Measurement of (n,xn) reactions

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OUTLINE

Introduction

1. Applications
2. Facilities
3. Cross-section measurements
    1. Activation technique
    2. n,xnγ gamma
    3. Direct measurement of secondary neutrons
4. Double differential measurements
5. Examples of experiments

n,xn reactions

$$n \quad + \quad {}^{A}_{Z}X \quad \rightarrow \quad {}^{A-x+1}_{\quad Z}X \quad + \quad x\,n$$

- Production of an isotope
  - Same element (no chemical separation)
  - Can decay on other element (β decay….)

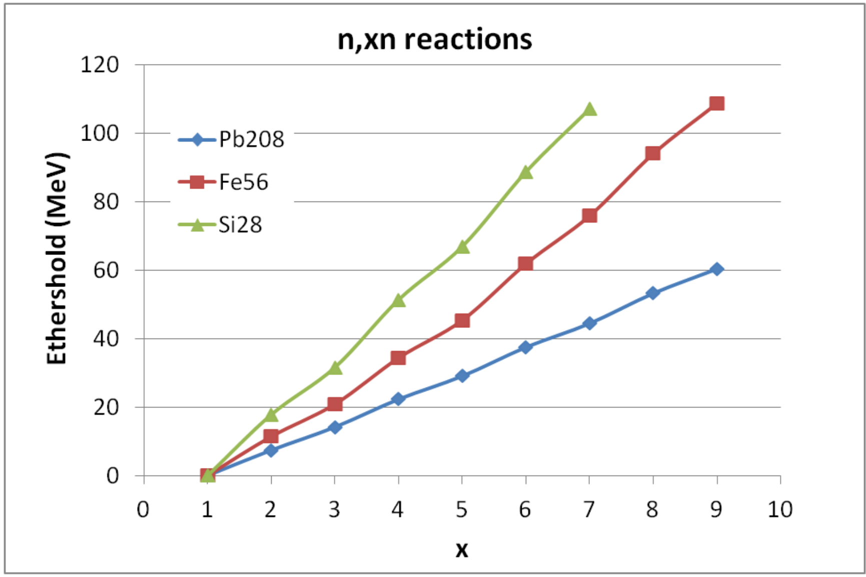
- Threshold
  - n,n'   the energy of the first excited level
  - n,xn depends on the Q-value

$$Q = {}^{A-x+1}_{\quad Z}M + x\,M_n - \left({}^{A}_{Z}M + M_n\right)$$

$$Q = \Delta(A-1,Z) + (x-1)\Delta n - \Delta(A,Z)$$

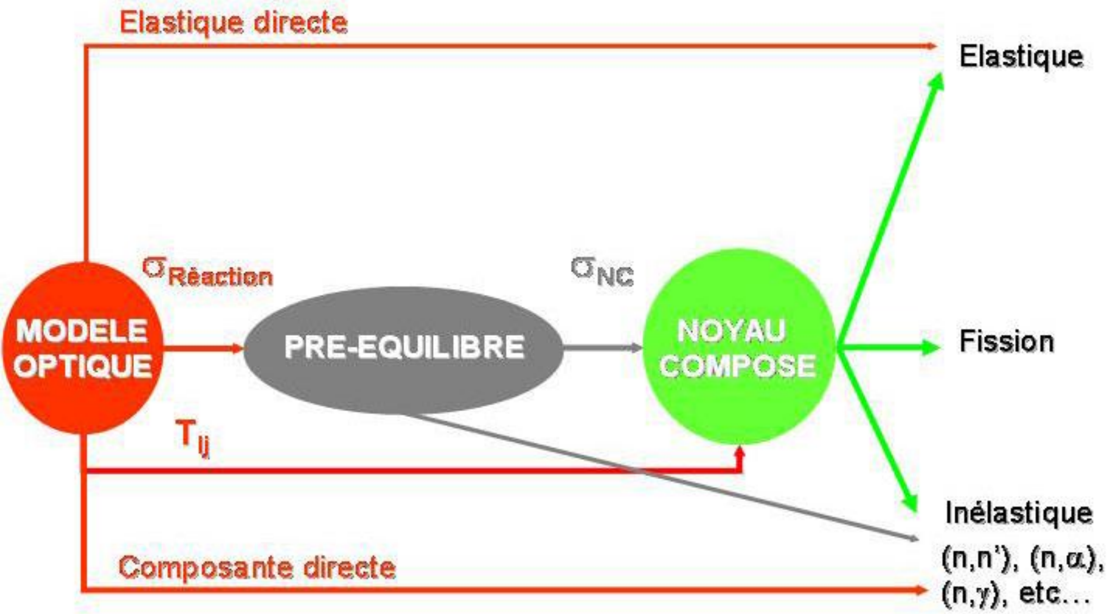
$$E_{th} = -Q\,\frac{M_n + M_X}{M_X} \cong -Q\,\frac{A+1}{A}$$

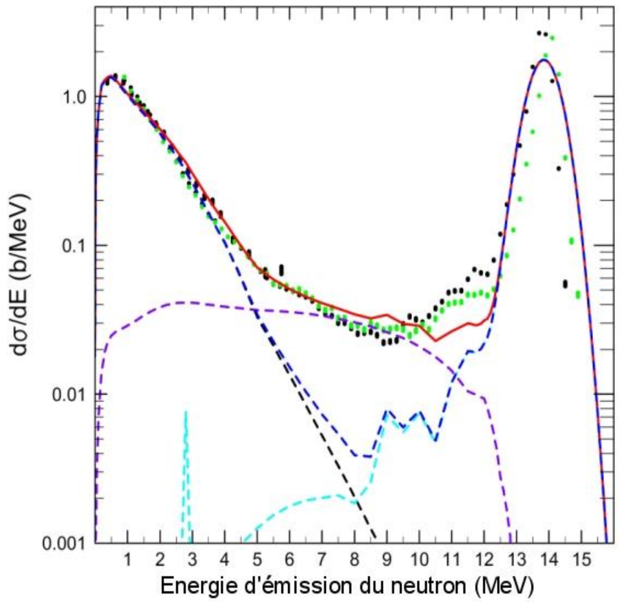
$\Delta(A,Z)$ The mass excess of nuclei A,Z

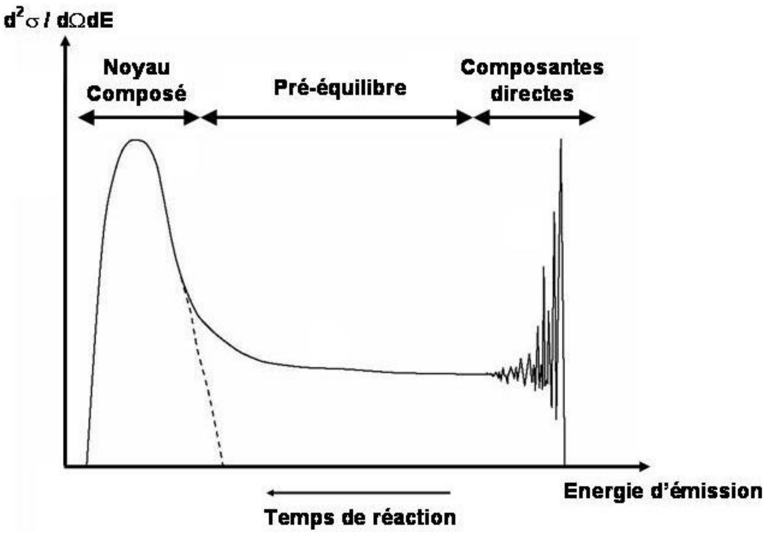


	Ethres	Q
$^{208}Pb(n,2n)^{207}Pb$	7,403	-7,367
$^{208}Pb(n,3n)^{206}Pb$	14,174	-14,105
$^{208}Pb(n,4n)^{208}Pb$	22,299	-22,192

Reaction process







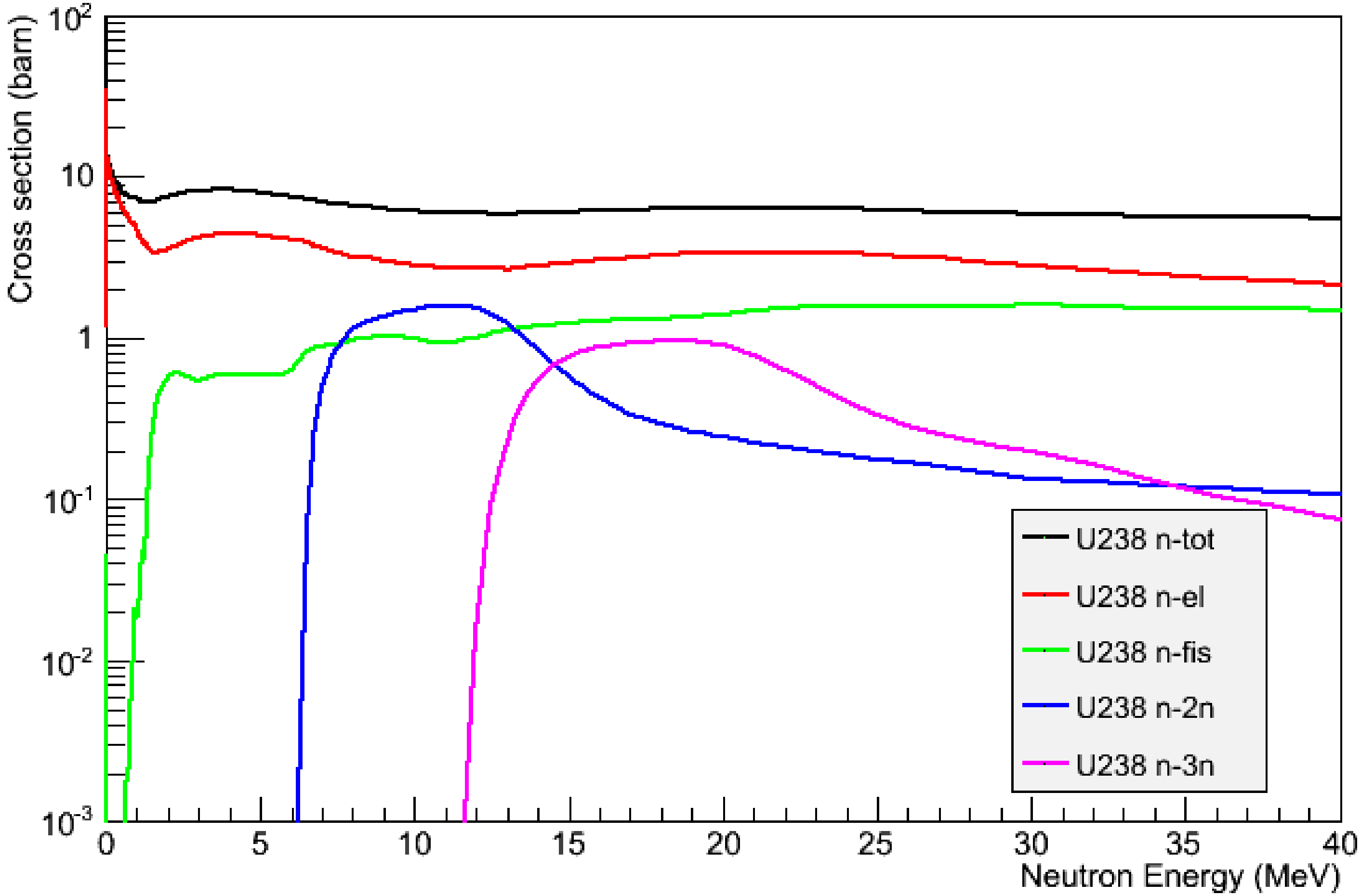
Neutrons are emitted during:

- Direct component : elastic component
- The evaporation of compound nuclei
- During the pre-equilibrium intermediate energy

Importance of (n,xn) reactions

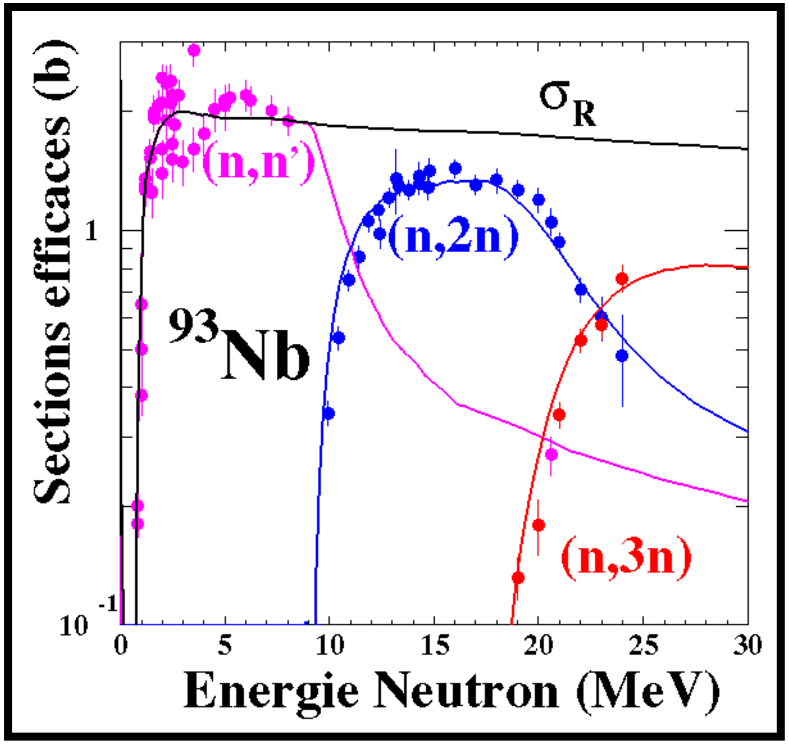
(n,xn) reactions represent the main part of the reaction cross-section above MeV

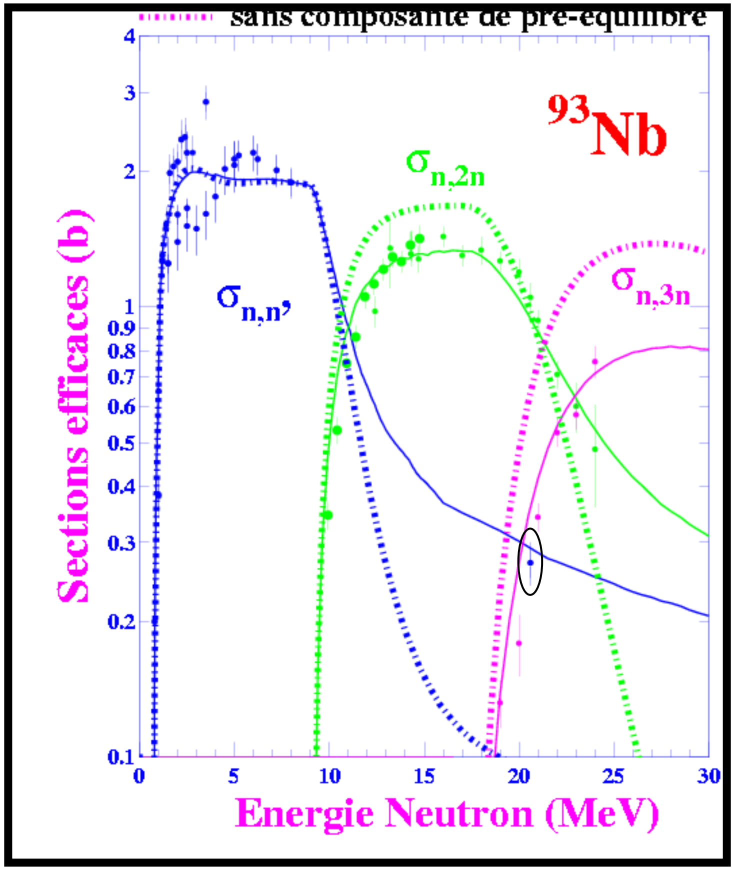
Reactions on ^{238}U



Role of the pre-equilibrium process in (n,xn) reaction

The pre-equilibrium process is an important process of the n,xn reactions





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Applications

- Reactor and accelerator driven systems: n,xn contributes to
  - Energy loss mechanism
  - Neutron multiplication
  - Production of radioactive isotopes
- Production of nuclear waste (fusion technology)
- Nuclear data evaluation (all the channels have to be studied)
- Neutron field characterization
  - Fluence
  - Energy and angular distribution

Reliable evaluated data bases are request → accurate measurements

Neutron field characterization

Threshold reactions including (n,n') and (n,xn) reactions are used for determining the differential flux from neutron sources by activation techniques.

- ❑ Irradiation of a set of material i in a flux Φ :
- ❑ Measurement of the activity of each sample i :

$$A_i^{mes} = k \int_{E_s}^{E_m} \frac{d\Phi}{dE}(E_n)\sigma_i(E_n)dE_n$$

- ❑ Use a simulated neutron spectrum: ψ(E) to calculate A_i^{sim}

$$A_i^{sim} = k \int_{E_s}^{E_m} \frac{d\Psi}{dE}(E_n)\sigma_i(E_n)dE_n$$

- ❑ Adjust ψ(E) in order to minimize

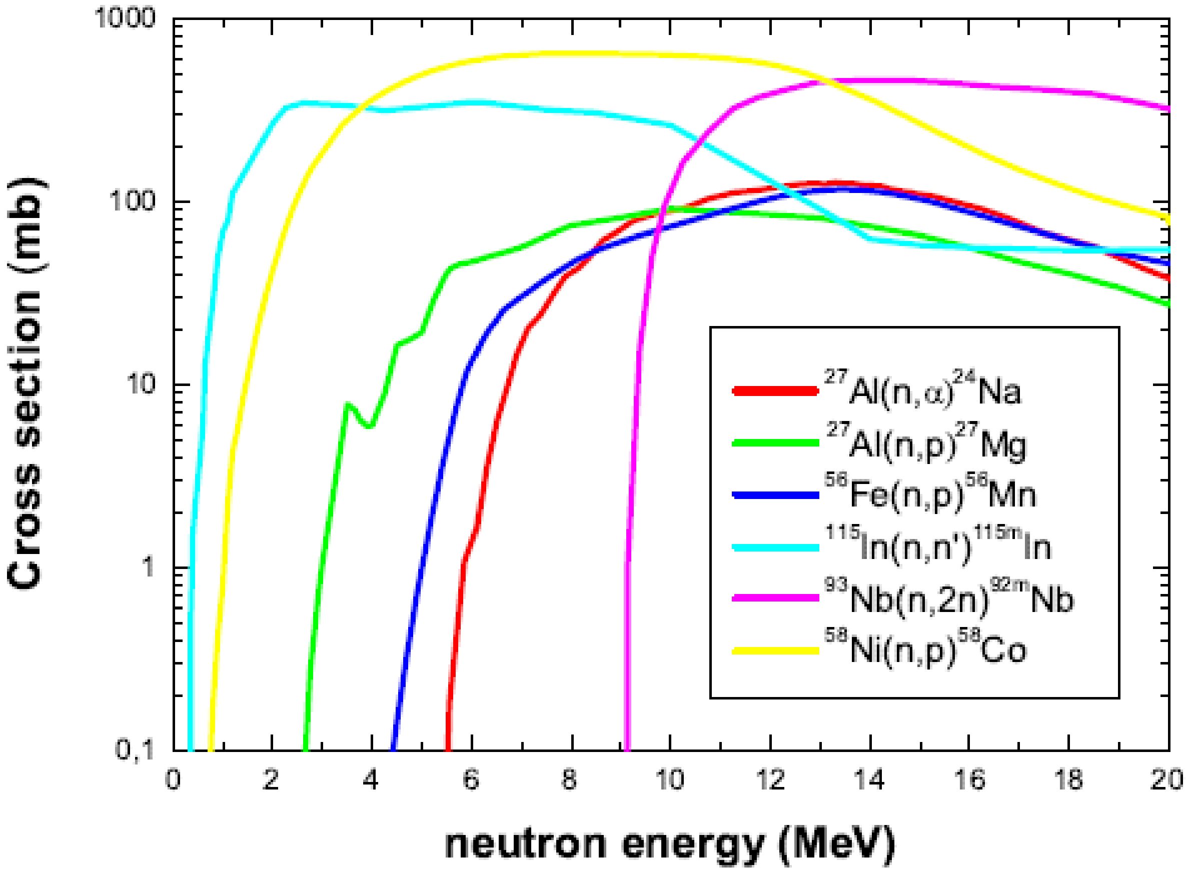
$$\chi^2 = \frac{1}{m}\sum_i \frac{\left(A_i^{mes} - A_i^{sim}\right)^2}{\varepsilon_i^2}$$

