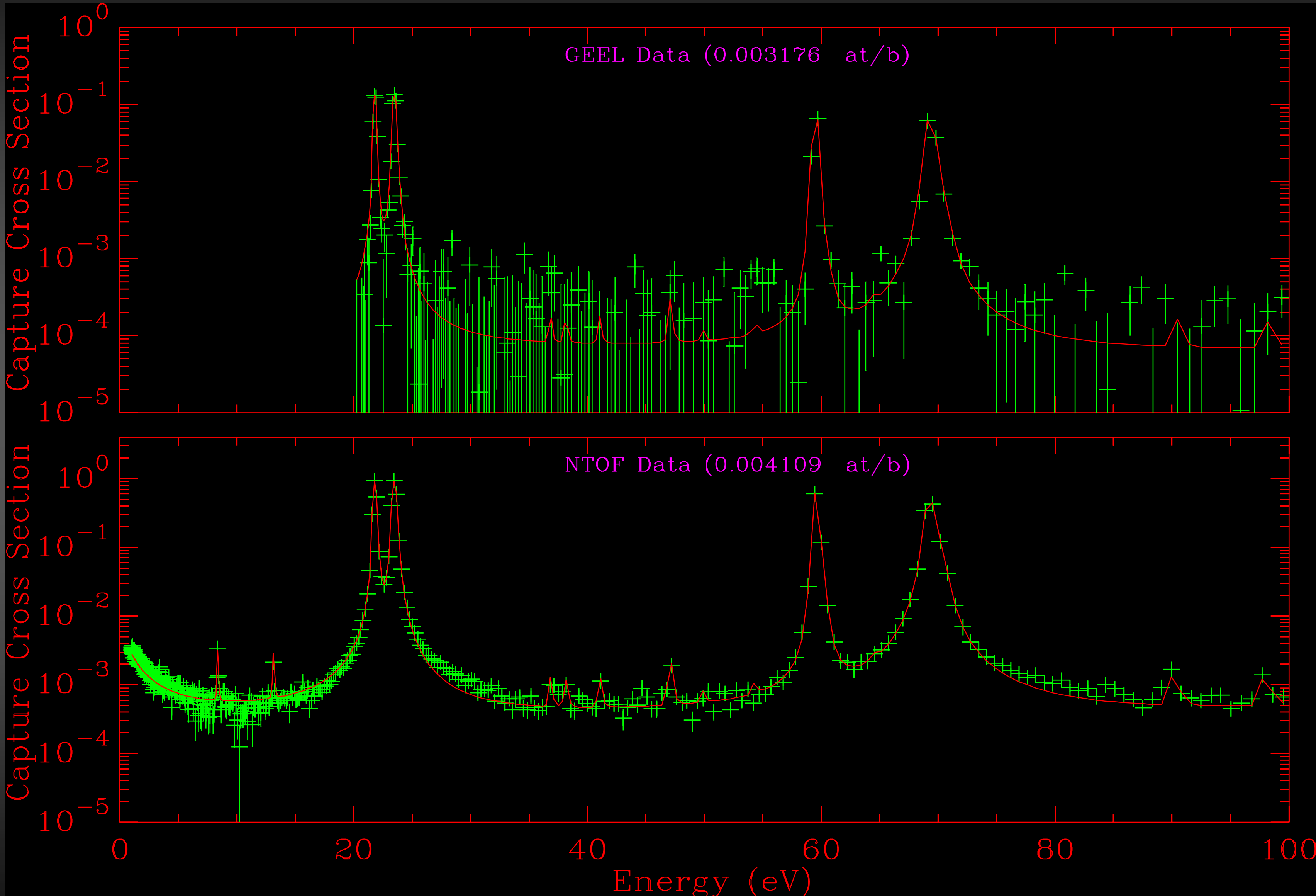


Performance Report
CERN-INTC-2002-037, January 2003
CERN-SL-2002-053 ECT

World scene for tof measurements

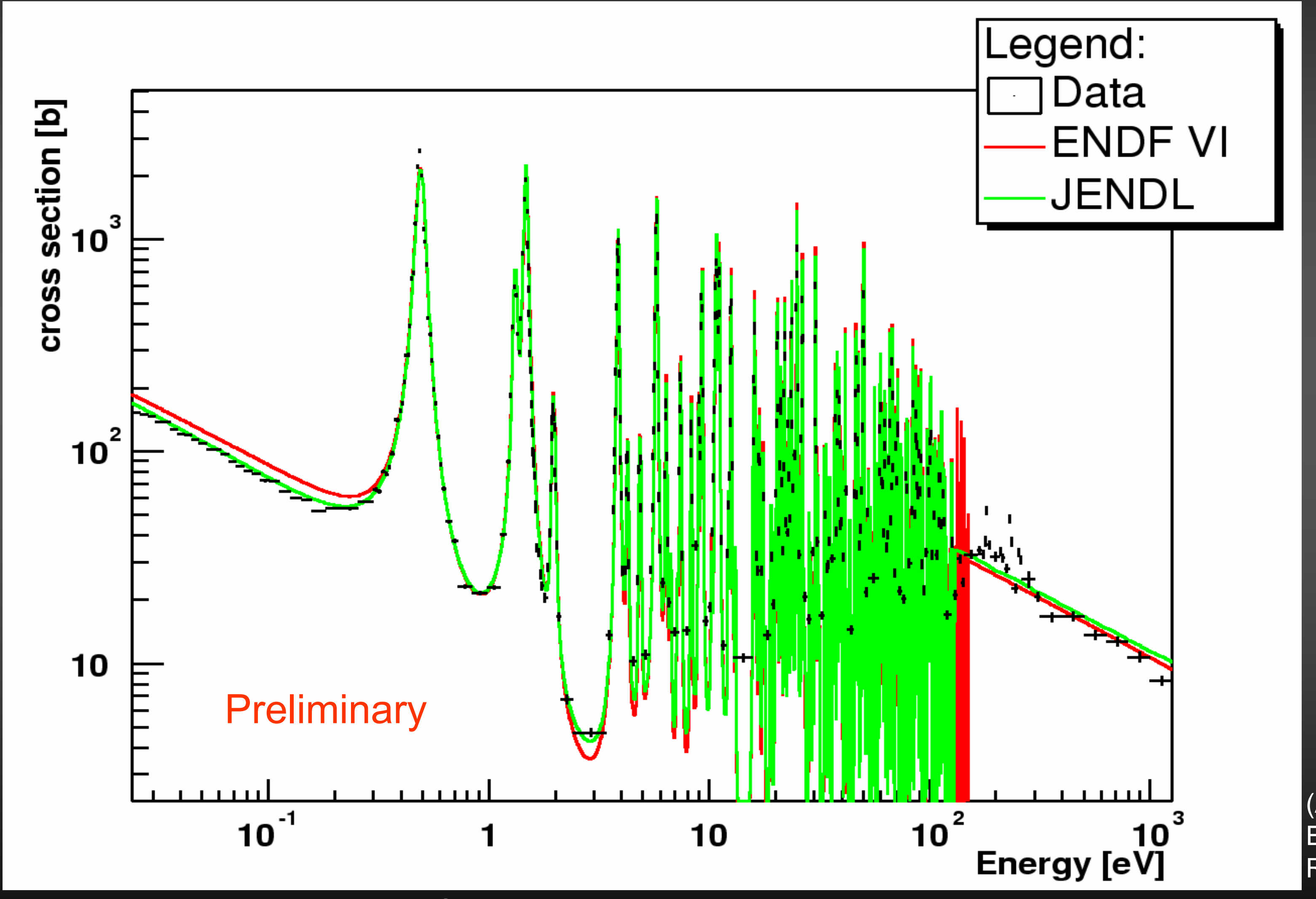
facility		driver and energy	repetition rate	n source	n energy range	flight path length
FZK TIT …	Karlsruhe Tokyo …	varii in the MeV range	MHz	$^{7}Li(p,n)$ & others	few keV up to 1 MeV monoE above	10s cm
GELINA	EC-JRC Geel	electron linac 150 MeV	800 Hz	photo-n photo-f	10 meV – 20 MeV	10m to 400m
LANSCE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

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

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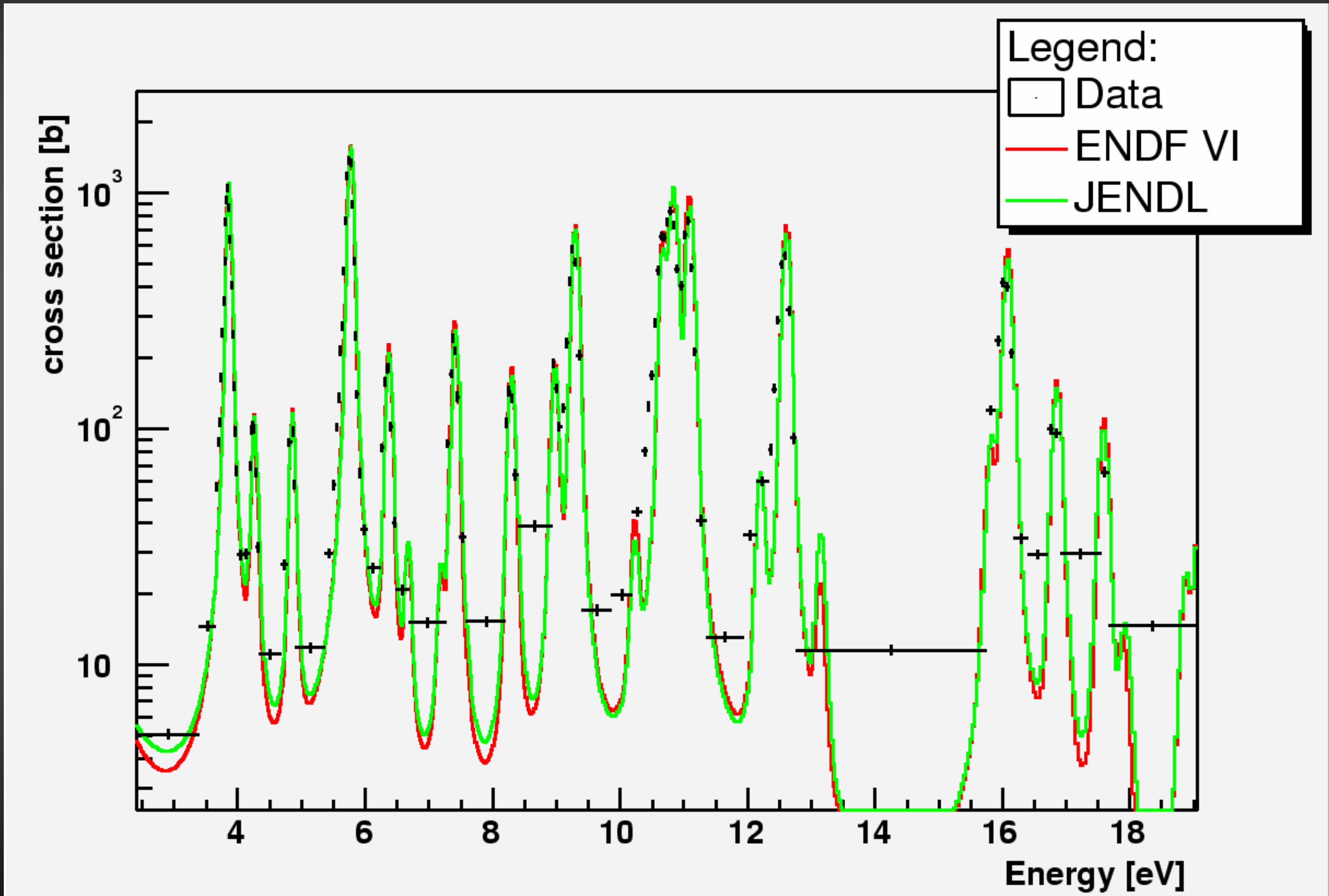

(Analysis by E.I. Esch and R. Reifarth)

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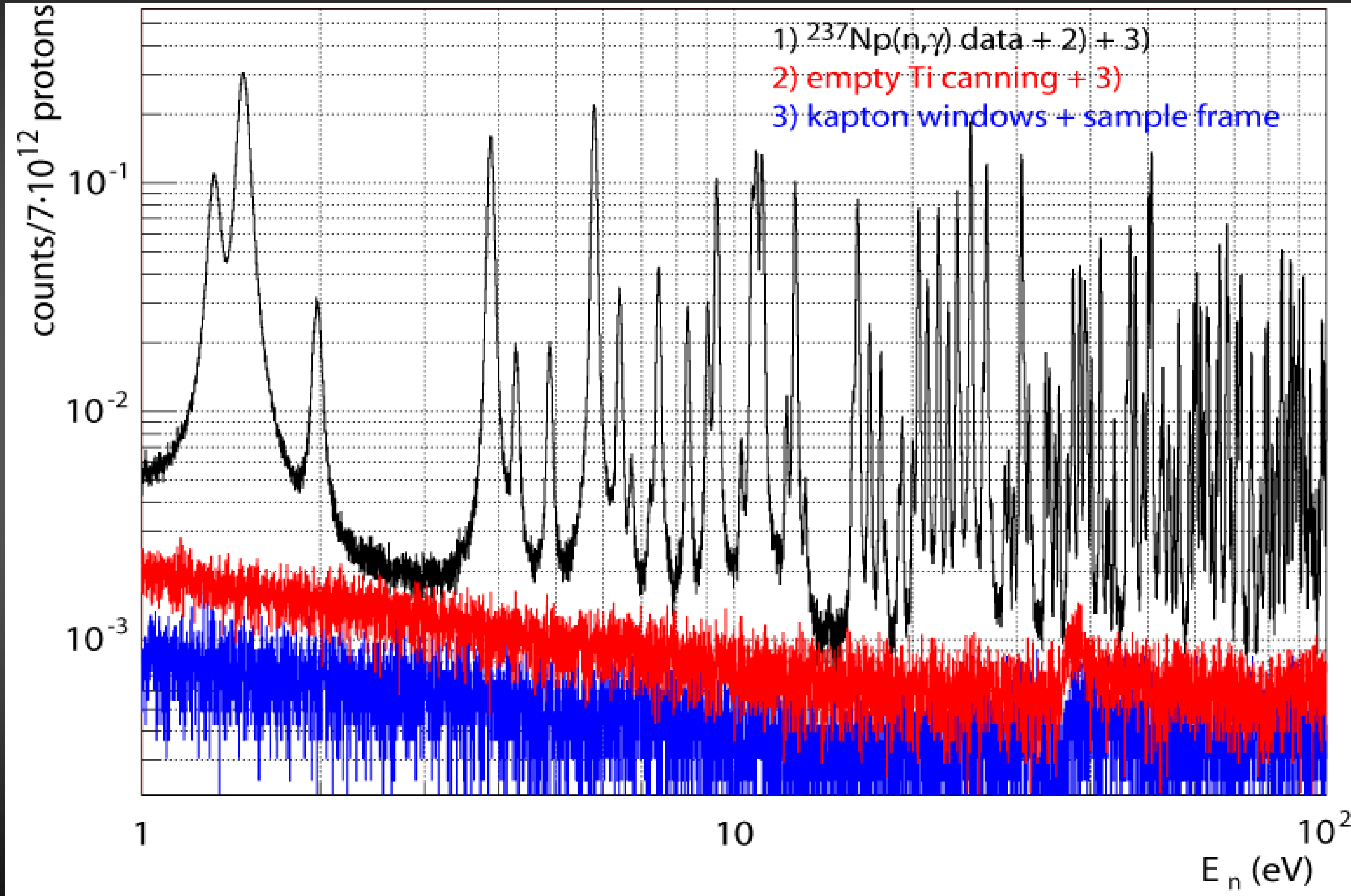
$^{237}Np(n,\gamma)$ at n_TOF



Uniqueness of n_TOF

Combines:

- Highest instantaneous intensity neutron source worldwide at a 185 m flight path used in TOF cross section measurements

- Excellent energy resolution

- Innovative data Acquisition system based on flash ADCs (2 Tbytes/day via CERN CASTOR system)

- Latest generation of detectors and beam monitors:

    - (n,γ): ultra low neutron sensitivity C_6D_6 detectors, high performance Total Absorption Calorimeter

    - (n,f): Low background PPAC setup, FIC detector

    - Beam monitors: redundant ^{197}Au(n,γ), ^{6}Li(n,α)t, ^{235}U(n,f) monitors

- Fully characterized facility for neutron cross section measurements

Best facility for: radioactive, rare, low cross section samples and high energy measurements

Objectives of the activity at n_TOF

1. Cross sections relevant for Nuclear Astrophysics

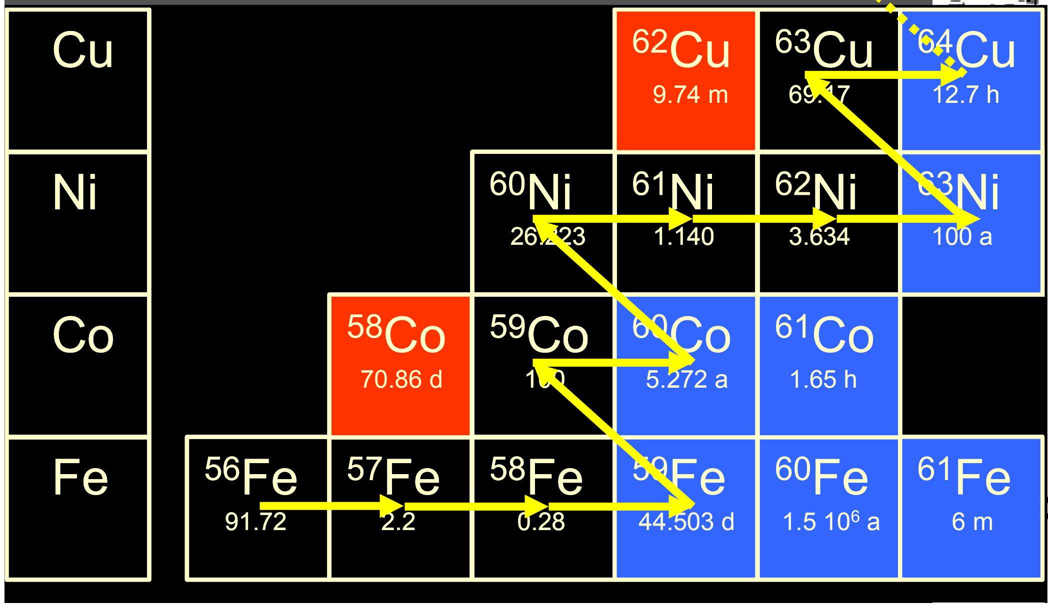
2. Measurements of neutron cross sections relevant for Nuclear Waste Transmutation and related Nuclear Technologies

