

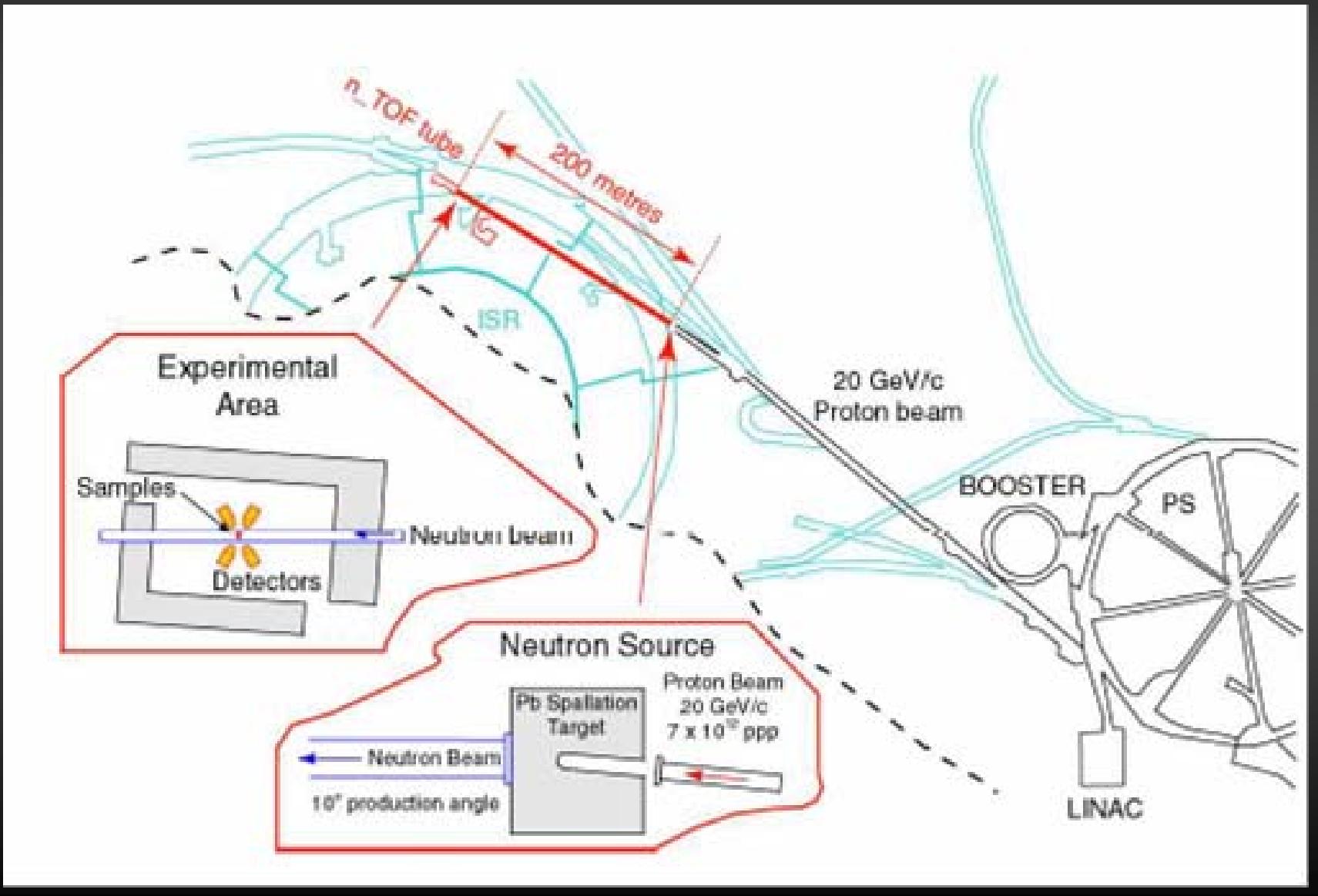
# The Future of/at n\_TOF

The physics case and the related proposal for measurements at n\_TOF for 2006 and beyond

A Mengoni  
IAEA, Vienna

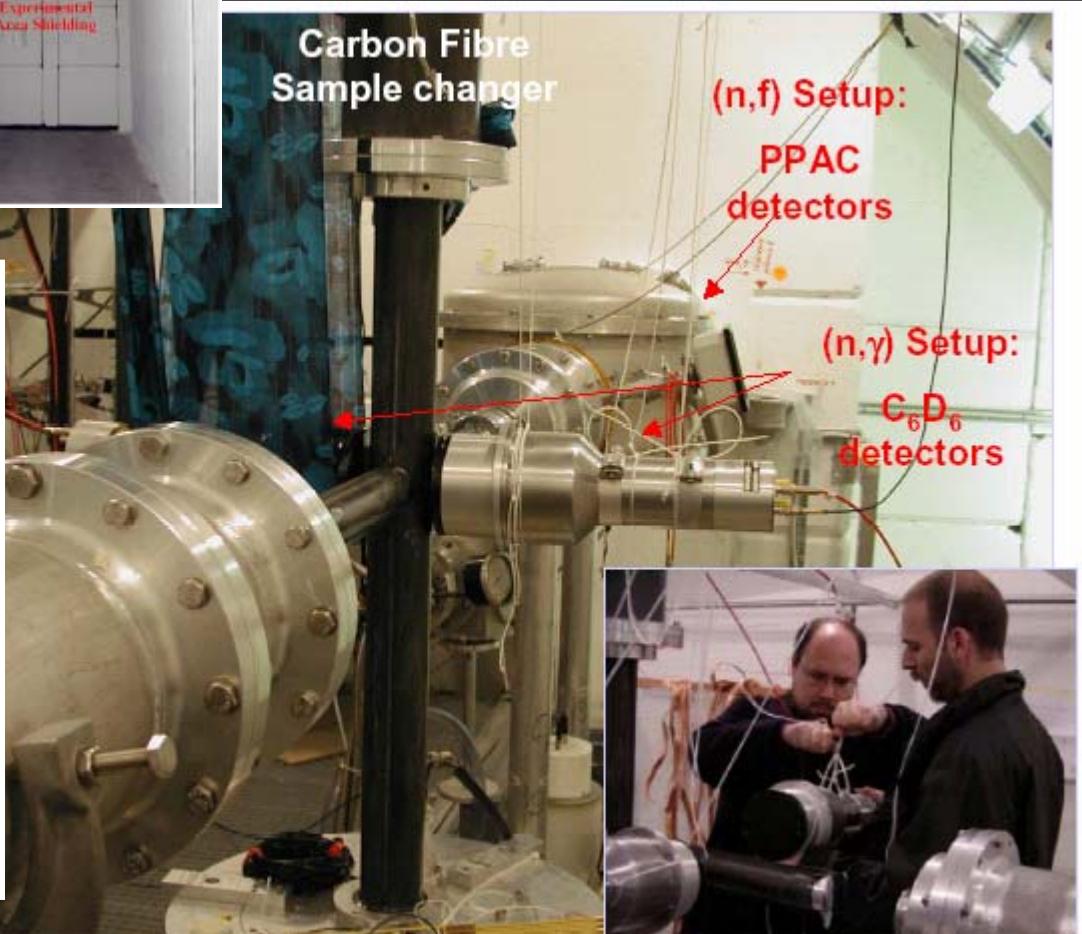
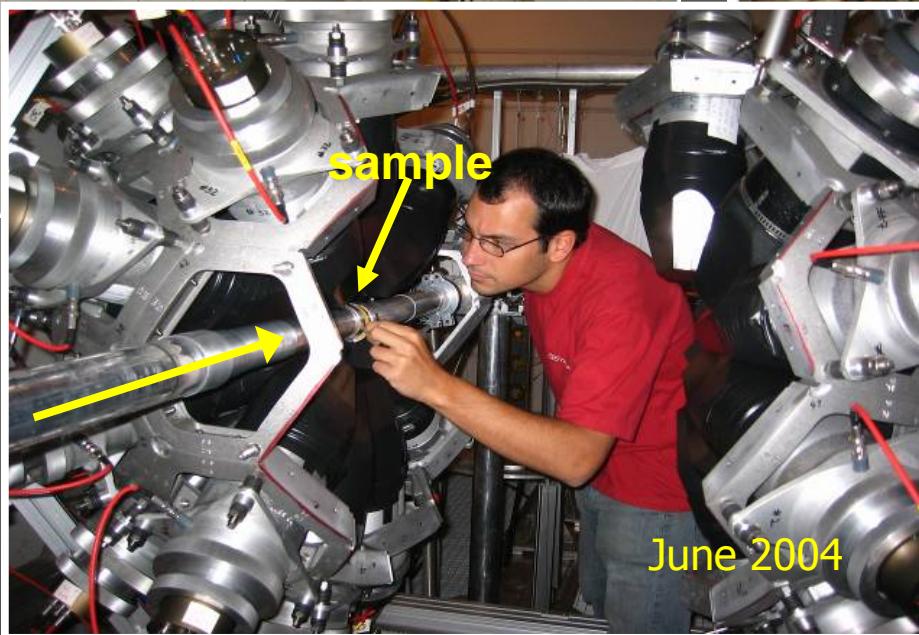
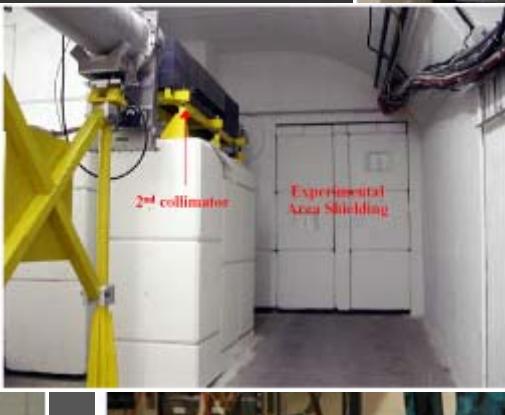
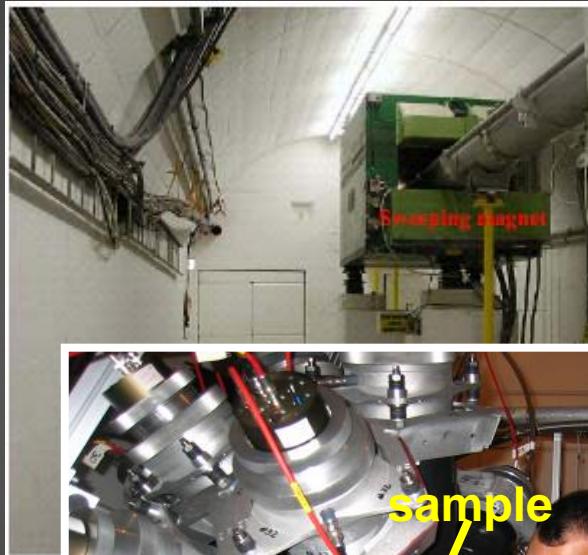
- the CERN n\_TOF Facility
- the physics case for the activities at n\_TOF
- plan for measurements in Phase-2
- opportunities with a new, shorter flight-path: EAR-2

# The n\_TOF facility at CERN



# n\_TOF

- n\_TOF commissioned in 2002



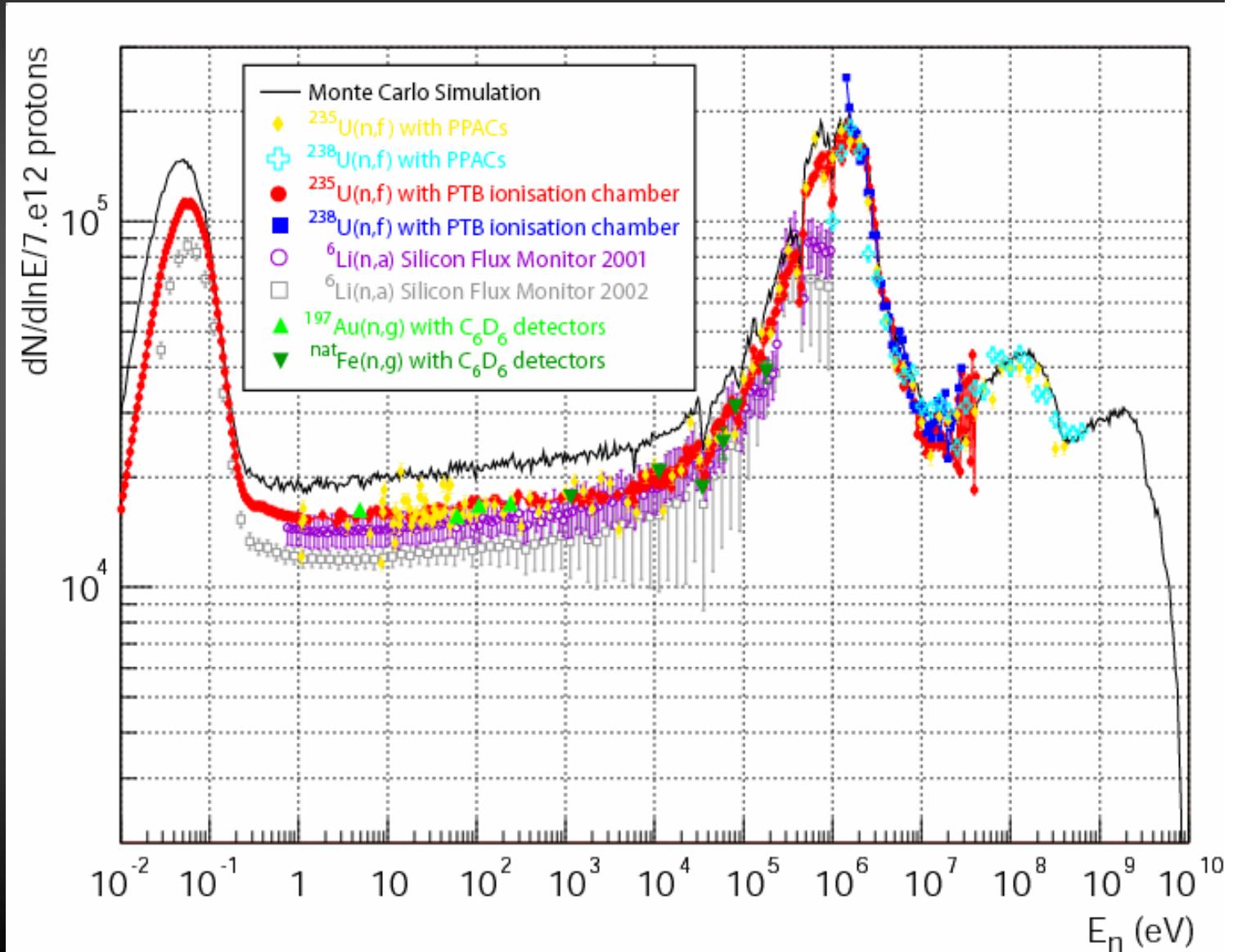
# n\_TOF basic parameters

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

# The neutron flux

2<sup>nd</sup> collimator  $\phi=1.8$  cm

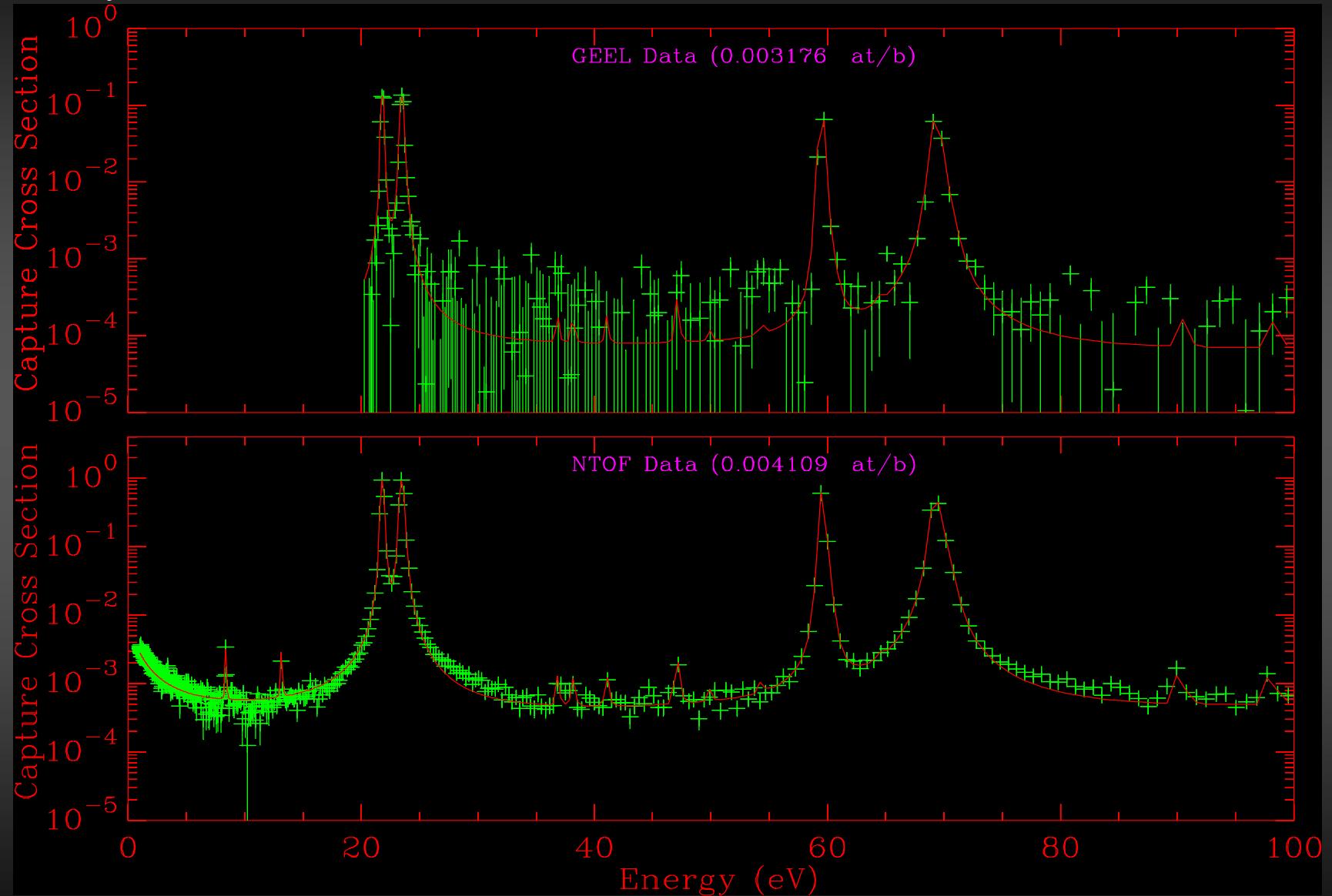
Neutron Energy	$\Delta E/E$
1 ev	$3.0 \times 10^{-4}$
30 keV	$1.1 \times 10^{-3}$
1 MeV	$4.2 \times 10^{-3}$
100 MeV	$2.1 \times 10^{-2}$



