

Neutron detection at n_TOF



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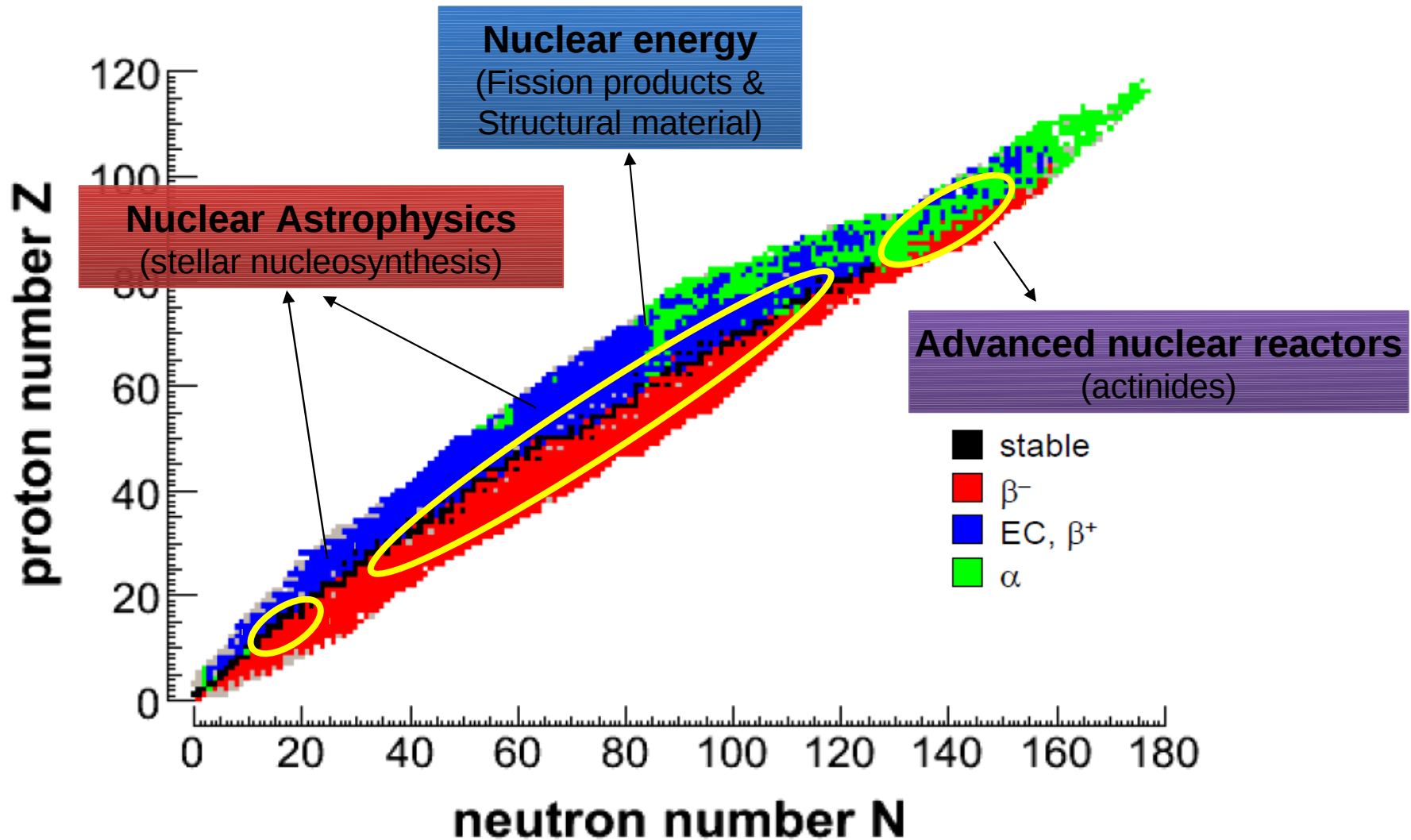


NEDENSAA NuPNET Collaboration Meeting 2013

20-22 February 2013, Acireale

n_TOF measurements at glance

Neutron induced fission and capture reactions



The s-process nucleosynthesis

s-process nucleosynthesis proceeds through **neutron captures** and successive **β -decay**.

The abundance of elements in the Universe depends on **thermodinamic conditions** (temperture and neutron density) and on the **neutron capture cross-sections**.

s-process

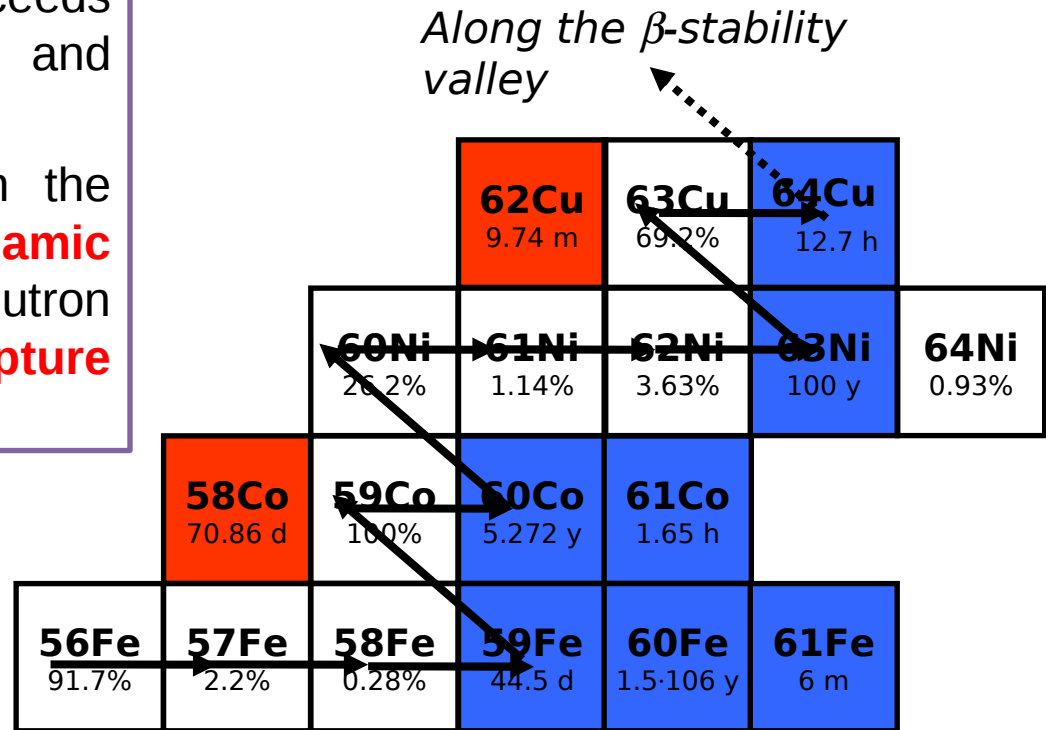
				62Cu 9.74 m	63Cu 69.2%	64Cu 12.7 h	
		60Ni 26.2%	61Ni 1.14%	62Ni 3.63%	63Ni 100 y	64Ni 0.93%	
	58Co 70.86 d	59Co 100%	60Co 5.272 y	61Co 1.65 h			
56Fe 91.7%	57Fe 2.2%	58Fe 0.28%	59Fe 44.5 d	60Fe 1.5-106 y	61Fe 6 m		

The s-process nucleosynthesis

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s-process



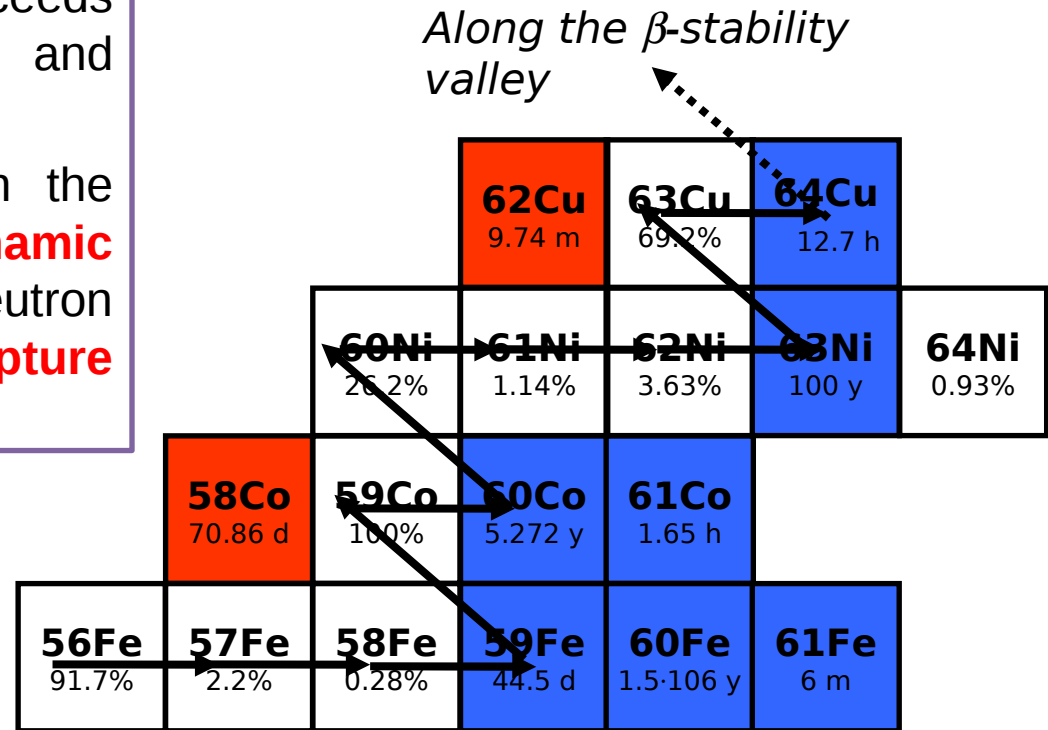
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s-process

$\sigma(n,\gamma)$ is a key quantity



Need of new and accurate neutron cross-sections:

- **refine models** of stellar nucleosynthesis in the Universe
- obtain information on the **stellar environment and evolution**

Nuclear technologies

	Cm 238 2,4 h e α 5,52	Cm 239 3 h e γ 188... g	Cm 240 27 d sf α 5,291; 6,248... sf g	Cm 241 32,8 d sf α 5,339... γ 472; 431; 132... g	Cm 242 162,94 d sf α 5,113; 6,069... sf; g γ 278; 229; 210...; e ⁻ α 20 α 50 + 570; α ₁ 3,1	Cm 243 29,1 a sf α 5,785; 5,742... e ⁻ ; sf; g γ 278; 229; 210...; e ⁻ α 130; α ₁ 620	Cm 244 18,10 a sf α 5,803; 5,762... sf; g γ (43...); e ⁻ α 15; α ₁ 1,1	Cm 245 8500 a sf α 5,361; 5,364... sf; g γ 175; 133... α 360; α ₁ 2100	Cm 246 4730 a sf; g α 5,388; 5,343... γ (45); e ⁻ α 1,2; α ₁ 0,16
Am 236 ? 3,7 m e α 6,41	Am 237 73,0 m sf α 6,042 γ 200; 438; 474; 909... g	Am 238 1,63 h sf α 5,94 γ 963; 519; 561; 605... g	Am 239 11,9 h sf α 5,774... γ 278; 228... g	Am 240 50,8 h sf α 5,378... γ 988; 889... g	Am 241 432,2 a sf α 5,488; 5,443... sf; γ 60; 26... e ⁻ ; g α 50 + 570; α ₁ 3,1	Am 242 141 a sf α 5,204... sf; γ (43...); e ⁻ γ 1790 α ₁ 2100	Am 243 7370 a sf α 5,275; 5,230... sf; γ 75; 44... e 75 + 5 α ₁ 0,074	Am 244 10,1 h sf α 5,275; 5,230... sf; γ 75; 44... e 75 + 5 α ₁ 0,074	Am 245 2,05 h sf α 5,275; 5,230... sf; γ 75; 44... e 75 + 5 α ₁ 0,074
Pu 235 25,3 m sf α 5,80 γ 48; (756; 34...) e ⁻	Pu 236 2,858 a sf α 5,788; 5,721... sf; Mg 20 γ 48; 109...; e ⁻ α ₁ 160	Pu 237 45,2 d sf α 5,334... γ 62...; e ⁻ α ₁ 2300	Pu 238 87,74 a sf α 5,490; 5,456... sf; Mg γ (43; 100...); e ⁻ α 510; α ₁ 17	Pu 239 2,411 · 10 ⁴ a sf α 5,157; 5,144... sf; γ (52...) e ⁻ ; g α 270; α ₁ 752	Pu 240 6563 a sf α 5,168; 5,124... sf; γ (45...) e ⁻ ; g α 290; α ₁ 0,044	Pu 241 14,35 a sf β ⁻ 0,02; g α 4,880... γ (148...); e ⁻ α 370; α ₁ 1010	Pu 242 3,750 · 10 ⁵ a sf α 4,901; 4,856... sf; γ (45...) e ⁻ ; g α 15; α ₁ 0,2	Pu 243 4,956 h sf β ⁻ 0,6... γ 84...; g α 100; α ₁ 200	Pu 244 8,00 · 10 ⁷ a sf α 4,589; 4,545... sf; γ e ⁻ α 1,7
Np 234 4,4 d e; β ⁺ ... γ 1559; 1528; 1602... α 900	Np 235 396,1 d e; α 5,025; 5,007... γ (26; 84...); e ⁻ g; α 160 + 7	Np 236 22,5 h e; β ⁻ 0,5...; α 1... γ (642...); e ⁻ g; α 2700; α ₁ 2600	Np 237 2,144 · 10 ⁶ a sf α 4,790; 4,774... γ 29; 67...; e ⁻ α 180; α ₁ 0,020	Np 238 2,117 d β ⁻ 1,2... γ 984; 1029; 1026; 924...; e ⁻ g; α 2100	Np 239 2,355 d β ⁻ 0,4; 0,7... γ 106; 278; 228...; e ⁻ ; g α 32 + 19; α ₁ < 1	Np 240 7,22 m β ⁻ 2,2... γ 555; 567... e ⁻ α 448...; g	Np 241 13,9 m β ⁻ 1,3... γ 175; (133...) g	Np 242 2,2 m β ⁻ 2,7... γ 738; 748... 1473... g	Np 243 1,85 m β ⁻ γ 288 g
U 233 1,592 · 10 ⁵ a α 4,824; 4,783... Ne 25; γ (42; 97...); e ⁻ α 47; α ₁ 530	U 234 0,0055 2,455 · 10 ⁵ a α 4,775; 4,725...; sf Mg 28; Ne 3 (53; 121...); e ⁻ ; α 95; α ₁ < 0,06	U 235 0,7200 26 m α 4,388...; sf h ₁ (0,07) e ⁻ α 95; α ₁ 530	U 236 120 ns 2,342 · 10 ⁷ a α 4,494; 4,445... h ₁ 1783; sf; γ (49; 642...; 119...) e ⁻ ; α 5,1	U 237 6,75 d β ⁻ 0,2... γ 60; 208... e ⁻ α 100; α ₁ < 0,3	U 238 99,2745 270 ns 4,458 · 10 ⁸ a h ₁ 339; α 4,56...; sf 138...; 136... e ⁻ ; α 22; α ₁ 117	U 239 23,5 m β ⁻ 1,2; 1,3... γ 75; 44... α 22; α ₁ 15	U 240 14,1 h β ⁻ 0,4... γ 44; (190...) e ⁻ m		U 242 16,8 m β ⁻ γ 68; 58; 585; 573... m
Pa 232 1,31 d β ⁻ 0,3; 1,3...; e ⁻ γ 969; 894; 150...; e ⁻ α 460; α ₁ 700	Pa 233 27,0 d β ⁻ 0,3; 0,5... γ 312; 300; 341...; e ⁻ α 20 + 19; α ₁ < 0,1	Pa 234 1,17 m β ⁻ 2,3... γ (102...); 767...; e ⁻ h ₁ (74...); e ⁻ α 500	Pa 235 24,2 m β ⁻ 1,4... γ 128 - 659 m	Pa 236 9,1 m β ⁻ 2,0; 3,1... γ 642; 687; 1763...; g βsf ?	Pa 237 8,7 m β ⁻ 1,4; 2,3... γ 854; 865; 529; 541... g	Pa 238 2,3 m β ⁻ 1,7; 2,9... γ 1015; 635; 448; 680... g			
Th 231 25,5 h β ⁻ 0,3; 0,4... γ 26; 84... e ⁻	Th 232 100 1,405 · 10 ¹⁰ a α 4,013; 3,950...; sf γ (84...); e ⁻ α 7,37; α ₁ 0,000095	Th 233 22,3 m sf β ⁻ 1,2... γ 87; 29; 409...; e ⁻ α 1500; α ₁ 15	Th 234 24,10 d β ⁻ 0,2... γ 63; 92; 93... e ⁻ ; m α 1,8; α ₁ < 0,01	Th 235 7,1 m β ⁻ 1,4... γ 417; 727; 696... g	Th 236 37,5 m β ⁻ 1,0... γ 111; (647; 196...) g	Th 237 5,0 m β ⁻			