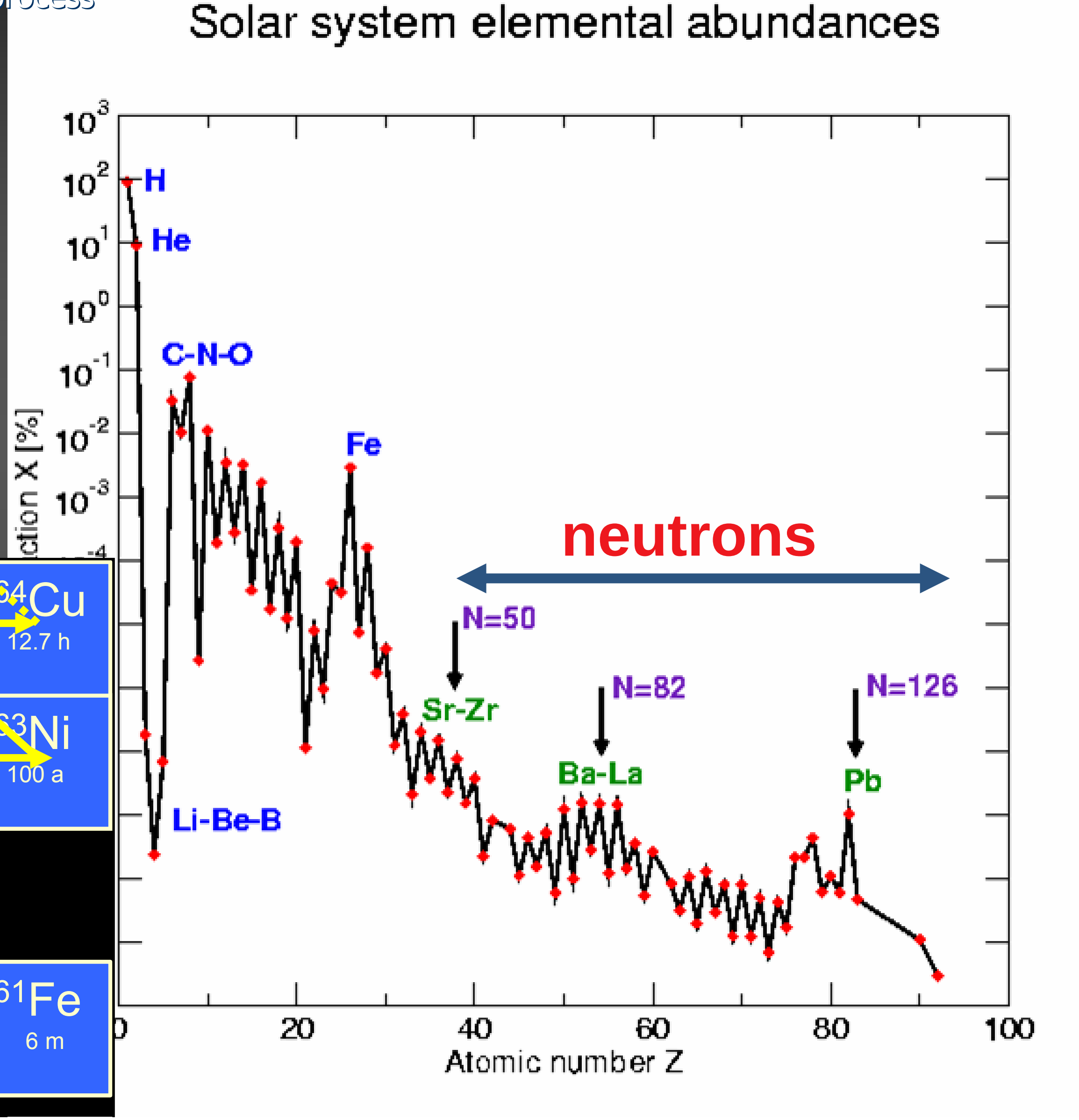
3. Neutrons as probes for fundamental Nuclear Physics

Nucleosynthesis: the s-process

- ½ of the elements above Fe are produced by the s-process
- The astrophysical sites of the s-process are:
  - He burning in intermediate/massive stars
  - Low-mass AGB's
- There exists a direct correlation between the neutron capture cross section and the abundance ($\sigma(n,\gamma) \cdot N = const.$)
- The neutron capture cross sections are key ingredients for s-process nucleosynthesis

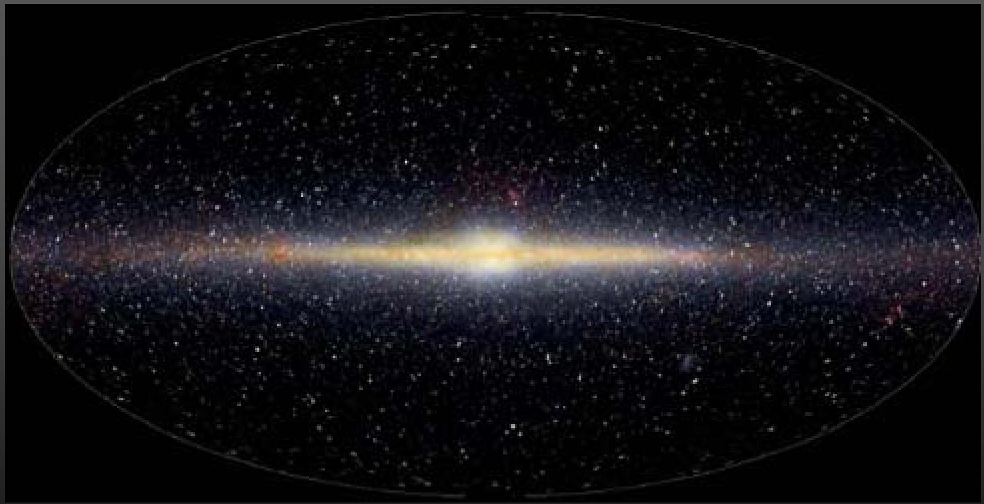
The canonical s-process

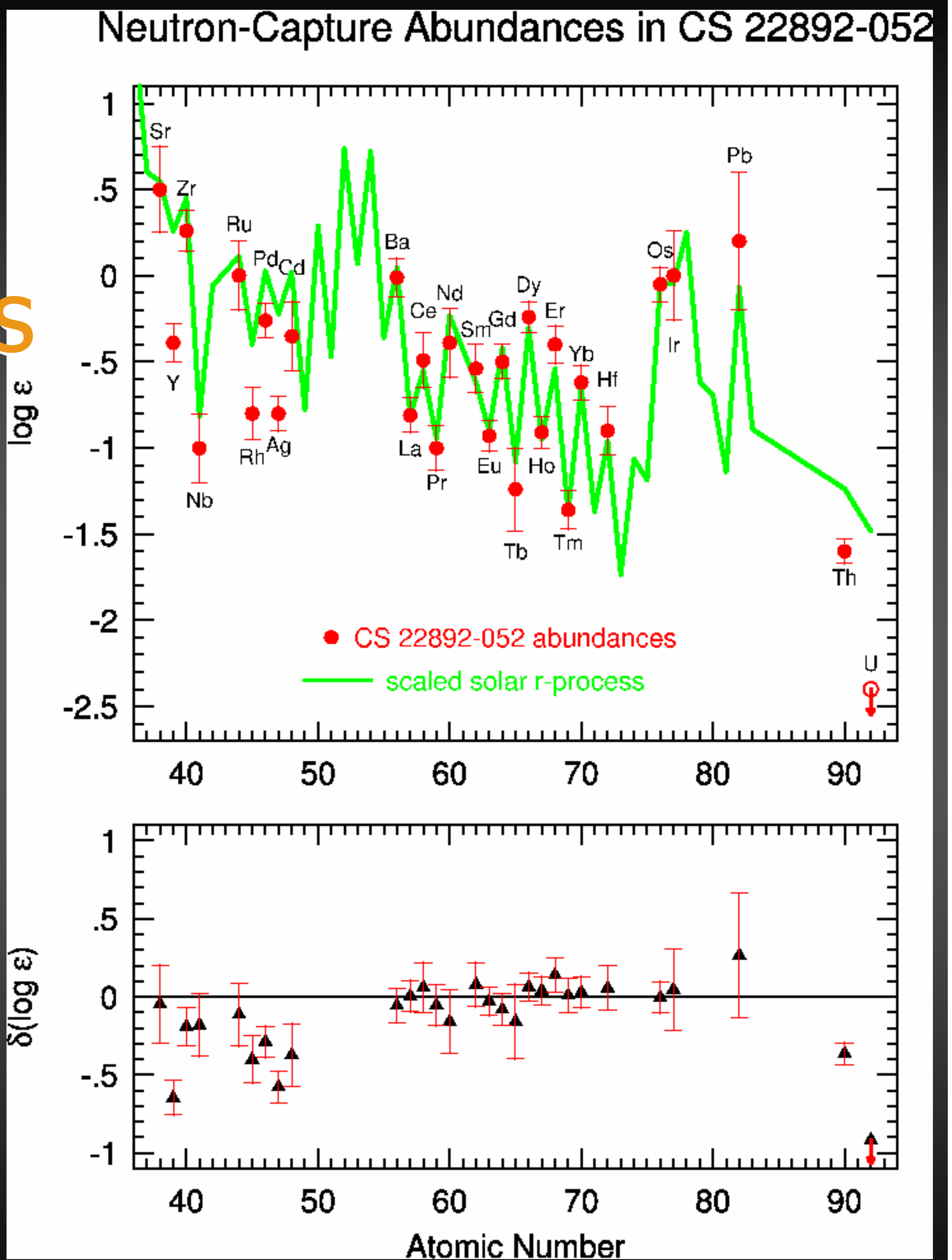




Nucleosynthesis:
the s-process & the r-process residuals

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





Objectives of the activity at n_TOF

1. Cross sections relevant for Nuclear Astrophysics

2. Measurements of neutron cross sections relevant for Nuclear Waste Transmutation and related Nuclear Technologies(*)

3. Neutrons as probes for fundamental Nuclear Physics

(*) contract with the EC within the FP5

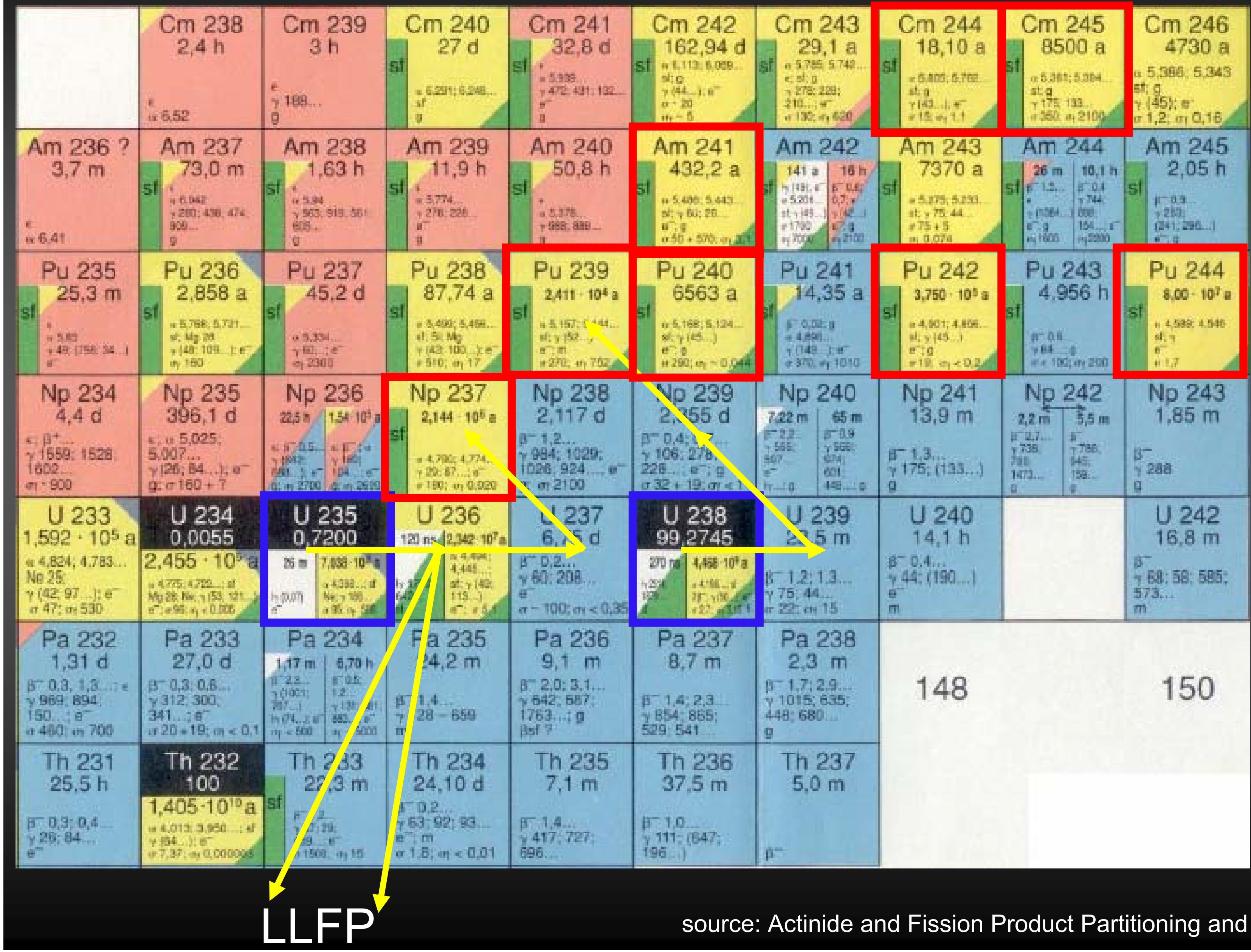
Sustainable nuclear energy or its phase-out ?

Expansion of electricity needs (in particular in developing countries)
&
Concern about CO_2 emission level

The nuclear power option will only be exercised, however, if the technology demonstrates better economics, improved safety, successful waste management, and low proliferation risk, and if public policies place a significant value on electricity production that does not produce CO_2.
(*from the MIT report, 2003*)

Nuclear waste

(1000 MWe LWR)



^{244}Cm
1.5 Kg/yr

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

^{239}Pu: 125 Kg/yr
(plus: $^{240,242,244}Pu$)

^{237}Np: 16 Kg/yr

LLFP
76.2 Kg/yr

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

Th/U fuel cycle

www.cern.ch/n_TOF

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

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

^{232}Th

^{209}Bi

^{237}Np

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

1. Cross sections relevant for Nuclear Astrophysics

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n_TOF experiments 2002-4

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

☐ data analysis completed (14/36)

NOTE: TAC started operation in July 2004

n_TOF publications	
Full papers	: 13 (+4 in preparation)
Conference Proceedings	: 31
Documents Total	: 107

All docs on: www.cern.ch/n_TOF

n_TOF experiments

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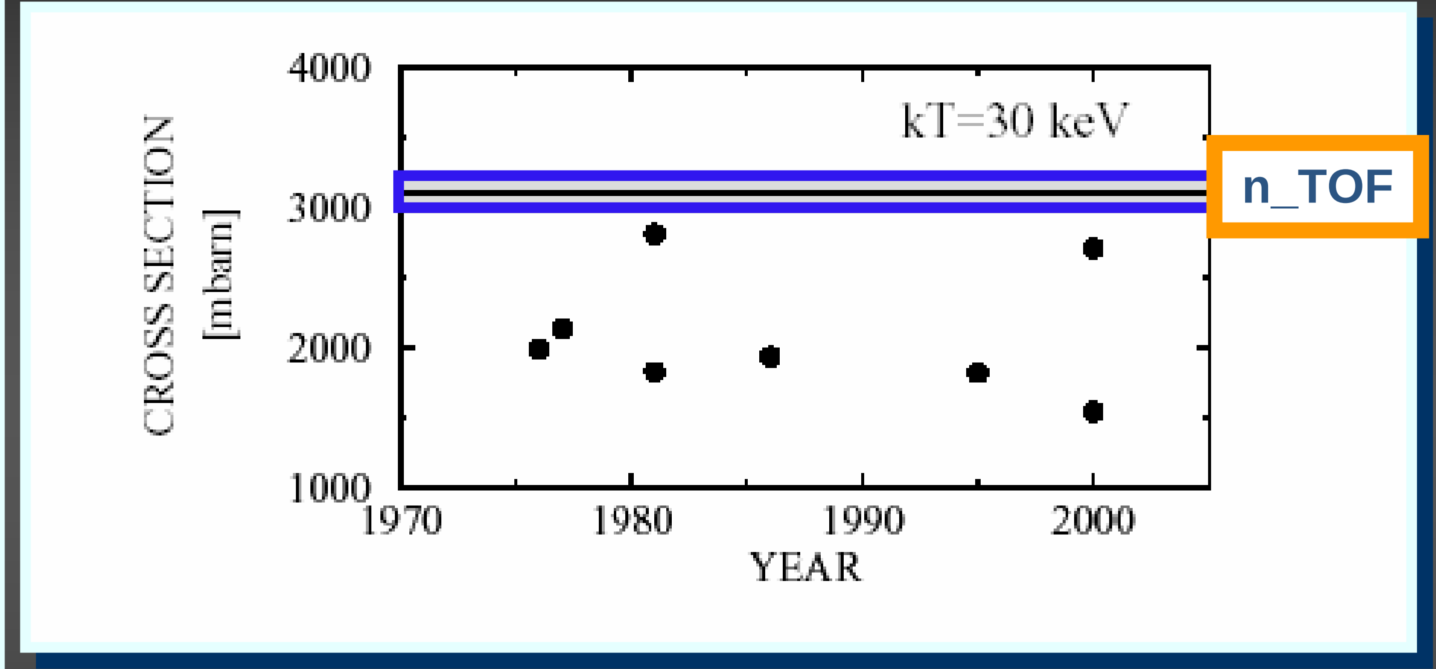
U Abbondanno et al. - The n_TOF Collaboration
Phys. Rev. Lett. **93** (2004), 161103



