Delayed neutrons: measurements and usage

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Grand Accélérateur National d'Ions Lourds

Large National Heavy Ions Accelerator

Short Curriculum Vitae

1992-1995 : PhD Thesis at GANIL

- Formation and de-excitation hot nuclei produced in reactions induced by proton (475MeV and 2 GeV) and ^{3}He (2 GeV) beams

1996-1998 : Post-doctoral position at CEA/DIF (Bruyères-le-Châtel)

- Measurement of neutron emission in spallation reaction between 800 MeV and 1600 MeV

1998-2012 : Permanent position at CEA/DIF (Bruyères-le-Châtel)

- n,xn reaction studies
- Production of isomeric nuclei by neutron capture in the resonances
- Delay neutrons measurements in fission induce by neutrons and photon
- Spokesperson of the Neutrons For Science Facility

Since 1992 : Permanent position at GANIL

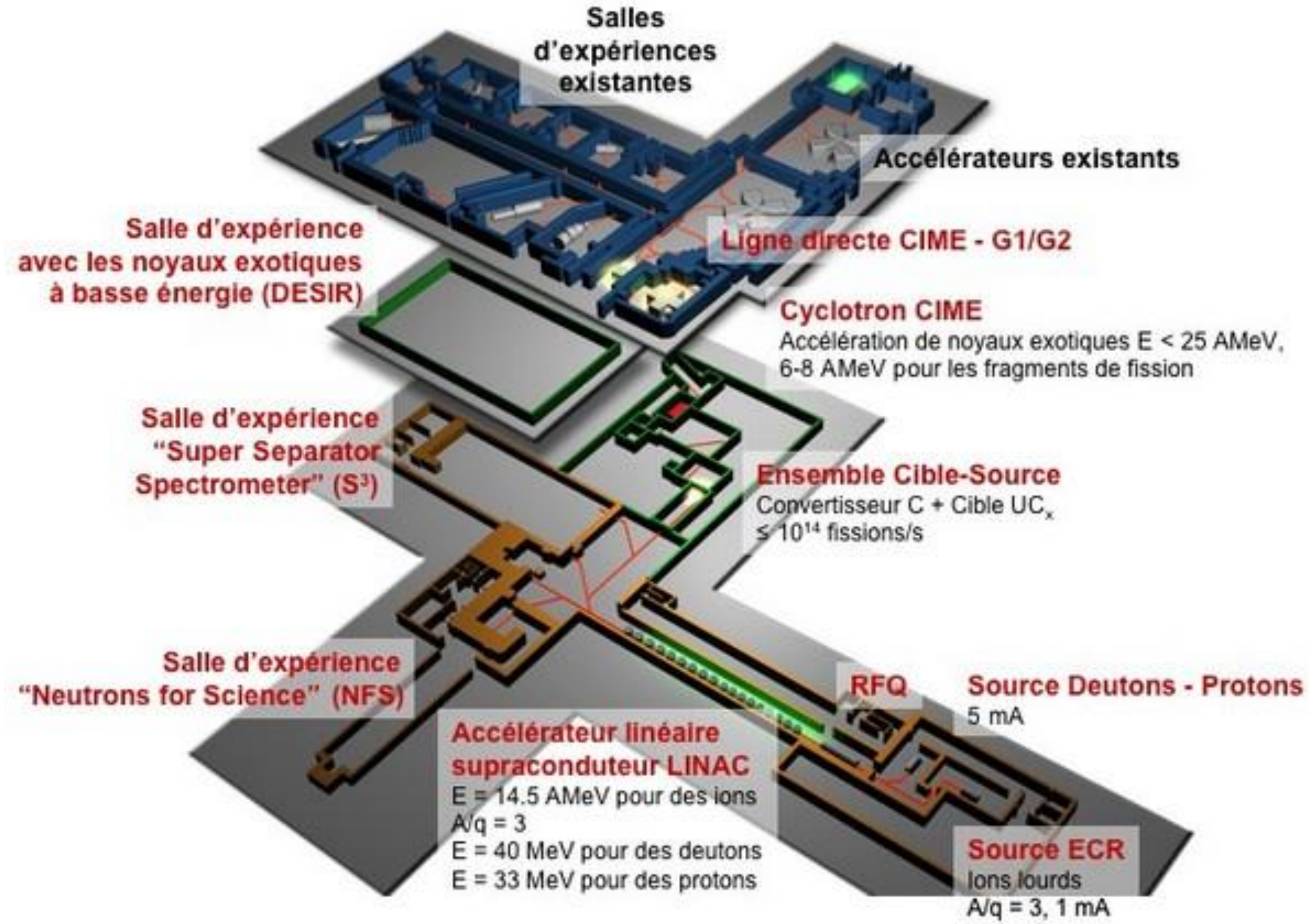
- Responsible of the Neutrons For Science facility at GANIL/SPIRAL-2


GANIL


SPIRAL-2

Photo Jean-Michel Enguerrand - 24 juin 2014

GANIL-Spiral2 facility



Salles d'expériences existantes

Accélérateurs existants

Salle d'expérience avec les noyaux exotiques à basse énergie (DESIR)

Ligne directe CIME - G1/G2

Cyclotron CIME
Accélération de noyaux exotiques E < 25 AMeV,
6-8 AMeV pour les fragments de fission

Salle d'expérience "Super Separator Spectrometer" (S^3)

Ensemble Cible-Source
Convertisseur C + Cible UC_x
$\leq 10^{14}$ fissions/s

Salle d'expérience "Neutrons for Science" (NFS)

RFQ

Source Deutons - Protons
5 mA

Accélérateur linéaire supraconduteur LINAC
E = 14.5 AMeV pour des ions
A/q = 3
E = 40 MeV pour des deutons
E = 33 MeV pour des protons

Source ECR
Ions lourds
A/q = 3, 1 mA

Neutrons For Science facility: intense fast neutron time-of-flight facility

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  - II. Reactor
- III. Measurement
  - I. Neutrons detectors for DN
  - II. Microscopic measurements
    - I. Techniques
    - II. Examples of experiments
  - III. Macroscopic measurements
    - I. ν_d measurement
    - II. Time distribution measurement
- IV. Examples of experiments

Physics cases with delayed neutrons

❑Nuclear power control and safety:

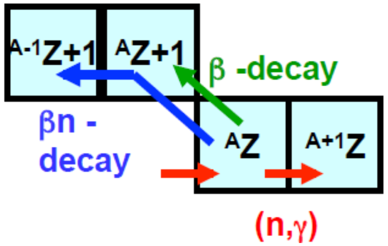
Some fission products undergo Beta Delayed Neutron Emission which is essential to control the reaction.

❑Interrogation techniques :

Some active interrogation techniques are based on the detection of delayed neutrons and/or photons. It is the signature of the presence of actinide.

❑Rapid neutron-capture process of stellar nucleosynthesis:

Short and very high neutron flux produces very neutron rich nuclei in short time.
β decay determines the speed of the process. β-n shapes the abundance of the distribution



❑Nuclear Structure:

Additionally the measured half-lives ($T_{1/2}$) and β-delayed neutron-emission probabilities (Pn) can be used as first probes of the structure of the β-decay daughter nuclei in this mass region.

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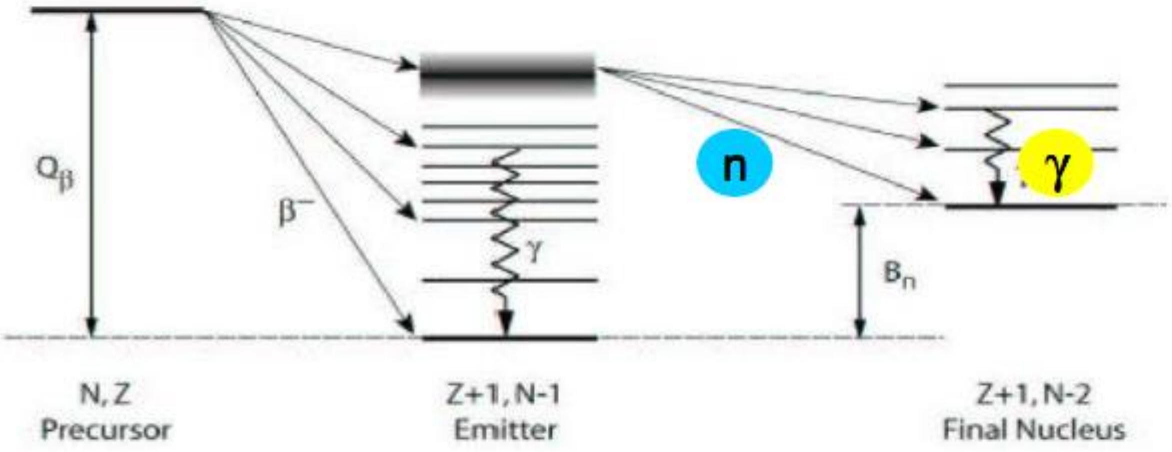
Beta – n decay

Neutron rich nuclei decays mainly by beta emission

$$^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + \beta^{-} + \overline{\upsilon_e}$$

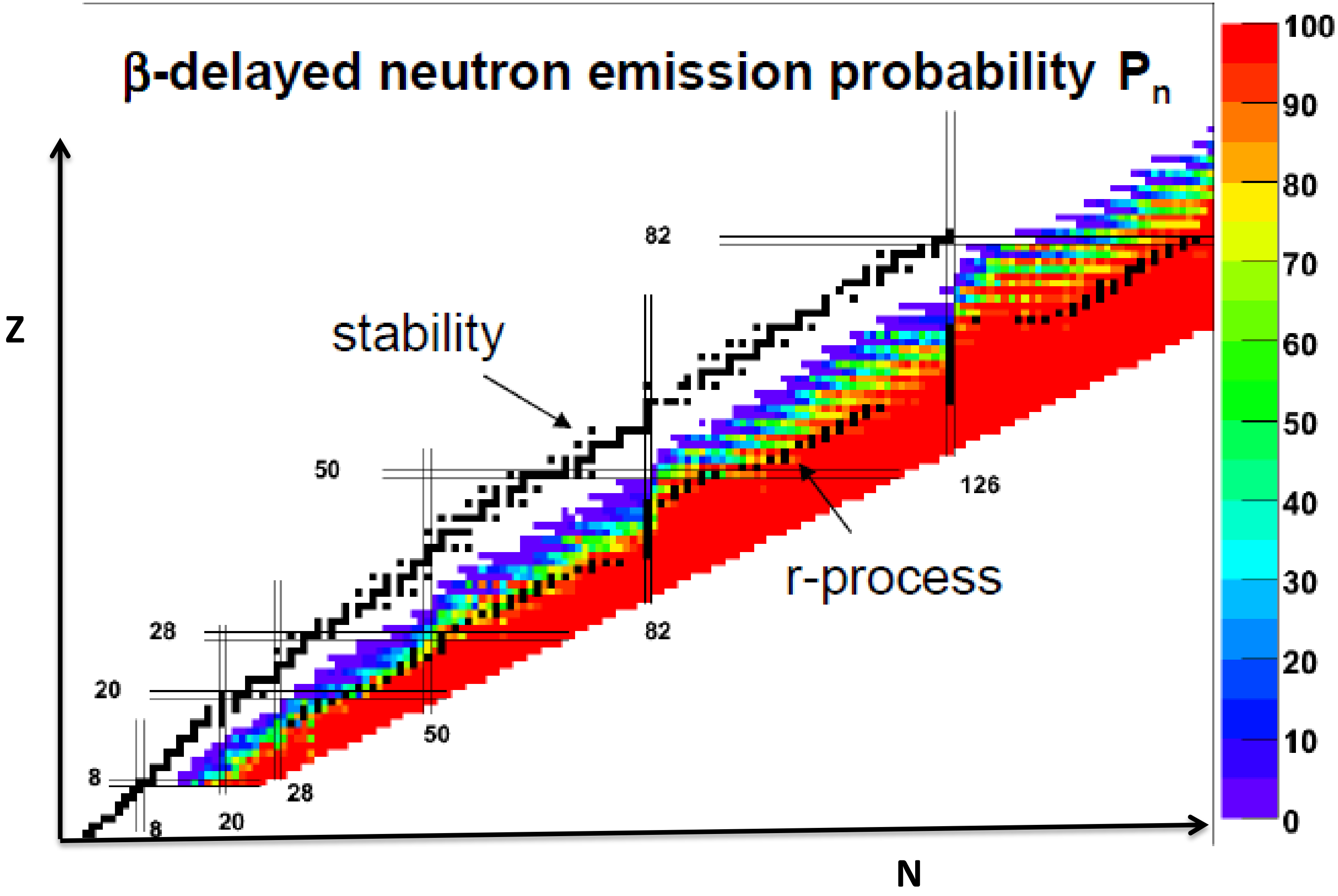
B_n : one neutron separation energy



For enough neutrons rich nuclei, $Q_b > B_n$

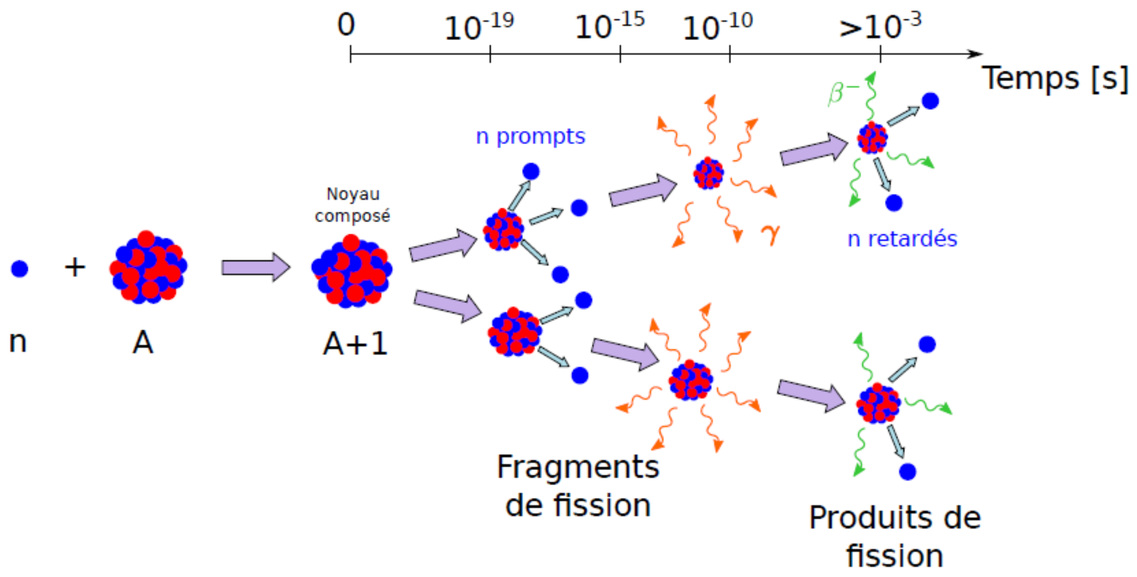
- If the decay proceeds to states above B_n: neutron emission dominates over γ-ray de-excitation
- Emission of a β, a neutron and sometimes photons
- These nucleus are called precursors (more than 300 exist)
- P_n probability that a precursor emits a neutrons
- The emission time distribution follows the precursor half-life

Neutron rich nuclei



Far from stability, β-delayed neutron emission becomes the dominant process

Neutrons emission in fission



- After a fission induced by n or γ, 2 large excited fragment are emitted
- They de-excite by neutrons and photons emission (prompt neutrons and photons)
- Leading to fission products, stable or radioactive
- The radioactive fission products de-excite mainly by Beta decay

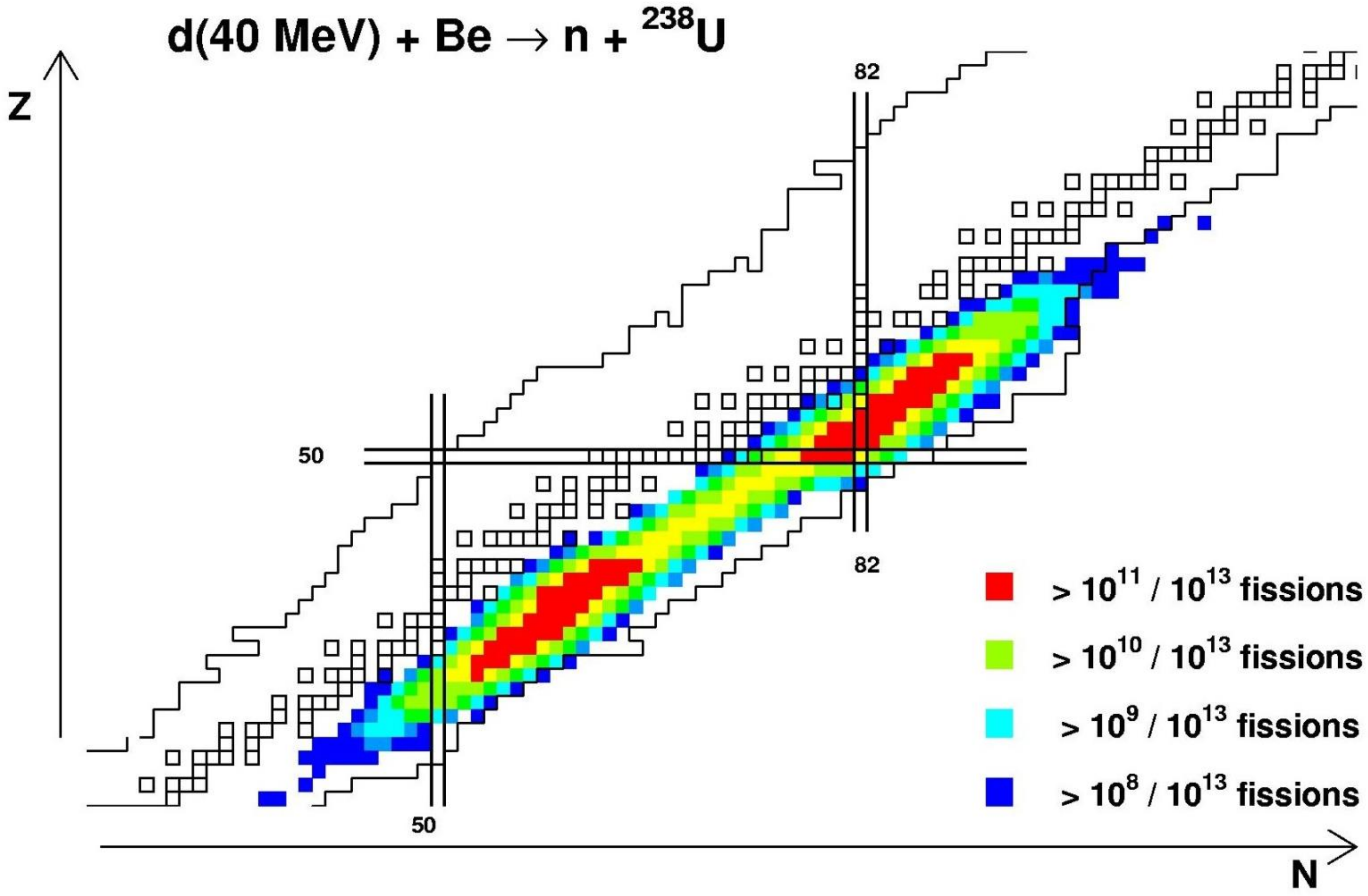
Number of prompt neutrons (per fission) $\bar{\upsilon}$ or υ_p 2 to 4