Nuclear technologies

	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
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 16 h	Am 243 7370 a	Am 244 10,1 h	Am 245 2,05 h
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 ⁴ a	Pu 240 6563 a	Pu 241 14,35 a	Pu 242 3,750 · 10 ⁵ a	Pu 243 4,956 h	Pu 244 8,00 · 10 ⁷ a
Np 234 4,4 d	Np 235 396,1 d	Np 236 22,5 h	Np 237 2,14 · 10 ⁶ a	Np 238 2,117 d	Np 239 2,355 d	Np 240 7,22 m	Np 241 13,9 m	Np 242 2,2 m	Np 243 1,85 m
U 233 1,592 · 10 ⁵ a	U 234 0,0055	U 235 0,7200	U 236 2,34 · 10 ⁷ a	U 237 4,75 d	U 238 99,2745	U 239 23,5 m	U 240 14,1 h		U 242 16,8 m
Pa 232 1,31 d	Pa 233 27,0 d	Pa 234 1,17 m	Pa 235 24,2 m	Pa 236 9,1 m	Pa 237 8,7 m	Pa 238 2,3 m			
Th 231 25,5 h	Th 232 100	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			

244, 245Cm
1.5 Kg/yr

241Am: 11.6 Kg/yr
243Am: 4.8 Kg/yr

239Pu: 125 Kg/yr

237Np: 16 Kg/yr

LLFP
76.2 Kg/yr

LLFP

Quantities refer to yearly production in 1 GWe LW reactor

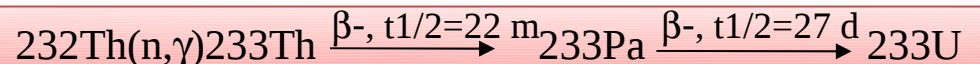
Nuclear technologies

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U 233 1,592 · 10 ⁵ a	U 234 0,0055	U 235 0,7200	U 236 120 ns	U 237 6,75 d	U 238 99,2745	U 239 23,5 m	U 240 14,1 h		U 242 16,8 m
Pa 232 1,31 d	Pa 233 27 d	Pa 234 1,17 m	Pa 235 24,3 m	Pa 236 9,1 m	Pa 237 8,7 m	Pa 238 2,3 m			
Th 231 25,5 h	Th 232 1,405 · 10 ¹⁰ a	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			

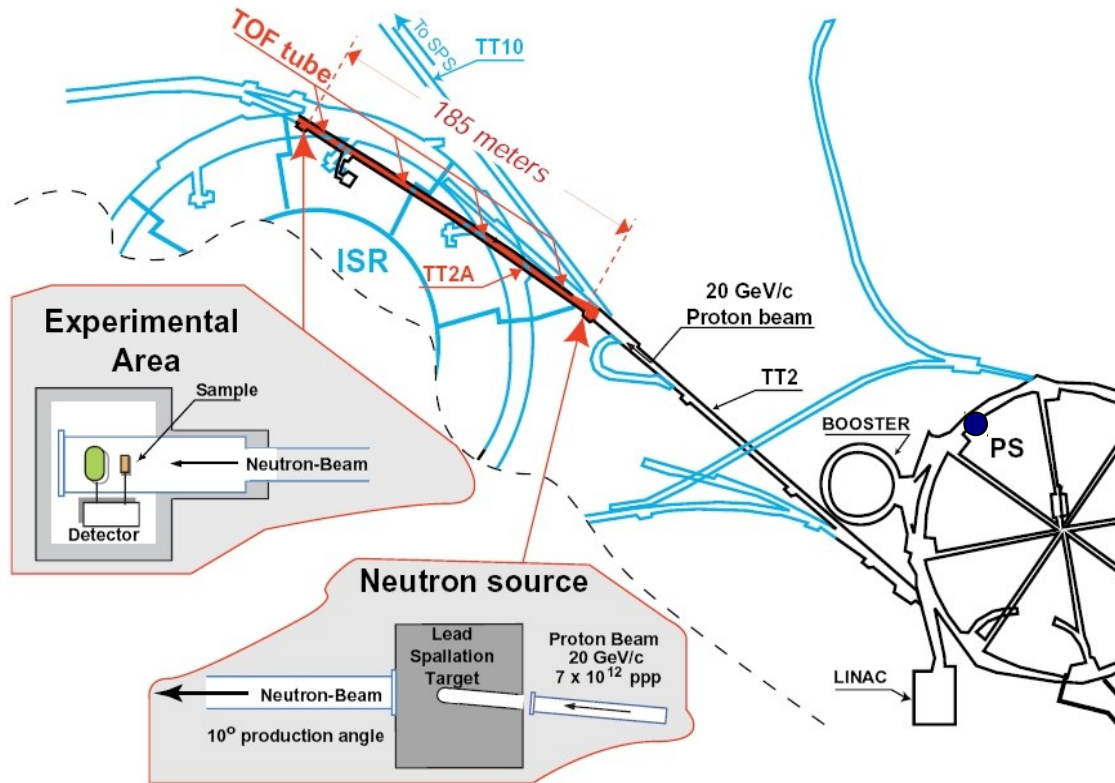
Th/U fuel cycle

LLFP

LLFP



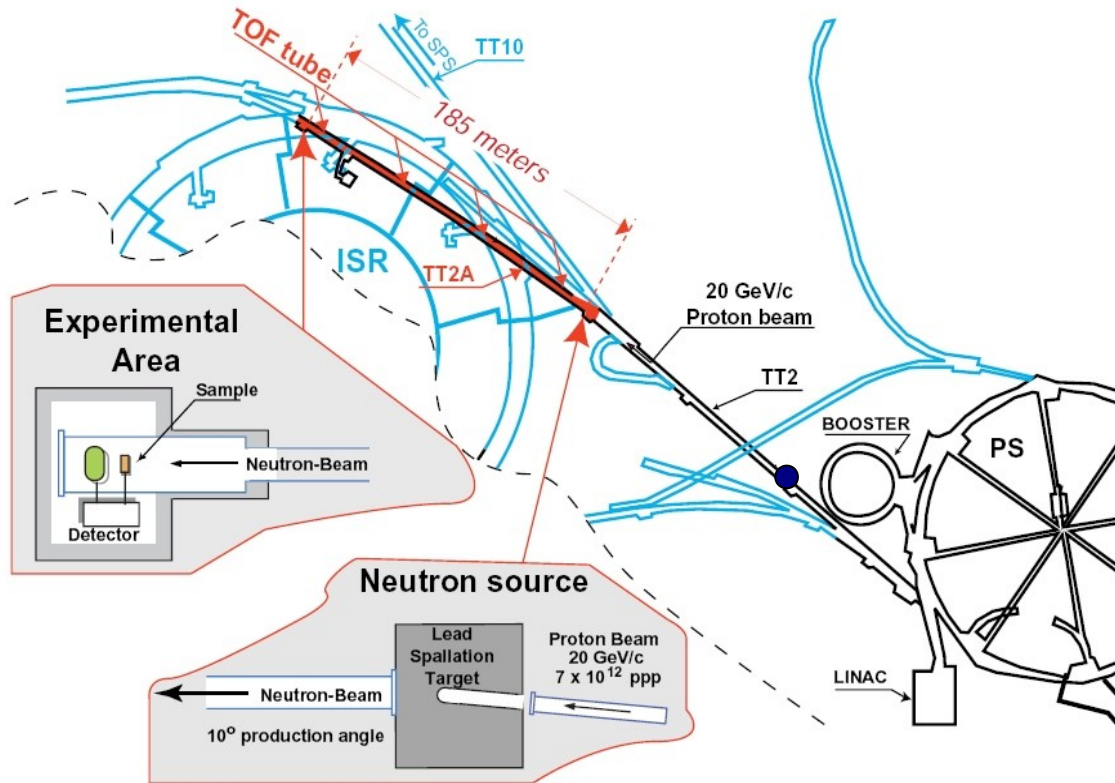
The n_TOF facility at CERN



n_TOF is a **spallation** neutron source based on **20 GeV/c protons** from the CERN PS hitting a **Pb block** (~350 neutrons per proton).

Experimental area at **200 m**.