MACS-30 = 3100 ± 160 mb

$\langle D_0 \rangle = 1.48 \pm 0.04$ eV, $S_0 = (3.87 \pm 0.20)\times 10^{-4}$

n_TOF experiments

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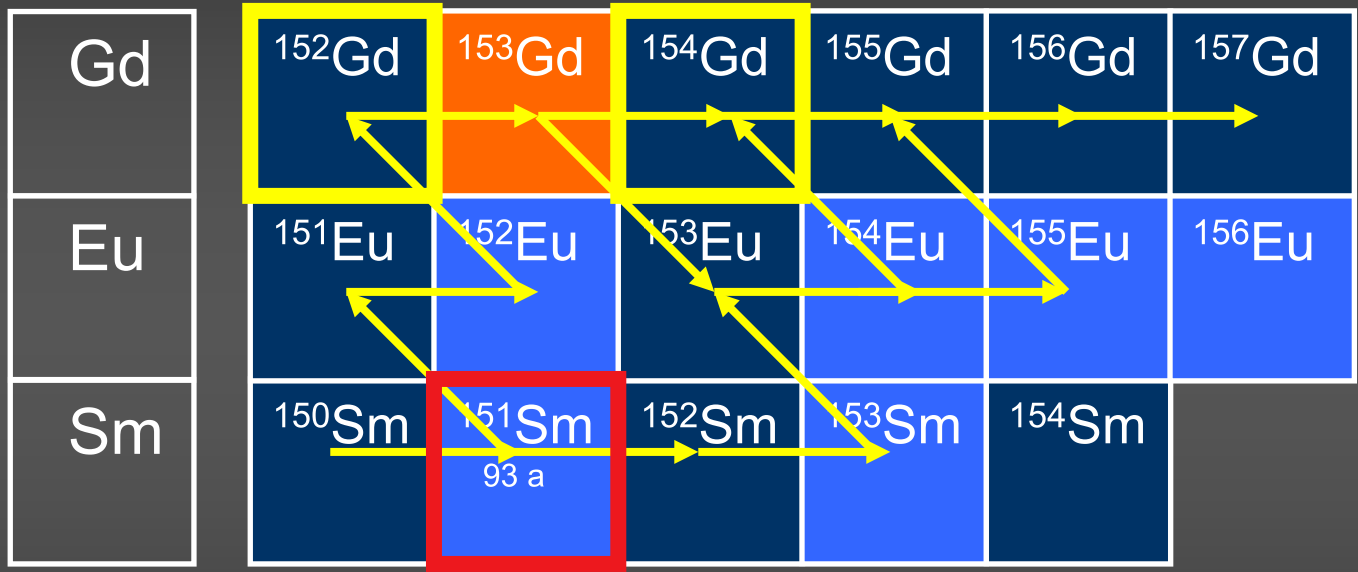

- $T_8 > 4$ using the "classical" s-process model
- from AGB modeling: 71% of ^{152}Gd

Present main uncertainty: $\lambda_\beta(T)$ of ^{151}Sm

The n_TOF Collaboration

n_TOF experiments

Capture

^{151}Sm

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

^{232}Th

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

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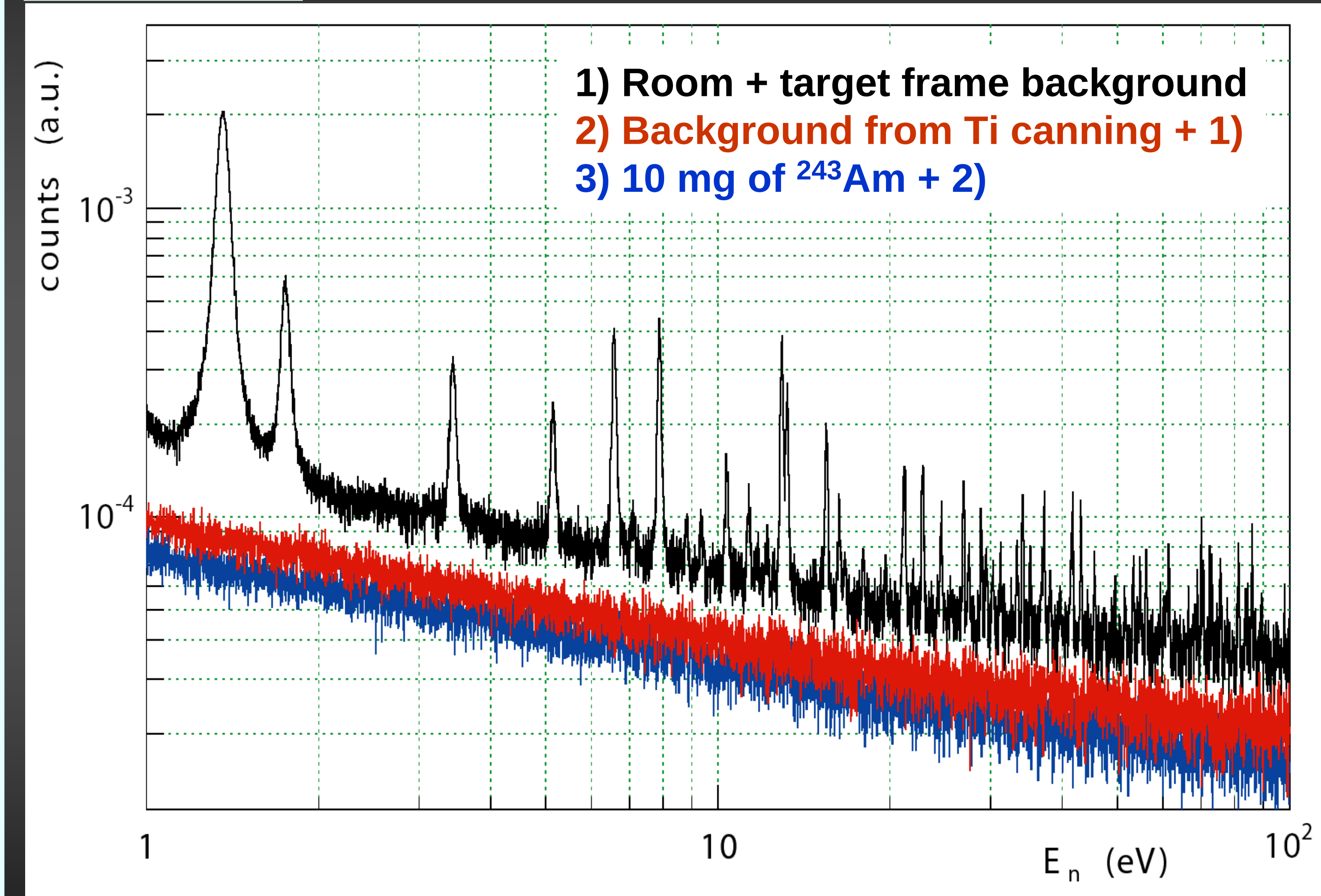
$^{241,243}Am$, ^{245}Cm

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

Measurement performed in September 2004



First $^{243}Am(n,\gamma)$ measurement EVER

sample: 10 mg, 185 MBq activity

The n_TOF Collaboration

Capture

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^{232}Th

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^{232}Th

^{209}Bi

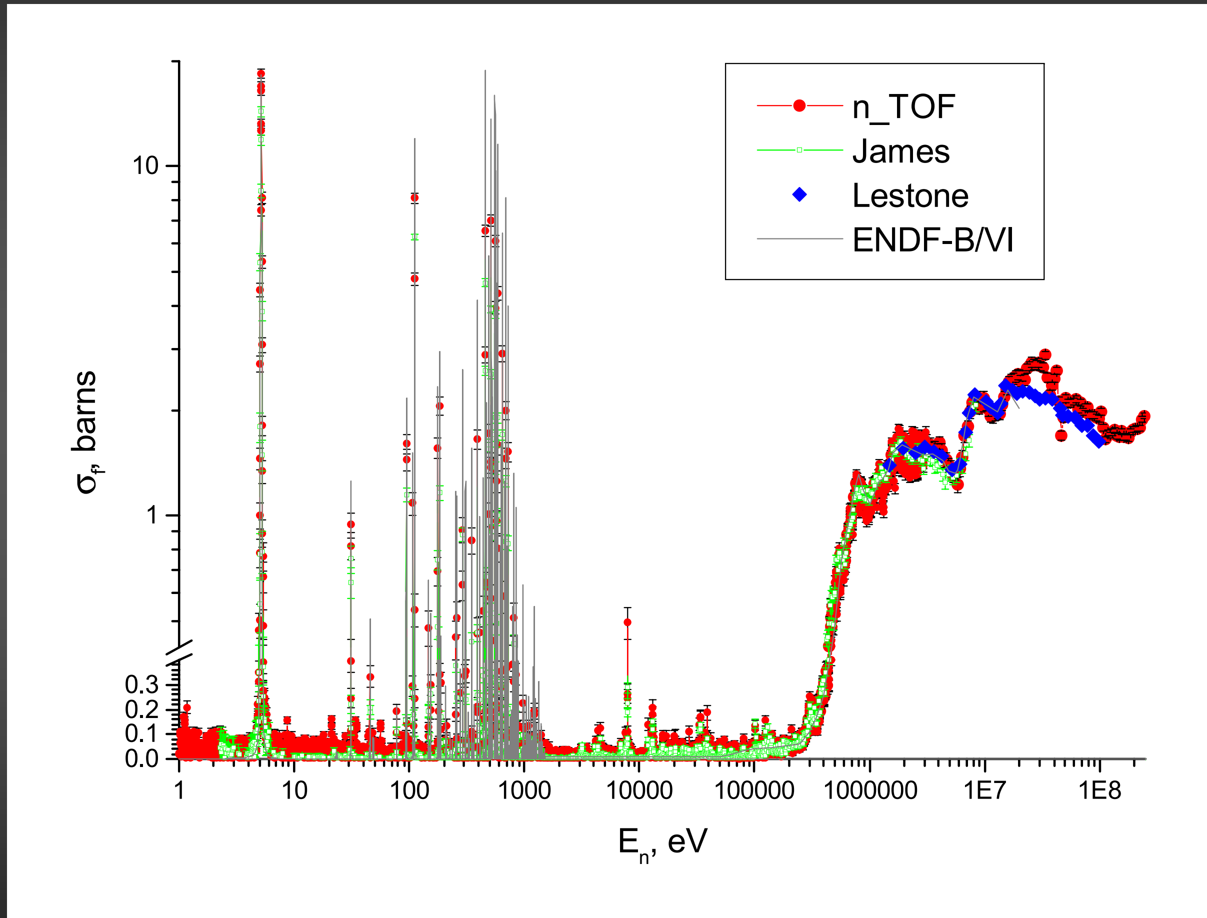
^{237}Np

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

FIC-1 (2003)

Capture

^{151}Sm

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^{232}Th

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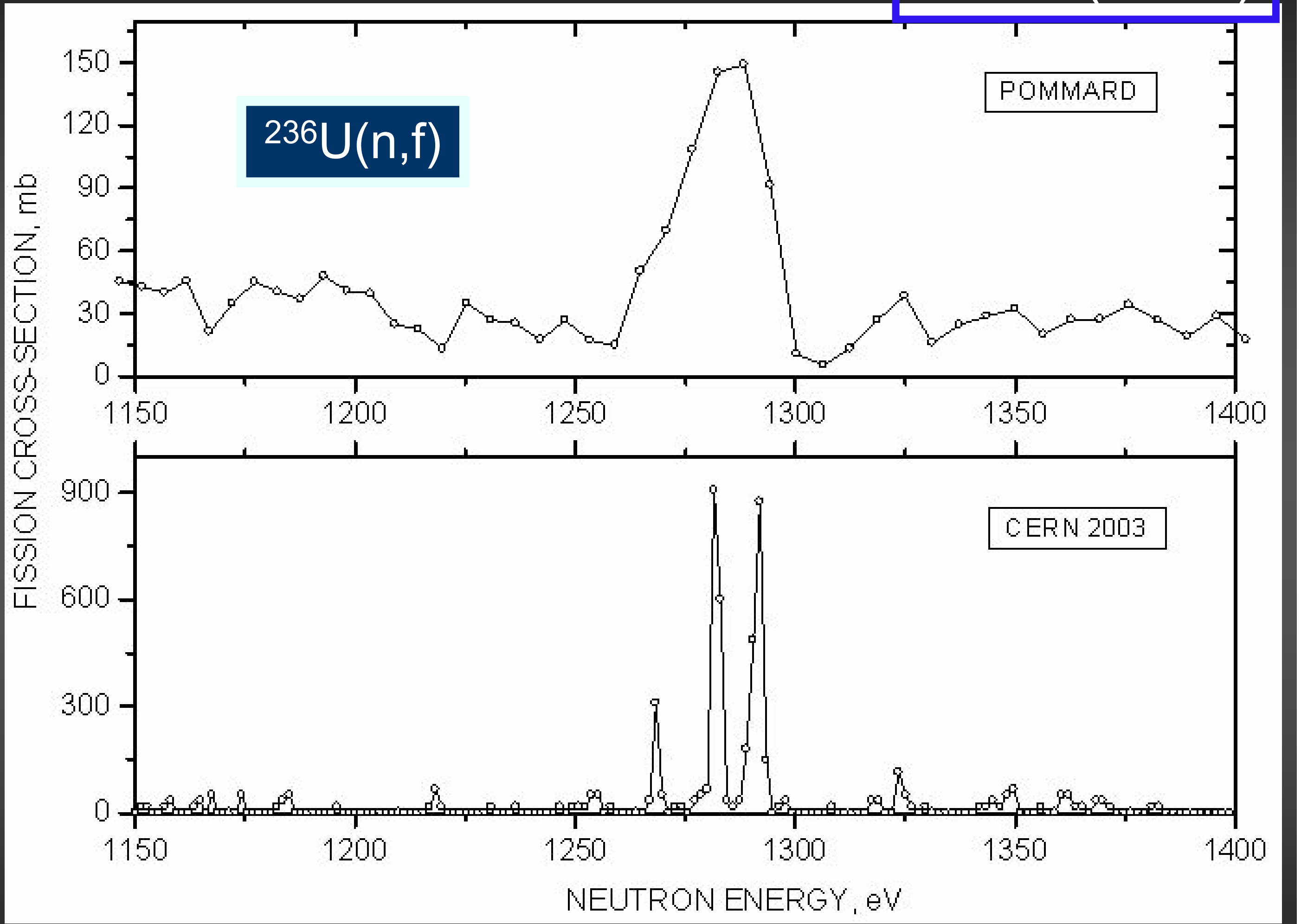

The very high resolution of the n_TOF installation allows for studing fine neutron resonance structure

n_TOF experiments

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^{151}Sm

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

^{232}Th

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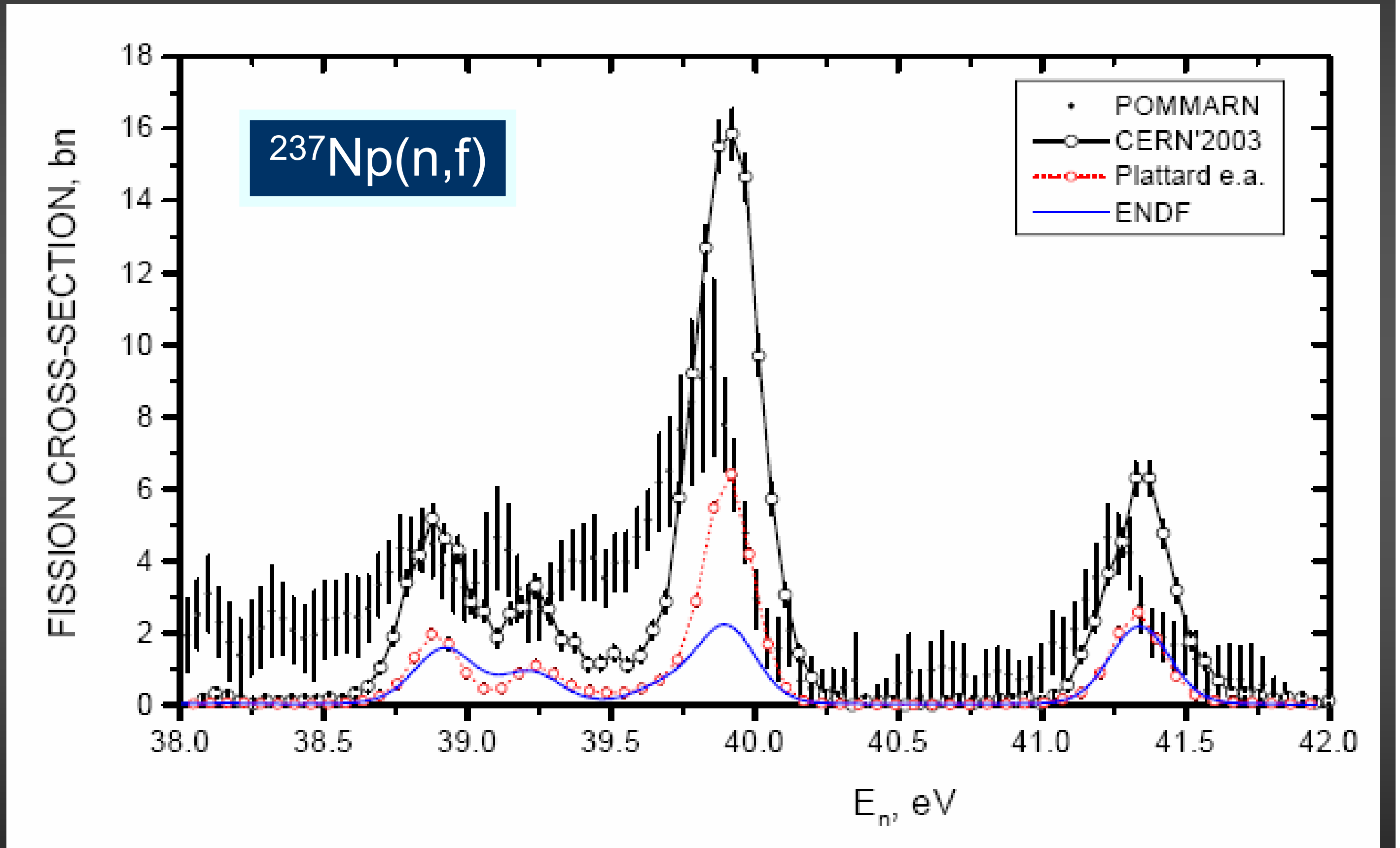