Number of delayed neutrons υ_d 0.1 to 5%

β fraction of delayed neutrons $\beta=\nu_d/\nu_p$

Neutron induced fission

Fission products of the 238U fission induced by fast neutrons ($E_{average}$=14MeV)



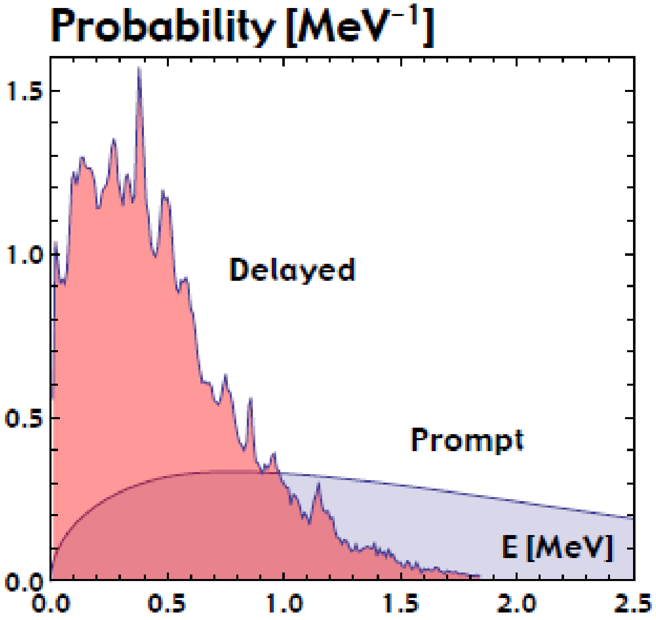
Fission fragments are neutron rich nuclei -> β and β-n decay

Delayed Neutron characteristics

More than 300 precursors exist after a fission

- ○ Life time between 10 ms and 1 min
- ○ DN yield: from 0,1 to 5 per 100 fissions
- ○ Usually merged in groups depending of the precursor half-live

	ν delayed	ν prompt	β=νd / νp
239-Pu	0,0061	2,87	0,0021
238-U fast	0,0450	2,84	0,01584
241-Pu	0,0154	3,14	0,0049
235-U thermal	0,0166	2,43	0,00683



Energy spectrum softer than prompt fission neutrons:

Delayed Neutrons E<1,5 MeV

Prompt neutrons <E>≈ 2 MeV

Groups of delayed neutrons

❑ Due to the number of precursors, the yield and time distribution can not be treated individually

❑ Groups depending of the time decay are defined.

❑ The delayed neutrons are characterized by :

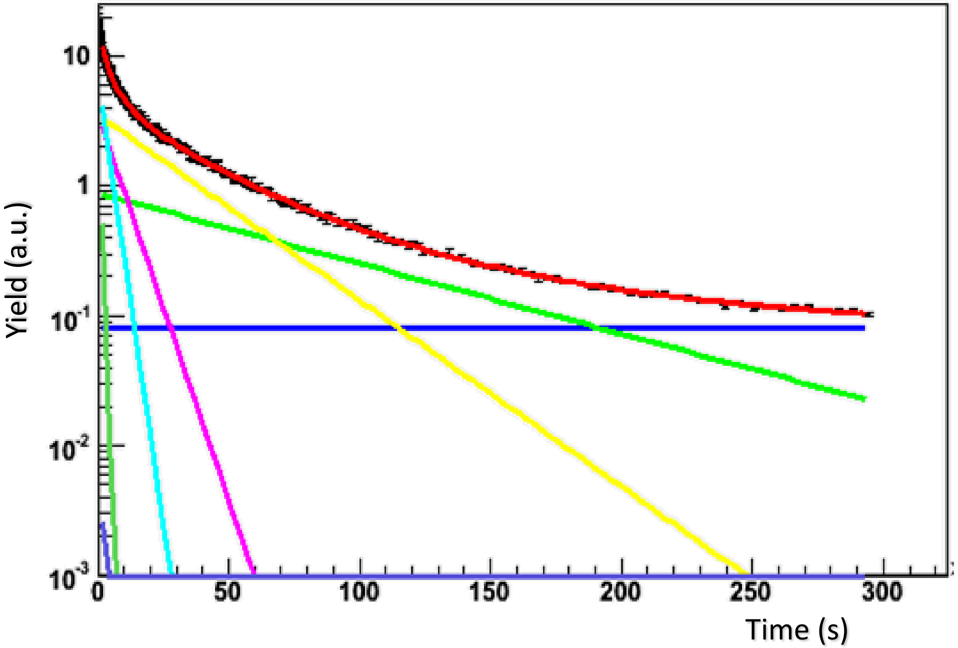
- the yield (per/fission)
- the time distribution depending on the half live of the precursors

a_i nb of delayed neutrons of group i

$\lambda_i = \ln(2)/T_i$, T_i period of group i

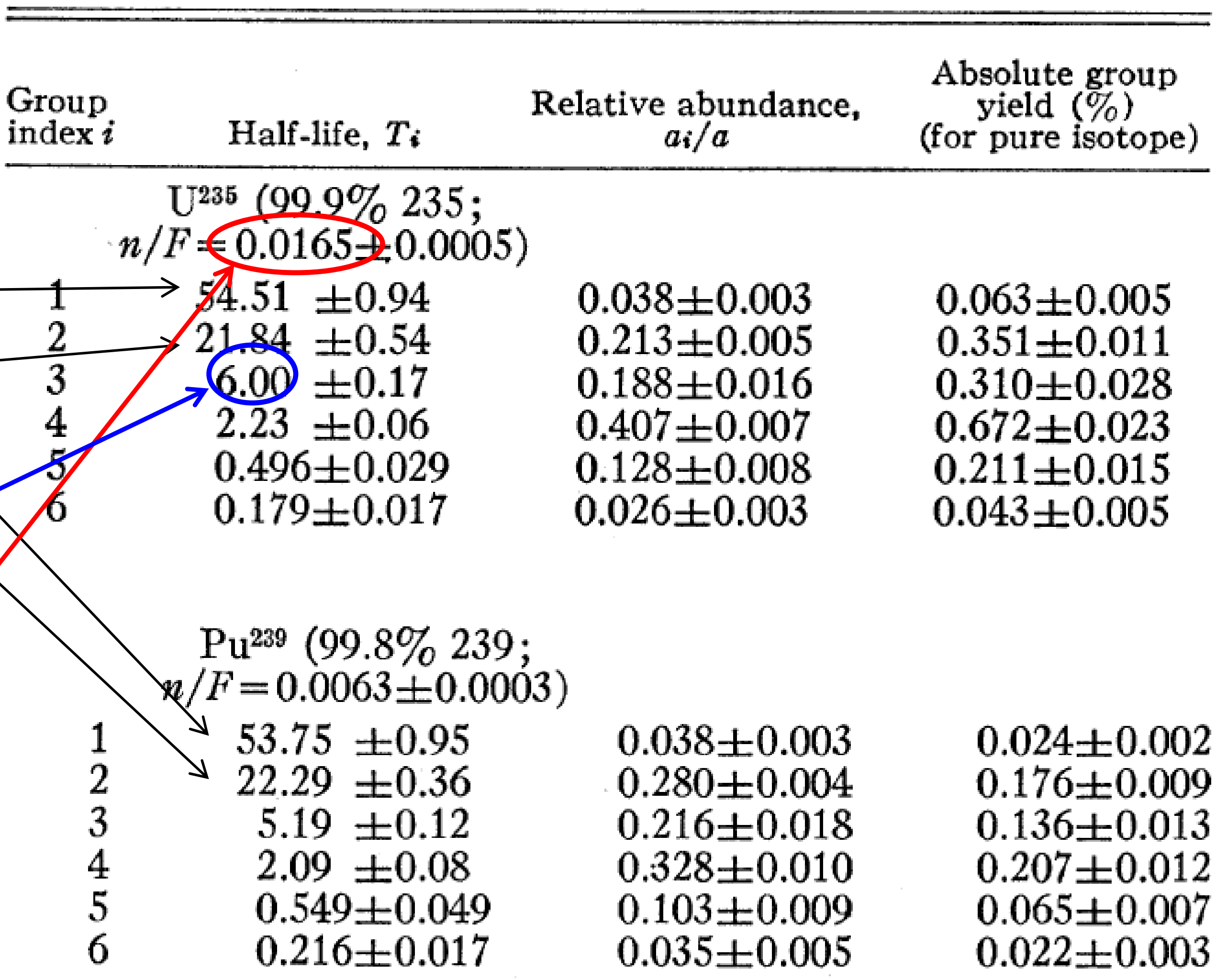
$$Y_{dn}(t) = \sum_{i=1,6} a_i \exp(-\lambda_i t)$$

$$\sum_{i=1,6} a_i = \nu_d$$



- Depending on the library and applications : 5,6 or 8 groups have been defined.
- In case of six groups 12 parameters allow characterizing the yield and time distribution

DN of ^{239}Pu and ^{235}U neutron induced fission



Group index *i*	Half-life, T_i	Relative abundance, a_i/a	Absolute group yield (%) (for pure isotope)
	U^{235} (99.9% 235; $n/F = 0.0165 \pm 0.0005$)		
1	54.51 ±0.94	0.038±0.003	0.063±0.005
2	21.84 ±0.54	0.213±0.005	0.351±0.011
3	6.00 ±0.17	0.188±0.016	0.310±0.028
4	2.23 ±0.06	0.407±0.007	0.672±0.023
5	0.496±0.029	0.128±0.008	0.211±0.015
6	0.179±0.017	0.026±0.003	0.043±0.005
	Pu^{239} (99.8% 239; $n/F = 0.0063 \pm 0.0003$)		
1	53.75 ±0.95	0.038±0.003	0.024±0.002
2	22.29 ±0.36	0.280±0.004	0.176±0.009
3	5.19 ±0.12	0.216±0.018	0.136±0.013
4	2.09 ±0.08	0.328±0.010	0.207±0.012
5	0.549±0.049	0.103±0.009	0.065±0.007
6	0.216±0.017	0.035±0.005	0.022±0.003

^{87}Br, $T_{1/2}$=55,9s

^{137}I, $T_{1/2}$=24,5 s

$$Y_{dn}(t) = \sum_{i=1,6} a_i \exp(-\lambda_i t)$$

$$\sum_{i=1,6} a_i = \nu_d$$

Sometime 1 dominant precursor for the group

G. R. Keepin et al, PR107,vol 107, num 4, 1957

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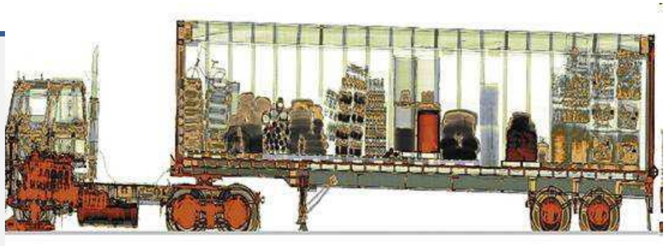
Actinide detection

Goal : detection of the presence of actinide in a container, waste,….

- Safeguard
  - detection of nuclear weapon
  - nuclear material traffic
  - dirty bomb
- Monitoring the processes in nuclear fuel reprocessing
- Waste management :
  - presence of actinide in nuclear industry waste
  - verification of “old” container or concrete bloc



1. **Passive detection**

   gamma detection -> suspicious object

2. **Radiography**

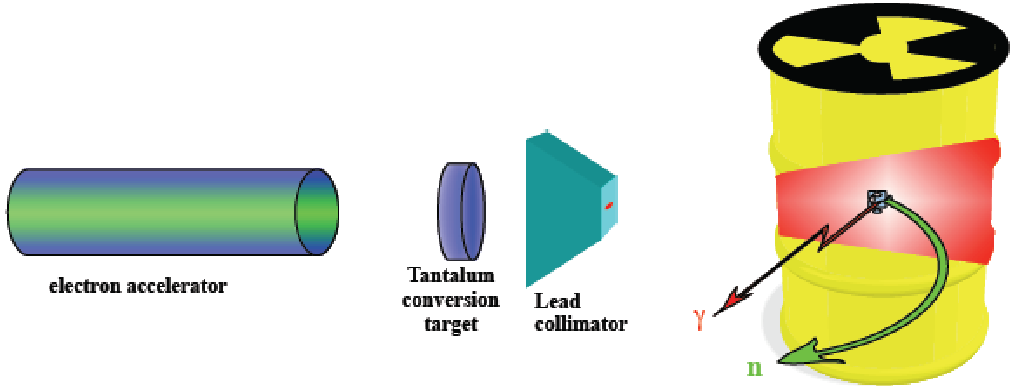
   The detection of high density material gives the area to investigate

3. **Active interrogation**

   Pulsed radiation fields can investigate time-correlated signatures which passive signature techniques generally cannot

Active interrogation technique

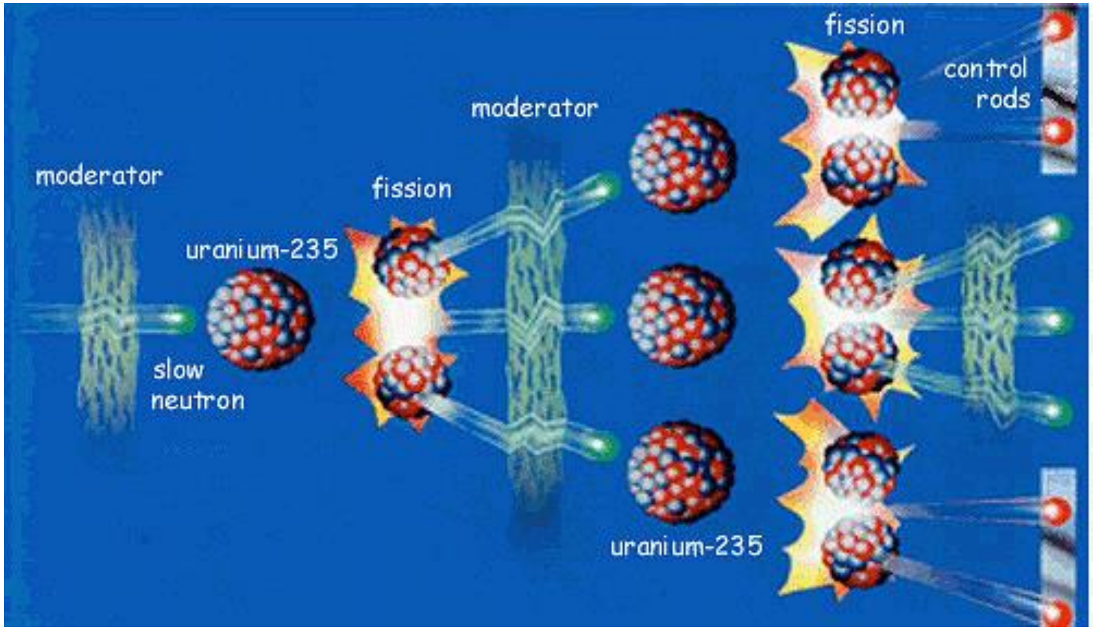
1. The “package” is irradiated by neutrons or photons
   - Emission of prompt neutrons and photons
   - Detection difficult : background induced by the beam
2. Neutrons and/or photons time distributions are measured after the irradiation
   - Delayed neutrons detection: very probably emitted by fission fragments
   - Yield and time dependence measurement : identification and mass of the actinide in the package
   - Delayed photons are also used in addition to DN



Simulations of the whole set-up including attenuation of induced and emitted neutrons and photons → Relevant data and especially accurate data of a_i λ_i for all actinides

Reactor control

Nuclear reactor run with chain reaction :