# World scene for tof measurements

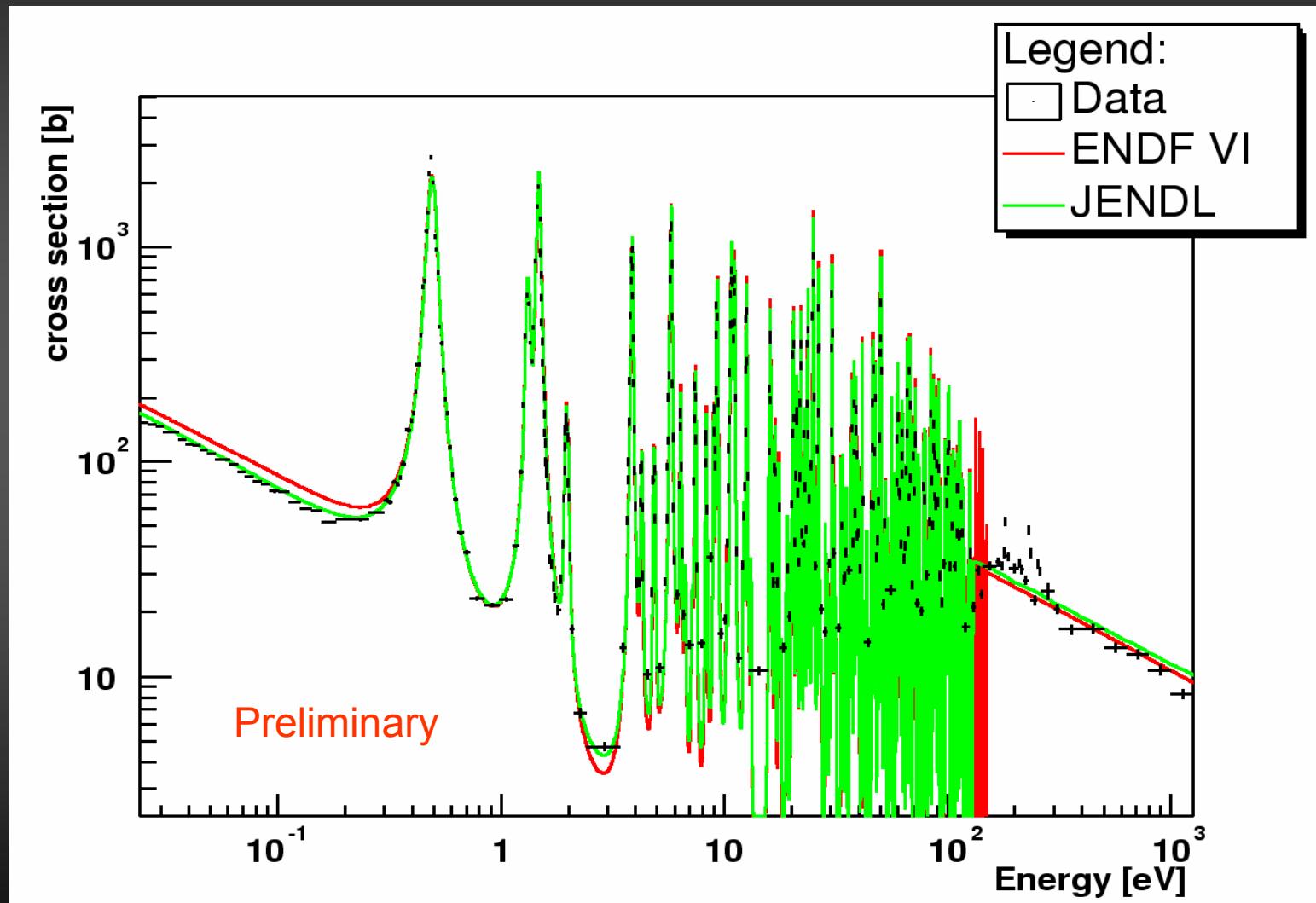
facility		driver and energy	repetition rate	n source	n energy range	flight path length
FZK TIT ...	Karlsruhe Tokyo ...	varii in the MeV range	MHz	<sup>7</sup> Li(p,n) & others	few keV up to 1 MeV monoE above	10s cm
GELINA	EC-JRC Geel	electron linac 150 MeV	800 Hz	photo-n photo-f	10 meV – 20 MeV	10m to 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

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



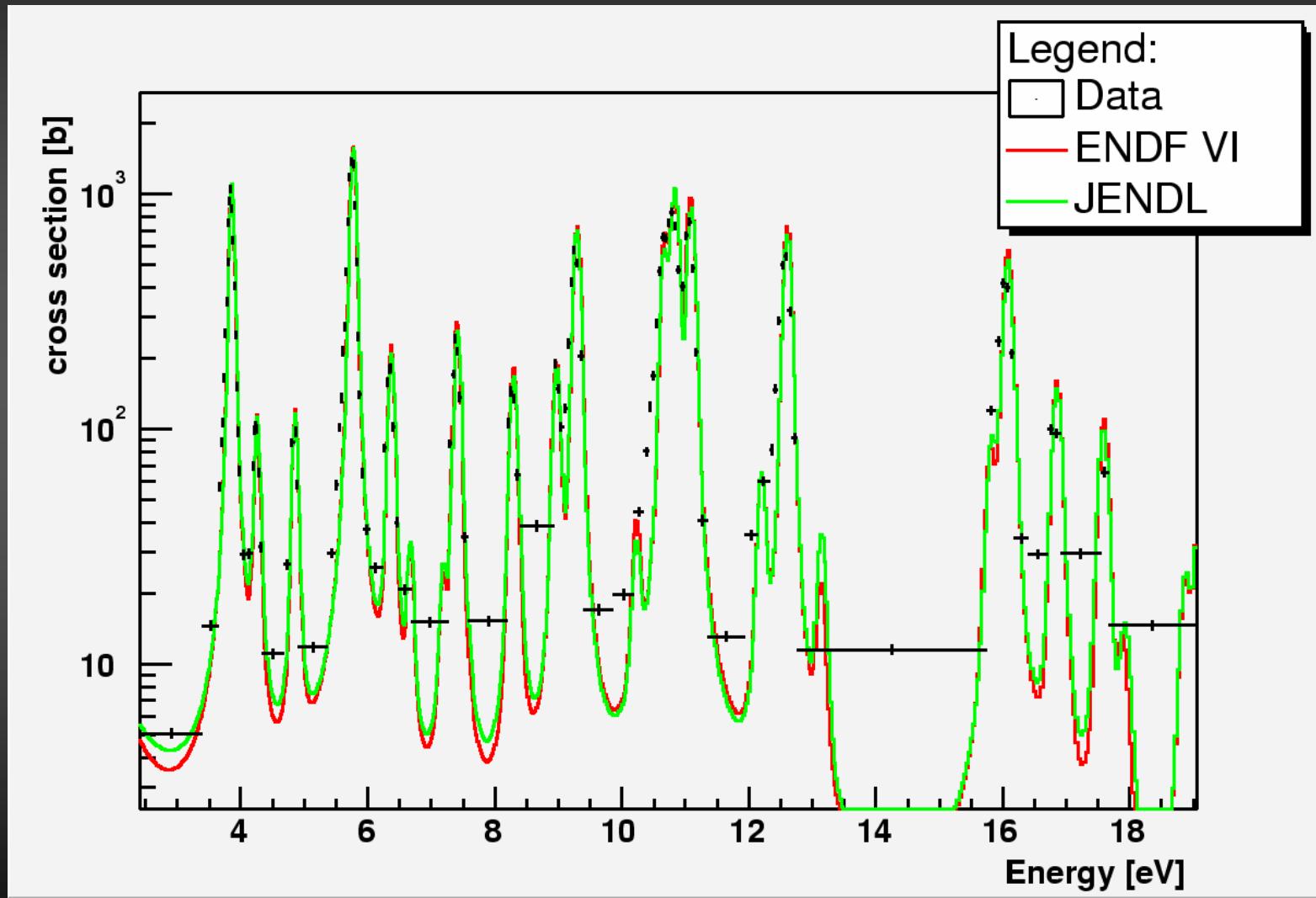
Source: L Leal, IAEA CRP meeting, December 2004

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



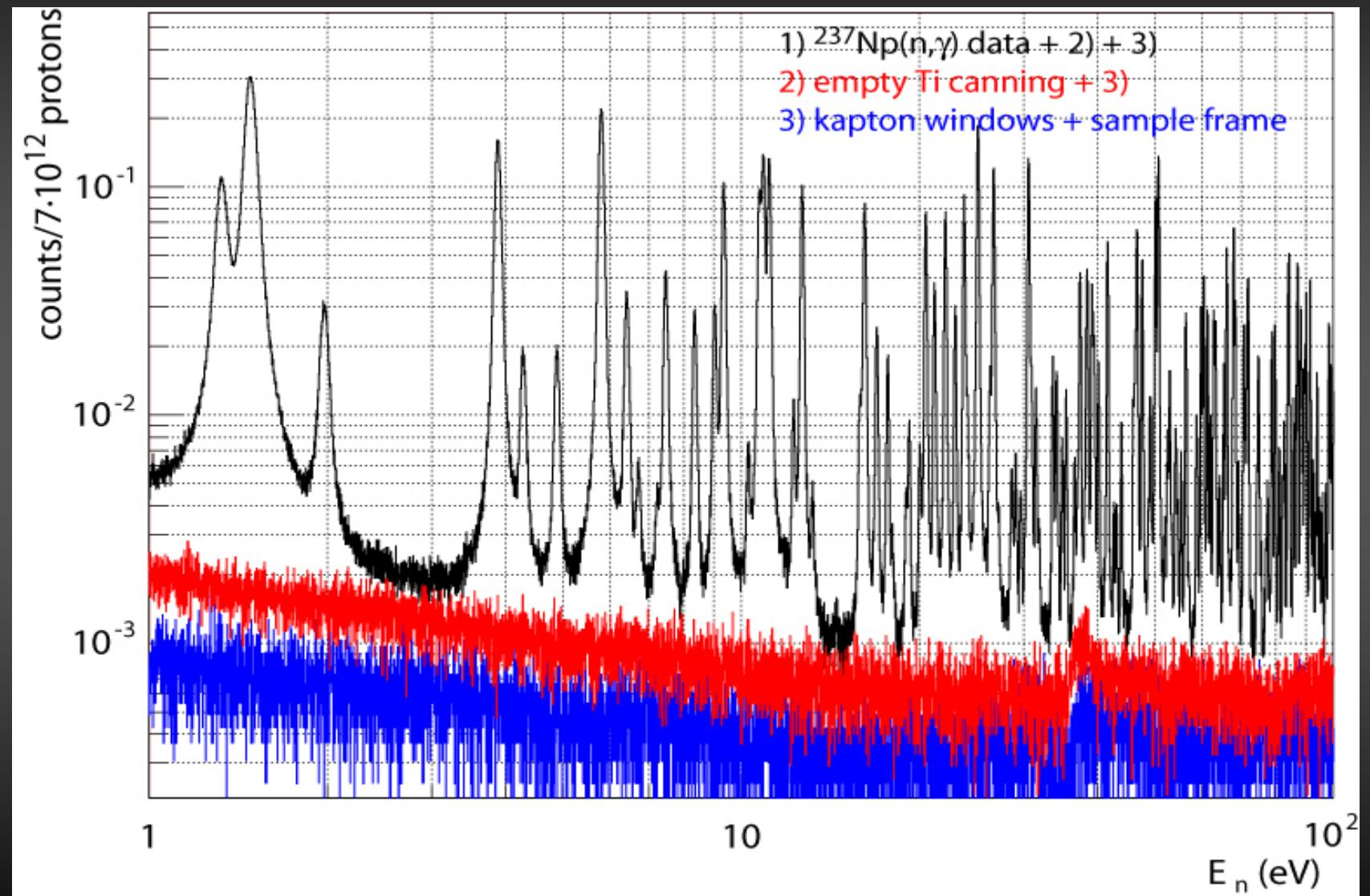
Source: J Ullman, n\_BANT workshop, CERN, March 2005

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



Source: J Ullman, n\_BANT workshop, CERN, March 2005

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



# 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, $\gamma$ ): ultra low neutron sensitivity  $C_6D_6$  detectors, high performance Total Absorption Calorimeter
  - (n,f): Low background PPAC setup, FIC detector
  - Beam monitors: redundant  $^{197}Au(n,\gamma)$ ,  $^6Li(n,\alpha)t$ ,  $^{235}U(n,f)$  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

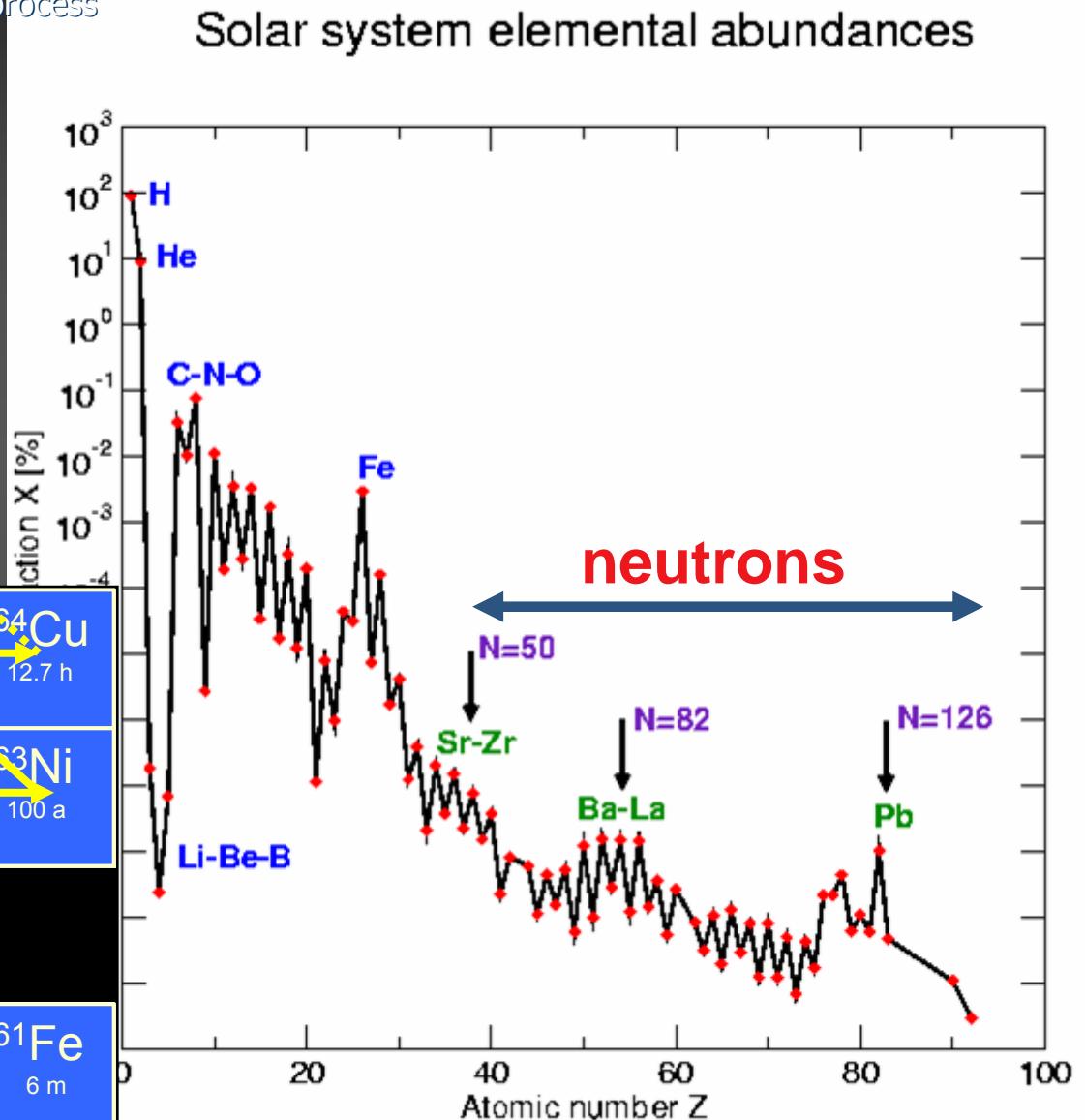
1. Cross sections relevant for Nuclear Astrophysics
2. Measurements of neutron cross sections relevant for Nuclear Waste Transmutation and related Nuclear Technologies
3. Neutrons as probes for fundamental Nuclear Physics

# 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

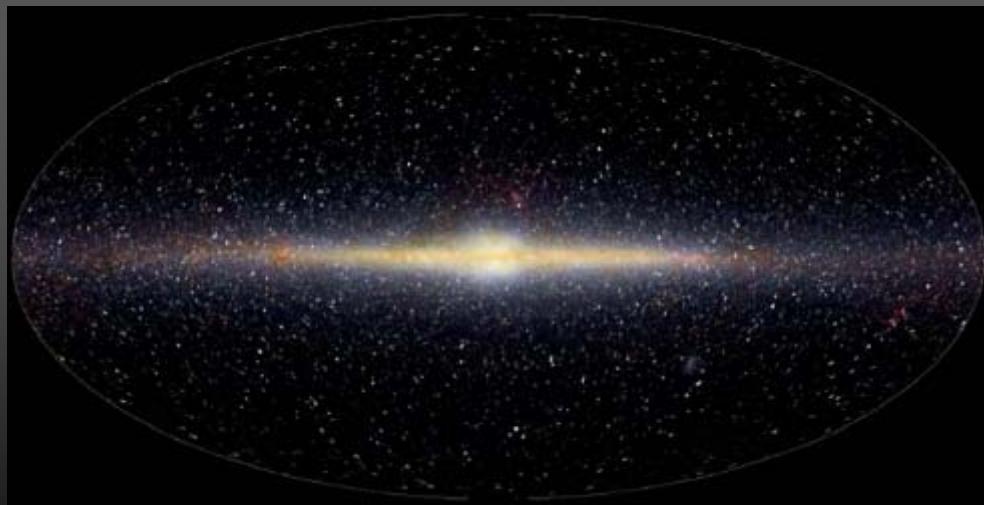
## The canonical s-process

Cu		<b>62Cu</b> 9.74 m	<b>63Cu</b> 69.17	<b>64Cu</b> 12.7 h
Ni		<b>60Ni</b> 26.23	<b>61Ni</b> 1.140	<b>62Ni</b> 3.634
Co		<b>58Co</b> 70.86 d	<b>59Co</b> 100	<b>60Co</b> 5.272 a
Fe		<b>56Fe</b> 91.72	<b>57Fe</b> 2.2	<b>58Fe</b> 0.28
				<b>59Fe</b> 44.503 d
				<b>60Fe</b> 1.5 $10^6$ a
				<b>61Fe</b> 6 m

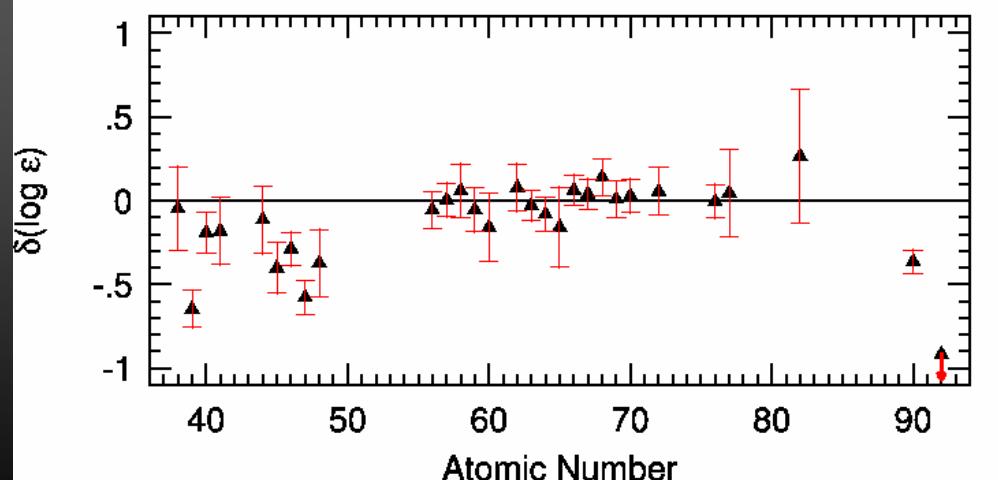
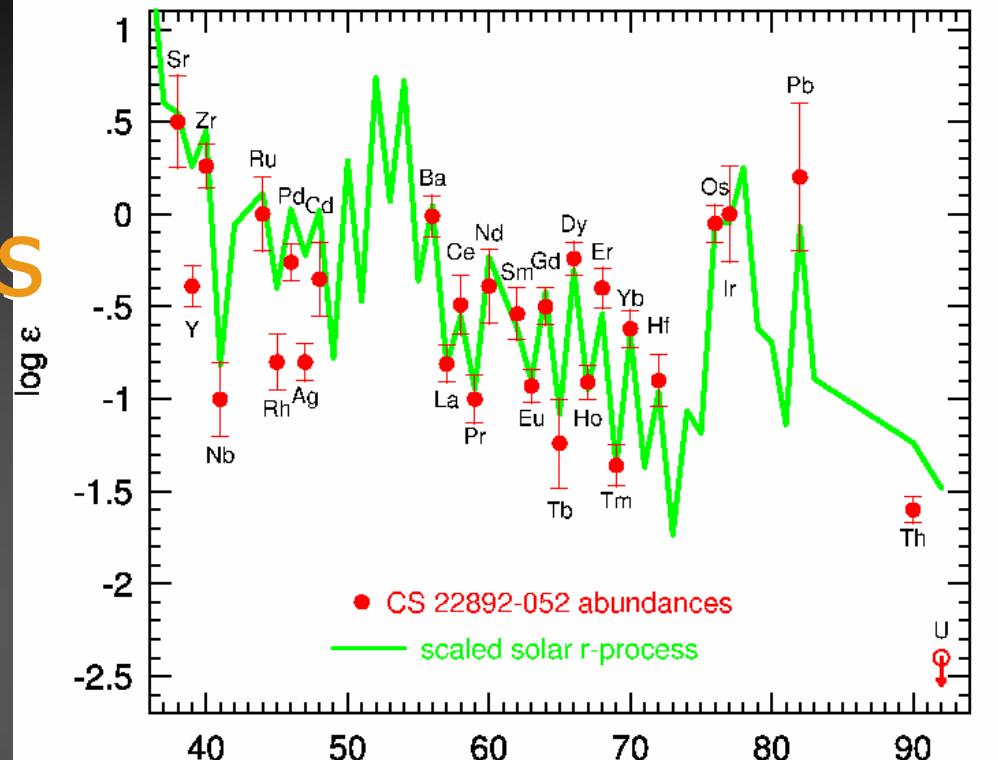


# Nucleosynthesis: the s-process & the r-process residuals

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



Neutron-Capture Abundances in CS 22892-052



# 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<sub>2</sub> 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<sub>2</sub>.