The choice of the reactions depends on:

- Energy threshold in order to cover the energy range of interest
- Product of reaction measurable (radioactive, period, decay mode)
- Reaction (n,p), (n,α), (n,n'), (n,xn)

Accurate knowledge of the cross-section reactions is required

Usable Reactions up to 20 MeV



N. Jovančević* et al., Physics Procedia 59 (2014) 154 – 159
Göran Lövestam et al., Radiation Measurements 44 (2009) 72–79

Above 20 MeV

Experimental determination of neutron spectra produced by bombarding thick targets:

(100 MeV/u) D + ^{9}Be, ^{238}U and (95 MeV/u) ^{36}Ar + ^{12}C

Experimental set-up

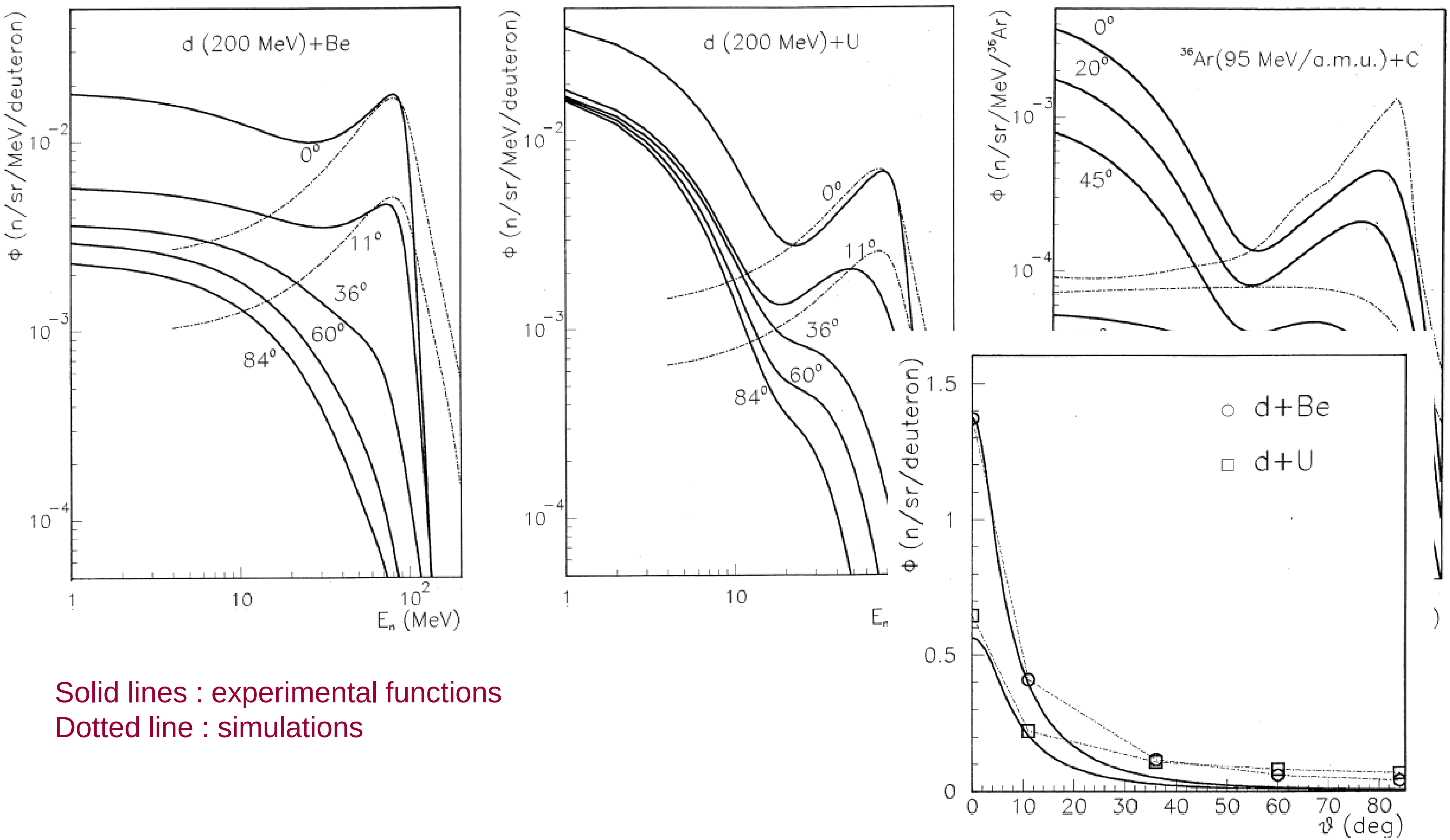
Incident beam	Energy (MeV/u)	Intensity (p.p.s)	Target	Irradiation time (min)	Activation detectors	Detector position
^{36}Ar	95	6.42×10^{11}	Carbon	88	Al, Ni, Bi	0°, 20°, 45°, 90°
Deuterons	100	6.72×10^{10}	Beryllium	373	Al, Ni, Co, Bi	0°, 11°, 36°, 60°, 84°
Deuterons	100	6.47×10^{10}	Uranium	376	Al, Ni, Co, Bi	0°, 11°, 36°, 60°, 84°

Reaction and isotopes characteristics

Detector	Reaction	Radionuclide	Half-life	Threshold energy (MeV)	γ-ray (keV)
Al	(n, α)	^{24}Na	15 h	6	1368.6
Al	(n, spall)	^{22}Na	2.6 yr	30	1274.5
Ni	(n, p)	^{58}Co	70.78 d	1	810.75
Co	(n, 2n)	^{58}Co	70.78 d	11	810.75
Co	(n, 3n)	^{57}Co	270 d	20	122.07
Co	(n, p)	^{59}Fe	45.1 d	4	1099.22
Bi	(n, 3n)	^{207}Bi	31.55 yr	14.42	1063.6
Bi	(n, 4n)	^{206}Bi	6.24 d	22.55	803
Bi	(n, 5n)	^{205}Bi	15.31 d	29.62	703.3
Bi	(n, 6n)	^{204}Bi	11.3 h	38.13	984
Bi	(n, 7n)	^{203}Bi	11.8 h	45.37	820.2
Bi	(n, 8n)	^{202}Bi	1.8 h	54.24	960.7
Bi	(n, 9n)	^{201}Bi	1.85 h	61.69	629.1
Bi	(n, 10n)	^{200}Bi	36 min	70.89	1026.5

N. Pauwels et al. / Nucl. Instr. and Meth. in Phys. Res. B 160 (2000) 315–327

Neutron spectra produced by bombarding thick targets: (100 MeV/u) D + ^{9}Be, ^{238}U and (95 MeV/u) ^{36}Ar + ^{12}C



Solid lines : experimental functions
Dotted line : simulations

OUTLINE

1. Definition
2. Application
3. Facilities
4. Cross-section measurements
    1. Activation technique
    2. n,xn gamma
    3. Direct measurement of secondary neutrons
5. Double differential measurements
6. Particular cases

Facilities

❑ Neutron production

- Nuclear reaction → accelerator
- Photofission → e^- accelerator + converter
- Nuclear fission → Reactor

❑ Parameters

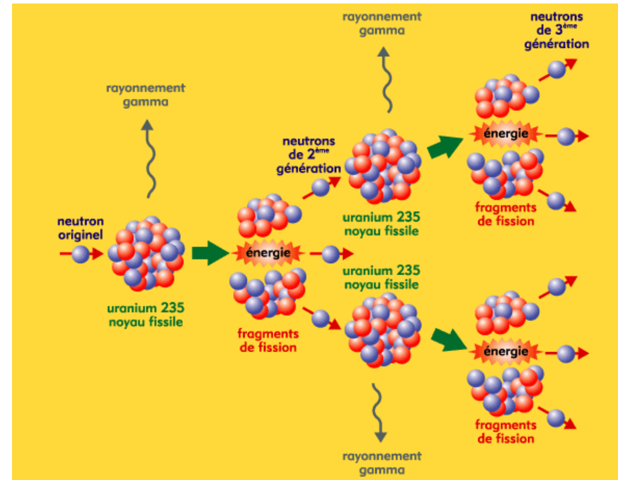
- Energy range 5-50 MeV for (n,xn) reactions
- Energy distribution mono-kinetic or white spectrum
- Fluence
- Time structure pulsed beam for tof measurement

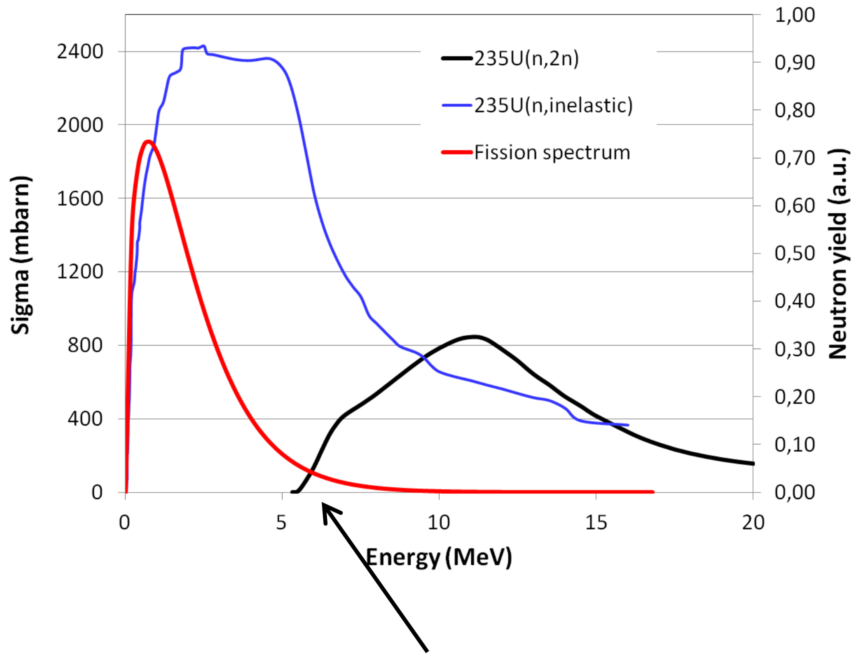
❑ Types of facilities

- Open field
- Collimated beam

Reactor

- Neutron fission
- High flux
- No time spectrum
- Energy limited to 10 MeV
- Energy spectrum (fast neutrons for n,xn)



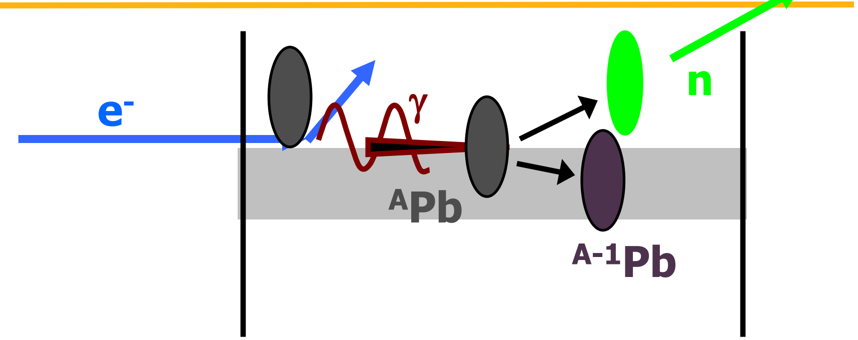


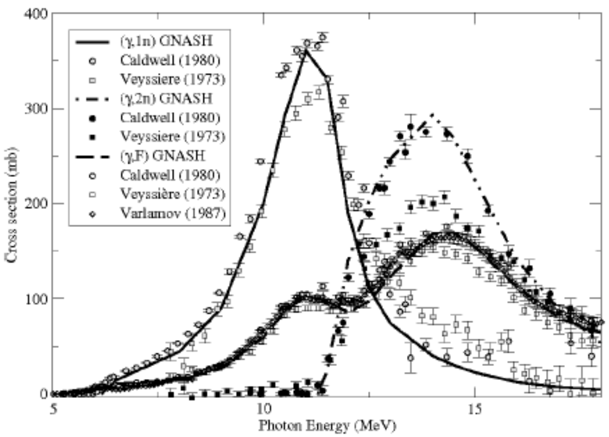
Opening of (n,2n) channel

Prospero reactor : CEA

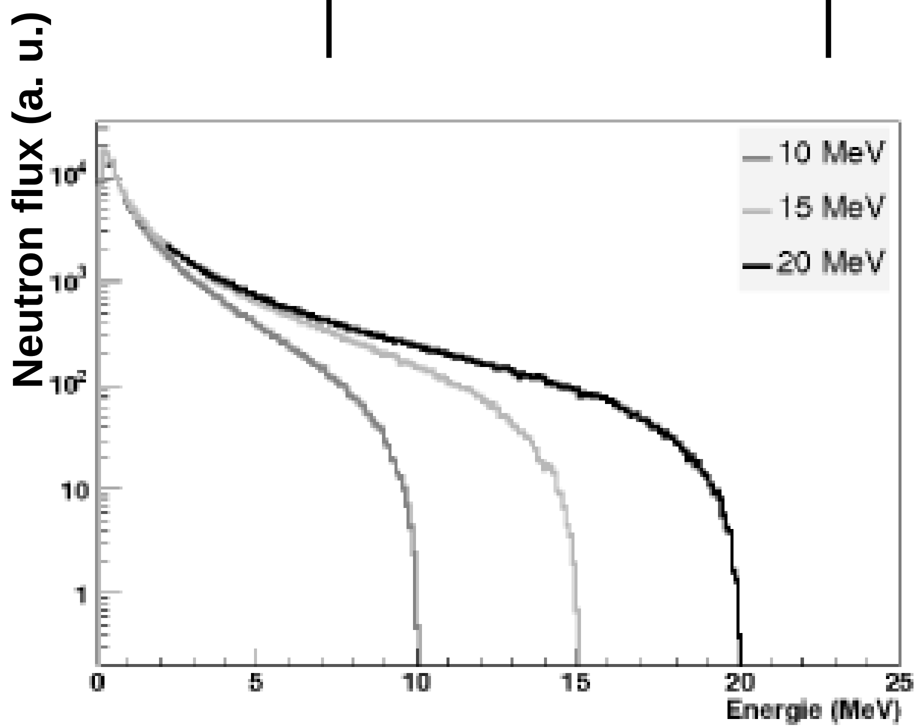
Photo-production of neutrons with bremsstrahlung

- Electron beam
- Photon production by Bremsstrahlung
- Neutron production by (γ,xn) or (γ,f) reaction





- Continuous neutron energy spectrum
- “Low cost” accelerator
- High power Accelerator



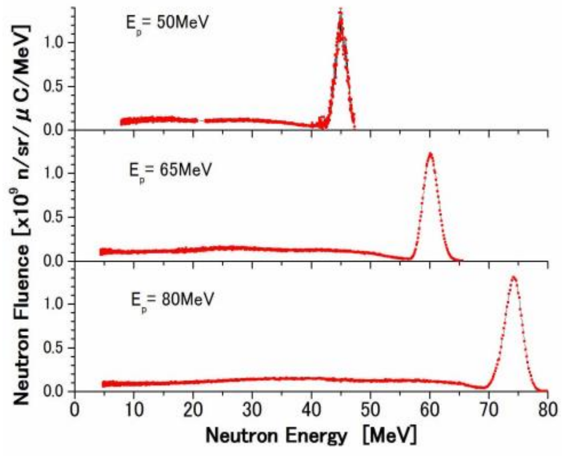
nELBE yield: $3*10^{11}$ n/s with 30 MeV 15 μA (Target:Pb, liquid) 200 kHz

GELINA yield: $3*10^{13}$ n/s with100 MeV 96 μA (Target: U(Hg cooled)) 800 Hz

Intermediate energy 20-200MeV

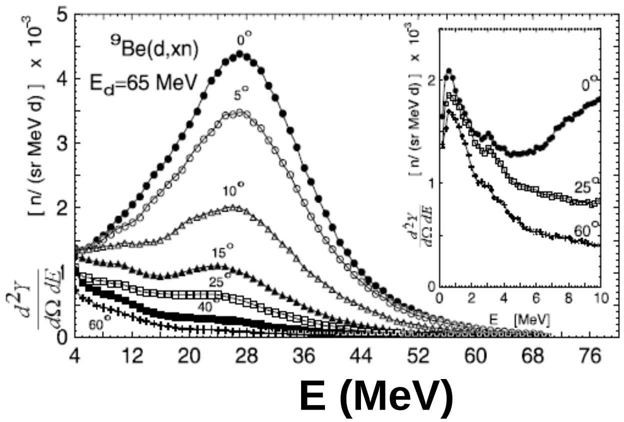
❑Quasi-mono-energetic spectrum:

- Proton beam on thin ^{7}Li converter
- ^{7}Li(p,n)^{7}Be reaction Q= -1,64 MeV → at 0° En ≈ Ep - 2 MeV
- Forward peak
- Limitations :
  - Spectrum not purely mono-energetic -> pulsed beam
  - Low melting point of Lithium (limited intensity) -> liquid target
  - Target highly activated (^{7}Be)



❑Continuous spectrum:

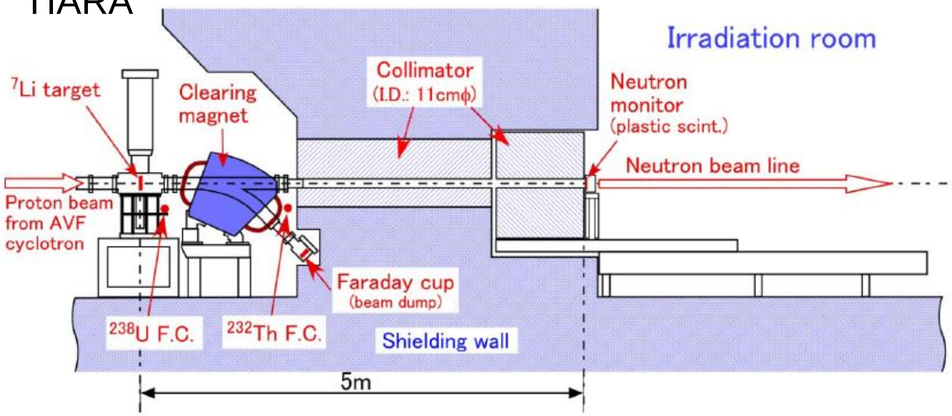
- Proton or deuteron beam on thick converter Be or C
- Continuous spectrum up to beam energy
- Flux increasing with energy
  - The beam stops in the converter
  - Large power deposition → cooling is challenging



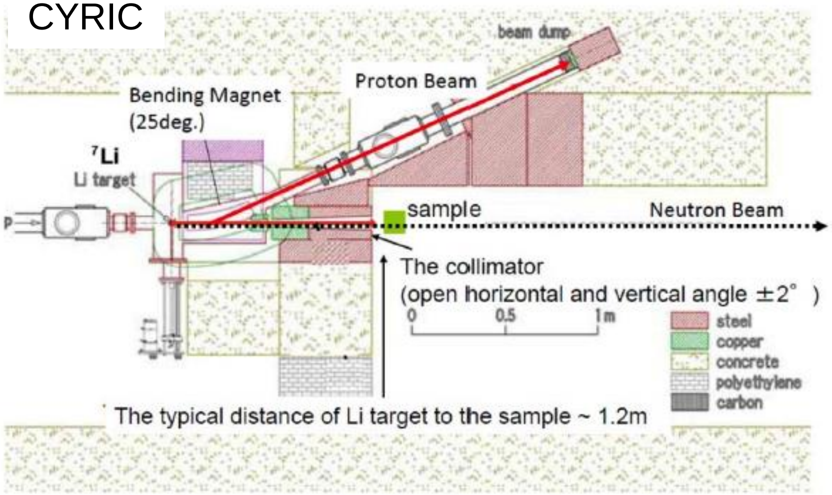
Several facilities proposes both types of spectra

Some Quasi-Monoenergetic facilities

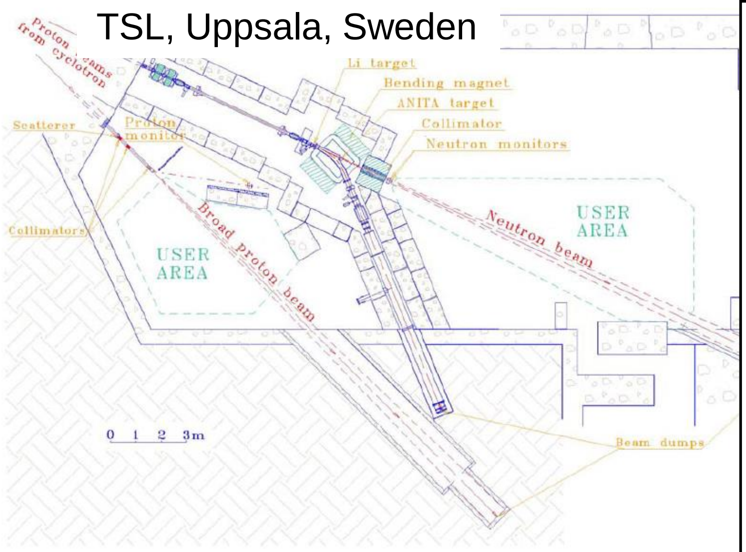
TIARA

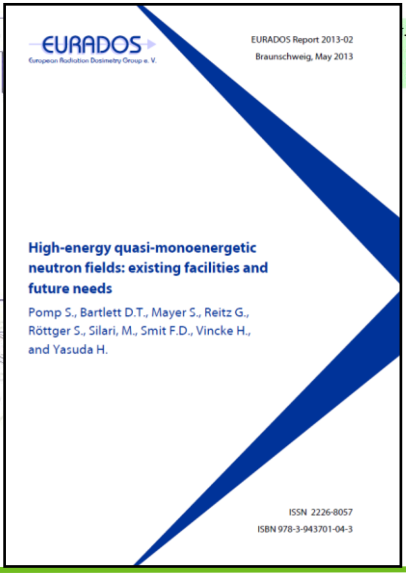


CYRIC



TSL, Uppsala, Sweden





EURADOS
European Radiation Dosimetry Group e. V.