K_{eff} nb of neutrons inducing a fission from one neutron

$K_{eff} < 1$ subcritical $K_{eff} > 1$ supercritical

Reactivity : $\rho = \frac{k_{eff} - 1}{k_{eff}}$

$K_{eff} = 1$ in reactor

^{235}U + neutron = 2,43 prompt neutrons + 0,0166 delayed neutrons (β=0,00685)
^{239}Pu + neutron = 2,91 prompt neutrons + 0,0061 delayed neutrons (β=0,0021)

Neutrons generation time

- Average generation time Λ =

  time between the birth of two fission neutrons in successive generations

- Population :

$$N(t+\Lambda)=k_{eff}N(t) \qquad \frac{dN(t)}{dt}=\frac{N(t+\Lambda)-N(t)}{\Lambda}=\frac{k_{eff}-1}{\Lambda}N(t) \qquad N(t)=N(0)\exp\left(\frac{k_{eff}-1}{\Lambda}t\right)$$

- Prompt neutrons
  - ➢Fast reactors $\Lambda_{prompt} \approx 1 \mu s$
  - ➢Thermal reactor $\Lambda_{prompt} \approx 25 \mu s$
- Delayed neutrons: ^{235}U n induced fission $\Lambda_{delayed} \approx 12{,}5$ s

$$\boxed{\Lambda_{average}=\Lambda_{prompt}(1-\beta)+\Lambda_{delayed}(\beta)}$$

Neutrons generation time

Neutrons multiplication in 1 sec in the case of PWR and ^{235}U with k=1,0001

β=0,0065 → Λ_{average} = 25.10^{-6} s x (1-0,0065) + 12,5 s x 0,0065

Λ_{average} = 0,0813 s

- Only prompt neutrons : $\Lambda_{\text{prompt}} \approx 25\mu s$

$$\frac{N(t=1s)}{N(0)} = \exp\left(\frac{1{,}0001-1}{25.10^{-6}}\right) = \exp(4) = 55$$

- With delayed neutrons → Λ_{average} = 0,0813 s

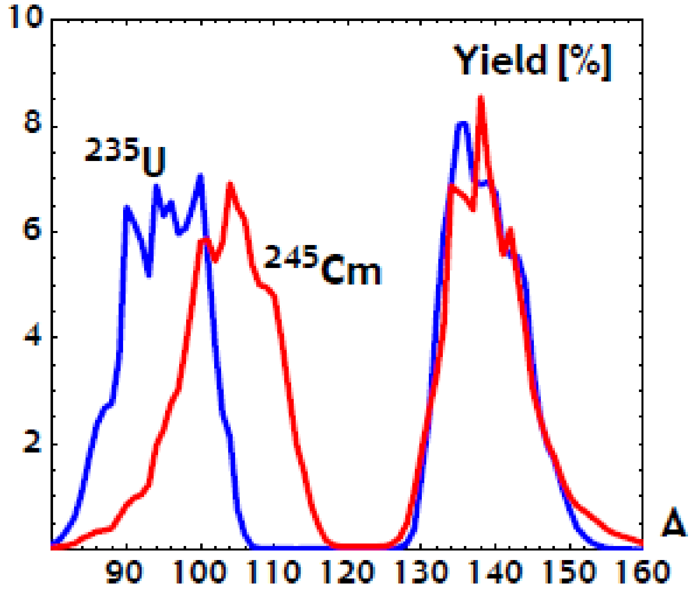
$$\frac{N(t=1s)}{N(0)} = \exp\left(\frac{1{,}0001-1}{0{,}0813}\right) = \exp(0{,}00123) = 1{,}00123$$

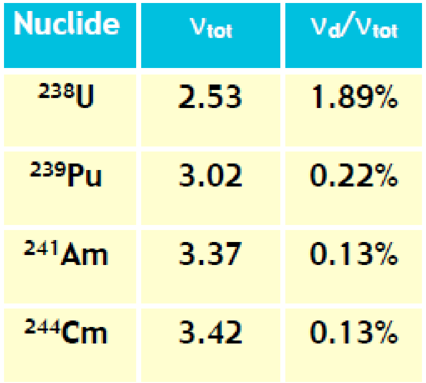
Delayed neutrons are responsible for the ability to control the rate at which power can rise in a reactor. If only prompt neutrons existed, reactor control would not be possible due to the rapid power changes

Dependence of DN yield with the actinide

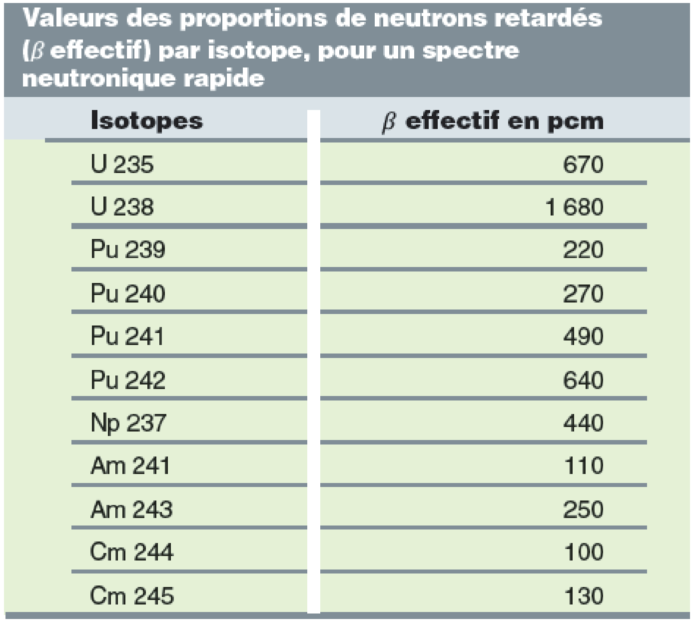
When actinide mass increases :

- Yield of important delayed neutrons emitters (Br) decreases → β decreases
- Number of prompt fission neutrons increases





Nuclide	ν_{tot}	ν_d/ν_{tot}
^{238}U	2.53	1.89%
^{239}Pu	3.02	0.22%
^{241}Am	3.37	0.13%
^{244}Cm	3.42	0.13%



Valeurs des proportions de neutrons retardés (β effectif) par isotope, pour un spectre neutronique rapide

Isotopes	β effectif en pcm
U 235	670
U 238	1 680
Pu 239	220
Pu 240	270
Pu 241	490
Pu 242	640
Np 237	440
Am 241	110
Am 243	250
Cm 244	100
Cm 245	130

- ☐ Fast reactors are more nervous than thermal ones
- ☐ When Pu, Am or Cm ↗ in the fuel β↘

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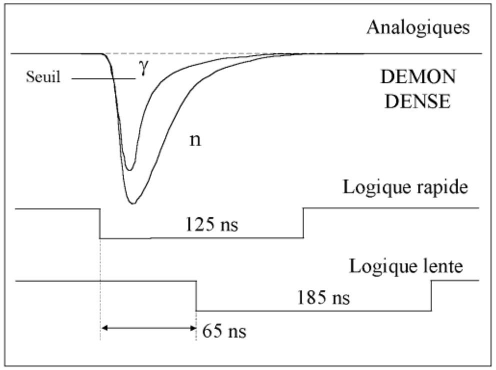
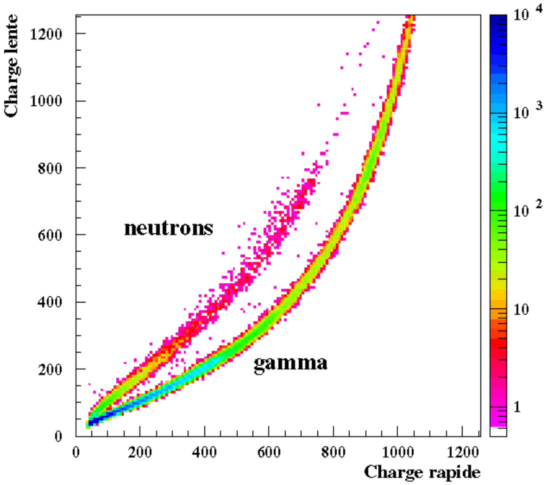
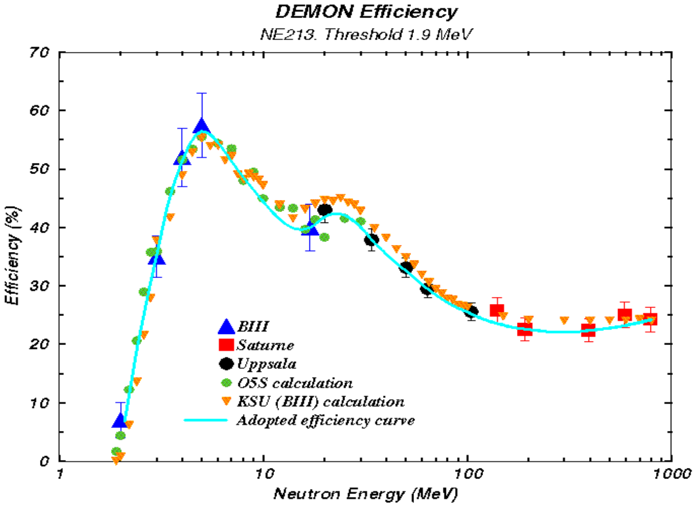
Liquid scintillator

- Cell of liquid scintillator coupled to a phototube
- Detection :
    - diffusion (n,p)
    - scintillation
    - light conversion to electric signal by the phototube
- Sensitive to gamma, neutrons and charged particles
- neutron- γ discrimination by pulse shape analysis
- Fast detector (≃ 1 ns)
- The intrinsic efficiency depends on the size of the cell
- Compromise between efficiency and energy resolution



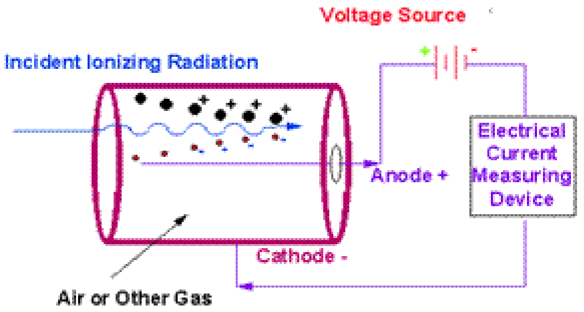


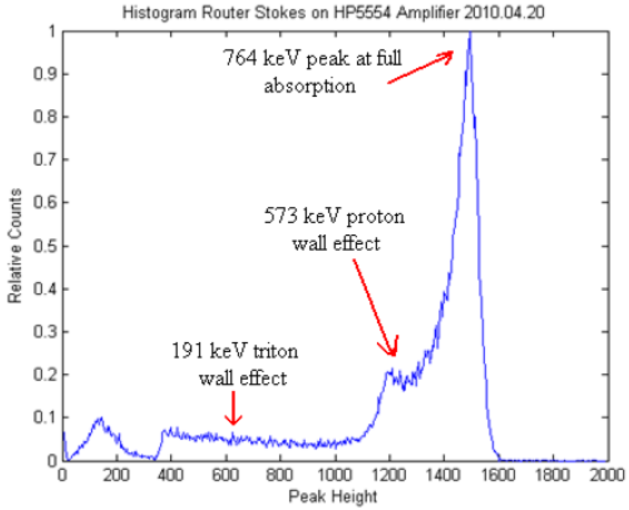


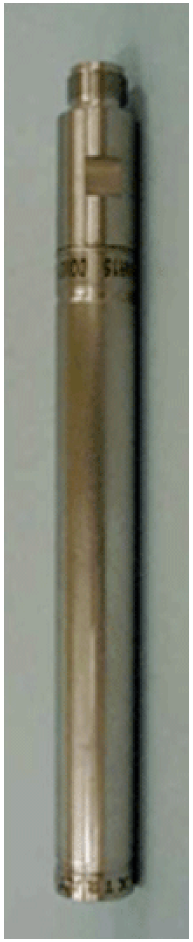
^{3}He gas detector

Neutron detection by $^{3}He(n,p)T$ reaction, Q value = 0,764MeV

Gas detector



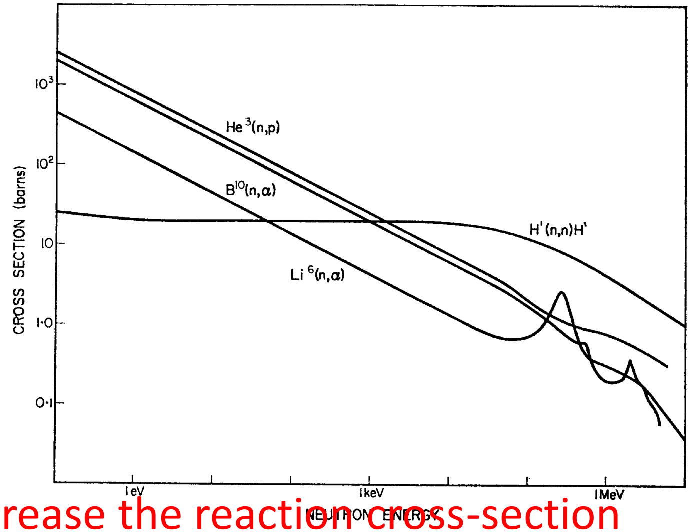




Almost not sensitive to photons

Cross-section:

- < 1 barn at 1 MeV
- > 5330 b at thermal energy



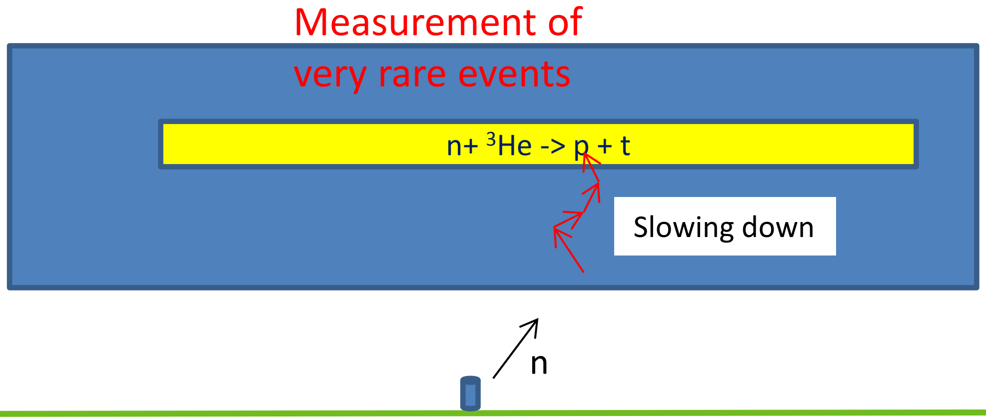
→ The neutron must be slowed down to increase the reaction cross-section

4 π neutrons detector

- ❑ How to increase the detection ?
  - ➢ The ^{3}He tubes are placed in a matrix of polyethylene
  - ➢ Increase the number of tubes
  - ➢ Use a 4π geometry

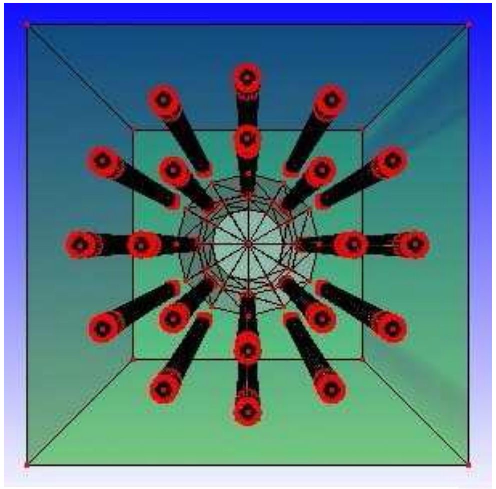
- ❑ Slow detector
  - ➢ The slowing down process takes several hundredths of microseconds
  - ➢ Energy measurement by TOF technique impossible
  - ➢ Fast enough compare to precursors half-live

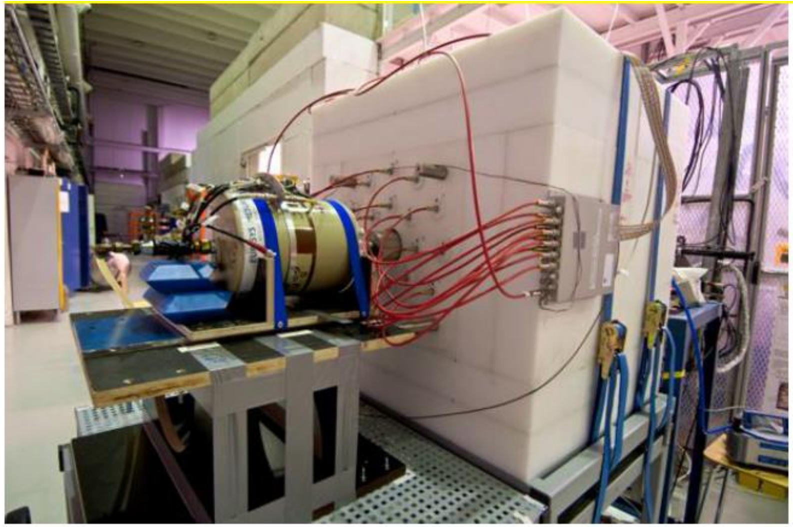
- ❑ Designed to have an efficiency constant in the energy range of delayed neutrons