*(from the MIT report, 2003)*



# Th/U fuel cycle

	Cm 238 2,4 h	Cm 239 3 h	Cm 240 27 d	Cm 241 32,8 d	Cm 242 162,94 d	Cm 243 29,1 a	Cm 244 18,10 a	Cm 245 8500 a	Cm 246 4730 a
	$\alpha$ 6,52	$\alpha$ $\gamma$ 188... g	$\alpha$ $\gamma$ 6,291; 6,248... sf g	$\alpha$ 5,336; $\gamma$ 472; 431; 132... sf g	$\alpha$ 6,113; 6,059... $\gamma$ 278; 229; sf g	$\alpha$ 5,785; 5,748... $\gamma$ 144...; 6... sf g	$\alpha$ 6,005; 6,702... $\gamma$ 175; 133... sf g	$\alpha$ 5,361; 5,304... $\gamma$ 143...; 6... sf g	$\alpha$ 5,386; 5,343... $\gamma$ 45...; 6... sf g
Am 236 ? 3,7 m	Am 237 73,0 m	Am 238 1,63 h	Am 239 11,9 h	Am 240 50,8 h	Am 241 432,2 a	Am 242 141 a 16 h	Am 243 7370 a	Am 244 26 m 10,1 h	Am 245 2,05 h
$\alpha$ 6,41	$\alpha$ 6,042 $\gamma$ 280; 438; 474... g	$\alpha$ 5,94 $\gamma$ 963; 913; 561... g	$\alpha$ 5,774... $\gamma$ 276; 228... g	$\alpha$ 5,376... $\gamma$ 988; 889... g	$\alpha$ 5,409; 5,443... $\gamma$ 80; 28... sf g	$\alpha$ 5,279; 5,233... $\gamma$ 75; 44... sf g	$\alpha$ 5,279; 5,233... $\gamma$ 75; 44... sf g	$\alpha$ 5,279; 5,233... $\gamma$ 75; 44... sf g	$\mu$ 0,9... $\gamma$ 253... (241; 296...) $\gamma$ g
Pu 235 25,3 m	Pu 236 2,858 a	Pu 237 45,2 d	Pu 238 87,74 a	Pu 239 2,411 - 10 <sup>4</sup> a	Pu 240 6563 a	Pu 241 14,35 a	Pu 242 3,750 - 10 <sup>5</sup> a	Pu 243 4,956 h	Pu 244 8,00 - 10 <sup>7</sup> a
$\alpha$ 5,80 $\gamma$ 49; (758; 34...) d	$\alpha$ 5,788; 5,721... $\gamma$ 51; Mg 28... $\gamma$ 140; 109...; e... $\gamma$ 180... sf	$\alpha$ 5,534... $\gamma$ 60...; e... $\gamma$ 2300	$\alpha$ 5,499; 5,469... $\gamma$ 51; Mg 28... $\gamma$ 142; 100...; e... $\gamma$ 510; m 17	$\alpha$ 5,157; 5,144... $\gamma$ 51; Mg 28... $\gamma$ 270; m 752	$\alpha$ 5,168; 5,124... $\gamma$ 49; (45...) $\gamma$ 290; m ~ 0,044	$\alpha$ 5,008; g $\gamma$ 4981... $\gamma$ 149...; e... $\gamma$ 370; m 1010	$\alpha$ 4,901; 4,856... $\gamma$ 45... $\gamma$ 19...; m < 0,2	$\alpha$ 4,901; 4,856... $\gamma$ 45... $\gamma$ 19...; m < 0,2	$\alpha$ 4,988; 4,946... $\gamma$ 1... $\gamma$ 100; m 200
Np 234 4,4 d	Np 235 396,1 d	Np 236 22,5 m 1,54 - 10 <sup>3</sup> a	Np 237 2,144 - 10 <sup>6</sup> a	Np 238 2,117 d	Np 239 2,355 d	Np 240 7,22 m 65 m	Np 241 13,9 m	Np 242 2,2 m 5,5 m	Np 243 1,85 m
$\alpha$ 5,3+... $\gamma$ 1559; 1528; 1602... m 900	$\alpha$ 5,025; 5,007... $\gamma$ (26; 84...); e- g; m 160 + ?	$\alpha$ 5,075 - 0,5... $\gamma$ 1582... $\gamma$ 100...; e... g; m 2700; d; m 2600	$\alpha$ 4,790; 4,774... $\gamma$ 29; 87...; e... g; m 180; m 0,020	$\beta^-$ 1,2... $\gamma$ 984; 1029; 1026; 924...; e... g; m 2100	$\beta^-$ 0,4; 0,7... $\gamma$ 106; 278; 228...; e...; g g; m < 1	$\beta^-$ 22... $\gamma$ 565... g; m 601... g; m 498...; g	$\beta^-$ 1,3... $\gamma$ 175; (133...)	$\beta^-$ 2,7... $\gamma$ 738... g; m 1473... g	$\beta^-$ 2,88... g
U 233 1,592 - 10 <sup>5</sup> a	U 234 0,0055 2,455 - 10 <sup>5</sup> a	U 235 0,7200	U 236 120 ns 2,342 - 10 <sup>7</sup> a	U 237 6,75 d	U 238 99,2745	U 239 23,5 m	U 240 14,1 h		U 242 16,8 m
$\alpha$ 4,824; 4,783... Ne 25... $\gamma$ (42; 97...); e- g; m 47; m 530	$\alpha$ 4,775; 4,729... Mg 28; Ne 1; (53; 121...) $\gamma$ 95; m 0,006	$\alpha$ 4,398...; d Ne 109... $\gamma$ 95; g; g	$\alpha$ 4,494... 4,448... $\gamma$ 60; 208... $\gamma$ 113... $\gamma$ ; m 4	$\beta^-$ 0,2... $\gamma$ 60; 208... $\gamma$ 113... $\gamma$ ; m 4	$\beta^-$ 0,98 - 10 <sup>3</sup> a 4,458... $\gamma$ 149...; g $\gamma$ 122; m 15	$\beta^-$ 1,2; 1,3... $\gamma$ 75; 44... $\gamma$ 22; m 15	$\beta^-$ 0,4... $\gamma$ 44; (190...) e- m		$\beta^-$ 68; 58; 585; 573... m
Pa 232 1,31 d	Pa 233 27,0 d	Pa 234 1,17 m	Pa 235 6,70 h	Pa 236 24,2 m	Pa 237 9,1 m	Pa 238 8,7 m	Pa 239 2,3 m		
$\beta^-$ 0,3; 1,3...; e- $\gamma$ 969; 894; 150...; e- g; m 460; m 700	$\beta^-$ 0,3; 0... $\gamma$ 312; 300... 341...; e- g; m 20 + 18; m < 0	$\beta^-$ 2,2... 1,003... 287... m 74...; e- g; m 600... g; m 5000	$\beta^-$ 1,4... $\gamma$ 128 - 659... m	$\beta^-$ 2,0; 3,1... $\gamma$ 842; 587; 1763...; g g; f?	$\beta^-$ 1,4; 2,3... $\gamma$ 854; 865; 529; 541... g	$\beta^-$ 1,7; 2,9... $\gamma$ 1015; 635; 448; 680... g		148	150
Th 231 25,5 h	Th 232 100 1,405 - 10 <sup>19</sup> a m 4,013; 3,980...; sf $\gamma$ 104...; e- $\gamma$ 7,37...; m 0,000065	Th 233 22,3 m	Th 234 24,10 d	Th 235 7,1 m	Th 236 37,5 m	Th 237 5,0 m			

## Capture

$^{151}\text{Sm}$

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

$^{232}\text{Th}$

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

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

$^{139}\text{La}$

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

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

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

## Fission

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

$^{232}\text{Th}$

$^{209}\text{Bi}$

$^{237}\text{Np}$

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

# $n_{\_}$ TOF experiments 2002-4

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

## Capture

$^{151}\text{Sm}$

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

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

$^{232}\text{Th}$

$^{209}\text{Bi}$

$^{237}\text{Np}$

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

# $n_{\text{-}}\text{TOF experiments 2002-4}$

data analysis completed (14/36)

NOTE: TAC started operation in July 2004

## $n_{\text{-}}\text{TOF publications}$

Full papers : 13 (+4 in preparation)

Conference

Proceedings : 31

Documents

Total : 107

All docs on: [www.cern.ch/n\\_TOF](http://www.cern.ch/n_TOF)

## Capture

$^{151}\text{Sm}$

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

$^{232}\text{Th}$

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

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

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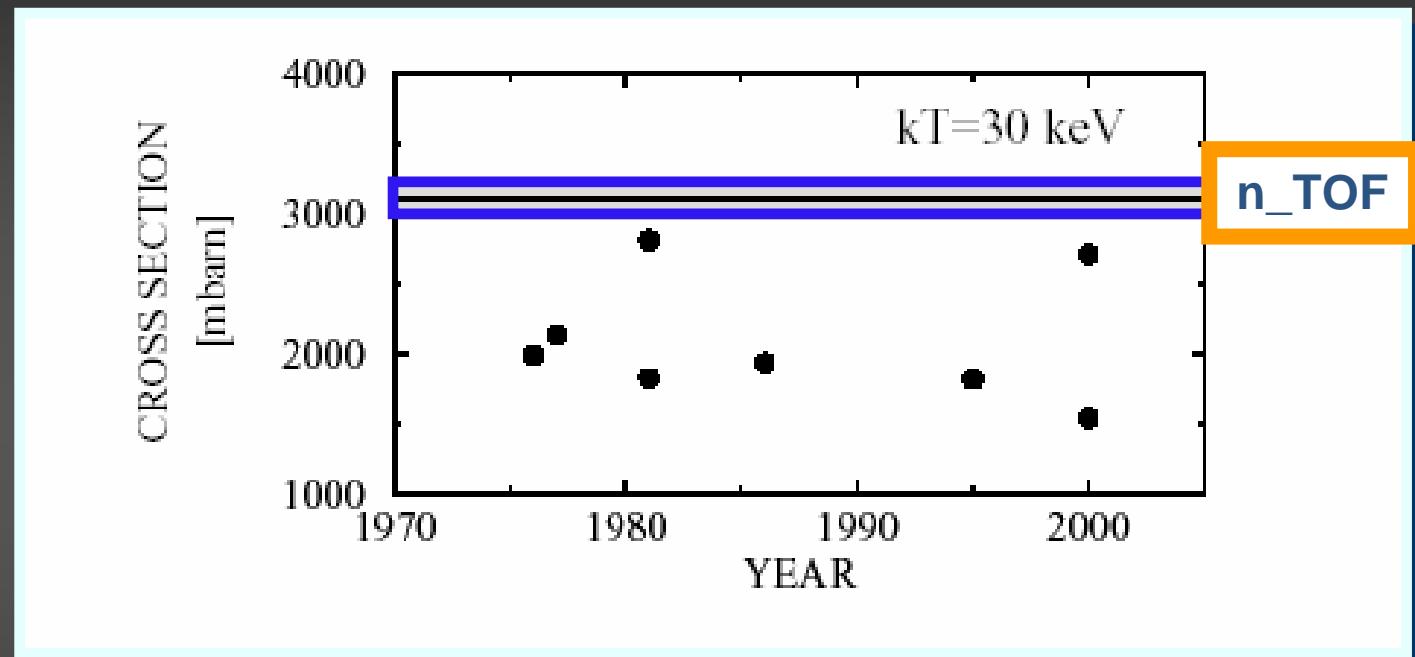
$^{237}\text{Np}$

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



# $n_{\_}$ TOF experiments

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



$$\text{MACS-30} = 3100 \pm 160 \text{ mb}$$

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

## Capture

$^{151}\text{Sm}$

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

$^{232}\text{Th}$

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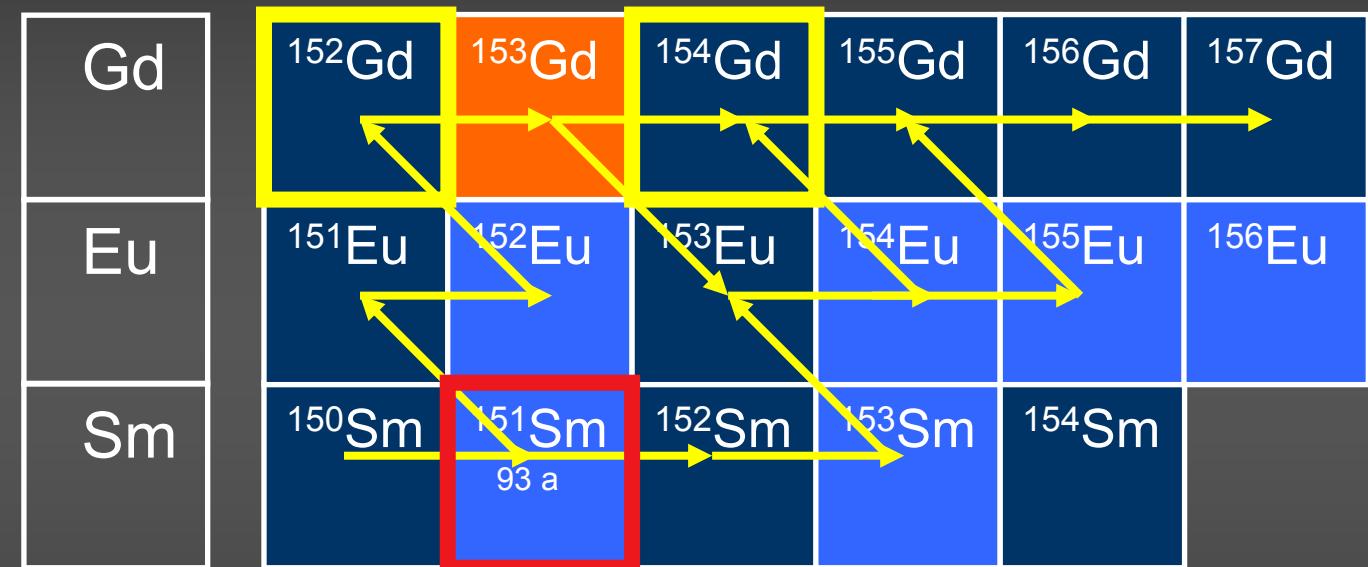
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# $n_{\text{-}}\text{TOF experiments}$

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

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

# Capture

$^{151}\text{Sm}$

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

$^{232}\text{Th}$

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

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

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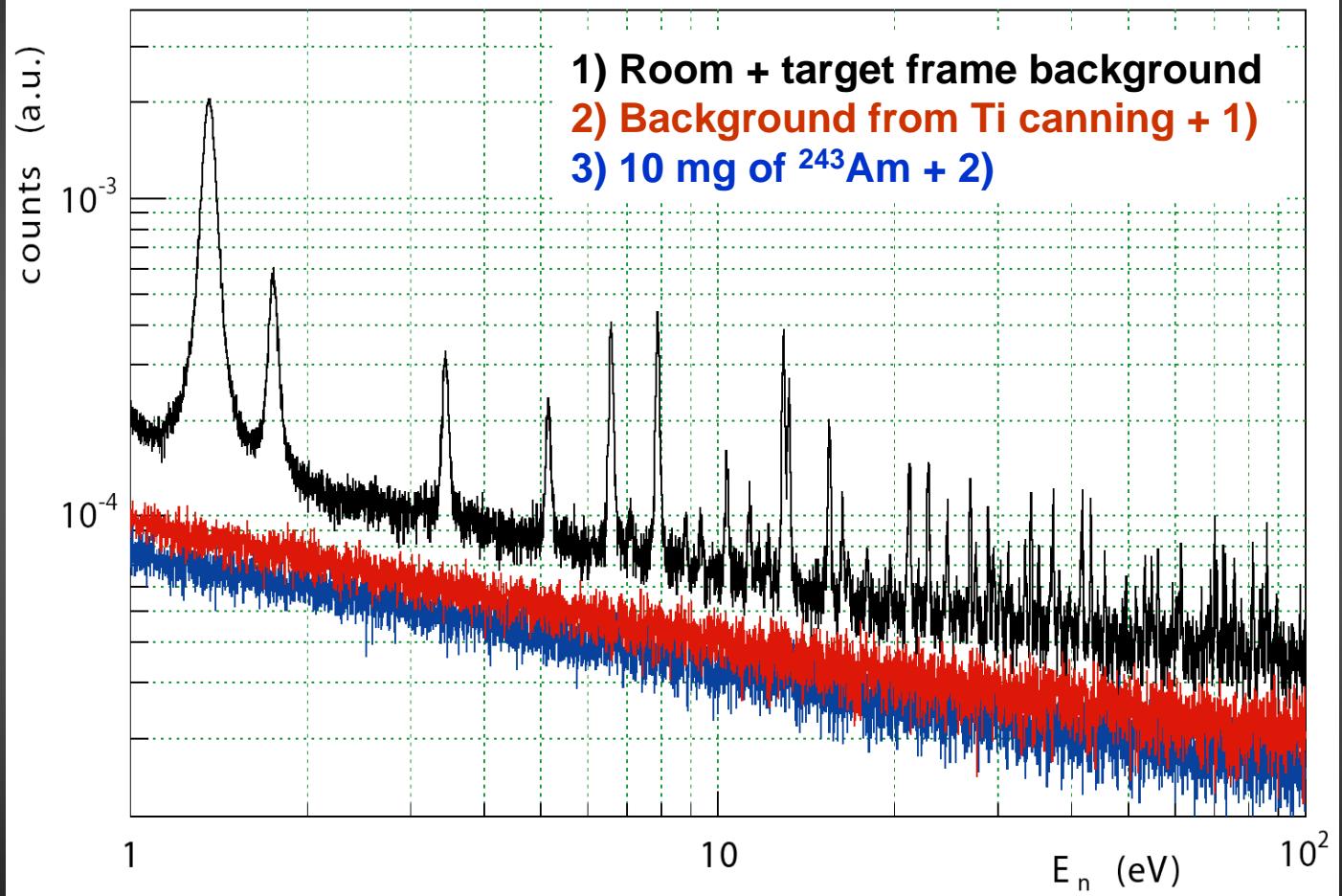
$^{241,243}\text{Am}$ ,  $^{245}\text{Cm}$



# $n_{\_}$ TOF experiments

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

Measurement performed in September 2004



First  $^{243}\text{Am}(n,\gamma)$  measurement EVER  
sample: 10 mg, 185 MBq activity

The  $n_{\_}$ TOF Collaboration

# Capture

$^{151}\text{Sm}$

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

$^{232}\text{Th}$

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

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

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# Fission

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

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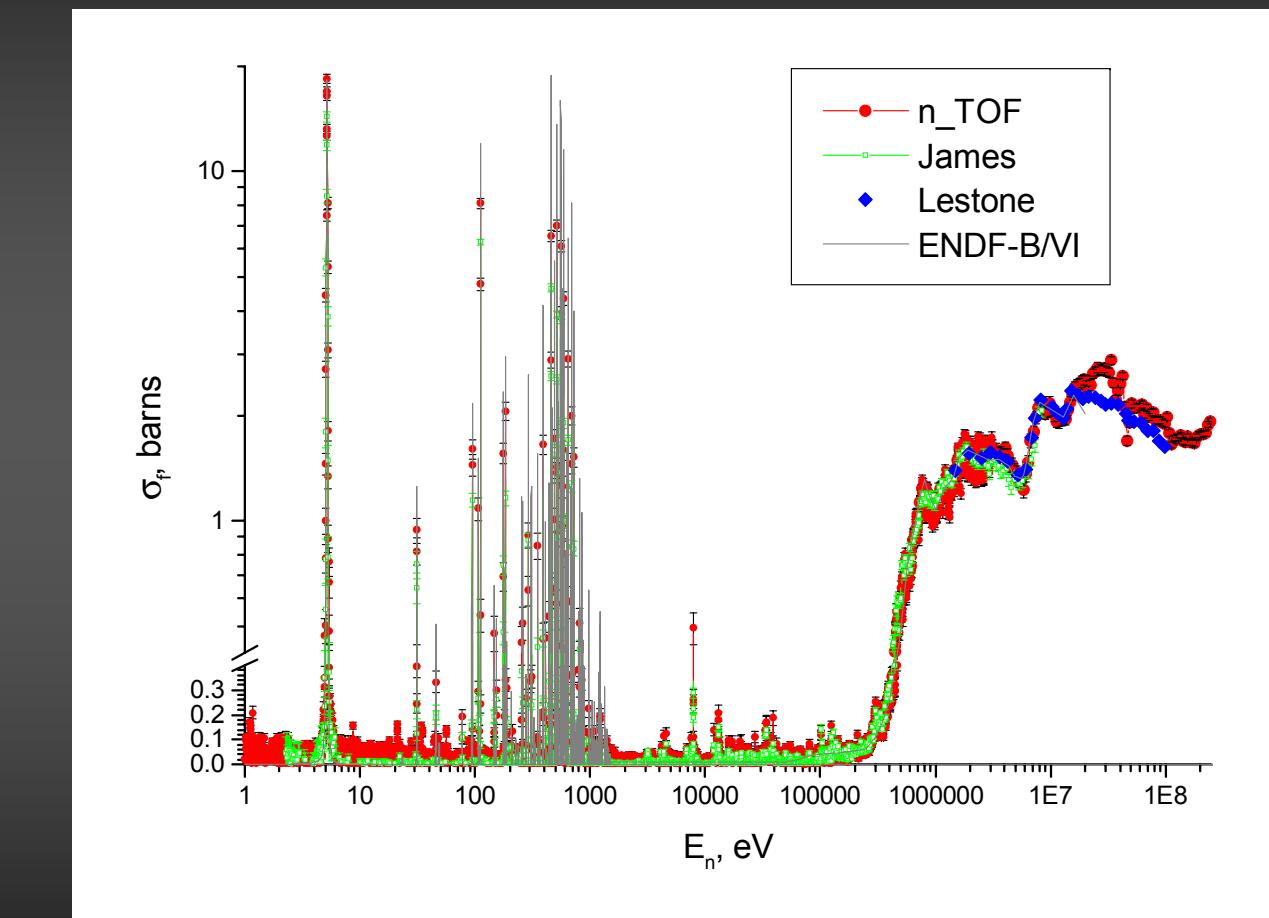
$^{241,243}\text{Am}, ^{245}\text{Cm}$