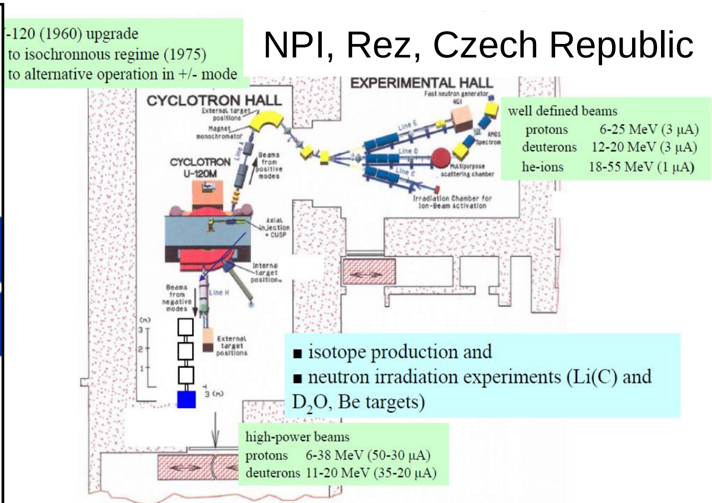
EURADOS Report 2013-02
Braunschweig, May 2013

High-energy quasi-monoenergetic neutron fields: existing facilities and future needs

Pomp S., Bartlett D.T., Mayer S., Reitz G., Röttger S., Silari, M., Smit F.D., Vincke H., and Yasuda H.

ISSN 2226-8057
ISBN 978-3-943701-04-3

NPI, Rez, Czech Republic



neutron flux up to 3 *10^8 n/cm^2/s

Mono-kinetic neutron sources

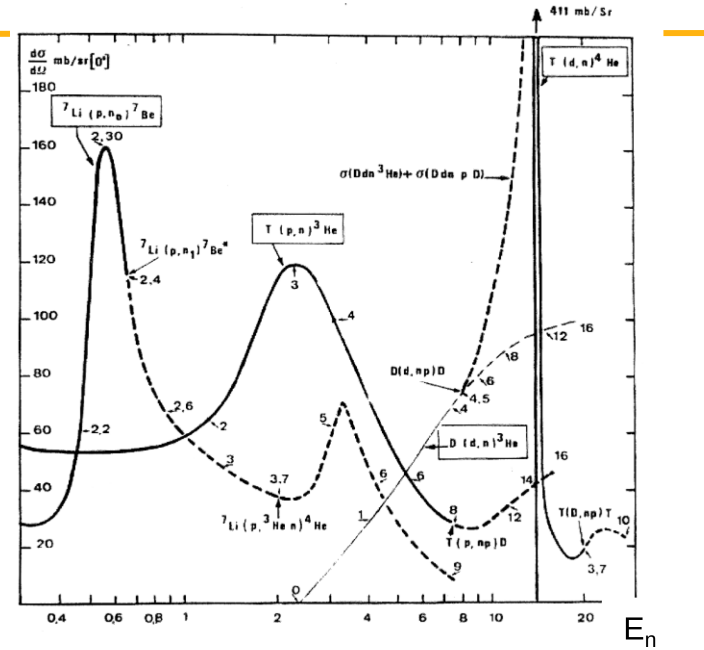
Nuclear reactions (The big four)

$p + {}^{7}Li \rightarrow n + {}^{7}Be$

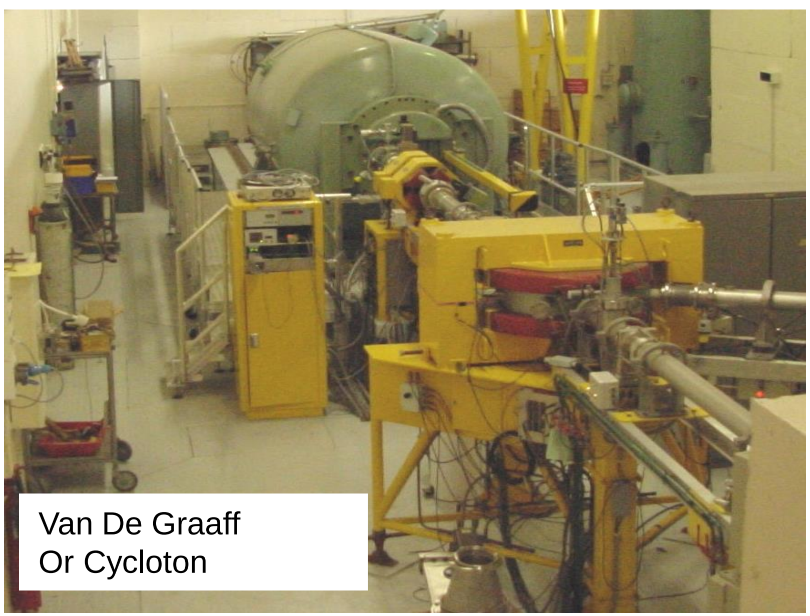
$p + {}^{3}H \rightarrow n + {}^{3}He$

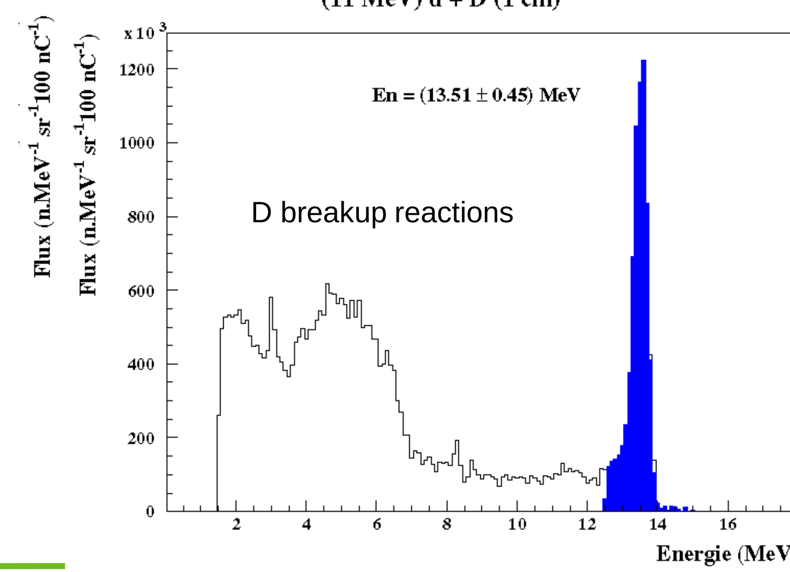
$d + {}^{2}H \rightarrow n + {}^{3}He$

$d + {}^{3}H \rightarrow n + {}^{4}He$

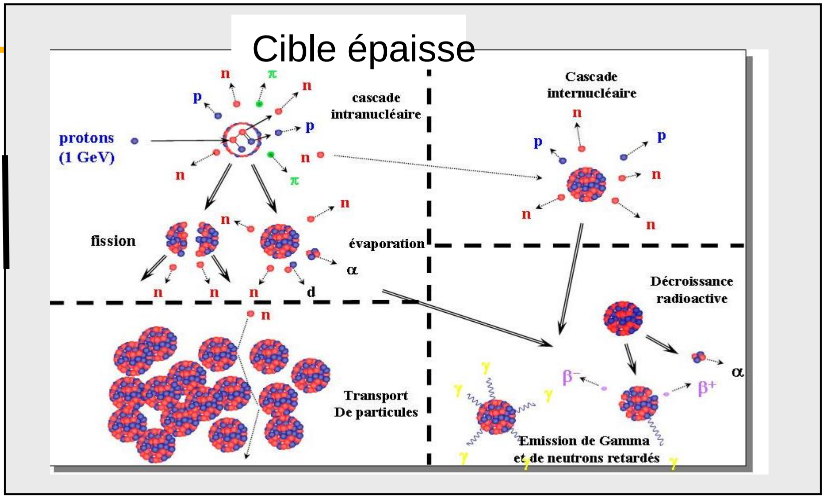


- Proton and deuteron beams with E< 4 MeV
- Purely mono-energetic neutrons for E<7 MeV and 14<E<17 MeV





Spallation reaction



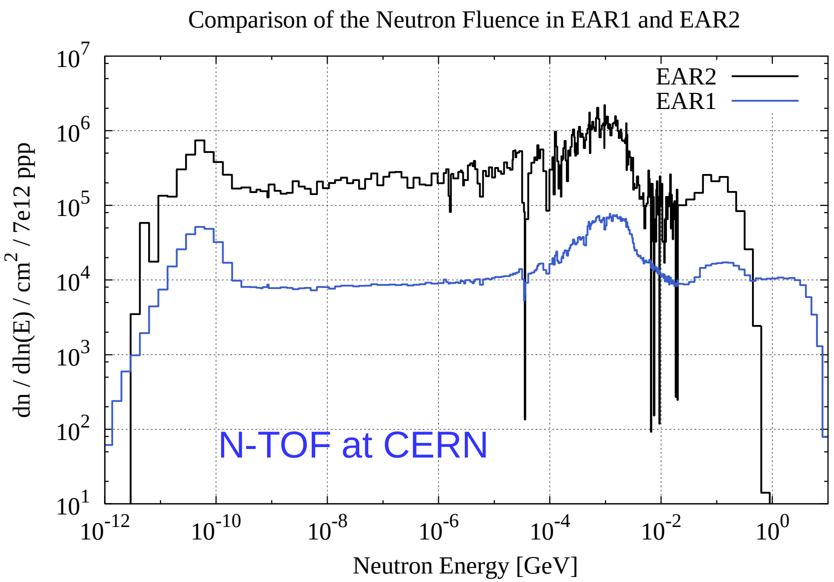
Proton beam with energy > 800MeV

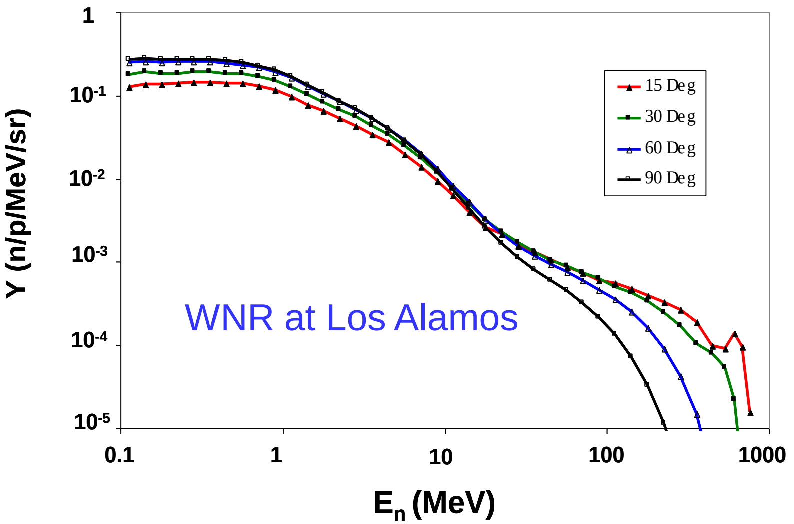
Very intense neutrons source

Proton accelerator 1 GeV x 1 mA = 1 MW

⇨ 10^{17} n/s

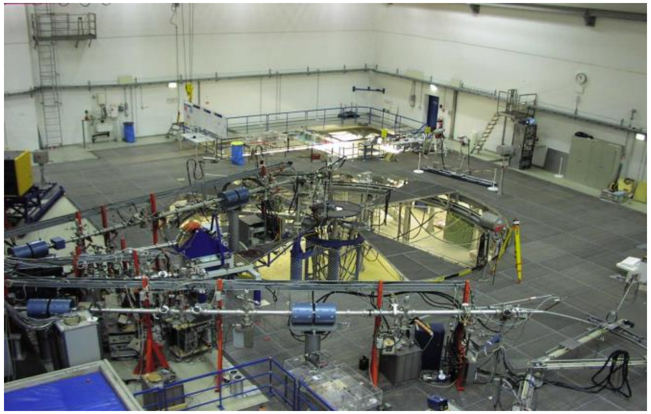
- Neutron production up to the proton energy
- Use of moderator to increase neutrons flux at low energy thermal or cold
- N-tof, WNR, SNS, ESS, JPARC



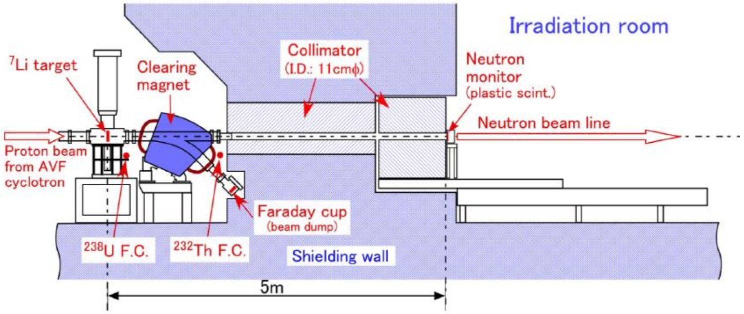


Type of beam

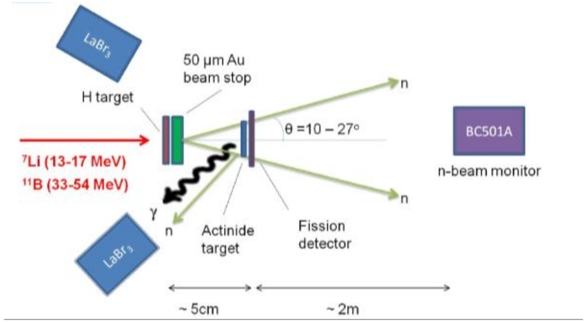
- Open field
  - Neutron emission in 4π
  - Background in the experimental area
  - The sample can be placed very close to the source
  - VdG, PTB



- Collimated beam
  - The detectors can be placed close to the sample
  - Low flux because of the distance source-sample
  - WNR, N-TOF, NFS



- "Conical" beam
  - Kinematic effect
  - Neutrons are emitted in a cone in the forward direction
  - LICORNE, FRANZ



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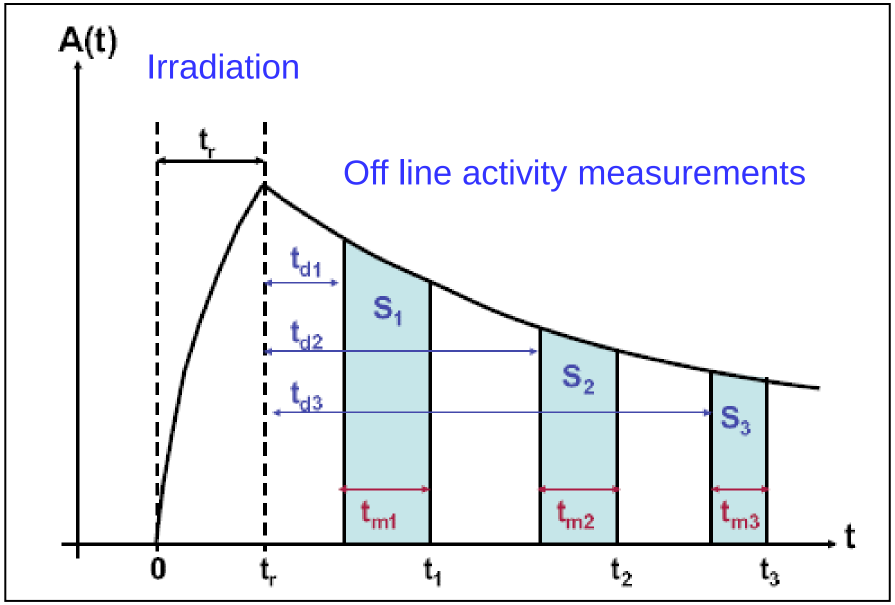
Activation technique

Also called radiochemical technique

Activation and off-line gamma ray spectrometric technique



$$n \quad + \quad {}^{A}_{Z}X \quad \rightarrow \quad {}^{A-x+1}_{Z}X \quad + \quad x\,n$$

Only if ${}^{A-x+1}_{Z}X$ radioactive

→ Period

Decay mode (γ, α, e)

Feeding ratio

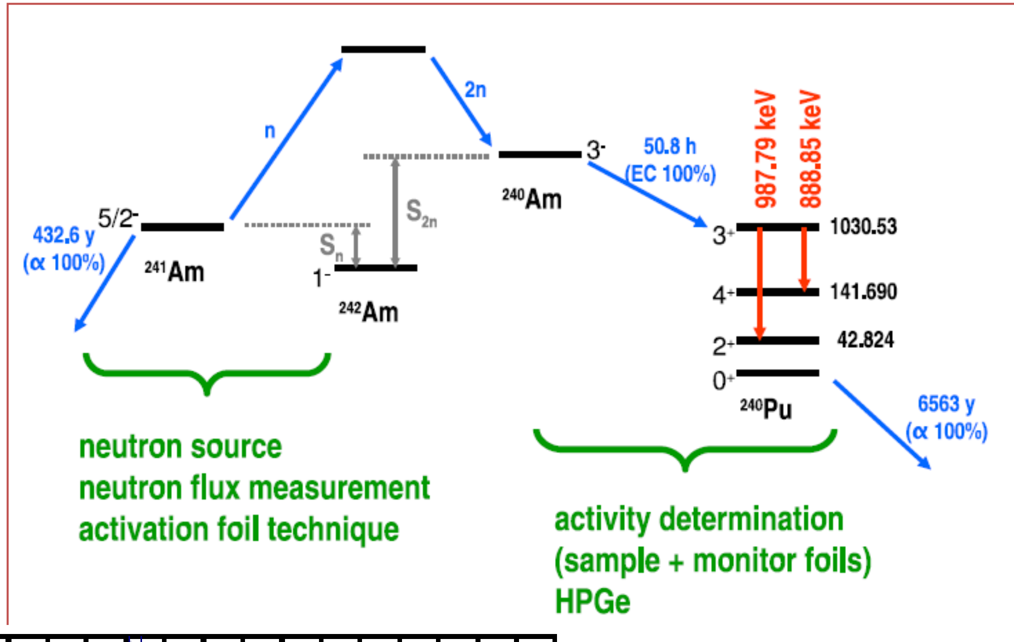
- **Advantages:**
  - Target do not need to be isotopic if $E_n < B_n$ (A+1)
  - No need of pulsed beam
- **Drawbacks :**
  - Incident energy is not measured → need mono-energetic beam
  - One measurement for each energy
  - One target for each energy