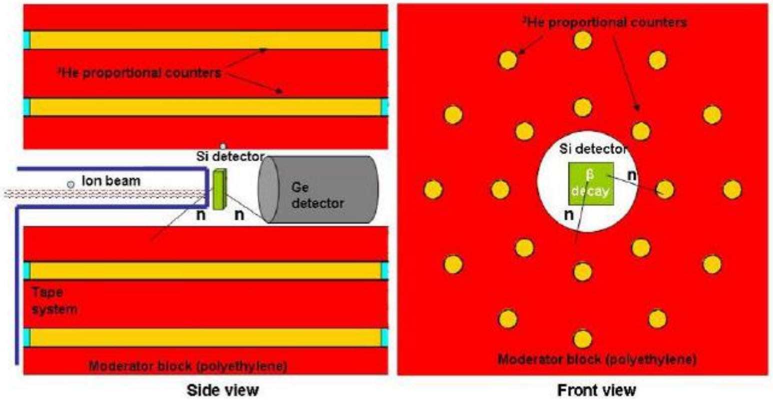


BELEN: Beta deLayEd Neutron detector

Two crowns of (8+12) ^{3}He detectors embedded in a polyethylene matrix with total dimensions 90x90x80 cm^3 and a r=5cm beam hole

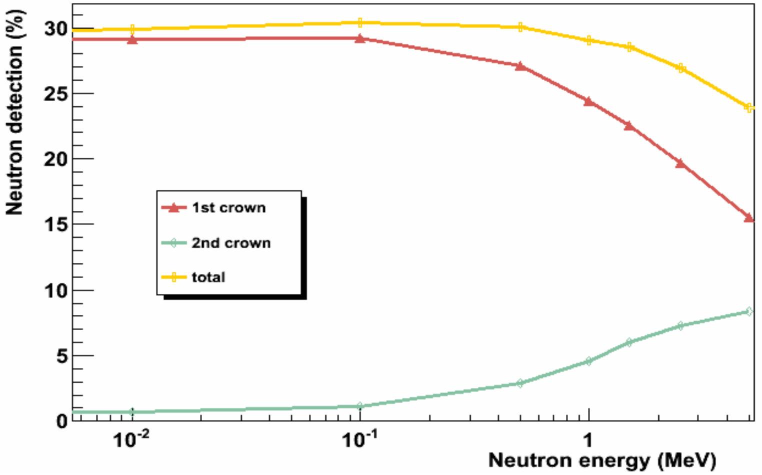






Side view

Front view

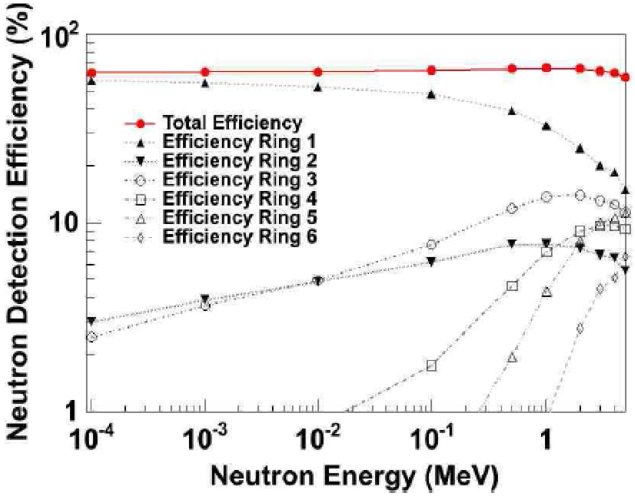


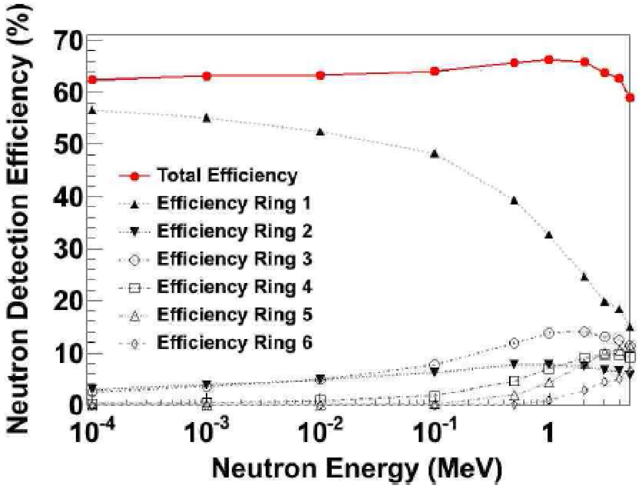
The thickness of CH2 and the position of the tube are optimized for an efficiency quite constant with En in below 1 MeV

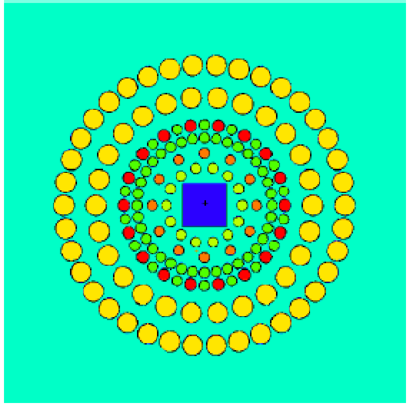
BRIKEN

International collaboration using a large number of 3He tubes of different size

BRIKEN stands for **B**eta delayed neutron measurements at **RIKEN**.







174 ^{3}He tubes of 6 different types:

Ring	Radius (cm)	# ^{3}He Tubes	Pressure (atm)	Diameter (inch)	Institute
1	9.4	14	10	1	ORNL
2	13	12+12	5.13	1	RIKEN
3	16.8	10+26	10/8	1	GSI/UPC
4	20	18+18	5/8	1.18/1	JINR/UPC
5	27	26	10	2	ORNL
6	35	38	10	2	ORNL

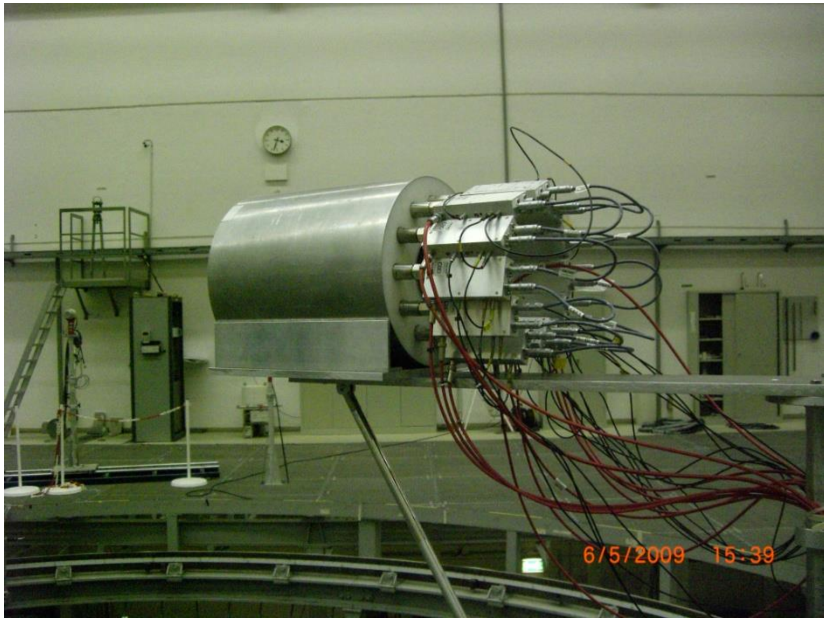
- High average efficiency of > 60 %
- Flat efficiency 6% up to 4 MeV, 12% up to 5 MeV.

C. Domingo-Pardo, BRIKEN Construction Proposal, NP-PAC, RIKEN Nishina Center 13-14/12/2013

CEA Deleayed Neutrons detector

Characteristics :

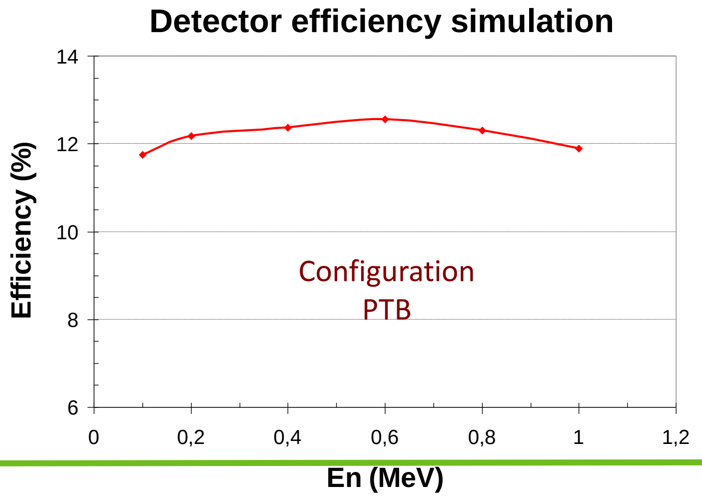
- efficiency ε > 20% (sample in centre)
- constant efficiency between 0.1 and 1 MeV
- not sensitive to gamma
- Cylinder of CH_2 (Φ_{int}=6 cm, $\Phi_{ext=}$16 cm, L=37cm)
- 12 tubes ^{3}He
- Also used for photofission studies



Efficiency :

- MCNPX simulations
- Measurements with Cf-252 sources

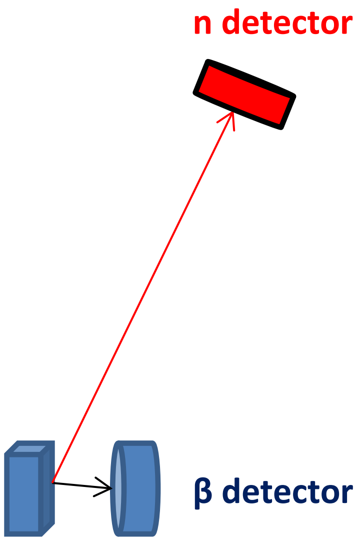
During this experiment the sample was not placed in the centre of the detector → Efficiency decreases →



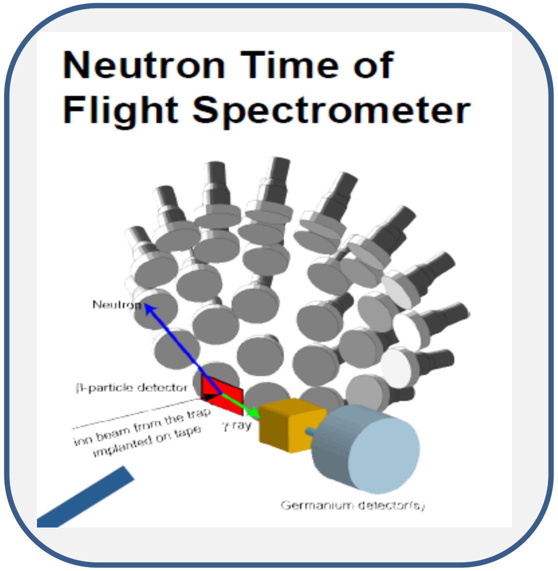
OUTLINE

Microscopic measurement

The β and the neutron are measured in coincidence



- Beta detection: thin target or implantation on Si detector
- Precursor identification :
  - Spectrometry
  - Mass spectrometer
- Neutron detector : Low energy threshold
  - Large to ensure En measurement
  - Possibility of β,2n measurement
- Time stamping

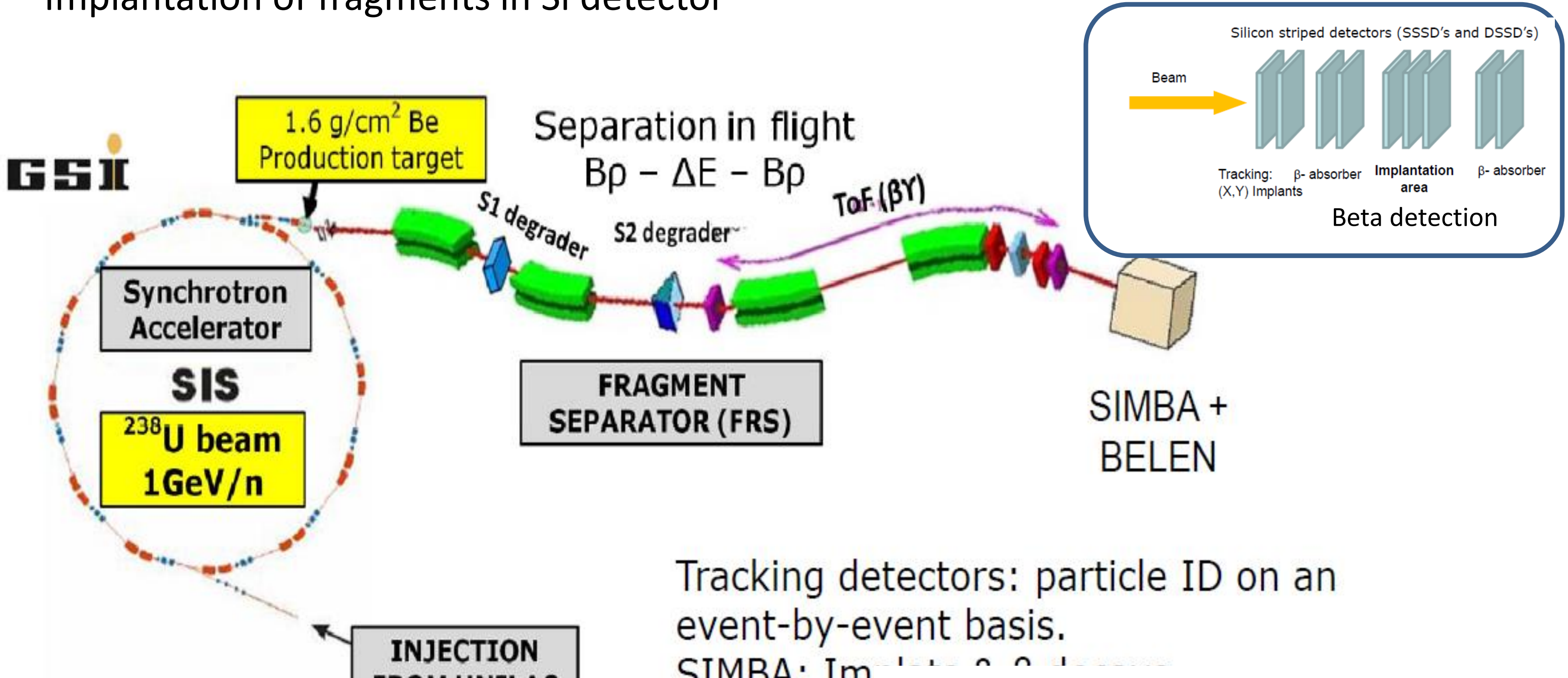

Neutron Time of Flight Spectrometer


4π Neutron Counter

Example : experiment at GSI

U238 fragmentation on Be target -> production of large number of nuclei

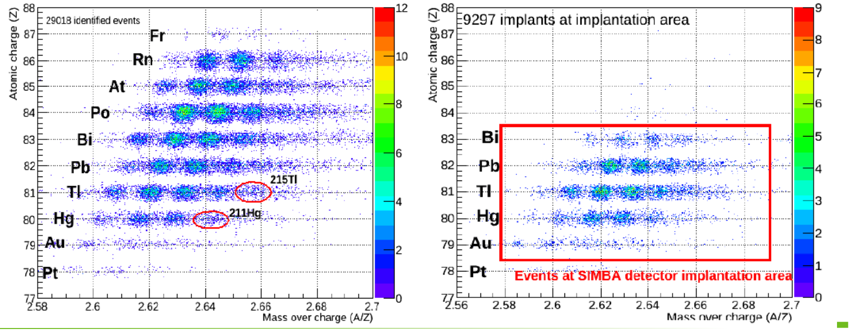
Implantation of fragments in Si detector



Tracking detectors: particle ID on an event-by-event basis.

