The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

1944-8

Joint ICTP-IAEA Workshop on Nuclear Reaction Data for Advanced Reactor Technologies

19 - 30 May 2008

Fission cross-section measurements for Minor Actinides.

N. Colonna

Istituto Nazionale di Fisica Nucleare
Sez. di Bari
Italy

Fission cross-section measurements for Minor Actinides

An informal discussion on new needs, experimental techniques, latest results and related uncertainties

Nicola Colonna

Istituto Nazionale Fisica Nucleare, Sez. di Bari

V. Orabona 4, 70126 Bari, Italy

nicola.colonna@ba.infn.it

Nuclear Data for Science, Technology and … Society (Hans Blix, ND 2007)

ICTP-IAEA, Trieste, 19-28 May, 2008

Outline – Part I

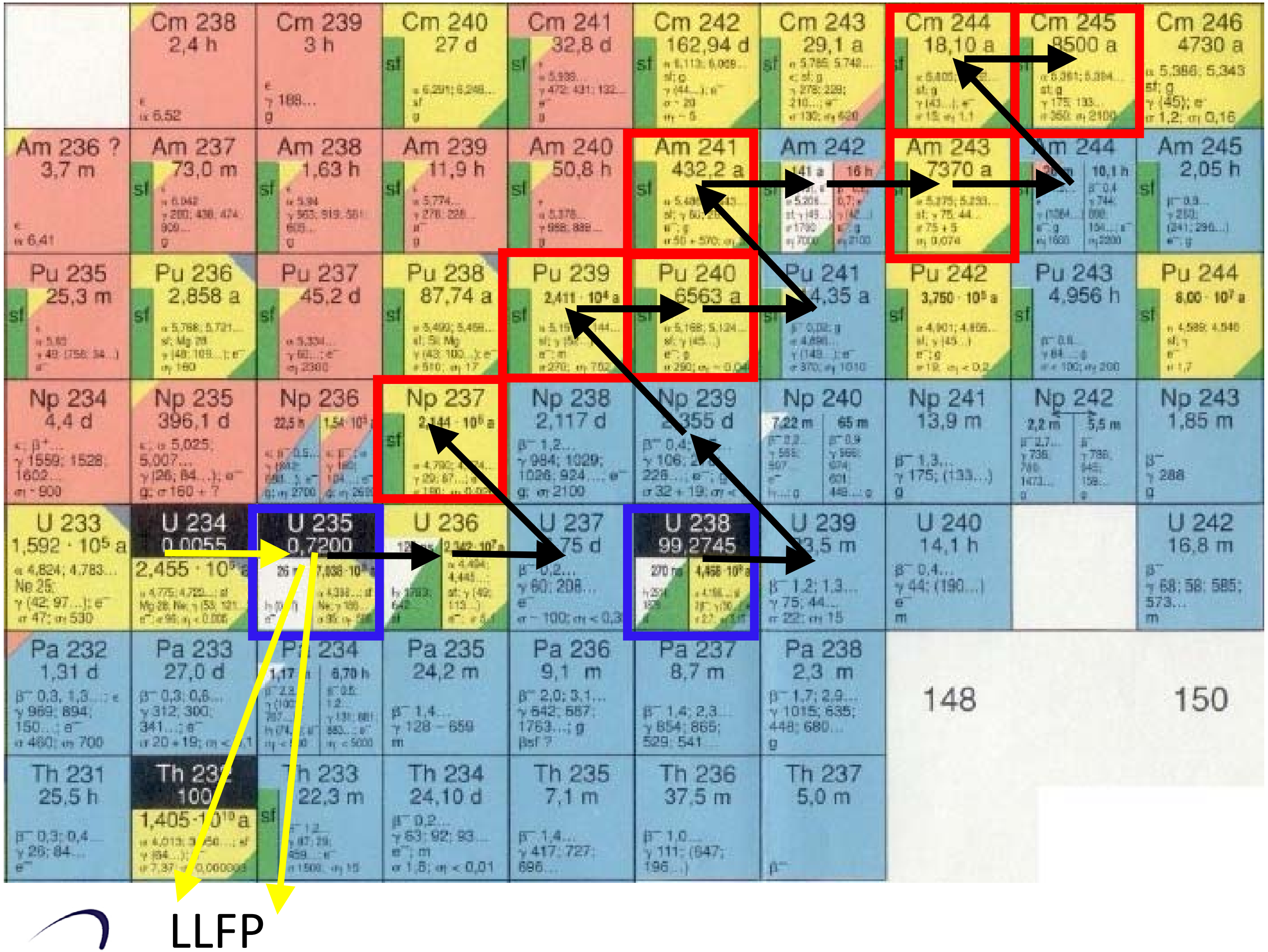
- **Motivations**
- **Neutron facilities for fission measurements**
- **The fission detectors**
- **Analysis techiques**

Outline – Part II

- Current status of fission cross-sections on Minor Actinides
- New results
- Other methods

Motivations

Nuclear waste composition (1 GW_e LWR)



$^{244,245}Cm$
1.5 Kg/yr

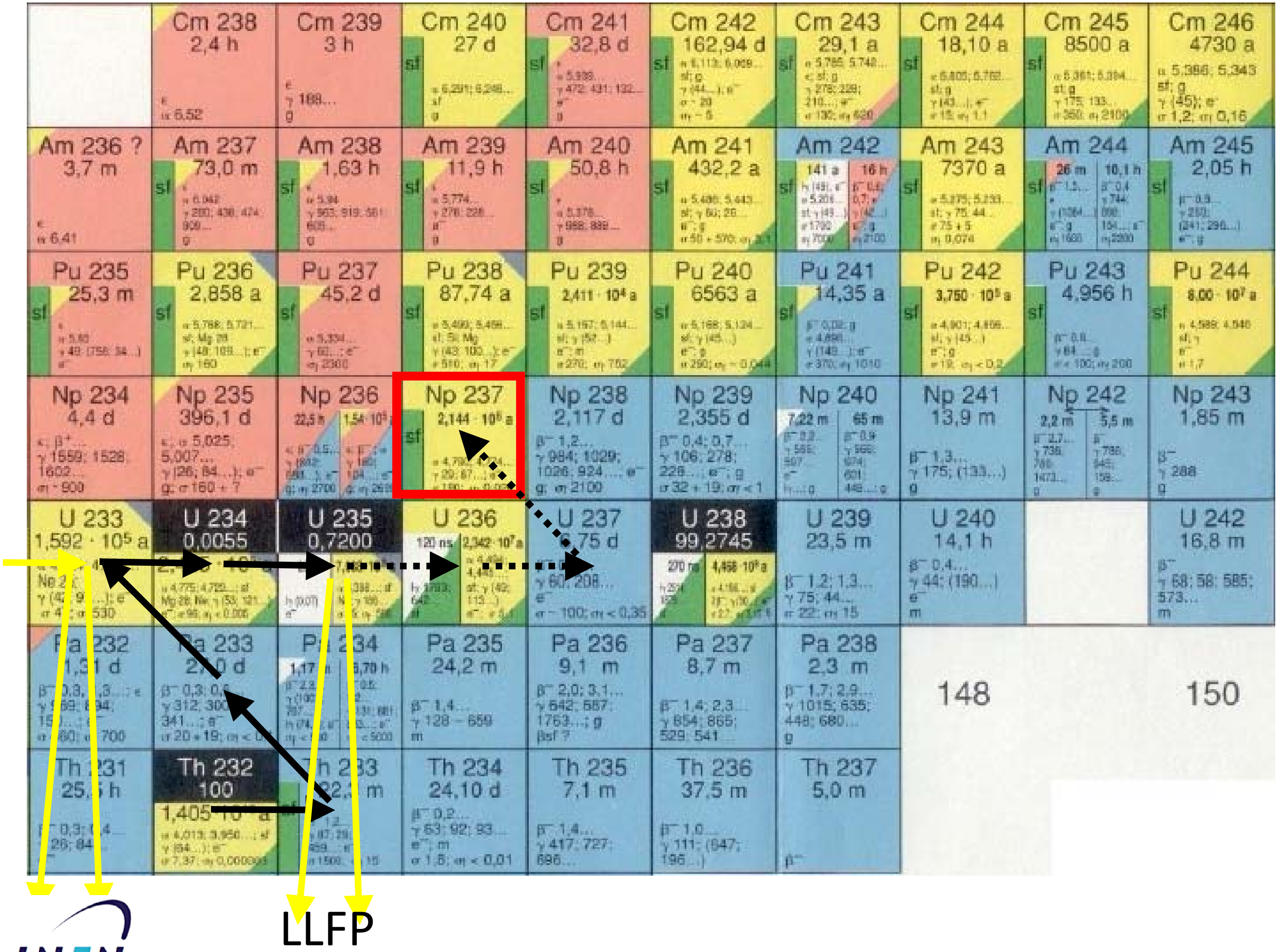
^{241}Am: 11.6 Kg/yr
^{243}Am: 4.8 Kg/yr

^{239}Pu: 125 Kg/yr

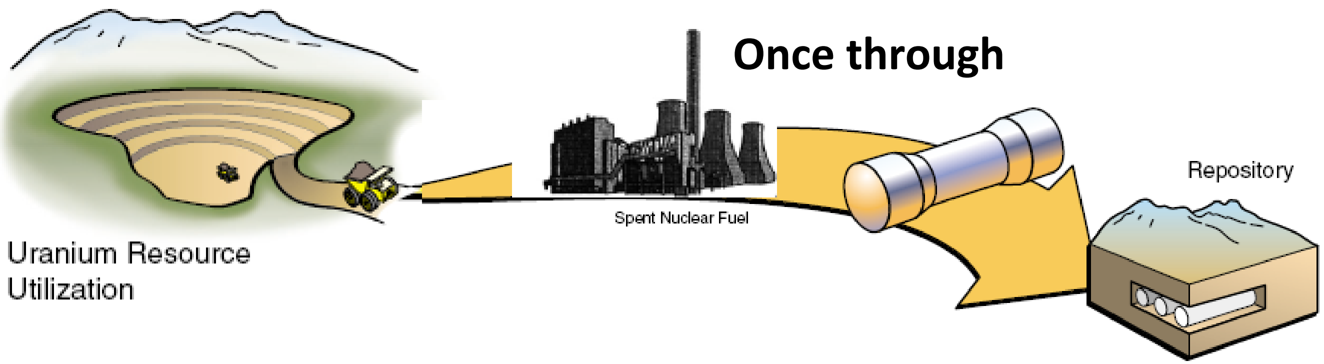
^{237}Np: 16 Kg/yr

LLFP
76.2 Kg/yr

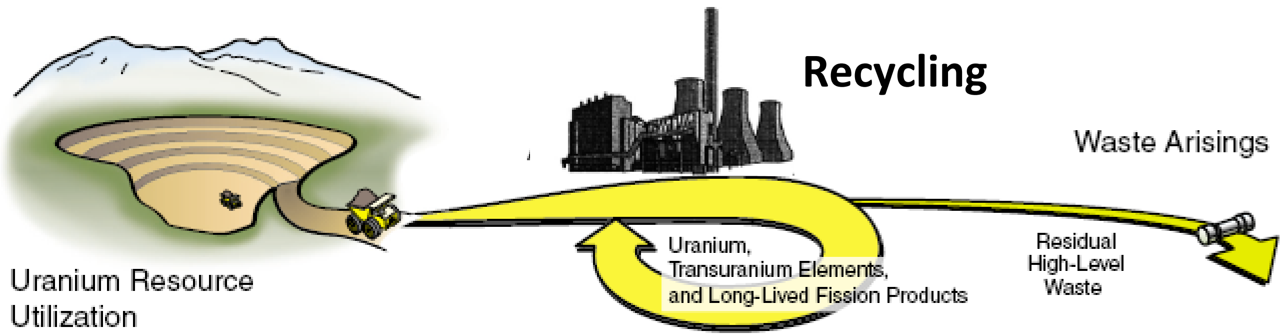
The Th/U fuel cycle



New generation reactors



Existing reactors have low **burn-up efficiency** and produce large amount of **radioactive waste.**



New generation reactors thought to **recyle** part of the **spent fuel.**

Advantages of **IV Generation** reactors (and Accelerator Driven Systems):

- Higher burn-up **efficiency** and lower production of waste
- Greater **safety and non-proliferation**
- lower **costs and construction time**

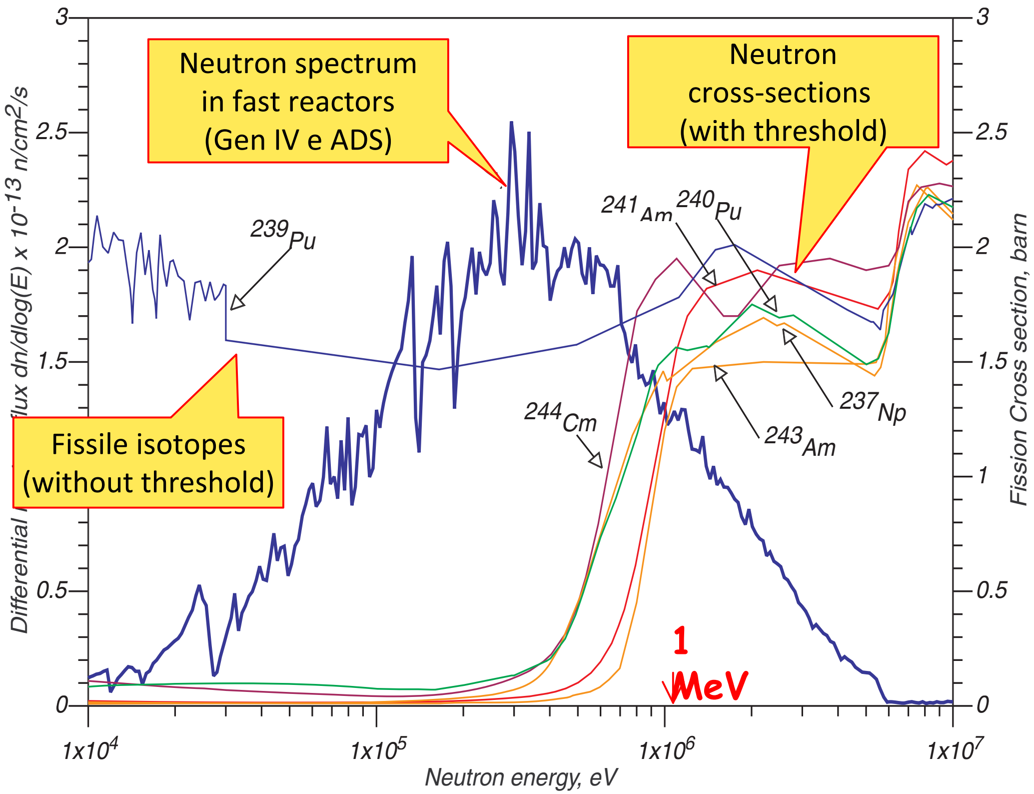
Reactor physics in Gen IV and ADS

The main innovation concerns the possibility to produce energy by burning the nuclear waste with higher radiotoxicity (minor actinides) : **Np, Am, Cm**

Apart for ^{245}Cm, minor actinides present a **fission threshold** around **MeV**.

To burn-up minor actinides, **fast neutrons** have to be used (E_n > 1 MeV).

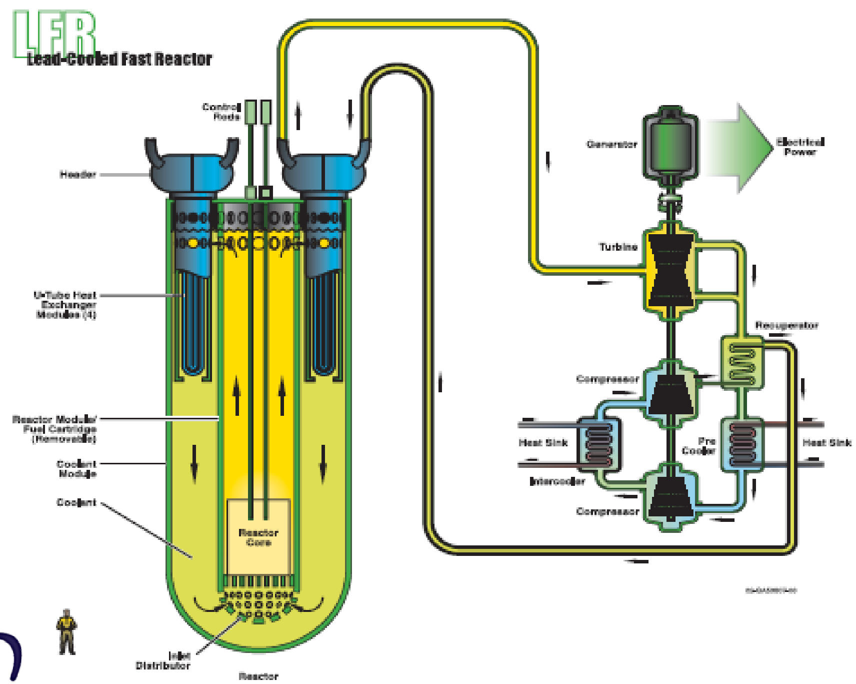
The **flux in the fast region** of advanced reactors require **higher precision** data in that region to minimize uncertainties in calculations of reactor **design** and **safety** parameters.

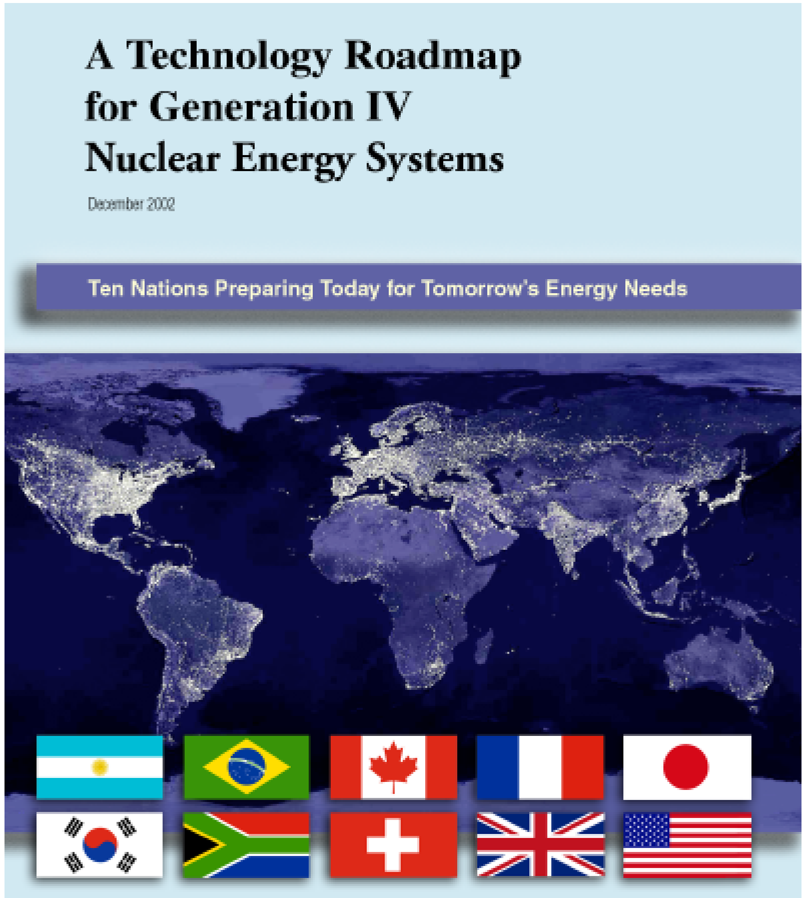


The development of Gen IV reactors **fast reactors** requires data on minor actinides

The Generation IV forum

Generation IV System	Acronym
Gas-Cooled Fast Reactor System	GFR
Lead-Cooled Fast Reactor System	LFR
Molten Salt Reactor System	MSR
Sodium-Cooled Fast Reactor System	SFR
Supercritical-Water-Cooled Reactor System	SCWR
Very-High-Temperature Reactor System	VHTR





10 Nations Preparing Today for Tomorrow's Energy Needs

Table 1. Summary Target Accuracies for Fast Reactors

		Energy Range	Current Accuracy (%)	Target Accuracy (%)
U238	inel	0.5 ÷6.1 MeV	10 ÷ 20	2 ÷ 3
	capt	2.04 ÷24.8 keV	3 ÷ 9	1.5 ÷ 2
Pu241	fiss	454. eV ÷1.35 MeV	8 ÷ 20	2 ÷ 5
Pu239	capt	2.04 ÷498 keV	7 ÷ 15	4 ÷ 7
Pu240	fiss	0.498 ÷1.35 MeV	6	1 ÷ 3
Pu242	fiss	0.498 ÷2.23 MeV	19 ÷ 21	3 ÷5
Pu238	fiss	0.183 ÷1.35 MeV	17	3 ÷5
Am242m	fiss	67.4 keV ÷1.35 MeV	17	3 ÷4
Am241	fiss	2.23 ÷6.07 MeV	9	2
Am243	fiss	0.498 ÷6.07 MeV	12	3
Cm244	fiss	0.498 ÷1.35 MeV	50	5
Cm245	Fiss	67.4 ÷183 keV	47	7
Fe56	Inel	0.498 ÷2.23 MeV	16 ÷ 25	3 ÷ 6
Na23	inel	0.498 ÷1.35 MeV	28	4 ÷10
Pb206	inel	1.35 ÷2.23 MeV	14	3
Pb207	Inel	0.498 ÷1.35 MeV	11	3
Si28	inel	1.35 ÷6.07 MeV	14 ÷ 50	3 ÷ 6
	capt	6.07 ÷19.6 MeV	53	6

Necessary accuracy better than **3 %** for most Pu isotopes and Minor Actinides, in the energy range from a few keV to several MeV

Source: Aliberti, Palmiotti, Salvatores, NEMEA-4 workshop, Prague 2007

Experimental challenges

^{241}Pu(n,f) ($\tau_{1/2}$=14.4 years) **500 eV < E_n < 2 MeV**

- Data needed for SFR, GFR, LFR
- Current uncertainty: 10-20 % Target accuracy: 2-6 %
- Similar needs for ^{240}Pu ($\tau_{1/2}$=6.5e3 years) and ^{242}Pu ($\tau_{1/2}$=3.75e5 years)

^{241}Am, ^{242m}Am, ^{244}Cm, ^{245}Cm(n,f) **En < 2 MeV**

- Data needed for SFR and ADS
- Current uncertainty: 10-40 % Target accuracy: 2-6 %

There is a **strong need** for more accurate measurements.