Cross-section of the ^{241}Am(n,2n) reaction

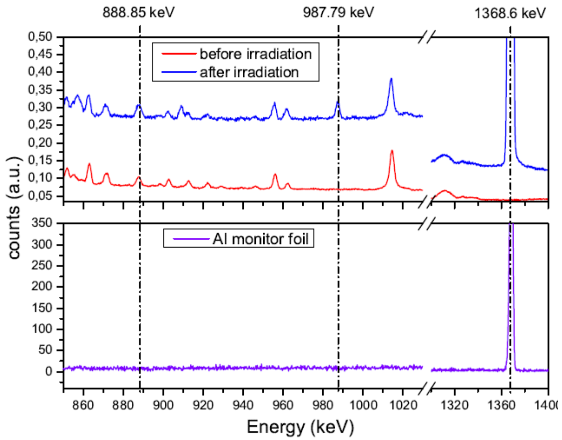
$$n + {}^{241}_{95}\mathrm{Am} \rightarrow {}^{240}_{95}\mathrm{Am} + 2\,n$$

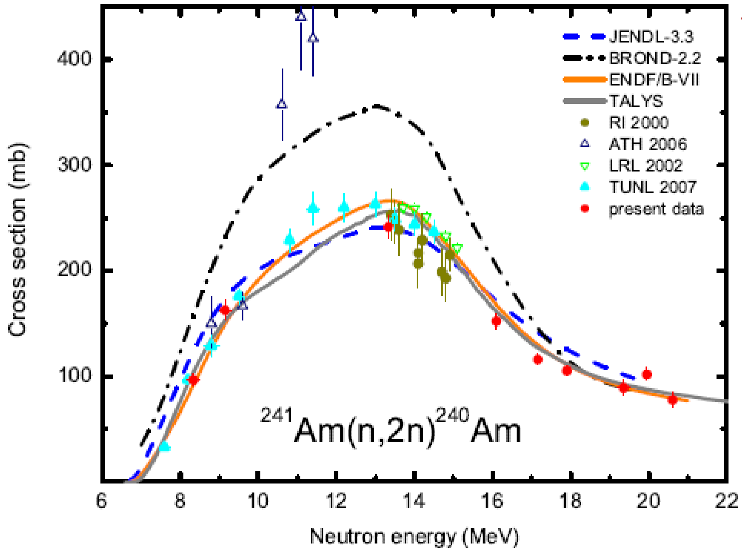
$T_{1/2} = 432$ y $\qquad T_{1/2} = 2{,}12$ d

IRMM Van de Graaff accelerator
Monitoring by activation of foils
Radioactive target



Targets
30-40 mg of ^{241}Am





C. Sage, PhD thesis

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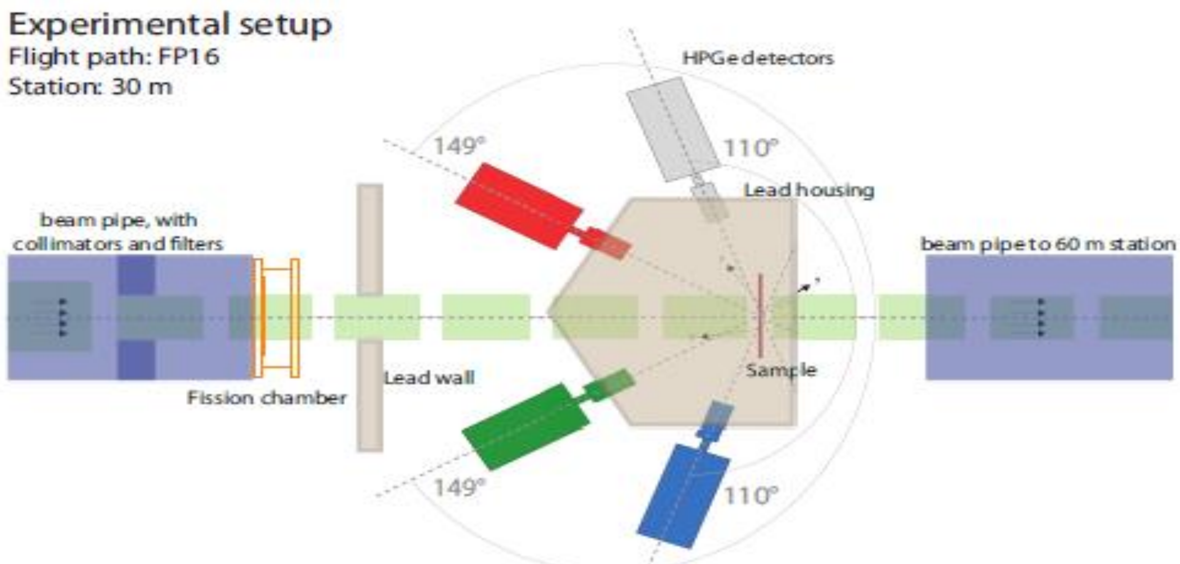
Prompt γ-ray spectroscopy

Detection of the γ**-rays stemming from the decay of excited states of nucleus created by the (n,xn) reaction.**

Measure on line of prompt gamma spectroscopy of the ${}^{A-x+1}_{Z}X$



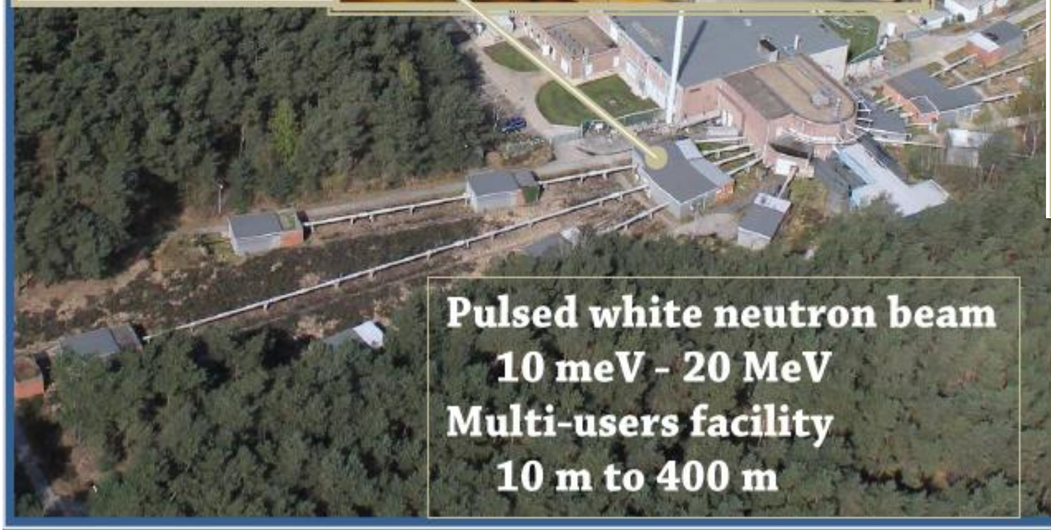
- **Advantages:**
  - The incident energy can be measured if the beam is pulsed
  - On-line measurement of several energies during the same run
  - Several isotopes can be measured simultaneously
- **Drawbacks :**
  - (n,xnγ) cross-section is measured
  - Calculations are required to determine the (n,xn) cross-section

Inelastic scattering and (n,xn) experimental studies

4 HPGe Planar
(110°,150°)
Actinides samples
ΔEn = 10 keV @ En = 1 MeV

Neutron Time of flight facility
GELINA@IRMM(Geel)

^{52}Cr : L.C. Mihailescu *et al.* **NPA786(2007)1**
^{209}Bi : L.C. Mihailescu *et al.* **NPA799(2008)1**
^{208}Pb : L.C. Mihailescu *et al.* **NPA811(2008)1**
^{23}Na : C. Rouki *et al.* **NIMA672(2012)82**
^{235}U : M. Kerveno *et al.* **PRC87(2013)024609**
$0\nu2\beta$: A. Negret *et al.* **PRC88(2013)027601**
^{28}Si : A. Negret et al. **PRC88(2013)034604**
^{76}Ge : C.Rouki *et al.* **PRC88(2013)054613**
^{56}Fe : A. Negret *et al.* **PRC90(2014)034602**
^{24}Mg : A.Olacel *et al.* **PRC90(2014)034603**
^{232}Th : M.Kerveno *et al.* **EPJA(2014) accepted**
^{7}Li, ^{12}C, ^{58}Ni, ^{nat,184,186}W, ^{206,207}Pb, ^{232}Th, ^{238}U: conf.



Pulsed white neutron beam
10 meV - 20 MeV
Multi-users facility
10 m to 400 m

^{12}C, ^{23}Na, ^{24}Mg, ^{28}Si, ^{52}Cr, ^{56}Fe, ^{58}Ni, ^{76}Ge, ^{nat}Zr, ^{nat,182,183,184,186}W, ^{206,207,208}Pb, ^{209}Bi, ^{232}Th, ^{235,238}U

12 HPGe Ø 80 mm x L 80 mm
(110°,150°)
ΔEn = 1 keV @ En = 1 MeV

Measurement of ^{235}U(n,n'γ) and ^{235}U(n,2nγ) cross-section

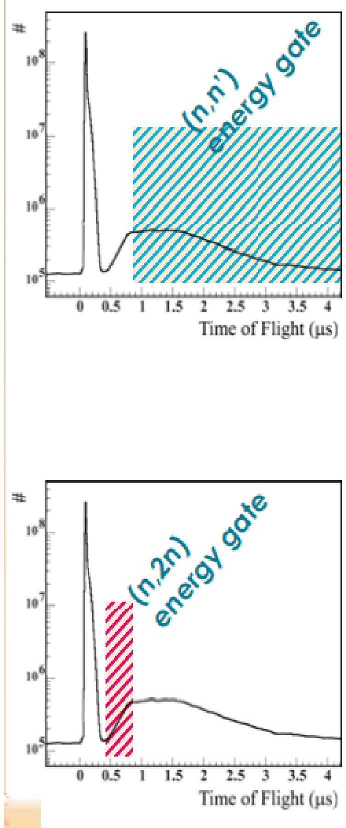
- **Beam time** : 1466 hours
- **Sample** :
  - enrichment ^{235}U 93,2%
  - m= 37,43 g
  - Φ= 12,00 cm
  - thickness 0,21 mm

M. Kerveno, WONDER 2012, Sept 25-28, 2012, Aix en Provence

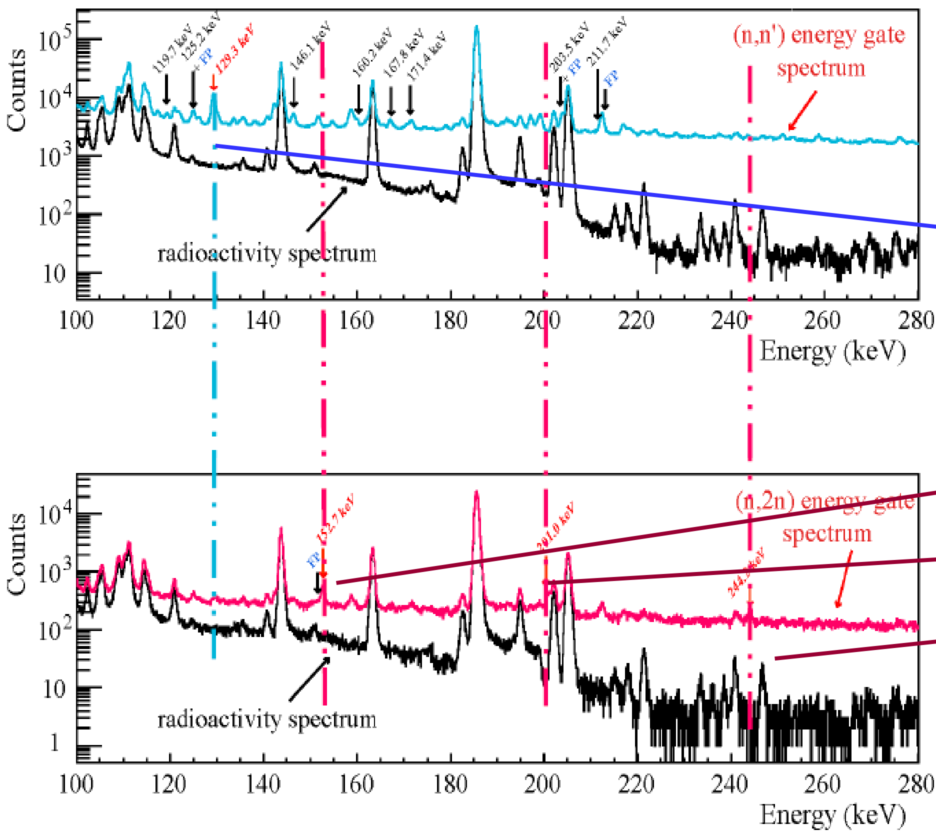
1γ transition in ^{235}U → ^{235}U(n,n' γ)

3 γ transitions in ^{234}U → ^{235}U(n,2n γ)

TOF spectra



Gamma spectra



^{235}U(n,n'γ)

129,3 keV 5/2$^-$ → 7/2$^-$

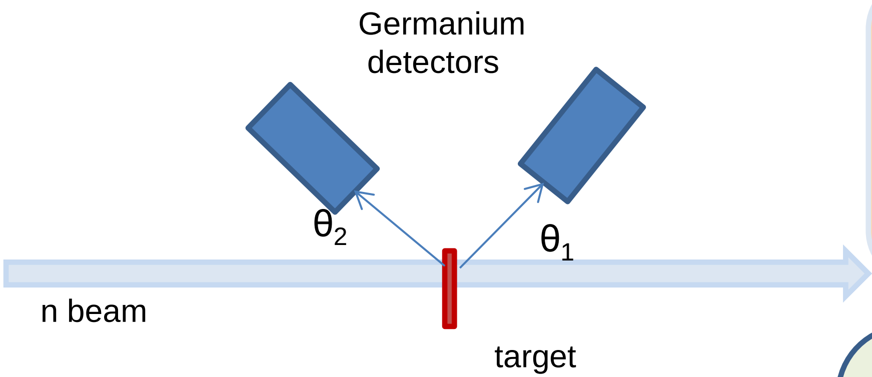
152,72 keV 6$^+$ → 4$^+$

200,96 keV 8$^+$ → 6$^+$

244,2 keV 10$^+$ → 8$^+$

^{235}U(n,2nγ)

Measurement of σ(n,xnγ)



$$\frac{d\sigma^{(n,xn\gamma)}}{d\Omega}(\theta) = \frac{n_{det}}{N_{at}\cdot\phi_n\cdot\varepsilon\cdot t}$$

n_{det} : number of detected γ
N_{at} : number of atoms in the sample
ϕ_n : neutron flux
ε : HPGe efficiency
t : measurement time

$$\sigma^{(n,xn\gamma)} = \int_{4\pi} \frac{d\sigma^{(n,xn\gamma)}}{d\Omega} d\Omega = 2\pi \int_{-1}^{1} \frac{d\sigma^{(n,xn\gamma)}}{d\Omega} d(\cos(\theta))$$

Gaussian quadrature Approximation →

$$\sigma^{(n,xn\gamma)} \approx 2\pi \sum_{i=1}^{N} w_i \frac{d\sigma^{(n,xn\gamma)}}{d\Omega}(\theta_i)$$

With θ_i such that for $P_n(\cos\theta)=0$

Legendre polynomial of order N=4

$\sqrt{\frac{15+2\sqrt{30}}{35}} = 0.8611$	30.6°	$\frac{-\sqrt{30}+18}{36} = 0.3479$
$\sqrt{\frac{15-2\sqrt{30}}{35}} = 0.3400$	70.1°	$\frac{\sqrt{30}+18}{36} = 0.6521$
$-\sqrt{\frac{15-2\sqrt{30}}{35}} = -0.3400$	109.9°	$\frac{\sqrt{30}+18}{36} = 0.6521$
$-\sqrt{\frac{15+2\sqrt{30}}{35}} = -0.8611$	149.4°	$\frac{-\sqrt{30}+18}{36} = 0.3479$

$$P_N(-x) = (-1)^N P_N(x),$$

σ(n,xnγ) can be deduced with 2 detectors

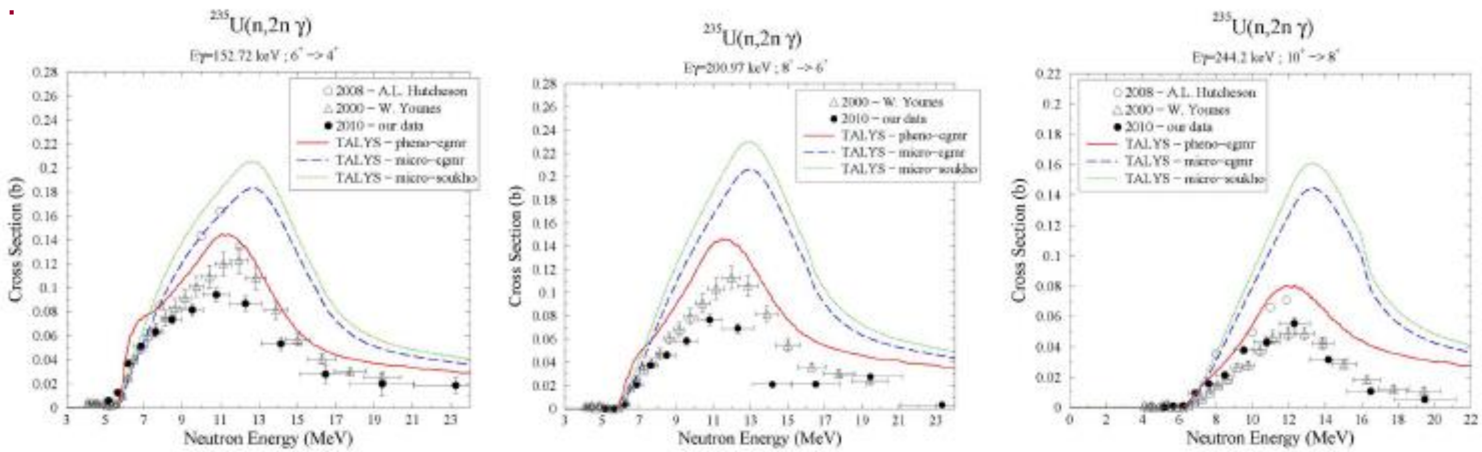
$$\sigma_{tot}^{(n,xn\gamma)} = 4\pi\left[w_1^*\frac{d\sigma}{d\Omega}(\theta_1^*) + w_2^*\frac{d\sigma}{d\Omega}(\theta_2^*)\right]$$

w_1 = 0.3479 for Θ_1 = 30.56° or 149.44° and
w_2 = 0.6571 for Θ_2 = 70.12° or 109.88°