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

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

PPACs & FIC-0 (2003)



An unprecedented wide energy range can be explored at  $n_{\_}\text{TOF}$  in a single experiment

## Capture

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$^{232}\text{Th}$

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

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$^{232}\text{Th}$

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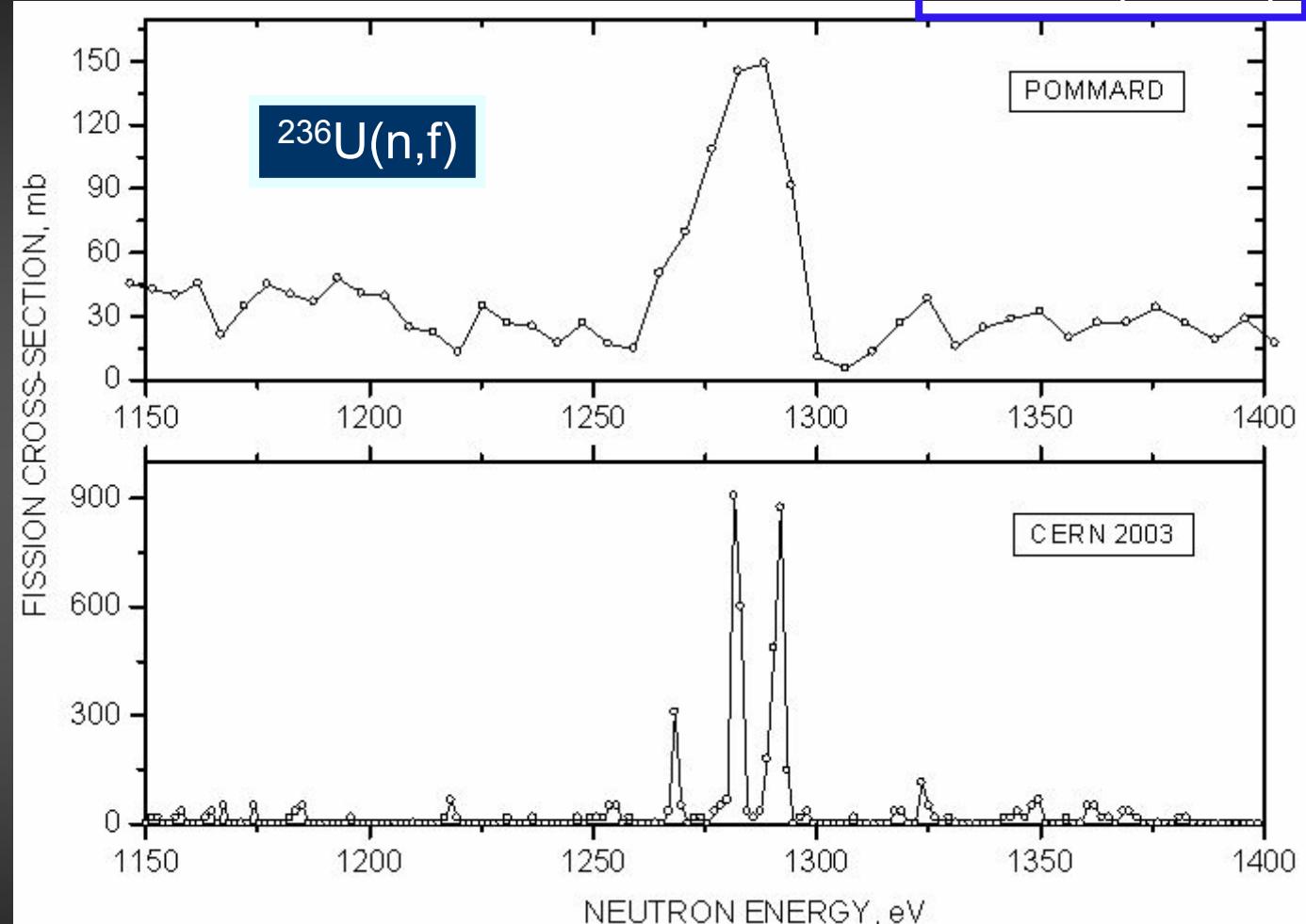
$^{237}\text{Np}$

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



# $n_{\_}$ TOF experiments

FIC-1 (2003)



The very high resolution of the  $n_{\_}$ TOF installation allows for studying fine neutron resonance structure

## Capture

$^{151}\text{Sm}$

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

$^{232}\text{Th}$

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

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## Fission

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

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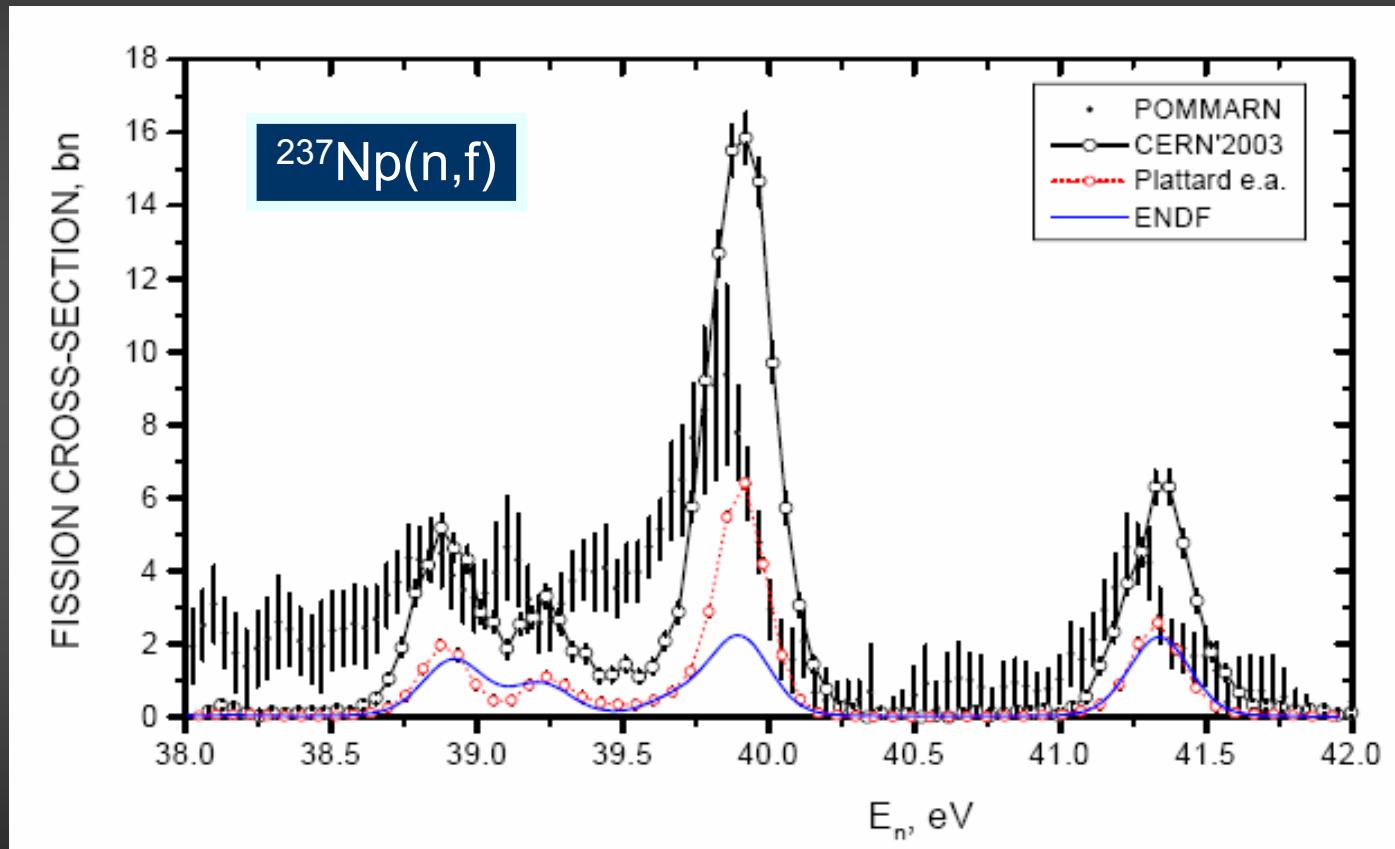
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# $n_{\_}$ TOF experiments

FIC-1 (2003)



The very high resolution of the  $n_{\_}$ TOF installation allows for studying 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)

$^{63}\text{Ni}$ ,  $^{79}\text{Se}$

s-process nucleosynthesis in massive stars

accurate nuclear data needs for structural materials

$A \approx 150$  (isotopes vari)

s-process branching points  
long-lived fission products

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

Th/U nuclear fuel cycle

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

standards, conventional U/Pu fuel cycle

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

incineration of minor actinides

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

# The n\_TOF-Ph2 experiments

## Fission measurements

MA

ADS, high-burnup, GEN-IV reactors

$^{235}\text{U}(n,f)$  with  $p(n,p')$

new  $^{235}\text{U}(n,f)$  cross section standard

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

study of vibrational resonances at the fission barrier

## Other measurements

$^{147}\text{Sm}(n,\alpha)$ ,  $^{67}\text{Zn}(n,\alpha)$ ,  $^{99}\text{Ru}(n,\alpha)$

p-process studies

$^{58}\text{Ni}(n,p)$ , other  $(n,lcp)$

gas production in structural materials

Al, V, Cr, Zr, Th,  $^{238}\text{U}(n,lcp)$

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

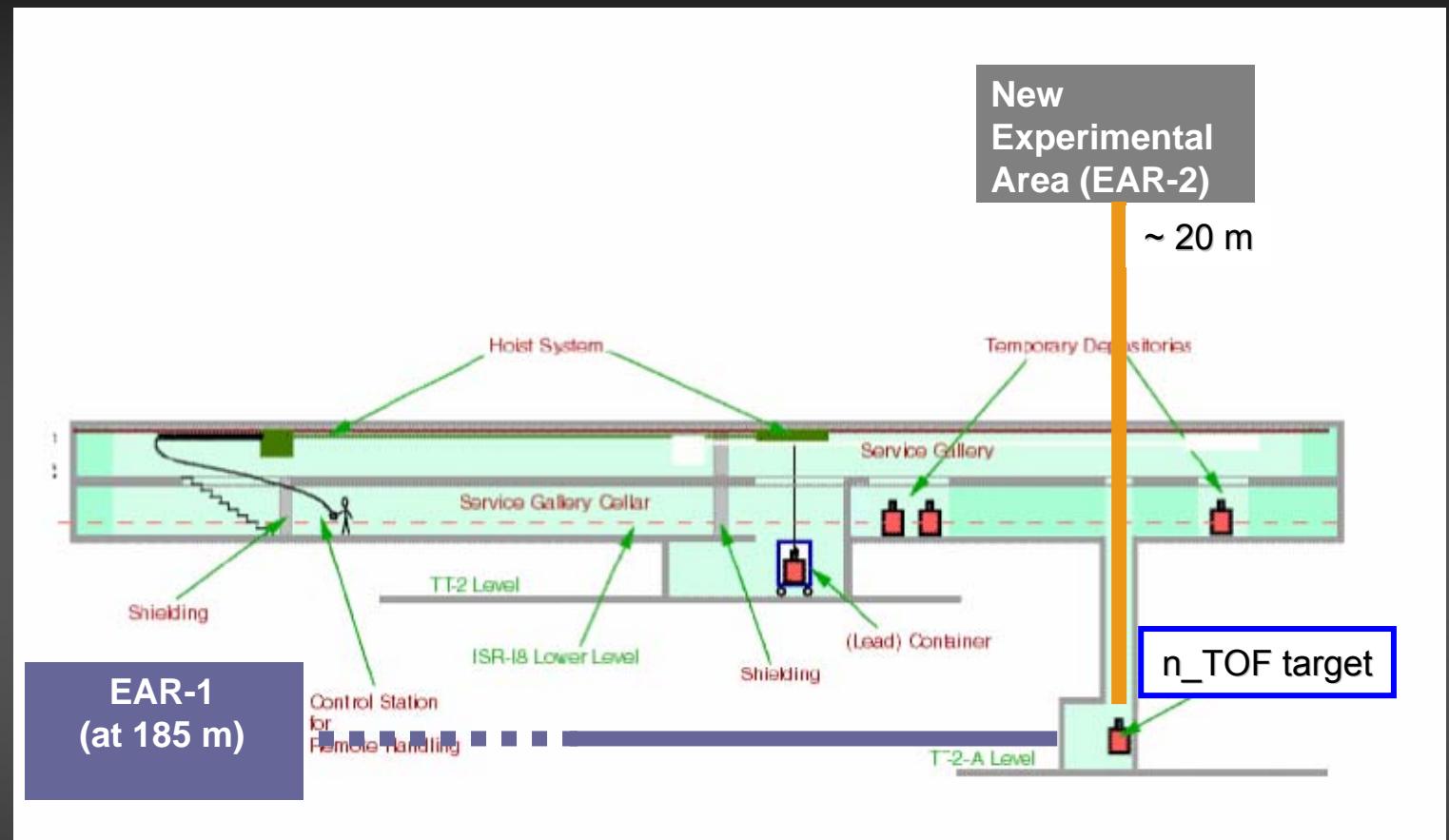
## In FP6

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: $^{151}\text{Sm}$ case)	consequences for sample mass
■ sample mass / 3 s/bkgd=1	✓ 50 mg
■ use $\text{BaF}_2$ TAC	$\epsilon \times 10$ ✓ 5 mg
■ use $\text{D}_2\text{O}$	$\Phi_{30} \times 5$ ■ 1 mg
■ use 20 m flight path	$\Phi_{30} \times 100$ ■ 10 $\mu\text{g}$

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<sup>14</sup>, G.Aerts<sup>7</sup>, H.Álvarez<sup>24</sup>, F.Alvarez-Velarde<sup>20</sup>, S.Andriamonje<sup>7</sup>, J.Andrzejewski<sup>33</sup>, P.Assimakopoulos<sup>9</sup>, L.Audouin<sup>5</sup>, G.Badurek<sup>1</sup>, P.Baumann<sup>6</sup>, F.Becvář<sup>31</sup>, J.Benlliure<sup>24</sup>, E.Berthoumieux<sup>7</sup>, F.Calviño<sup>25</sup>, D.Cano-Ott<sup>20</sup>, R.Capote<sup>23</sup>, A.Carrillo de Albornoz<sup>30</sup>, P.Cennini<sup>4</sup>, V.Chepel<sup>7</sup>, E.Chiaveri<sup>4</sup>, N.Colonna<sup>13</sup>, G.Cortes<sup>25</sup>, D.Cortina<sup>24</sup>, A.Couture<sup>29</sup>, J.Cox<sup>29</sup>, S.David<sup>5</sup>, R.Dolfini<sup>15</sup>, C.Domingo-Pardo<sup>21</sup>, W.Dridi<sup>7</sup>, I.Duran<sup>24</sup>, M.Embidi-Segura<sup>20</sup>, L.Ferrant<sup>5</sup>, A.Ferrari<sup>4</sup>, R.Ferreira-Marques<sup>17</sup>, L.Fitzpatrick<sup>4</sup>, H.Frais-Koelbl<sup>3</sup>, K.Fujii<sup>13</sup>, W.Furman<sup>18</sup>, C.Guerrero<sup>20</sup>, I.Goncalves<sup>30</sup>, R.Gallino<sup>36</sup>, E.Gonzalez-Romero<sup>20</sup>, A.Goverdovski<sup>19</sup>, F.Gramegna<sup>12</sup>, E.Griesmayer<sup>3</sup>, F.Gunsing<sup>7</sup>, B.Haas<sup>32</sup>, R.Haight<sup>27</sup>, M.Heil<sup>8</sup>, A.Herrera-Martinez<sup>4</sup>, M.Igashira<sup>37</sup>, S.Isaev<sup>5</sup>, E.Jericha<sup>1</sup>, Y.Kadi<sup>4</sup>, F.Käppeler<sup>8</sup>, D.Karamanis<sup>9</sup>, D.Karadimos<sup>9</sup>, M.Kerveno<sup>6</sup>, V.Ketlerov<sup>19</sup>, P.Koehler<sup>28</sup>, V.Konovalov<sup>18</sup>, E.Kossionides<sup>39</sup>, M.Krtička<sup>31</sup>, C.Lamboudis<sup>10</sup>, H.Leeb<sup>1</sup>, A.Lindote<sup>17</sup>, I.Lopes<sup>17</sup>, M.Lozano<sup>23</sup>, S.Lukic<sup>6</sup>, J.Marganiec<sup>33</sup>, L.Marques<sup>30</sup>, S.Marrone<sup>13</sup>, P.Mastinu<sup>12</sup>, A.Mengoni<sup>4</sup>, P.M.Milazzo<sup>14</sup>, C.Moreau<sup>14</sup>, M.Mosconi<sup>8</sup>, F.Neves<sup>17</sup>, H.Oberhummer<sup>1</sup>, S.O'Brien<sup>29</sup>, M.Oshima<sup>38</sup>, J.Pancin<sup>7</sup>, C.Papachristodoulou<sup>9</sup>, C.Papadopoulos<sup>40</sup>, C.Paradela<sup>24</sup>, N.Patronis<sup>9</sup>, A.Pavlik<sup>2</sup>, P.Pavlopoulos<sup>34</sup>, L.Perrot<sup>7</sup>, R.Plag<sup>8</sup>, A.Plompens<sup>16</sup>, A.Plukis<sup>7</sup>, A.Poch<sup>25</sup>, C.Pretel<sup>25</sup>, J.Quesada<sup>23</sup>, T.Rauscher<sup>26</sup>, R.Reifarth<sup>27</sup>, M.Rosetti<sup>11</sup>, C.Rubbia<sup>5</sup>, G.Rudolf<sup>6</sup>, P.Rullhusen<sup>16</sup>, J.Salgado<sup>30</sup>, L.Sarchiapone<sup>4</sup>, C.Stephan<sup>5</sup>, G.Tagliente<sup>13</sup>, J.L.Tain<sup>21</sup>, L.Tassan-Got<sup>5</sup>, L.Tavora<sup>30</sup>, R.Terlizzi<sup>13</sup>, G.Vannini<sup>35</sup>, P.Vaz<sup>30</sup>, A.Ventura<sup>11</sup>, D.Villamarin<sup>20</sup>, M.C.Vincente<sup>20</sup>, V.Vlachoudis<sup>4</sup>, R.Vlastou<sup>40</sup>, F.Voss<sup>8</sup>, H.Wendler<sup>4</sup>, M.Wiescher<sup>29</sup>, K.Wisshak<sup>8</sup>