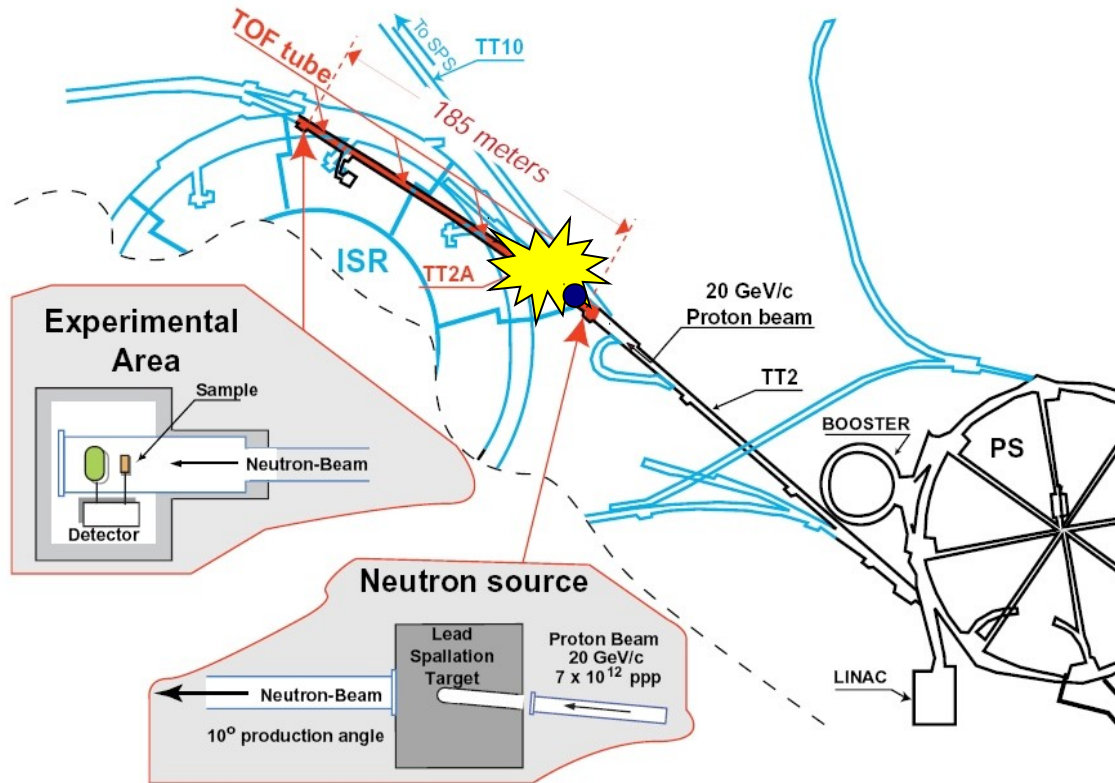
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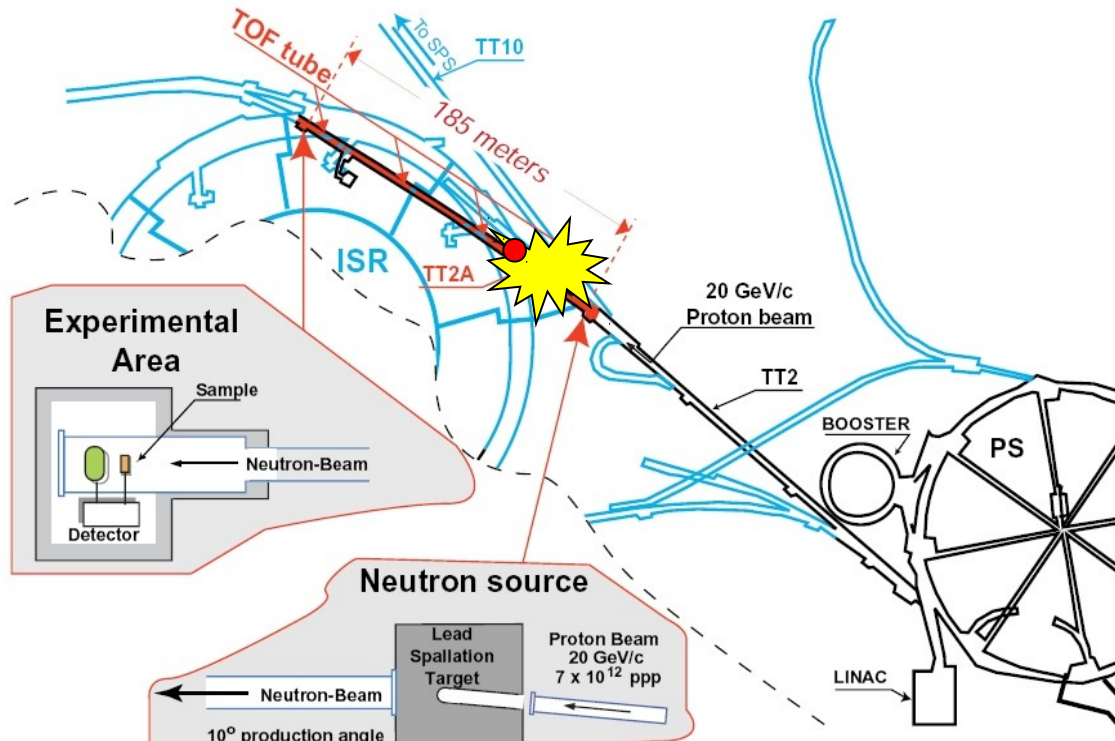
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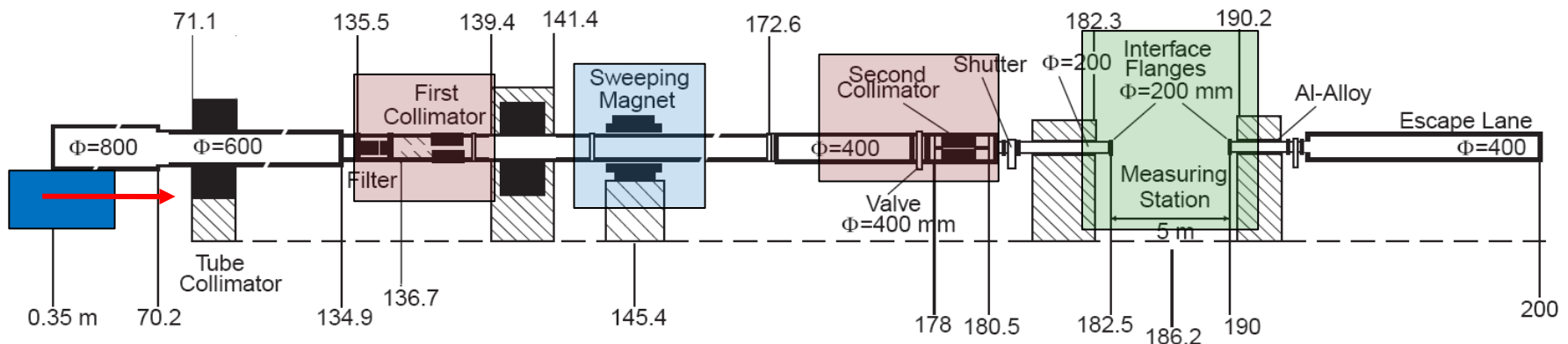
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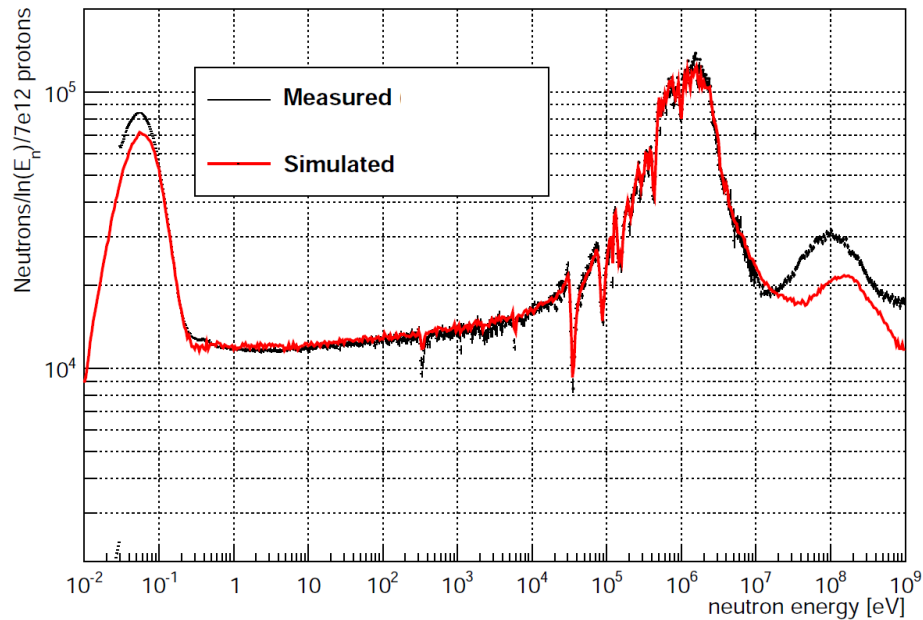


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n_TOF features



Main feature:

- **extremely high instantaneous neutron flux** (10^5 n/cm²/pulse).
- very convenient for measurements of **radioactive isotopes**,
- **low cross sections**,
- **Isotope available in small quantity**

Other features of the neutron beam:

- high **resolution in energy** ($\Delta E/E = 10^{-4}$) study **resonances**
- Wide **energy range** (25 meV < E_n < 1 GeV) measure **fission** up to 1 GeV
- low **repetition** rate (< 0.8 Hz) no **wrap-around**

n_TOF measurements

Phase 1 (2001-2004)

Capture

^{151}Sm

^{232}Th

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

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

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

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

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

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

Fission

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

^{232}Th

^{209}Bi

^{237}Np

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

Phase 2 (2009-2012)

Capture

^{25}Mg

^{88}Sr

$^{58,60,62}\text{Ni}$, ^{63}Ni

$^{54,56,57}\text{Fe}$

$^{236,238}\text{U}$

^{241}Am

Fission

$^{240,242}\text{Pu}$

$^{235}\text{U}(n,\gamma/f)$

^{232}Th , ^{234}U

^{237}Np (FF ang.distr.)

(n,α)

^{33}S , ^{59}Ni

n_TOF neutron flux

The accurate determination of **neutron cross sections** requires a high accuracy knowledge of the **neutron flux** (typically within 1-3 %)

$$\sigma_X(E_n) \propto \frac{C_X(E_n) - B(E_n)}{\Phi(E_n)}$$

Neutron measurements are a priority in every **time-of-flight facility**.

Particularly it is important to determine the **energy distribution of neutrons**