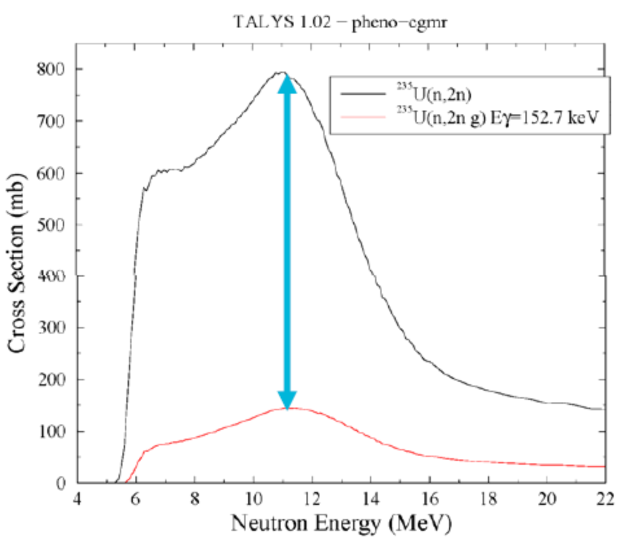
C.R. Brune / Nuclear Instruments and Methods in Physics Research A 493 (2002) 106–110

From (n,2nγ) to (n,2n) cross-section

Measurements :



Theoretical model :



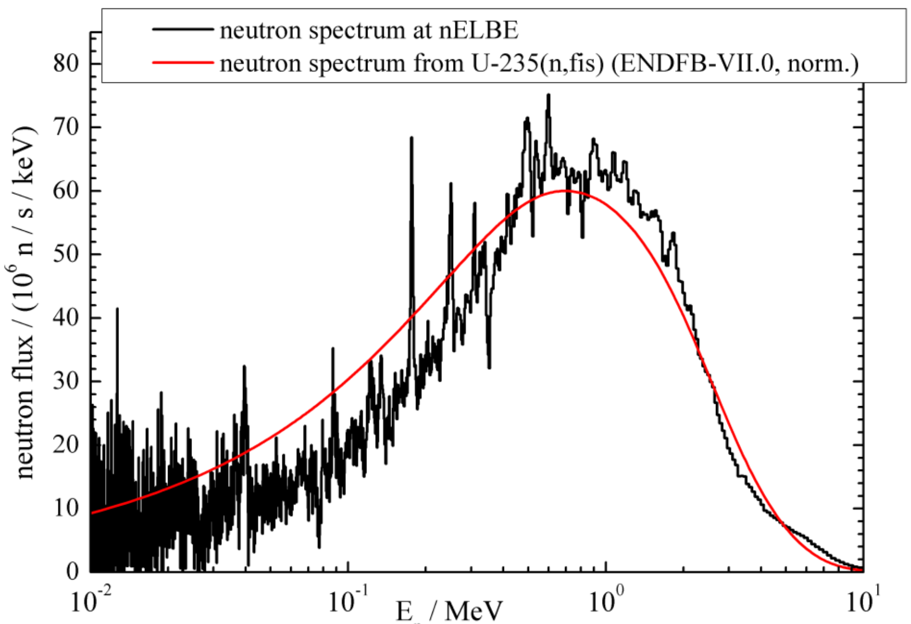
Only one part of the (n,2n) cross-section is measured

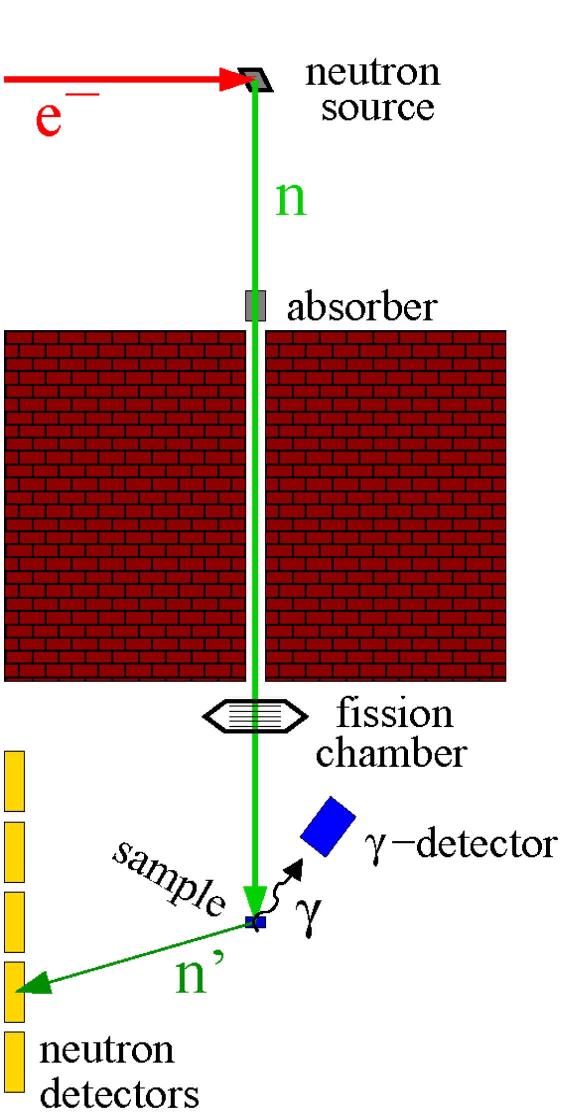
→ σ(n,2n)

(n,xnγ) measurement at nELBE

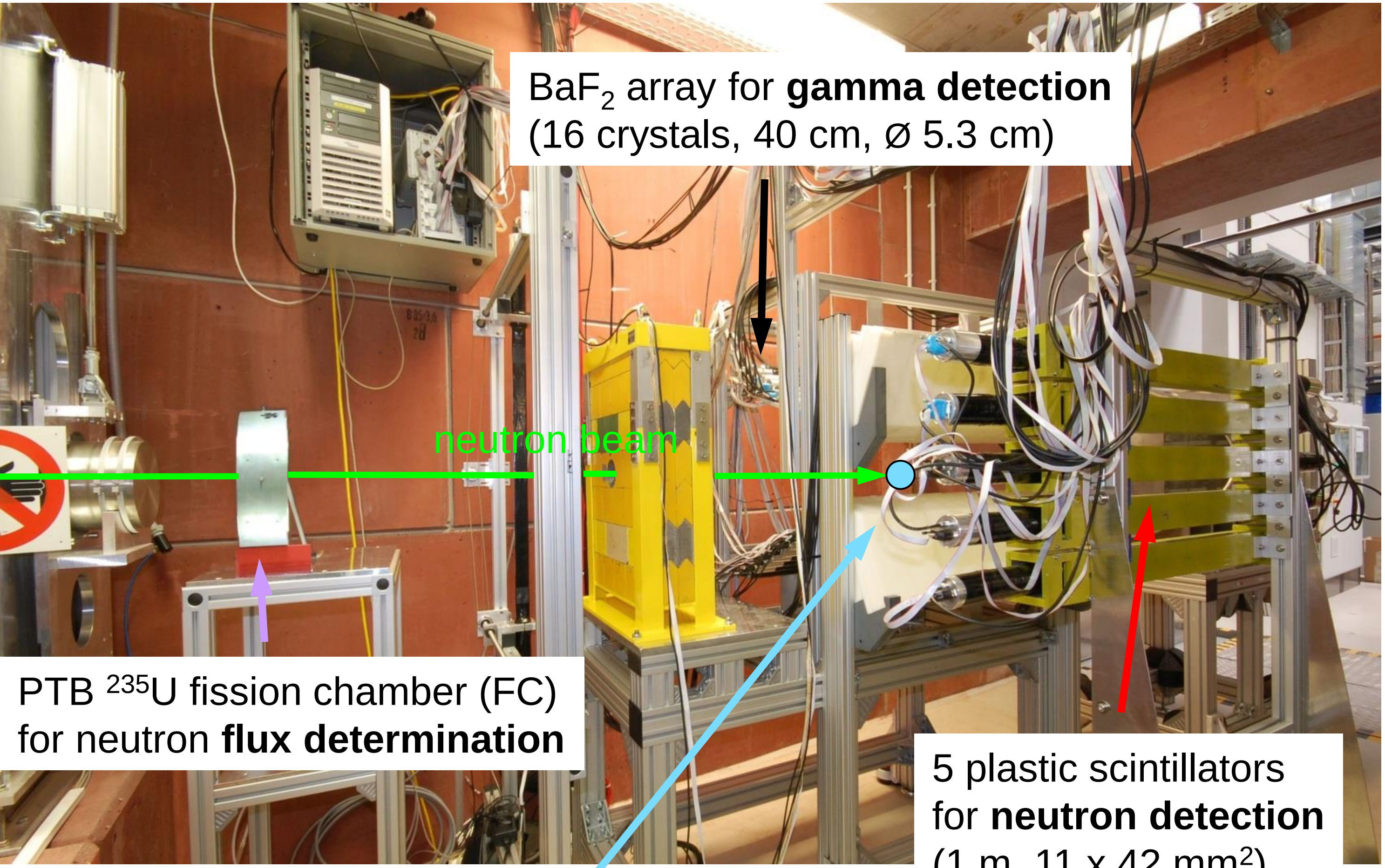
$$^{56}\text{Fe}(n,n'\gamma)^{56}\text{Fe} \left\{ \begin{array}{l} ^{56}\text{Fe} + n \rightarrow {}^{56}\text{Fe}^* + n' \\ ^{56}\text{Fe}^* \rightarrow {}^{56}\text{Fe} + \gamma \end{array} \right.$$

Neutron production : photo reaction
- E<10MeV
- Collimated beam
- Pulsed beam





nELBE – double ToF detector setup

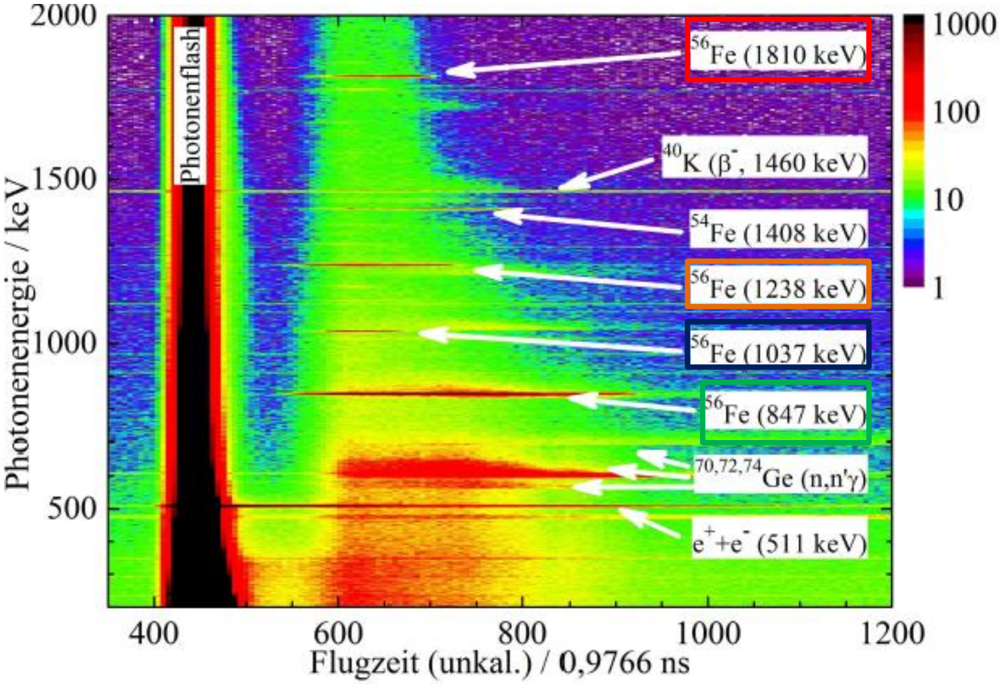


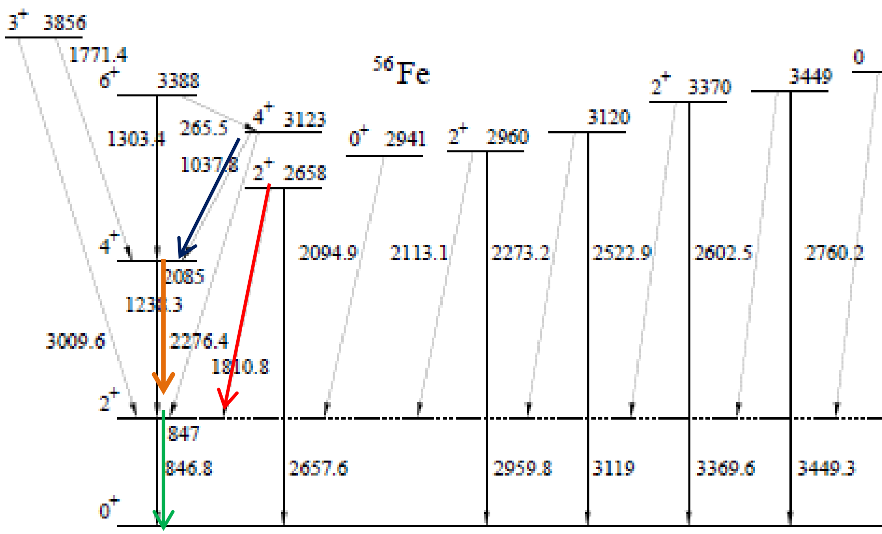
flight paths:
source - FC:
400 cm
source - sample:
600 cm
sample - BaF$_2$:
30 cm
sample - plastics:
100 cm

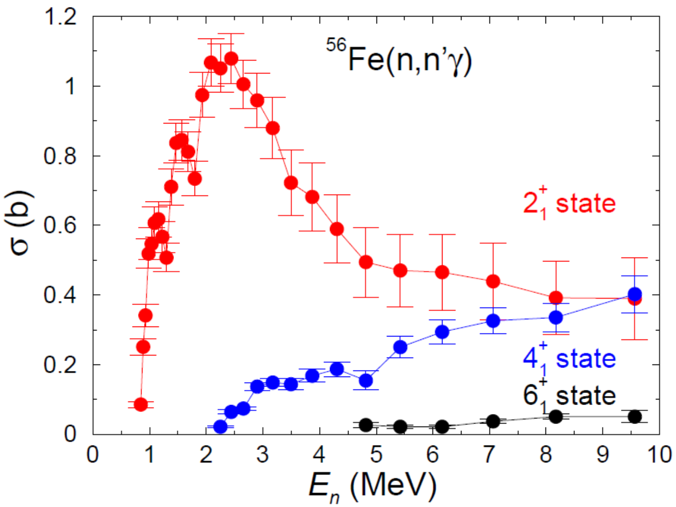
sample: ^{nat}**Fe** (99.8%) → 91.754% ^{56}Fe
mass: 19.82 g → 18.15 g ^{56}Fe

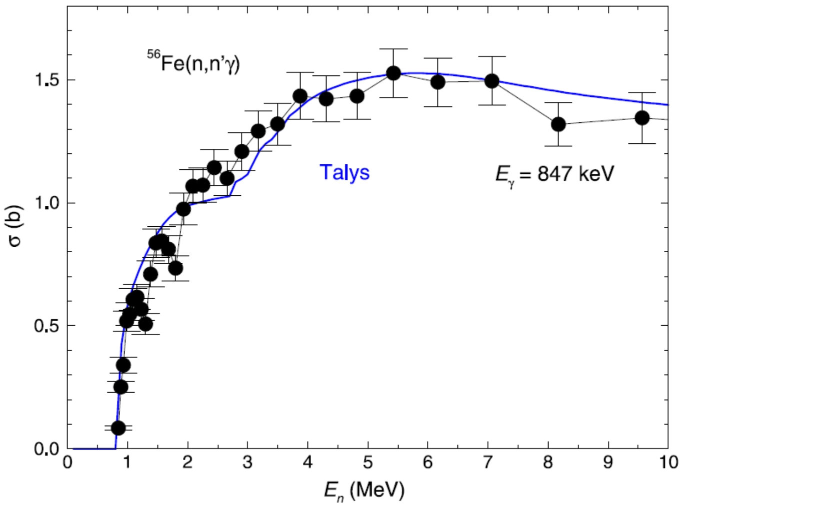
R. Beyer, PhD Thesis

^{56}Fe(n,xnγ) measurement at nELBE









R. Beyer et al., Nuclear Physics A 927 (2014)

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    2. n,xnγ gamma
    3. Direct measurement of secondary neutrons
4. Double differential measurements
5. Examples of experiments

Direct measurement of secondary neutrons

Measure the x neutrons emitted in the reaction

- Advantages :
  - Direct measurement
  - Applicable to all nuclei

- Drawbacks:
  - Need a mono-isotopic target
  - Neutron detector of high efficiency

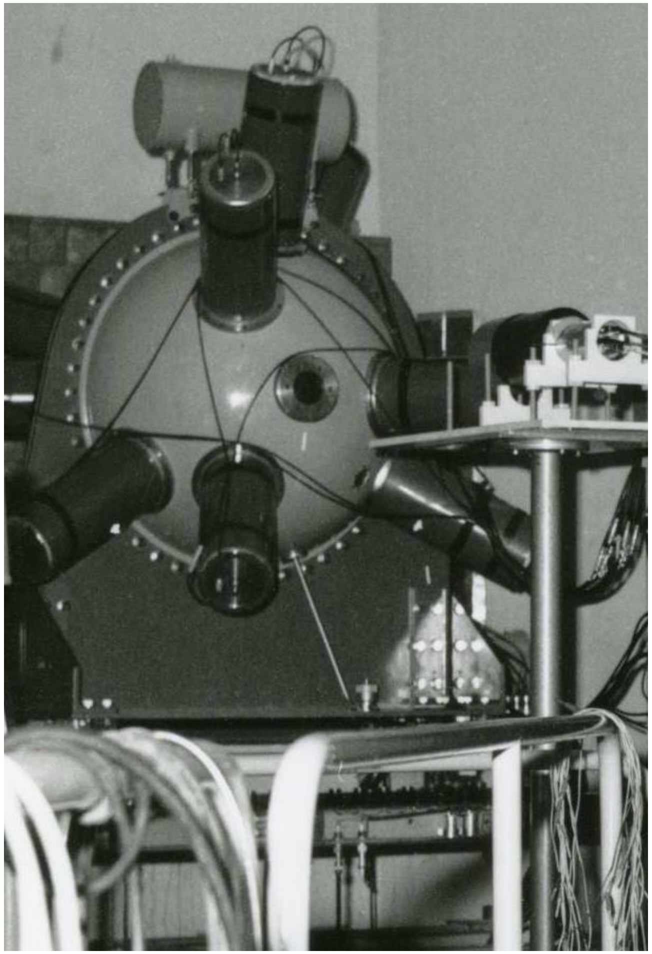
- Detector type :
  - Neutron balls
  - Neutron spectrometer

The neutron balls

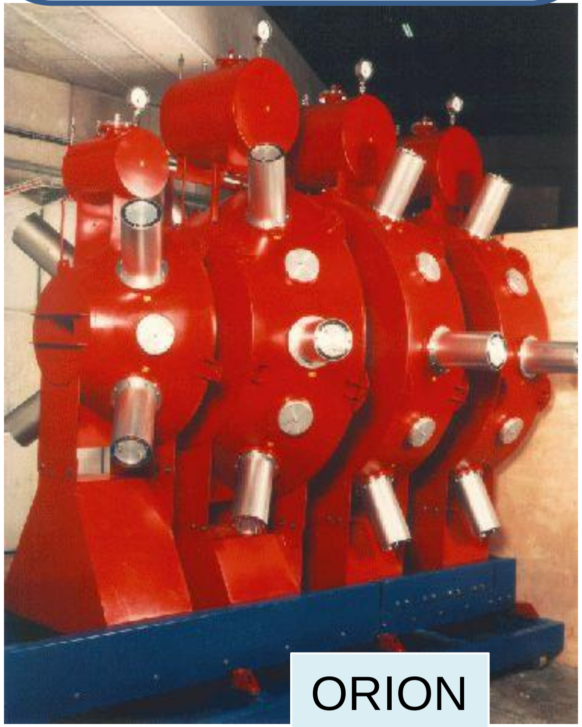
- Measurement of neutron multiplicity event by event
- Composed of a tank filled by liquid scintillator
- Phototubes detected the prompt and delayed signal

4π , high efficiency
High sensitivity to background

Application:
n,xn cross-section measurements
Nubar measurements
Hot nuclei studies