The various neutron facilities around the world can contribute to attack a large part of the **still open nuclear data requests**.

However, the most difficult measurements require **improvements** on the **experimental methods** and on **neutron facilities** (but there is still a question whether some measurements will be feasible in the near future)

Some "impossible" measurements can at present be done with other methods **(surrogate)**.

Needs for new data on fission cross-sections

New and accurate nuclear data for **Pu** and **Minor Actinides** needed for:

- increase fuel burn-up for all types of nuclear reactors (including existing)
- utilization of accumulated plutonium
- recycling of the nuclear fuel (closed cycle)
- transmutation of minor actinides in different types of nuclear power reactors and accelerator-driven systems

HPRL — The NEA High Priority Request List

Nuclear Data Standards | Dosimetry Reactions | Fusion Technology | Fission Reactor Technology | Medical and Industrial Applications | Intermediate Energies

OECD

www.nea.fr/html/dbdata/hprl/

Current compilation of neutron cross-sections (ENDF, JENDL, JEFF, BRONDL, etc…) are incomplete or discrepant among themselves or with experimental data, for many isotopes (Minor Actinides).

Clearly inadequate for the needs related to emerging nuclear technologies

Strong need of new and accurate fission cross-section data for several isotopes, many of which highly radioactive.

The neutron facilities

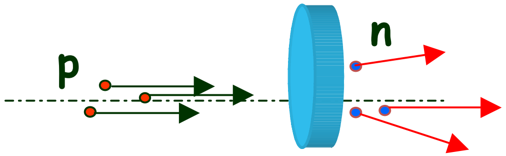
The different types of neutron sources

Thermal neutron beams:

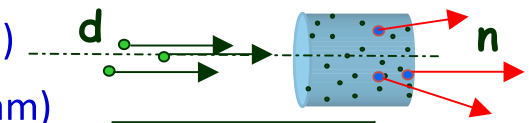
- high fluxes available at **nuclear reactors**
- **moderated** neutrons produced with **accelerators** (see below)

Monoenergetic neutron sources:

- typically based on **p- or d-induced** reaction
- D(d,n), T(p,n), T(d,n), ^{7}Li(p,n), ^{9}Be(p,n), ec…,
- **thin** production targets
- based on **low- and medium-energy** accelerators (VdG, Pelletron, …)
- **accordable** neutron energy (by changing energy of the primary beam)
- neutron energies up to **20 MeV**



T (p,n)^{3}He



D (d,n)^{3}He

Time-of-flight facilities (ToF):

- wide energy spectrum, neutron energy determined from ToF
- choice of flight base trade-off between flux and energy resolution
- Requires pulsed accelerator

Time-of-flight facilities

Different types of neutron **time-of-flight** facilities

(p,n) and (d,n) reactions:

- Low and medium energy accelerator (pulsed)
- thick targets (for higher flux)
- moderated spectrum

High-intensity **electron beams**:

- neutron production though (γ,n) reactions
- target made of high-Z material (and U, in some cases)
- moderated spectra

Spallation neutron sources:

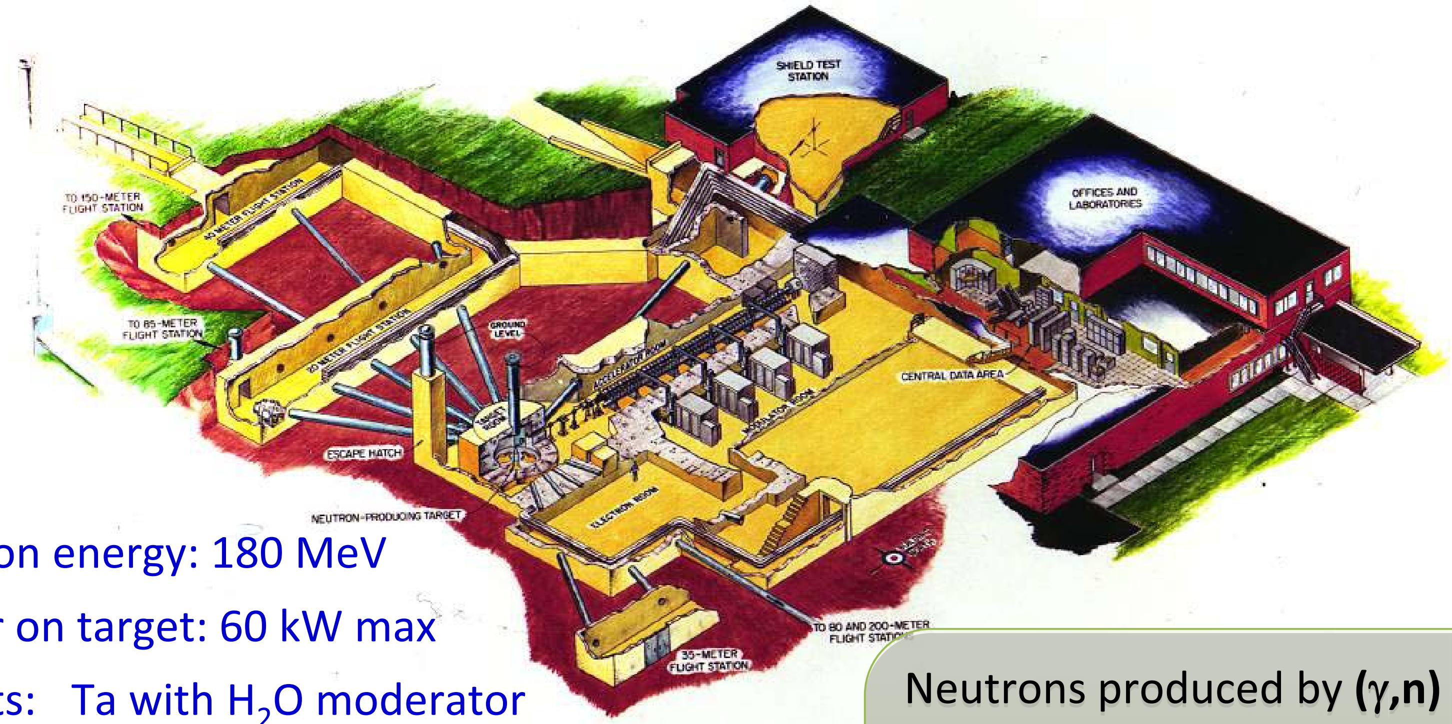
- based on high-energy (GeV) protons beams
- Large blocks of heavy material
- Moderated spectrum

The neutron facilities at JRC-IRMM

Already shown by P. Schillenbeeckx

The ORELA neutron facility

The Oak Ridge Electron Linear Accelerator (Oak Ridge, Tennessee, USA)



Electron energy: 180 MeV

Power on target: 60 kW max

Targets: Ta with H_2O moderator
Be block (E_n > 1 MeV)

Neutron production: 10^{11} n/pulse (Ta target)
10^{14} n/sec at 50 kW

Number of flight paths: 11 (from 9 to 200 m)

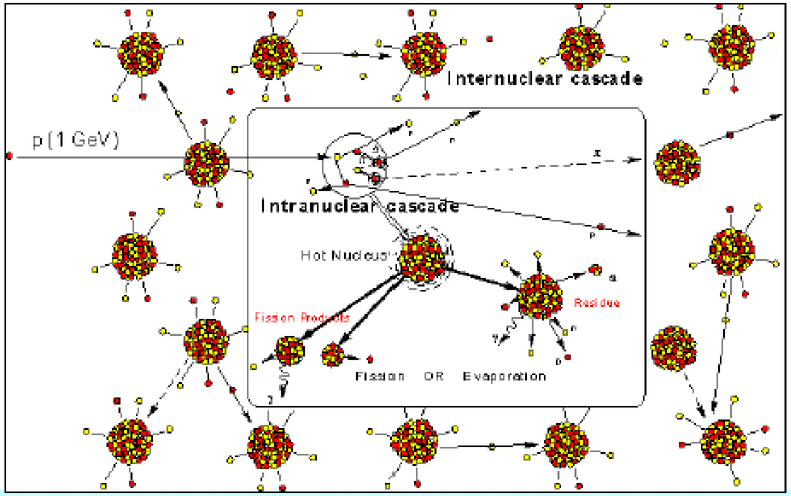
Neutrons produced by **(γ,n) reactions**

γ-rays produced by **bremsstrahlung** of electron beams

High resolution facility

Many measurements done here

Spallation neutron sources



Neutrons produced by a **series of nuclear reactions** (intranuclear cascade, preequilibrium, evaporation, etc…)

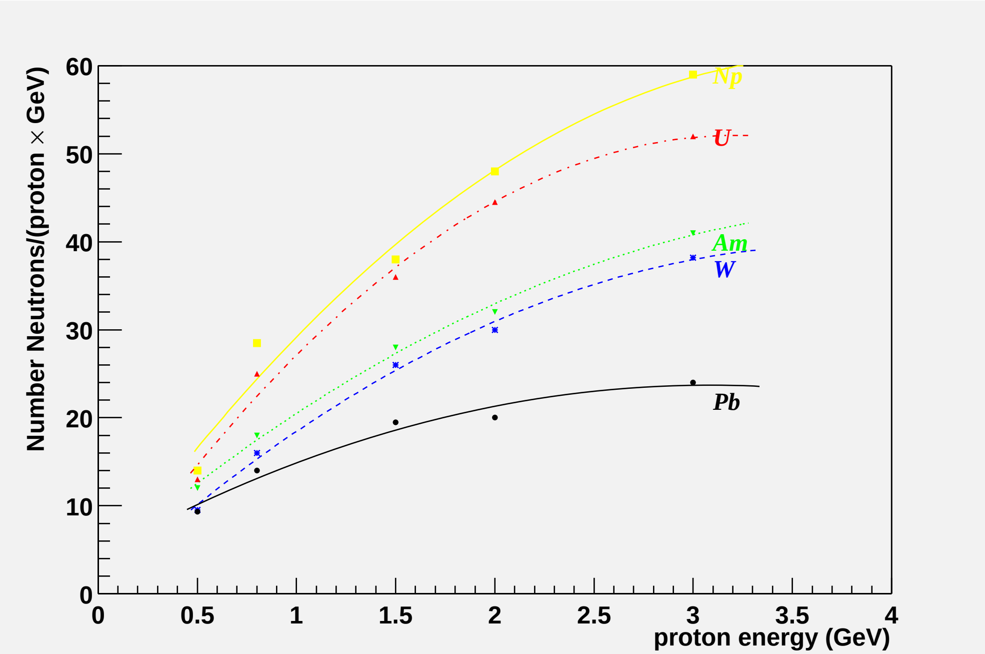
Need **high-energy proton** beams

Large volume spallation targets

Neutron production depends on **atomic weight** and **density** of the material ➡ high-Z material needed

Depends on **proton energy**

Choice of **target** depends also on other factors (radiation resistance, costs, etc…)



The Los Alamos Neutron Science Center (LANSCE)

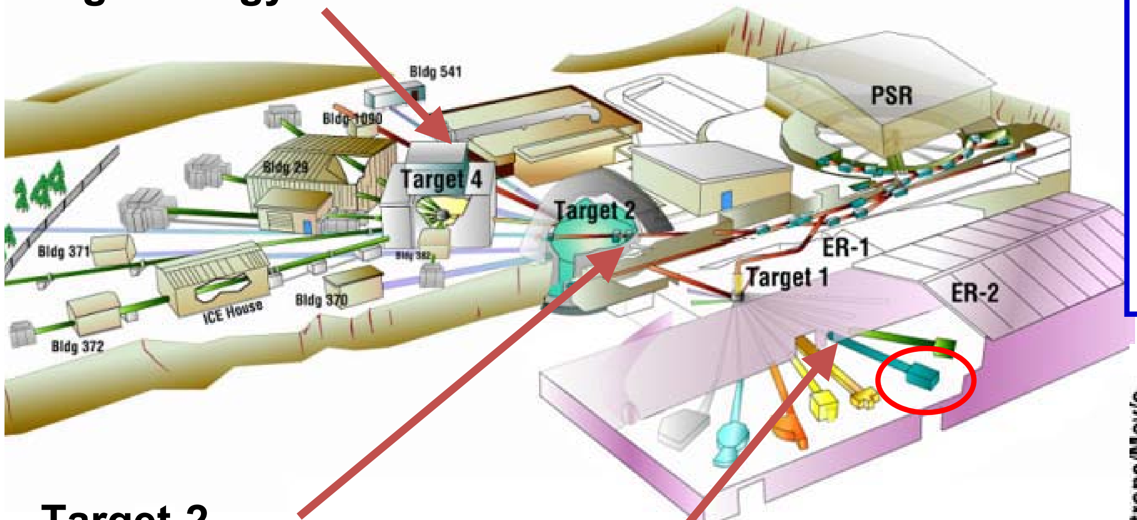
Based on the **spallation** of 800 MeV proton beam on Tungsten **targets**

Use of the **proton storage ring** to increase proton beam current (and therefore, neutron flux)

Different target/moderator assembly allow measurements in a wide energy range:

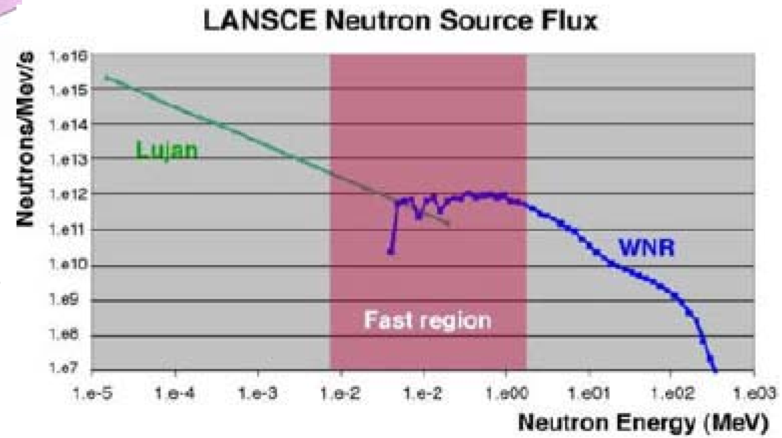
- W target with moderator for low-energy measurements
- W target without moderator for measurements up to 200 MeV

Target-4 WNR
High-energy neutron research

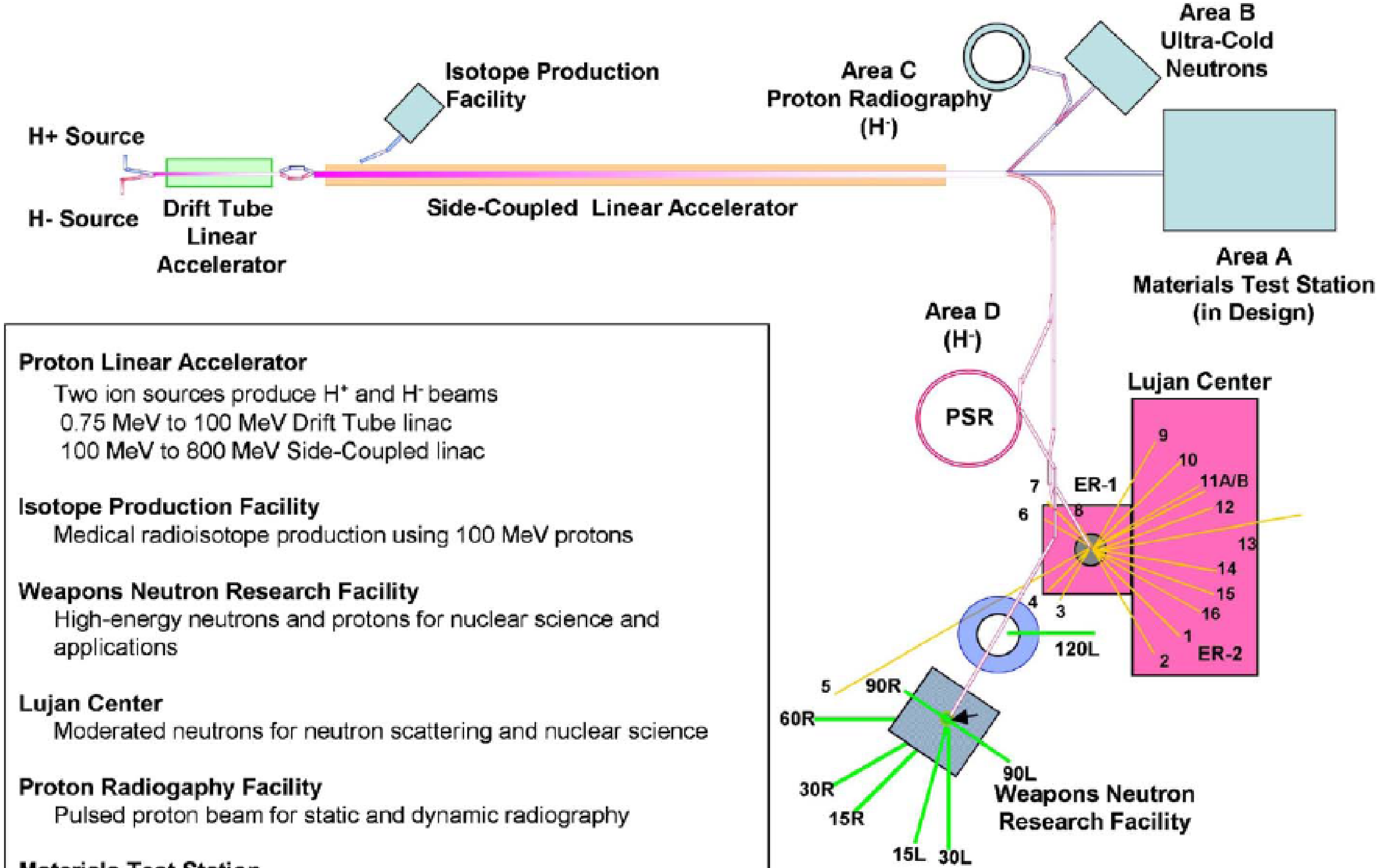


Target-2
- Proton-induced reactions
- Single-pulse experiments (Sandia)
- Lead Slowing-Down Spectrometer

Lujan Center
Low-energy neutrons
- Material science
- Nuclear science



The LANL neutron facilities



Proton Linear Accelerator
Two ion sources produce H^+ and H^- beams
0.75 MeV to 100 MeV Drift Tube linac
100 MeV to 800 MeV Side-Coupled linac

Isotope Production Facility
Medical radioisotope production using 100 MeV protons

Weapons Neutron Research Facility
High-energy neutrons and protons for nuclear science and applications