SIMBA: Im

BELEN: Ne



ROGER CABALLERO-FOLCH (DFEN –UPC)
& S410 experiment collaboration
Barcelona, 14 de juny de 2013

Time-of-Flight technique

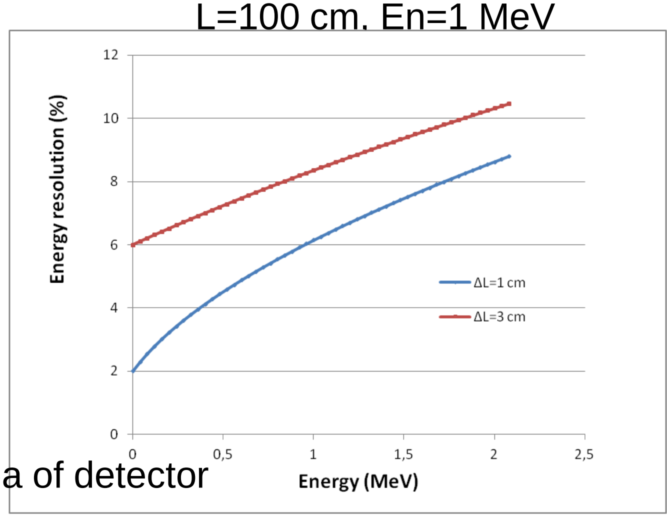
The measurement of the time between the beta and the neutrons allows to determine En

$$E_n = \frac{1}{2} m v^2 = \frac{1}{2} m \left(\frac{L}{t}\right)^2$$

$$\frac{\Delta E_n}{E_n} = 2\sqrt{\left(\frac{\Delta L}{L}\right)^2 + \left(\frac{\Delta t}{t}\right)^2}$$

L : flight path (cm)
t : time of flight
ΔL : flight path resolution
Δt : time resolution

Example :
L=100 cm, En=1 MeV



Optimization of the energy resolution :

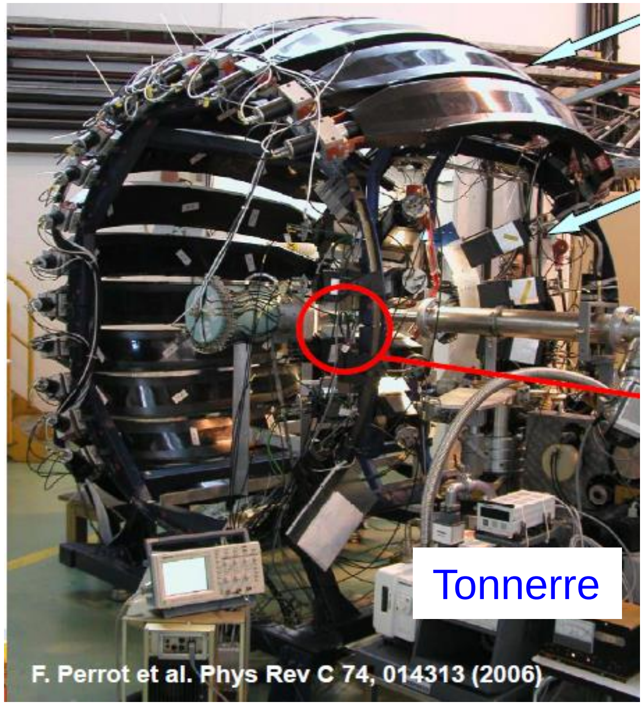
- short Δt: fast detectors (β and neutrons) ≈ ns
- small ΔL: thin detector -> reduced efficiency
- large L: small solid angle -> need to increase number or area of detector

- Drawback: Evaluation of Cross-talk between several detectors
- Advantage: Possibility of efficiency correction ε=f(E)
- Neutron detector not sensitive to photons or (n, γ) discrimination capability

→ Liquid scintillator or plastic scintillator

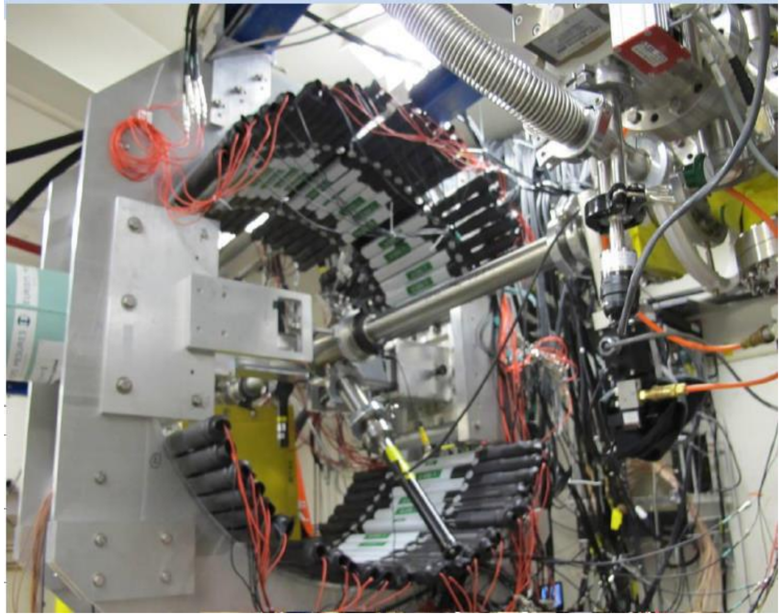
Detector with plastic scintillator

- Detectors with a large number of plastic scintillator bars equipped with 2 Phototubes
- Neutron localization by the ratio of the PM signals
- Energy measurement by TOF



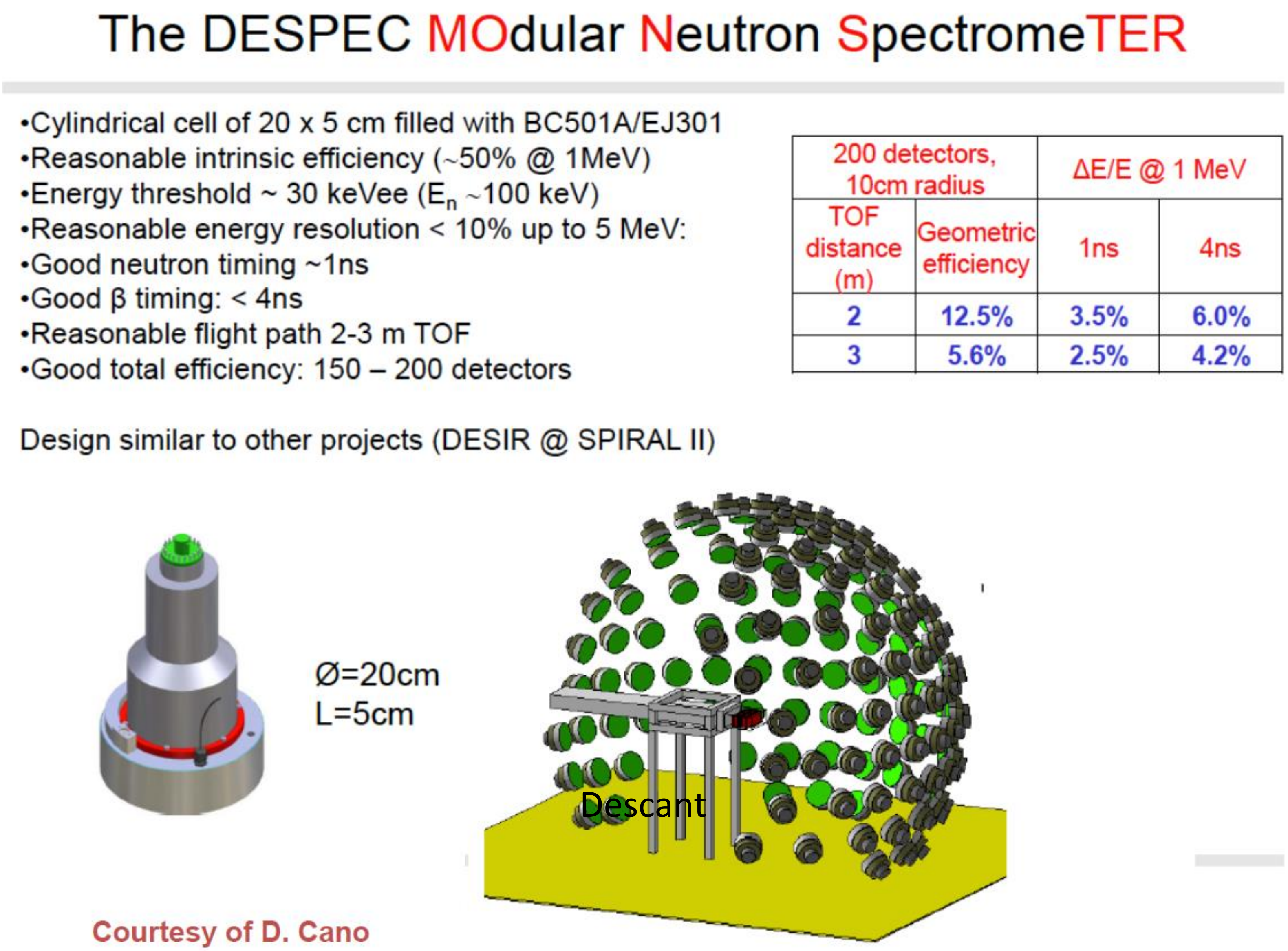
A. Buta et al., NIMA455, p412 (2000)
32 BC400 plastic scintillator
50% of 4π
E=30% at 2MeV, $\delta E/E$=10%

VANDLE
Versatile Array of Neutron Detectors at Low Energy



Proceeding on 10th symposium on Nuclei in cosmos, 2008, Mackinac Island, Michigan, USA, Proceeding of Science

Spectrometer with multiple cells



The DESPEC MOdular Neutron SpectrometeTER

- Cylindrical cell of 20 x 5 cm filled with BC501A/EJ301
- Reasonable intrinsic efficiency (~50% @ 1MeV)
- Energy threshold ~ 30 keVee (E_n ~100 keV)
- Reasonable energy resolution < 10% up to 5 MeV:
- Good neutron timing ~1ns
- Good β timing: < 4ns
- Reasonable flight path 2-3 m TOF
- Good total efficiency: 150 – 200 detectors

200 detectors, 10cm radius		ΔE/E @ 1 MeV	
TOF distance (m)	Geometric efficiency	1ns	4ns
2	12.5%	3.5%	6.0%
3	5.6%	2.5%	4.2%

Design similar to other projects (DESIR @ SPIRAL II)

Ø=20cm
L=5cm

Descant

Courtesy of D. Cano

OUTLINE

1. Definition and characteristics
   1. Yield
   2. Time distribution
2. Applications :
   1. Active interrogation techniques
   2. Reactor
3. Measurement
   1. Neutrons detectors for DN
   2. Microscopic measurements
      1. Techniques
      2. Examples of experiments
   3. Macroscopic measurements
      1. ν_d measurement
      2. Time distribution measurement
4. Examples of experiments

Macroscopic measurements

The beta and neutron are not detected in coincidence

❑What is needed :

❑ The fission rate:

- Calculated from
  - sample characteristics (mass and purity are requested)
  - flux and energy distribution (monitoring)
- Measured (detector based on fission of the same actinide)

❑ A beam time cut-off quite fast (with respect to the shorter half life group)

❑ Neutron detector(s)

- High efficiency
- Not sensitive to photons
- Efficiency independent of neutrons energy

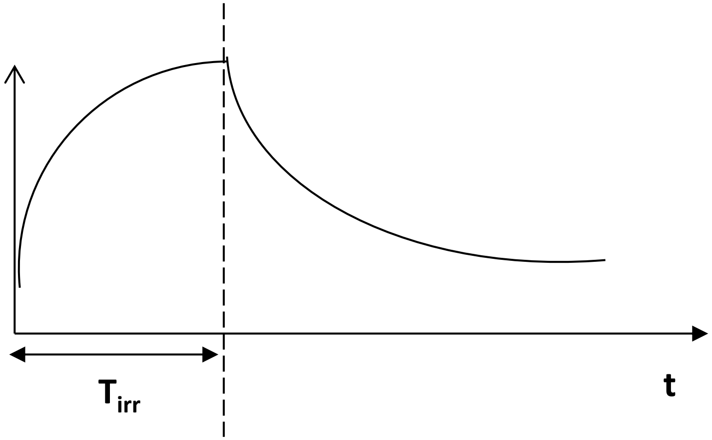
4π neutrons detector

ν_d measurement

A sample of masse m is irradiated by a flux φ of neutrons or photons

The fission rate:
$$R\left(s^{-1}\right)=\frac{m}{A}N_{av}\int_E \Phi(E)\sigma(E)dE$$

σ(E) fission cross-section
A atomic number of the actinide,
a_i nb of DN yield of group i



The delayed neutrons rate of group i

- Emitted during the irradiation: $Y_{n,i}(t)=R\,a_i\left(1-e^{-\lambda_i t}\right)$
- During the decay after an irradiation time T_{irr}: $Y_{n,i}(t)=R\,a_i\left(1-e^{-\lambda_i T_{irr}}\right)e^{-\lambda_i (t-T_{irr})}$
- For all the groups : $Y_n(t)=\sum_i R\,a_i\left(1-e^{-\lambda_i T_{irr}}\right)e^{-\lambda_i (t-T_{irr})}$

ν_d measurement strategy ($T_{irr} >> T_i$)

F_n number of detected neutrons with efficiency ε

$$Y_n(t) = \frac{F_n(t)}{\varepsilon}$$

If $T_{irr} >> T_i$, all the precursors are at equilibrium (infinite irradiation)

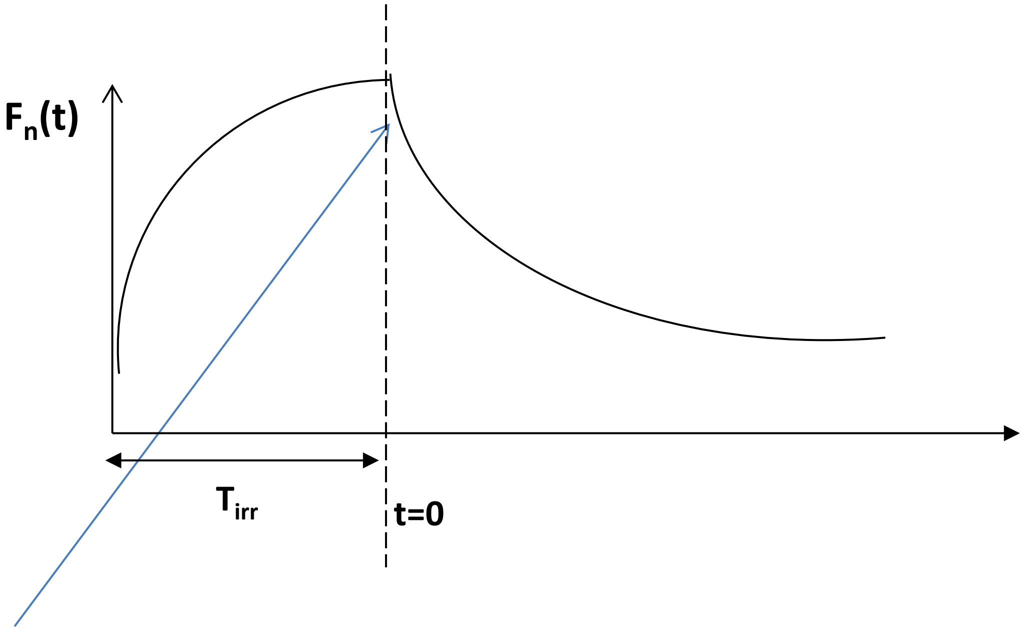
$$1 - e^{-\lambda_i T_{irr}} = 1$$

$$Y_{n,i}(t) = R\,a_i\left(1 - e^{-\lambda_i T_{irr}}\right)e^{-\lambda_i t} \Longrightarrow Y_n(t) = \sum_i R\,a_i\,e^{-\lambda_i t}$$

$$Y_n(0) = R\sum_i a_i$$

$$\sum_i a_i = \frac{Y_n(t=0)}{R}$$

$$\sum_i a_i = \frac{F_n(t=0)}{\varepsilon\,R}$$



We must measure : $F_n(t=0)$

ν_d measurement strategy ($T_{irr} << T_i$)

F_n number of detected neutrons with efficiency ε

$$Y_n(t) = \frac{F_n(t)}{\varepsilon}$$

If $T_{irr} << T_i$ (prompt burst irradiation)

$$e^{-\lambda_i T_{irr}} = 1 - \lambda_i T_{irr}$$

$$Y_{n,i}(t) = R\, a_i \left(1 - e^{-\lambda_i T_{irr}}\right) e^{-\lambda_i t} \Longrightarrow Y_n(t) = R \sum_i a_i\, \lambda_i T_{irr} e^{-\lambda_i t}$$