The very high resolution of the n_TOF installation allows for studing fine neutron resonance structure

n_TOF-Ph2 objectives

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

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) ^{63}Ni, ^{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

In 2006 : (a) all stable Ni isotopes + ^{63}Ni
(b) ^{236}U, ^{238}U

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

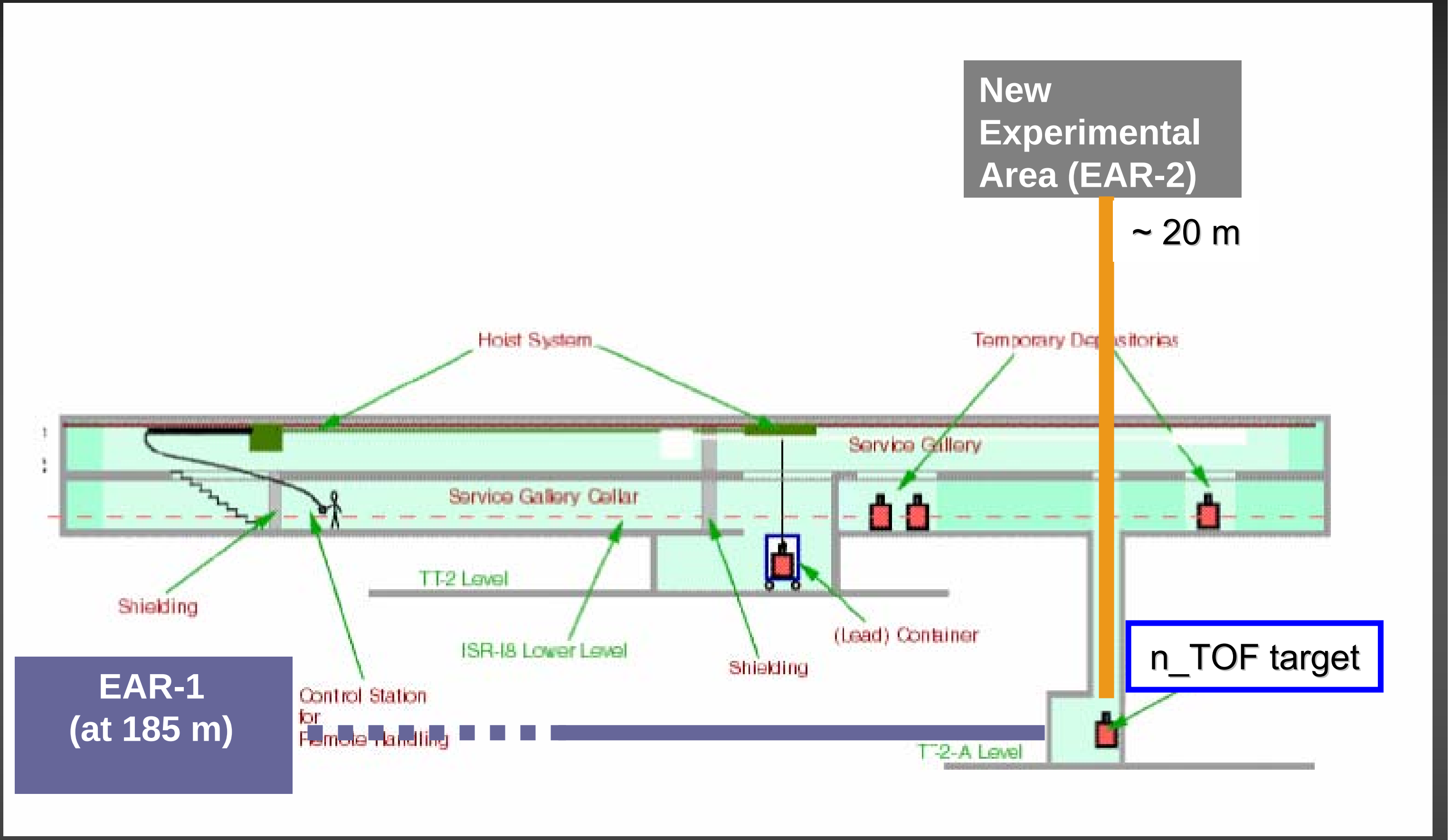
n_TOF (Phase-1) financial scheme

Investments		
Installation	2.3 MEUR	CERN
Experimental equipments	2.0 MEUR	Part of a 2.4 MEUR from a FP5 EC Project (total investment: 6.4 MEUR)
Maintenance & Operation		
M&O costs	300 kCHF/yr 300 kCHF/yr	CERN The n_TOF Collaboration
Personnel	2 FTE + 0.5 Admin 5 people for shifts	CERN The n_TOF Collaboration

n_TOF-Ph2: basic startup funds

In FP6		
NUDATRA	Part of the EUROTRANS IP	
EFNUDAT (facilities network)	Just submitted	
Maintenance & Operation		
M&O costs	300 kCHF/yr 300 kCHF/yr	CERN The n_TOF Collaboration
Personnel	2 FTE + 0.5 Admin 5 people for shifts	CERN The n_TOF Collaboration

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 !**
(a factor of 100 ONLY from flux boost)

→ problems of sample production and safety issues relaxed

Road-map towards n_TOF-Ph2

- Letter of Intent
  - signed by 24 research labs of the n_TOF Collaboration + 4 newcomers (January 2005)
- n_TOF-Ph2 scientific proposal
  - the n_TOF 1-2-3 document (September 2004)
  - CB meeting of February 10-11, 2005
  - the n_BANT Symposium (March 2005)
  - Proposal presented to the INTC (May 2005)
  - NuPAC (Nuclear Physics and Astrophysics at CERN), October 10-12, 2005
- The n_TOF-Ph2 MoU – end of 2005/beginning of 2006

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]

41 Research Groups
120 researchers

www.cern.ch/n_TOF

Conclusions

- n_TOF is a facility with unique characteristics for x-section measurements on:

  radioactive samples
  rare isotopes
  isotopes with small cross sections
  in wide energy range (in particular at high energies)

- n_TOF just started to operate, providing best world results in several cases

- Still large campaigns are needed to exploit its capabilities in the present configuration

- A new plan for measurements has been elaborated for 2006 and beyond

- The additional beam line (EAR-2) could boost the facility performances much beyond any presently available installations

The End

Capture studies

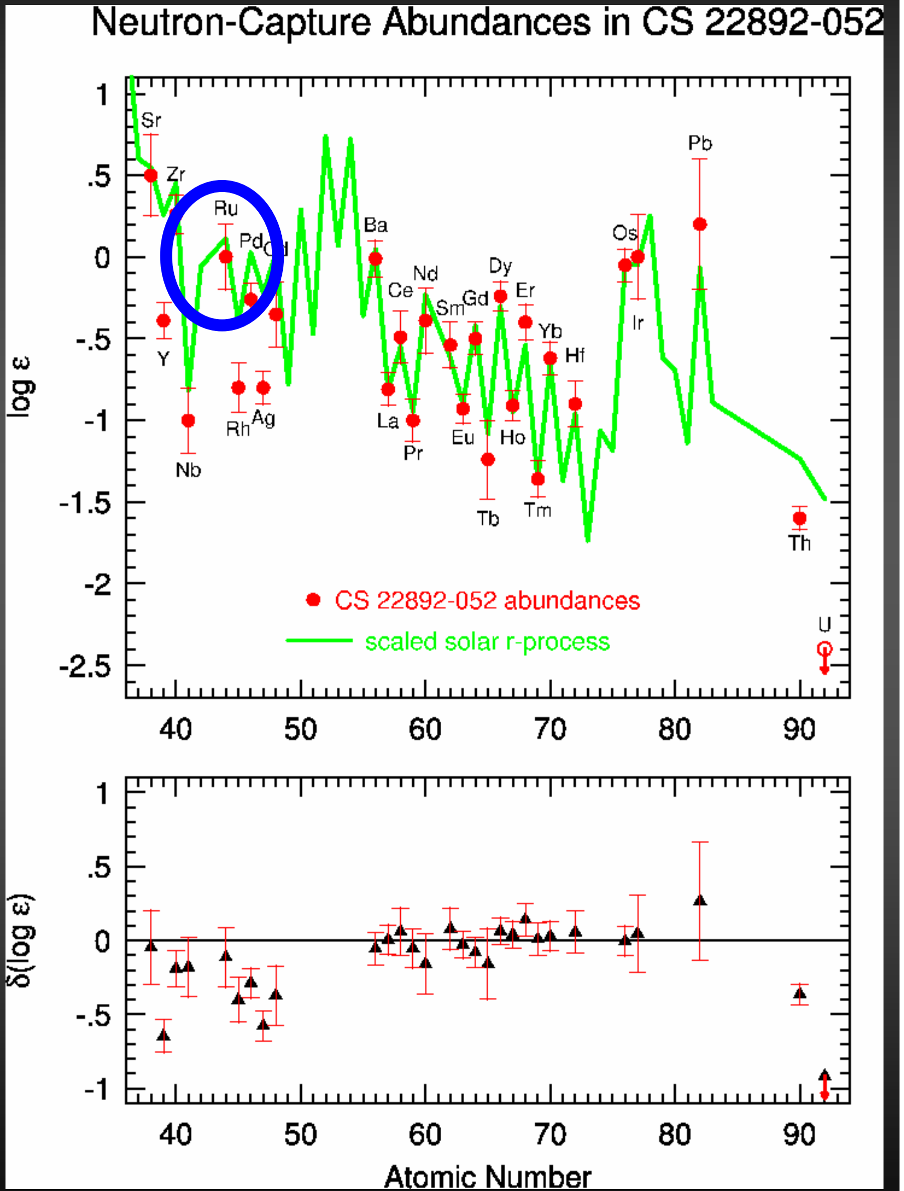
Capture studies: Mo, Ru, and Pd

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.

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

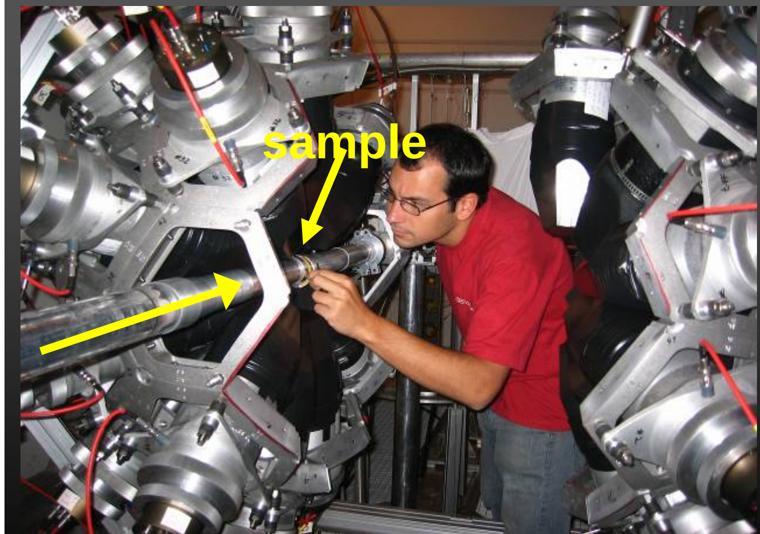


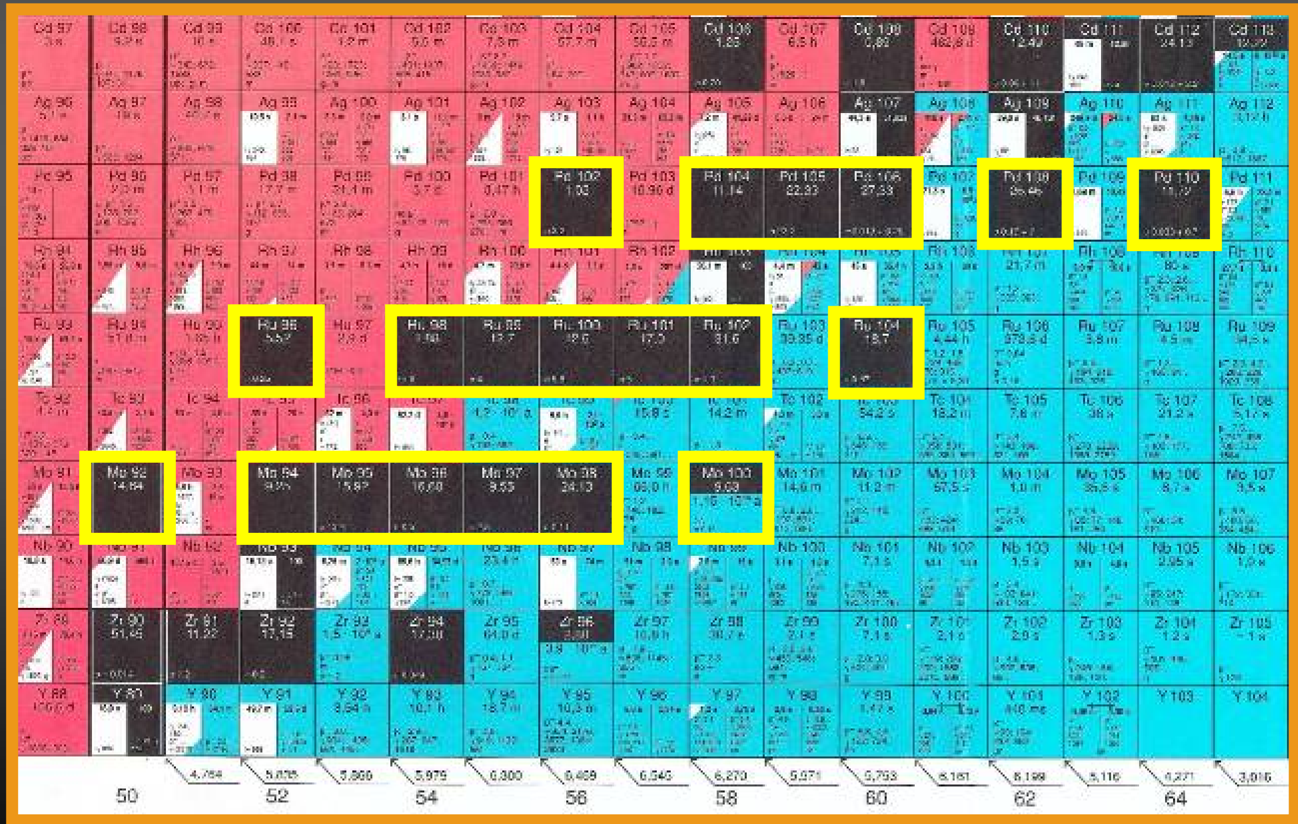
Capture studies: Mo, Ru, and Pd

- 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)

<< back

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





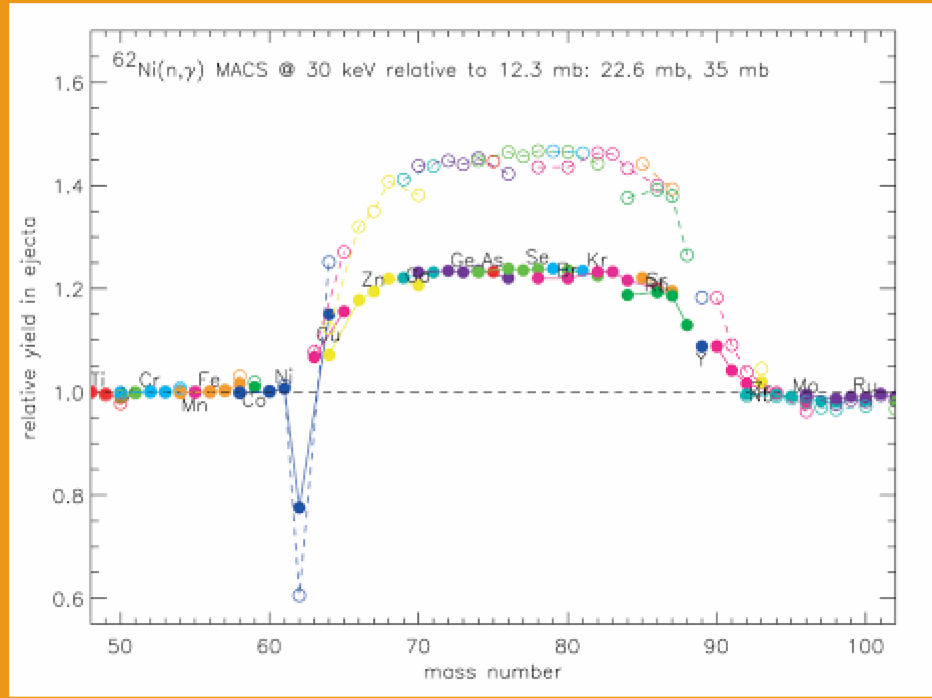
Capture studies: Fe, Ni, Zn and Se

Motivations:

• Study of the weak s-process component (nucleosynthesis up to A ~ 90)

• Contribution of massive stars (core He-burning phase) to the s-process nucleosynthesis.