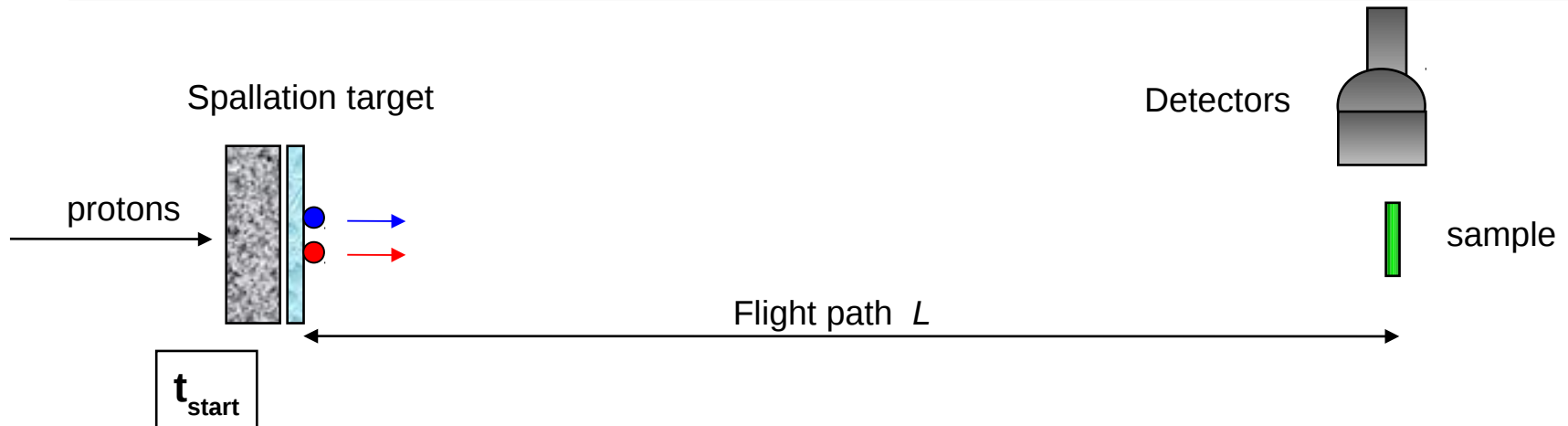
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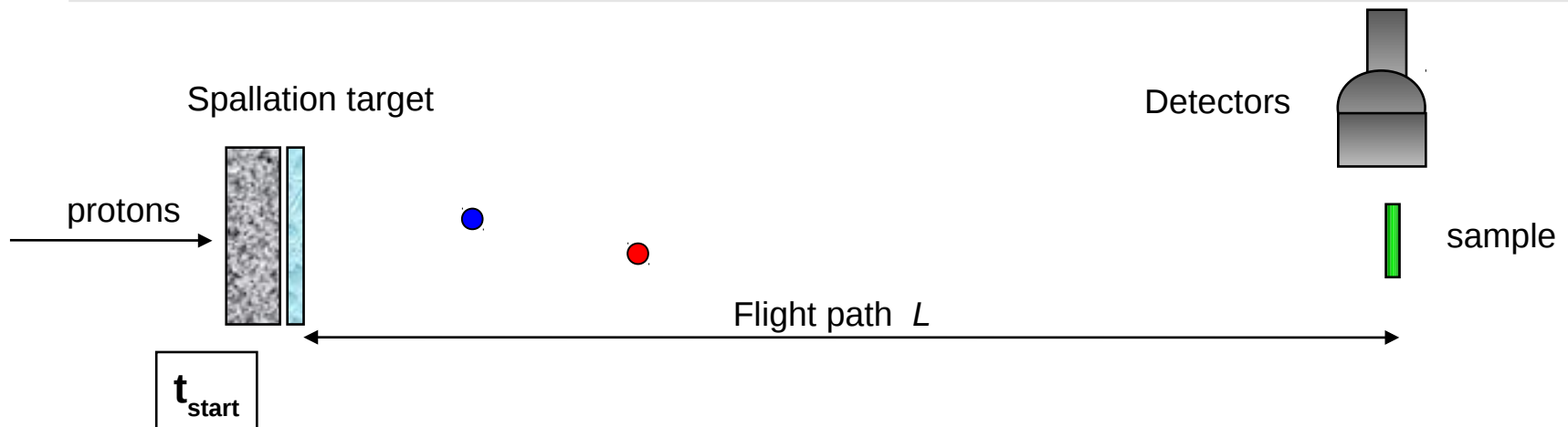
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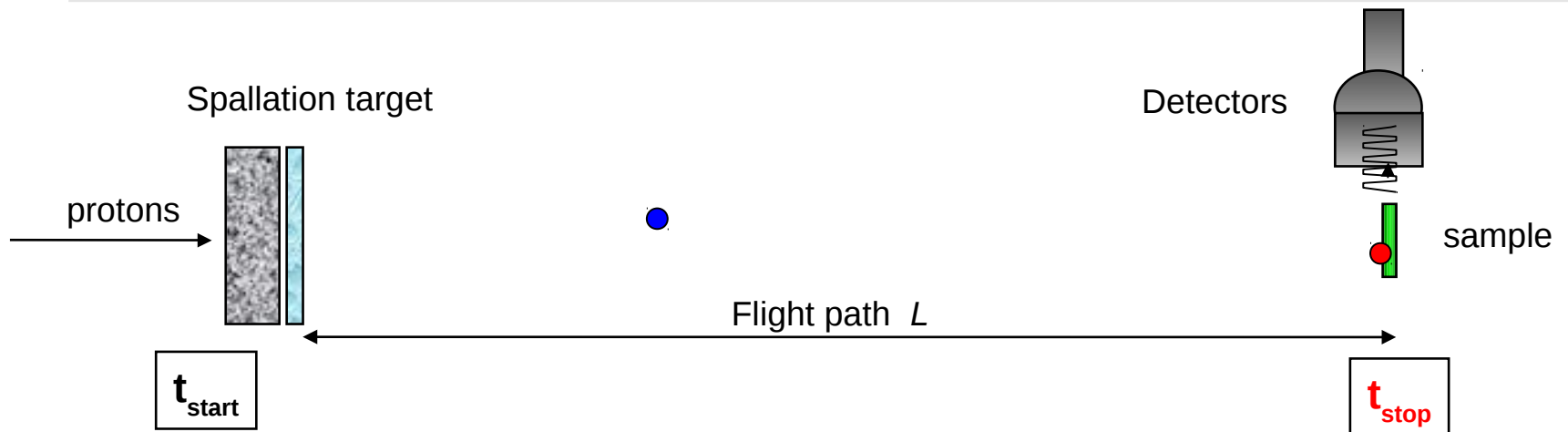
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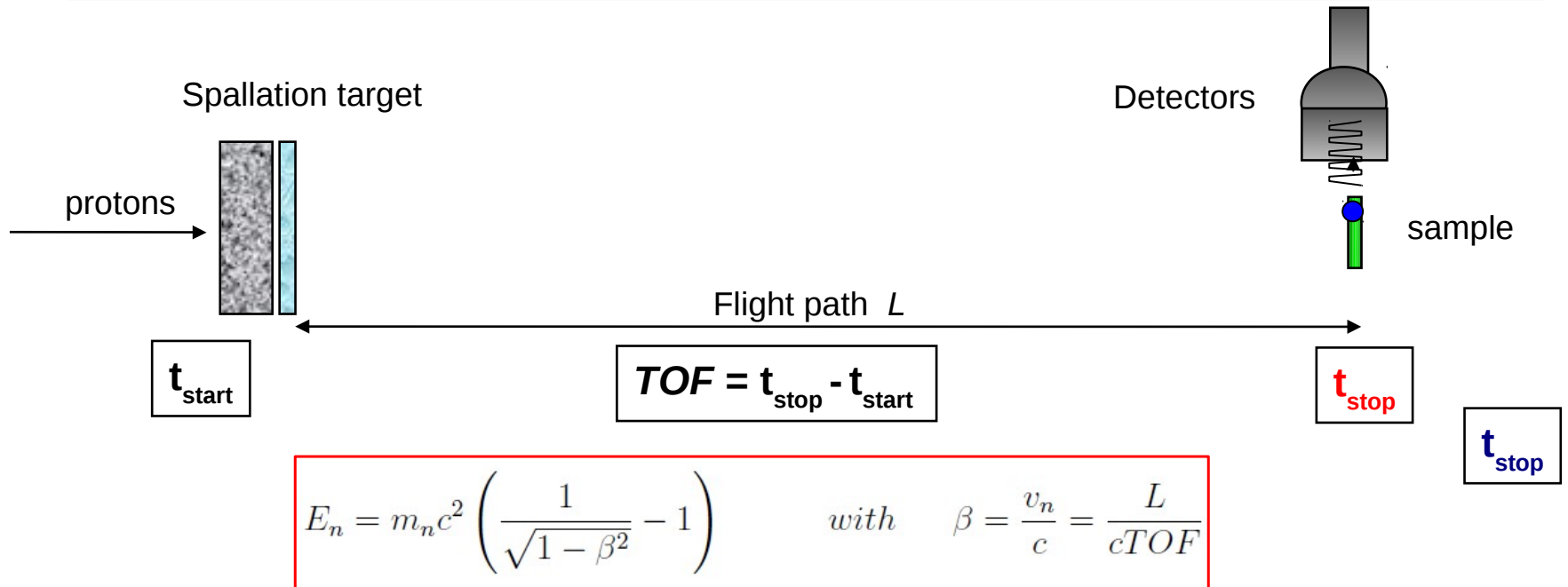
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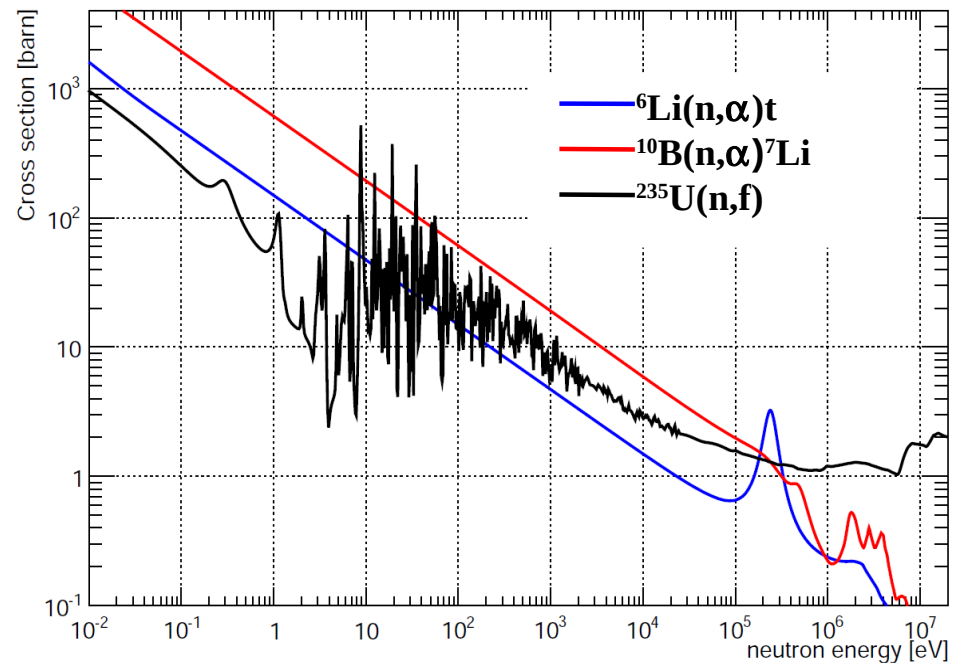
Particularly it is important to determine the **energy distribution of neutrons**



neutron detection at n_TOF

At n_TOF, **4 different neutron detection systems** based on **3 different reactions** are used to measure neutrons and to monitor the neutron flux.

Such an approach allows to achieve **high accuracy** (quantified later) in flux determination



Reaction	Standard energy range
$H(n, n)$	1 keV to 20 MeV
$^3\text{He}(n, t)$	0.0253 eV to 50 keV
$^6\text{Li}(n, \alpha)$	0.0253 eV to 1 MeV
$^{10}\text{B}(n, \alpha)$	0.0253 eV to 1 MeV
$^{197}\text{Au}(n, \gamma)$	0.0253 eV and 0.2 MeV to 2.5 MeV
$^{235}\text{U}(n, f)$	0.0253 eV and 0.15 MeV to 200 MeV
$^{238}\text{U}(n, f)$	2 MeV to 200 MeV

$$\Phi(E_n) = \frac{C_X(E_n) - B(E_n)}{n \cdot \varepsilon(E_n) \cdot \sigma_X(E_n)}$$

neutron detectors at n_TOF

Neutron detectors are used at n_TOF both to **measure** and **monitor** neutron flux.

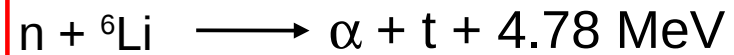
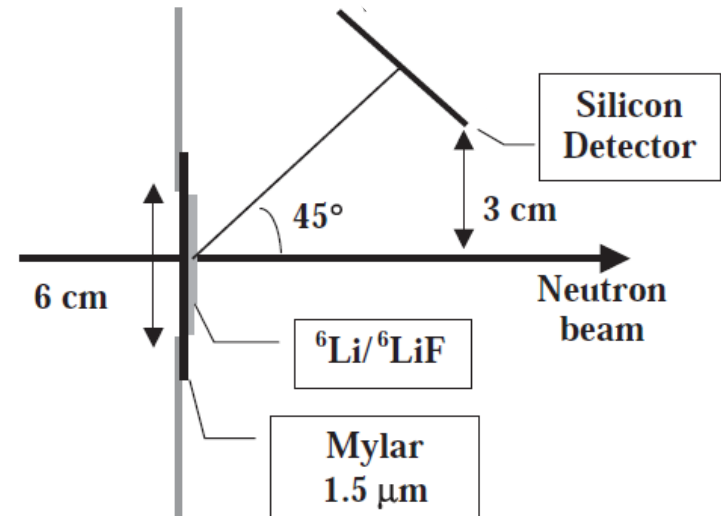
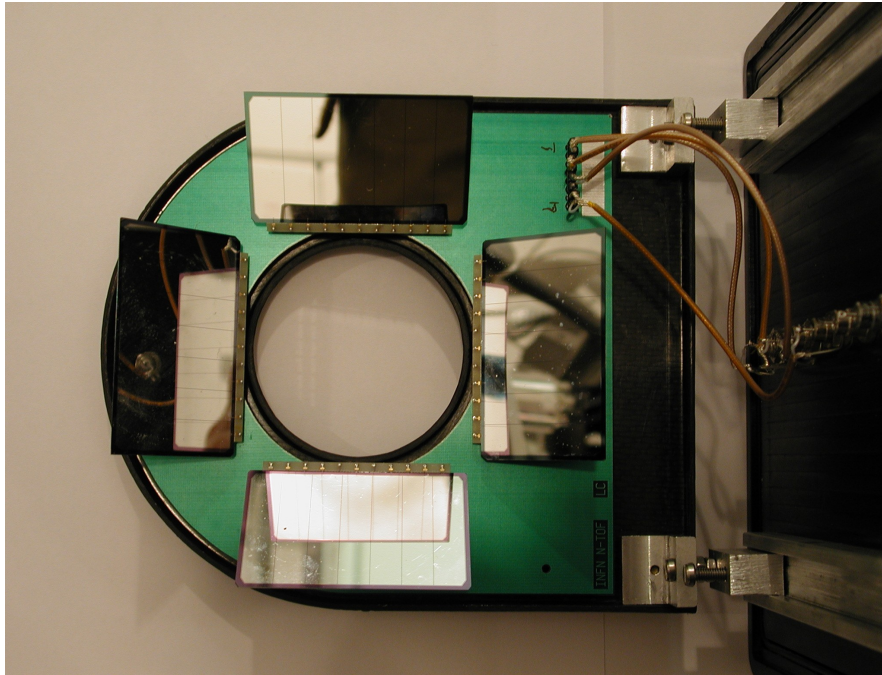
- **1 Silicon based detection system**
- **2 Micromegas detectors**
- **1 Calibrated fission chamber**
- **1 Parallel Plate Avalanche Counter**

General features:

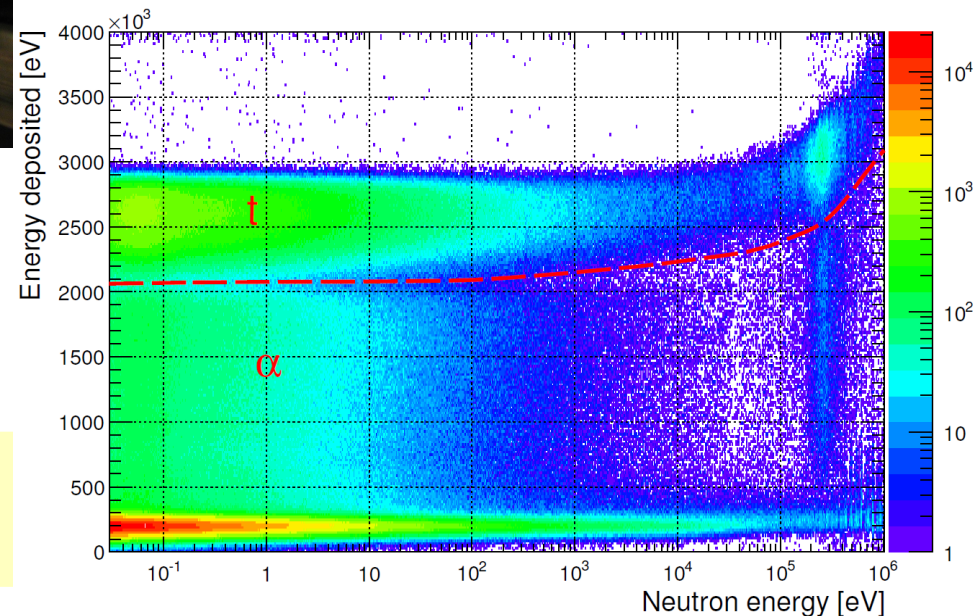
- **Low efficiency** (few % or less)
- **Small in-beam masses** (transparency)
- **Fast response** (~ ns)
- **Radiation hardness**

Silicon Monitor (SiMon)

Array of **four** 6x4 cm² **silicon detectors** + a 300 μm ⁶Li thin converter foil