Lujan Center
Moderated neutrons for neutron scattering and nuclear science

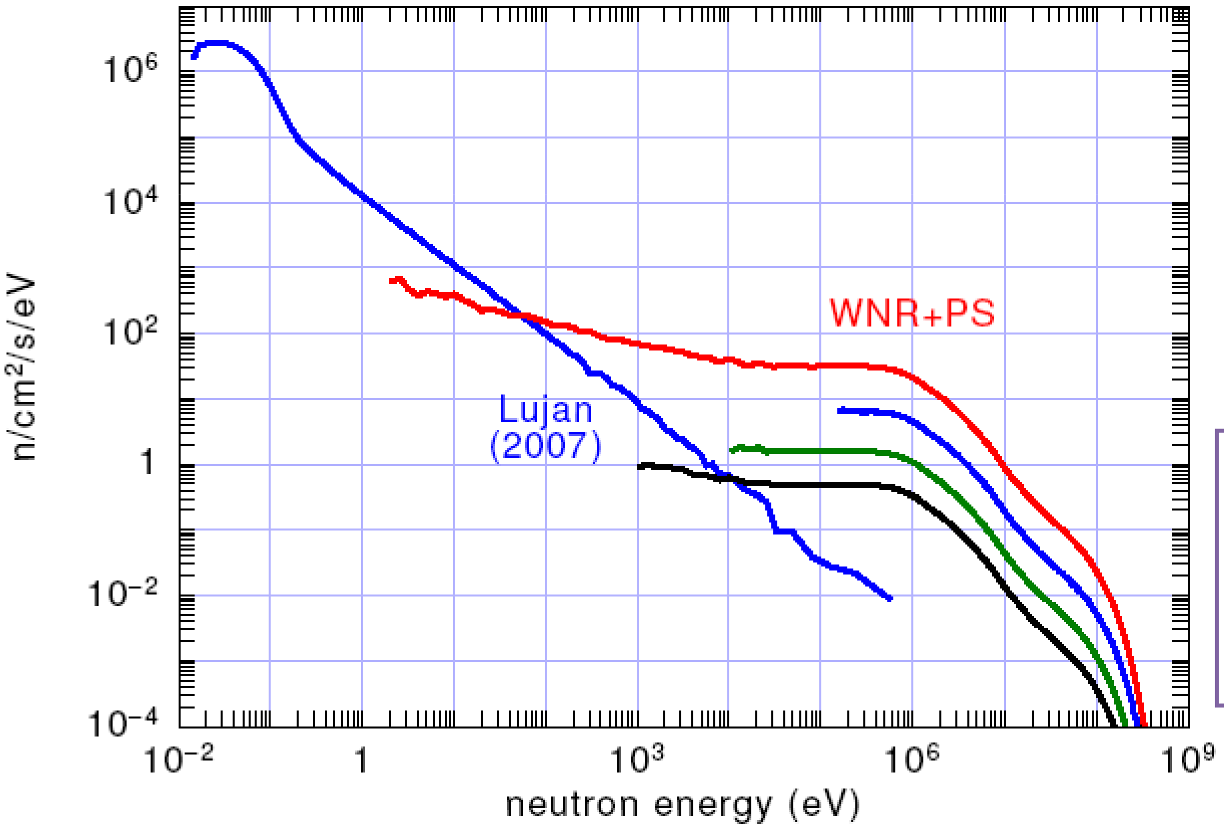
Proton Radiogaphy Facility
Pulsed proton beam for static and dynamic radiography

Materials Test Station
High-power fast neutron irradiation of reactor fuels and components

Ultra Cold Neutron Facility
Fundamental physics experiments with UCN

P.W. Lisowski et al., NIM A562, 910 (2006)

Neutron flux available at LANL

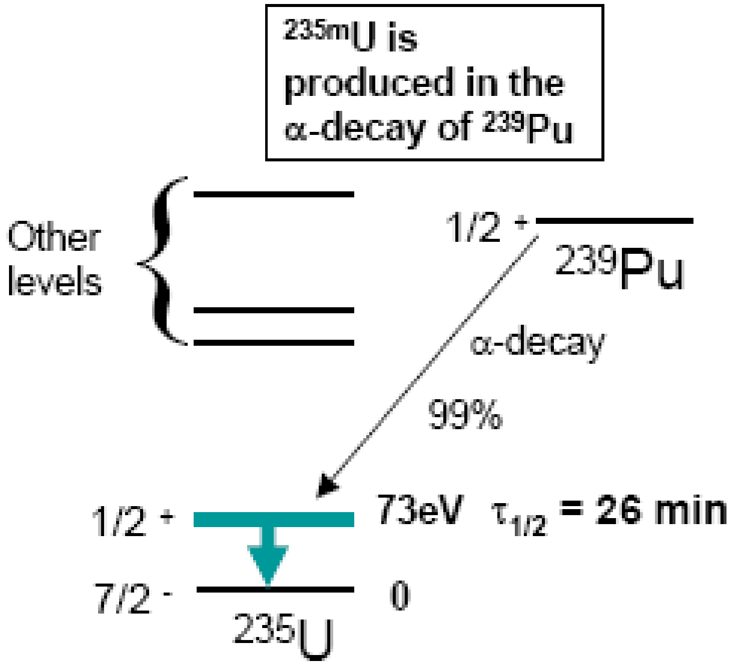


The "pulse stacking" mode, using the **proton storage ring**, increases neutron flux and decreases repetition rate (neutrons wrap-around at lower energy)

20 μA WNR pulse stacking
4 μA WNR 1.8 μs spacing
1 μA WNR 7.2 μs spacing
4/13 μA 23.4 μs spacing

Fission cross-section for very small samples

The $^{235m}U(n,f)$ case



An isomeric state of ^{235}U is produced as a result of ^{239}Pu α-decay (with 99 % of branching ratio)

Half life of ^{235m}U $\tau_{1/2}$= 26 min

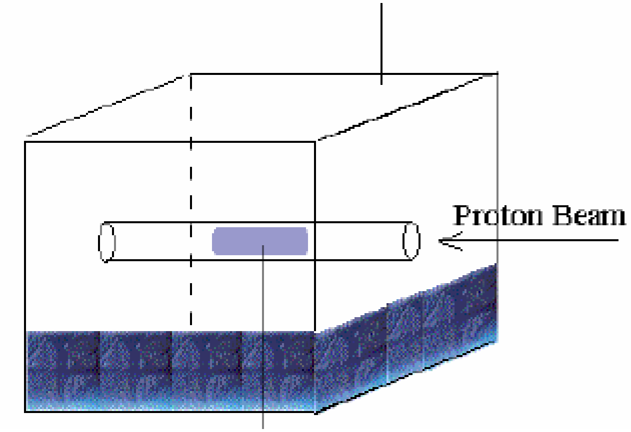
Need 500 mg of Pu to produce 1 ng of ^{235m}U
Very small amount of ^{235m}U can therefore be available (plus, a fast separation technique is needed)

To meaured the $^{235m}U(n,f)$, necessary huge neutron flux (up to 10^4 times those currently available)

Lead Slowing Down Spectrometer

Fission cross section measurements for isotopes **highly radioactive** or available in small quantities need **extremely high** neutron flux

The solution is the **"Lead Slowing Down Spectrometer"**



Neutrons interactions in Pb: only **inelastic** and **elastic** collisions (small capture cross-sections)

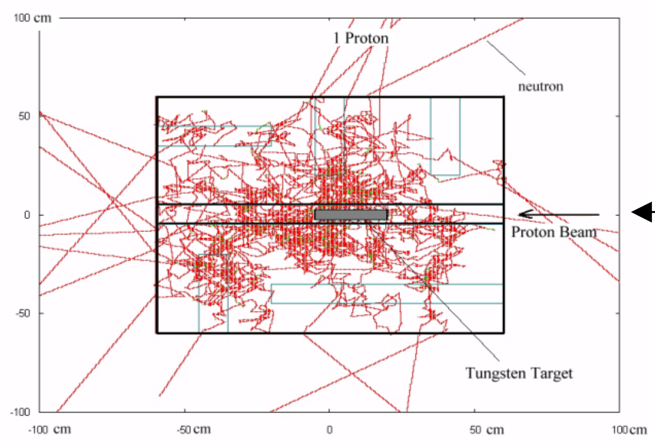
In each interaction, **little energy** is lost

Neutrons are **trapped** inside Pb block

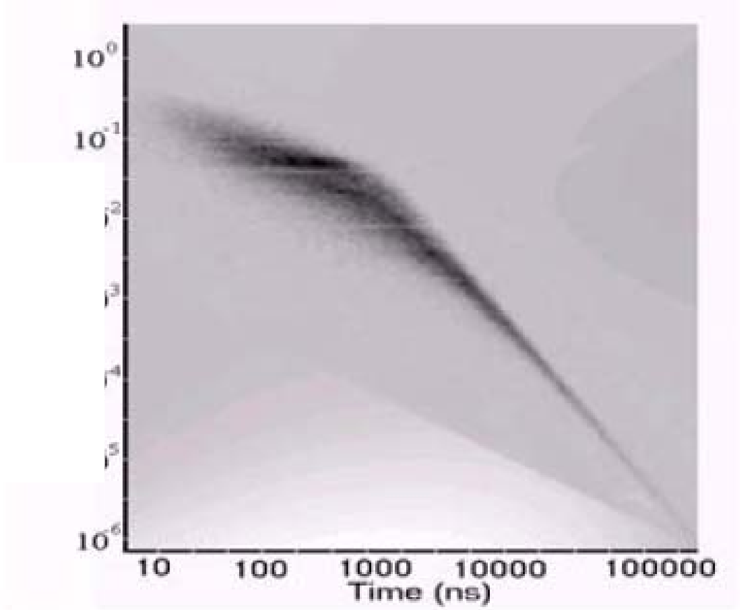
At LANL, 800 MeV p on W, inside 1 m^3 Pb cube

Lead Slowing Down Spectrometer

Simulations



One proton



Time-energy relation

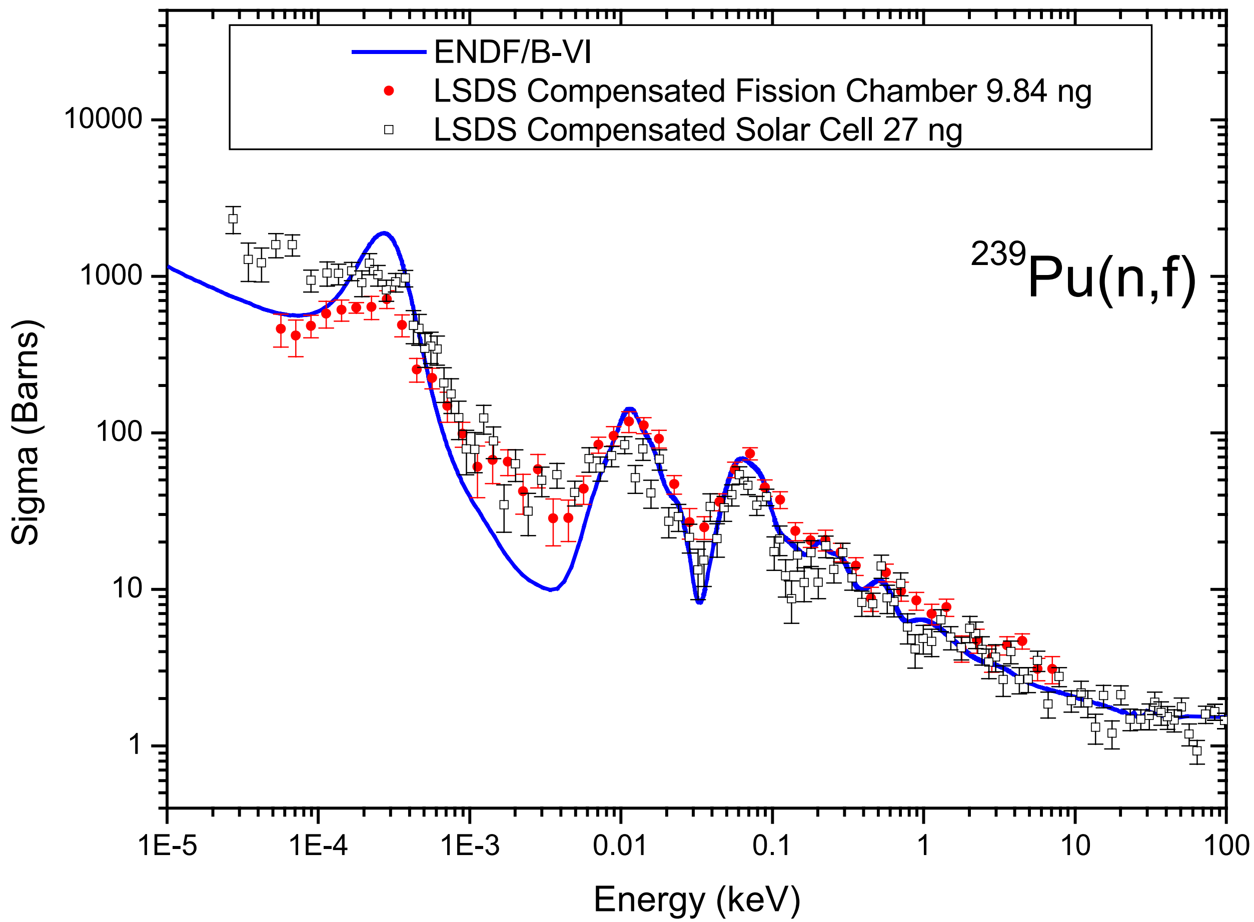
LSDS @ LANL:

- 20 tons of high purity lead
- pulsed proton beam ➡ pulsed neutron source in center
- Different channels in the lead assembly
- Fission chamber (with sample) inserted in the channels

Properties:

- Some time-energy relation is retained, but relatively poor energy resolution
- Trapped neutrons allows measurements on extremely small samples (ng)

An example of fission measurement with LSDS



Proof of principle with **^{239}Pu(n,f)** (standard fission reaction)

Sample size of **9.87 ng**

Good results up to **100 keV**

Data obtained in a few hours at 1 μA

D. Rochman, et al., Nucl. Instru. Meth. A 550, 397 (2005)

D. Rochman, et al., Nucl. Instru. Meth. A 564, 400 (2006)

Neutron facilities in Japan and Russia

JAPAN

Reactors: JRR-3 (JAEA, 20MW), KURRI (Kyoto, 1MW)

Time-of-flight facilities:

- Kyoto: 30 MV Electron LINAC
- Tokio Institute of Technology: 3 MV Pelletron
- JAEA: 4 MV Pelletron

Under construction at J-PARC (Japan Proton Accelerator Research Center):

- Innovative high-intensity neutron beam facility based on 3 GeV proton beam (1 MW power)

RUSSIA

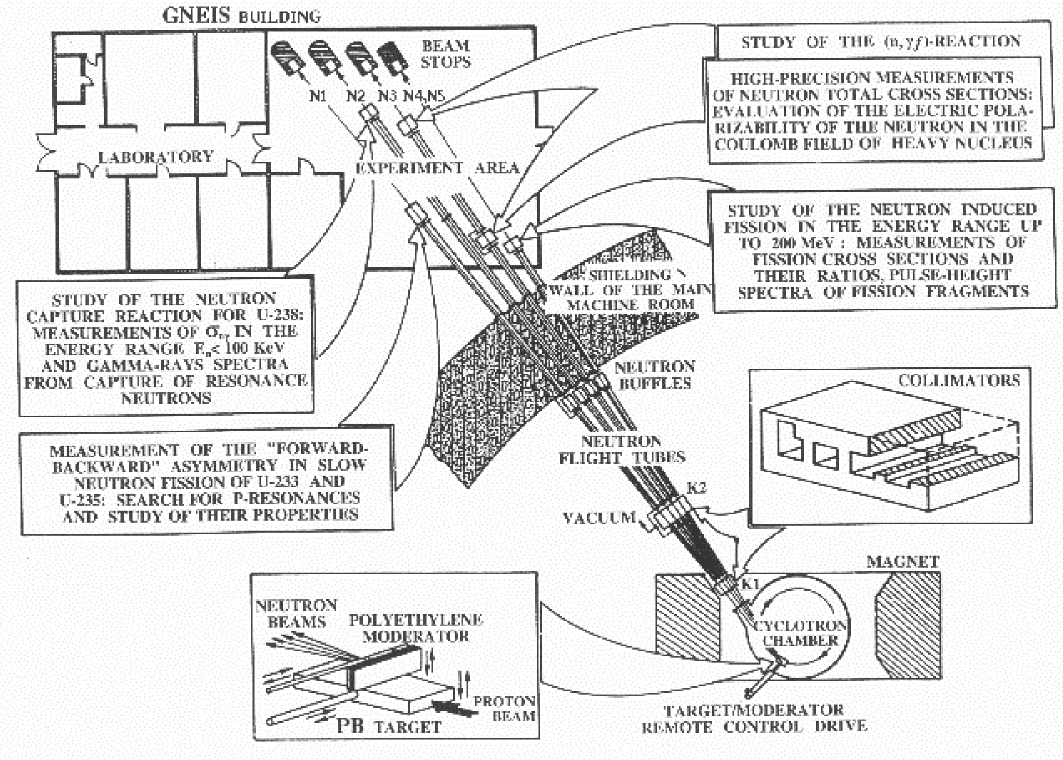
Monoenergetic neutrons (VdG, IPPE, Obninsk);

Time-of-Flight facility at LU-50 electron accelerator (Sarov);

Lead slowing down spectrometer (Troitsk)

GNEIS (PNPI, S. Petersbourg)

Neutron facilities in Japan and Russia



GNEIS based on 1 GeV protons on lead block (2 kW)

Water cooled and polyethilene moderator

50 Hz repetition rate

5 beam lines between 35 and 50 m

The fission measurements in Russia

At low energy (0.5 eV<E_n<30 keV), with LSDS

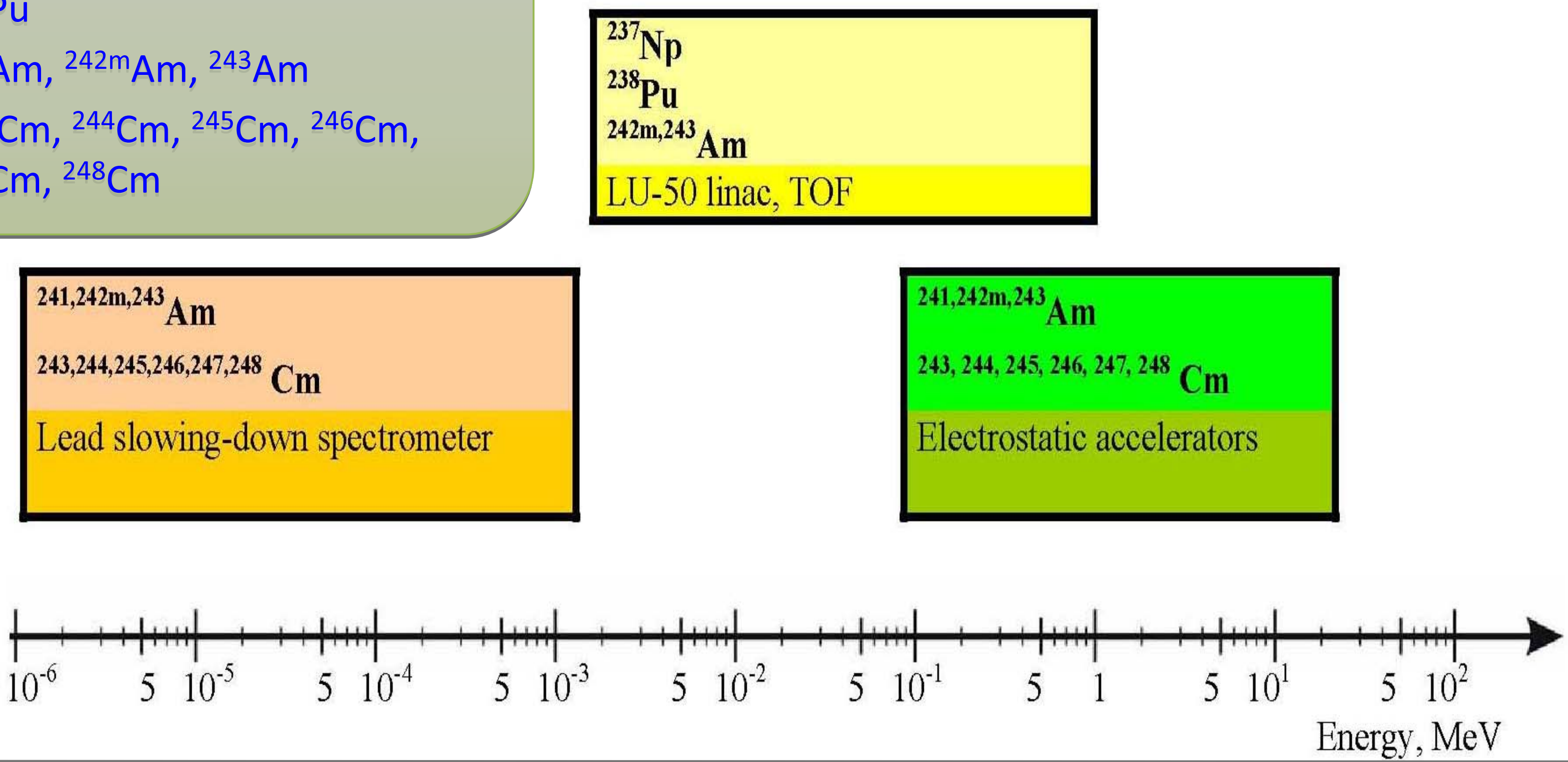
At "intermediate energy" (40 keV<E_n<10 MeV), with LU-50

At high energy (5 MeV<E_n<20 MeV) with electrostatic accelerator

Integral experiment at FKBN-2M facility

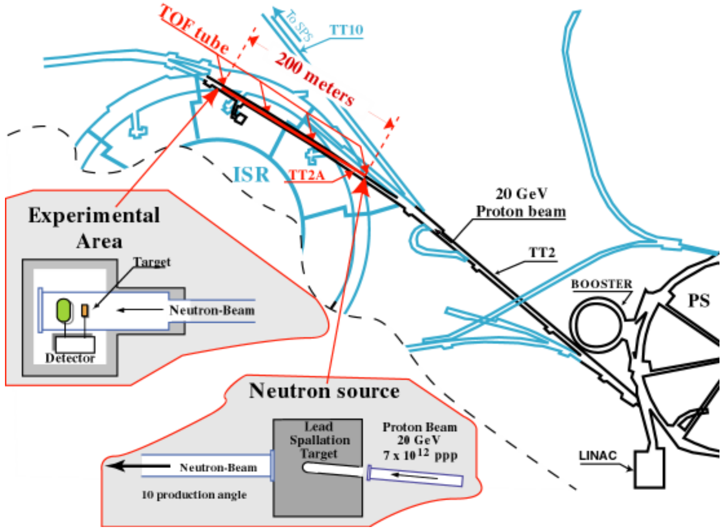
Fission XS of minor actinides:

- ^{237}Np
- ^{238}Pu
- ^{241}Am, ^{242m}Am, ^{243}Am
- ^{243}Cm, ^{244}Cm, ^{245}Cm, ^{246}Cm, ^{247}Cm, ^{248}Cm



The n_TOF facility

n_TOF is a **spallation** neutron source based on 20 GeV/c protons from the del ProtoSyncrotron of CERN (at this energy, produced ~360 neutrons per proton).