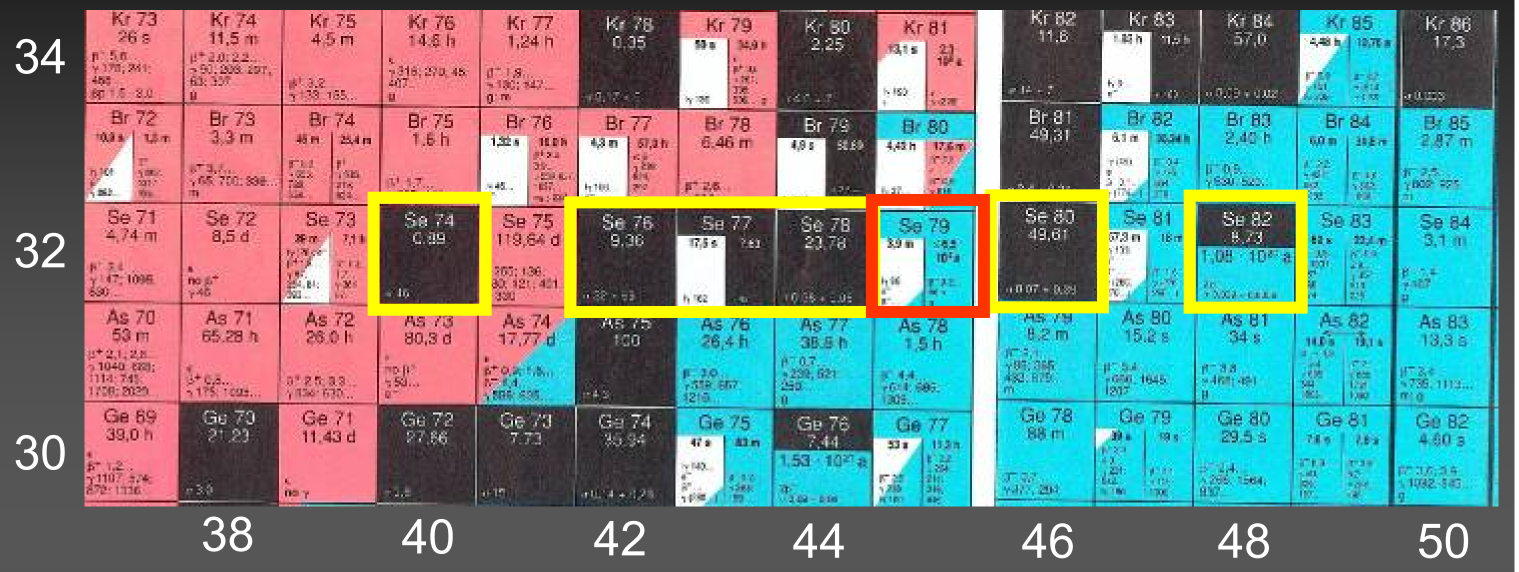
• s-process efficiency due to bottleneck cross sections (Example: ^{62}Ni)



In addition:

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

Capture studies: Fe, Ni, Zn and Se



The ^{79}Se case

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

<< back

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)

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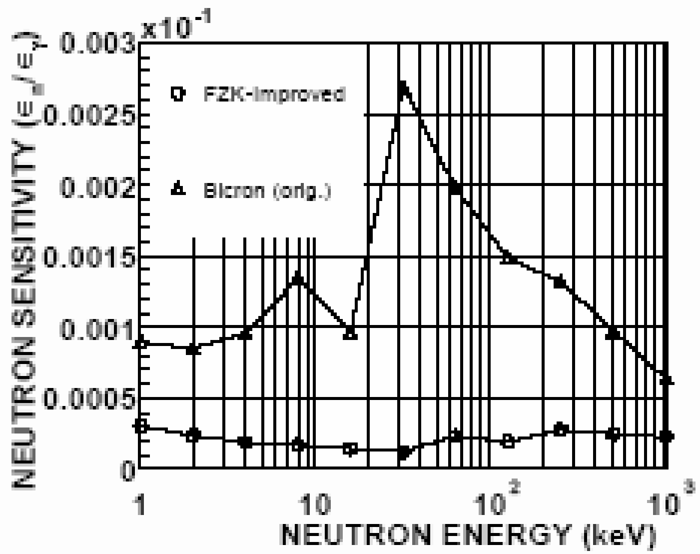
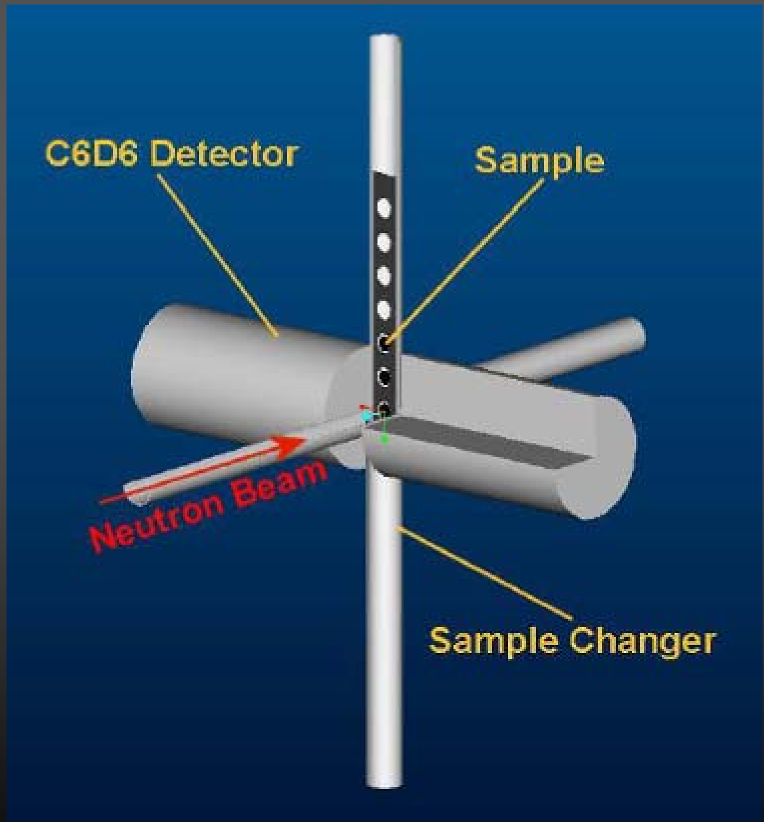
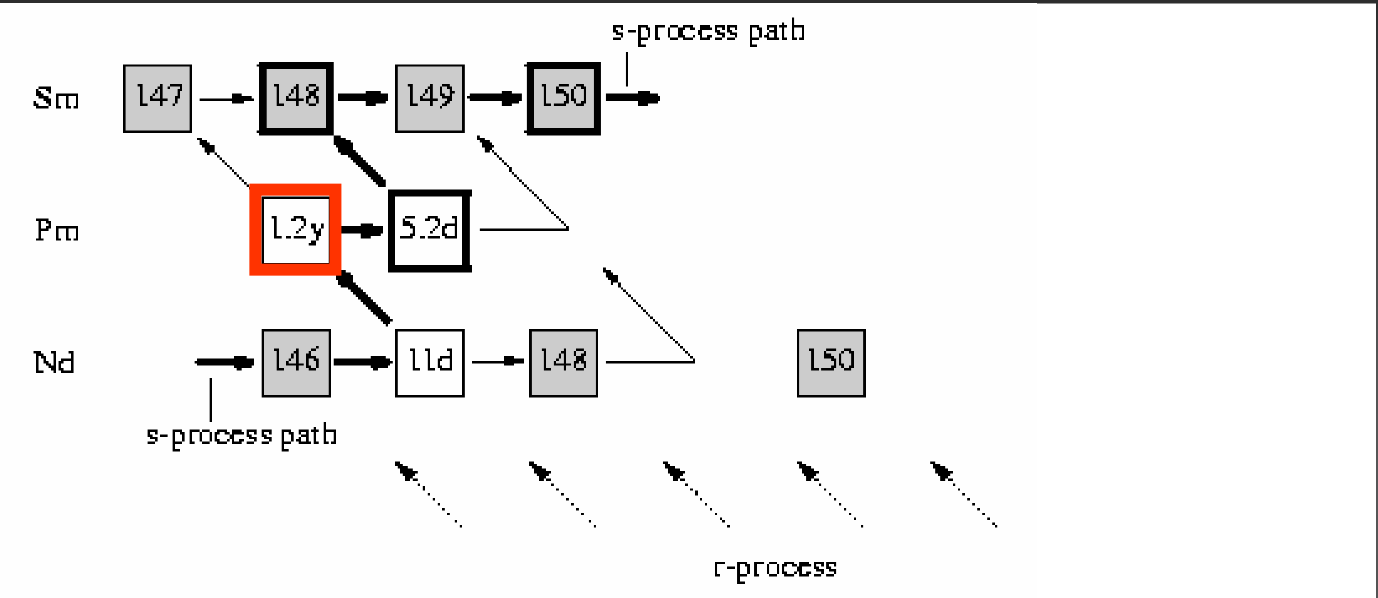




(*) except ^{79}Se

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!)

<< back

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 ^{233}Pa)

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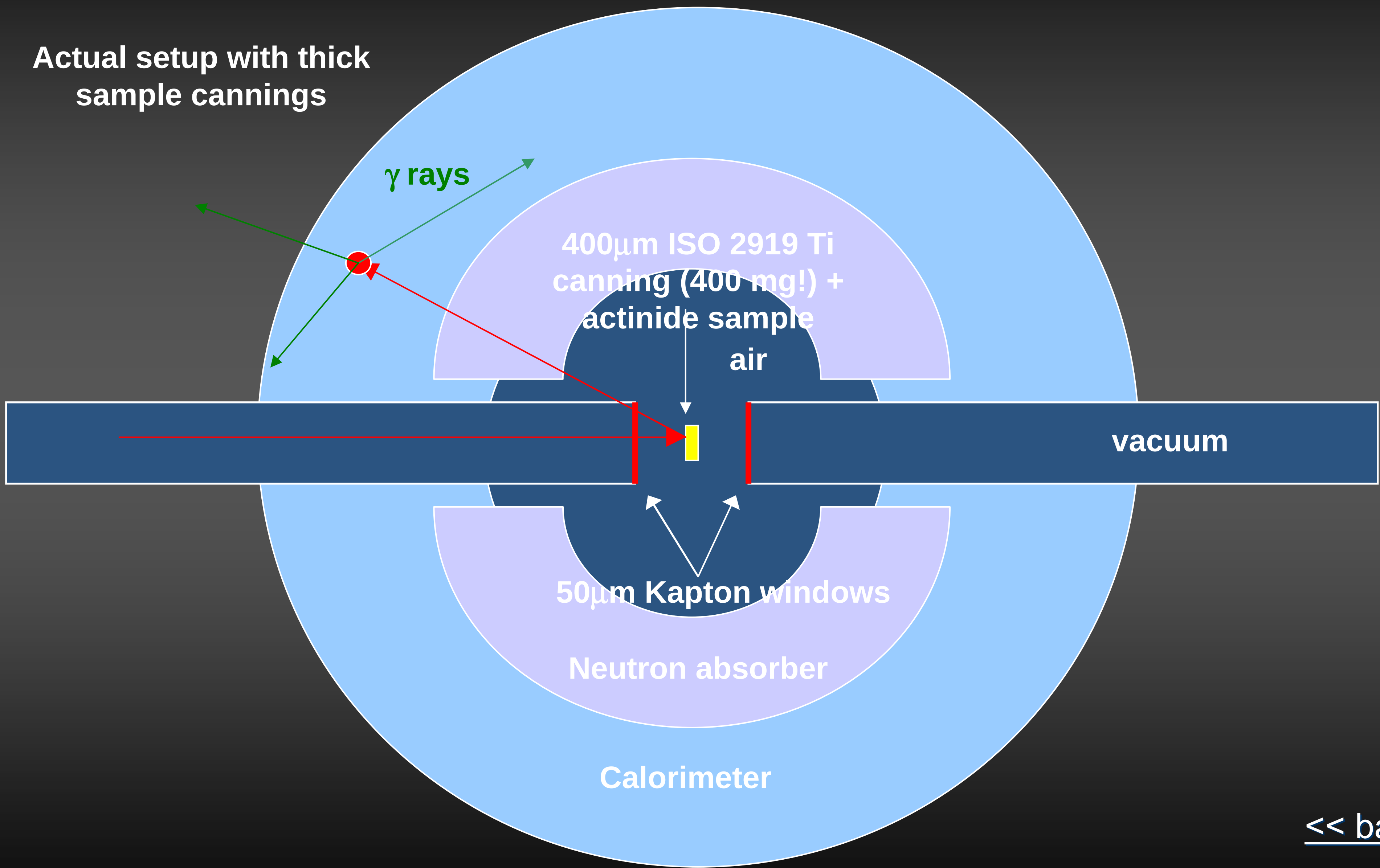
Capture studies: actual TAC setup