41 Research Groups  
120 researchers

# 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

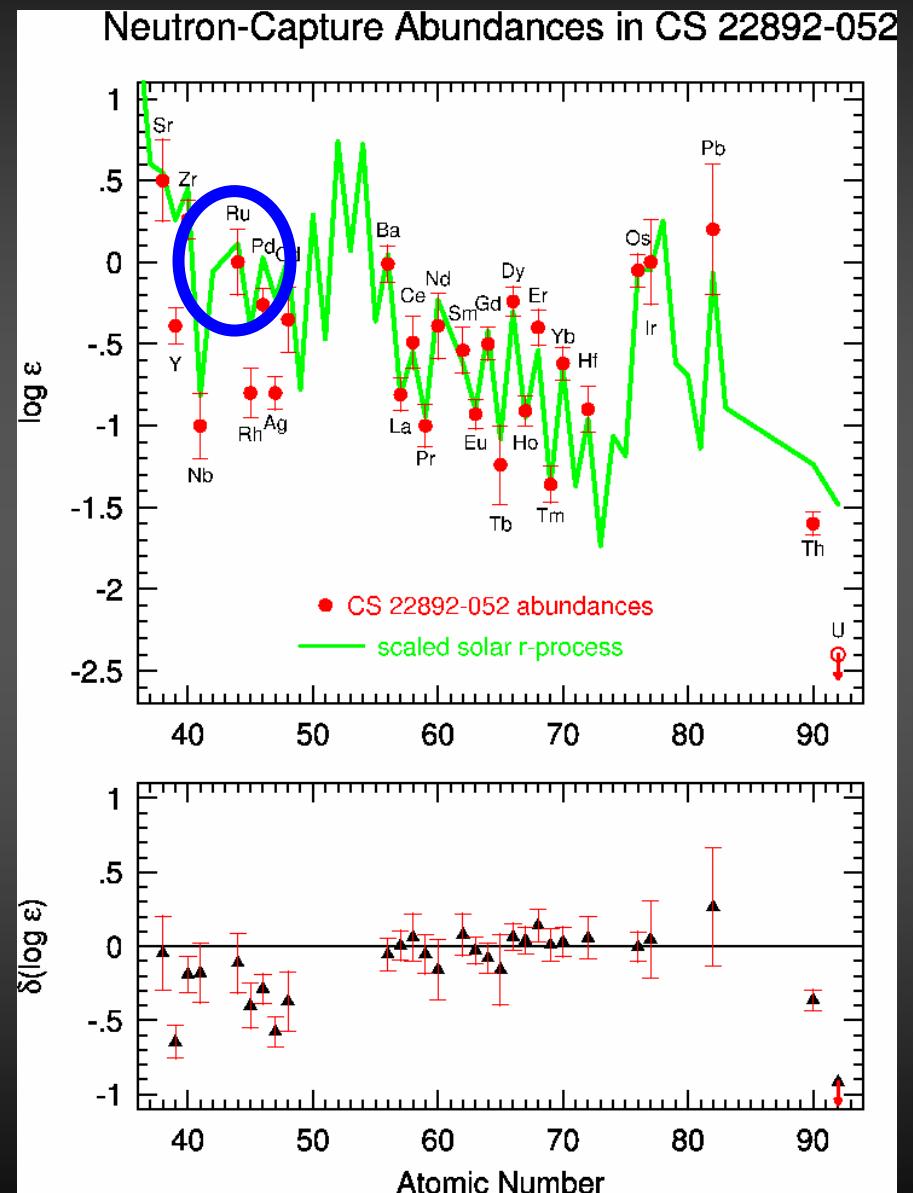
# Capture studies

# 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.

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



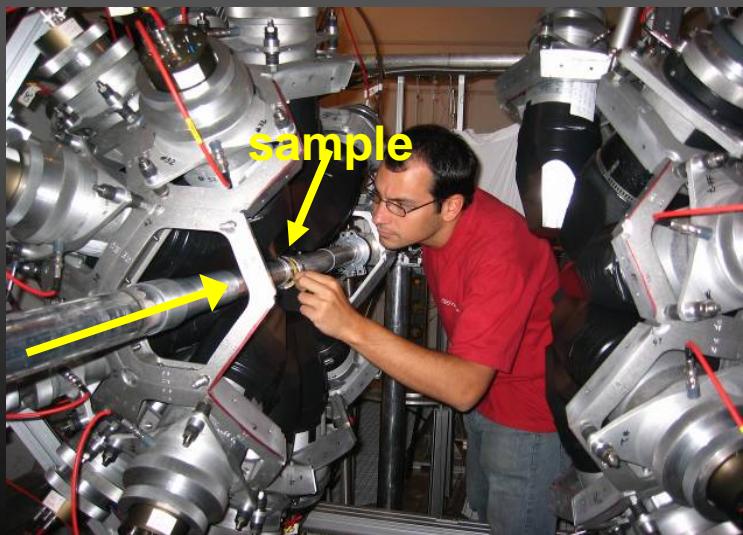
n\_TOF-Ph2

# Capture studies: Mo, Ru, and Pd

- Setup: The **n\_TOF TAC** in EAR-1  
(a few cases with C<sub>6</sub>D<sub>6</sub> if larger neutron scattering)
- All samples are stable and non-hazardous
- Metal samples preferable (oxides acceptable)

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



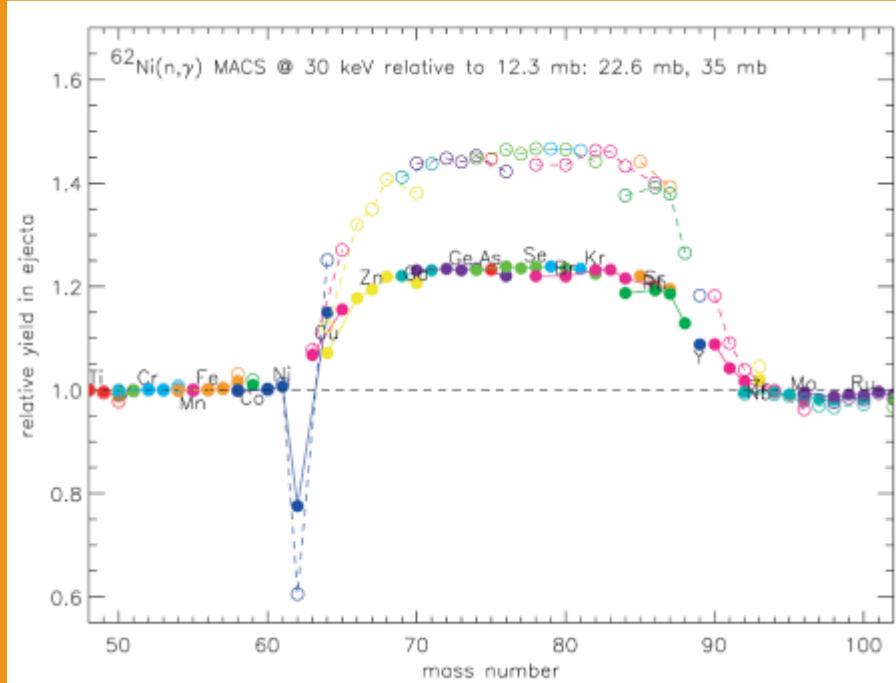
Cd 97	Cd 98	Cd 99	Cd 100	Cd 101	Cd 102	Cd 103	Cd 104	Cd 105	Cd 106	Cd 107	Cd 108	Cd 109	Cd 110	Cd 111	Cd 112	Cd 113
Ag 96	Ag 97	Ag 98	Ag 99	Ag 100	Ag 101	Ag 102	Ag 103	Ag 104	Ag 105	Ag 106	Ag 107	Ag 108	Ag 109	Ag 110	Ag 111	Ag 112
Pd 95	Pd 96	Pd 97	Pd 98	Pd 99	Pd 100	Pd 101	Pd 102	Pd 103	Pd 104	Pd 105	Pd 106	Pd 107	Pd 108	Pd 109	Pd 110	Pd 111
Rh 94	Rh 95	Rh 96	Rh 97	Rh 98	Rh 99	Rh 100	Rh 101	Rh 102	Rh 103	Rh 104	Rh 105	Rh 106	Rh 107	Rh 108	Rh 109	Rh 110
Ru 93	Ru 94	Ru 95	Ru 96	Ru 97	Ru 98	Ru 99	Ru 100	Ru 101	Ru 102	Ru 103	Ru 104	Ru 105	Ru 106	Ru 107	Ru 108	Ru 109
Tc 92	Tc 93	Tc 94	Tc 95	Tc 96	Tc 97	Tc 98	Tc 99	Tc 100	Tc 101	Tc 102	Tc 103	Tc 104	Tc 105	Tc 106	Tc 107	Tc 108
Mo 91	Mo 92	Mo 93	Mo 94	Mo 95	Mo 96	Mo 97	Mo 98	Mo 99	Mo 100	Mo 101	Mo 102	Mo 103	Mo 104	Mo 105	Mo 106	Mo 107
Nb 90	Nb 91	Nb 92	Nb 93	Nb 94	Nb 95	Nb 96	Nb 97	Nb 98	Nb 99	Nb 100	Nb 101	Nb 102	Nb 103	Nb 104	Nb 105	Nb 106
Zr 86	Zr 87	Zr 88	Zr 89	Zr 90	Zr 91	Zr 92	Zr 93	Zr 94	Zr 95	Zr 96	Zr 97	Zr 98	Zr 99	Zr 100	Zr 101	Zr 102
Y 80	Y 81	Y 82	Y 83	Y 84	Y 85	Y 86	Y 87	Y 88	Y 89	Y 90	Y 91	Y 92	Y 93	Y 94	Y 95	Y 96

n\_TOF-Ph2

# 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:  $^{62}\text{Ni}$ )



## 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

34	Kr 73 26.8	Kr 74 11.5 m	Kr 75 4.5 m	Kr 76 14.6 h	Kr 77 1.24 h	Kr 78 0.35	Kr 79 59 s	Kr 80 2.25	Kr 81 13.1 s	Kr 82 11.6	Kr 83 1.84 h	Kr 84 57.0	Kr 85 4.48 h	Kr 86 17.3			
	$\mu^+$ : 2.0; 2.2... $\gamma$ : 170; 241; 409... $\delta\tau$ : 17 - 3.0	$\mu^+$ : 2.0; 2.2... $\gamma$ : 50; 208; 297... 63; 327... $\delta\tau$ : 138 - 165...	$\mu^+$ : 3.2... $\gamma$ : 138 - 165...	$\gamma$ : 318; 270; 48... 407... 8...	$\beta^-$ : 1.8... $\gamma$ : 180; 147... 9 m...	$\gamma$ : 0.17 + 0.1...	$\gamma$ : 198...	$\gamma$ : 162...	$\gamma$ : 162...	$\gamma$ : 17...	$\gamma$ : 17...	$\gamma$ : 0.03 + 0.02...	$\gamma$ : 17...	$\gamma$ : 0.03			
	Br 72 10.3 s	Br 73 3.3 m	Br 74 48 m	Br 74 25.4 m	Br 75 1.6 h	Br 76 1.22 s	Br 76 11.8 h	Br 77 4.3 m	Br 77 6.46 m	Br 78 4.8 s	Br 78 58.69	Br 79 4.43 h	Br 80 17.6 m	Br 81 49.31			
32	Se 71 4.74 m	Se 72 8.5 d	Se 73 38 m	Se 73 7.1 s	Se 74 0.89	Se 75 118.64 d	Se 76 + 16	Se 76 9.36	Se 77 17.56	Se 77 22.78	Se 78 3.9 s	Se 79 39 s	Se 80 49.61	Se 81 73.8 s	Se 82 8.73	Se 83 82 s	Se 84 3.1 m
	$\mu^+$ : 5.8... $\gamma$ : 47; 1095... 580...	$\mu^+$ : no $\mu^+$ $\gamma$ : 45...	$\mu^+$ : 2.9... $\gamma$ : 17...	$\mu^+$ : 2.2... $\gamma$ : 135; 215... 222...	$\mu^+$ : 1.7...	$\gamma$ : 205; 196... 82; 121; 401... 332...	$\gamma$ : 32 + 9.9...	$\gamma$ : 162...	$\gamma$ : 162...	$\gamma$ : 162...	$\gamma$ : 162...	$\gamma$ : 0.07 + 0.05...	$\gamma$ : 0.07 + 0.05...	$\gamma$ : 0.05 + 0.05...	$\gamma$ : 0.03 + 0.03...	$\gamma$ : 0.02 + 0.02...	
	As 70 53 m	As 71 65.29 h	As 72 26.0 h	As 73 80.3 d	As 74 17.77 d	As 75 100	As 76 26.4 h	As 77 38.5 h	As 78 1.5 h	As 79 8.2 m	As 80 15.2 s	As 81 34 s	As 82 14.5 s	As 83 13.3 s			
30	Ge 69 39.0 h	Ge 70 21.23	Ge 71 11.43 d	Ge 72 27.86	Ge 73 7.73	Ge 74 35.34	Ge 75 47 s	Ge 76 83 m	Ge 76 1.53 - 10 <sup>21</sup> s	Ge 77 53 s	Ge 78 88 m	Ge 79 39 s	Ge 80 29.5 s	Ge 81 78 s	Ge 82 4.60 s		
	$\mu^+$ : 1.2... 2.1107; 3.24... 2.72; 3.36...	$\mu^+$ : 3.0...	$\mu^+$ : no $\mu^+$ $\gamma$ : 1.8...	$\mu^+$ : 1.5...	$\mu^+$ : 1.4 + 1.28...	$\gamma$ : 100...	$\gamma$ : 100...	$\gamma$ : 100...	$\gamma$ : 100...	$\gamma$ : 100...	$\gamma$ : 100...	$\gamma$ : 100...	$\gamma$ : 100...	$\gamma$ : 100...	$\gamma$ : 100...	$\gamma$ : 100...	

## The <sup>79</sup>Se case

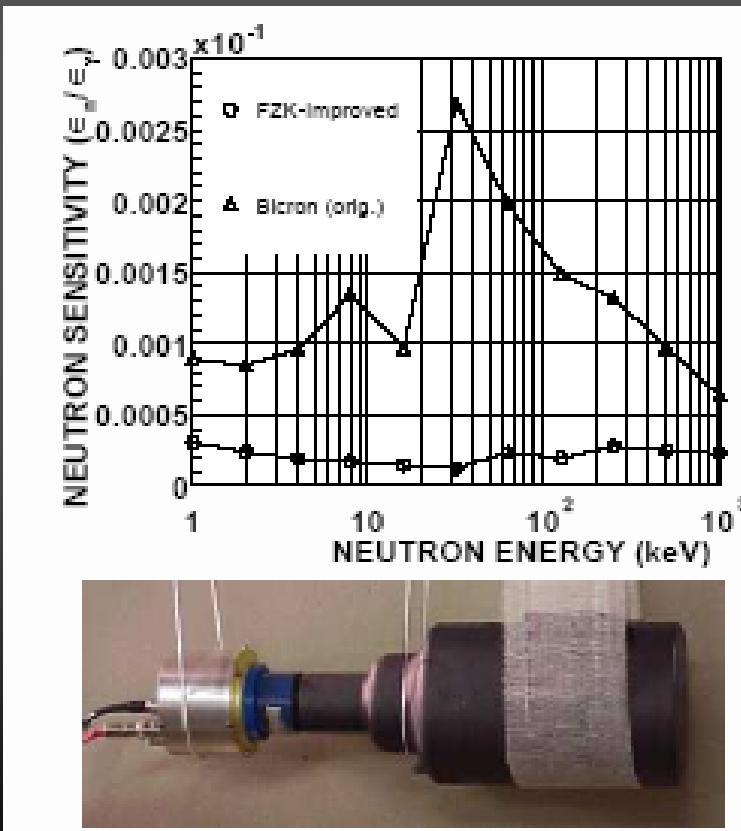
- s-process branching: neutron density & temperature conditions for the weak component.
- $t_{1/2} < 6.5 \times 10^4$  yr

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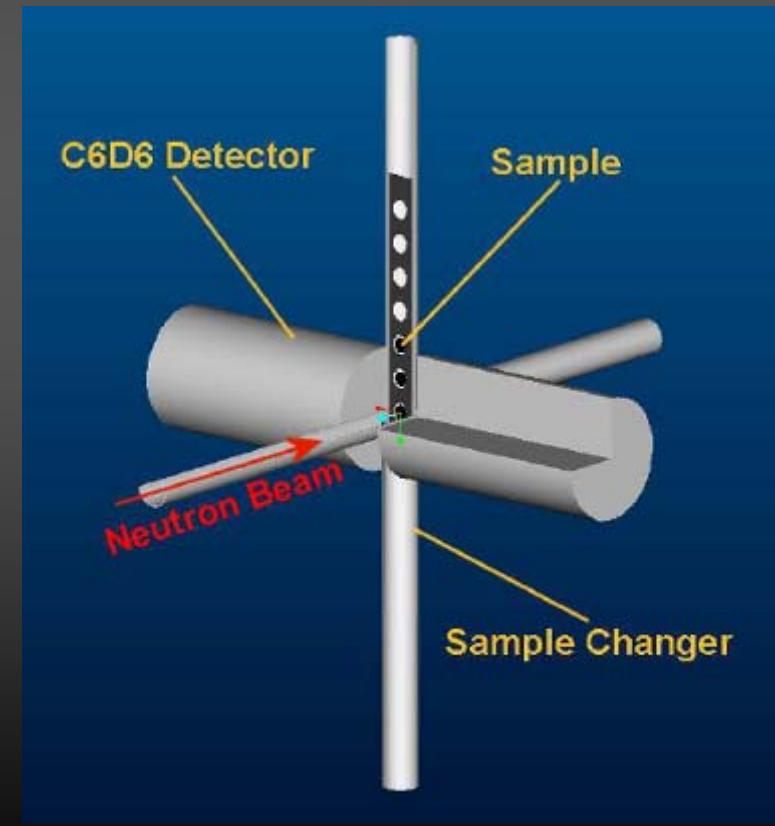
# Capture studies: Fe, Ni, Zn and Se

- Setup:  $\text{C}_6\text{D}_6$  in EAR-1
- All samples are stable(\*) and non-hazardous
- Metal samples preferable (oxides acceptable)

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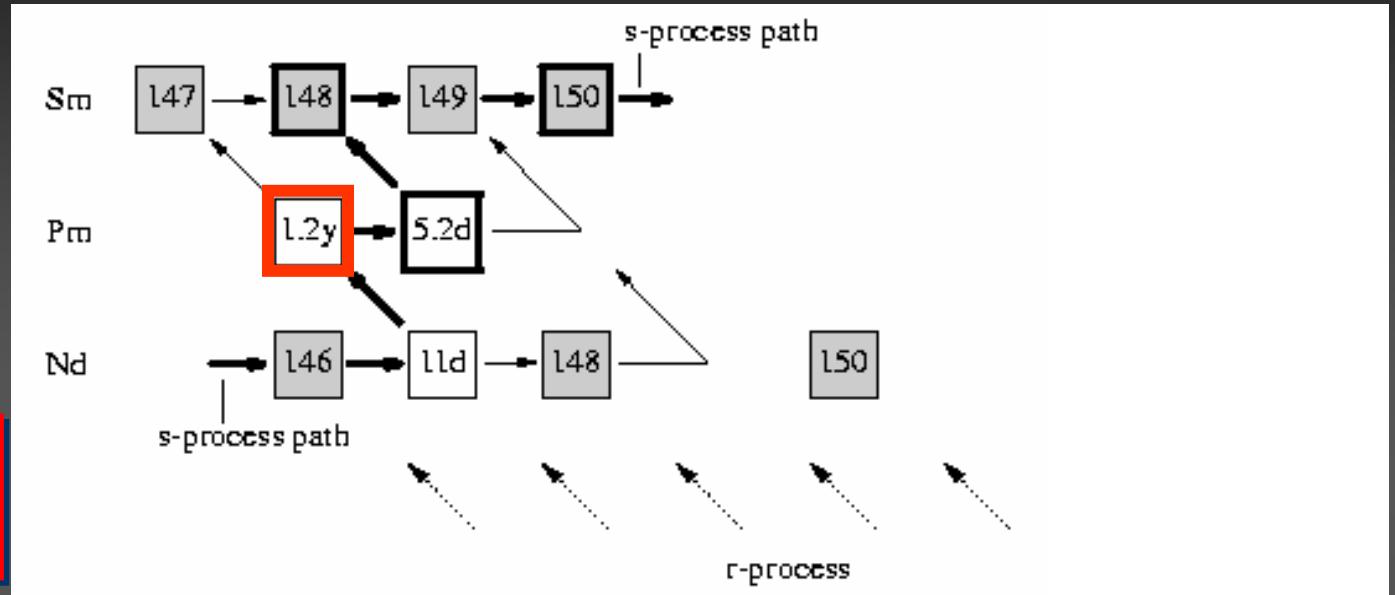


(\*) except  $^{79}\text{Se}$



# Capture studies: $A \approx 150$

- EAR-2 required
- Sample from ISOLDE?