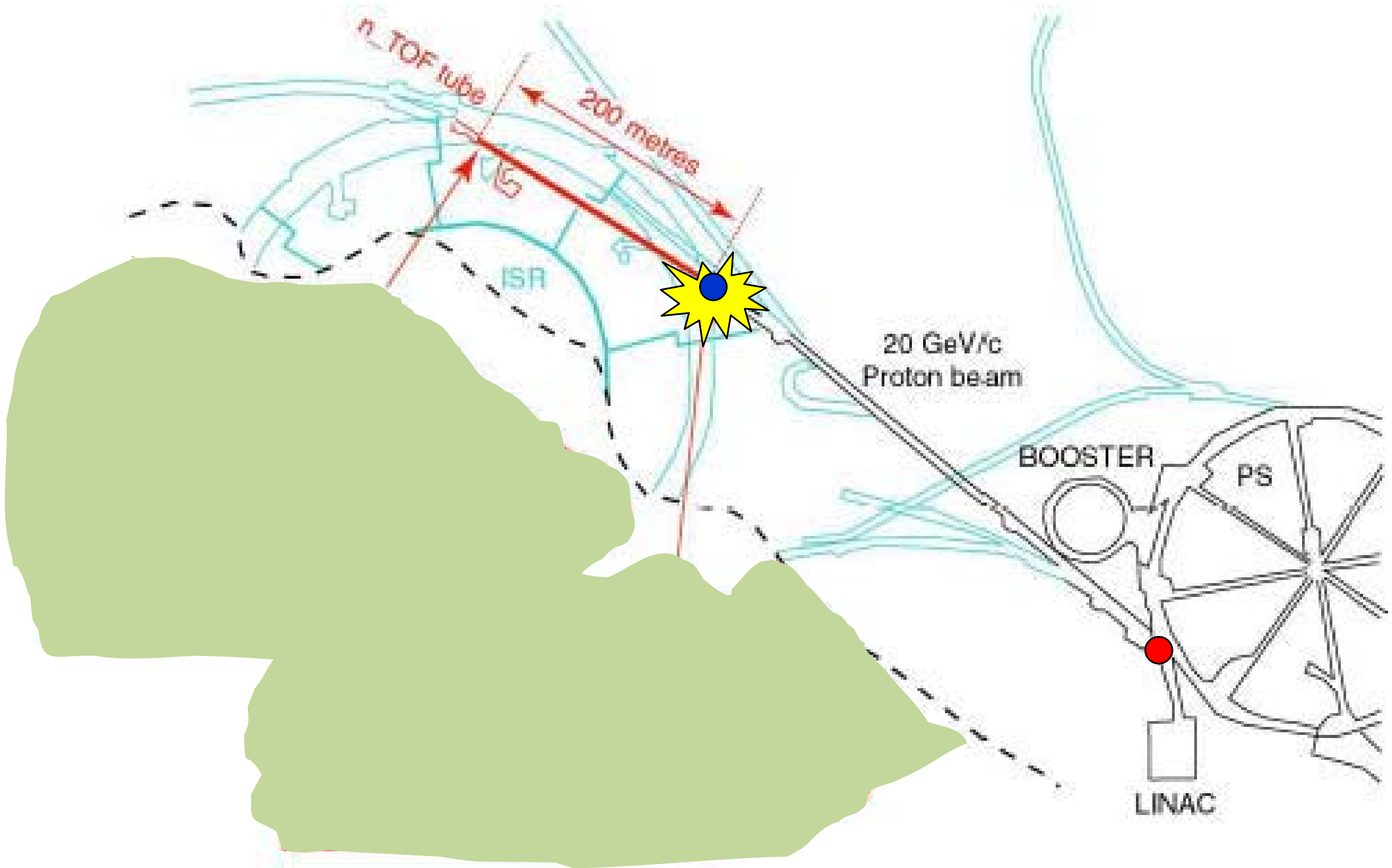


- **Spallation** target of Pb, **80x80x60** cm^3, water-cooled (H2O also as moderator)
- Flight base **~200 m**
- Two **collimators**, three **schielding** walls, one **magnet**
- Possibility to change **beam profile** in experimental hall (for capture or fission measurements).

Very high instantaneous flux	10^5 n/cm^2/pulse
Wide energy range	1 eV < E_n < 250 MeV
Good energy resolution	$\Delta E/E \sim 10^{-4}$ (fino a 100 keV)
Low repetition rate	1 pulse/2.4 s (0.8 Hz)
Low background	10^{-5} (1 particle/cm^2/pulse)

The neutron production at n_TOF

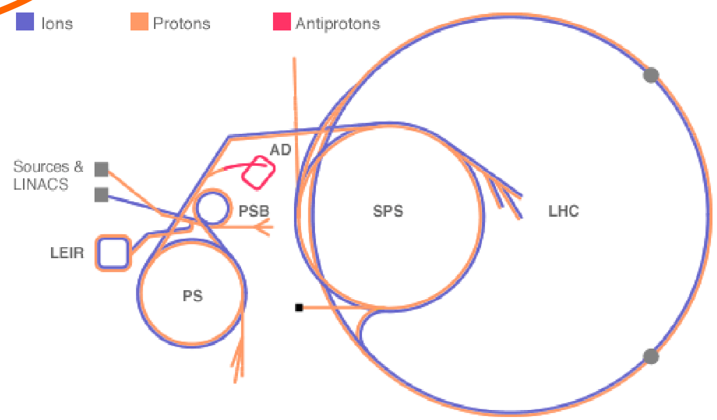
Built in record time at CERN (1.5 years)



n_TOF at CERN

The *facility* started operation in 2001, after 1.5 years of construction

Experimental area located here

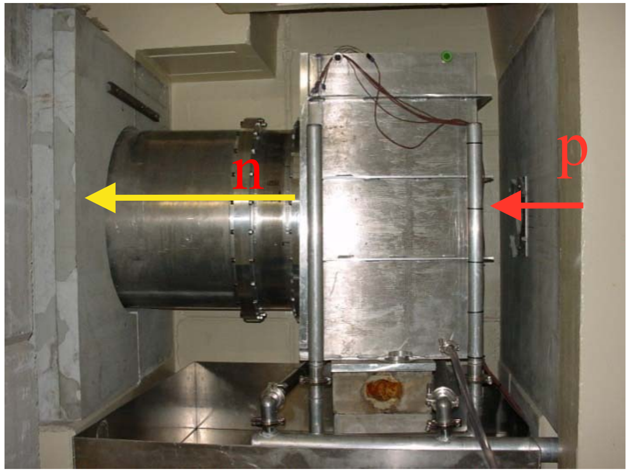


n_TOF dedicated to measurements of capture and fission cross-sections for:

- Nuclear Astrophysics (capture)
- Emerging nuclear technologies (capture and fission)
- Fundamental nuclear physics (fission)

Some pictures

- Spallation target: block of Pb 80x80x40 cm^3
- Moderator: 5 cm water (used also for neutron moderation, to produce isolethargic flux)
- 200 m time-of-flight tunnel
- Walls of iron and concrete for shielding n, γ, μ, etc…
- Deflecting magnet for charged particles
- Collimators (2 cm for capture, 6 cm for fission)



The experimental activity at n_TOF

Capture

^{151}Sm

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

$^{24,25,26}Mg$

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

$^{186,187,188}Os$, ^{139}La

^{232}Th, $^{233,234}U$

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

Fission

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

^{232}Th, ^{209}Bi

^{237}Np

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

Measurement campaign 2002-4

– **Misurements of capture reactions:**

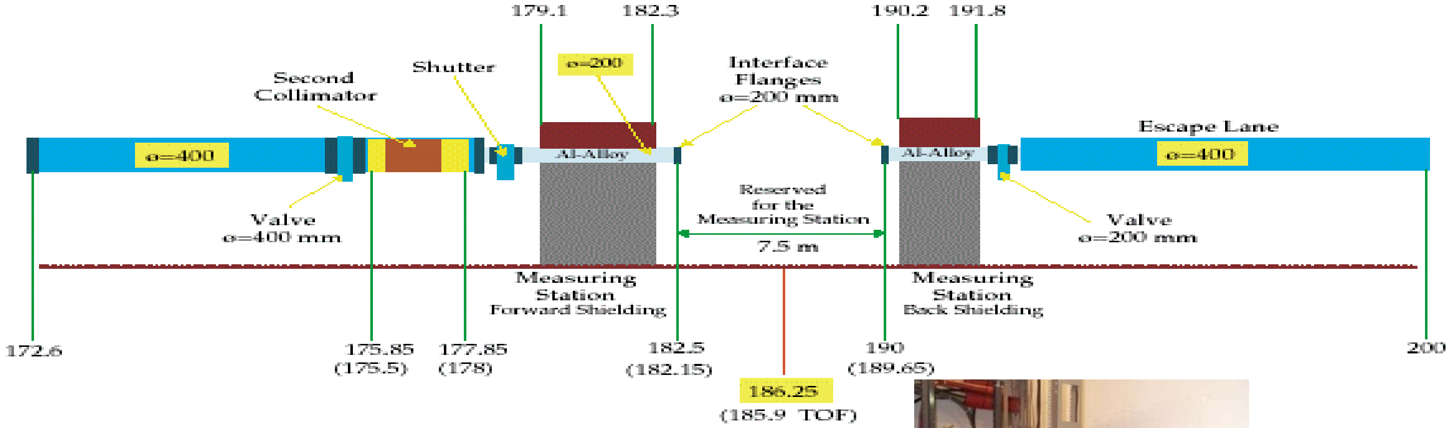
- **25 Isotopes** (8 of which radioactive)
- Often of double interest (AstroF and applications)
- Most results already available
- Several publications and conference proceedings

– **Measurements of fission cross-sections**:

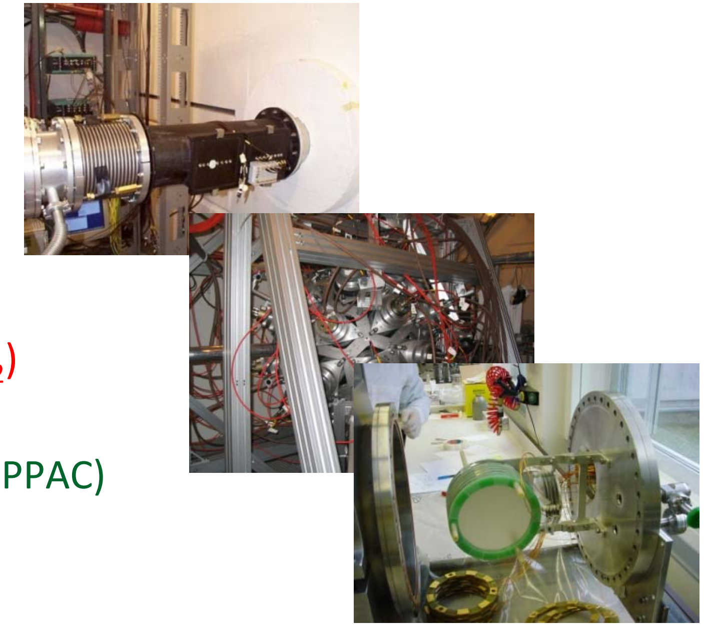
- **11 isotopes** (10 radioactive)
- Mainly linked to **Th/U cycle e transmutation**
- **strong interest** to the data by International Nuclear Agencies
- Results are now becoming available

The n_TOF experimental set-ups

Experimental area located at 180 mt from spallation target

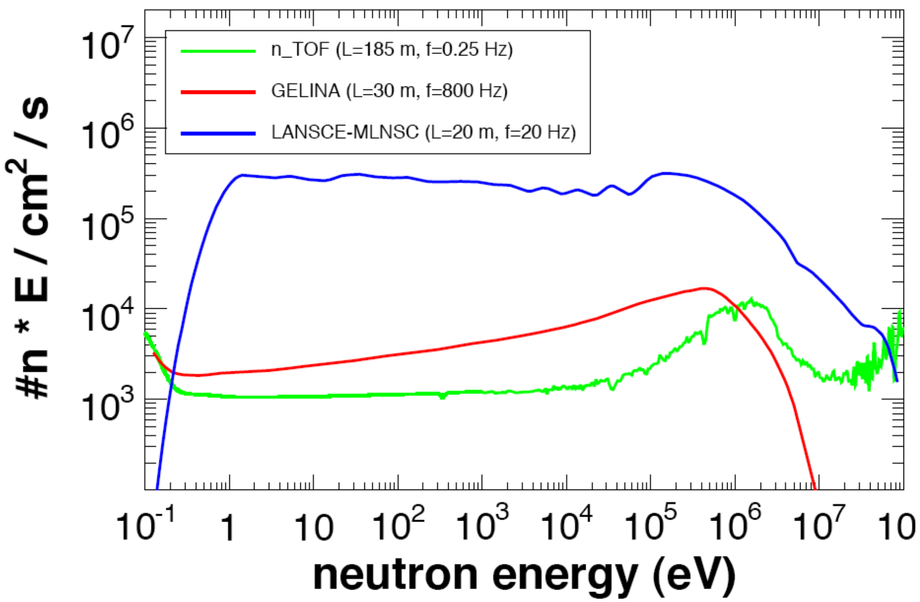


- Neutron flux monitor
  - Silicon detectors (SiMon)
  - BF_3 monitor
- Capture detectors
  - C_6D_6 liquid scintillator detectors
  - Total Absorption Calorimeter (BaF_2)
- Fission detectors
  - Parallel Plate Avalanche Counters (PPAC)
  - Fission Ionization Chamber (FIC)

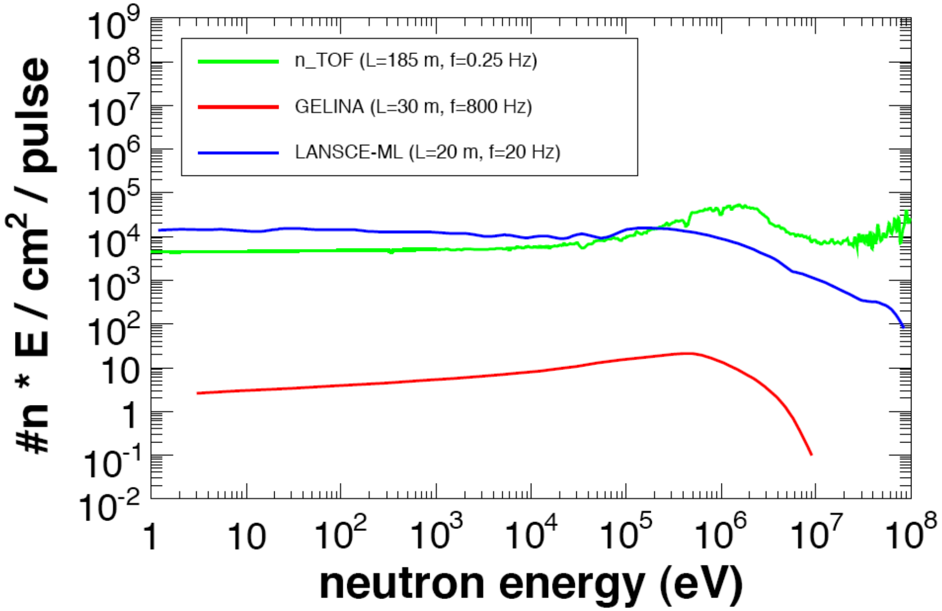


n_TOF vs other facilities

Average flux



Instantaneous flux



Innovative facility, allows to:

- measure **radioactive isotopes** (actinides)
- extend the **resolved resonance** region to **higher energy**
- measure **fission up to very high energies** (at least 500 MeV)

Proposed the construction of a **second** experimental hall at **20 m** (flux x 100) !!

The fission detectors

General concepts:

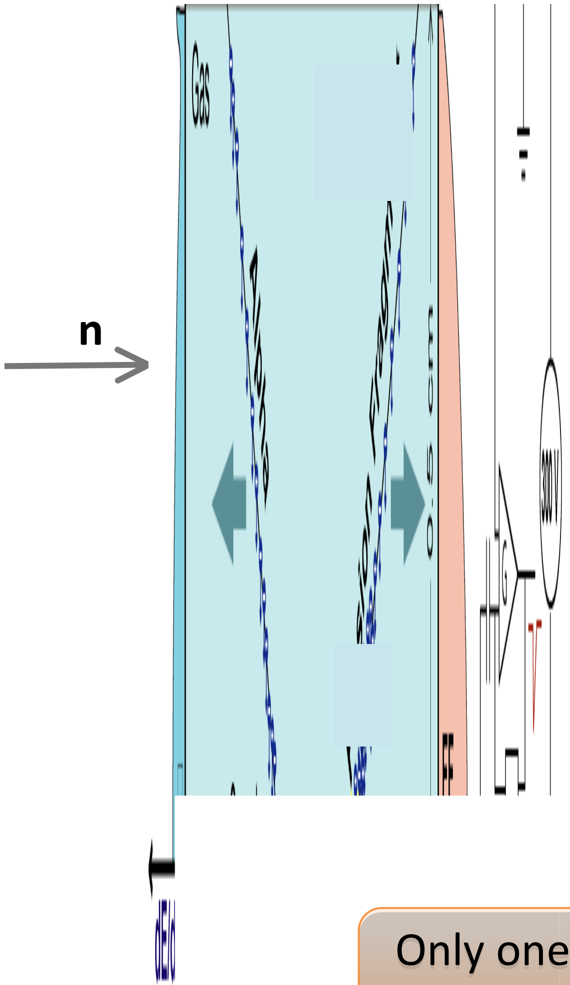
- Fission cross-sections are measured by detecting **fission fragments**
- Two methods: **single** fragment or **coincidence**
- Several **choices of detectors**

Cross-sections measured relative to a reference:

- reaction with well-known cross-sections (some are “standard”)
- $^{235}U(n,f)$, $^{238}U(n,f)$, $^{209}Bi(n,f)$, ^{239}Pu, $H(n,n)$

Ratio measurements minimize systematic uncertainties (in principle down to a few percent)

The fission chamber



"Fission Chamber" is the most common detector used for fission cross-section measurements:

•easy to build and operate

•**high** efficiency (close to 100 %)

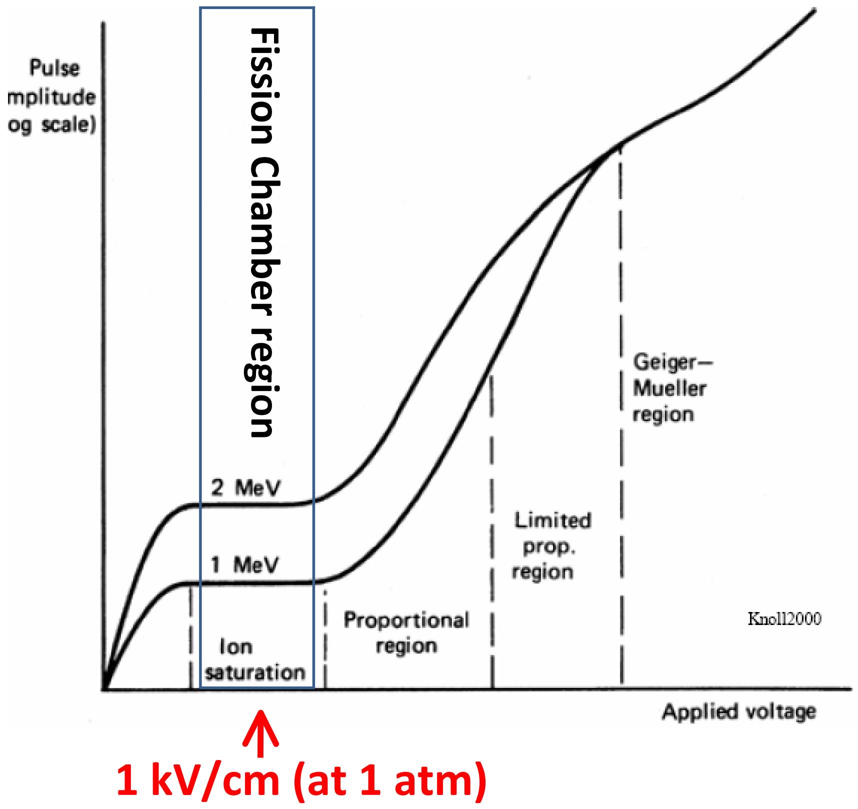
•good **background rejection** capability