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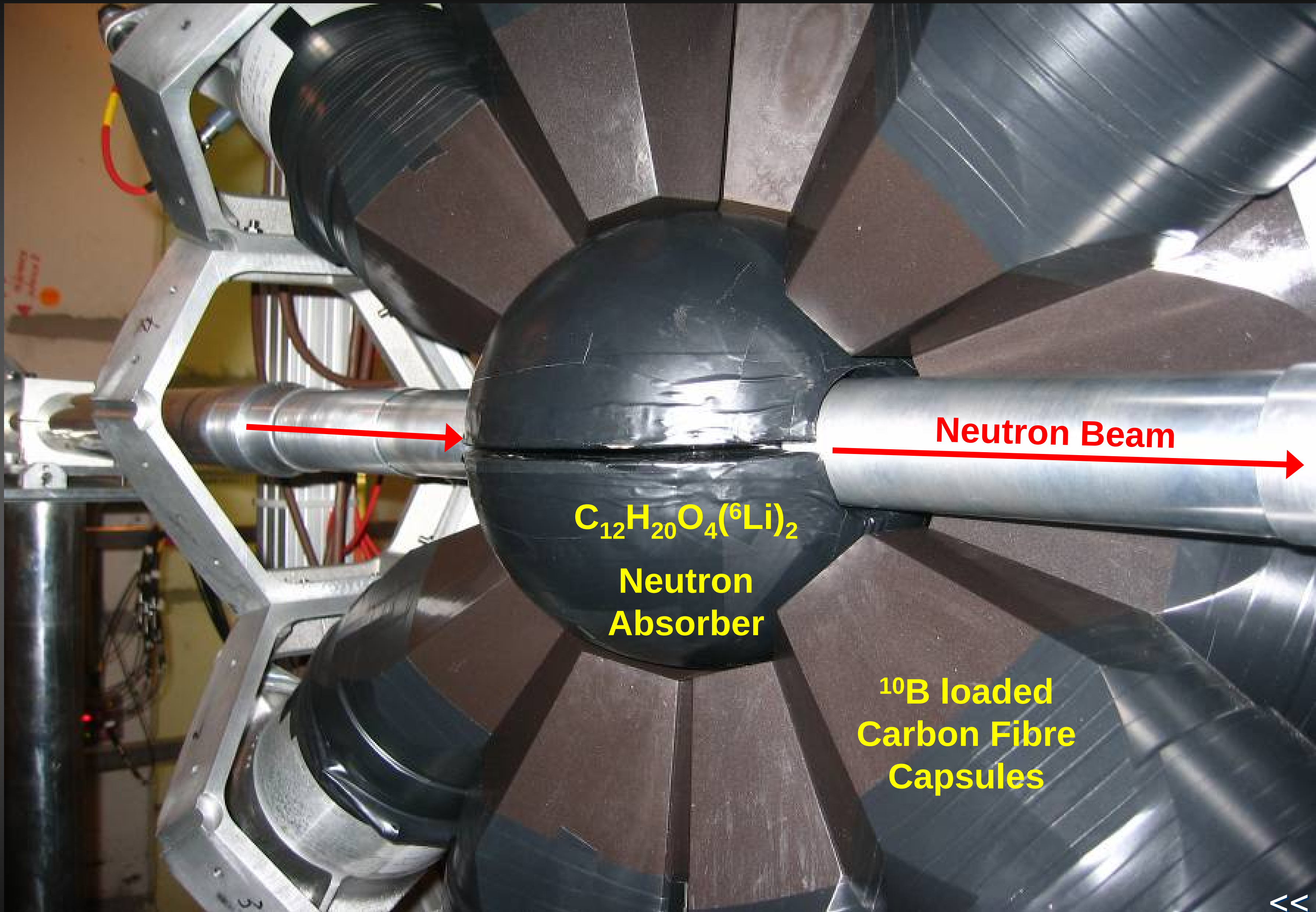
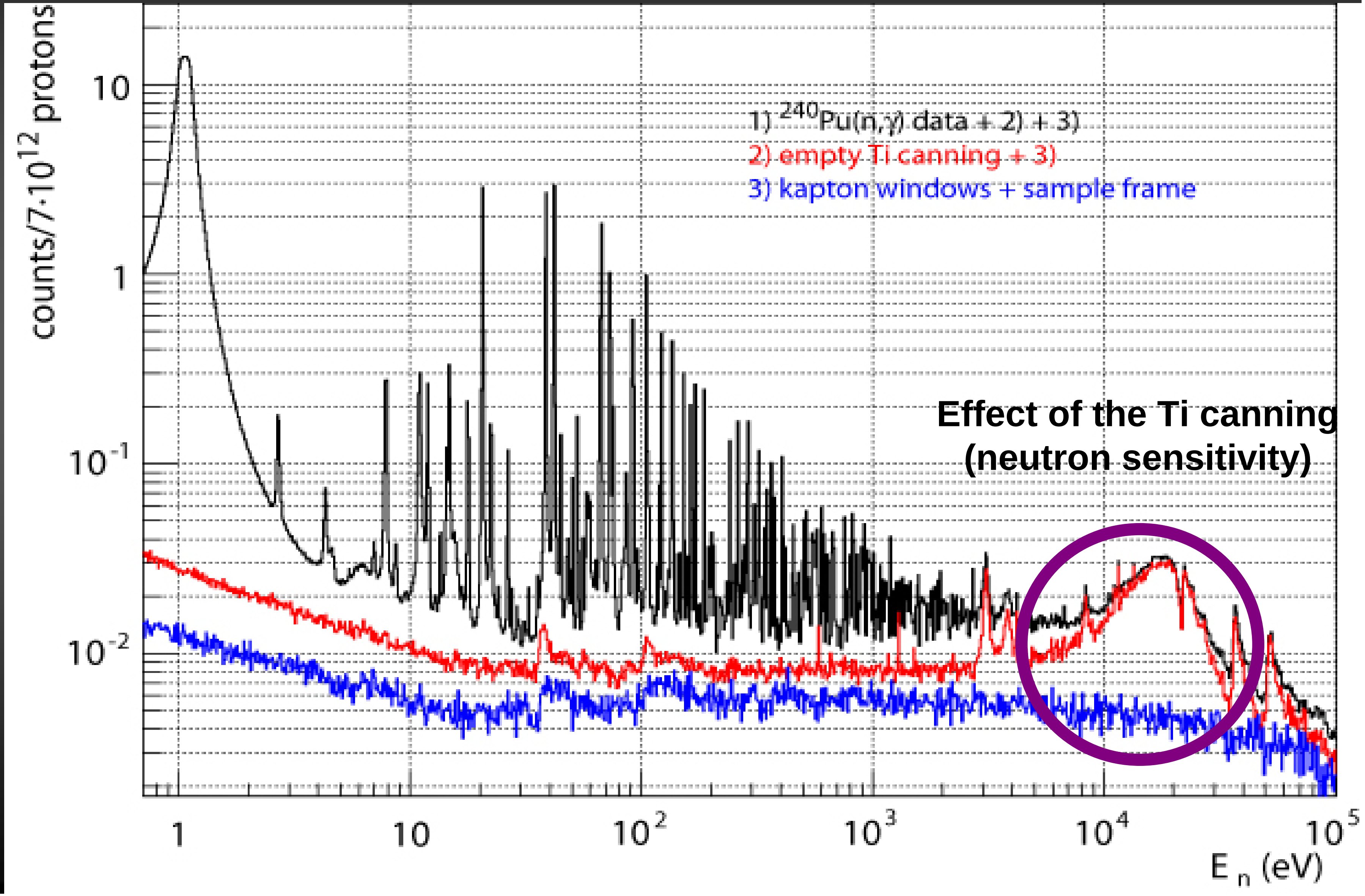
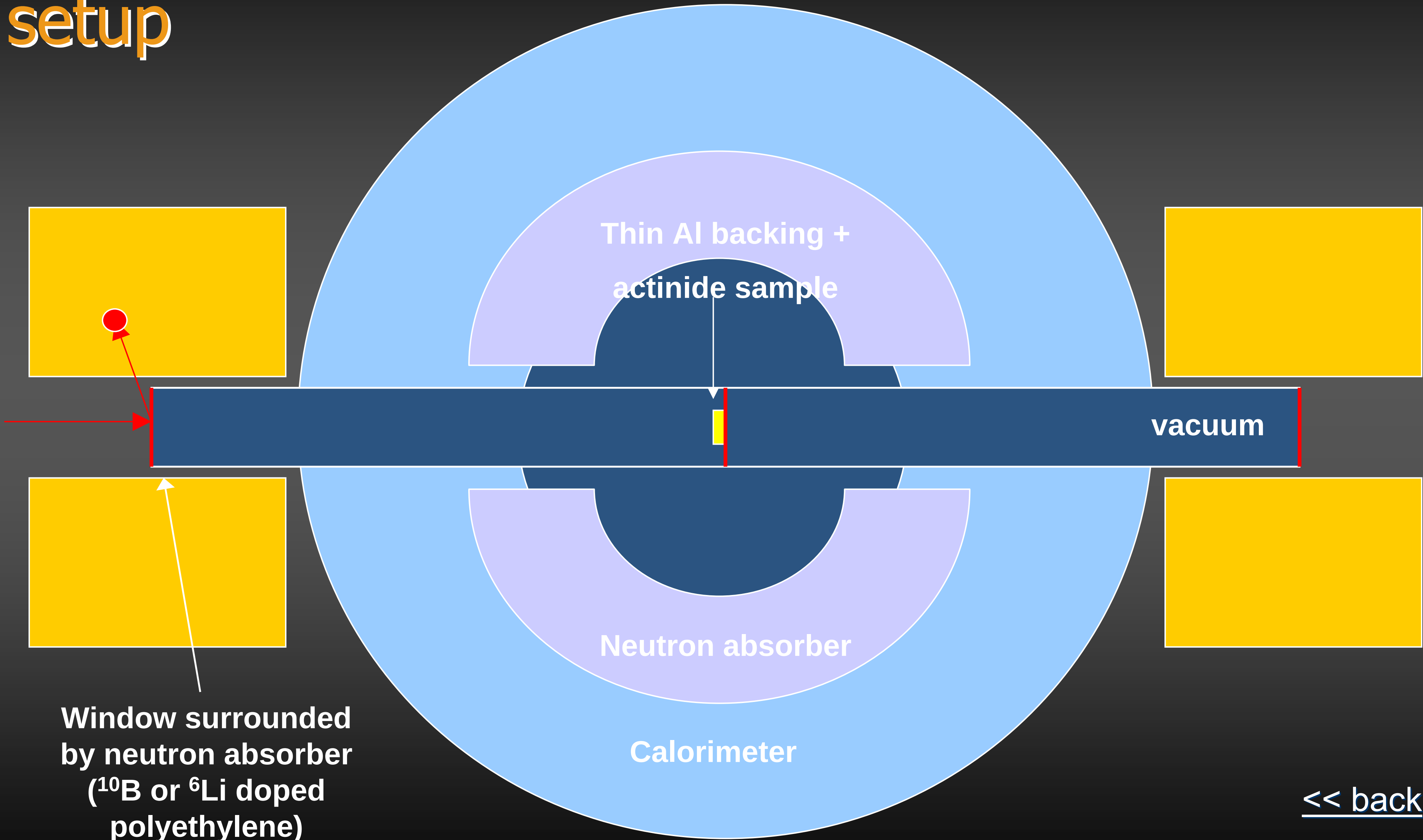

Neutron Beam
C12H20O4(6Li)2
Neutron Absorber
10B loaded Carbon Fibre Capsules

<< back

Capture studies: actual TAC setup



Capture studies: Low neutron sensitivity setup



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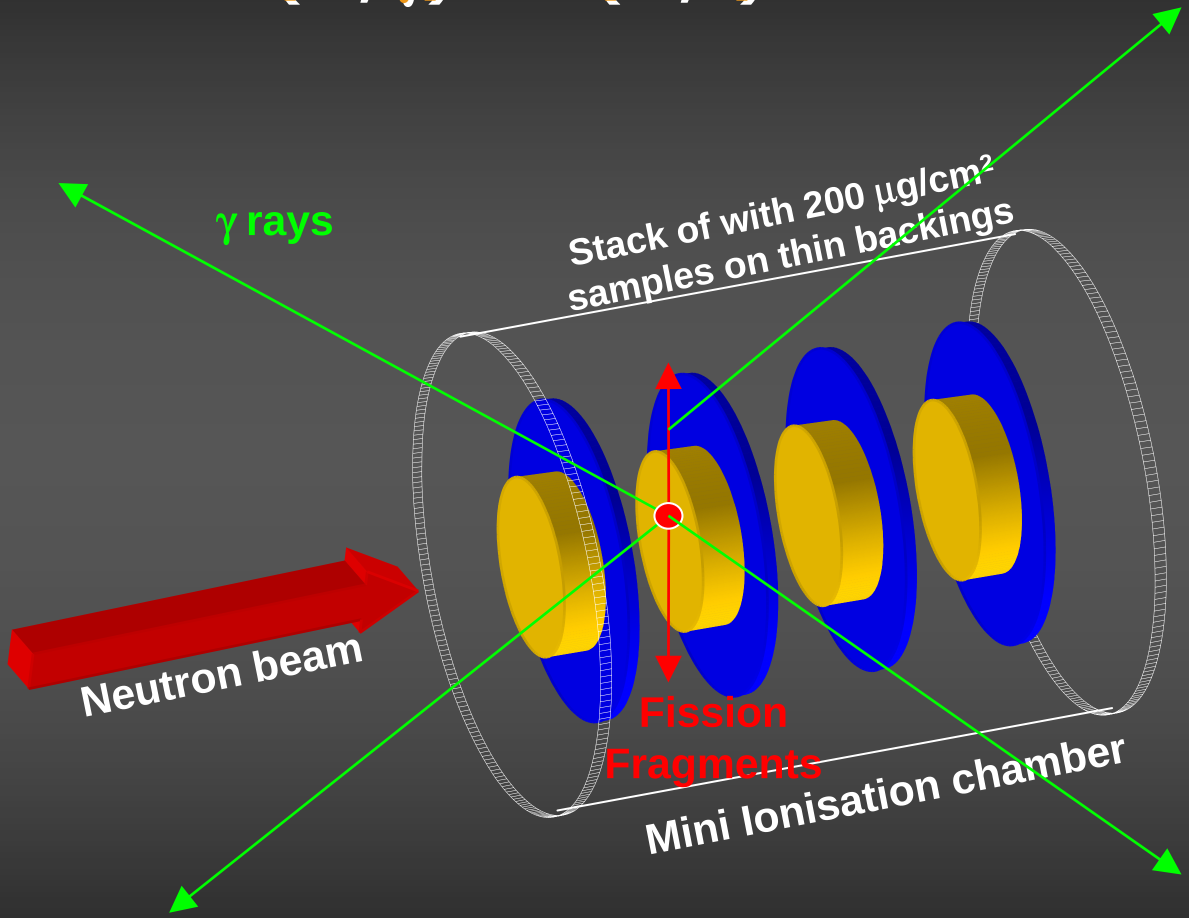
Capture studies: active canning for simultaneous (n,γ) & (n,f) measurements



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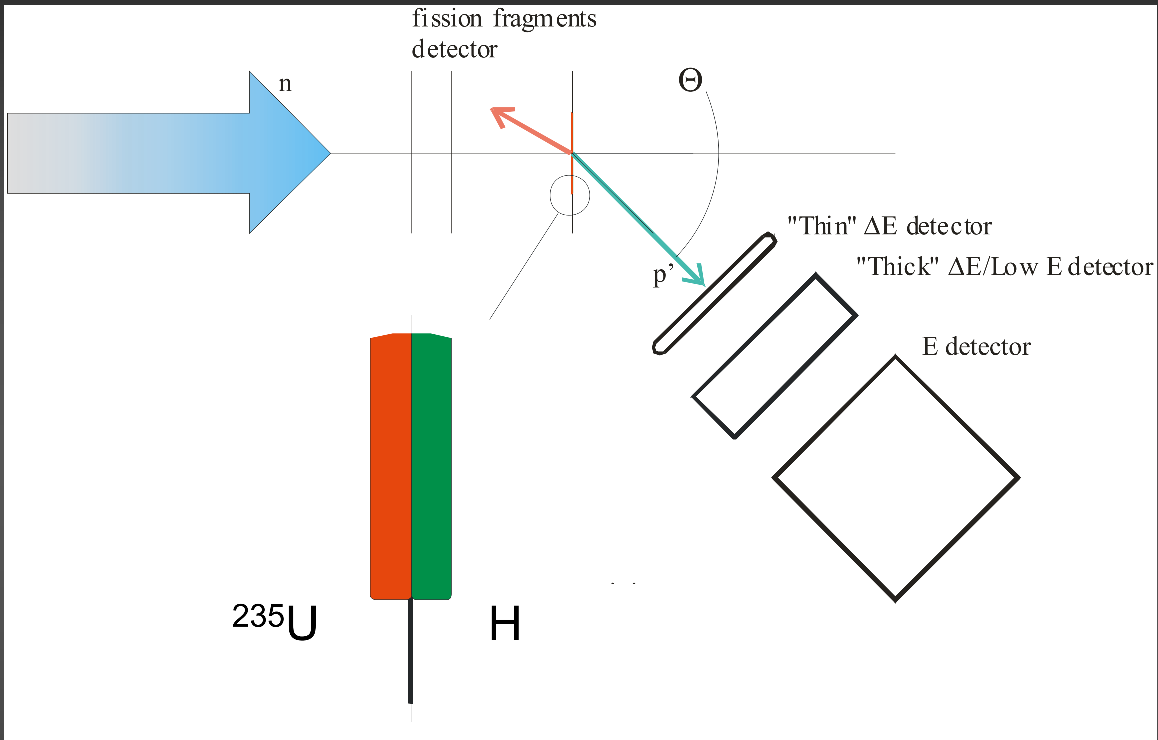
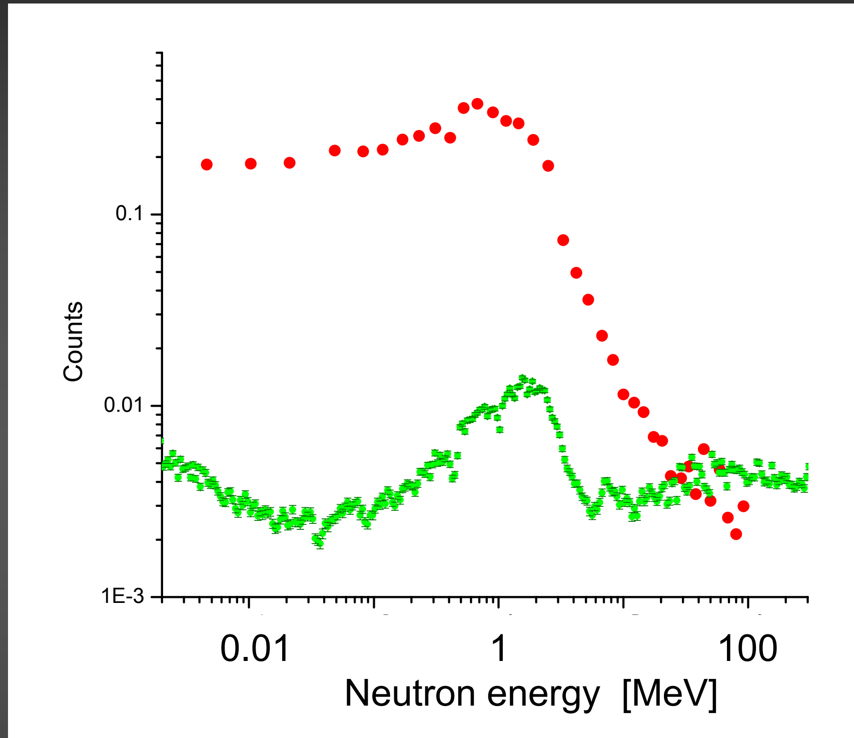
Measurement of capture cross sections of fissile materials (veto) and measurement of the (n,γ)/(n,f) ratio.

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

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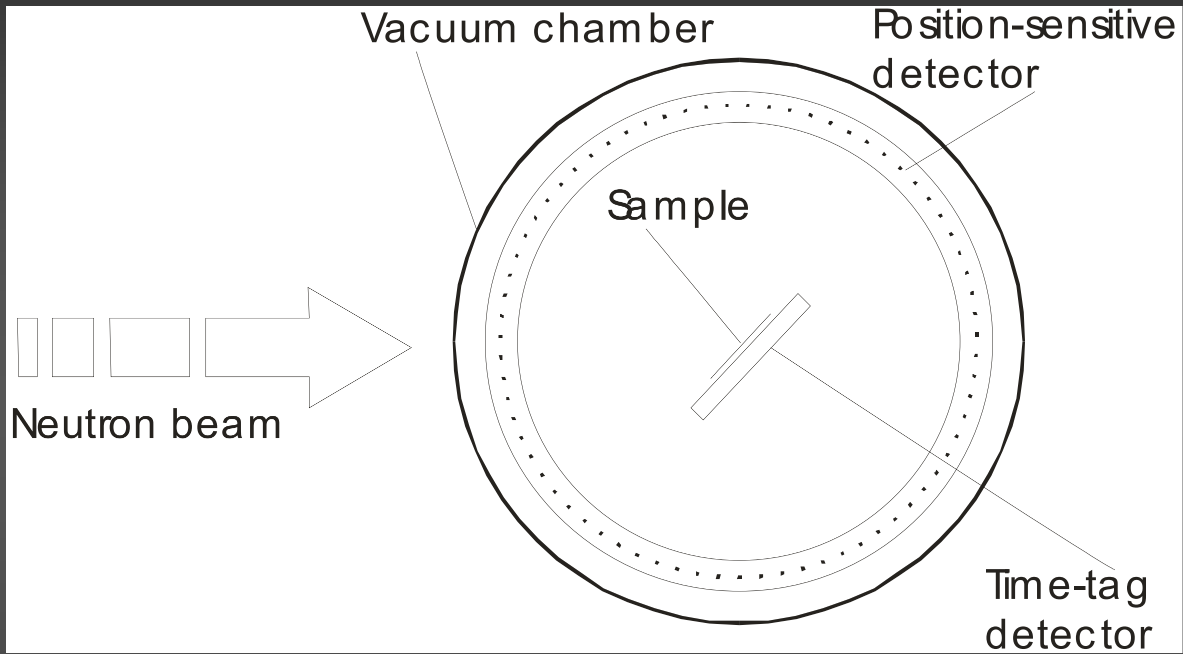
Fission studies