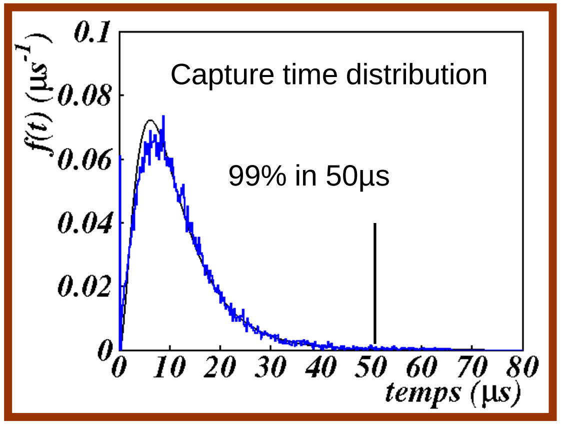
CARMEN

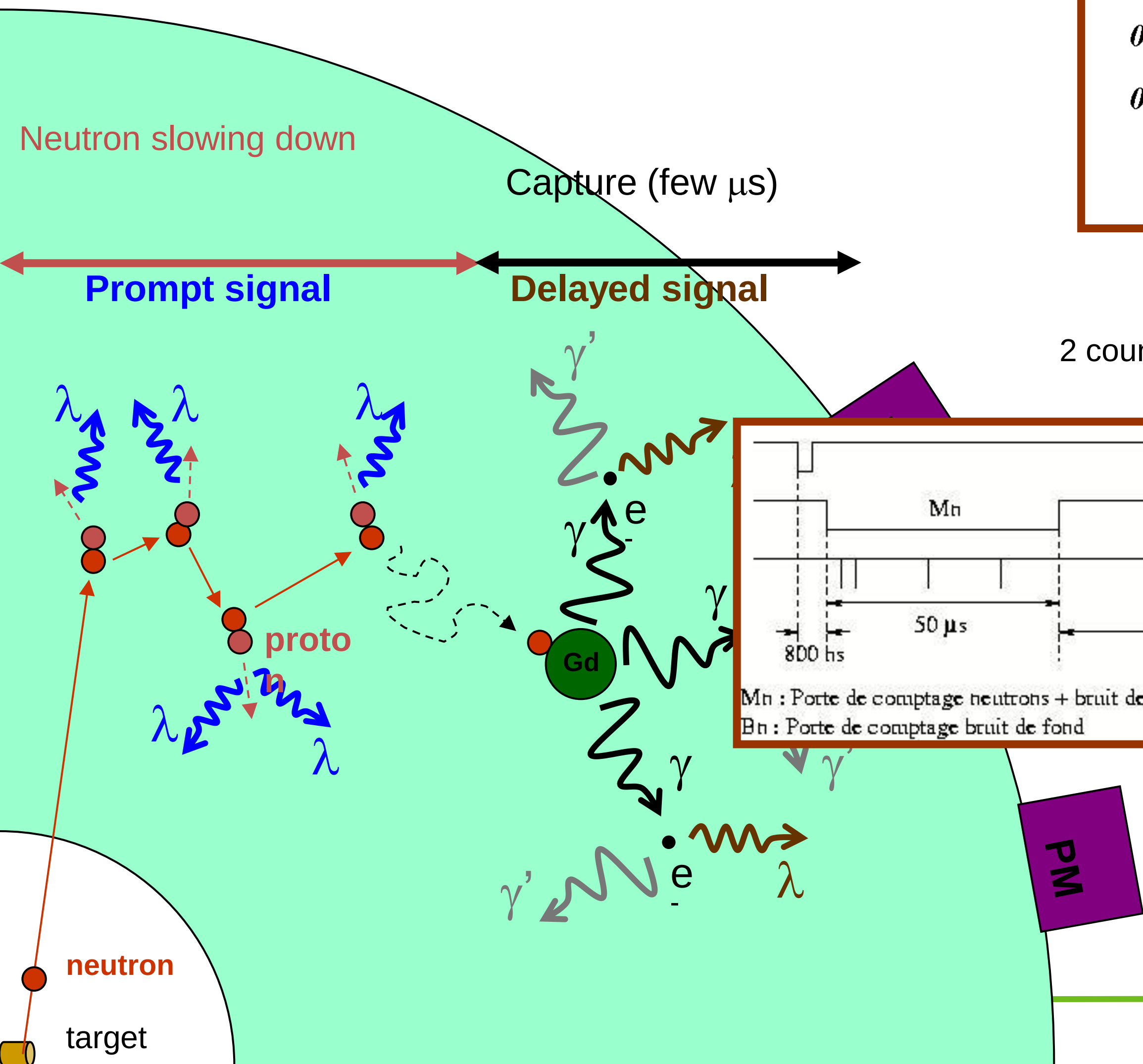


ORION

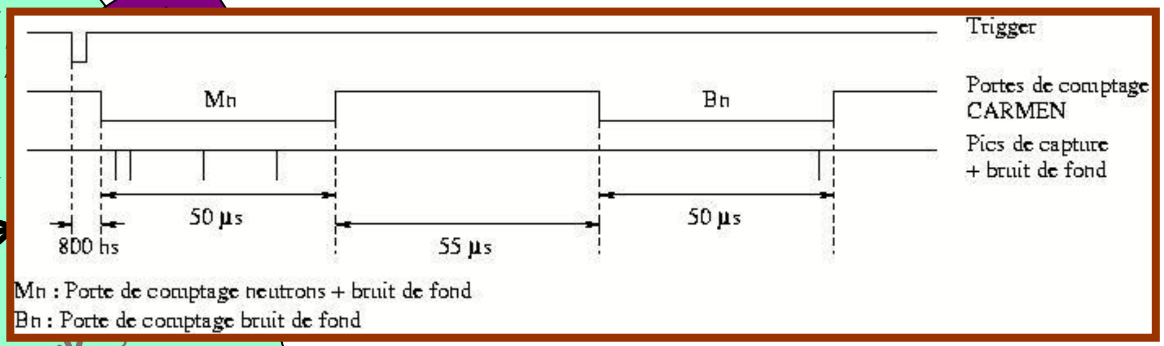
Measurement of neutron
Multiplicity distribution

The neutron balls : working process





2 counting gates of 50 µs long



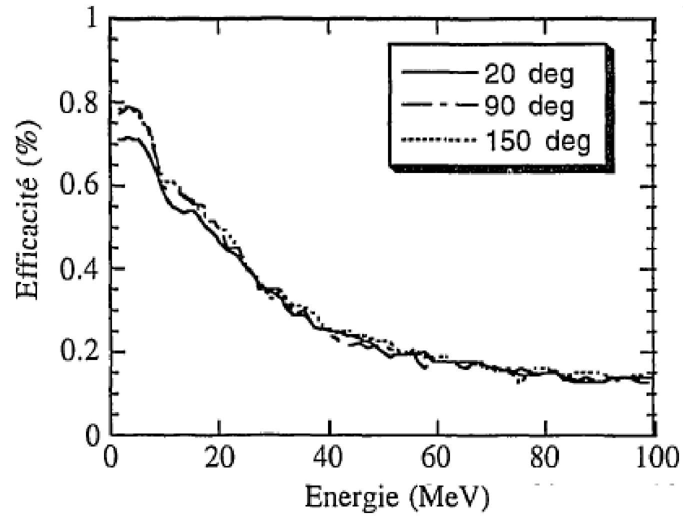
Efficiency

$$\varepsilon = \varepsilon_{capt} \cdot \varepsilon_{lum} \cdot \varepsilon_{coll}$$

Number of PM

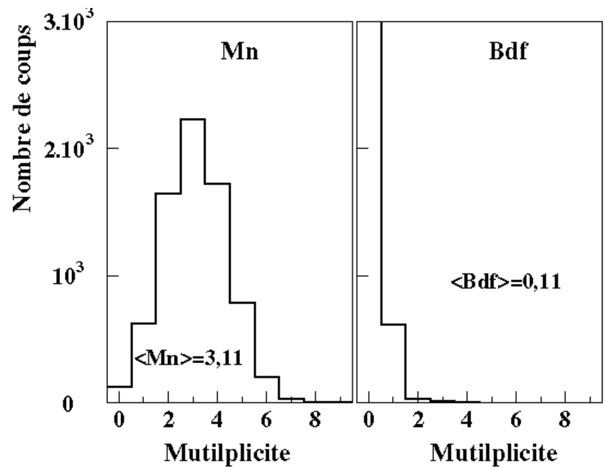
Size of detector, En

- The efficiency decreases when E_n increases :
  - escape probability
  - reactions on C
- Increase the thickness r would increase the efficiency but :
  - volume increases as r^3
  - increase the background sensitivity



Efficiency determination :

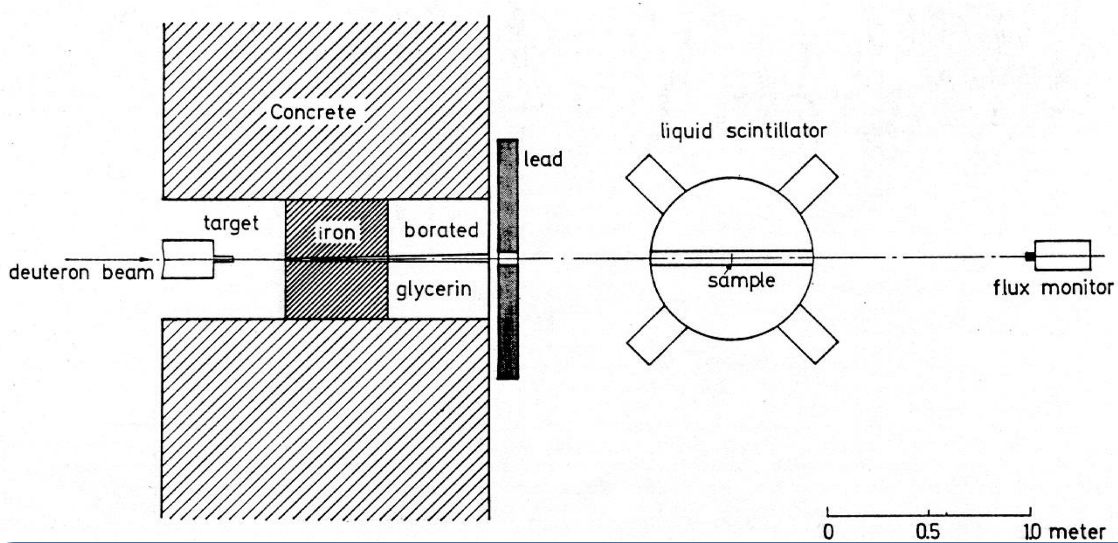
- Monte-Carlo Simulations
- Measurement
  - ^{252}Cf source (<ν>=3,78)
  - Mn distribution in coincidence with the detection of fission fragment



Efficiency ≈ 85% to fission neutrons

n,xn cross section measurement

Measurement of Mn(x) :number of reactions with neutron multiplicity x



$$\sigma_{n,xn} = \frac{M_n(x)}{\Phi\, N_{at}\, \varepsilon}$$

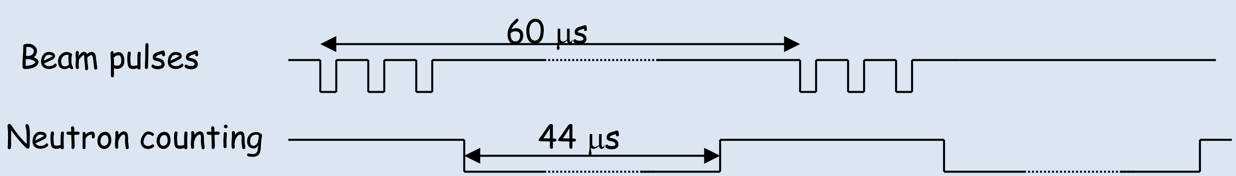
Φ = flux (cm^{-2})

N_{at} = m N_{av} / A

ε = efficiency

Trigger: prompt peak

Background : 2 gates and deconvolution



Passive target :

Mono-energetic neutrons

Efficiency : Cf source

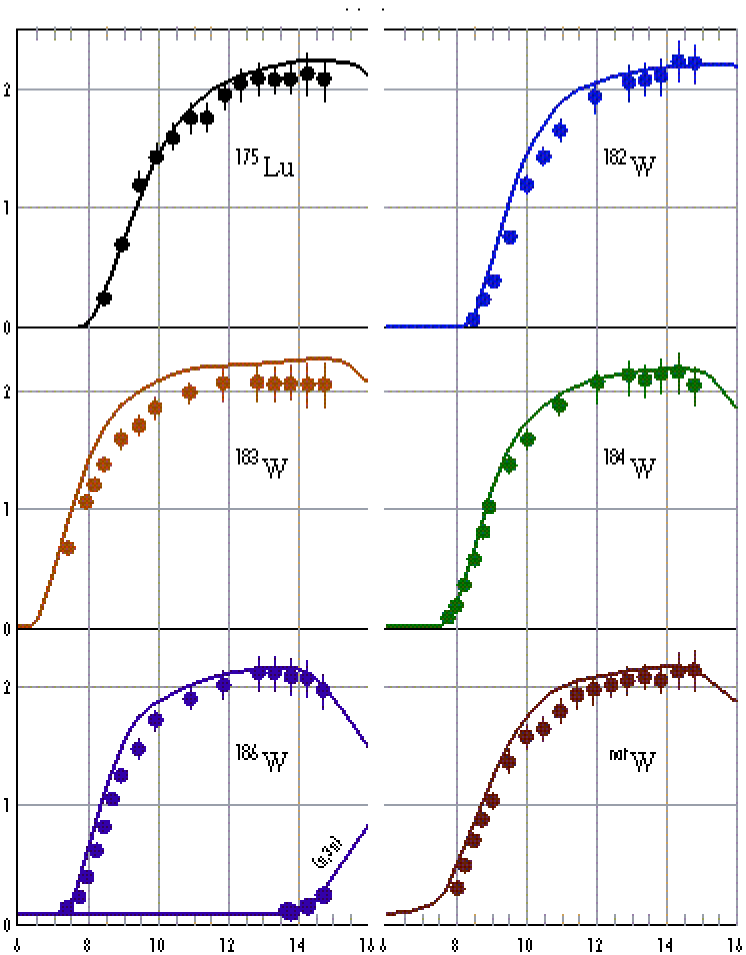
simulations to take into account the energy and angular distributions

J. Fréhaut, Nuclear Instruments and Methods 135 (1976) 511-518

V. J. Ashby et al., Physical Review 111, num 2 (1958) p 616

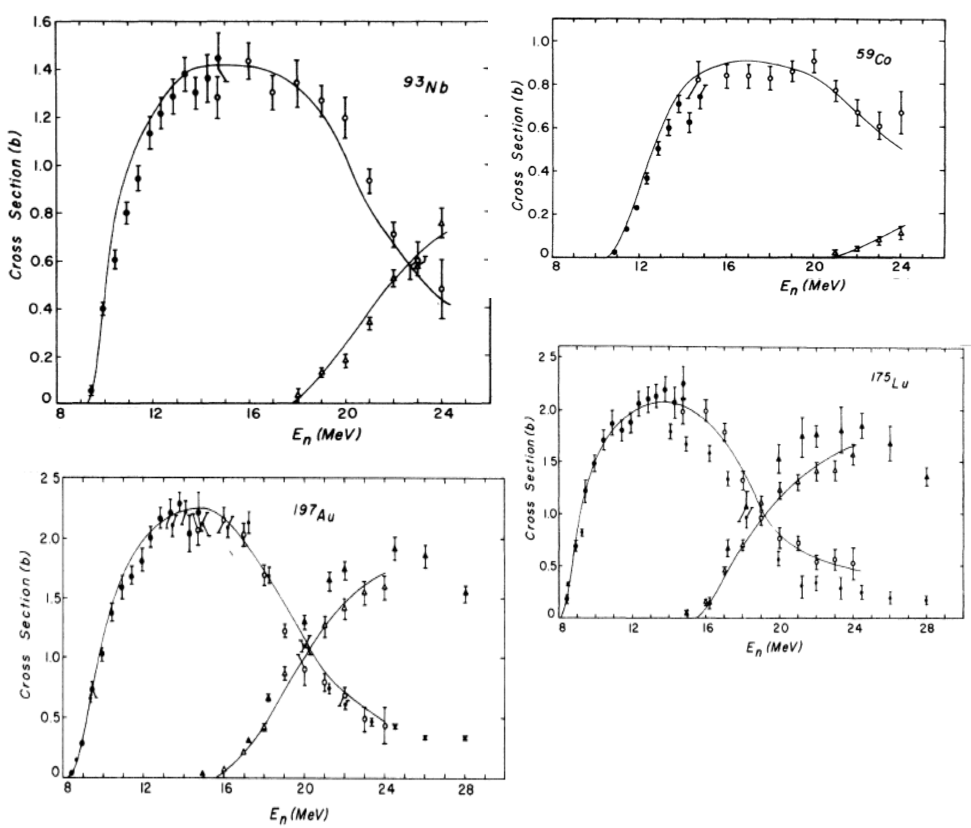
Some σ(n,2n) and σ(n,3n) measured with neutron balls

Fréhaut et al.



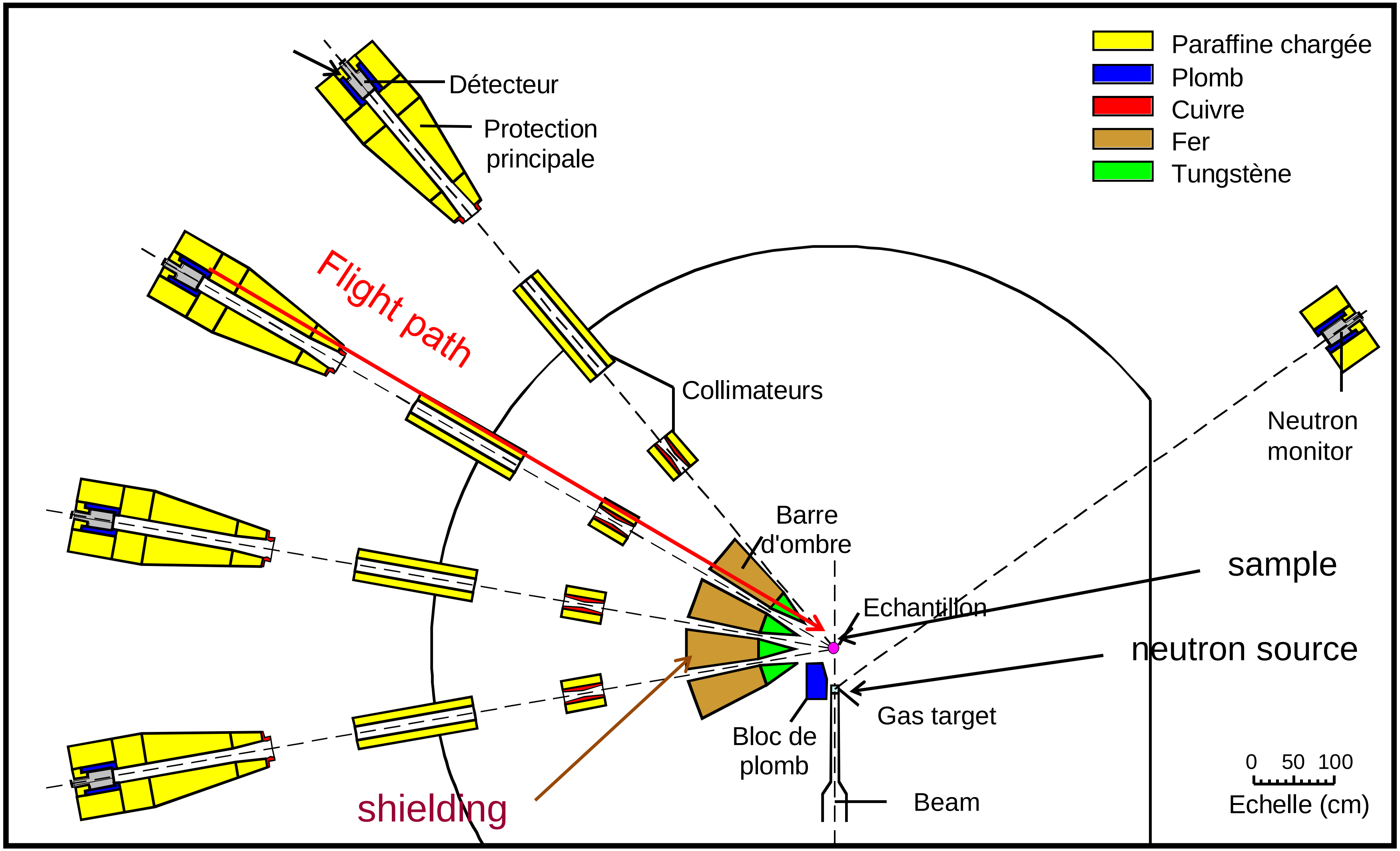
L. R. Veeser et al., PRC 16, num 5 (1977) p 1792