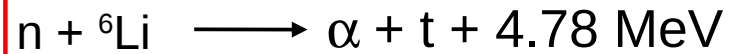
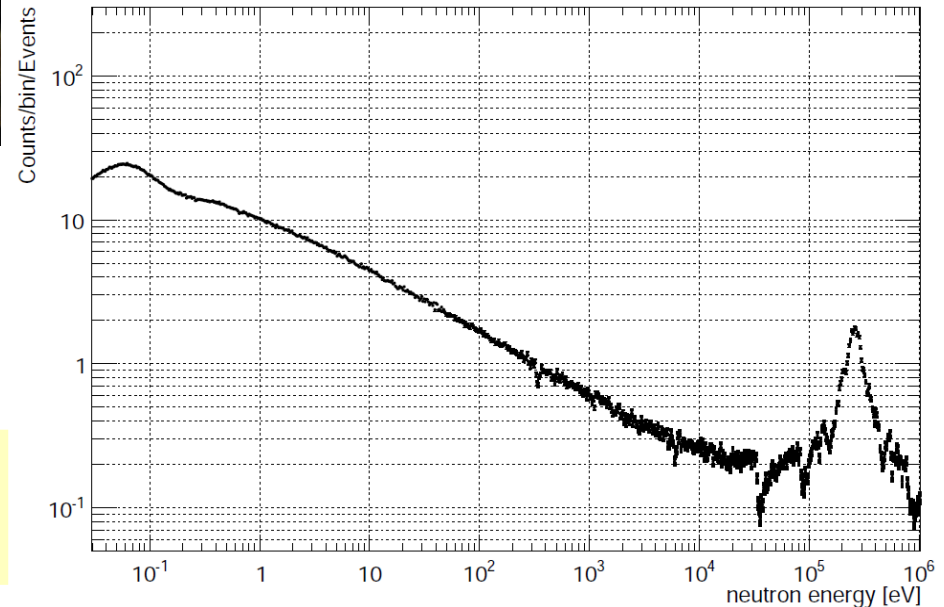
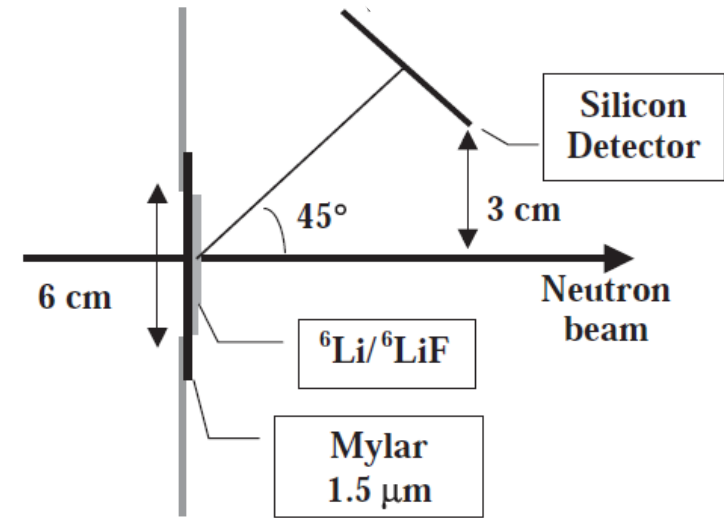
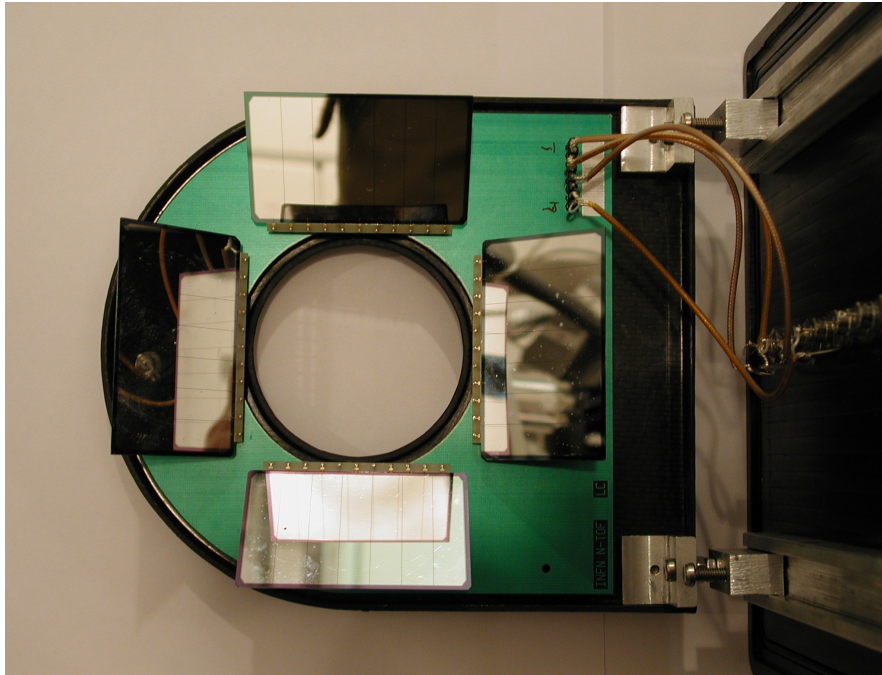


Detection efficiency ~ 0.4% at thermal energy



Silicon Monitor (SiMon)

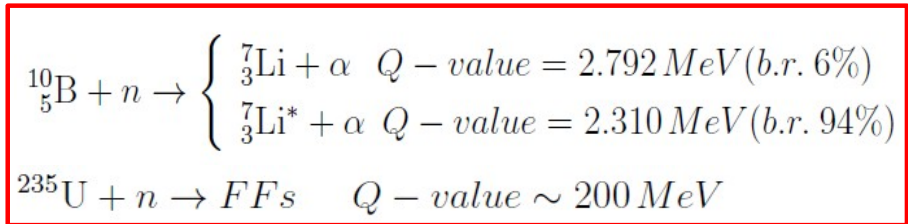
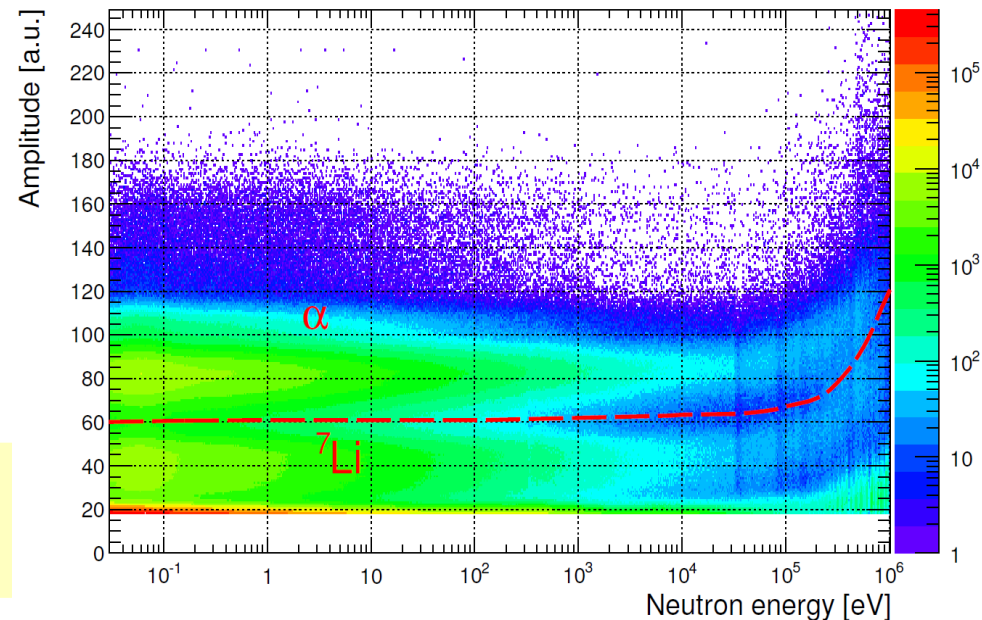
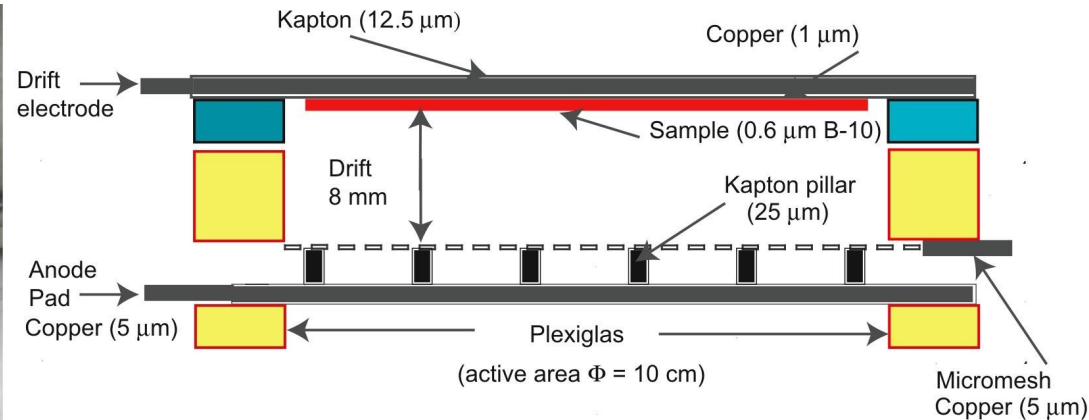
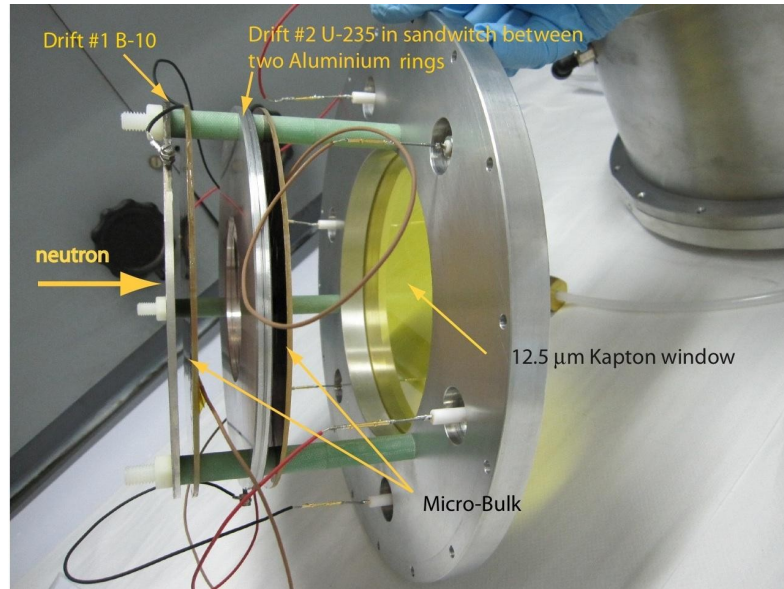
Array of **four** 6x4 cm² **silicon detectors** + a 300 μm ⁶Li thin converter foil



Detection efficiency ~ 0.4% at thermal energy

MicroMegas detectors

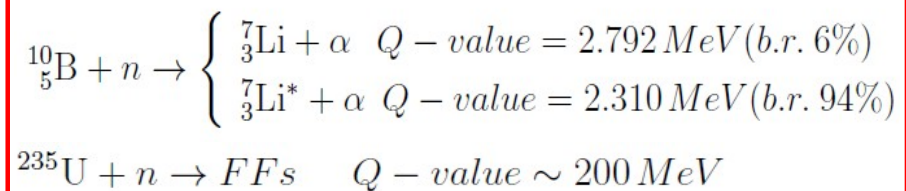
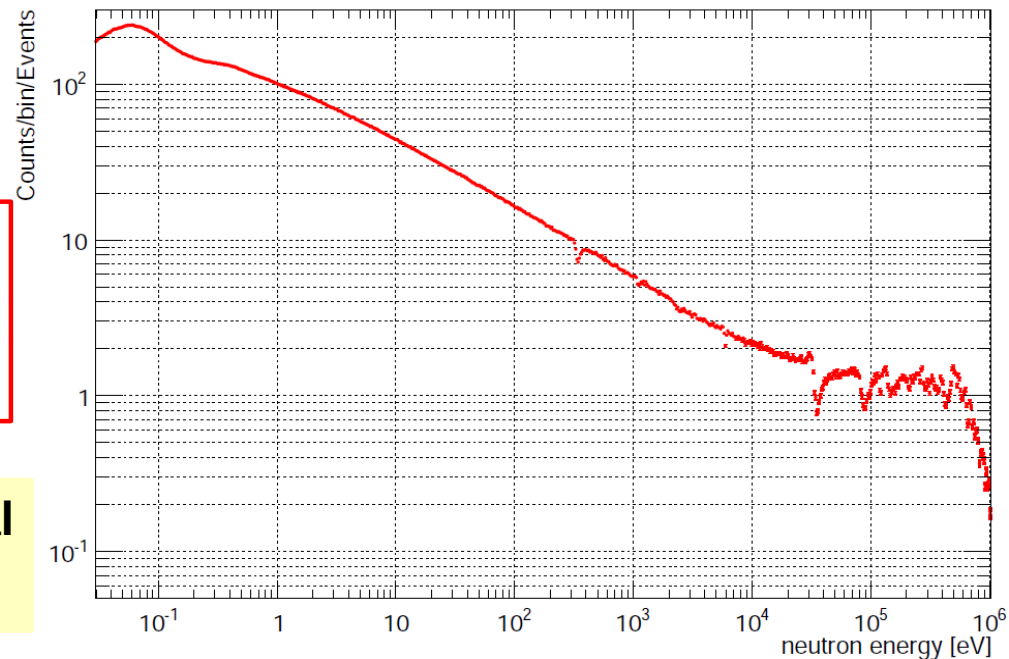
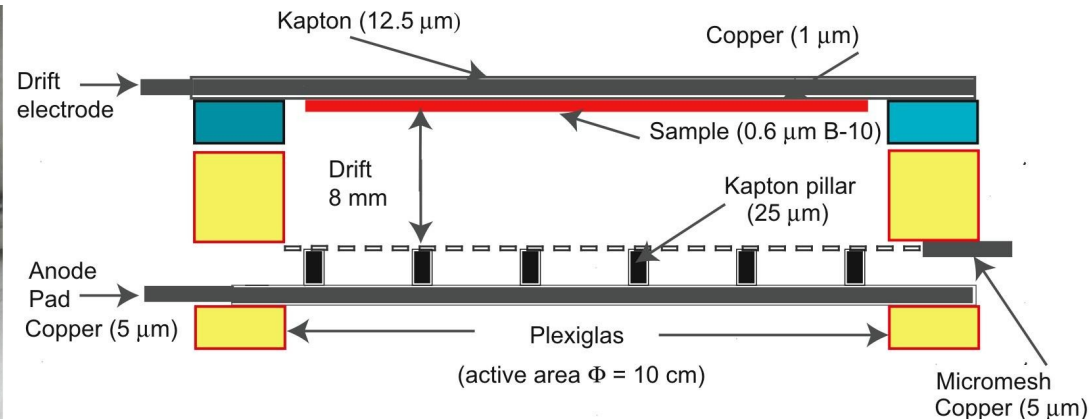
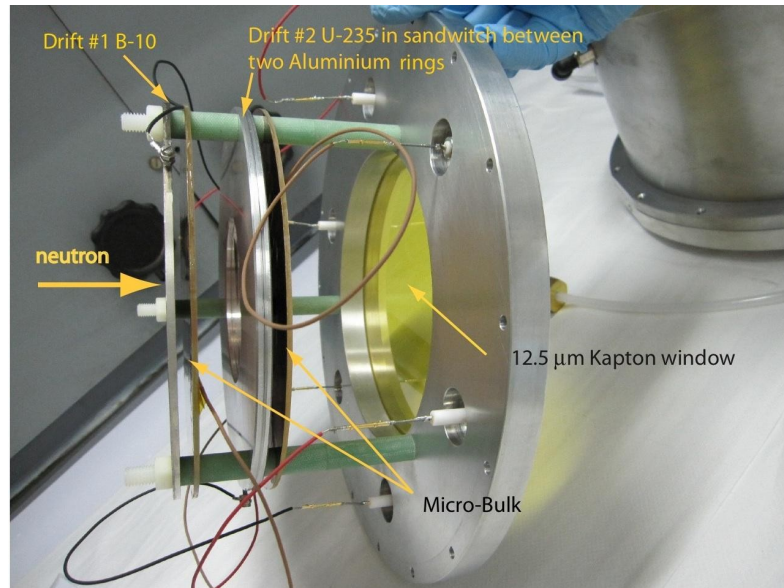
2 MicroMegas detectors equipped with ^{10}B ($0.6\ \mu\text{m}$) and ^{235}U (1 mg) deposits