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

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# Capture studies: actinides

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

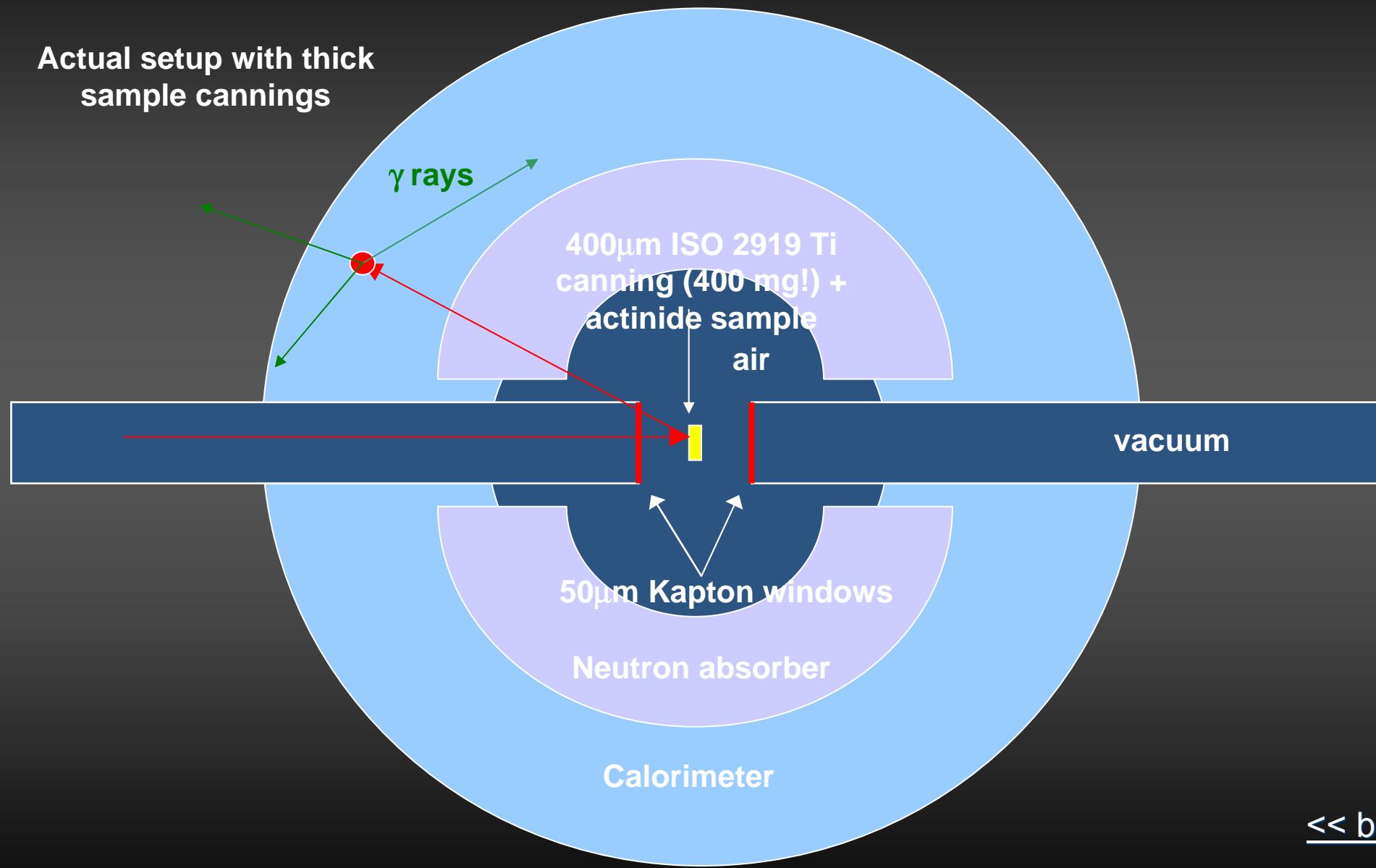
$^{241,243}\text{Am}$	The most important neutron poison in the fuels proposed for transmutation scenarios. Build up of Cm isotopes.
$^{239,240,242}\text{Pu}$	(n, $\gamma$ ) and (n,f) with active canning. Build up of Am and Cm isotopes.
$^{245}\text{Cm}$	No data available.
$^{235,238}\text{U}$	Improvement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

All measurements can be done in EAR-1 (except  $^{233}\text{Pa}$ )

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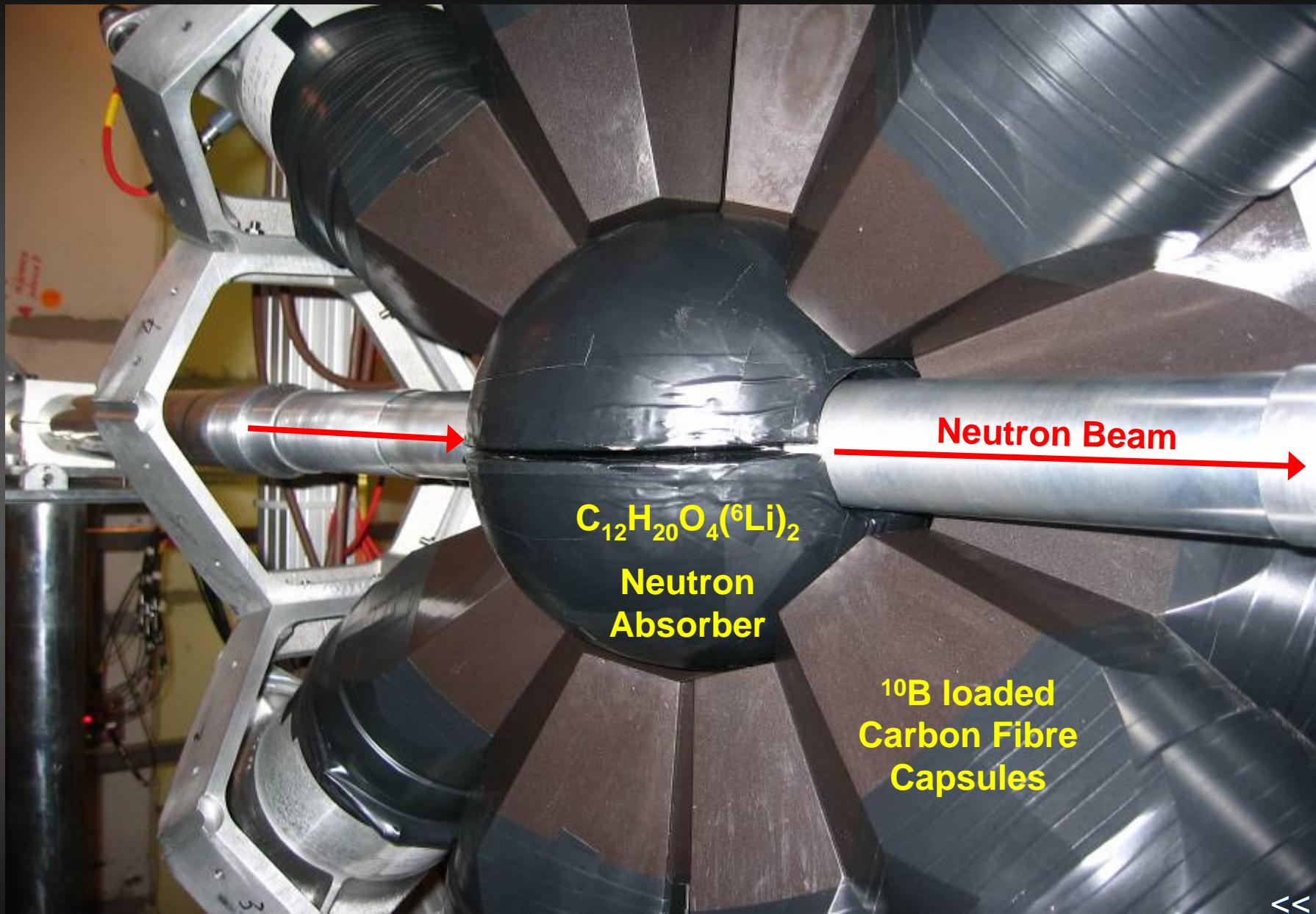
# Capture studies: actual TAC setup

Actual setup with thick sample canning



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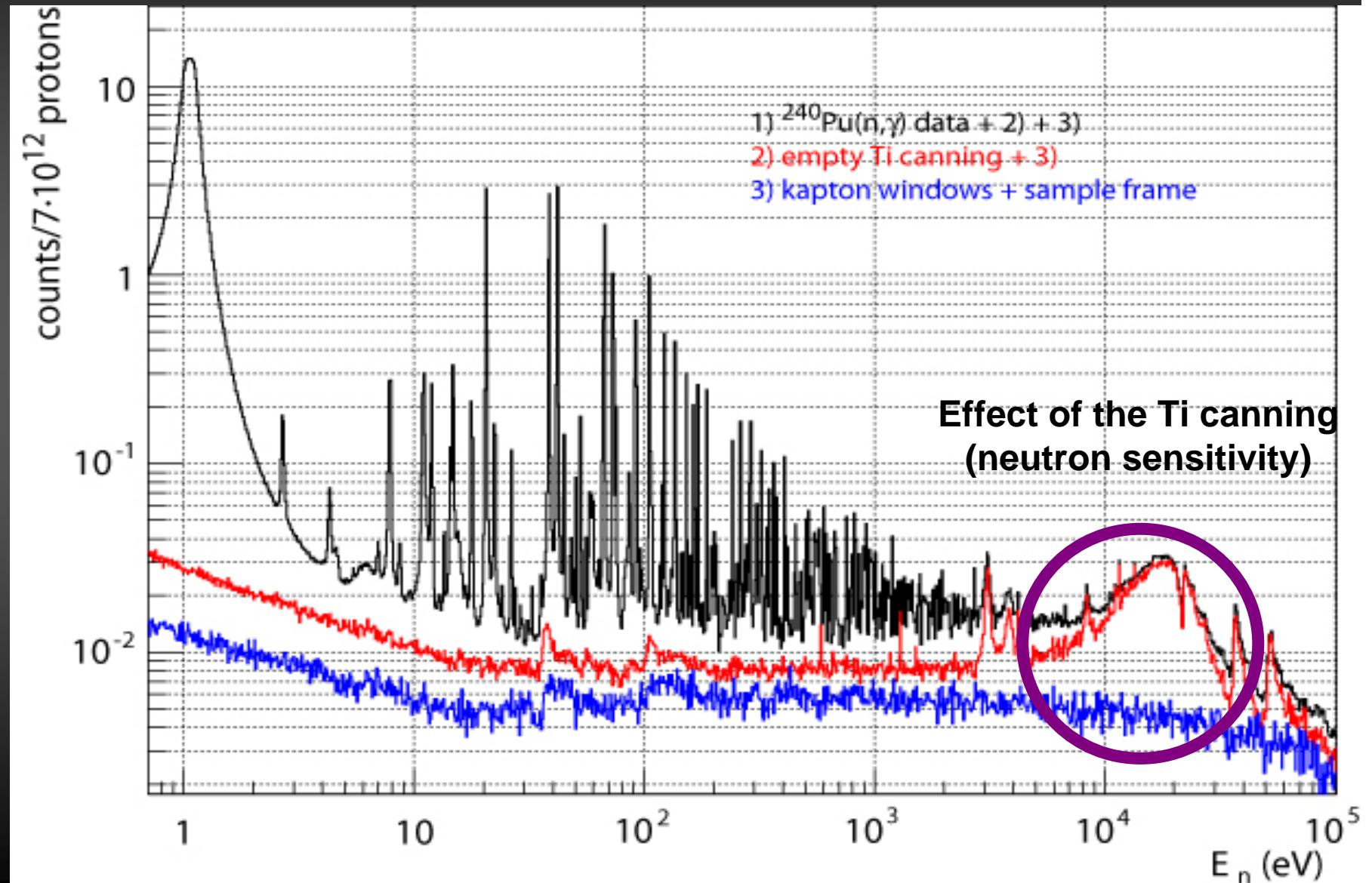
n\_TOF-Ph2



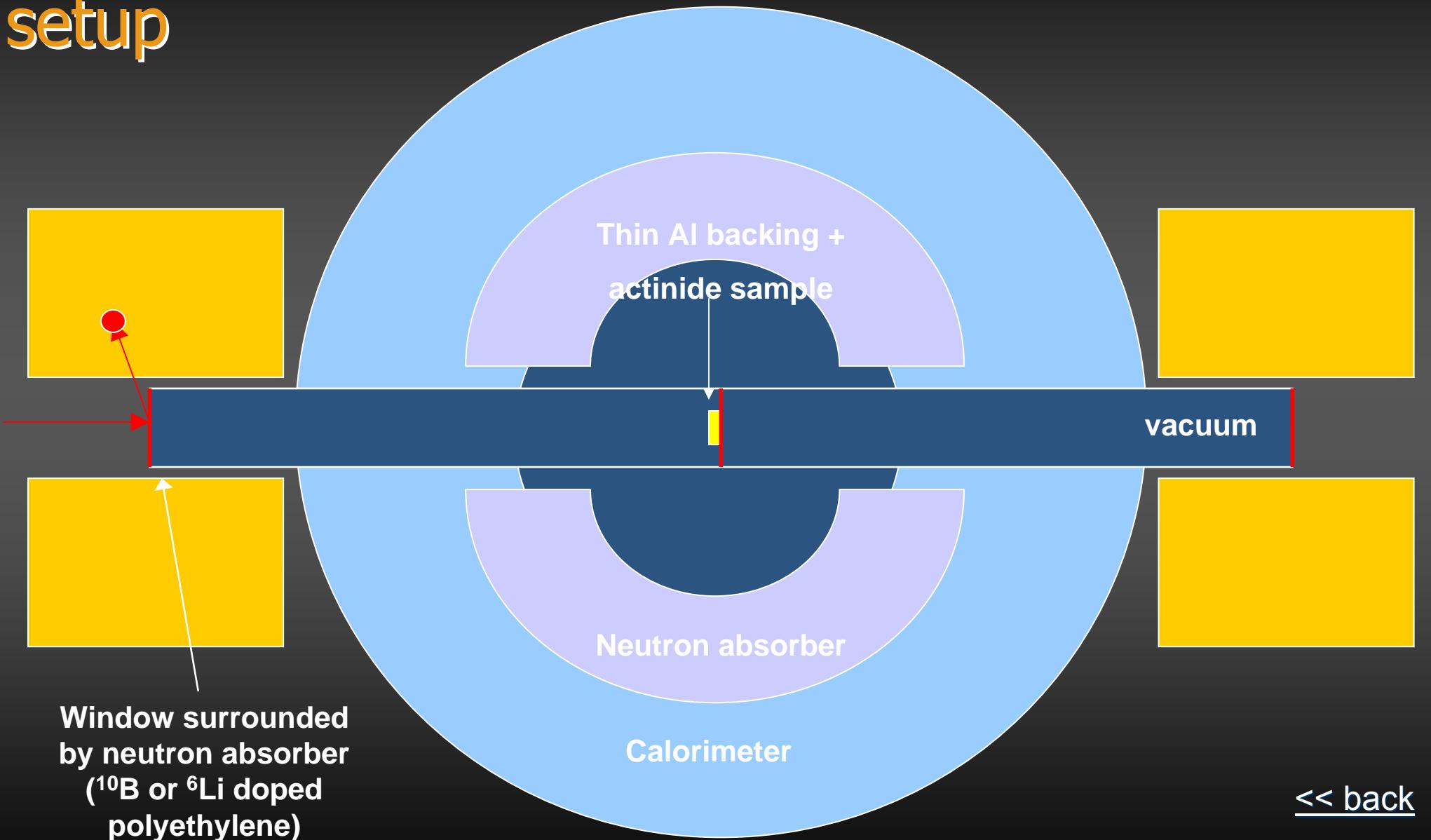
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n\_TOF-Ph2

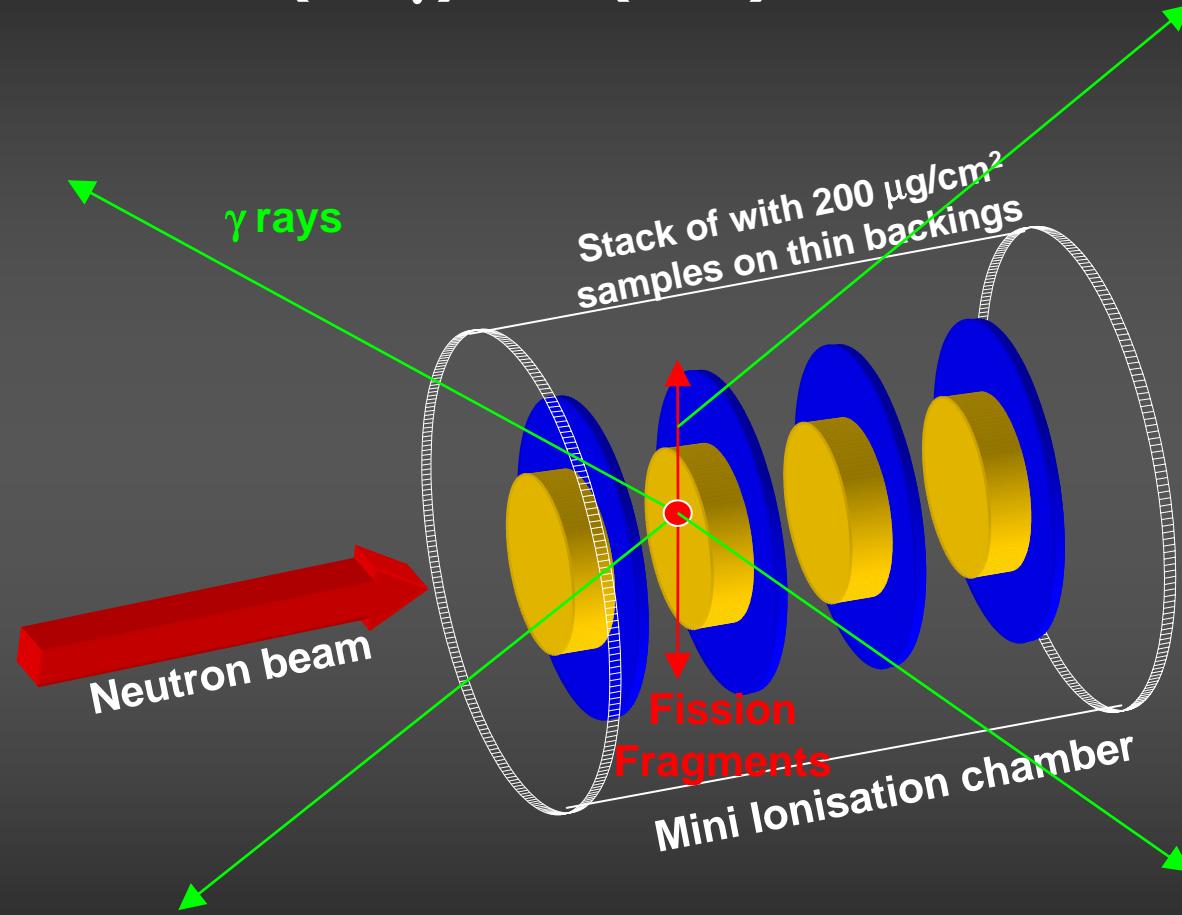
# Capture studies: actual TAC setup



# Capture studies: Low neutron sensitivity setup



# Capture studies: active canning for simultaneous $(n,\gamma)$ & $(n,f)$ measurements

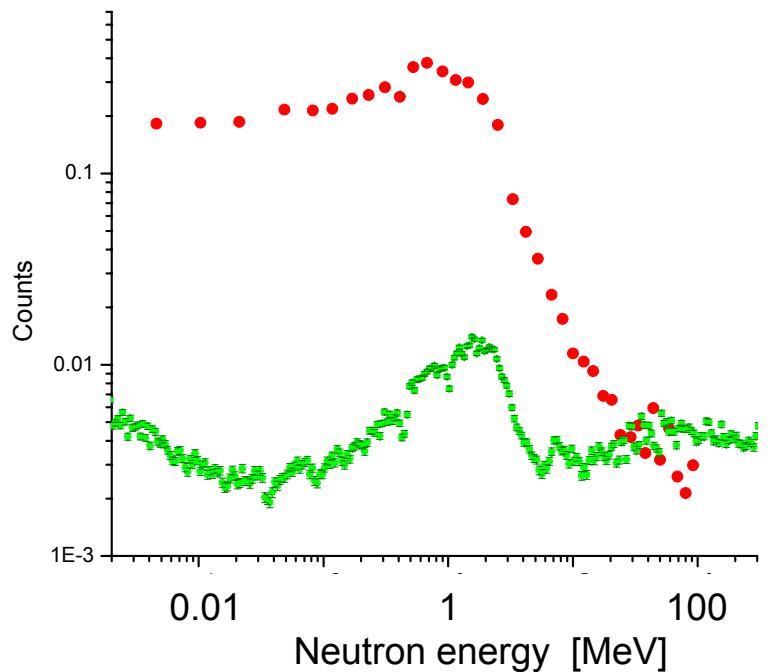
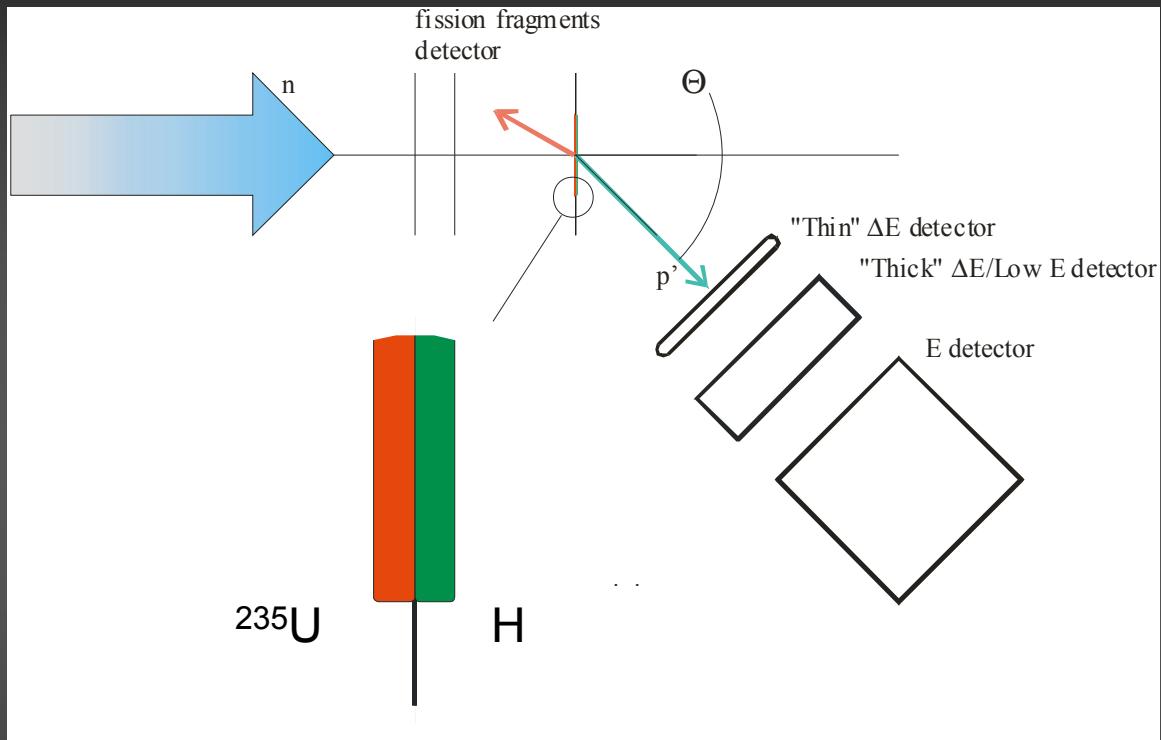


Measurement of capture cross sections of fissile materials (veto) and measurement of the  $(n,\gamma)/(n,f)$  ratio.