Comparison with radiochemical measurements



Neutron spectrometer

Elastic and inelastic cross-section measurements

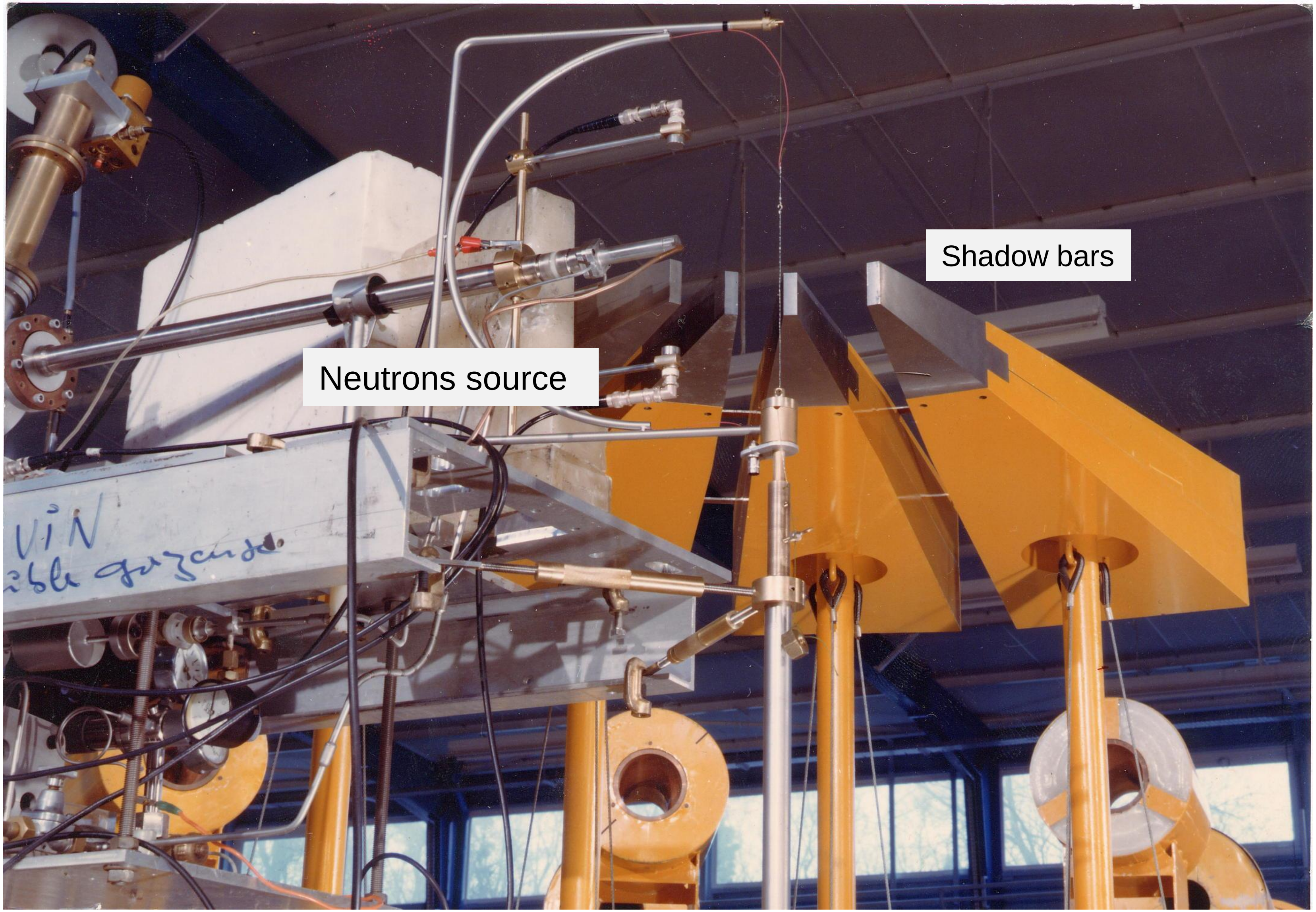


Spectrometer of CEA/Bruyères-le-Châtel

Low background facility
High resolution measurement

J. Lachkar, M. T. Mc Ellistrem, G. Haouat, Y. Patin, J. Sigaud and F. Coçu, *Phys. Rev.* **C 14**, 933 (1976)
G. Haouat, J. Lachkar, J. Sigaud, Y. Patin and F. Coçu, *Nucl. Sci. Eng.* **65**, 331-346 (1978)
G. Haouat, J. Lachkar, Ch. Lagrange, J. Jary, J. Sigaud, and Y. Patin, Nucl. Sci. Eng. 81, 491-511 (1982)

Sample and shadow bars



Neutron energy measurement

Energy measurement:

Flight path : d
tof_n

$$\Rightarrow v = \frac{d}{tof_n} \Rightarrow \beta = \frac{v}{c} \Rightarrow \gamma = \frac{1}{\sqrt{1-\beta^2}} \Rightarrow E = (\gamma - 1) m c^2$$

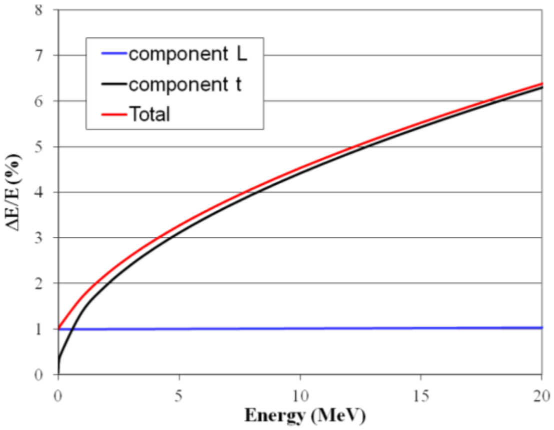
Start and stop signals : detector + accelerator or active target

Energy resolution:

$$\frac{\Delta E}{E} = \gamma(\gamma+1)\sqrt{\left(\frac{\Delta t}{t}\right)^2 + \left(\frac{\Delta d}{d}\right)^2}$$

Δt time resolution detector + accelerator ≈1ns

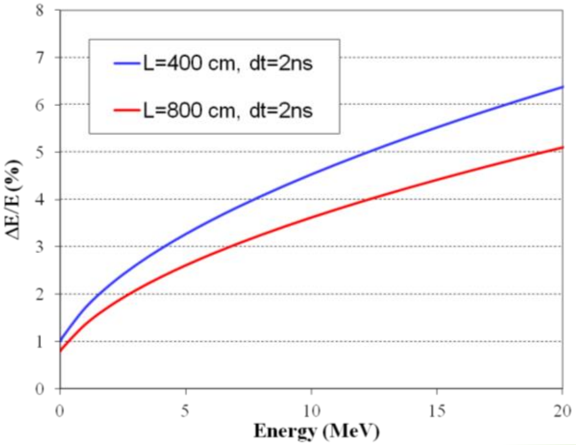
ΔL flight path uncertainty



The Flight path is a compromise between

The energy resolution

The efficiency

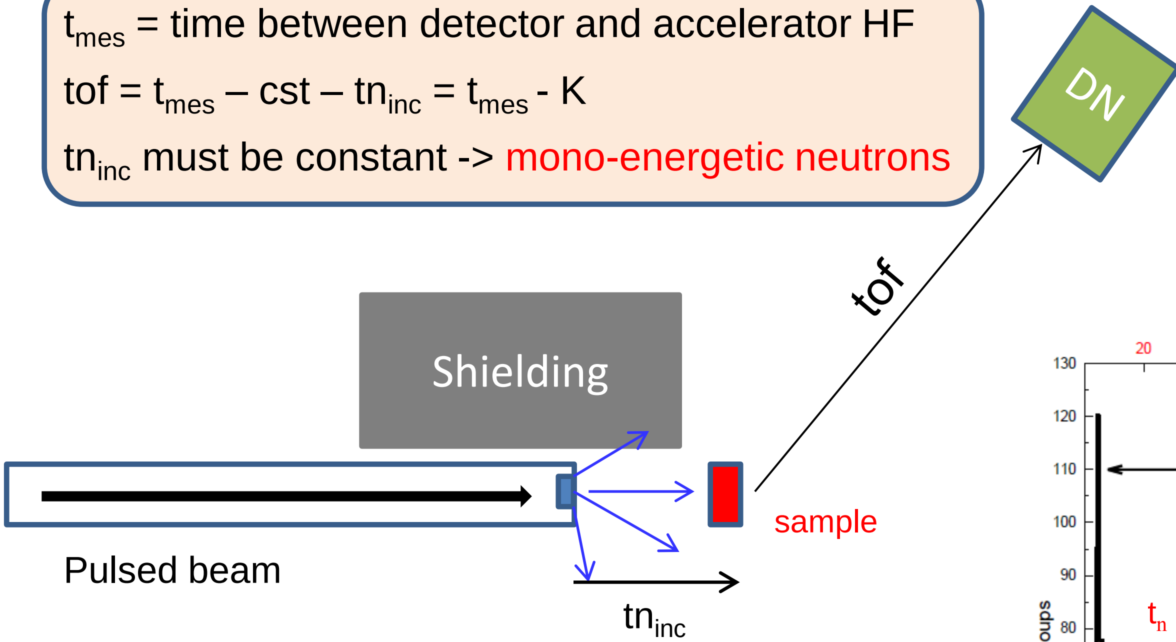


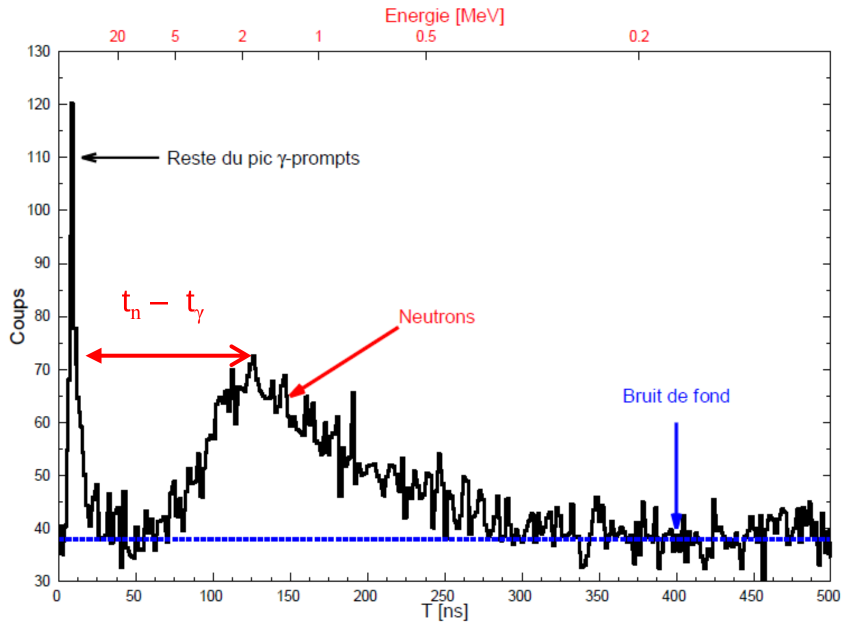
TOF technique

t_{mes} = time between detector and accelerator HF

$tof = t_{mes} - cst - tn_{inc} = t_{mes} - K$

tn_{inc} must be constant -> mono-energetic neutrons



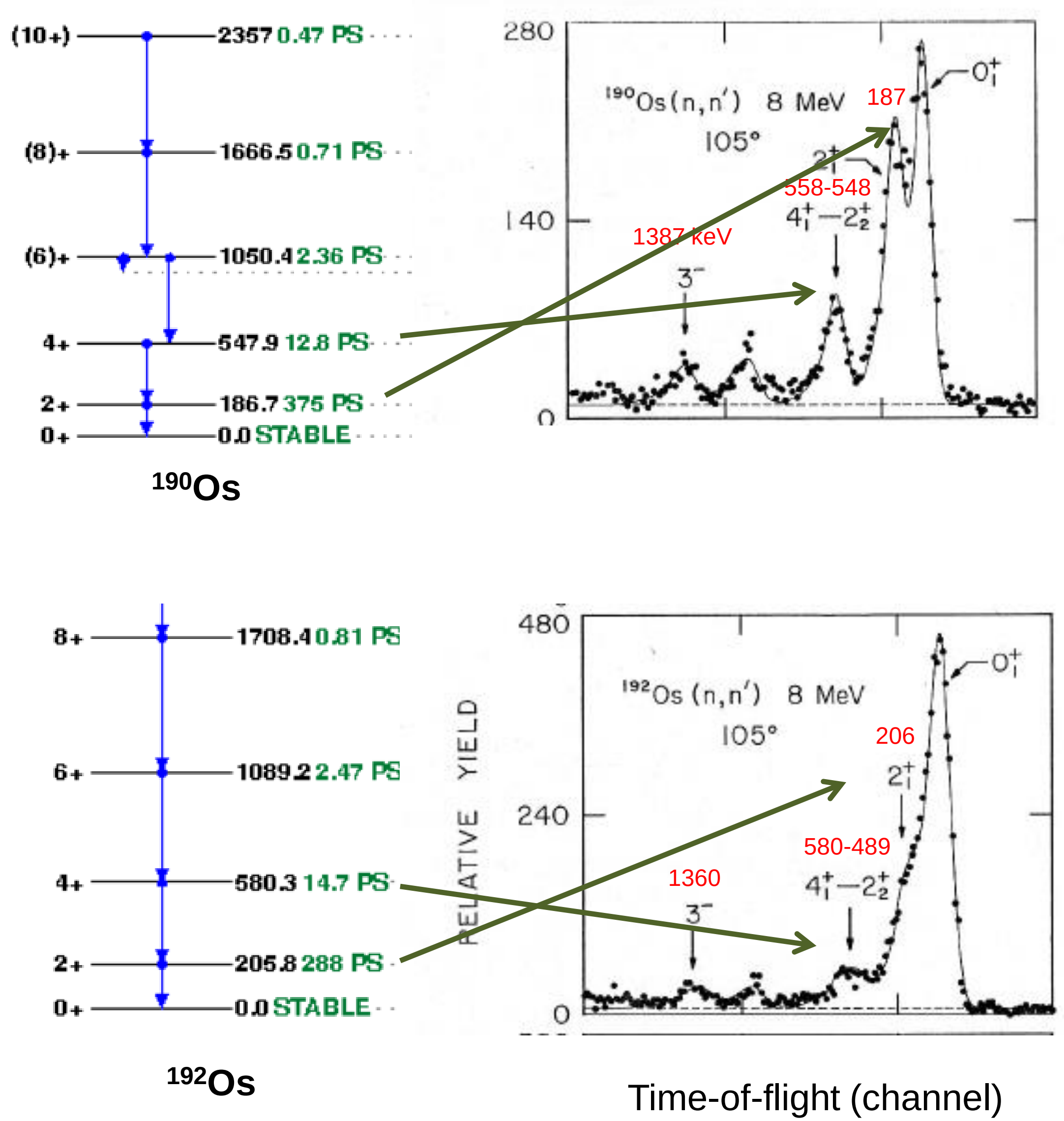


- ○ tof is not a absolute measurement
- ○ use of gamma to calibrate tof
- ○ $tof_\gamma = t_\gamma - K = d/c$
- ○ $K = t_\gamma - d/c$
- ○ $tof_n = t_n - K = t_n - t_\gamma + d/c$

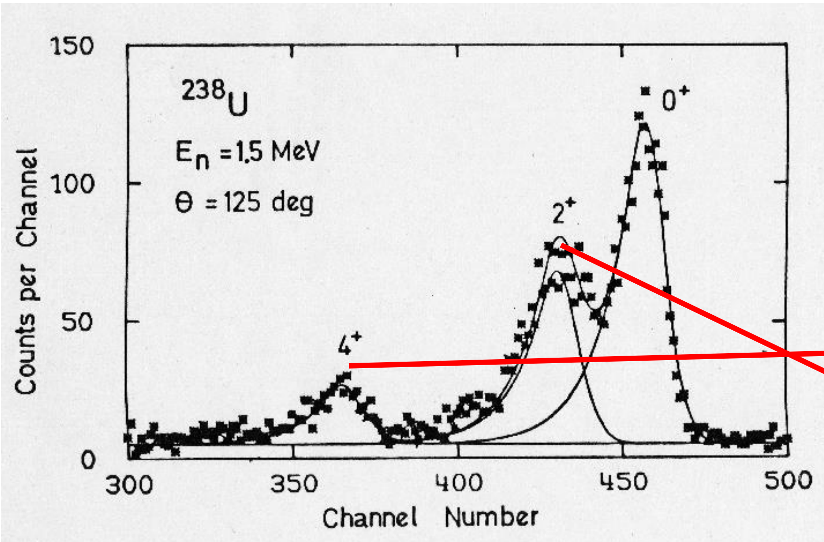
$^{190}Os(n,n')^{190}Os$

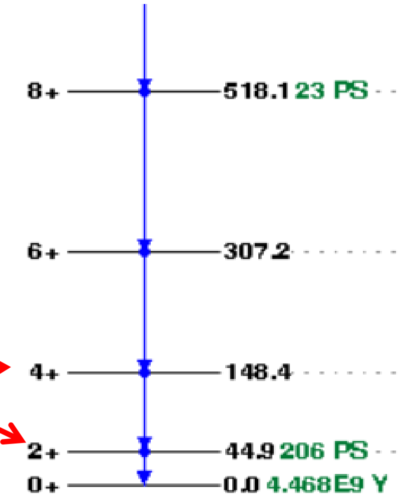
- E_n = 8,0 MeV
- L = 8,0 m
- θ = 105°
- Samples (Cylinders of metal)

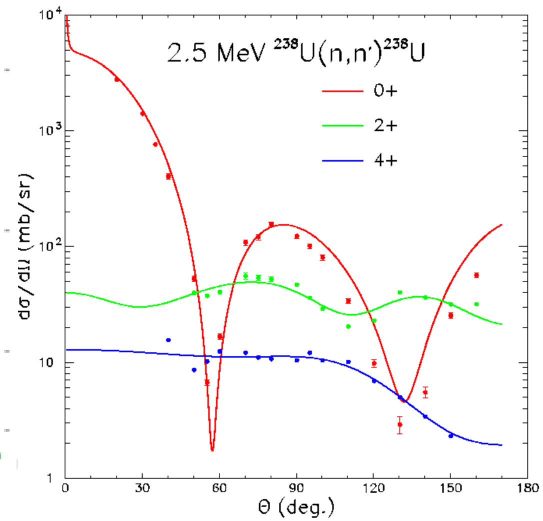
Noyau	m(g)
^{190}Os	38,82
^{192}Os	66,63