Detection efficiency < 1% at thermal energy

MicroMegas detectors

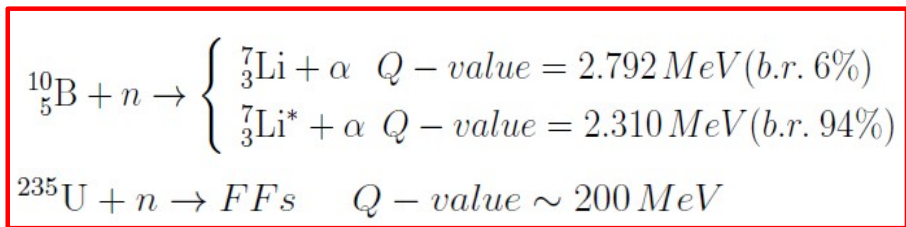
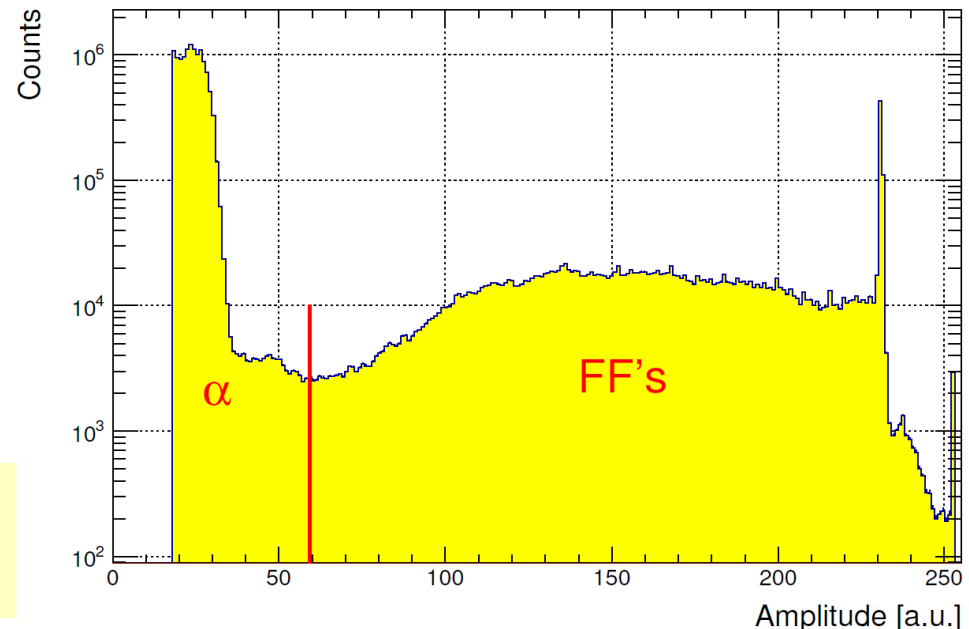
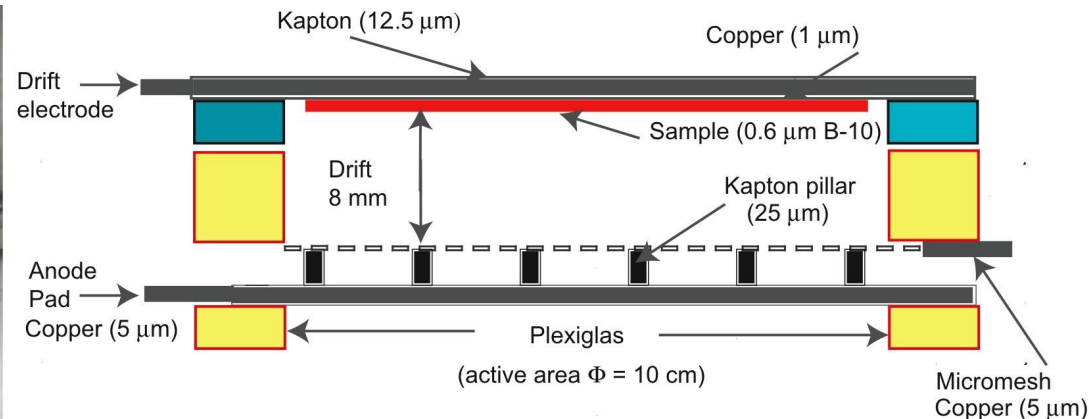
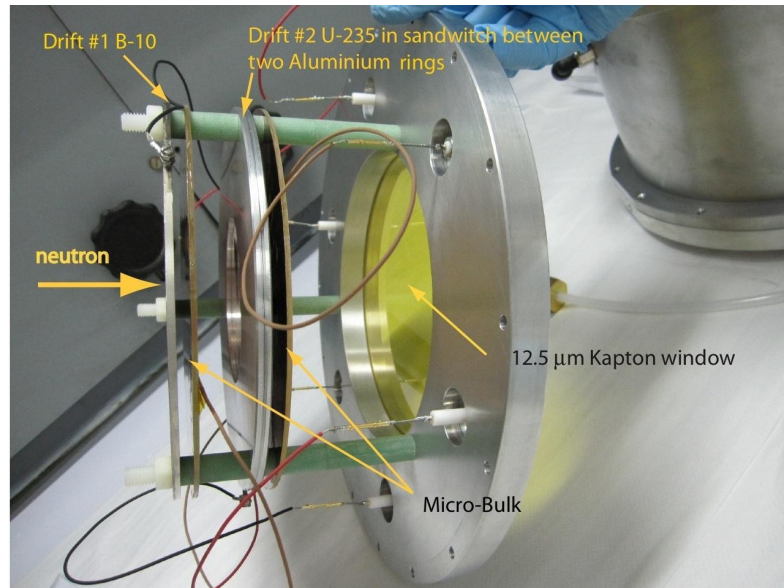
2 MicroMegas detectors equipped with ^{10}B ($0.6\ \mu\text{m}$) and ^{235}U (1 mg) deposits



Detection efficiency < 1% at thermal energy

MicroMegas detectors

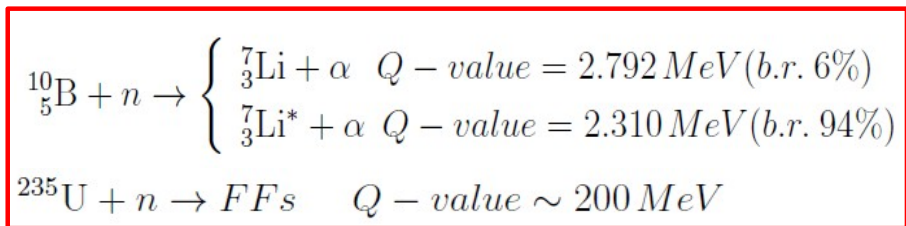
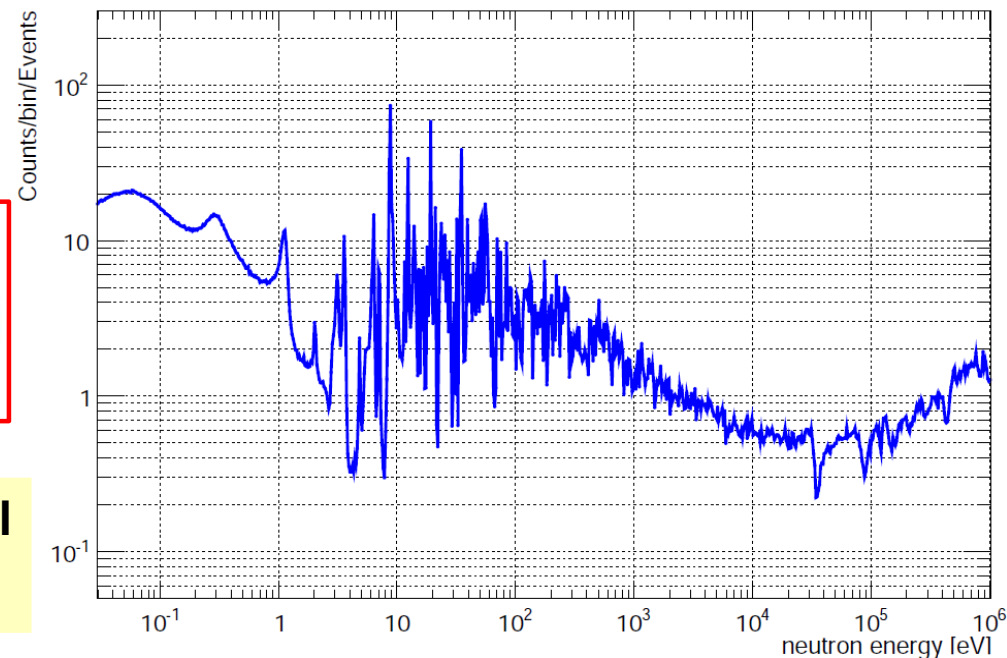
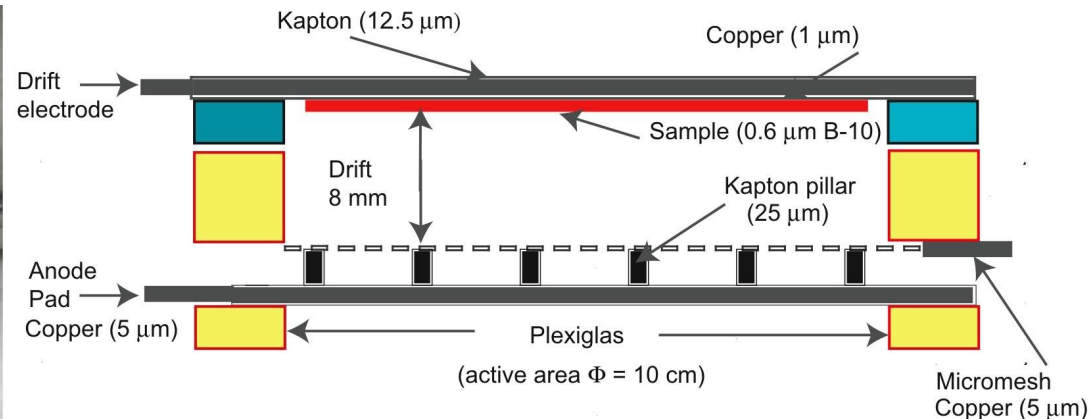
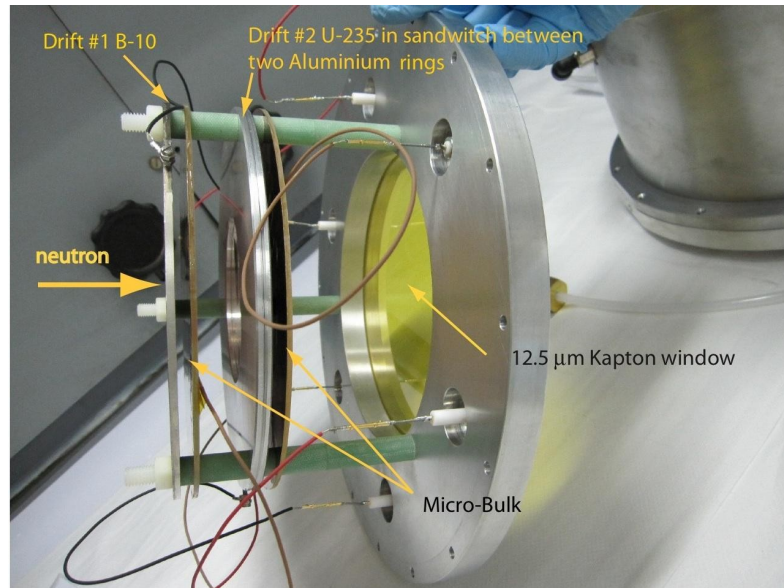
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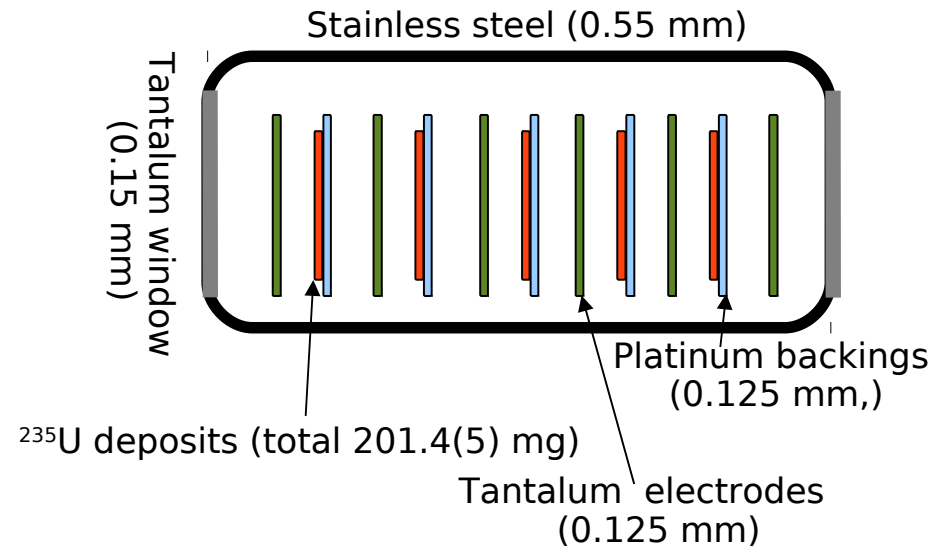
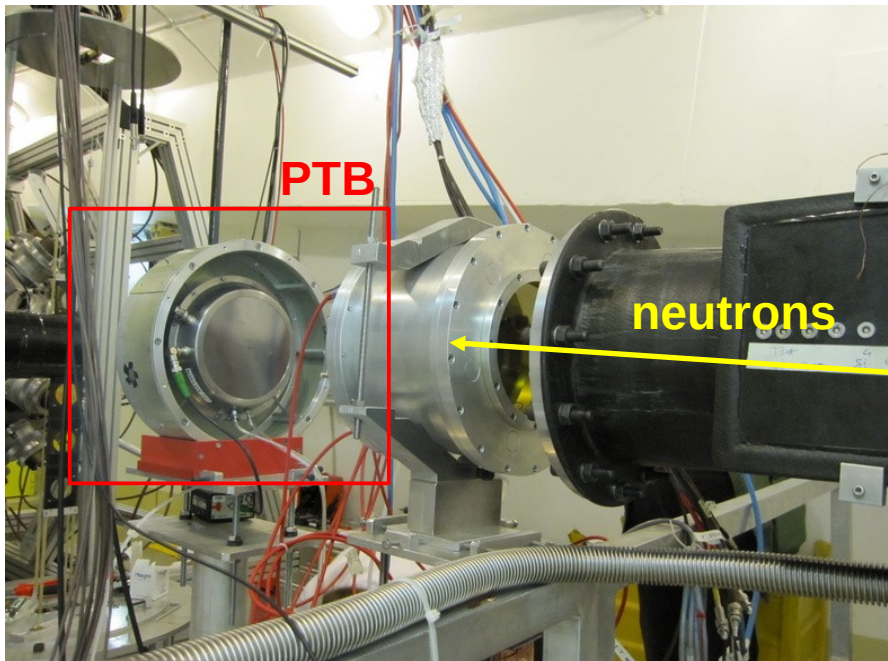
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Detection efficiency < 1% at thermal energy