How does it work:

- two parallel electrodes, with gas in between (typical pressure a few atm)
- Sample attached (or deposited) on one electrode
- Usually contains sample of interest + reference (^{235}U, ^{238}U, …)
- Used often for neutron flux measurements and monitoring

Only one fragment per event is detected, the second one is absorbed in the backing

The fission chamber



Electron and ion pairs produced inside the gas by **ionization** from FF and α-particles:

- Charge produced depends on energy lost in gas, and on gas type

Voltage applied between the electrods to avoid recombination and **collect charge.**

Electric field such that no charge multiplication occurs:

- "ionization region"
- typical values of E/P = 1 kV/(cm·atm)

Drift of electrons and ions towards the electrodes depend on:

- applied voltage and type of gas

For measurements with actinides, extremely important to have a **FAST** gas, in order to avoid **pile-up** (mainly due to α-activity)

Electron mobility in gas (in mm/μs)

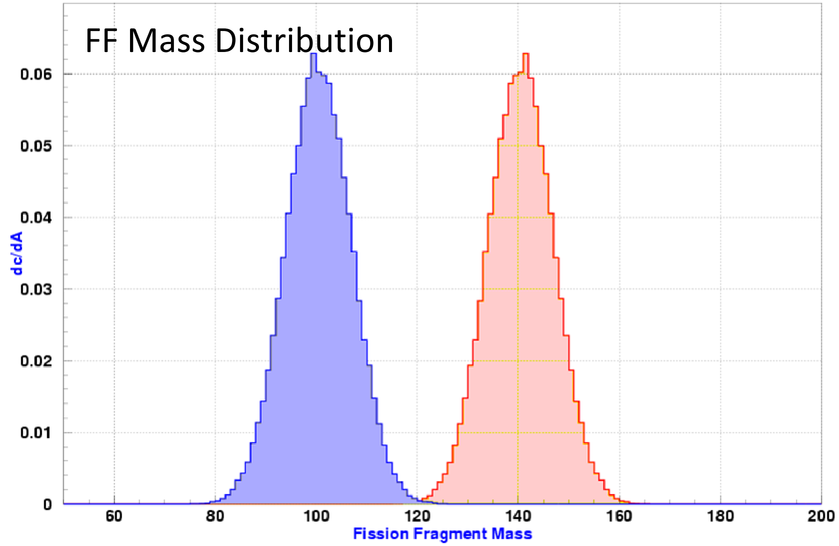
Gas	Electric Field per unit pressure $(E/p)/(\mathrm{V\ m\ N^{-1}})$											
	0.075	0.15	0.3	0.45	0.6	0.75	1.5	3	4.5	6	7.5	15
H_2	3.1	5	6.8	8.0	9.2	10	15	23	30	36	42	70
He	2.7	4	6	7	8.5	9.6	15	36				
N_2	3.1	3.9	5	6	7	8	14	22	30	36	43	80
Ne	4	5	7	10	12	16	26	52				
Ar	2.3	2.7	3.2	3.5	3.9	4.1	6.2	13	30			
Kr	1.5	1.8	2.1	2.4	2.5	3.1						
Xe	1.0	1.2	1.4	1.6	1.7	1.8						
CO_2	0.56	1.1	2.3	3.4	4.6	5.7	11	33	66	94	109	137
CO	4.8	6.5	9.4	11	13	14	17	20	25	28	29	
BF_3	0.13	0.25	0.5	0.75	1.0	1.3	2.5	5.0	7.5	10	12.5	25
Air	3.5	5	8	9.3	11	12	17	26	34	43	51	88
CH_4	8	24	60	80	95	100	100					
CF_4	30	51	74	87	96	101	117	140	141	129	116	95
Ar/CH_4	49	55	45	36	32	30	26	24				
Ar/C_2H_2	14.3	27.3	44.3	49.3	48.3	45.8	45.2					
Ar/CF_4	34	63	100	120	120	111	66					
He/CF_4	6	10.8	19.2	25.8	31.4	36						
Ar/CO_2	5.0	10.6	26.5	37.3	43	42						

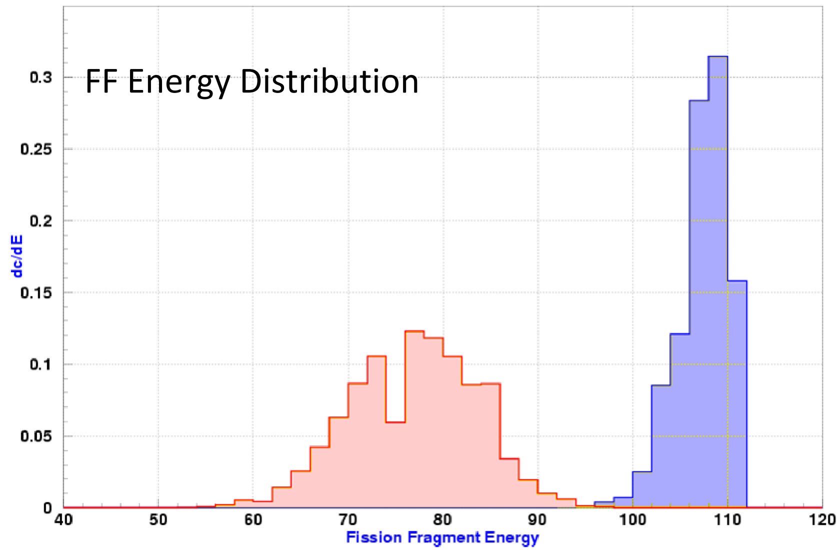
Energy deposition in fission chambers

α-particles:
- Energy ≈ 5-6 MeV
- Isotropically emitted over 2π
- Leave at most 5 MeV in the gas

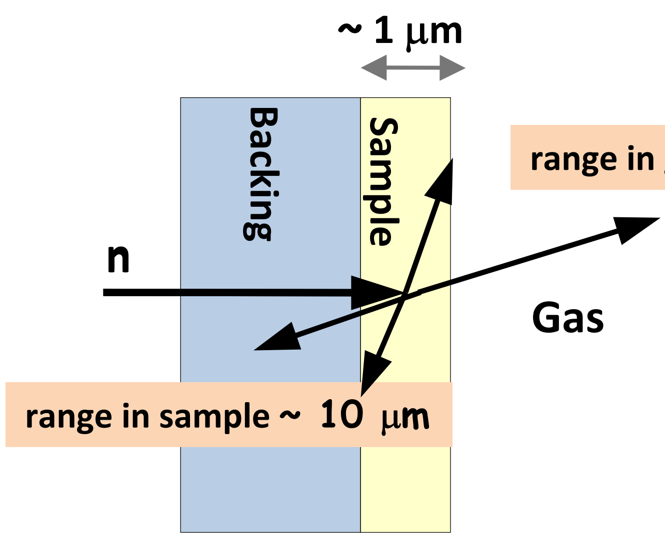
Fission Fragments:
- asymmetric mass distribution asymmetric (for low energy neutrons)
- total energy shared among fragments (inversely proportional to their mass)
- fraction of FF energy released inside the sample (depends on the emission angle and interaction point)

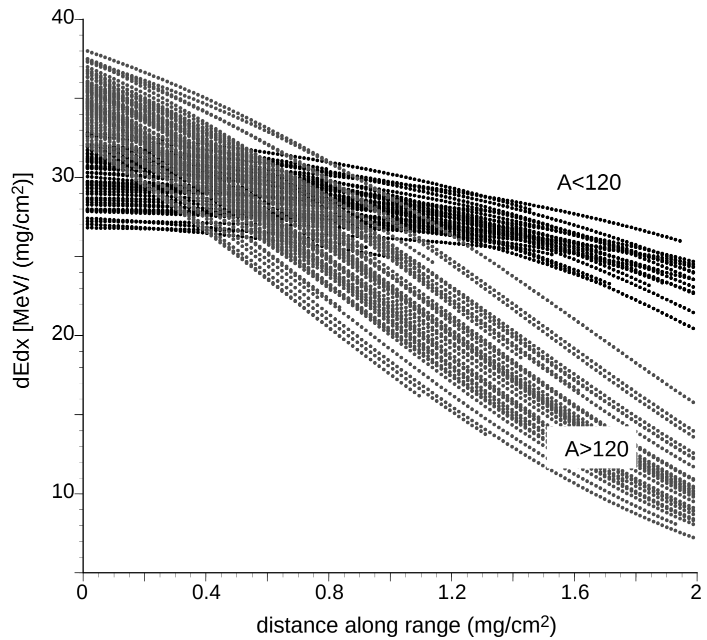
Energy deposition in sample and gas:
- simple Bethe-Block formula not valid
- depend on effective charge of fragments (fragment velocity)
- use energy loss table and programs





Energy deposition in fission chambers



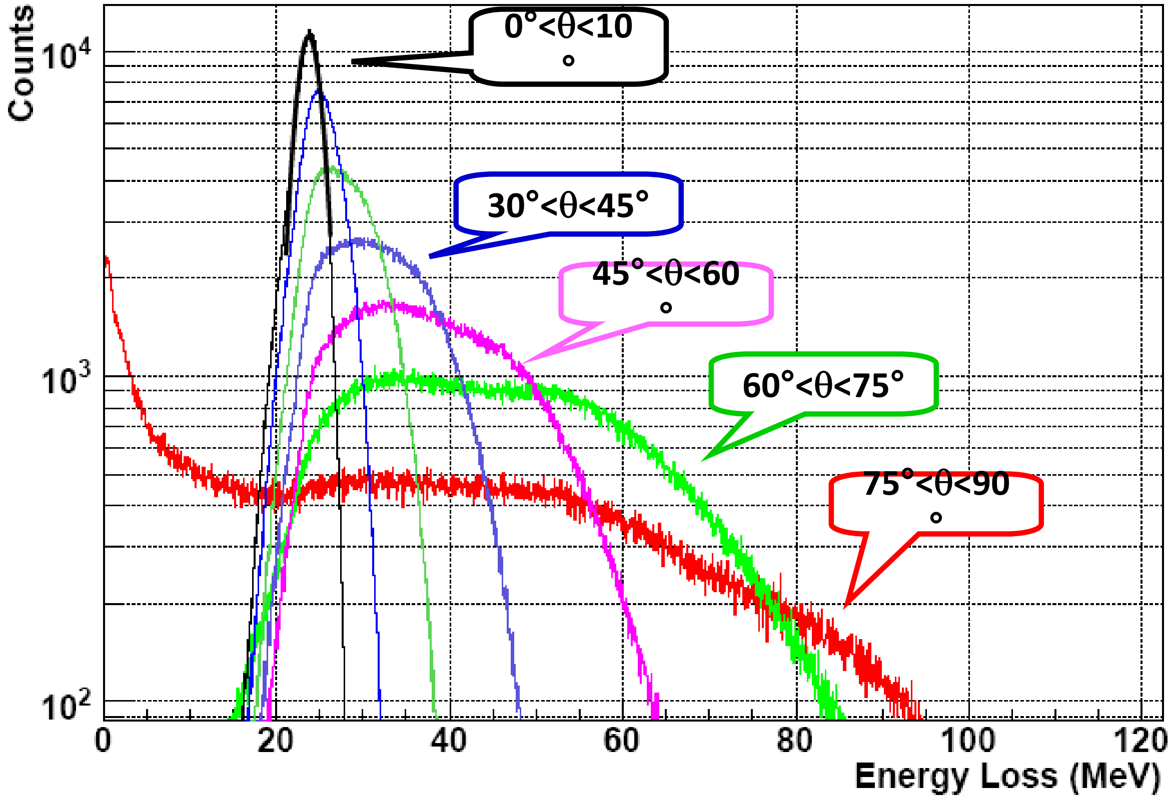


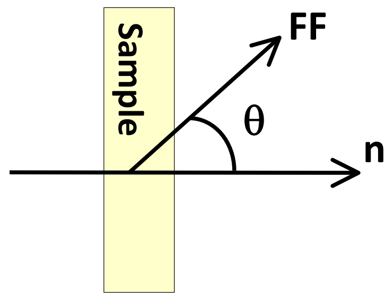
$$-\frac{dE}{dx}\left[MeV/(mg/cm^2)\right] = 3.072\times10^{-4}\,\frac{Z_{eff}^2}{\beta^2}\frac{Z_M}{A_M}\ln\left(\frac{2m_eV^2}{I}\right)$$

$$Z_{eff} = \gamma Z \qquad \gamma = 1-\left(a_0+\frac{1}{E}\right)\exp\left(-b_0V_R + b_1V_R^2\right)$$

Typical efficiency very close to 100 %. Loss of efficiency due to FF emitted at large angles (absorbed in the sample)

Energy deposition in the gas





At **small angles**, FF come out with high energy:

- **small energy** released in gas

At **large angles**, FF come out with small energy:

- **large energy** released in gas

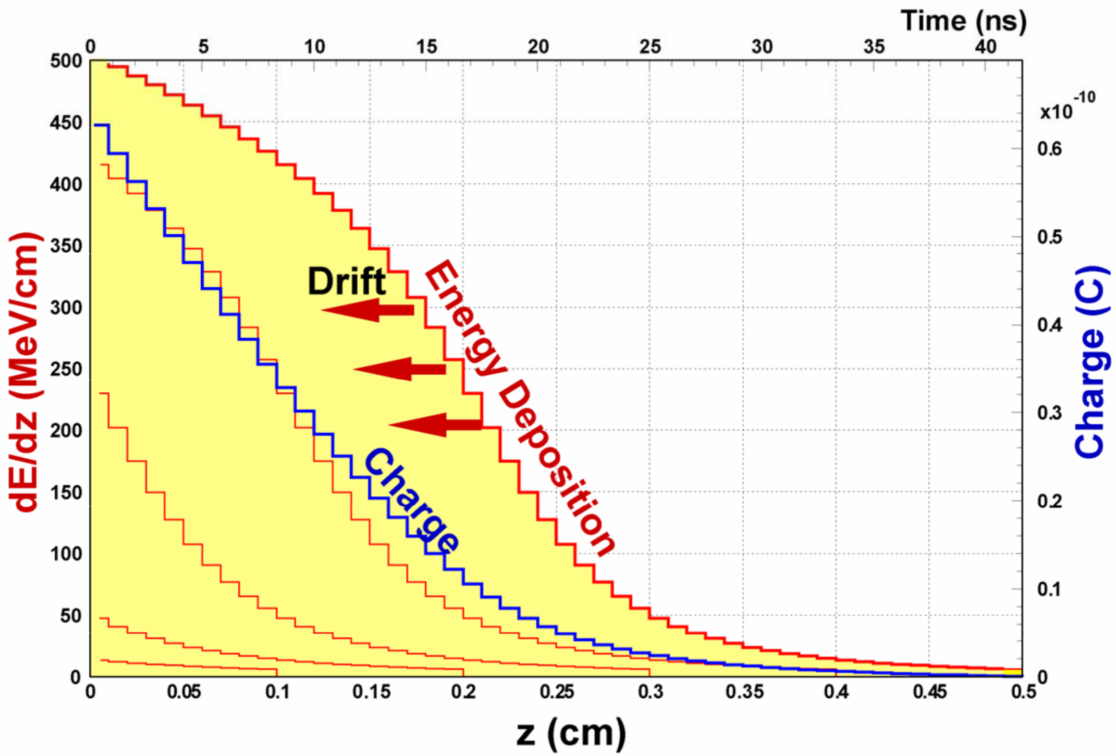
At **very large angles**, some FF are **absorbed** in deposit or exit with energy **below threshold**

For very high accuracy (1-2 %), **very important** to estimate correctly the **efficiency,** which depends on sample thickness and threshold on energy deposited in the gas

From energy deposition to charge

$$Q(t) = \int_0^{z_m} \frac{dE_n(z,t)}{W_f} = \frac{1}{W_f}\int_{v\cdot t}^{z_m} E_n(x)\cdot dx$$

- $dE_n(z,t)=dE_n(z+vt)$ — energy deposited along path
- v — drift velocity (12 cm/μs)
- W_f — work function (≈ 25 eV/electron)

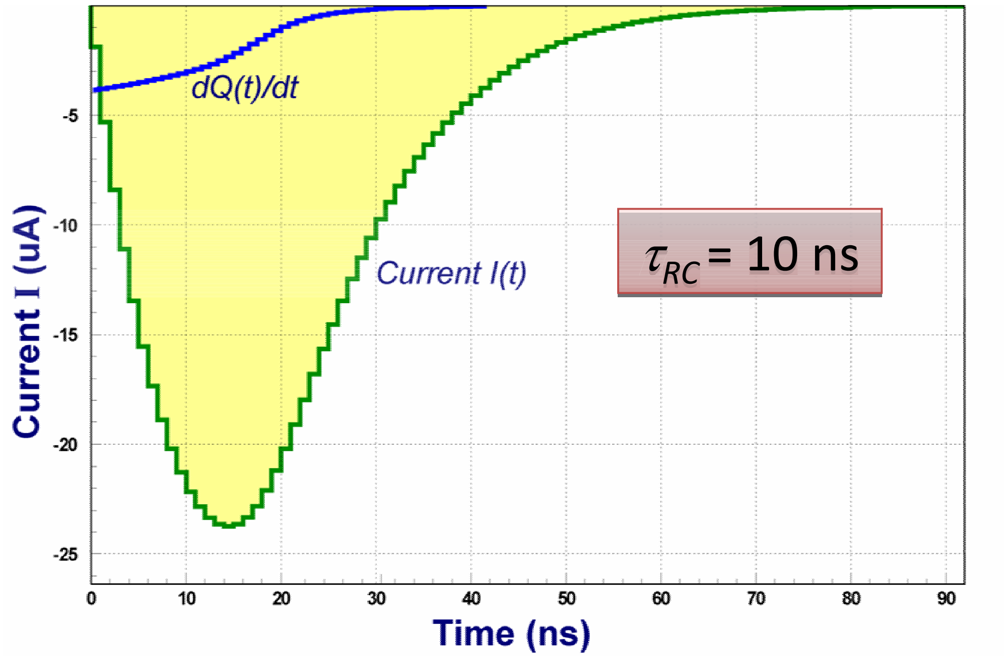


From charge to signal

Signals generated by drift of e$^-$ and ions

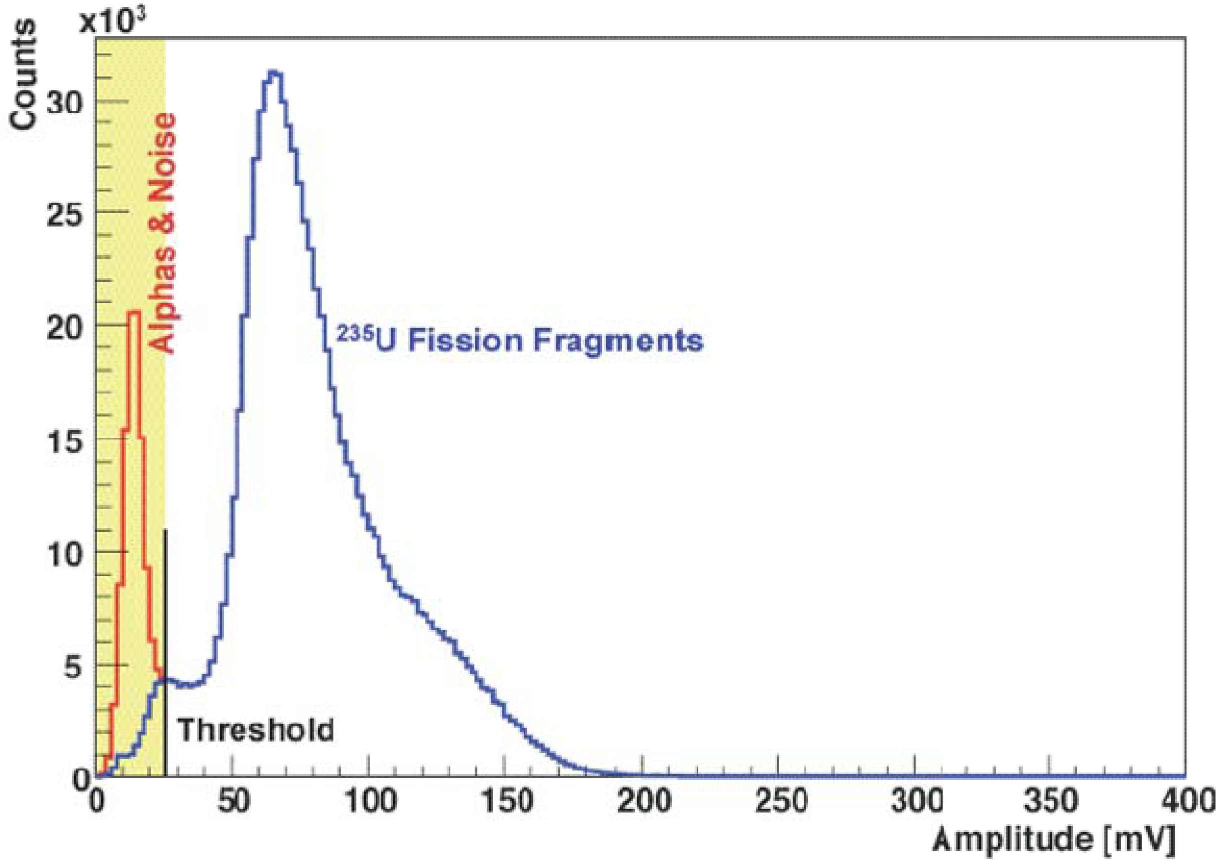
The charge collected on the electrode is processed through a preamplifier and a shaping amplifier.