# Fission studies

# Fission studies

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



Beam	capture mode (2 mm Ø)
Scattering angle	30°
Target thickness	250 µg/cm²
Detector radius	20 mm
Target-to-detector distance	250 mm

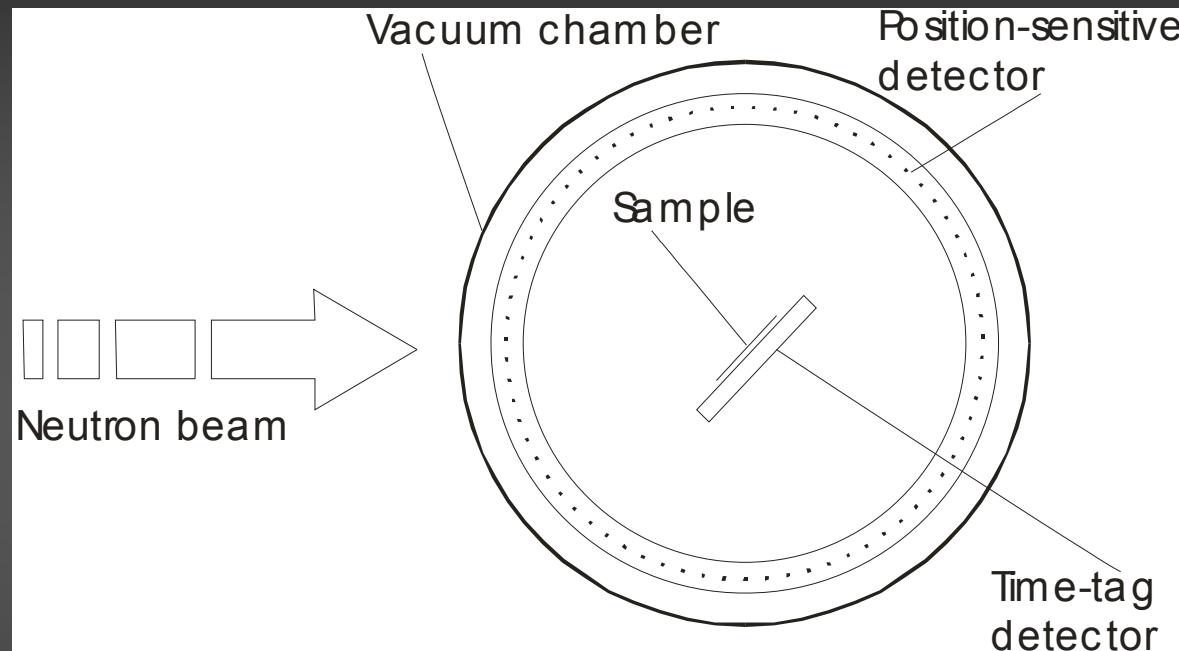
$(n,p)$  larger or comparable up to 100 MeV

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n\_TOF-Ph2

# Fission studies

## FF distributions in vibrational resonances

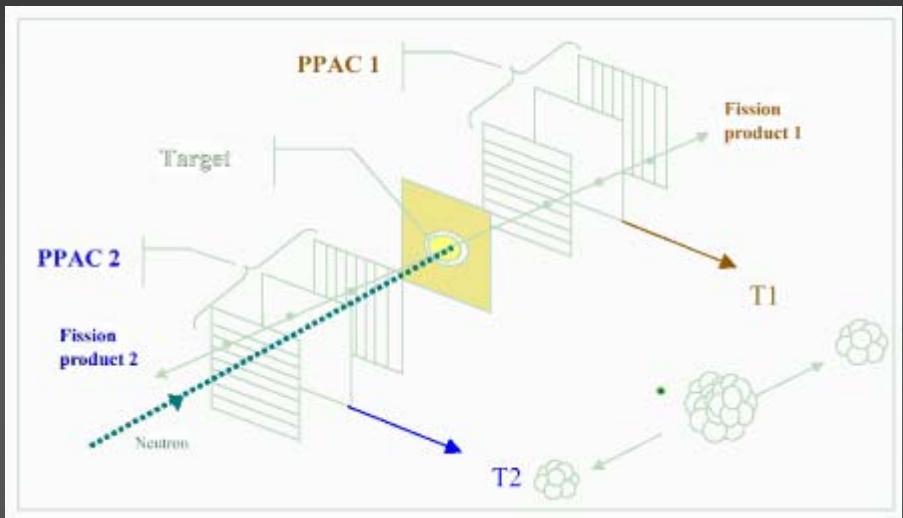


### Principles:

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

# Fission studies

## cross sections with PPAC detectors: present setup



### Measurements:

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

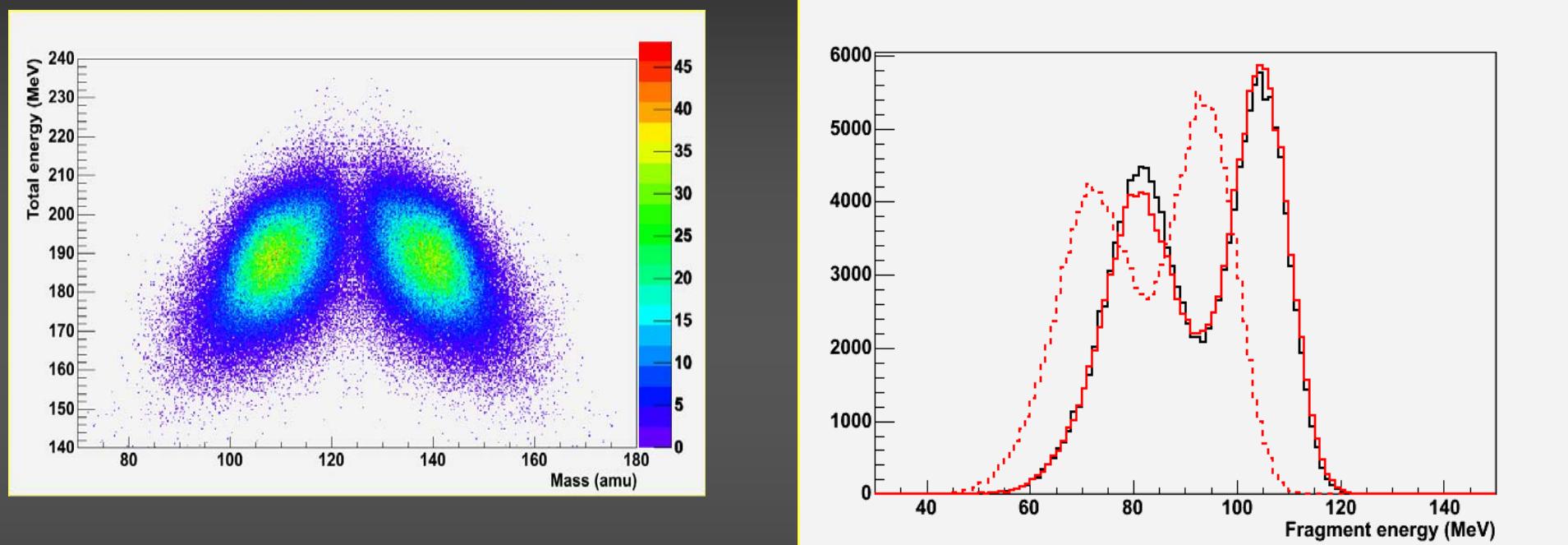
### EAR-2 boost:

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

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n\_TOF-Ph2

# Fission studies with twin ionization chamber



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

## Measurements:

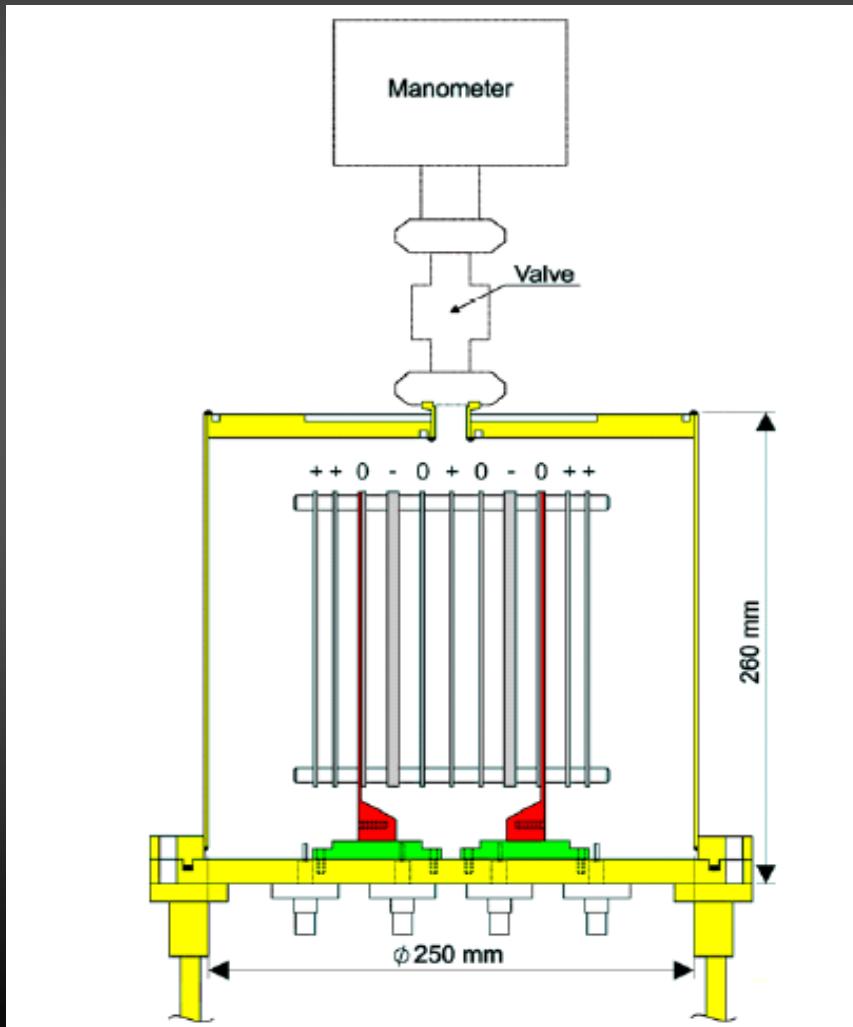
- FF yields: mass & charge
- Test measurement with  $^{235}\text{U}$  then measurements of other MA

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n\_TOF-Ph2

# $(n,p)$ , $(n,\alpha)$ & $(n,\text{lcp})$ measurements

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



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

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

Measurements:

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

EAR-2 boost:

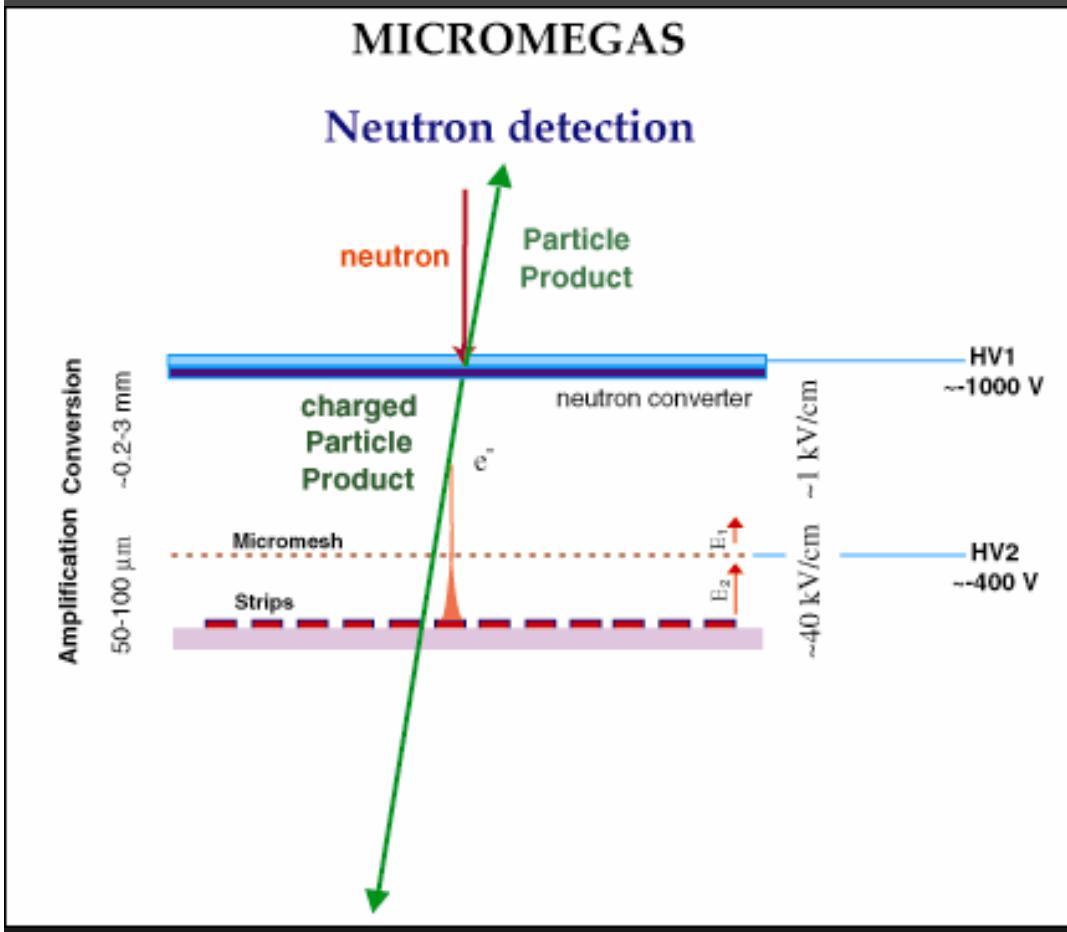
- approx 100 times the ORELA count rate expected
- $^{67}\text{Zn}$  and  $^{99}\text{Ru}$  ( $n,\alpha$ ) measurements

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

# $(n,p)$ , $(n,\alpha)$ & $(n,\text{lcp})$ measurements

## 2. MICROMEGAS

already used for measurements of nuclear recoils at  $n_{\text{TOF}}$



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

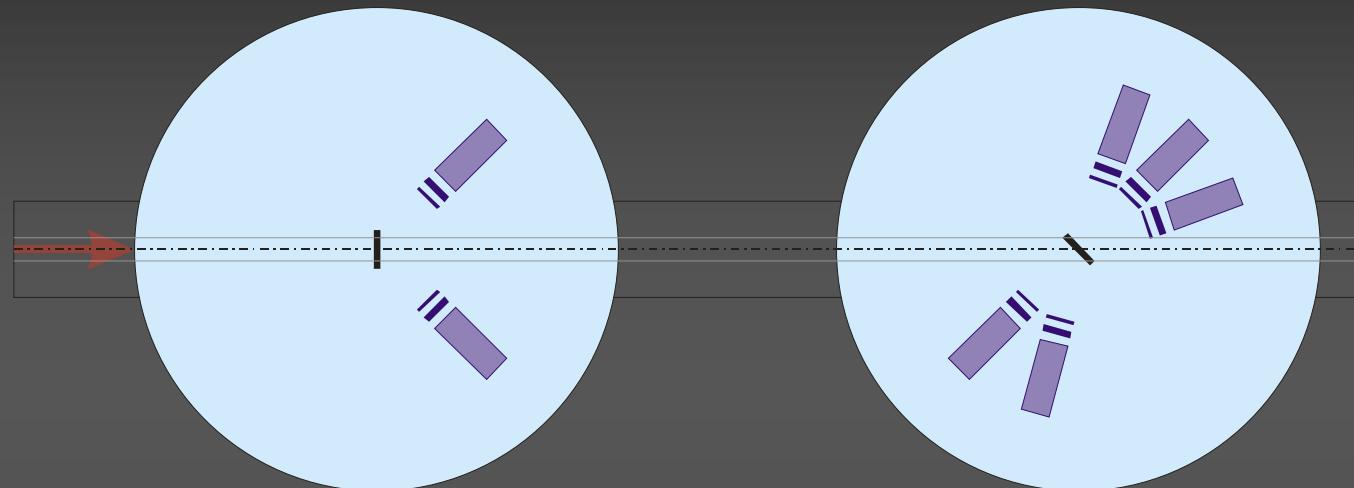
- converter replaced by sample
- expected count rate: 1 reaction/pulse ( $\sigma=200 \text{ mb}$ ,  $\varnothing=5\text{cm}$ ,  $1\mu\text{m}$  thick)

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

# $(n,p)$ , $(n,\alpha)$ & $(n,lcp)$ measurements

## 3. Scattering chambers with $\Delta E$ - $E$ or $\Delta E$ - $\Delta E$ - $E$ telescopes



Setup: in parallel with fission detectors

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

Measurements:

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

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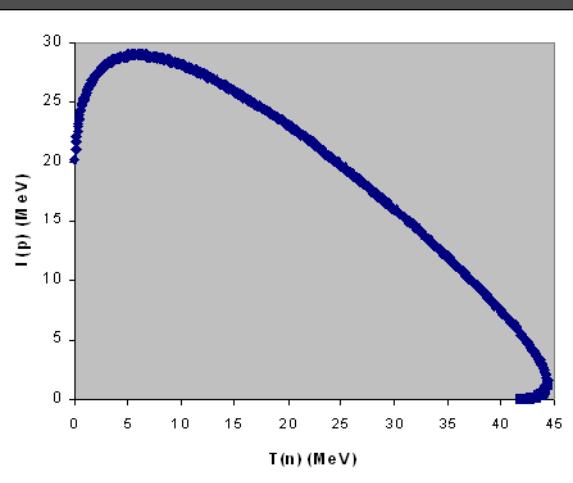
n\_TOF-Ph2

# Neutron scattering reactions

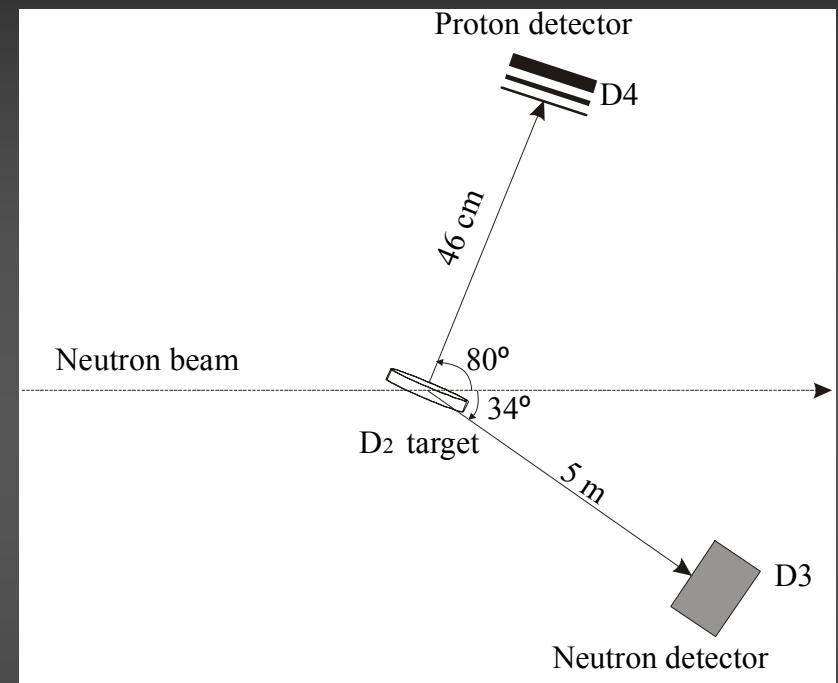
Direct  $n + n$  scattering experiment not feasible!