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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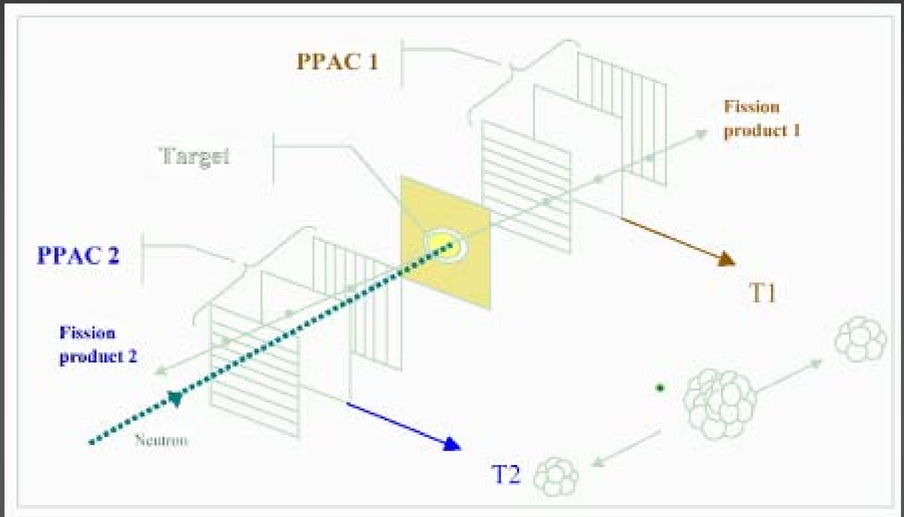
Fission studies

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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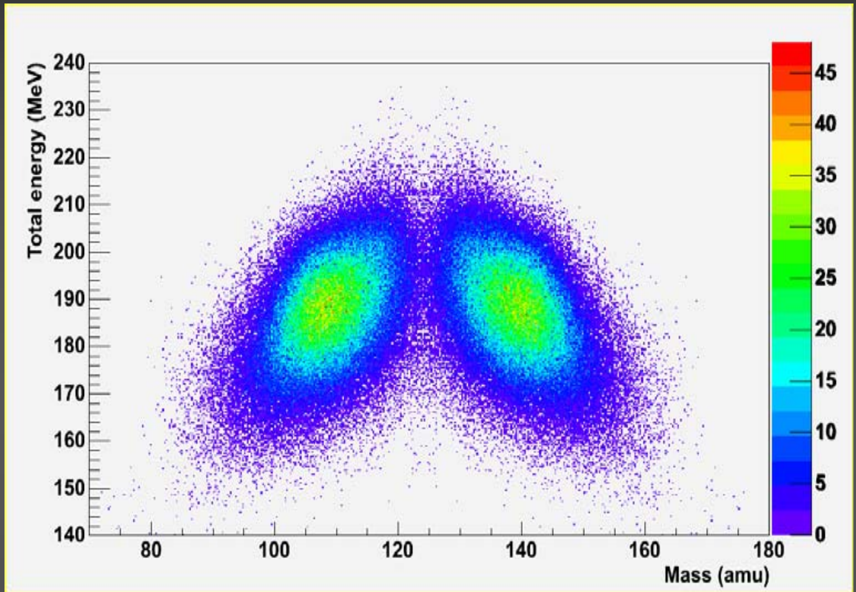
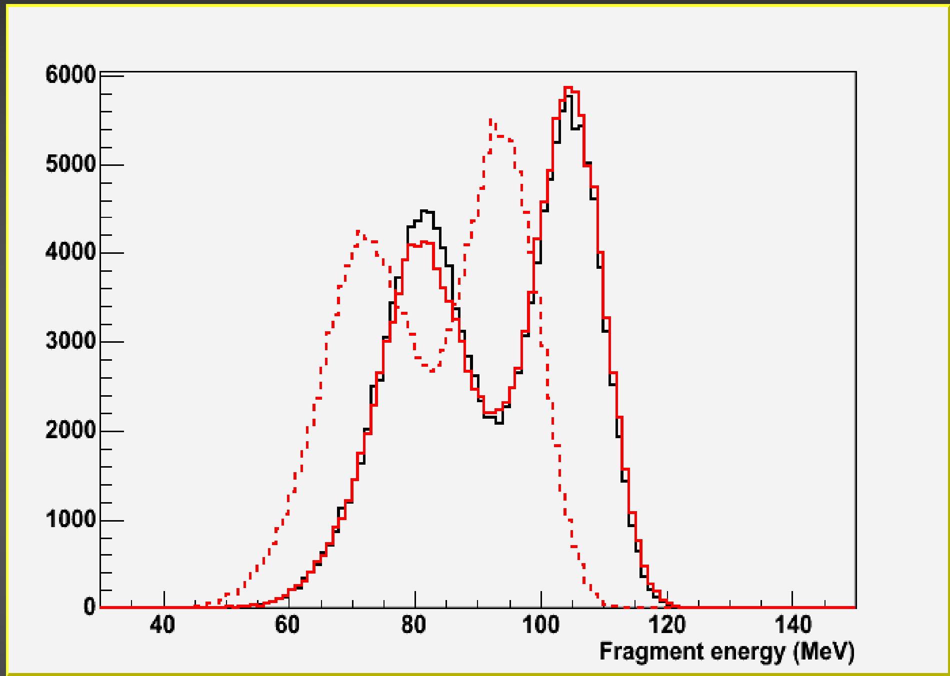
Fission studies
with twin ionization chamber





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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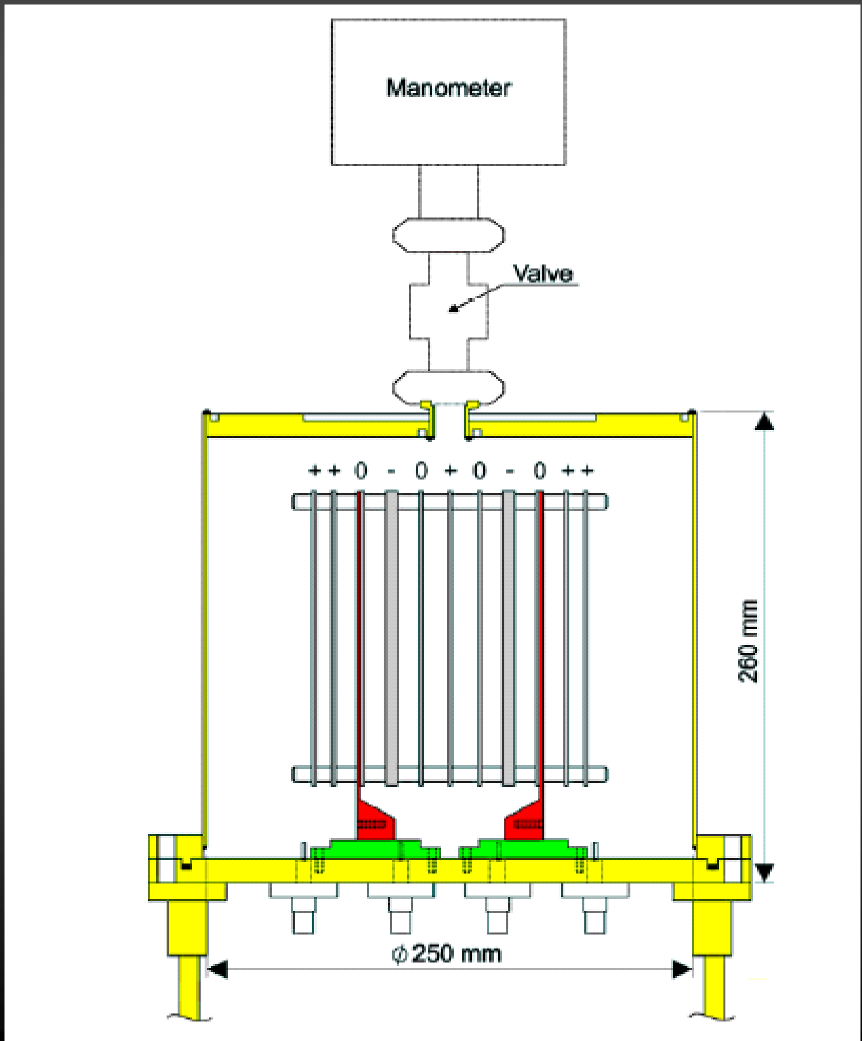
(n,p), (n,α) & (n,lcp) measurements

1. CIC: compensated ion chamber already tested at n_TOF



For n_TOF-Ph2:

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

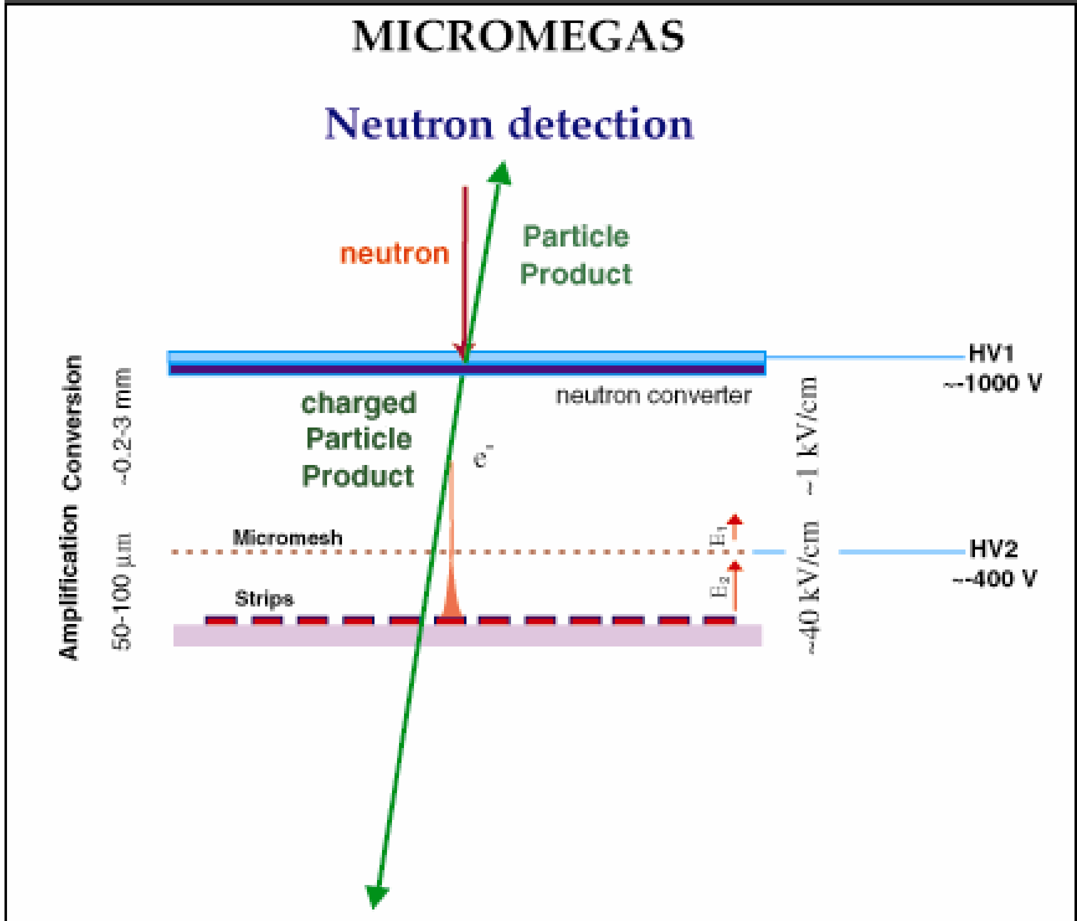
Measurements:

• $^{147}Sm(n,\alpha)$ (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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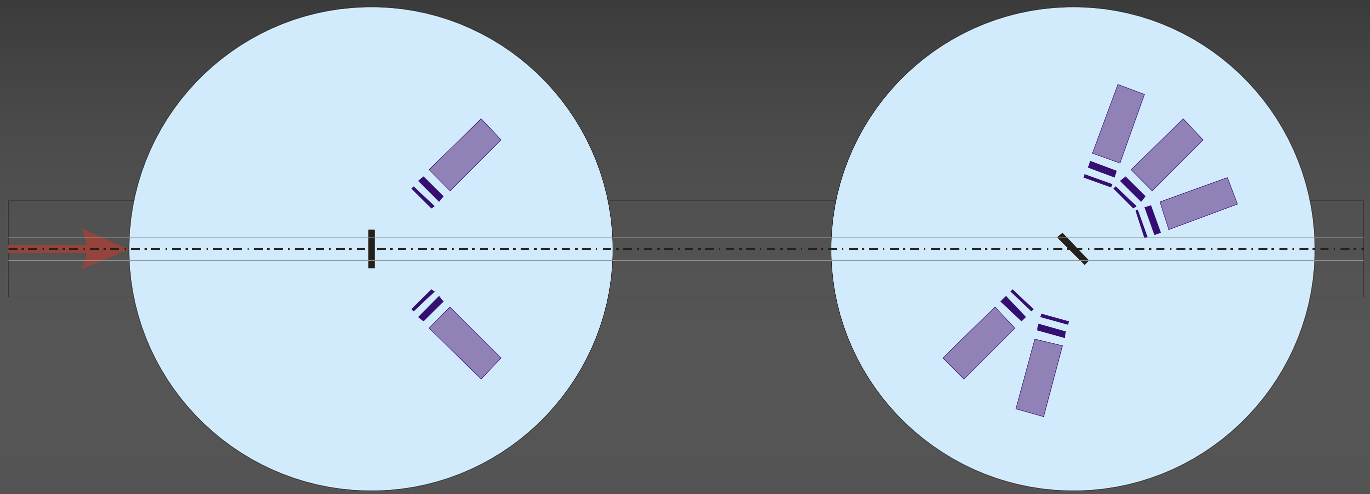
(n,p), (n,α) & (n,lcp) measurements

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

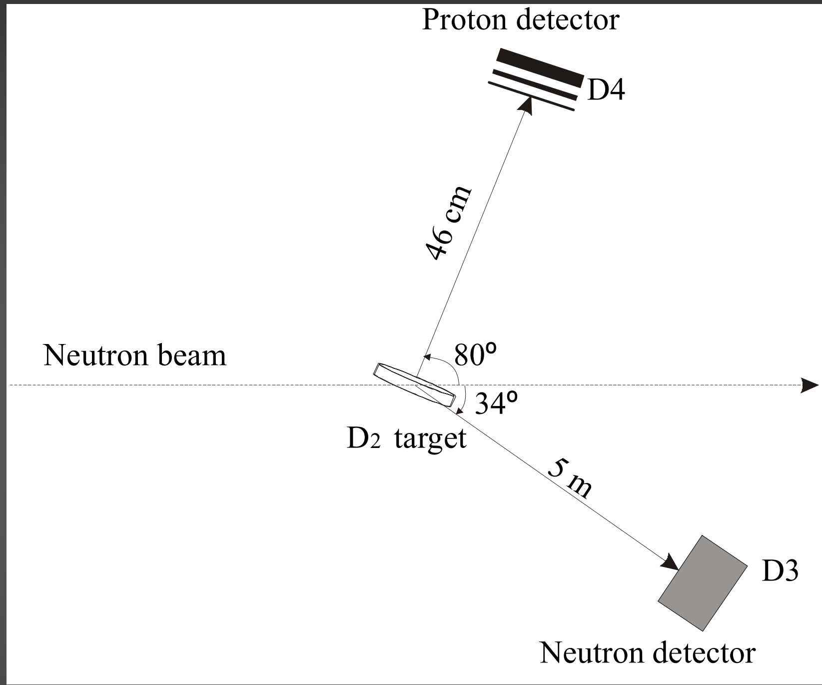
<< back

Neutron scattering reactions

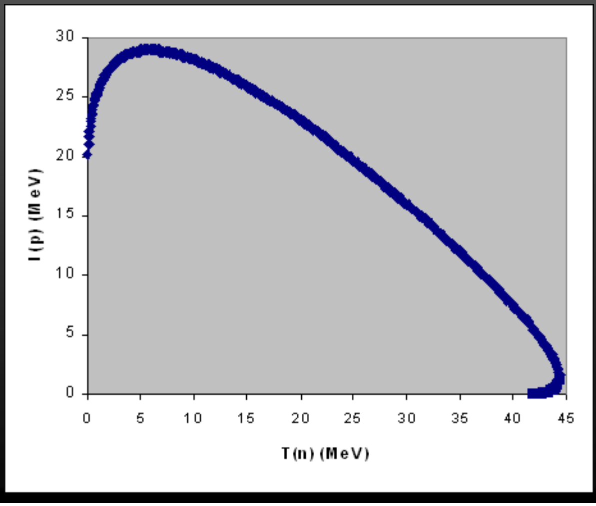
Direct n + n scattering experiment not feasible!

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

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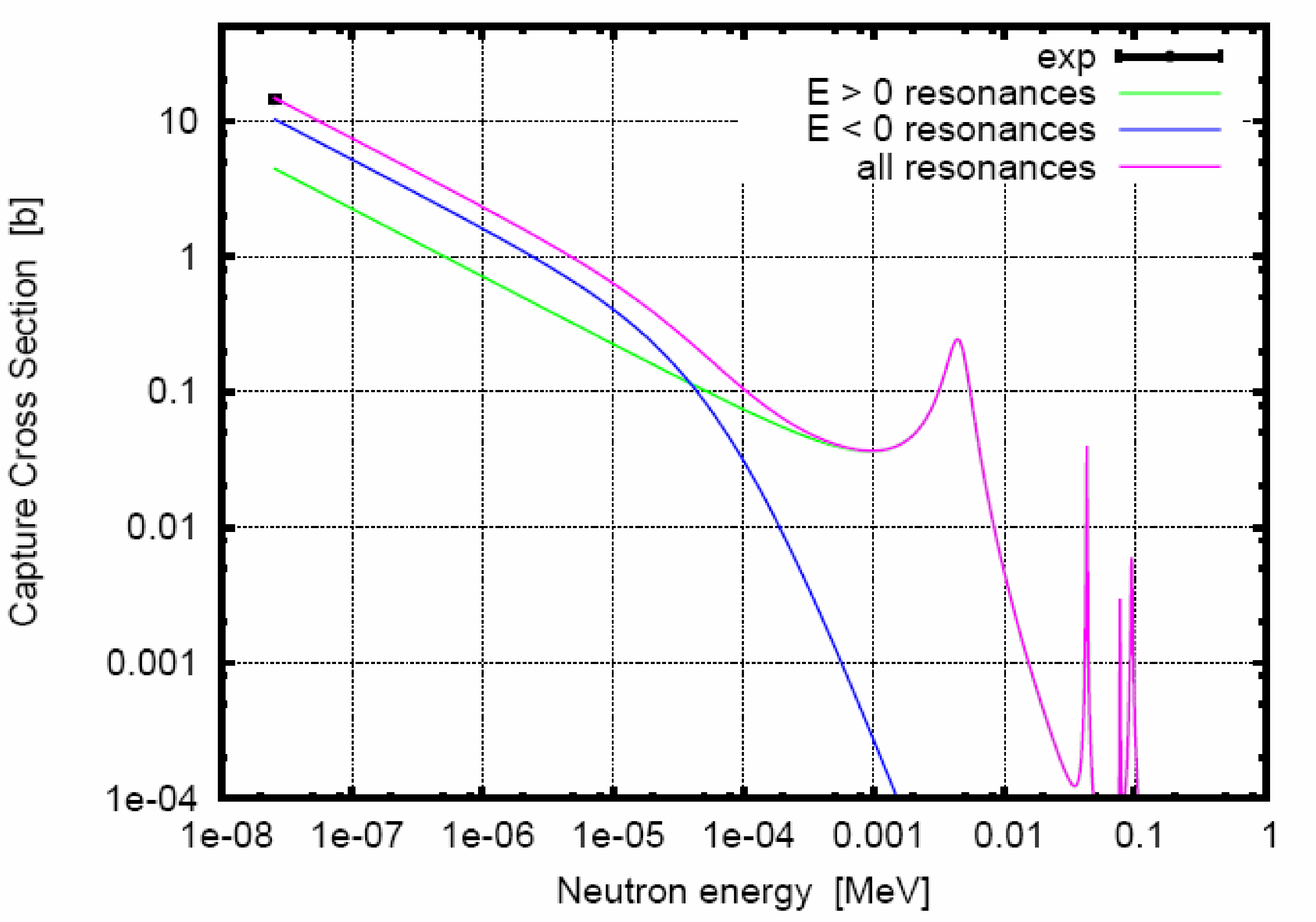
$^{62}Ni(n,\gamma)^{63}Ni$: what do we know?