The final signal is the convolution of the charge collected on the electrode with the RC of the electronic circuit (amplifier)



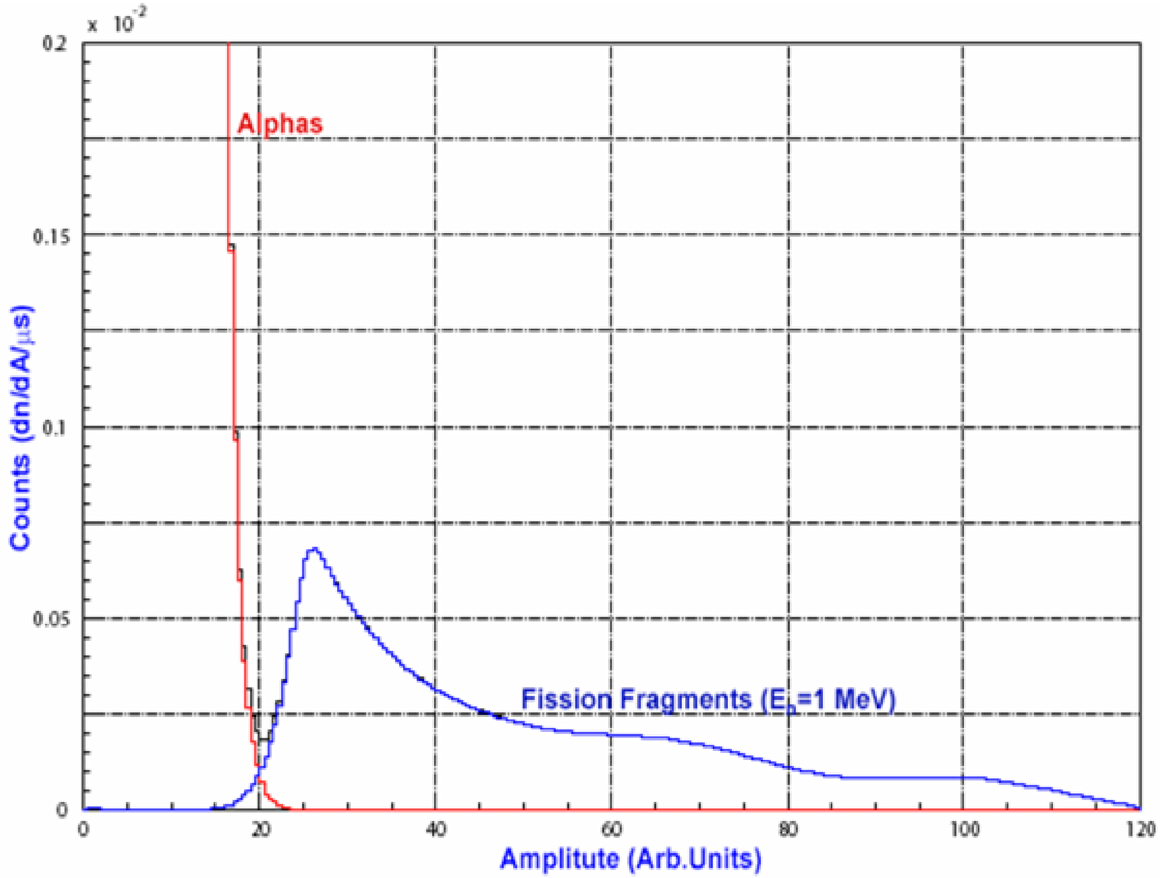
$$I(t) = \int_0^t \frac{dQ(x)}{dt} \cdot e^{-\frac{t-x}{\tau_{RC}}} dx$$

Amplitude distribution for ^{235}U



Although fission produces two distinct groups of fission fragments, the energy deposited in gas shows only one peak due to absorption in sample.
For ^{235}U, easy to reject α-background, simply with amplitude threshold

Simulated amplitude distribution for ^{241}Am



In theory, still good separation FF and a with 250 MBq ^{241}Am target
However, problems with detector response and pile-up of signals.

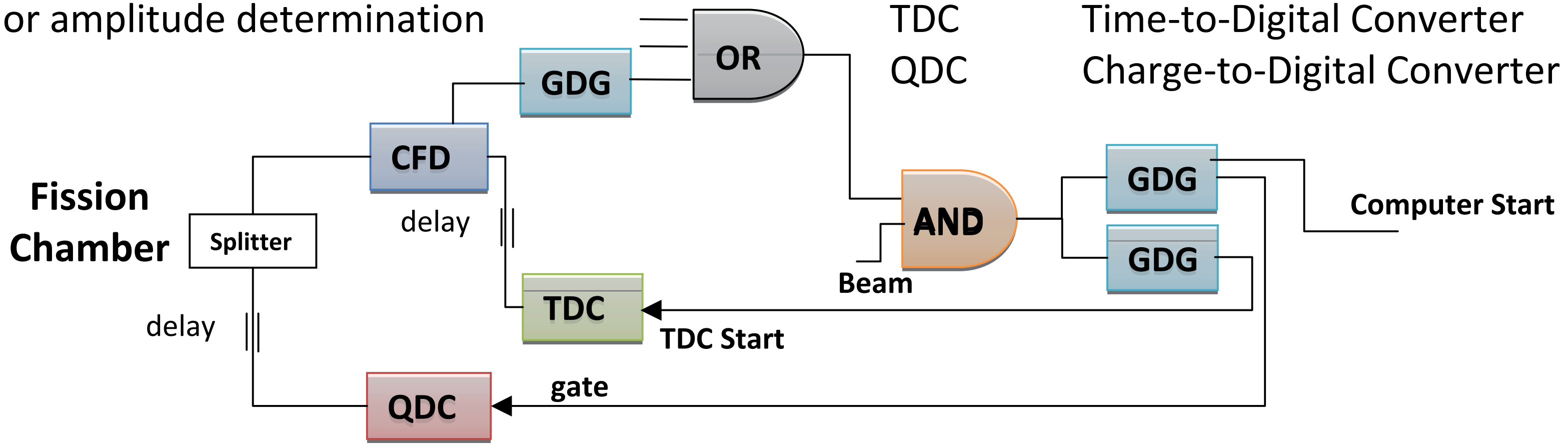
Data acquisition

Traditional signal processing and data acquisition system

Several electronic modules for:

- trigger formation (CFD)
- time determination (TDC)
- charge or amplitude determination

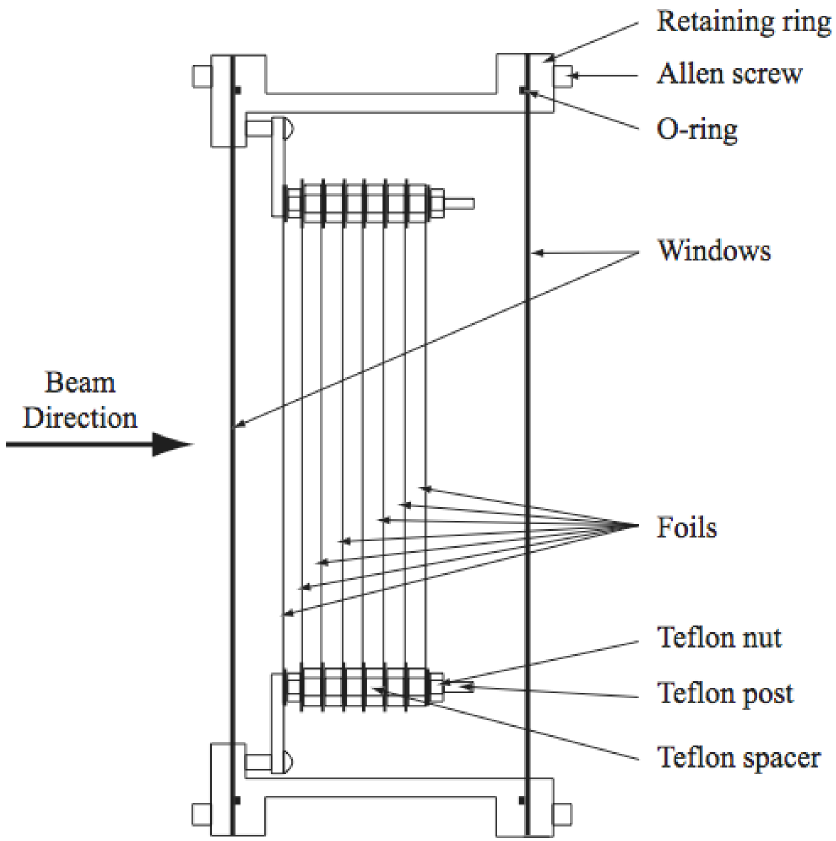
CFD	Constant Fraction Discriminator
GDG	Gate and Delay Generator
TDC	Time-to-Digital Converter
QDC	Charge-to-Digital Converter



New signal processing and data acquisition system

P.S.: All informations from the signal exracted by software

The Parallel Place Ionization Chamber (PPIC)



Typically made of **several chambers** within a common volume of gas

Stack of samples (and electrodes) for beam-time optimization

Include **reference samples** for cross-section normalization:

- ^{235}U, ^{238}U, ^{239}Pu, etc…

Gas circulation not necessary

- very convenient for MA, for safety reasons

Important to **minimize material** in the beam (windows and electrodes)

Detector-related systematic uncertainties:

- target **non-uniformity** (with non-uniform beam)
- detection **efficiency**
- Background induced by neutron **scattering**
- cross-section of reference **isotope**

The reference reactions (cross-section standards)

Neutron cross-section **"standards"** are very important, since avoid need of absolute measurements of neutron flux. Widely used to normalize cross-section data.

Some reactions **have gained** the status of "standards", since their cross-sections in the years have been determined **very accurately**.

Cross-section standards based on a **large number of experimental data**, and on evaluations (specific committee are set-up to this purpose IAEA-CRP, NEA-WPEC, CSEWG)

Reaction	Energy range	Comment
H(n,n)	1 keV – 20 MeV	Where it all starts
^{3}He(n,p)	25.3 meV – 50 keV	
^{6}Li(n,t)	25.3 meV – 1 MeV	Relative to H(n,n)
^{10}B(n,α)	25.3 meV – 250 keV	Relative to H(n,n) and ^{6}Li(n,a)
C(n,n)	up to 1.8 MeV	….
Au(n,γ)	25.3 meV and 0.2 – 2.5 MeV	
^{235}U(n,f)	25.3 meV and 0.15 eV – 200 MeV	
^{238}U(n,f)	2 – 200 MeV	

The cross-section standards for fission

Most common normalization methods, to **measure simultaneously** fission of **^{235}U** or **^{239}Pu** (reference samples):

- eliminates the need for many **corrections** (see later)
- **minimizes** uncertainties
- **easy** to measure (same detector)

Fundamental to measure with same experimental conditions

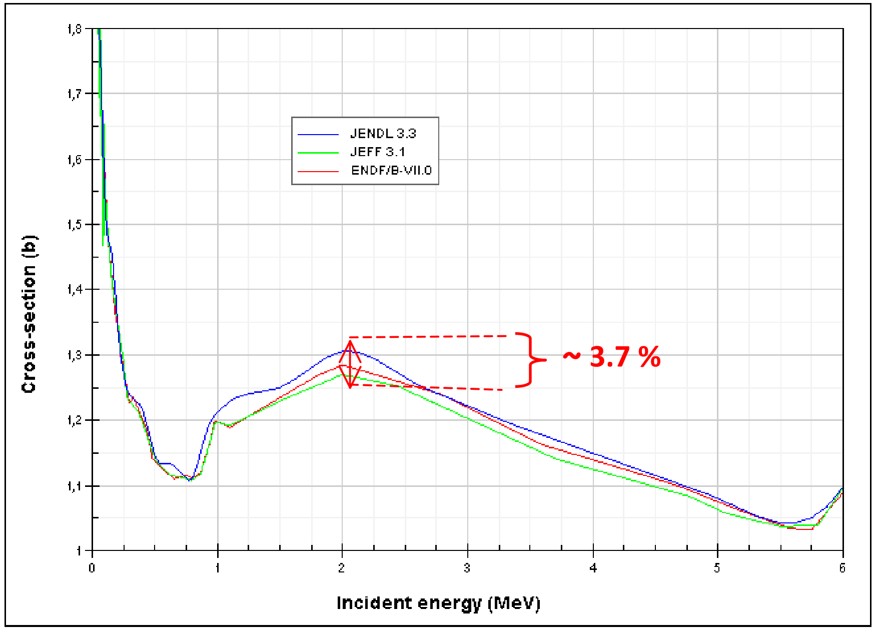
- **same area** for same intercepted flux
- approximately **same count-rate**, to minimize dead-time correction
- if possible, **same thickness**, to minimize efficiency corrections

The reference reactions: the H(n,n)

The ^{235}U(n,f) in the MeV region affected by **some uncertainty** (3 %).

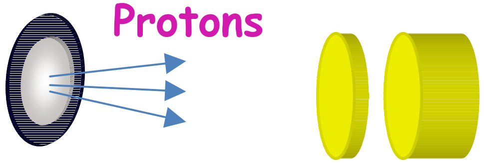
Use the H(n,n) reaction for normalization:

- **lower uncertainty** in the cross-sections
- neutron flux determined with higher accuracy



Neutron flux detector

scattered Protons



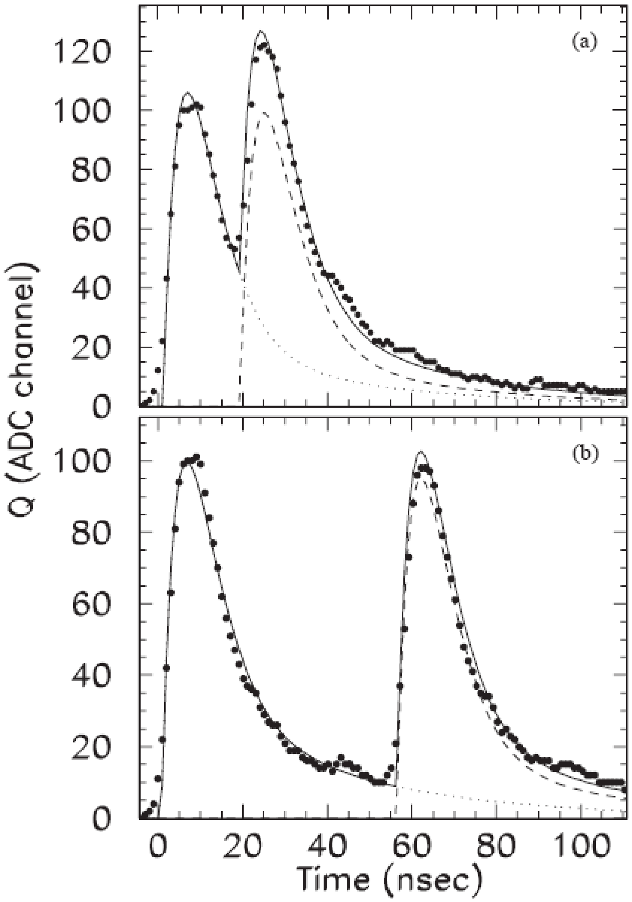
Polypropylene
$(C_3H_6)n$
10-50 μm

ΔE - E
Si Telescope

Disadvantages:

- can be used only for E_n above a few MeV
- need to consider **many corrections** in fission data (efficiency, flux interception, dead-time, etc…)
- complicates data analysis
- at the end, **global uncertainty** may not be smaller than previous normalization method

Signal pile-up



Two signals close in time give **pile-up.**

If not minimized, pile-up may result in loss of events (one signal instead of two)

LOSS OF EFFICIENCY

Pile-up probability function of **count-rate.** It depends on:

- sample **thickness** and **cross-section**
- neutron flux
- detector **time-response**

Even in ratio measurements, a **correction** is needed (pile-up may be different for sample and reference, if different count-rate).

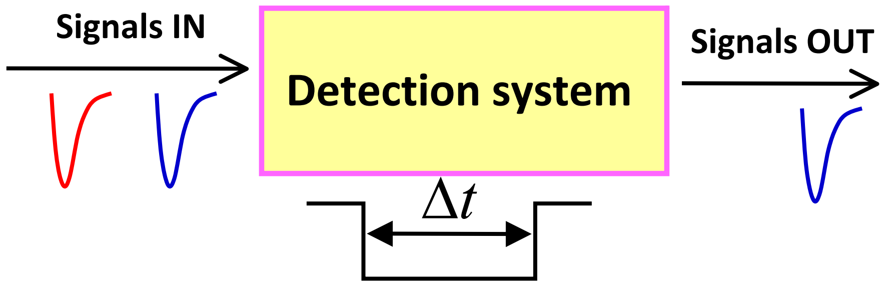
Problem minimized by using **Flash ADC**

The problem of dead-time

When the detector or electronics or DAQ is busy processing an event, if a new one occurs it is LOST

⇩

LOSS OF EFFICIENCY



The number of events lost depends on:

- count rate (C_m)
- dead-time (Δt)

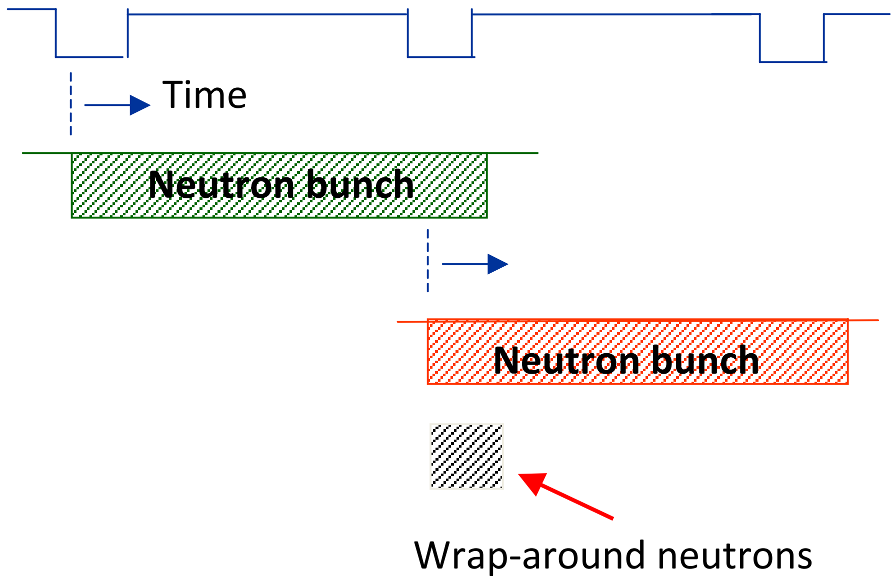
$$C_R = \frac{C_m}{1 - C_m \cdot \Delta t}$$

- C_m measured count-rate
- C_R true count-rate
- ΔT dead-time

In traditional data acquisition systems, the dead-time is typically of the order of μs (or hundreds of μs). In new systems, based on Flash ADC, much smaller (tens of ns).

As for pile-up, the dead-time may be different for sample and reference (different count-rates) . A correction needs to be applied !!

Background due to wrap-around



Low energy neutrons from one pulse may arrive at the fission detector at the same time as high energy neutrons from the next pulse.

Pulse overlap causes background: important for some samples:
High fission cross-section at low energy results in a large number of events contaminating the high-energy part

Two possibility:

- measurements with filters (to cut low-energy neutrons)
- increase the spacing between pulses
- Determine the background with "threshold" isotopes (like ^{238}U)

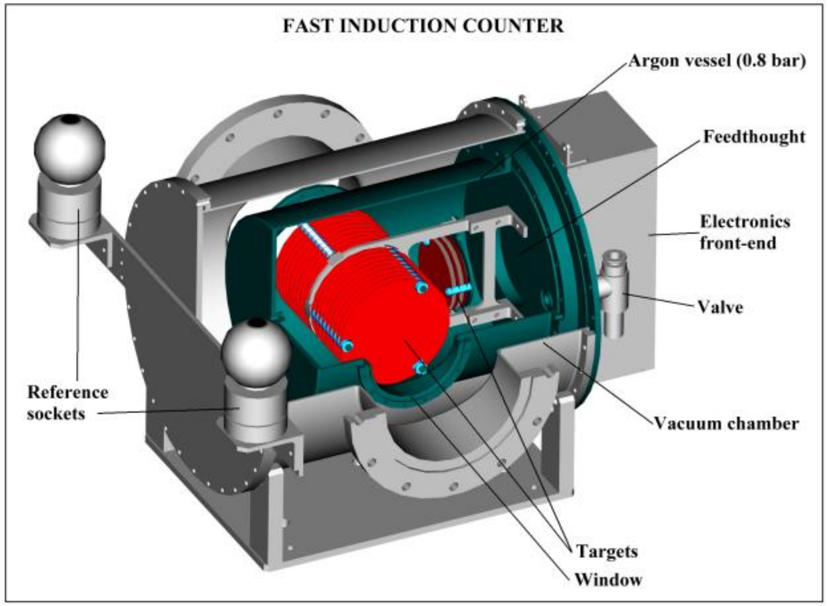
The n_TOF fission chamber (FIC)

The detector is a stack of 16 ionization chambers mounted along the beam direction.