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

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



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



Neutron incident energy 30 – 75 MeV  
in 2.5 MeV bins

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

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

$$\Gamma_\gamma = 0.76 \text{ meV}$$

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

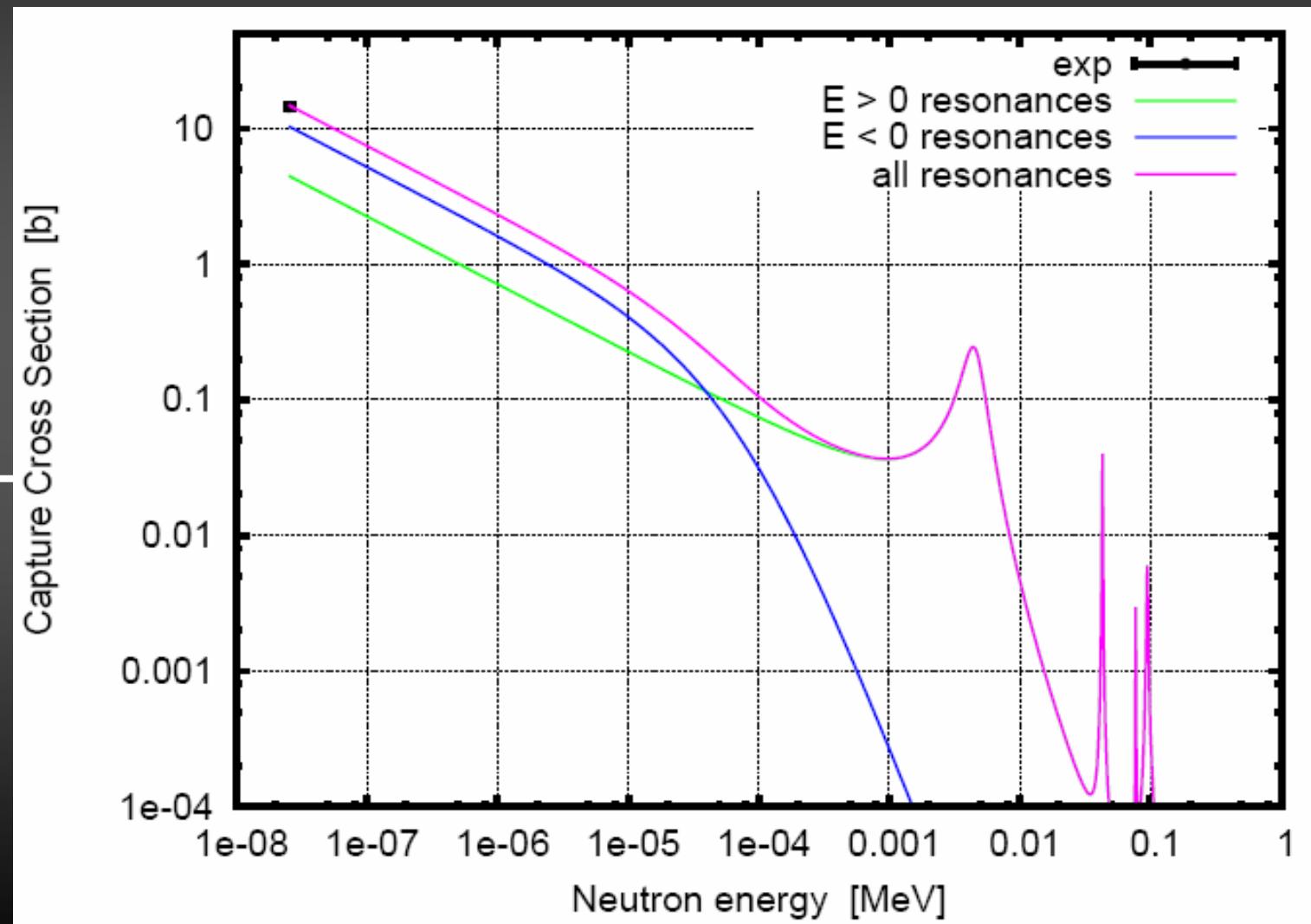
$$\langle\sigma\rangle_{25\text{keV}}$$

$$28.4 \pm 2.8 \text{ mb } (\text{a})$$

$$49.5 \pm 4.4 \text{ mb } (\text{b})$$

(a) H Nassar et al. (2005)

(b) N Tomyo et al. (2005)



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

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

$$\Gamma_\gamma = 2.38 \text{ meV}$$

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

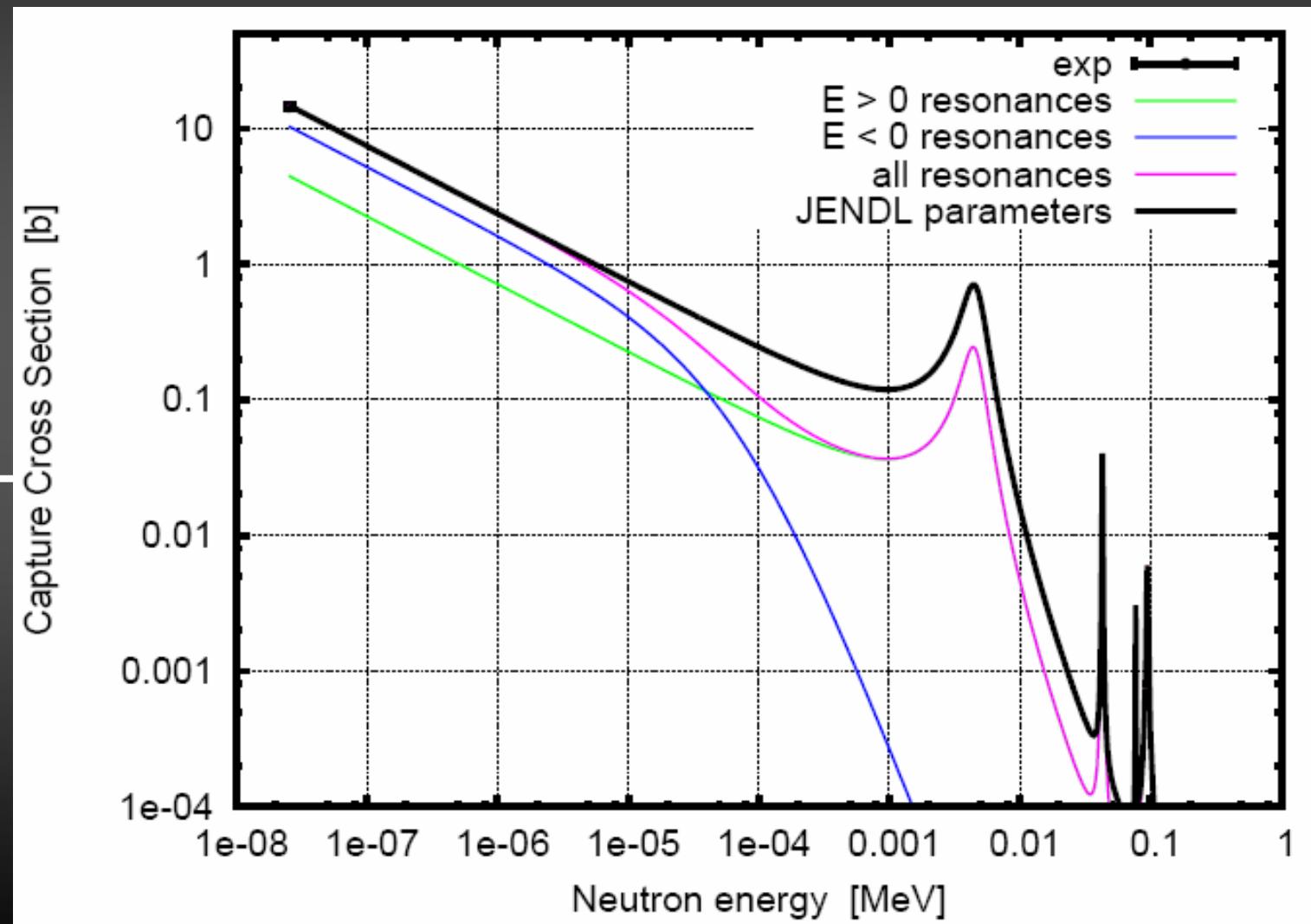
$$\langle\sigma\rangle_{25\text{keV}}$$

$$28.4 \pm 2.8 \text{ mb } (\text{a})$$

$$49.5 \pm 4.4 \text{ mb } (\text{b})$$

(a) H Nassar et al. (2005)

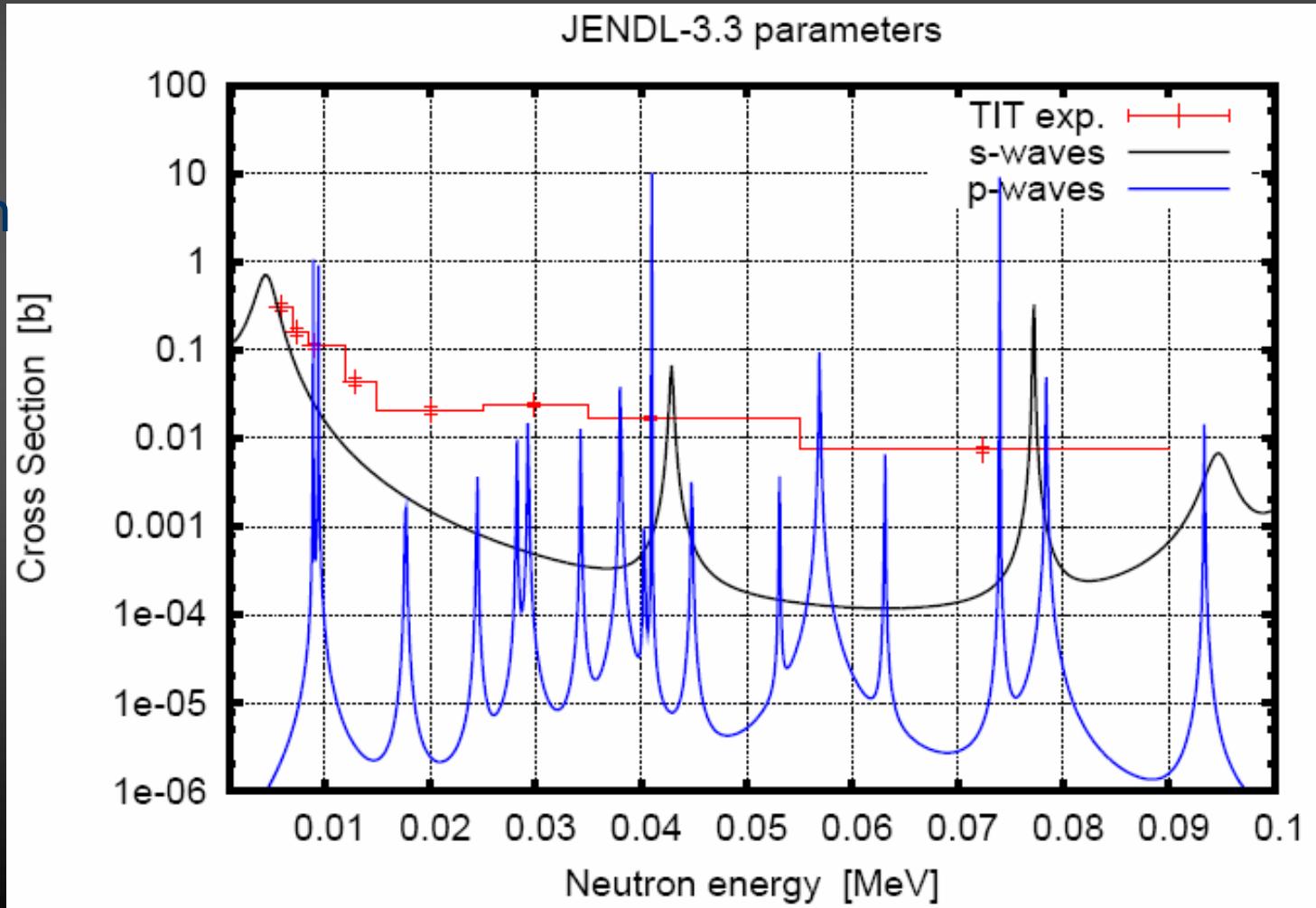
(b) N Tomyo et al. (2005)



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

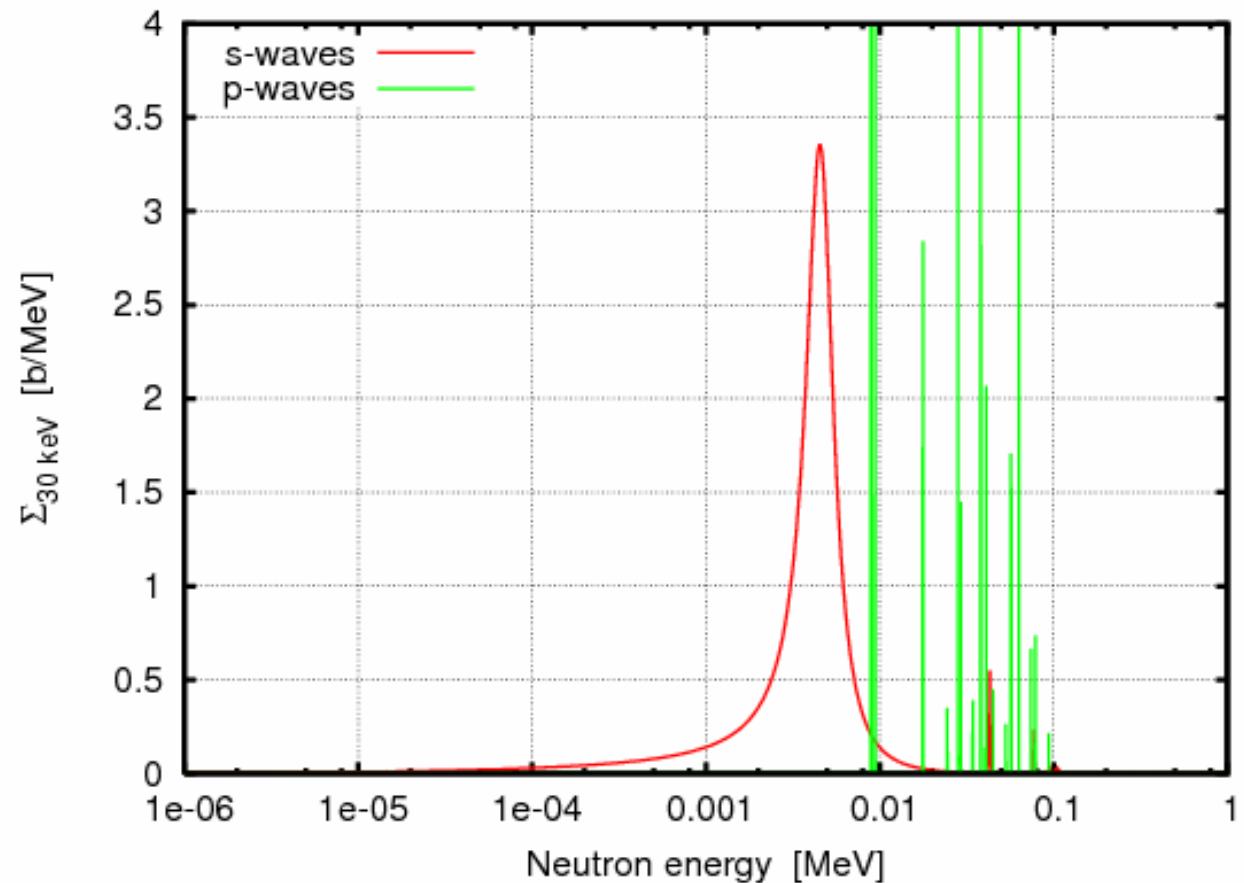
a high-resolution  
 $(n,\gamma)$  cross section  
measurement  
is called for

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



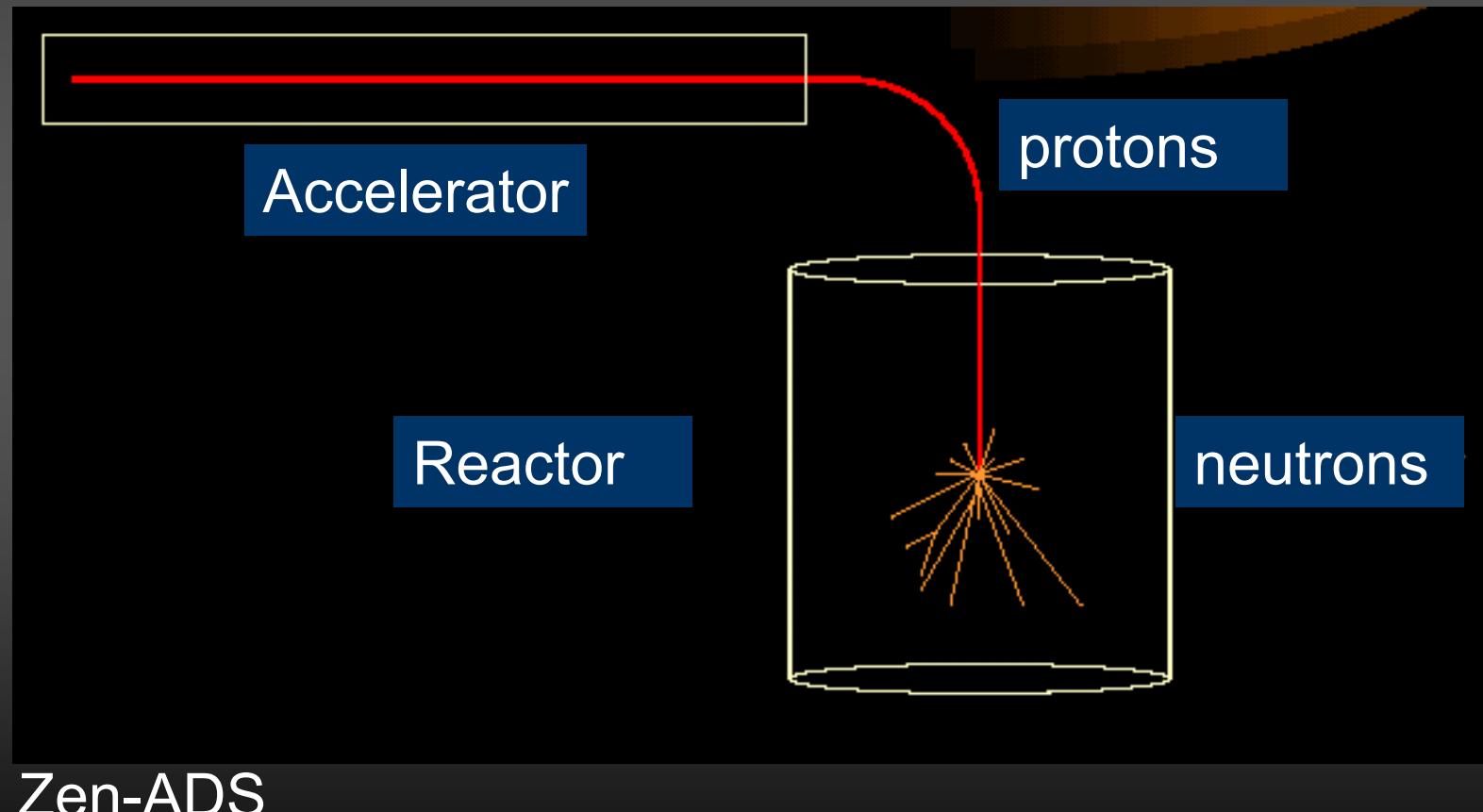
# $^{62}\text{Ni}(n,\gamma)^{63}\text{Ni}$ : what do we know?

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