$\sigma_{n,\gamma}^{th} = 14.5 \pm 0.5$ b

$\Gamma_\gamma = 0.76$ meV

$\langle\sigma\rangle_{25keV} = 13.3$ mb



$\langle\sigma\rangle_{25keV}$

28.4 ± 2.8 mb (a)
49.5 ± 4.4 mb (b)

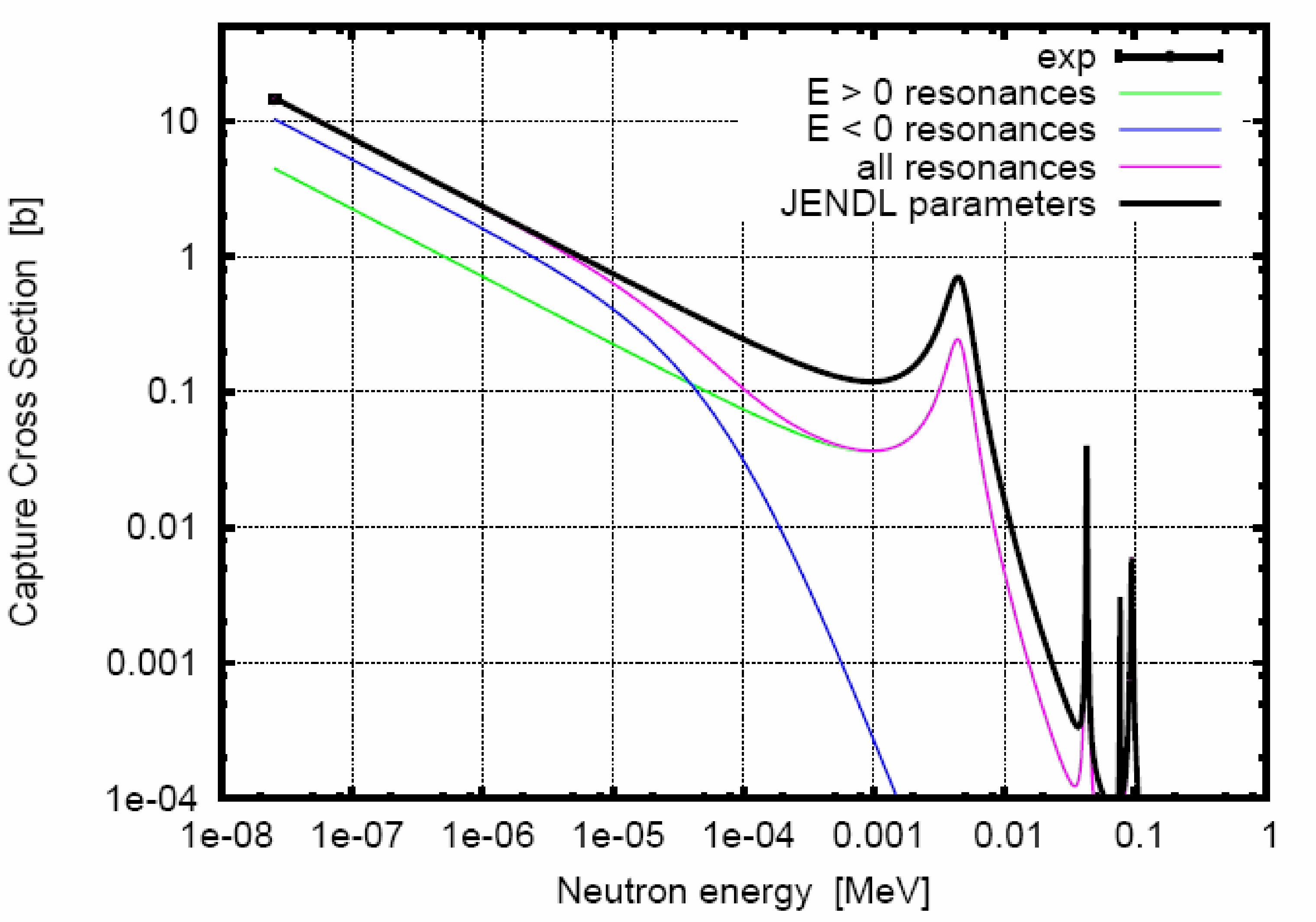
(a) H Nassar et al. (2005)
(b) N Tomyo et al. (2005)

$^{62}Ni(n,\gamma)^{63}Ni$: what do we know?

$\sigma_{n,\gamma}^{th} = 14.5 \pm 0.5$ b

$\Gamma_\gamma = 2.38$ meV

$\langle \sigma \rangle_{25keV} = 23.1$ mb



$\langle \sigma \rangle_{25keV}$

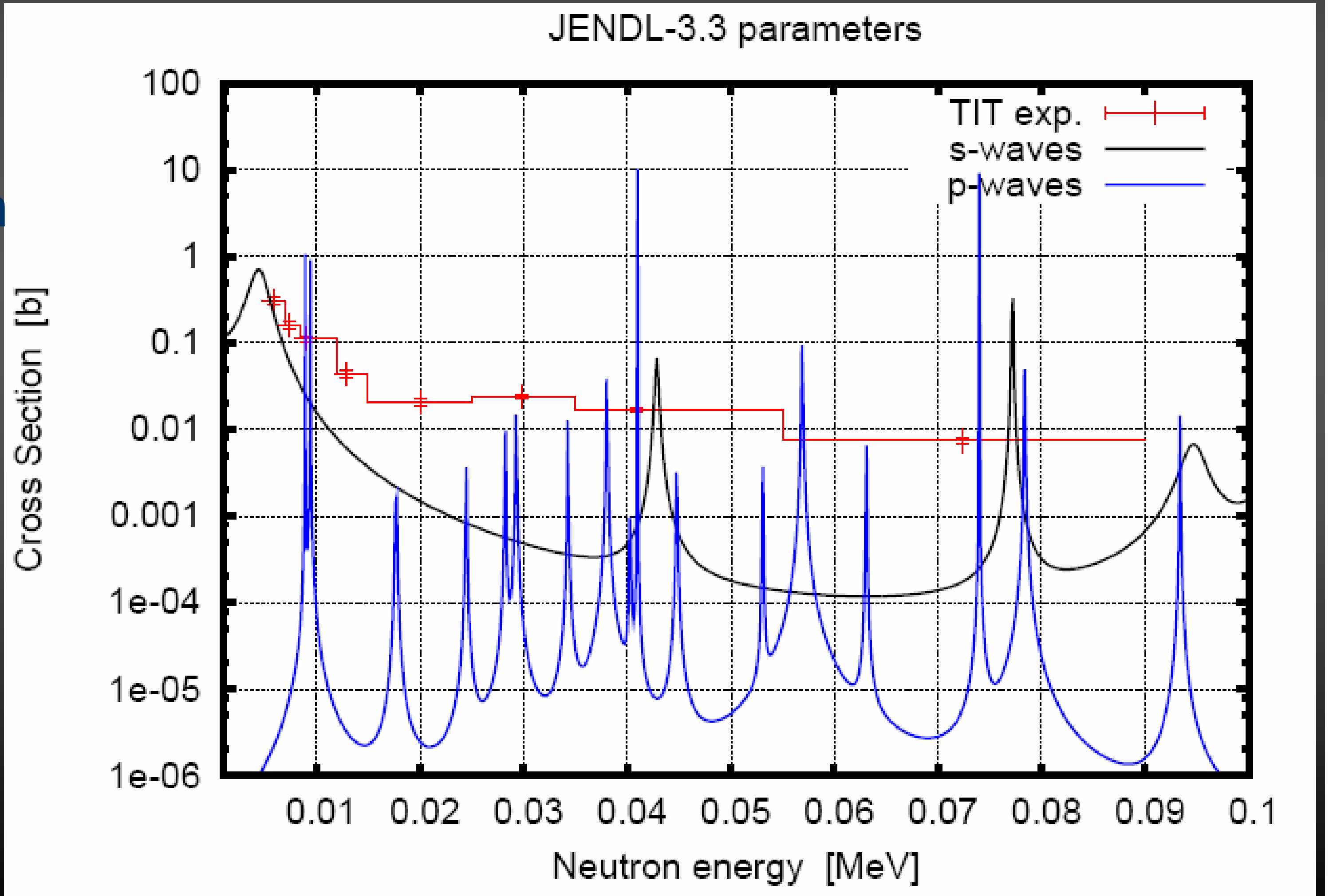
28.4 ± 2.8 mb (a)
49.5 ± 4.4 mb (b)

(a) H Nassar et al. (2005)
(b) N Tomyo et al. (2005)

$^{62}Ni(n,\gamma)^{63}Ni$: what do we know?

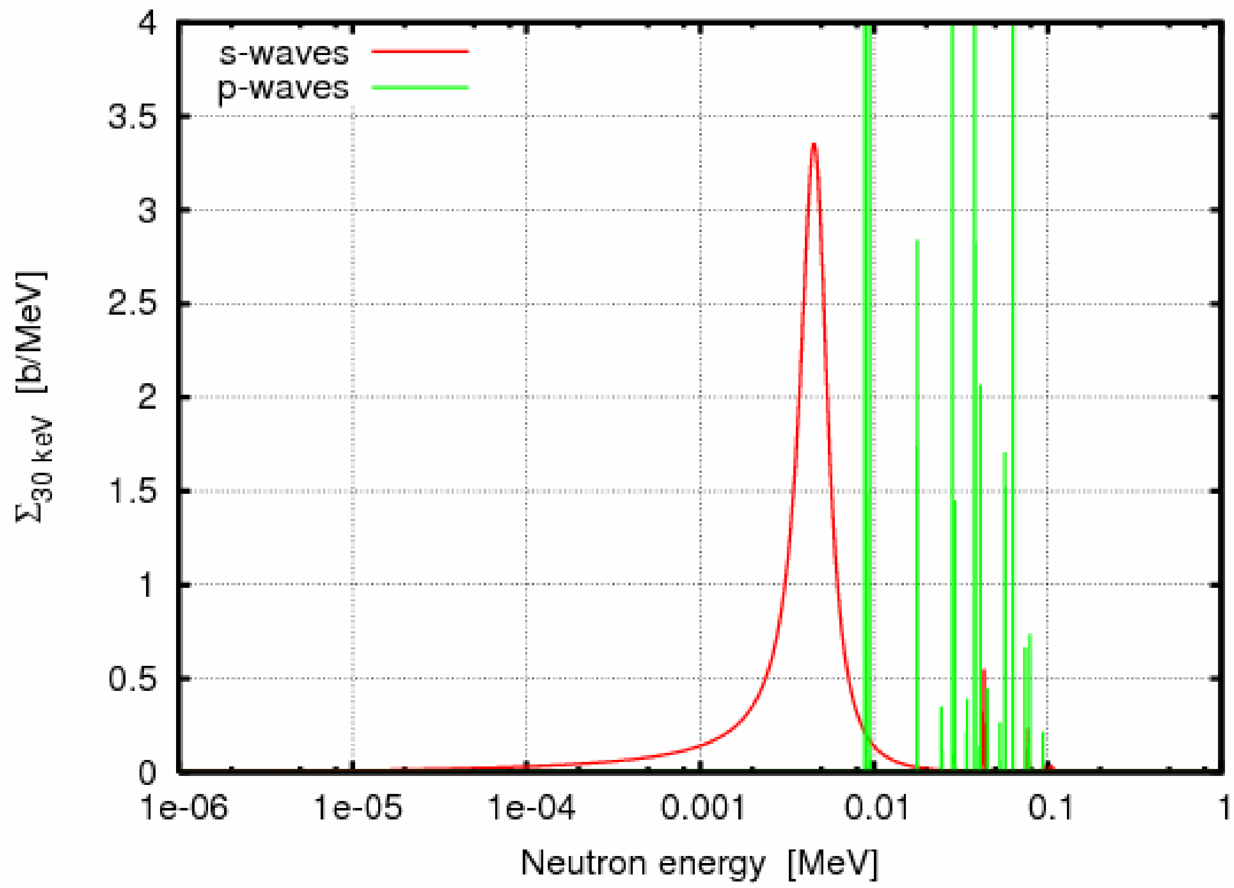
a high-resolution (n,γ) cross section measurement is called for

planned for n_TOF-Ph2



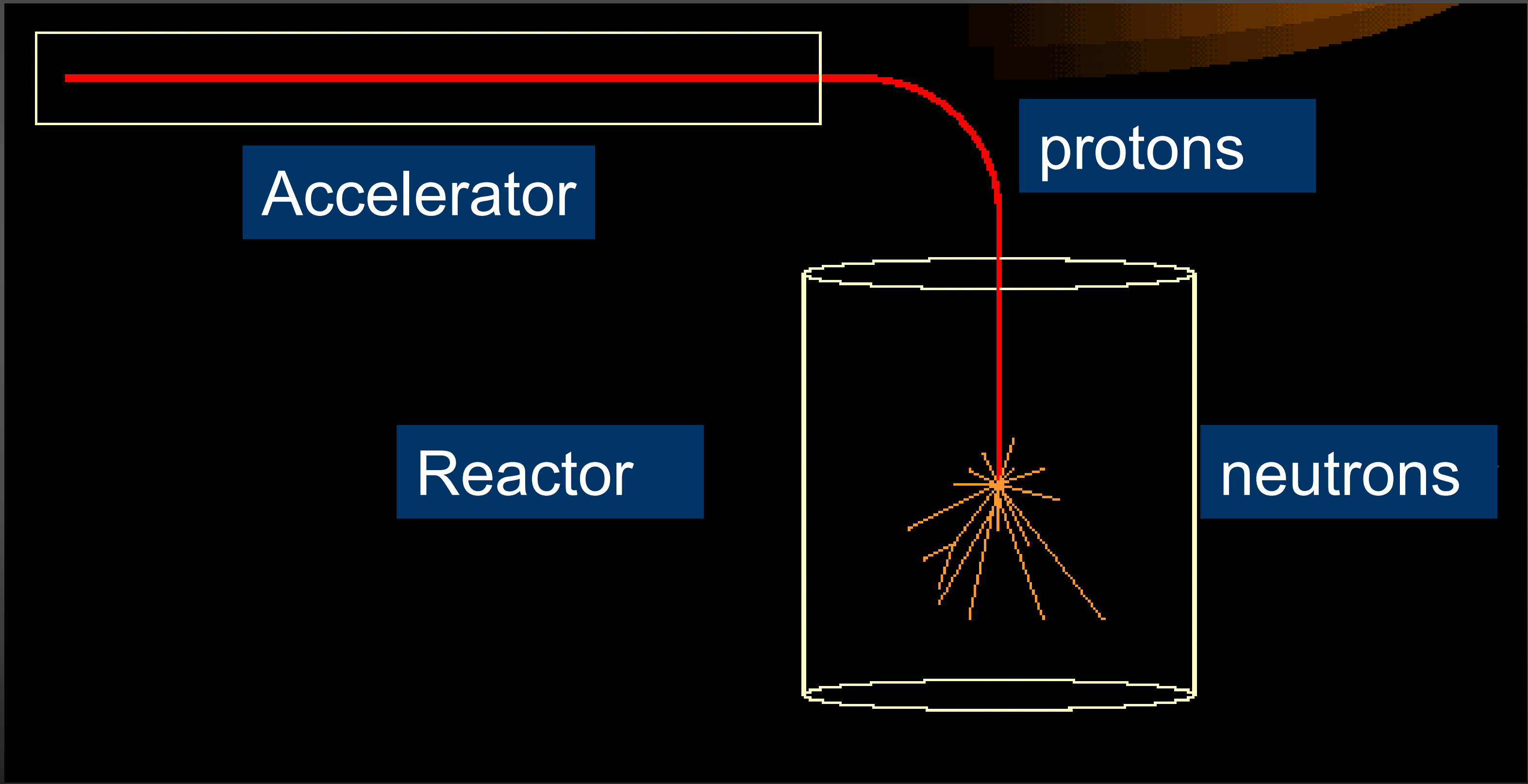
$^{62}Ni(n,\gamma)^{63}Ni$: what do we know?

p-waves could contribute up to 30% of the total strength



Nuclear Data needs for ADS

- Subcritical reactor core
- Spallation neutrons: high energies
- Trasmutation of TRU: exotic fuel



Zen-ADS