Mounted together to allow the simultaneous measurement of fission cross sections for various isotopes:

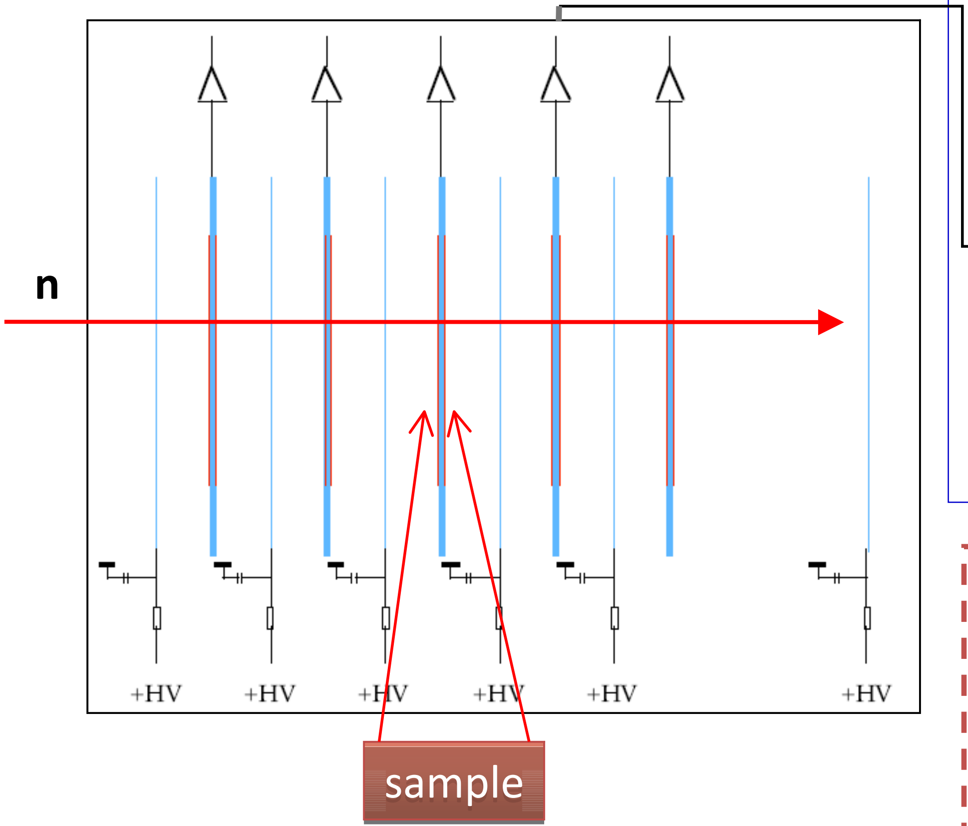
- 13 chambers in the beam
- 3 chambers normal to beam

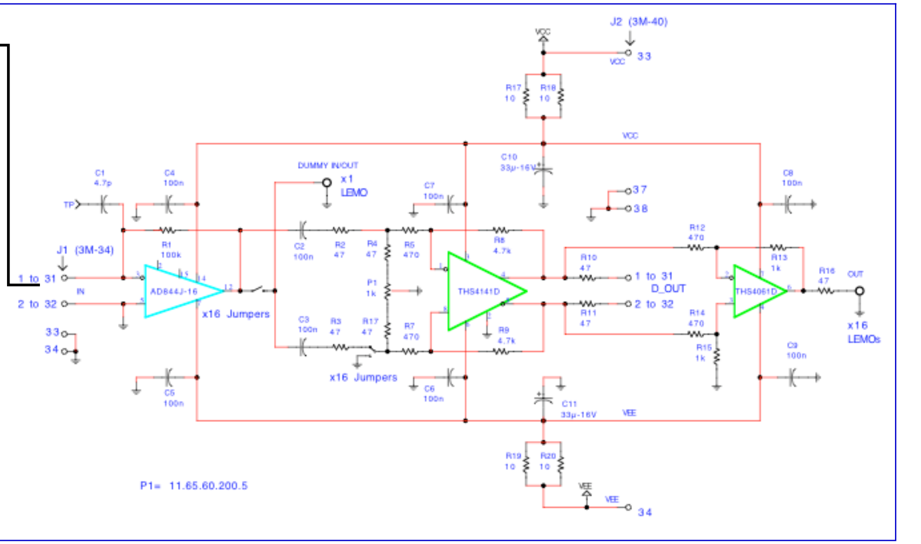
Developed by CERN, JINR (Dubna), IPPE (Obninsk) and INFN



Gas	Ar (90%) + CF4 (10%)
Gas pressure	720 mbar
Electric field	600 V/cm
Sample diameter	8 cm
Sample thickness	4-450 $\mu g/cm^2$
Backing thickness	100 μm
Sample uniformity	5-10 %

The n_TOF FIC





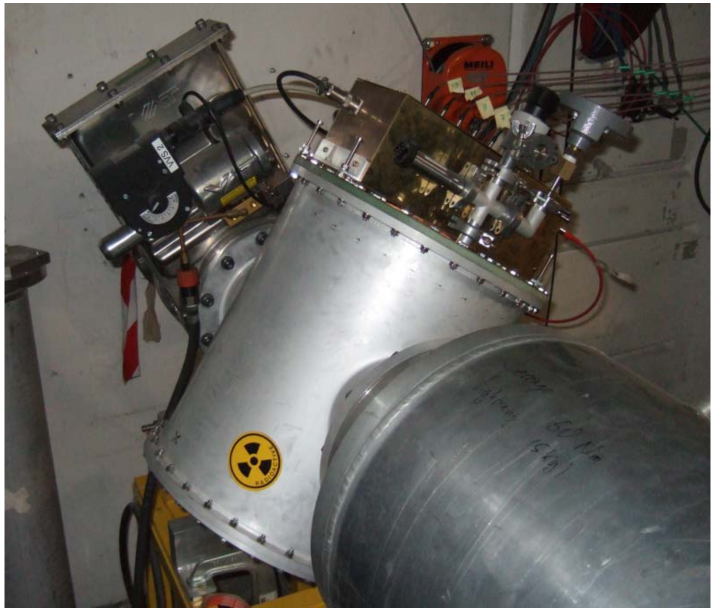
The basic cell has three electrodes:

- one central plated on both sides with a fissile isotope
- two external ones used to define the electric field

The signal is collected on the central electrode, processed with on-board electronic circuit (preamplifier and amplifier) and finally sent to a Flash ADC

The n_TOF FIC

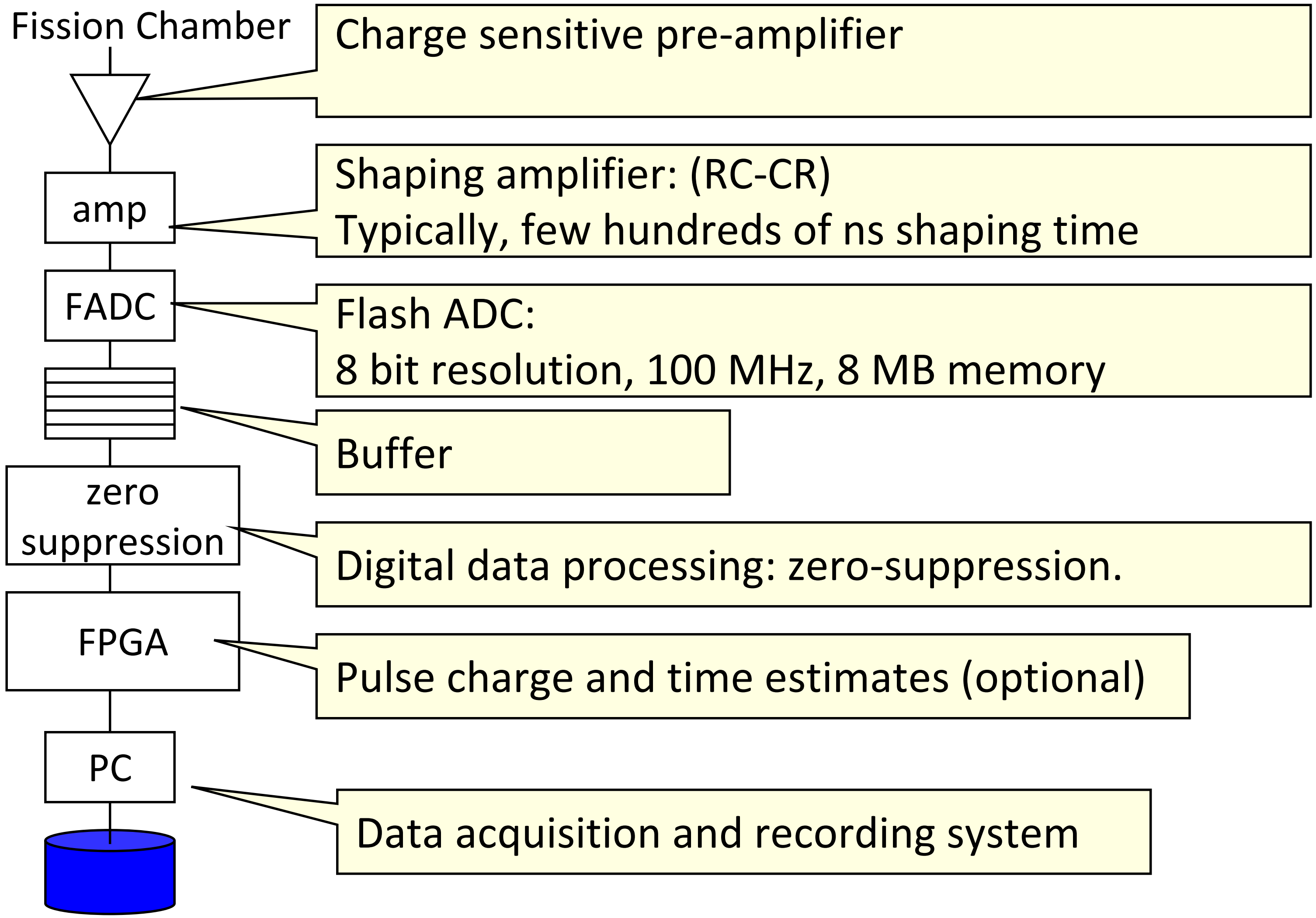
FIC1 – sealed source ISO2919
^{233,235,238}U ,^{241,243}Am ^{245}Cm



FIC2 – low activity isotopes
^{235,238}U

Large collimator (8 cm diameter) for count-rate optimization
Background from scattered neutrons measured with off-beam samples
Background from α-decay measured with beam off

Signal processing and data acquisition



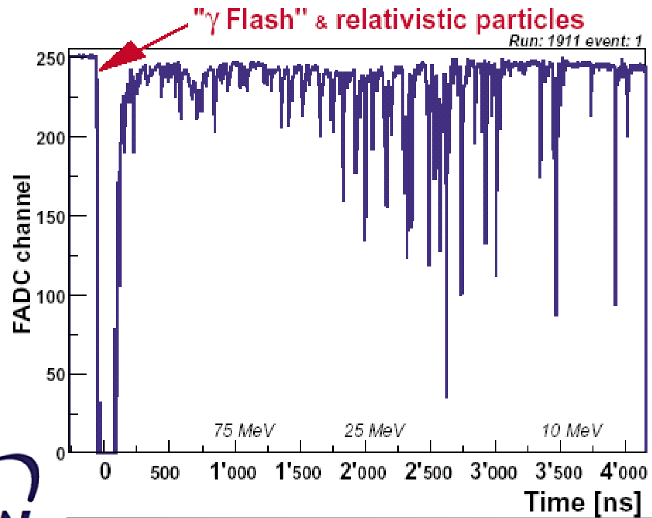
The n_TOF data acquisition system

High instantaneous neutron flux → high probability of pile-up between signals

Standard DAQ methods are inadequate

n_TOF DAQ entirely based on Flash ADC

- Up to 1 GSample/s (500 MHz bandwidth), 16 MB buffer memory
- Software Zero suppression
- Commercially available in compact_PCI standard (from Acqiris and ETEP)

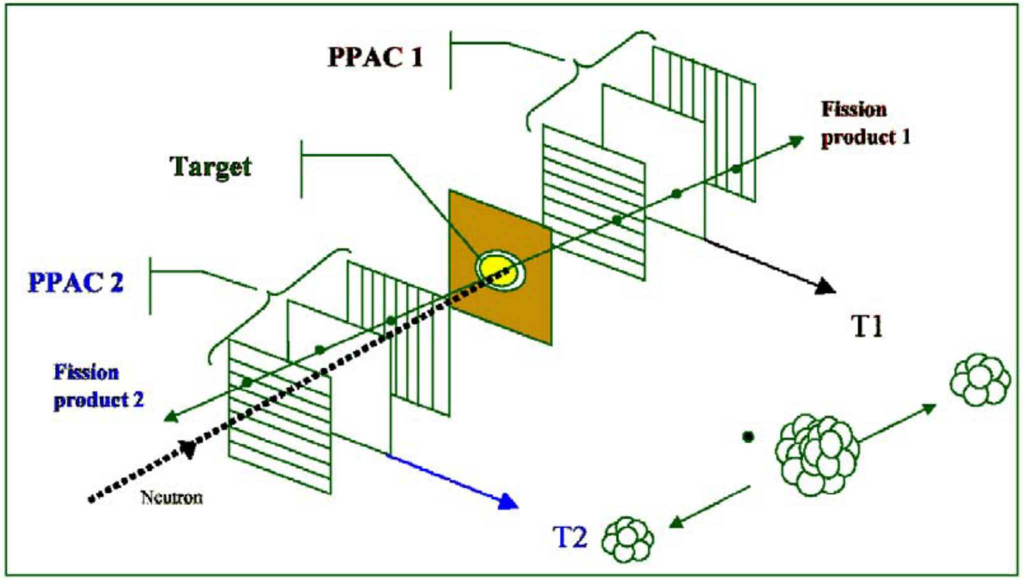


Offline signal reconstruction for time and charge information

- Simple algorithm for a single signal
- Fitting procedure for pile-up events

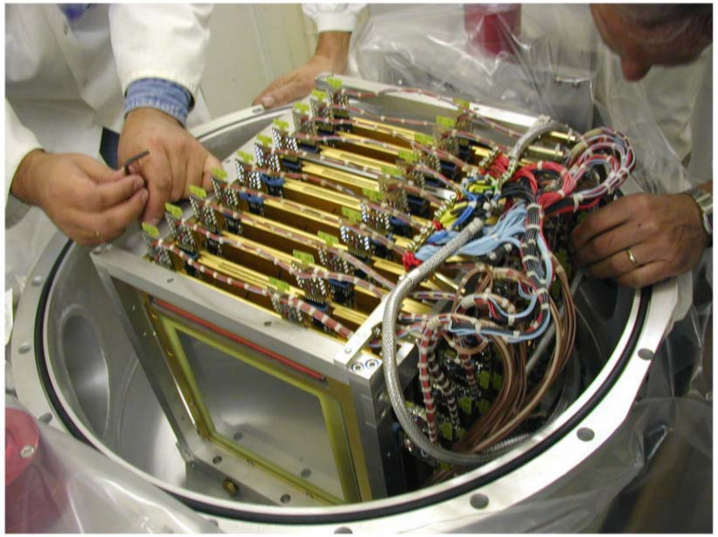
R.Plag et al., Nucl. Instr. And Meth. A538 (2005) 692

The coincidence method (PPAC)



Parallel Plate Avalanche Counters:

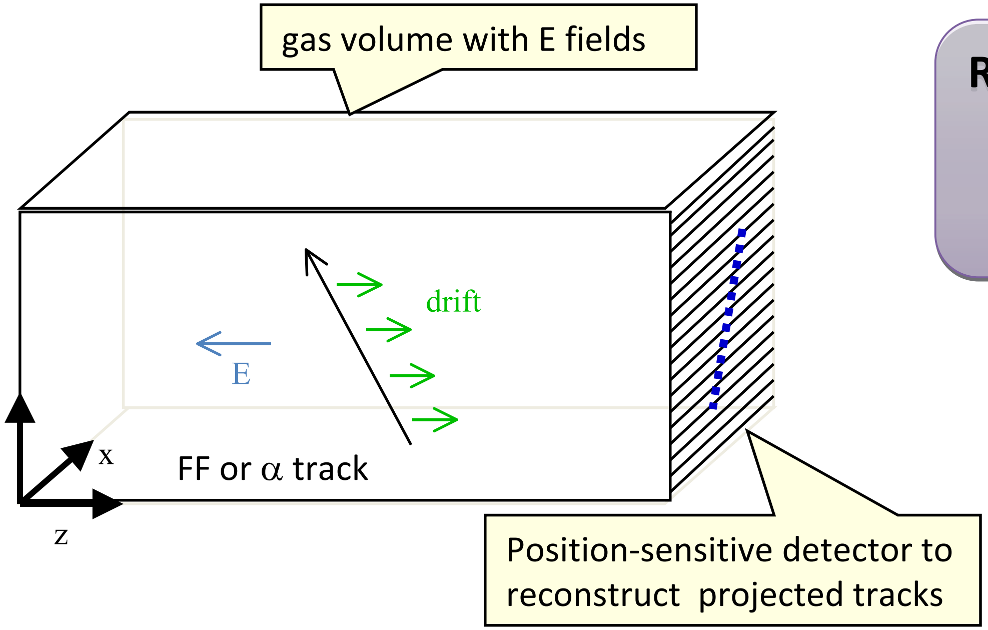
- both fission fragments detected, **in coincidence**
- very good **rejection** of alpha background
- fast timing (0.5 ns resolution)
- require **very thin samples** and **very thin backing**



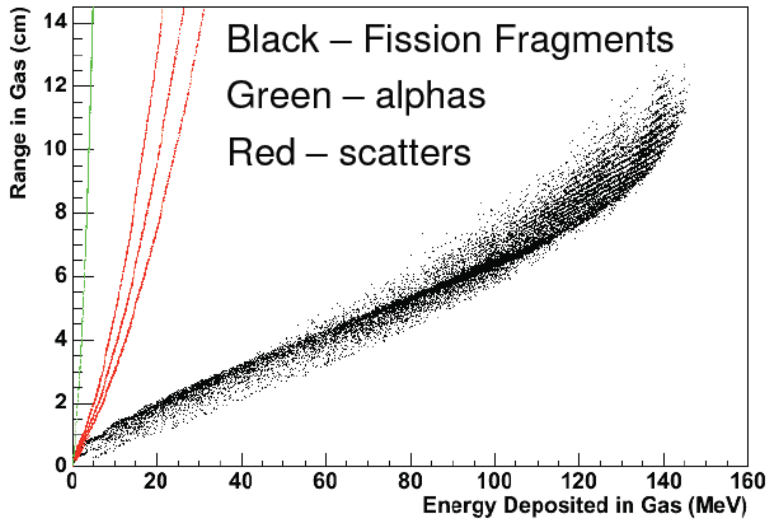
Measured isotopes:

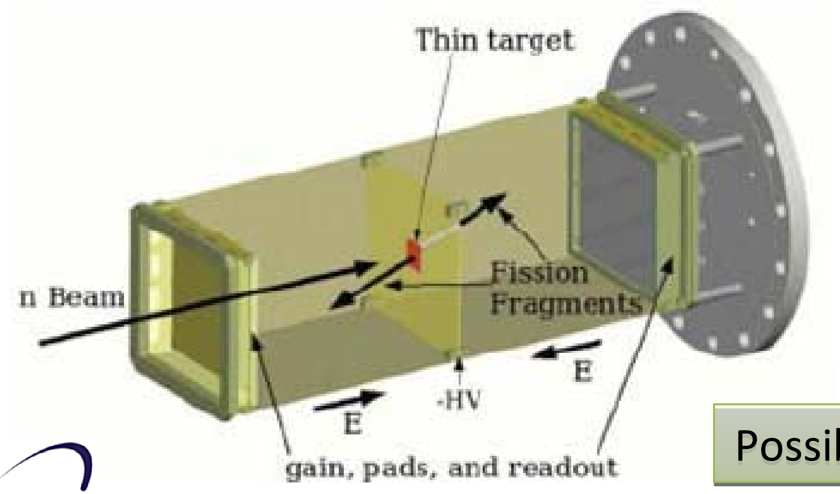
- **^{235}U, ^{238}U** (standard di misura)
- **^{233,234}U, ^{232}Th** (ciclo Th/U)
- **^{237}Np** (trasmutazione e Gen IV)
- **^{209}Bi, ^{nat}Pb** (spallation target)

The Time Projection Chamber



Recorded:
- **Energy loss** in gas
- Emission **angle**
- **Track** reconstruction (gives Z)