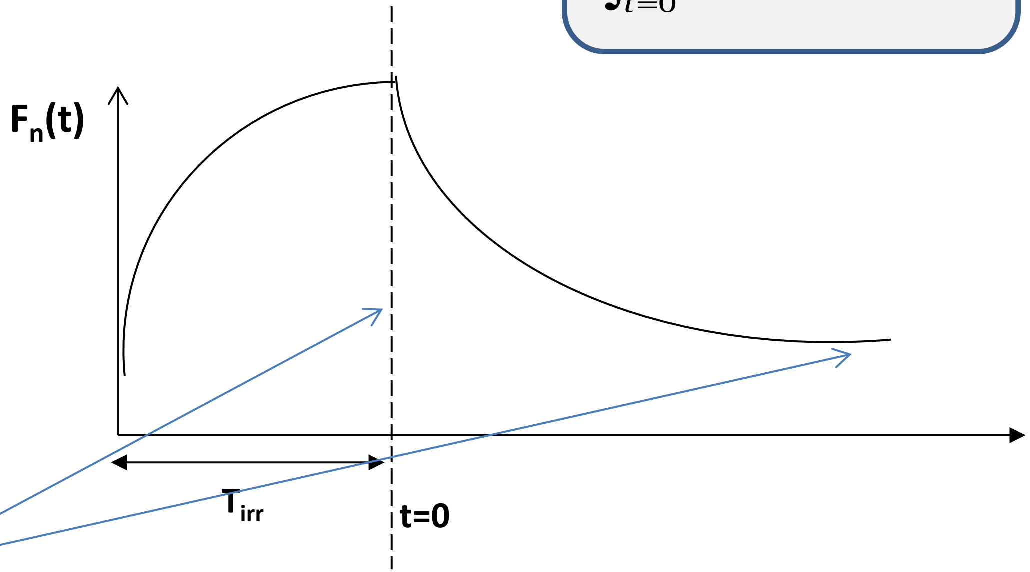
$$\int_{t=0}^{t=\infty} Y_n(t)\,dt = R\, T_{irr} \sum_i a_i \int_{t=0}^{t=\infty} \lambda_i e^{-\lambda_i t} dt$$

$$N_{fission} = R\, T_{irr}$$

$$\int_{t=0}^{t=\infty} \lambda_i e^{-\lambda_i t} dt = 1$$

$$\int_{t=0}^{t=\infty} Y_n(t)\,dt = N_{fissions} \sum_i a_i$$

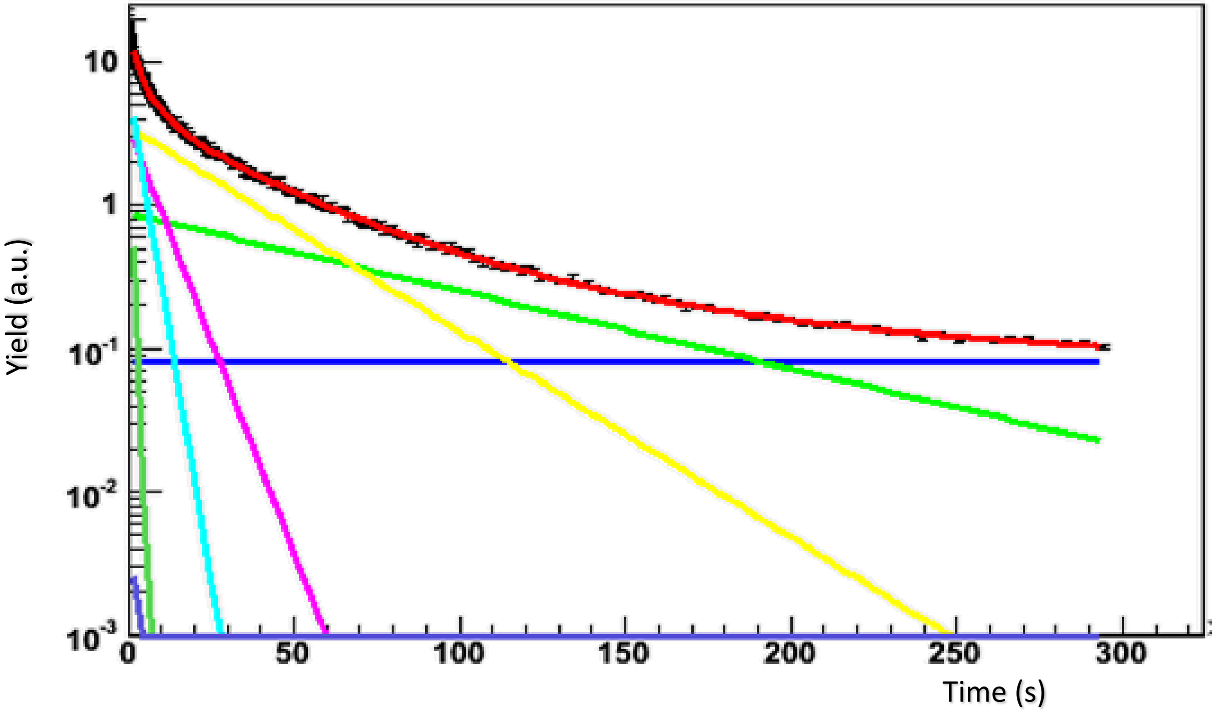
$$\sum_i a_i = \frac{F_n}{N_{fissions}\,\varepsilon}$$



We must measure the integral of that

DN time distribution

$$Y_d(t) = \sum_{i=1,6} a_i \, e^{-\lambda_i t}\left(1 - e^{-\lambda_i T_{irr}}\right) \qquad \nu_d = \sum_i a_i$$



Half-lives
G1 ~55 s
G2 ~20 s
G3 ~5 s
G4 ~2 s
G5 ~0.5 s
G6 ~0.2 s

- The irradiation – detection times must be adapted to the half life of the group to be measured
    - Short irradiation < 1 s for groups 5 and 6
    - Medium 10 s for groups 4 and 3
    - Long irradiation for groups 1and 2

Strategy for group parameters determination

$$Y_{dn}(t) = \sum_{i=1,6} a_i \exp(-\lambda_i t)(1-\exp(-\lambda_i T_{irr}))$$

Three types of irradiation

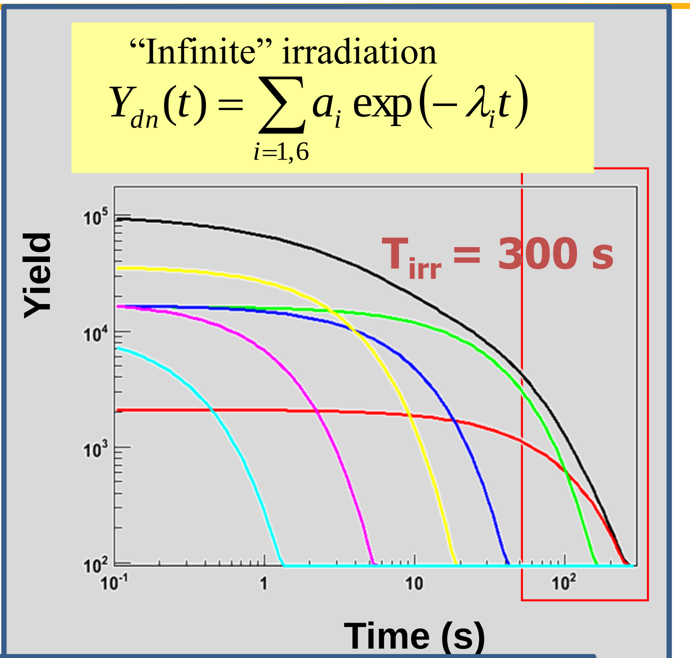
100 μs – 40 s

10 s – 100 s

300 s – 300 s

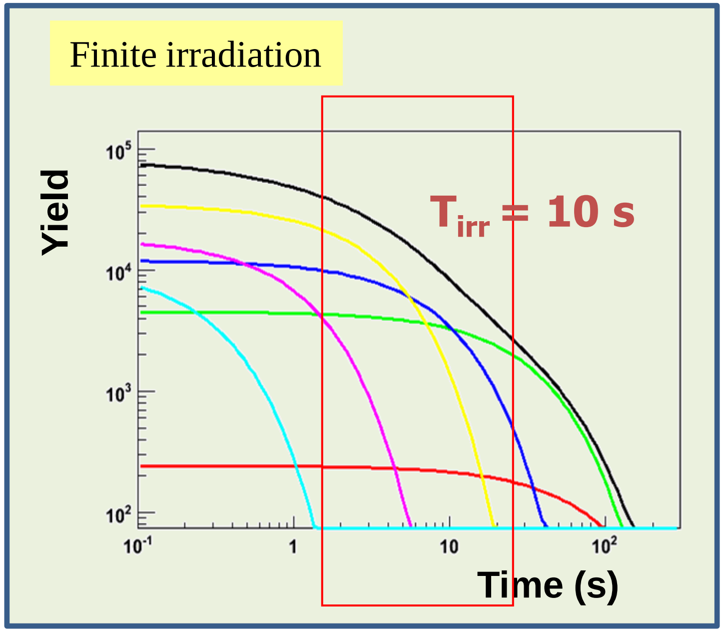
Half-lives

G1 ~55 s
G2 ~20 s
G3 ~5 s
G4 ~2 s
G5 ~0.5 s
G6 ~0.2 s

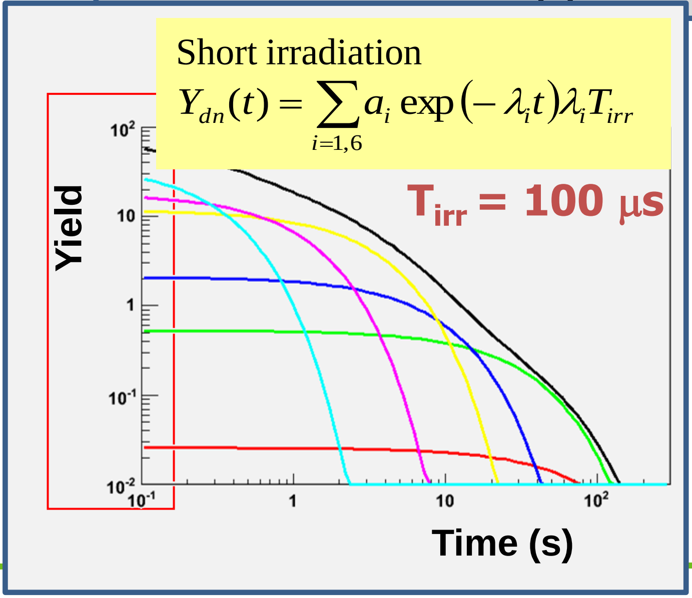


“Infinite” irradiation

$$Y_{dn}(t) = \sum_{i=1,6} a_i \exp(-\lambda_i t)$$



Finite irradiation



Short irradiation

$$Y_{dn}(t) = \sum_{i=1,6} a_i \exp(-\lambda_i t)\lambda_i T_{irr}$$

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        II. Time distribution measurement
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Study of multi-neutron emission in the β-decay of ^{11}Li

Lynda Achouri
LPC Caen

for the
IS525 Collaboration

XIXth COLLOQUE GANIL, October 12th-16th, Anglet

Experimental set up @ ISOLDE

39 liquid scintillator modules

- 20 or 15 cm in diam., 5 cm thick

- MONSTER

(Martinez and al., Nuclear Data Sheets 120 (2014) 78–80)

- EDEN

- CEA cells

- ≈40 % intrinsic efficiency
- n-γ discrimination

Near array: d = 1.5 m

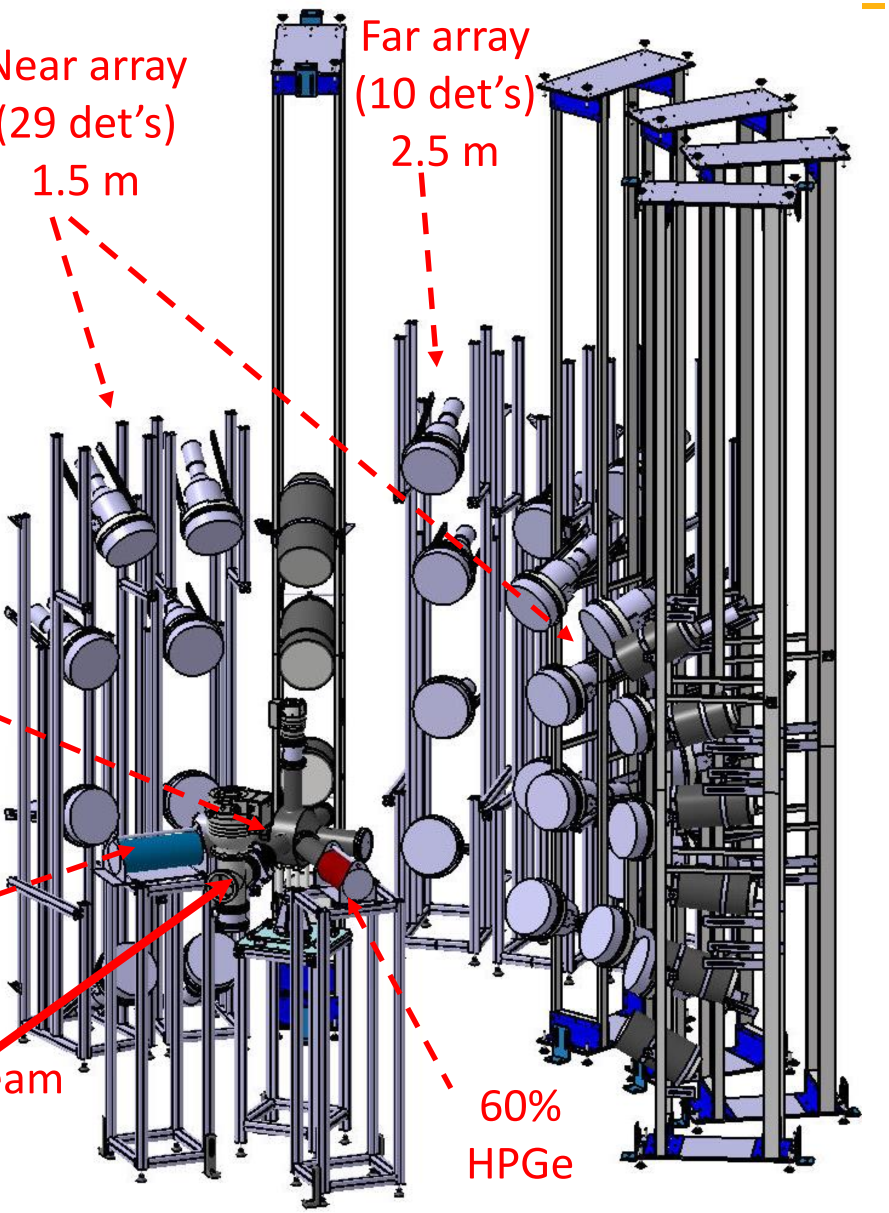
- δE = 60 keV at 1 MeV
- Ω = 3 % of 4π

⇒ n-n coincidences

Far array: d = 2.5 m

- δE = 35 keV at 1 MeV
- Ω = 0.3 % of 4π

⇒ Improved 1n data



Near array
(29 det's)
1.5 m

Far array
(10 det's)
2.5 m

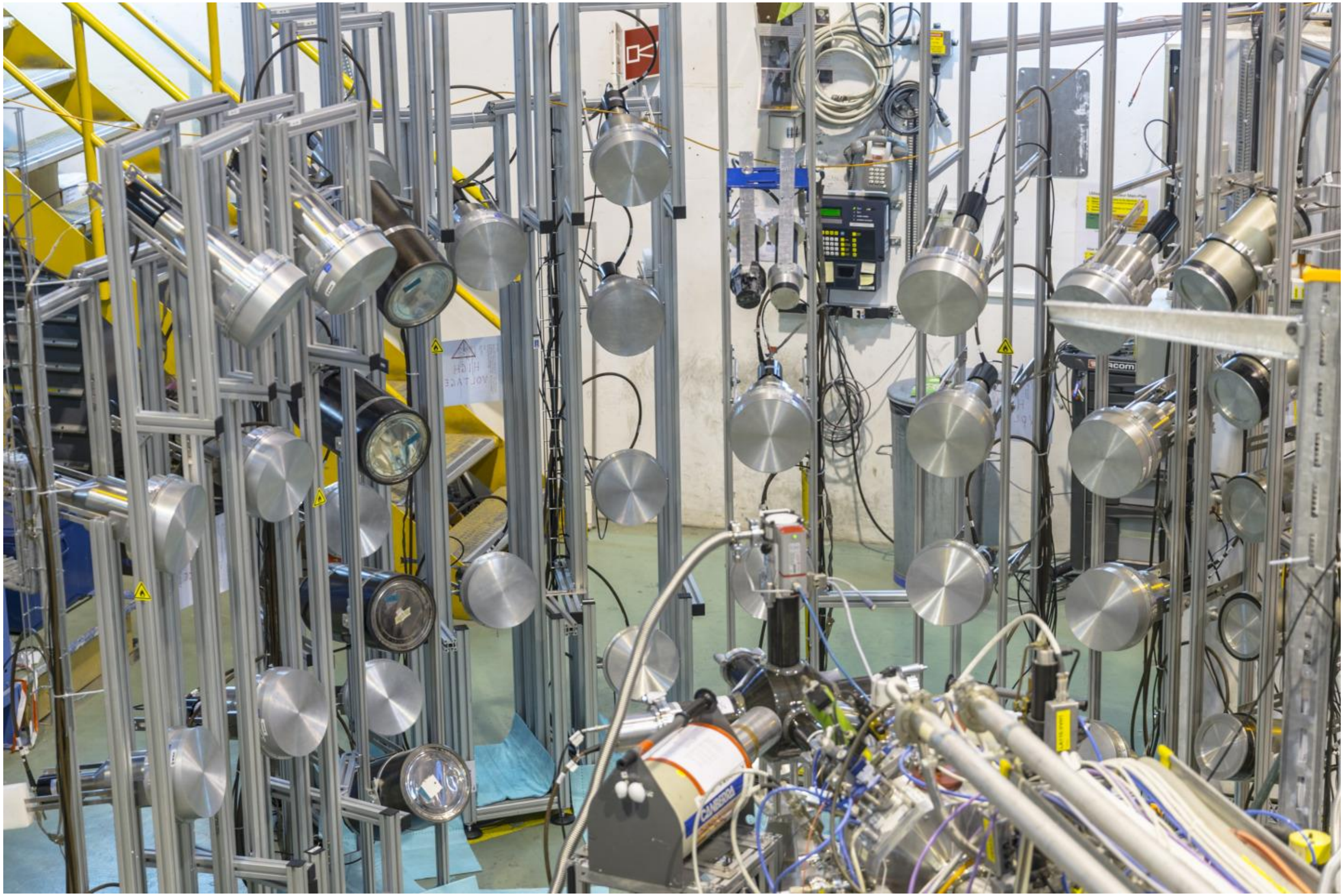
Al foil
Plastic scint.
⇒ β rays
⇒ TOF start