The PTB calibrated fission chamber

PTB detector is a **fission chamber** loaded with 201.4(5) mg of ^{235}U in five deposits.

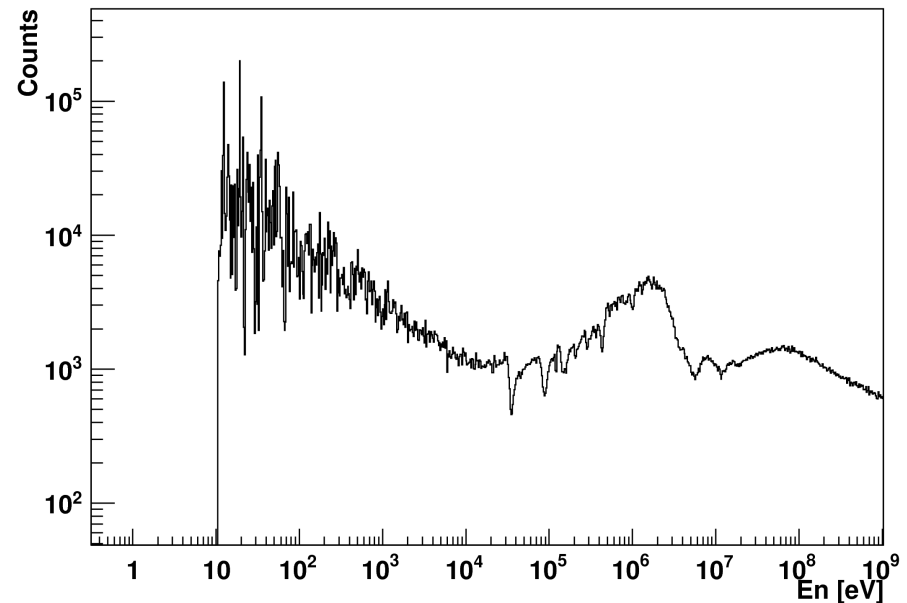
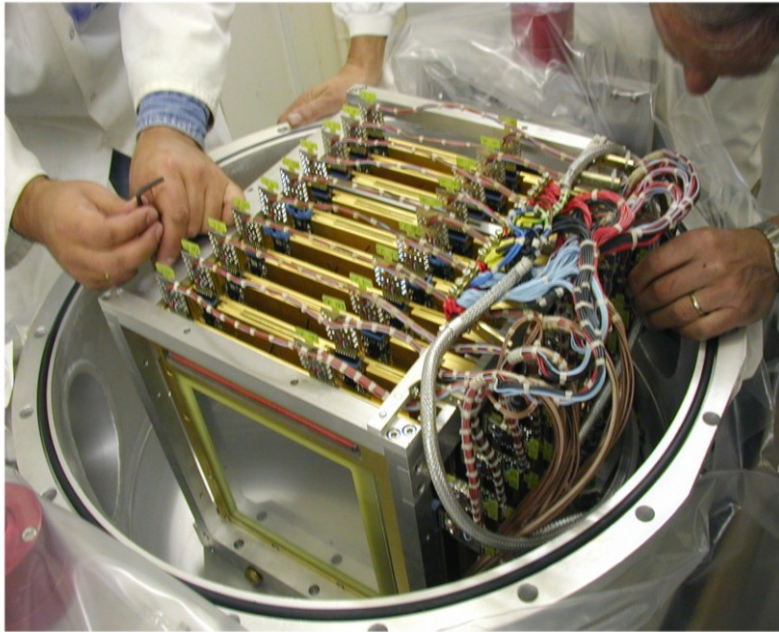


The PTB chamber is calibrated, meaning that the **mass of ^{235}U** and the **detection efficiency** are well known from previous “international intercomparisons”.

Reference detector in measuring neutron flux, not only at n_TOF.

Parallel Plate Avalanche Counter (PPAC)

At n_TOF PPAC detector is a stack of 10 parallel plate avalanche counters. Some of them are loaded with ^{235}U or ^{238}U in order to measure neutron flux.

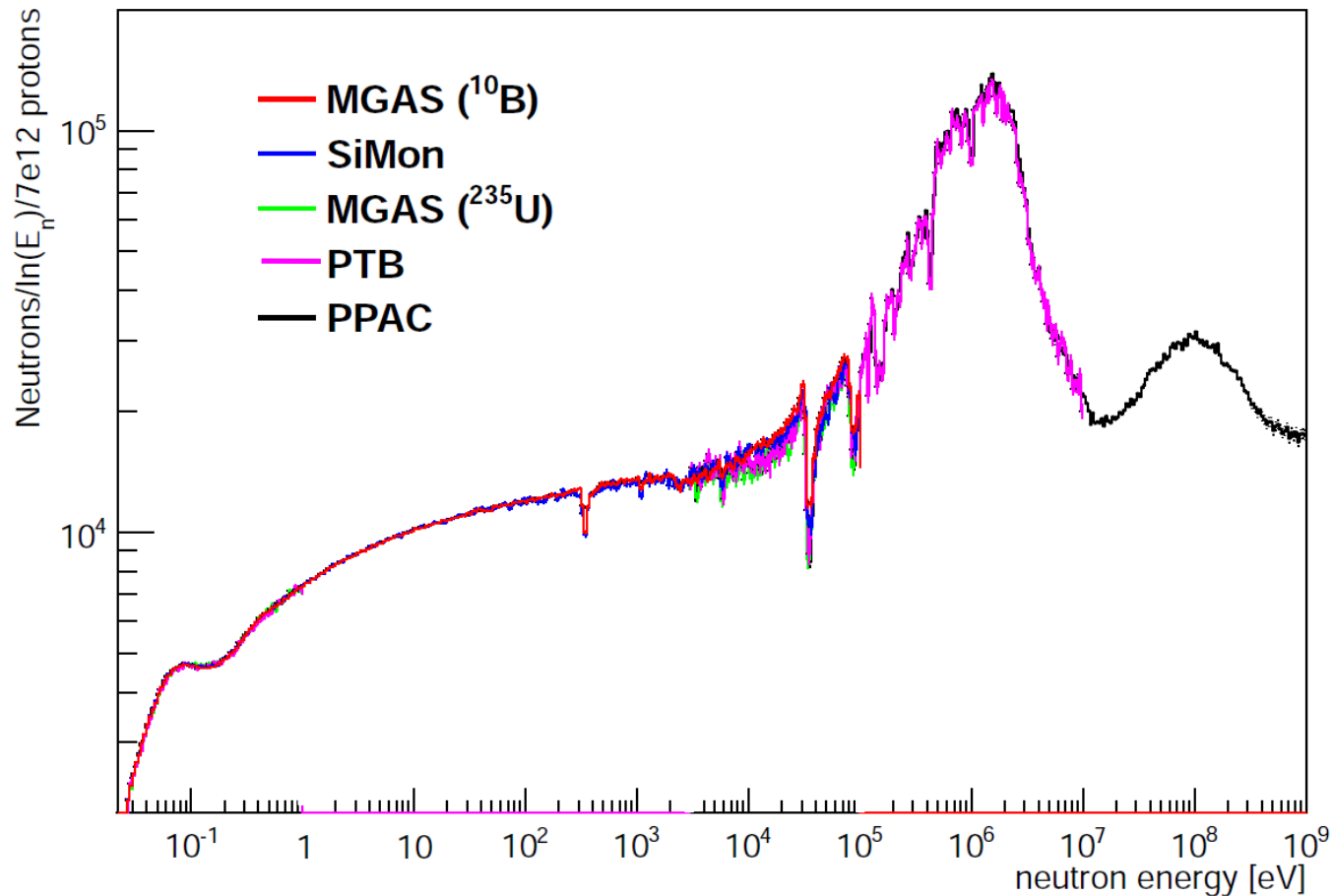


Fission fragments detected **in coincidence**, rejection of α background.

Fast response

Very low sensitivity to γ

Results from neutron measurements

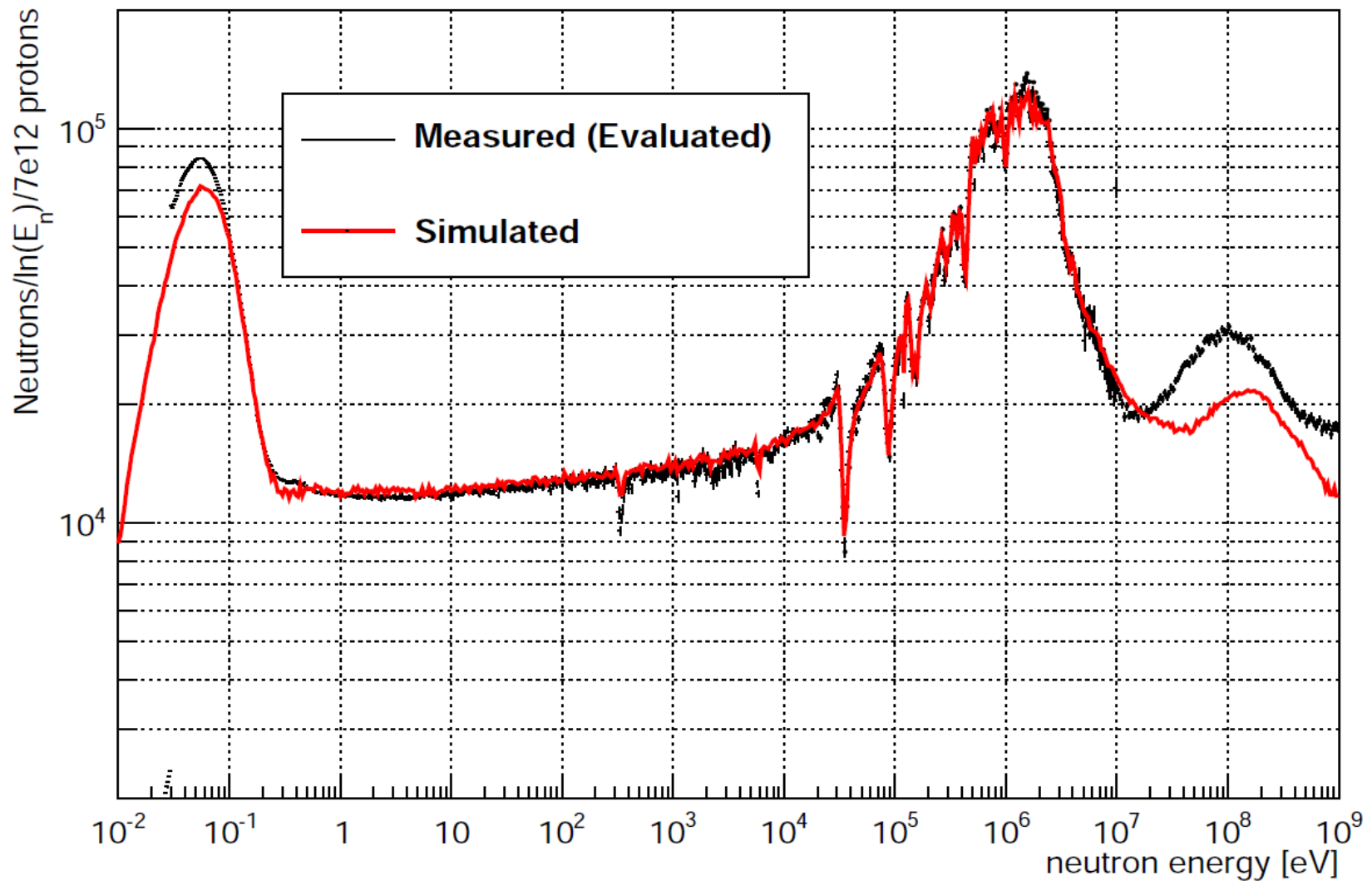


Measurements from 0.025 eV up to 1 GeV

Up to few keV results from different detectors agree within 2% (or less)