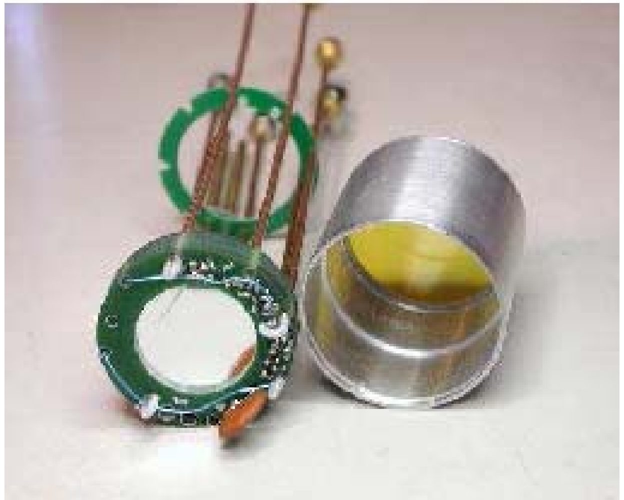




Advantages:
- Charge-particle identification
- Higher background rejection

Possibility to improve accuracy to ~1 %

Detector for simultaneous σ_γ/σ_f measurement



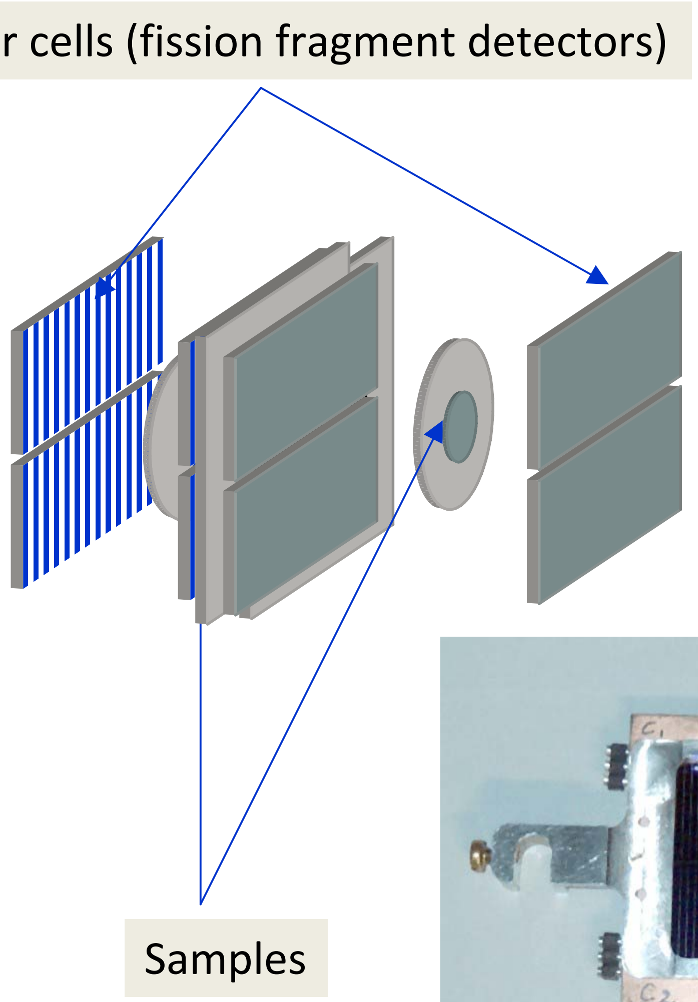
- Small fission detector (mainly PPAC), that can be operated in conjunction with a γ-ray detector (for example, inside calorimeter)
- Can be used to measure at the same time capture and fission (σ_γ/σ_f) or as a veto for fission events
- Typical example at LANL, where PPAC used inside DANCE (4π Total Absorption Calorimeter)

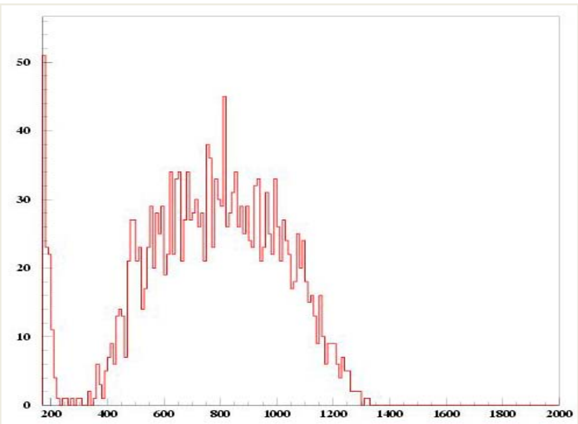
Problem: the small dimensions of the chamber often imply a low counting rate (one cannot use thick samples as for pure capture measurements)

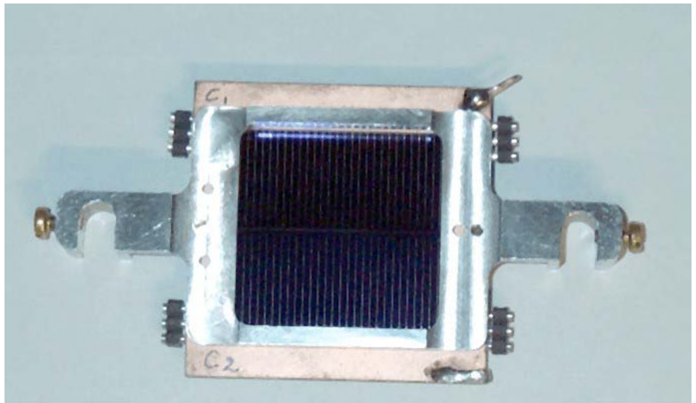
The solar cell detectors

Characteristics:

- very **compact** geometry
- Intrinsic efficiency **~100%**
- robust and **easy** to operate
- no gas involved
- good **α-background** rejection capability



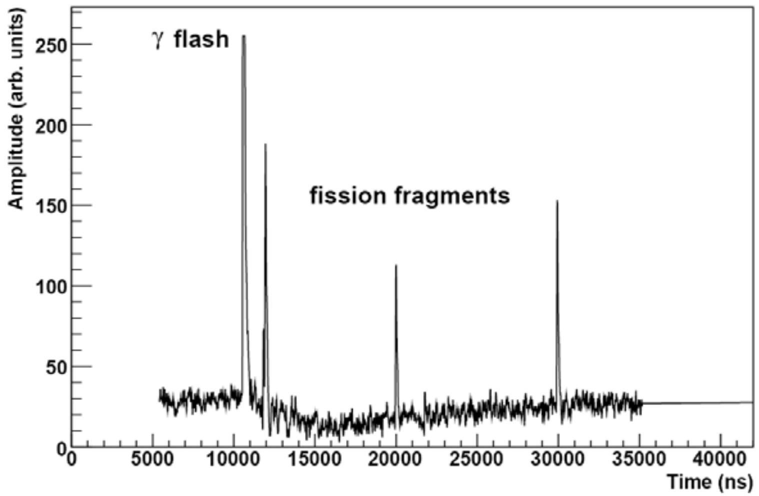


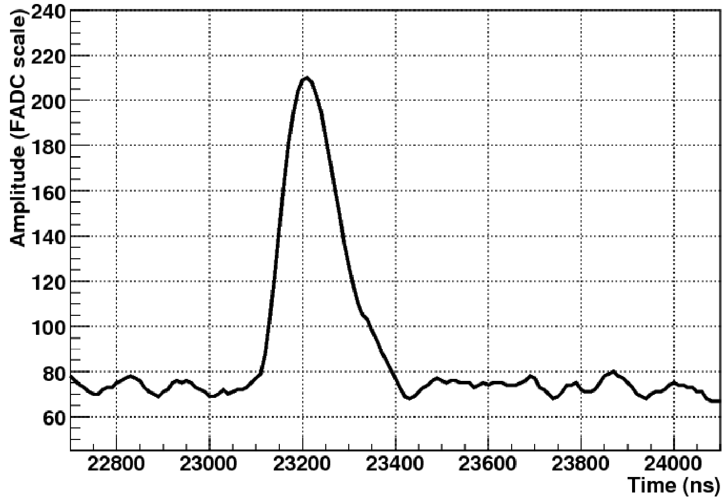


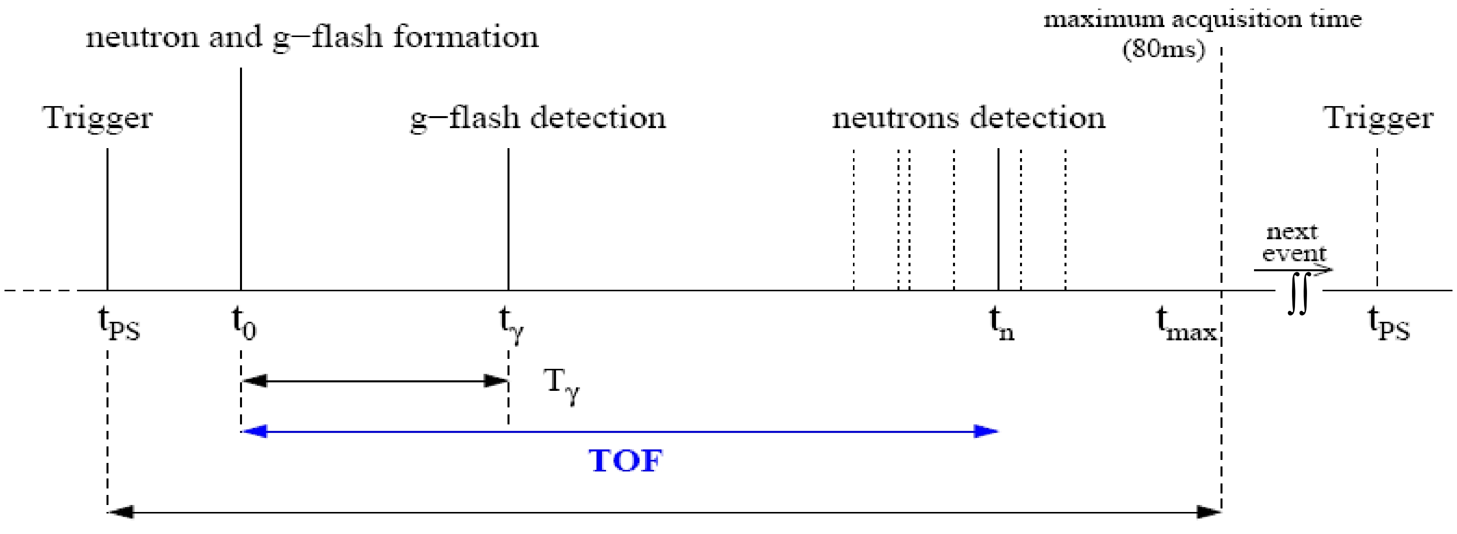
Silicon monocristal of 350 μm thick, covered by a 100 nm TiO2 layer. (20x40 mm)

Data analysis

Time-of-flight reconstruction





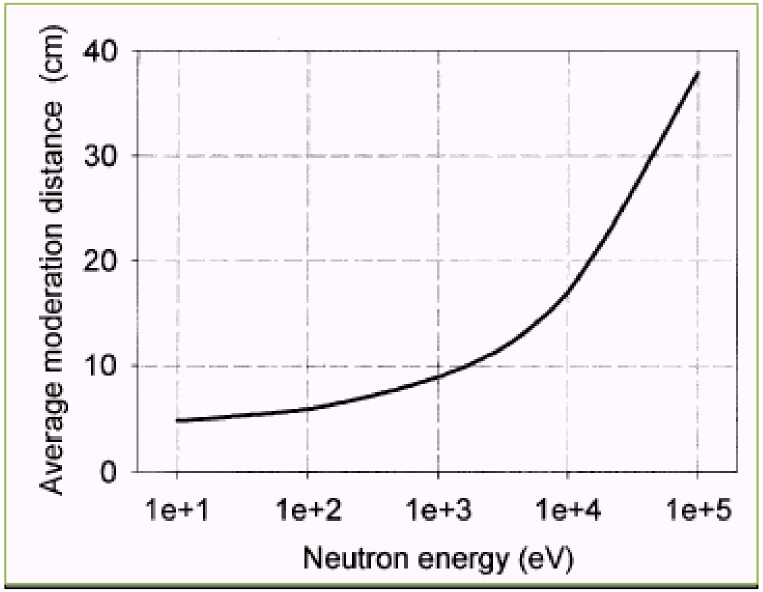


Calibration of neutron energy in ToF measurements

The neutron energy (at low energy) is determined from the time-of-flight according to:

$$E = \left(\frac{72.2977 \cdot L}{ToF - T_c} \right)^2$$

L = flight path length
ToF = time of flight
T_c=correction term



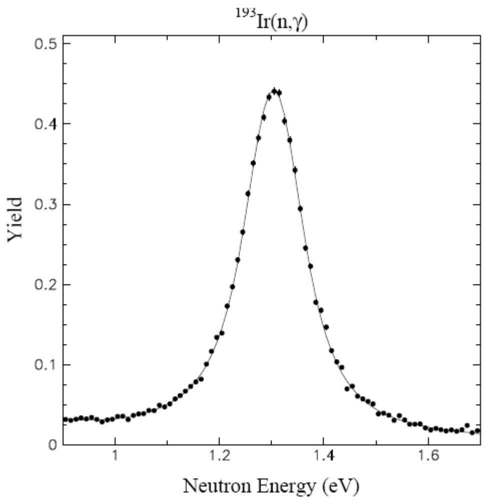
The "time-start" (or **physical reference** t_0) for the time-of-flight is typically given by a **"prompt flash"** (γ-rays, high-energy charged particles, etc…).

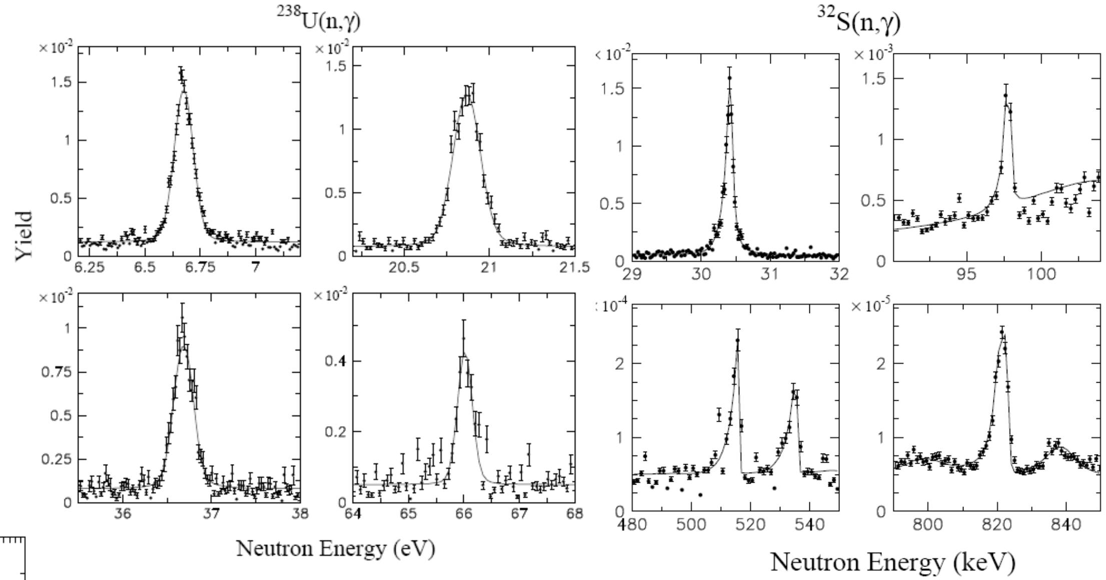
In **moderated** neutron beams, L does not coincide with the **geometric distance** from neutron source, since neutrons **travel** some distance inside the target/moderator.

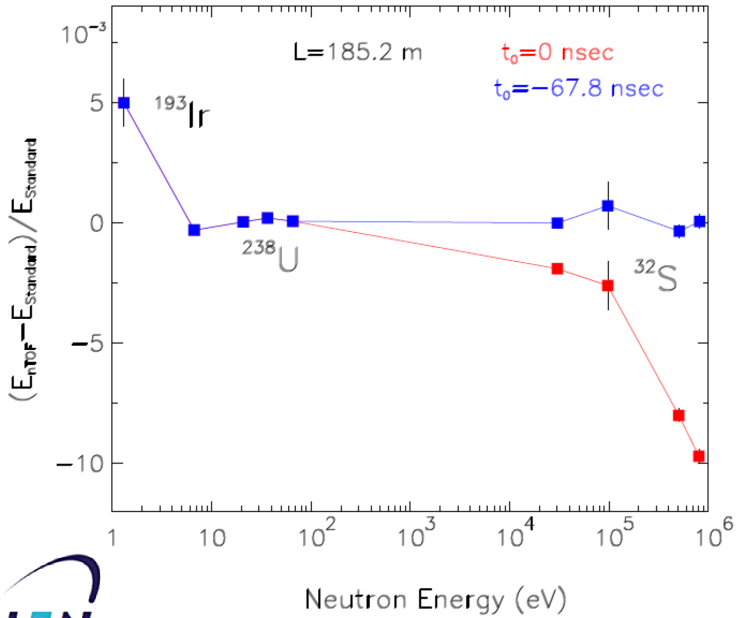
The "moderation distance" **v·t** depends on the neutron energy (t=moderation time).

Necessary to calibratate the neutron energy with respect to energy standards

Calibration of neutron energy in ToF measurements







Data analysis

Number of counts at E_n

Background

$$\sigma_f(E_n) = \frac{C_{^AX}(E_n) - B_{^AX}(E_n)}{\Phi(E_n)\cdot N_{^AX}\cdot \varepsilon \cdot cf}$$

Neutron flux

Atoms/barn of the sample

Efficiency

Other correction factors (dead-time, …)

^AX sample being investigated

E_n neutron energy

$$\mathrm{ratio}(E_n) = \frac{C_{^AX} - B_{^AX}}{\Phi(E_n)\cdot N_{^AX}\cdot \varepsilon_{^AX}\cdot cf_{^AX}} \bigg/ \frac{C_{^{235}U} - B_{^{235}U}}{\Phi(E_n)\cdot N_{^{235}U}\cdot \varepsilon_{^{235}U}\cdot cf_{^{235}U}}$$

$$\mathrm{ratio}(E_n) = \frac{C_{^AX} - B_{^AX}}{C_{^{235}U} - B_{^{235}U}} \cdot \frac{N_{^{235}U}\cdot \varepsilon_{^{235}U}\cdot cf_{^{235}U}}{N_{^AX}\cdot \varepsilon_{^AX}\cdot cf_{^AX}}$$

In the ratio, the neutron flux cancels out

Data analysis

$$\sigma_f\left({}^{A}X, E_n\right) = \text{ratio}\left(E_n\right) \cdot \sigma_f\left({}^{235}U, E_n\right)$$

Standard cross-section used as reference (from evaluated data file)

$$\text{ratio}(E_n) = \frac{C_{{}^{A}X} - B_{{}^{A}X}}{C_{{}^{235}U} - B_{{}^{235}U}} \cdot \frac{N_{{}^{235}U} \cdot \varepsilon_{{}^{235}U} \cdot cf_{{}^{235}U}}{N_{{}^{A}X} \cdot \varepsilon_{{}^{A}X} \cdot cf_{{}^{A}X}}$$

Things to **remember** about the use of ^{235}U (or ^{239}Pu) as reference samples:

- reference samples typically mounted inside the **same chamber** for same efficiency
- all samples with the **same area** to avoid correction for the flux interception
- if possible, **same thickness**, to minimize efficiency corrections (ε)
- approximately **same count-rate**, to minimize dead-time correction (cf)
- need to correct for **anysotropy** in angular distribution of fission fragments (particularly important at high energy). Included in the factor cf.

Possible sources of background

Several sources of background may affect the measurements of fission cross-sections:

- electronic noise ………………………………………………………… } **runs with no beam**
- α-particle from radioactive decay of samples …………… } **runs with no beam**
- spontaneous fission ……………………………………………… } **runs with no beam**
- ambient neutrons ……………………………………………………………………… } **sample outside beam**
- neutrons scattered from the detector and surrounding material …… } **sample outside beam**
- wrap-around neutrons ……………………………………………… **measured with filters …**
- resolution function ………………………………………………… **simulations (mainly)**

It is preferable to try and **minimize** all possibile sources of background, to increase signal-to-background ratio and minimize uncertainty on background subtraction:

- **high neutron flux** (to minimize ambient background and natural radioactivity)
- minimize **mass** of the detector and surrounding material (for neutron scattering)

Uncertainty analysis

When extracting the fission cross-sections with ratio method, **uncertainties** related to:

• **mass** of the sample and of the reference	typically, 1 %
• presence of other isotopes (**contaminants**) in the samples	depends on the sample
• **background** subtraction	depends on the sample
• **wrap-around** neutrons	depends on the facility
• **efficiency** and **dead-time** corrections	depends on detector
• neutron beam **attenuation**	depends on set-up
• **evaluated cross-sections** used as reference	typically, 1-3 %

In addition, other possible sources of uncertainty are:

- sample **non-uniformity** (combined with beam non-uniformity)
- **misallignement** between sample and reference (don't intercept the same neutron flux)