70%
HPGe

^{11}Li beam

60%
HPGe

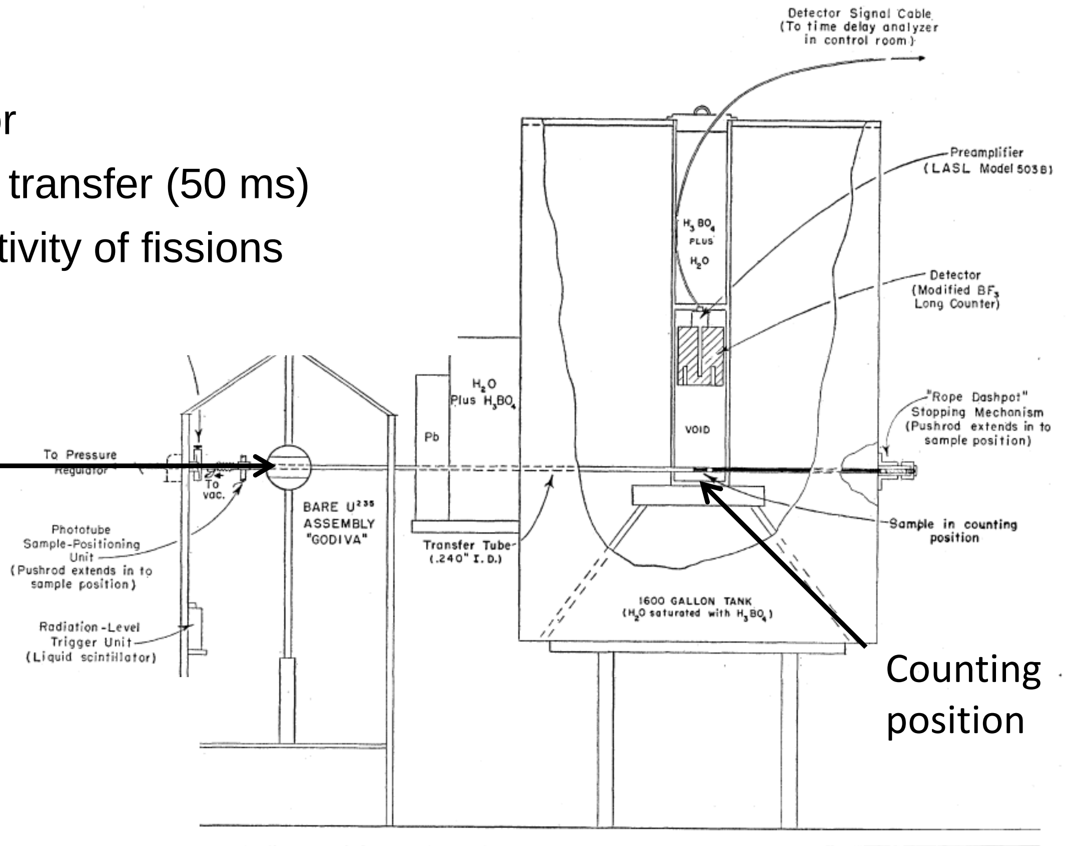
Experimental set up @ ISOLDE



DN of ^{235}U and ^{239}Pu in n induced fission

Reactor **GODIVA**, Los Alamos, Instantaneous pulse 10^{16} fissions

- Detection long counter BF_3
- Sample (2-5g) irradiation inside a reactor
- Sample move to detector by pneumatic transfer (50 ms)
- Number of fissions measured by the activity of fissions fragment (Mo99)



Irradiation position

Counting position

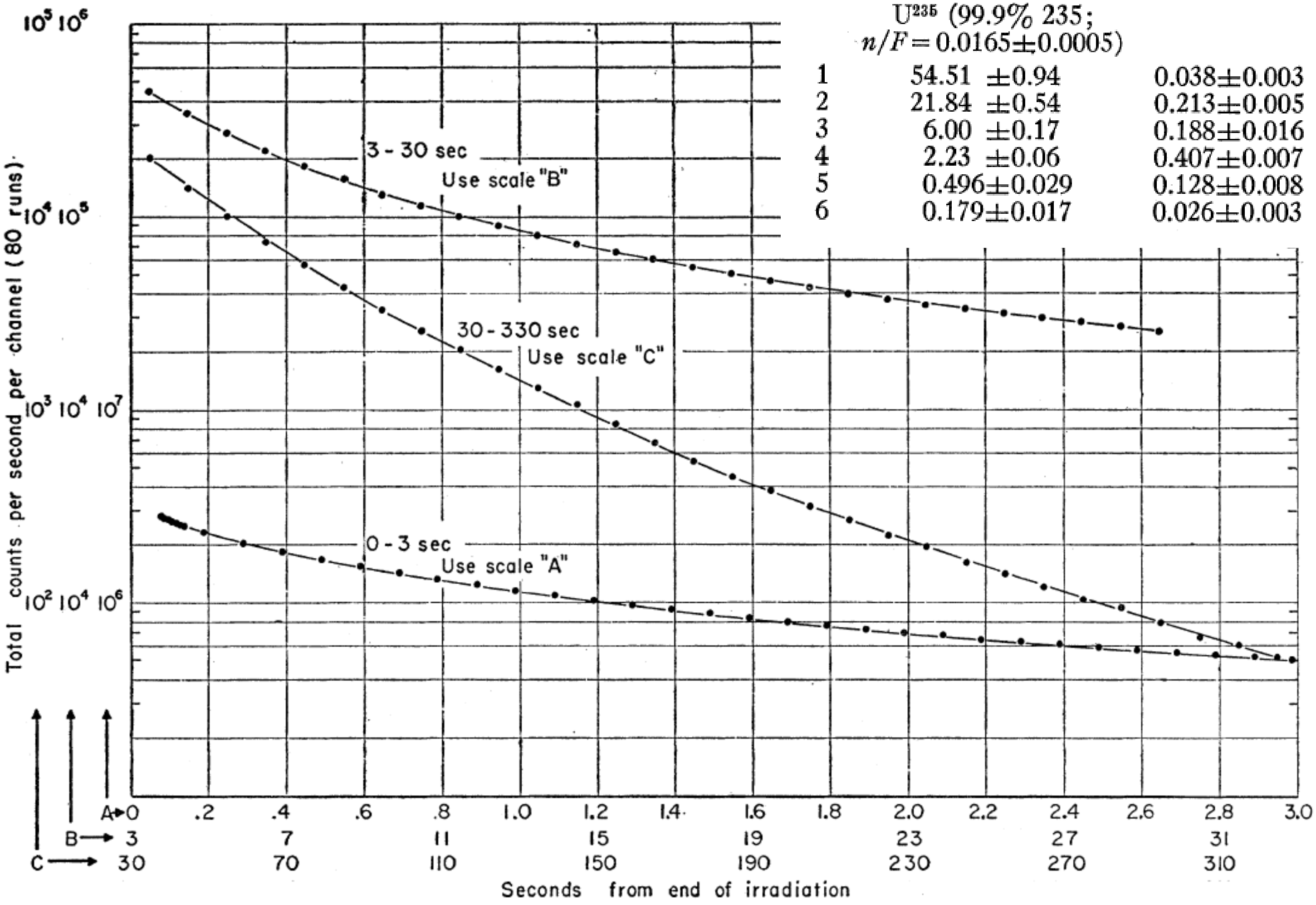
ematic diagram of the experimental arrangement for delayed-neutron studies at Los Alamos.

- **Advantage :**
  - high flux -> small sample
- **Drawback :**
  - no short time cut
  - detection set-up should be placed far away
  - only thermal or fast neutron

G. Keepin et al., PRC 107, num 4 (1957)

Keepin's results

Group index i	Half-life, T_i	Relative abundance, a_i/a	Absolute group yield (%) (for pure isotope)
U^{235} (99.9% 235; $n/F = 0.0165 \pm 0.0005$)			
1	54.51 ±0.94	0.038±0.003	0.063±0.005
2	21.84 ±0.54	0.213±0.005	0.351±0.011
3	6.00 ±0.17	0.188±0.016	0.310±0.028
4	2.23 ±0.06	0.407±0.007	0.672±0.023
5	0.496±0.029	0.128±0.008	0.211±0.015
6	0.179±0.017	0.026±0.003	0.043±0.005

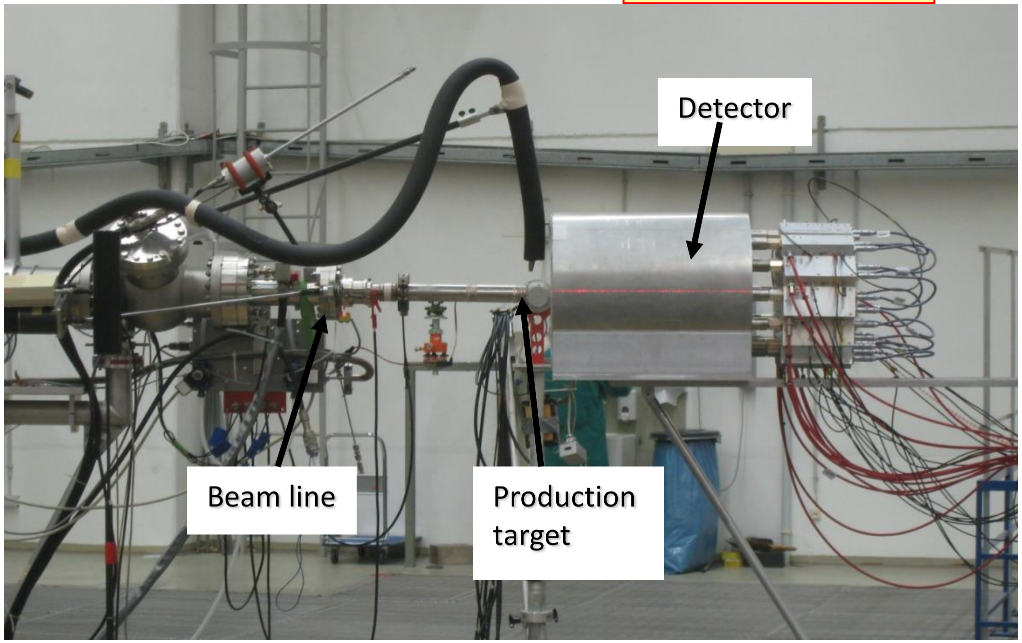


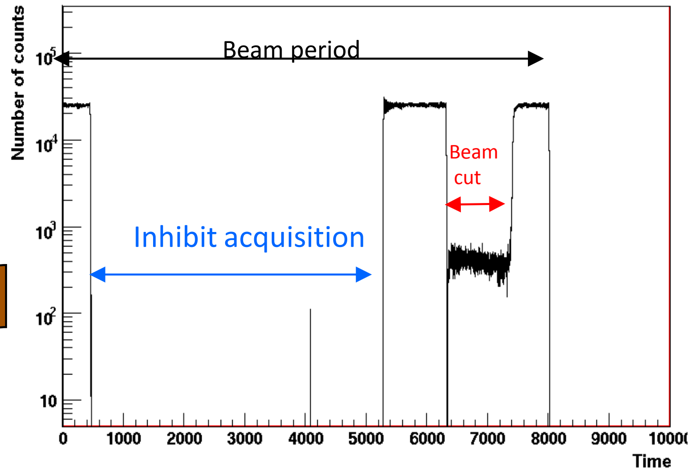
DN yield measurement on ^{232}Th(n,f)

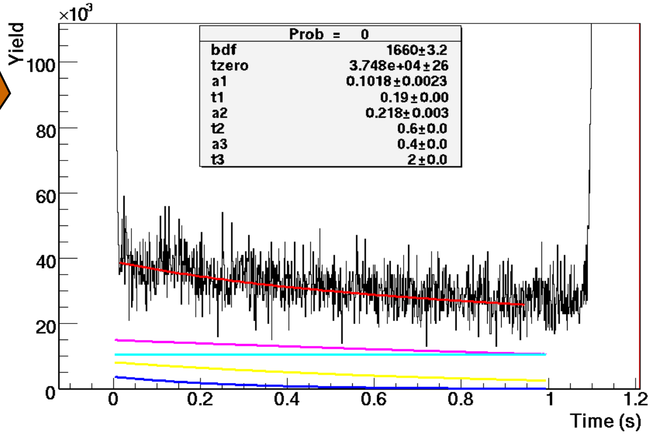
Goal : measurement of DN yield in neutrons induced fission on Th 232 between 1 and 16 MeV

- Facility : PIAF (PTB)
- Detector : 4π ^{3}He + CH_2
- Technique : pulsed beam 7s beam-1 s off
- Measurement of Y(t=0)
- $N_{fissions}$: flux measurement + MCNPX

$$\upsilon_d = \frac{F_{\mathrm{det}}(0)}{N_{fissions}\,\varepsilon}$$







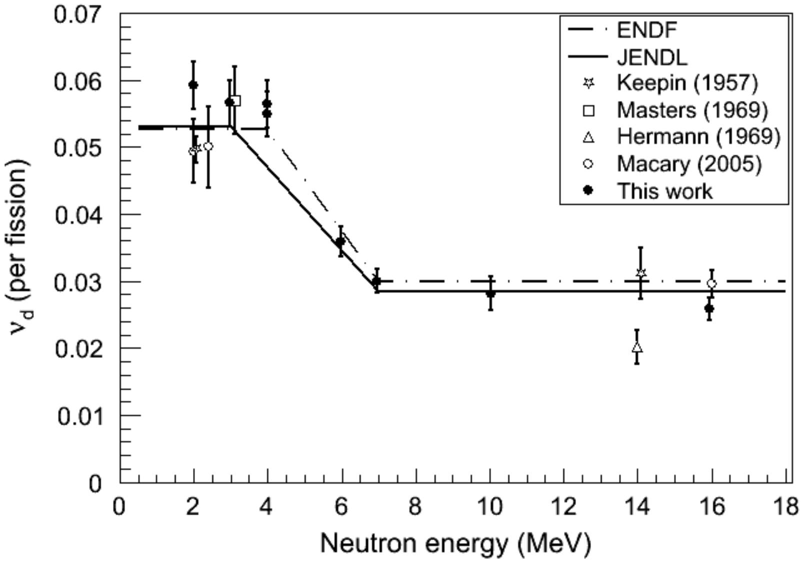
DN yield measurement on ^{232}Th(n,f)

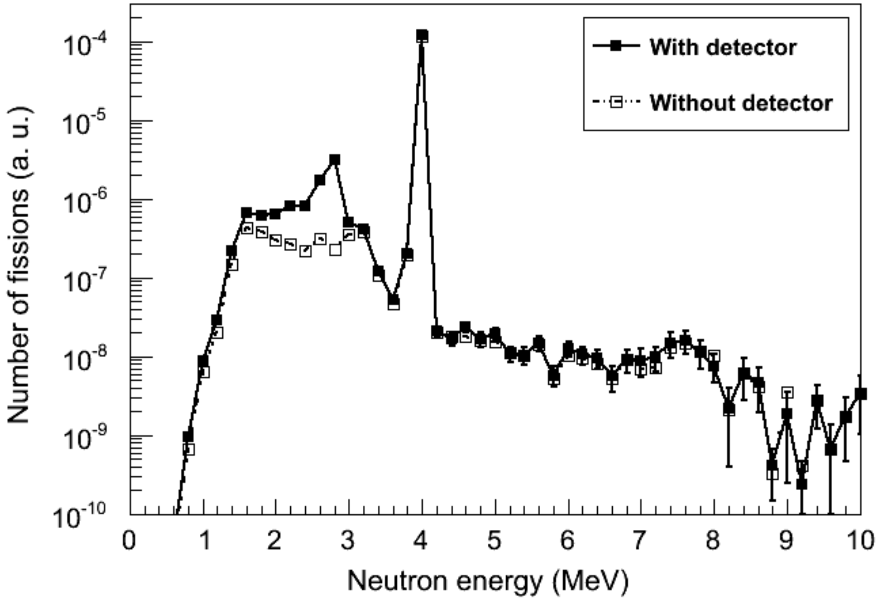
Corrections to be performed :

- Open source : some neutrons deflected by the detector can induce fission
- Thick target : fission induced by secondary fission
- Not infinite irradiation time

$$DN = \upsilon_d^{mono}\, N_{fiss}^{mono} + \upsilon_d^{up}\, N_{fiss}^{up} + \upsilon_d^{dowm}\, N_{fiss}^{down}$$

$$\boxed{\upsilon_d^{mono} = \frac{DN - (\upsilon_d^{up}\, N_{fiss}^{up} + \upsilon_d^{dowm}\, N_{fiss}^{down})}{N_{fiss}^{mono}}}$$



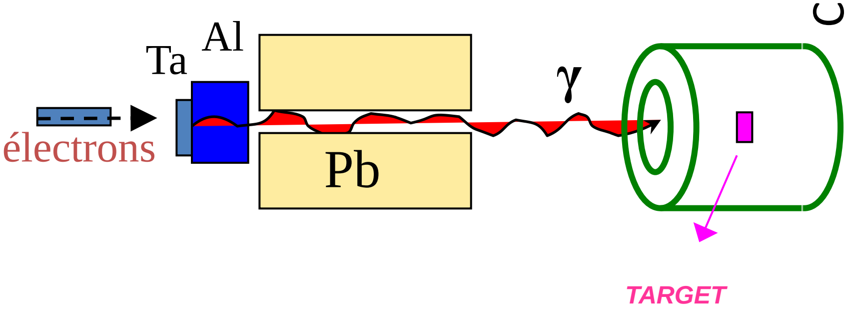


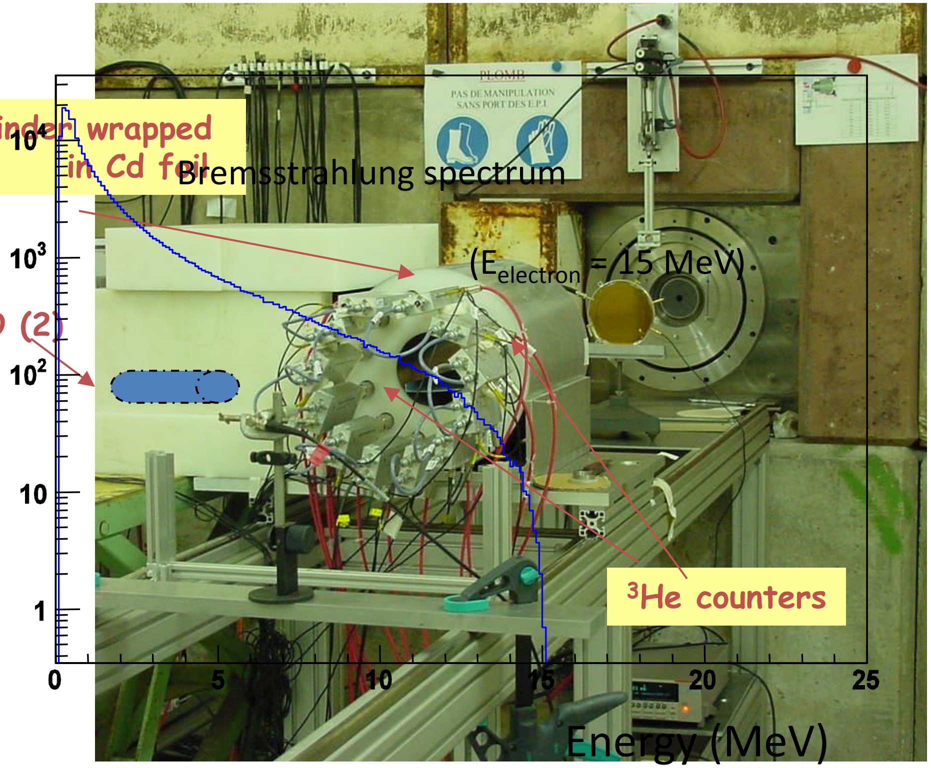
X. Ledoux et al., Annals of Nuclear Energy 76 (2015) 514–520