From few keV to higher energies agreement within 4-5%

Results from neutron measurements



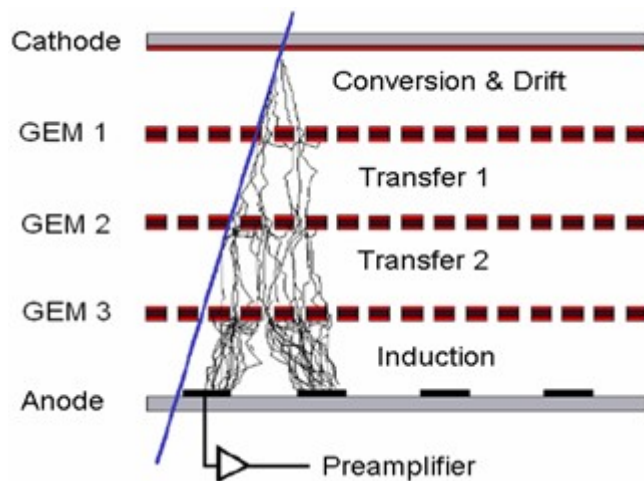
After careful comparisons an **evaluated neutron flux** has been then determined **combining results** from all the **detectors** where they are considered reliable.

Other neutron detectors

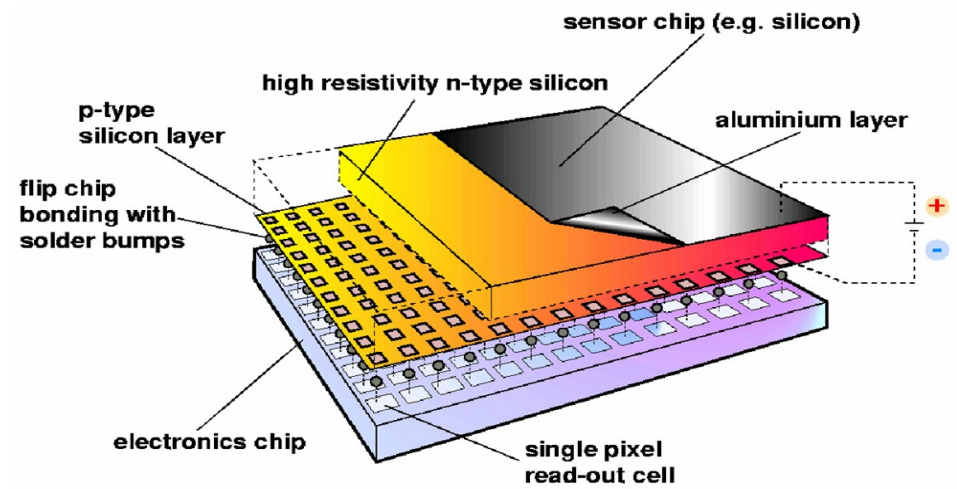
At n_TOF some measurements are also dedicated to test innovative neutron detectors, **both** in the context of the collaboration **and** from proposals of external research groups.

Recently (among others):

Triple GEM detector



MEDIPIX detector



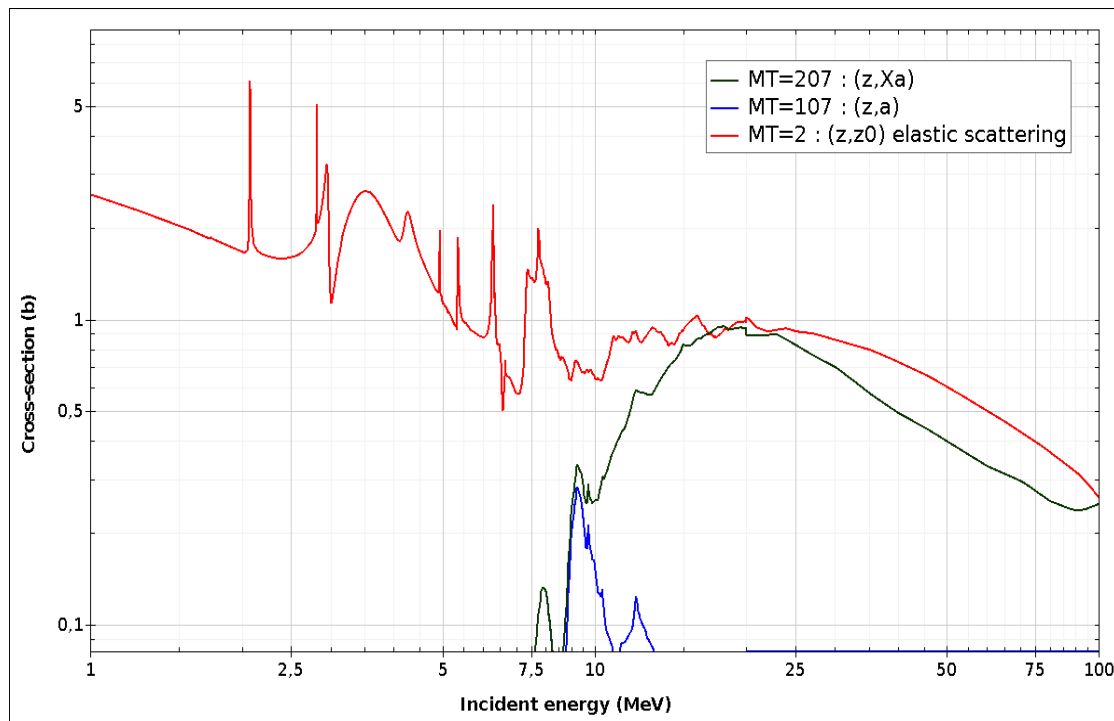
Fast neutron (elastic scattering in Polyethylene)
Slow neutron (^{10}B converter)

Other neutron detectors

At n_TOF some measurements are also dedicated to test innovative neutron detectors, **both** in the context of the collaboration **and** from proposals of external research groups.

Recently (among others):

Single-Crystal Diamond Detector (SDD)



Fast neutron detection is achieved by detecting charge particles produced via the reactions:

- $^{12}\text{C}(n,\alpha)^9\text{Be}$
($Q_{\text{value}}=5.7$ MeV, $E_{\text{thr}}=6.17$ MeV)
- $^{12}\text{C}(n,n')^3\alpha$
($Q_{\text{value}}=7.23$ MeV, $E_{\text{thr}}=7$ MeV)

Conclusions

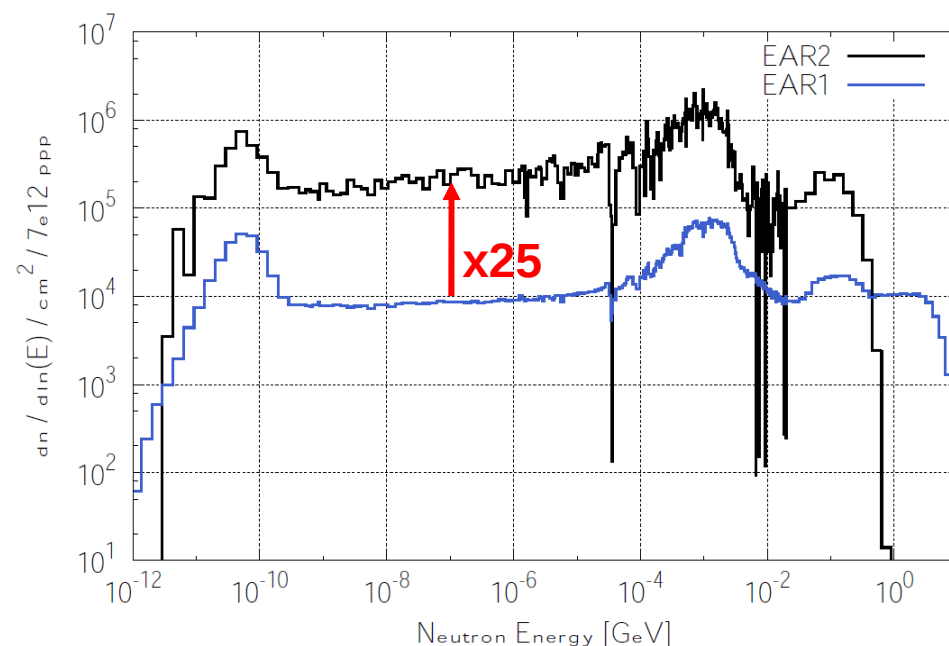
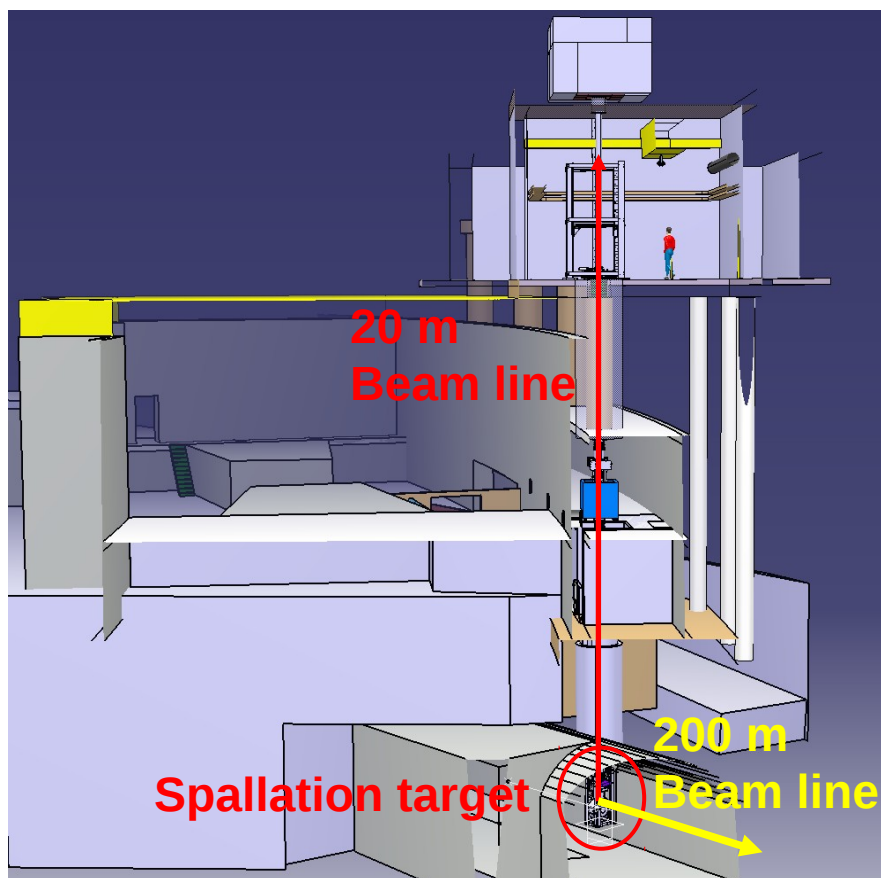
- The **n_TOF facility** is active since 2001, with the aim of addressing the request of accurated nuclear data for **nuclear astrophysics** and **nuclear technologies**.
- The **high quality** of its **neutron beam** makes **n_TOF** a unique facility in the world for cross section measurements of neutron induced reactions.
- **Several neutron detection systems** based on **standard reactions** are used to measure neutrons flux with high accuracy. Results show a very nice agreement.
- **R&D activity** is welcome...

Conclusions

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- **R&D activity** is welcome....also for measurements in the second experimental area presently under construction.

~~Conclusions~~ EAR2

Experimental Area 2 will be placed at 20 m from the spallation target.



Higher fluence, by a factor of 25, relative to EAR1.

The **shorter flight path** implies a factor of 10 smaller time-of-flight.

Global gain by a factor of **250 in the signal/background ratio** for radioactive isotopes!

Conclusions

- The **n_TOF facility** is active since 2001, with the aim of addressing the request of accurated nuclear data for **nuclear astrophysics** and **nuclear technologies**.
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Thanks for your kind attention

Back-up slides

Back-up slide