DN measurements in fission induced by photons

ELSA (CEA-DIF,
Bruyères-le-Châtel)

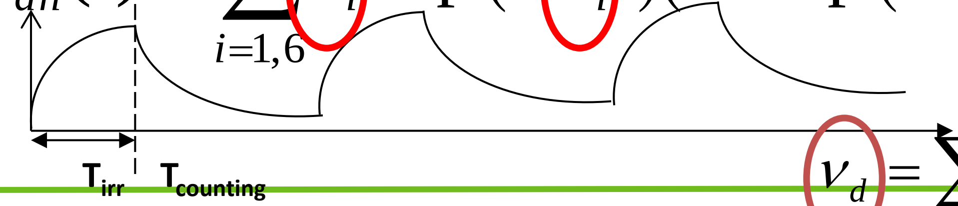
Ee- ≤ 19 MeV
Imax= 10 μA
Freq = 1-10 Hz



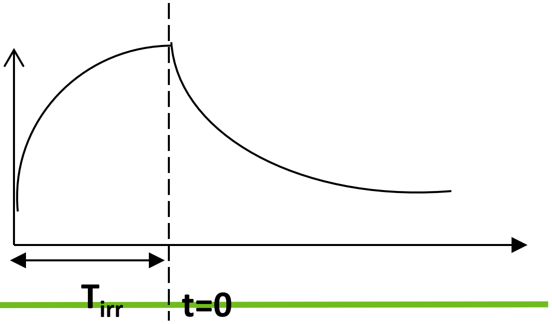


Repetetive cycles of irradiation and counting

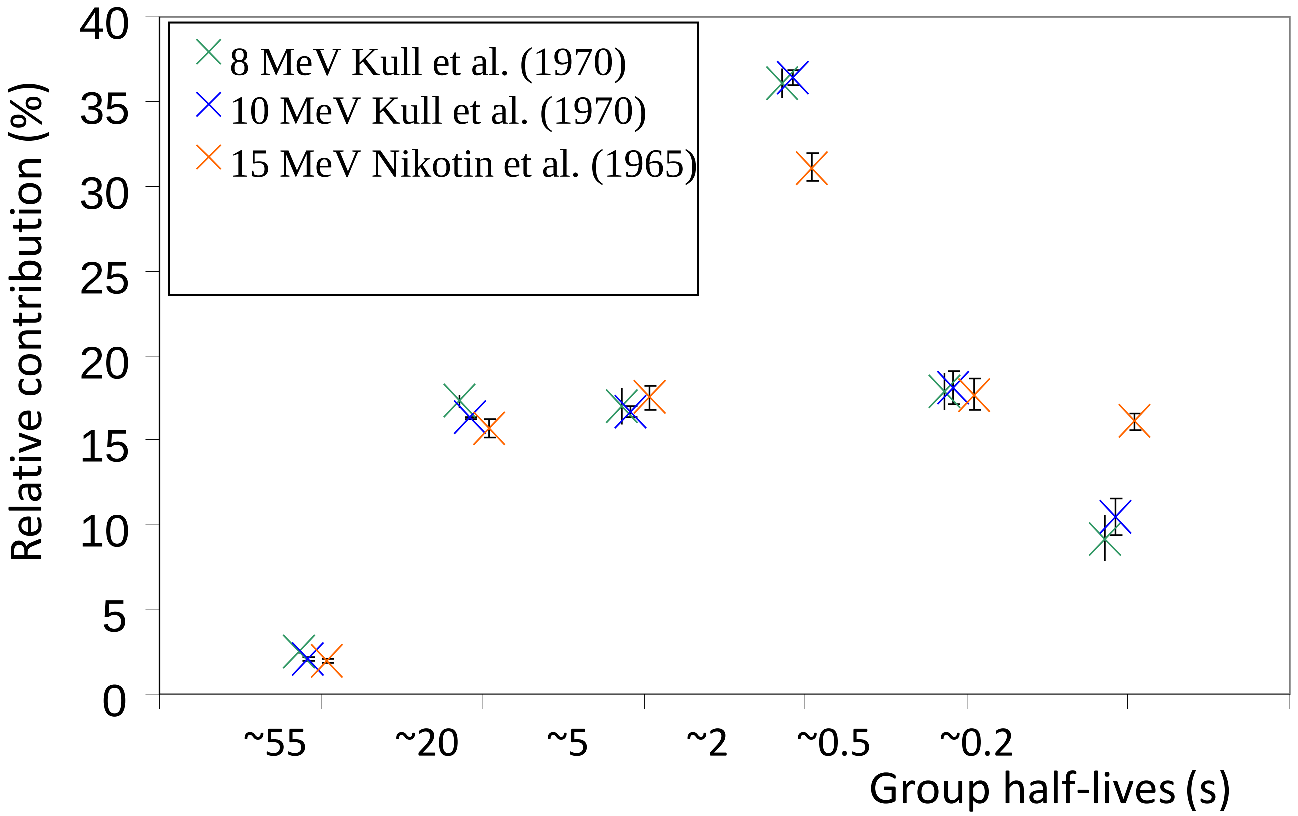
$$Y_{dn}(t)=\sum_{i=1,6} a_i \exp\left(-\lambda_i t\right)\left(1-\exp\left(-\lambda_i T_{irr}\right)\right)$$



$$\nu_d=\sum_i a_i$$



DN in photofission of ^{238}U



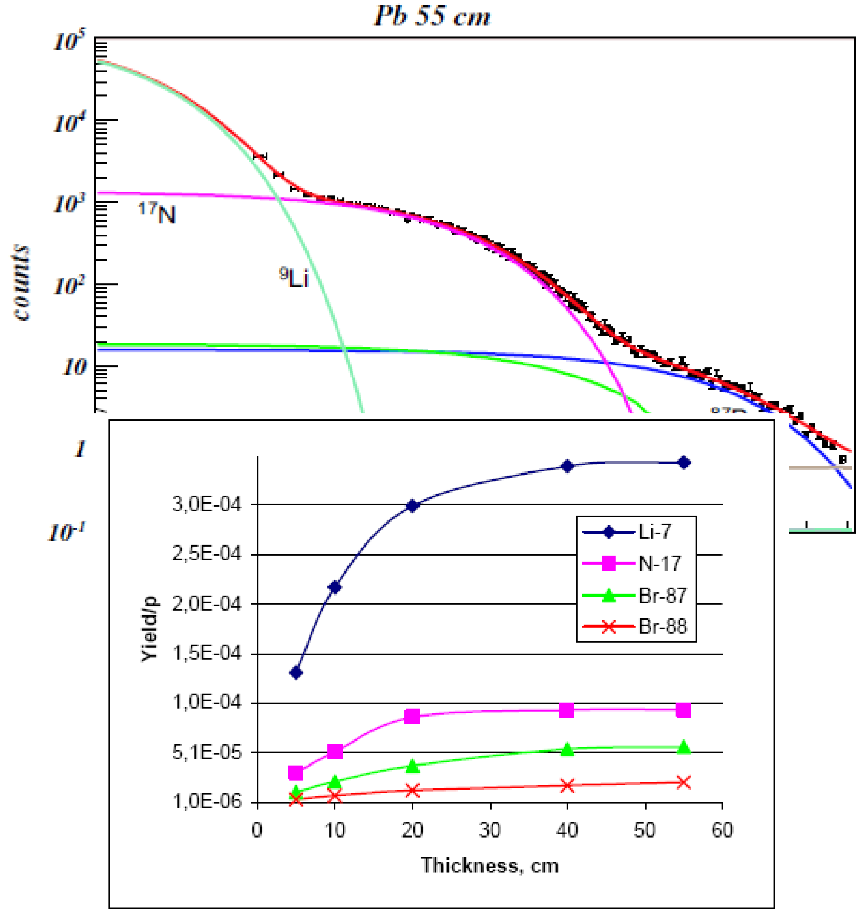
Differencies have been measured in comparison with data from Nikotin

Very important for applications : identification by activation technique

D. Doré et al., ND2007, ACCAPP 2007

Measurement of DN in spallation reaction

- 1 GeV p + thick lead target
- Detection of neutrons yield and time distribution
- Measurement of cross-section production of ^{87}Br, ^{88}Br, ^{9}Li and ^{17}N
- Comparison with spallation codes



Experiment performed at Gatchina

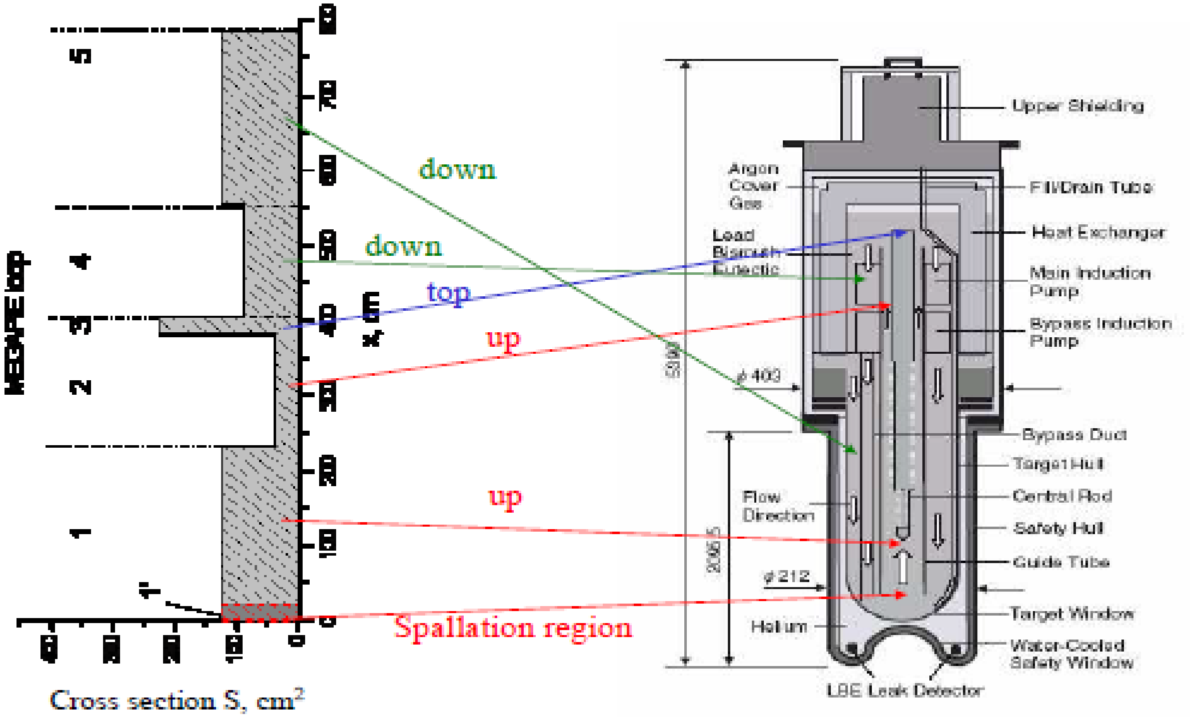
D. Ridikas et al., Eur. Phys. J. A32, 1-4,(2007)

DN yield in liquid target (1)

- MegaPie target (PSI)
- Production of neutrons by spallation reaction in thick target
- 1 MW liquid metal target

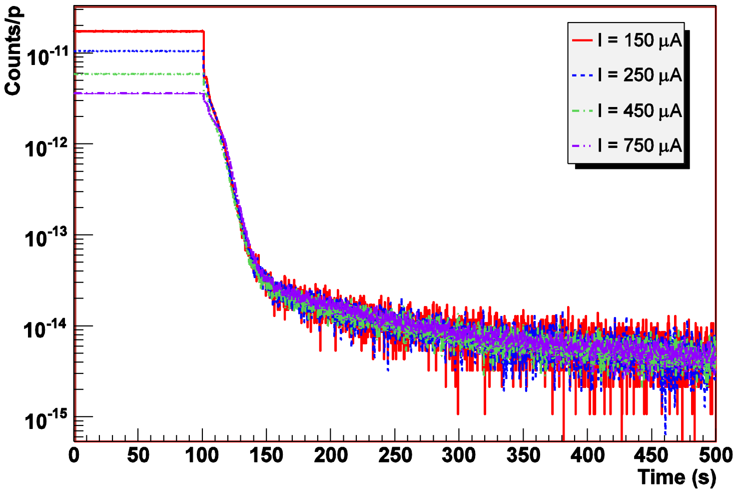
Loop of Pb-Bi liquid -> DN are emitted outside of the core of the target :

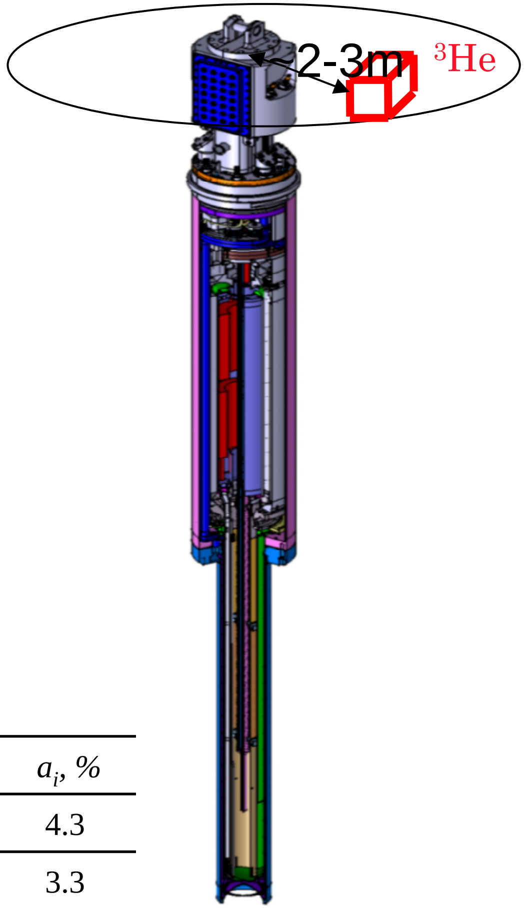
displacement of the neutrons dose in the facility

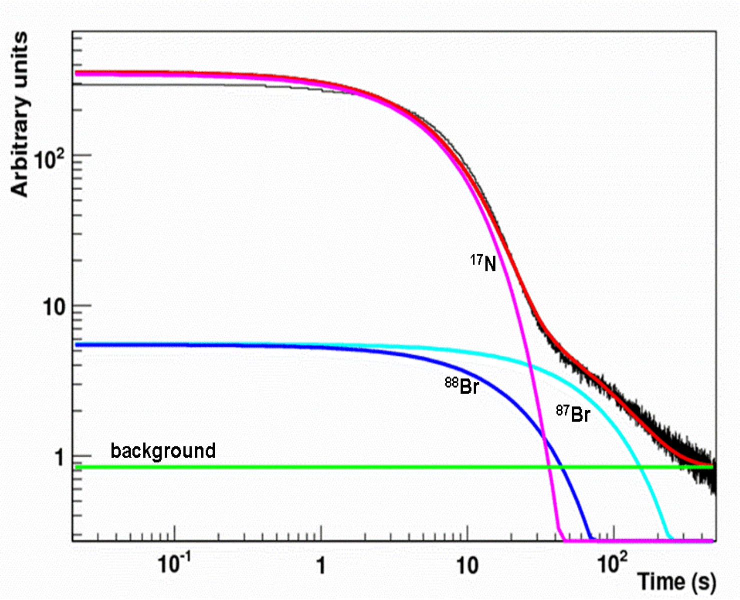


DN flux at the top of the target is of the same order than prompt neutrons

DN yield in liquid target (2)







Group	Precursor	Half-lif e(s)	a_i, %
1	^{87}Br	55.60	4.3
2	^{88}Br	16.29	3.3
3	^{17}N	4.173	92.4

S. Panebianco et al., ND2007, ACCAPP 2007

Summary

- ❑ Delayed neutrons play an important role in several topics
    - Control of fission reactors
    - Active interrogation
    - Astrophysics
    - Nuclear structure
- ❑ Microscopic measurements
    - Pn of an identified nuclei
    - Energy spectrum of the DN
- ❑ Macroscopic measurements
    - Delayed neutrons yield
    - Time distribution
    - Groups parameters