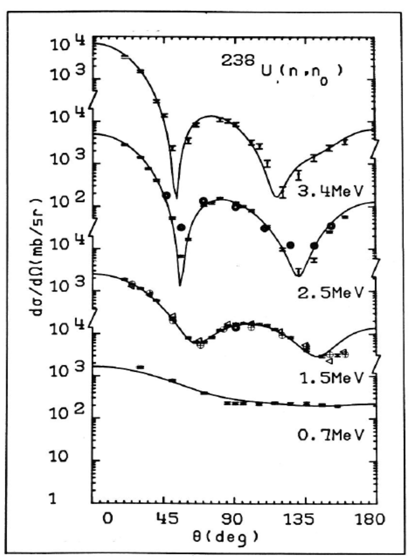


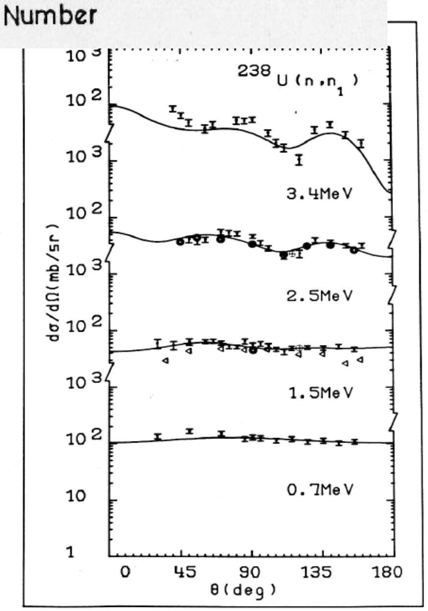
$^{238}U(n,n')^{238}U$

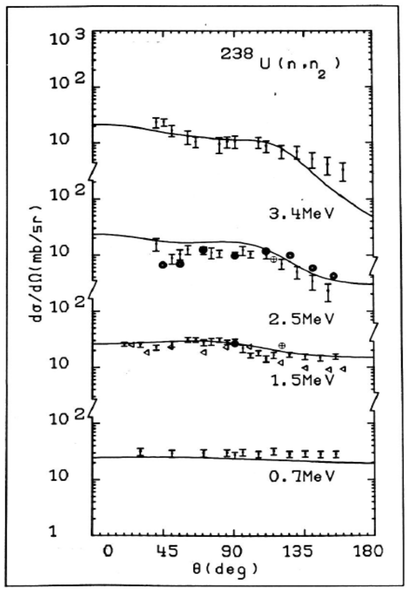












The first excited state 45 keV requires a very good energy resolution

E(MeV)	TOF (ns)
1,5	295
1,455	300
1,355	311

Counting rate estimation

- Neutron source
  - I= 3 to 5 µA
  - Tritium target

    Flux : $\Phi = 3.10^{8}$ n.sr^{-1}.s^{-1}
- Sample
  - m=30 g
  - A=190
  - Distance source sample d = 7 cm

    $d\sigma/d\Omega$= 10 mb.sr^{-1}
- Detector:
  - Surface detector = $\pi * r^2 = 122 cm^2$
  - Intrinsic efficiency = 10%
  - Distance from sample L=800 cm

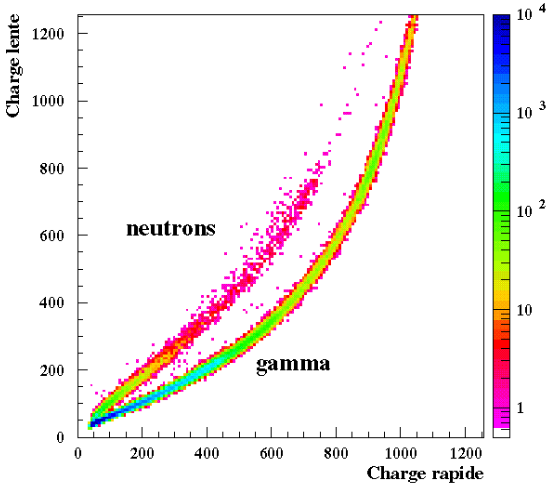
Number of neutrons detected by second :

$$N_{\det} = \frac{\Phi}{d^2} \frac{m N_{avo}}{A} \frac{d\sigma}{d\Omega} \frac{S}{L^2} \varepsilon$$

$N_{det} \approx 1$ counts/s

Multicells detectors

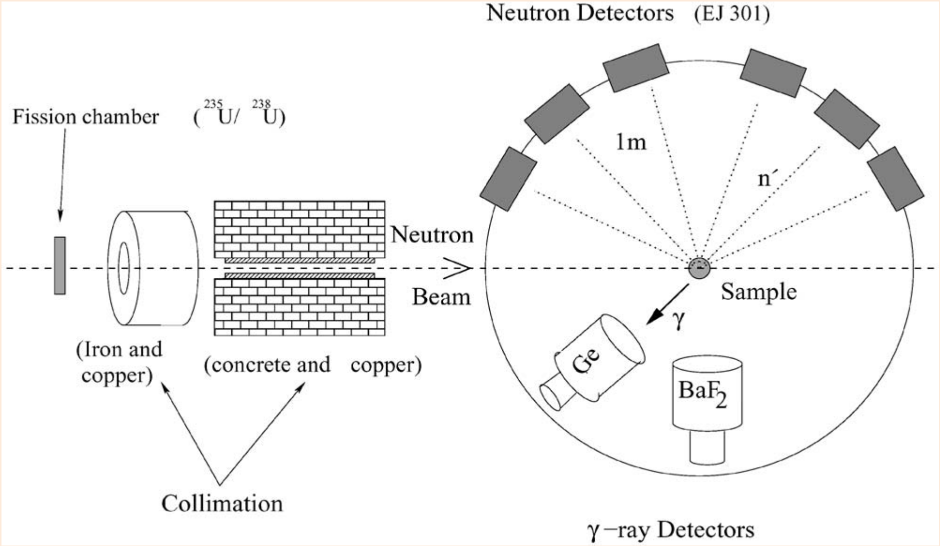
- ❑ Array of neutrons detector cells
- ❑ Low efficiency:
  - ○ Geometrical effect
  - ○ Intrinsic efficiency ≈ 20 %
- ❑ Measurement of average neutron multiplicity
- ❑ Measurement of energy and angular distributions



need a trigger signal

The FIGARO facility

(n,xn') measurements



20 EJ301 liquid scintillator
45 to 135°
1m of flight path

Nuclear Instruments and Methods in Physics Research A 523 (2004) 102–115

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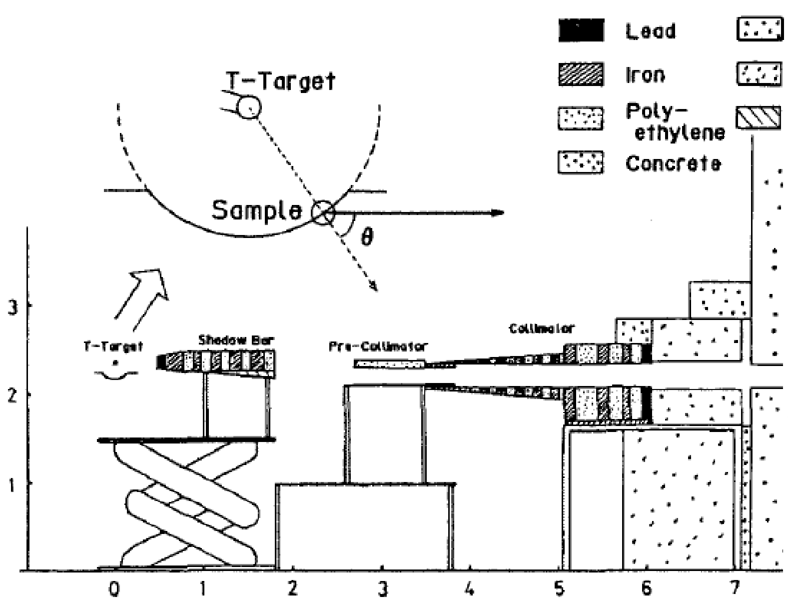
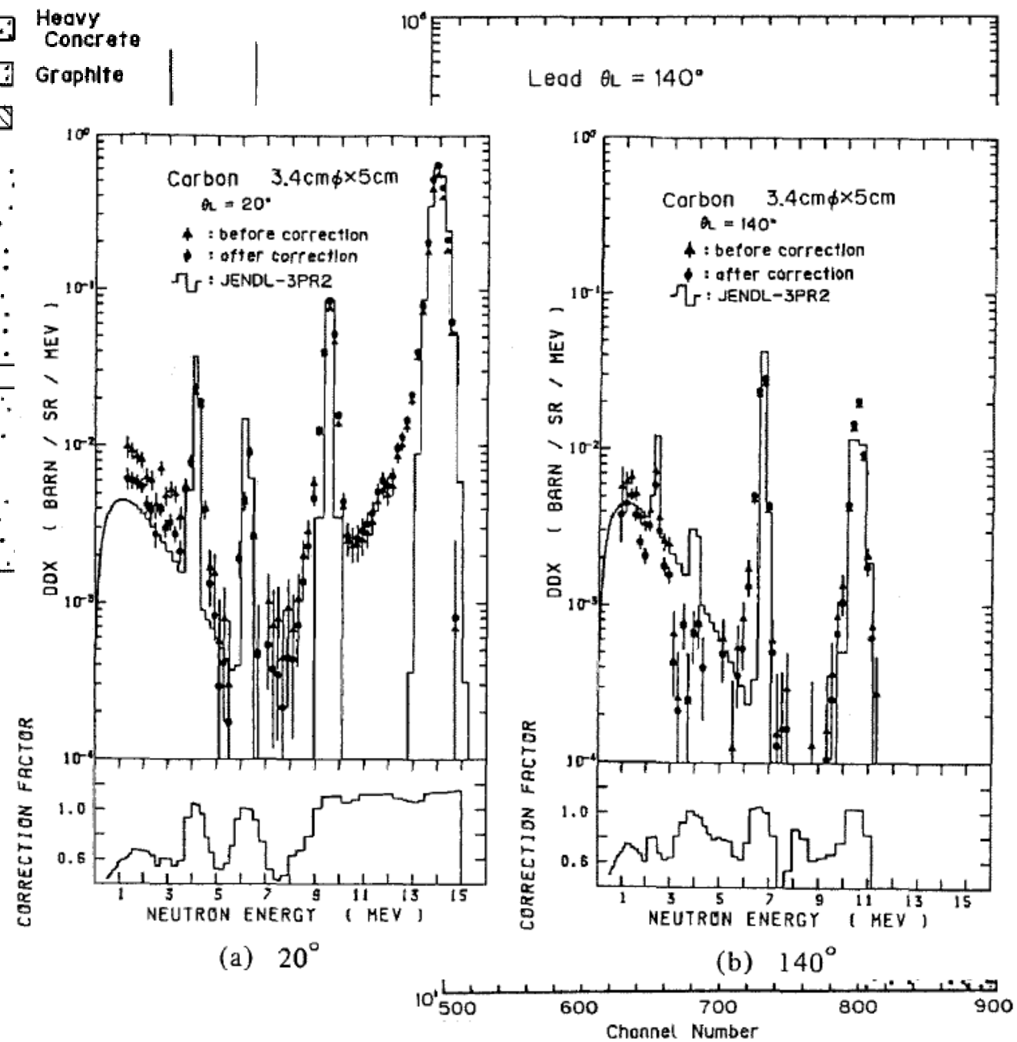
Measurement of double differential emission cross-section for incident neutrons of 14,1 MeV



Journal of Nuclear Science and Technology 25 (1985) pp 215



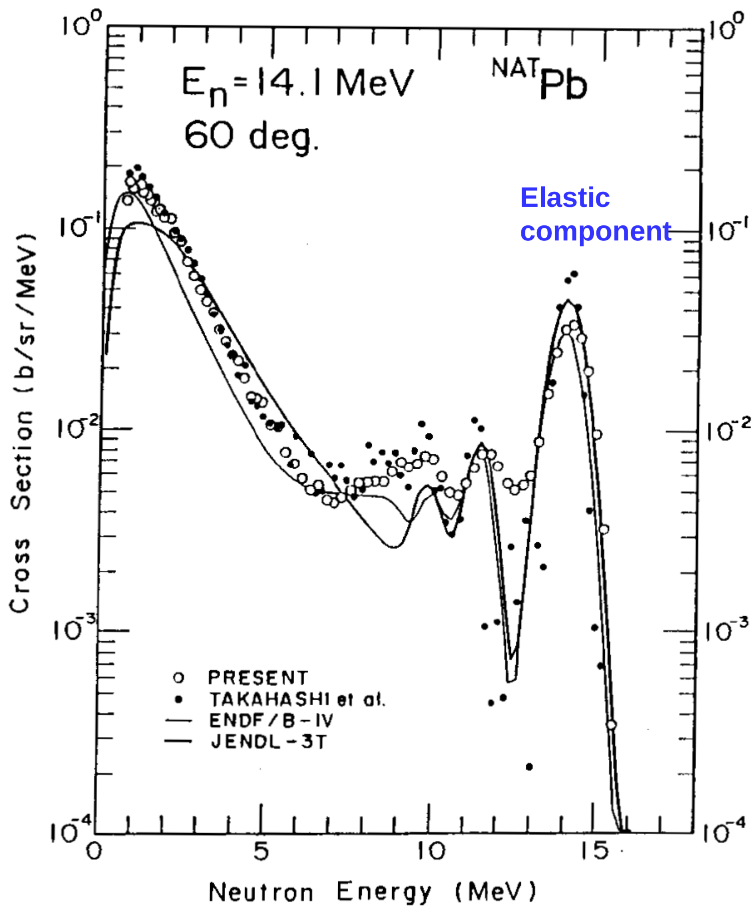
Sample Φ=3m scattering correction
Neutron source D-T
Beam frequency 1kH to 2 MHz
Flight path 8,3 m
Detector NE213

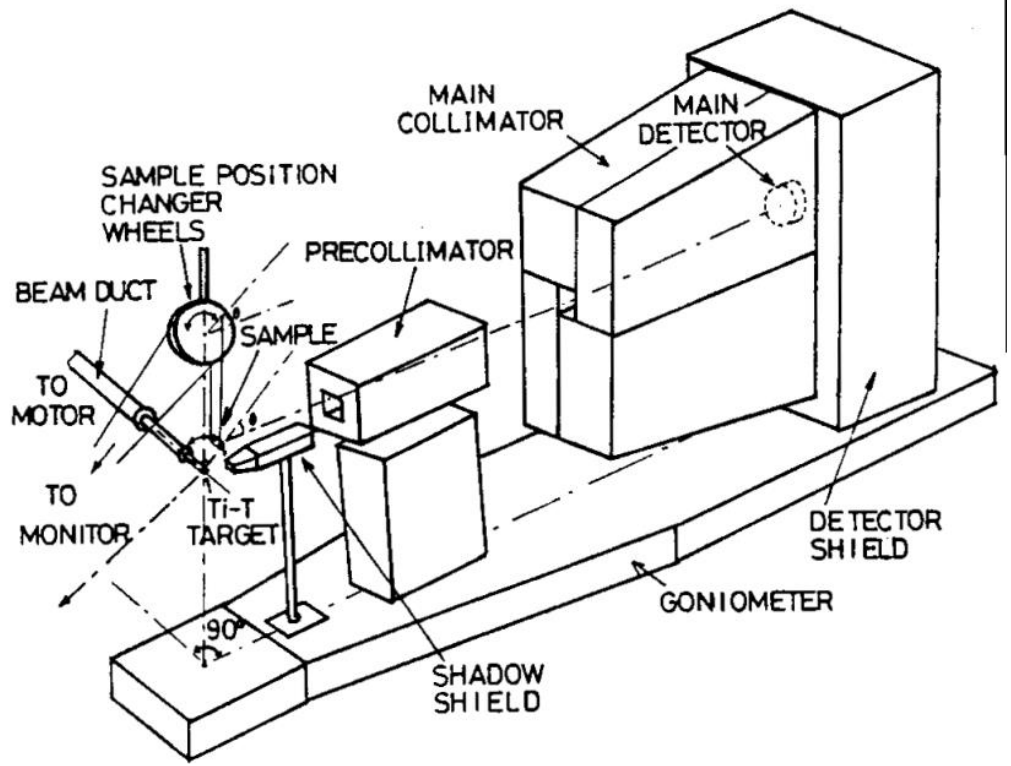
The neutron spectrum is the sum of all the channels where at least one neutron is emitted

Pb(n,2n)

Nuclear Data for Science and Technology (1988 MITO), 229- 232, Copyright © 1988 JAERI.

Sample Φ=3cm, h=4cm
Source d+T
Pulsed beam





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Department of Nuclear Engineering , Tohoku University
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^{239}Pu(n,2n) reaction cross-section measurement

$$n \quad + \quad {}^{239}_{94}Pu \quad \rightarrow \quad {}^{238}_{94}Pu \quad + \quad 2\,n$$

$T_{1/2}$= 24110 y

$T_{1/2}$= 87,7 y

α emitter 5456 keV
5499 keV

- Activation technique
- Measurement of direct neutrons
- n,xnγ measurement

^{239}Pu(n,2n)^{238}Pu cross-section by Activation technique

^{239}Pu(n,2n) cross-section measurement near E_n=14MeV, R. W. Lougheed, Radiochim. Acta 90, 833-843 (2002)

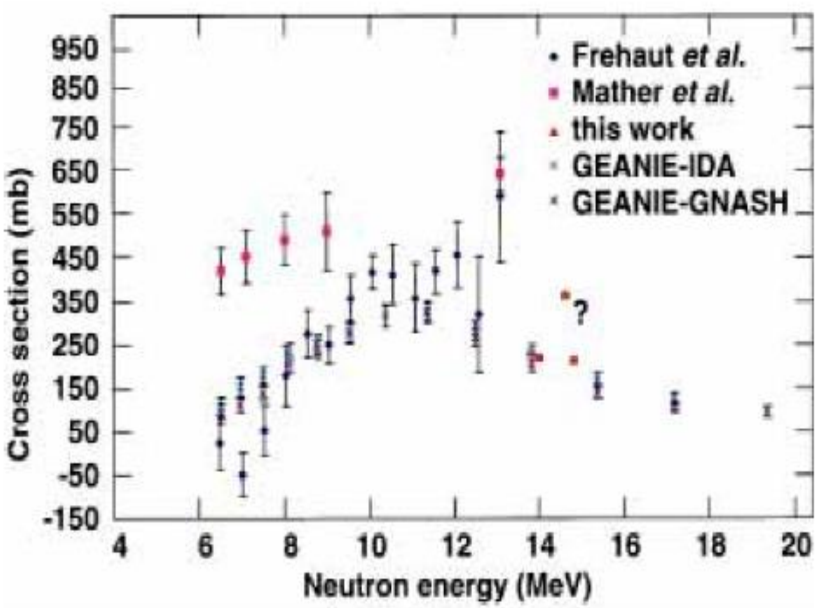
Irradiation :

- Neutrons produced by d+T reaction
- Flux : 5,5.10^{11} n.cm^{-2}.s^{-1}
- Integrated fluence : 8,98.10^{17} n in 4π

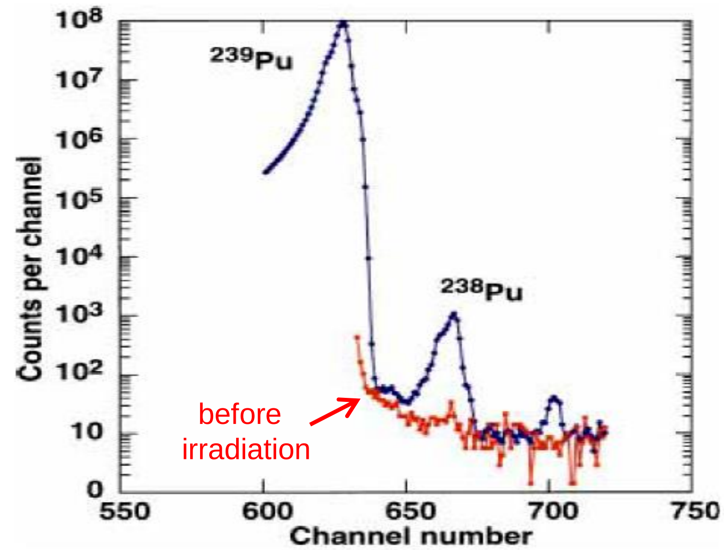
Sample :

- 130µg.cm^{-2}, Φ=3 mm →10µg
- ^{238}Pu/^{239}Pu ≈ 6.10^{-10} before irradiation
- Distance source sample 4mm

Monitoring : Au(n,2n) cross-section



^{238}Pu Activity → alpha spectroscopy

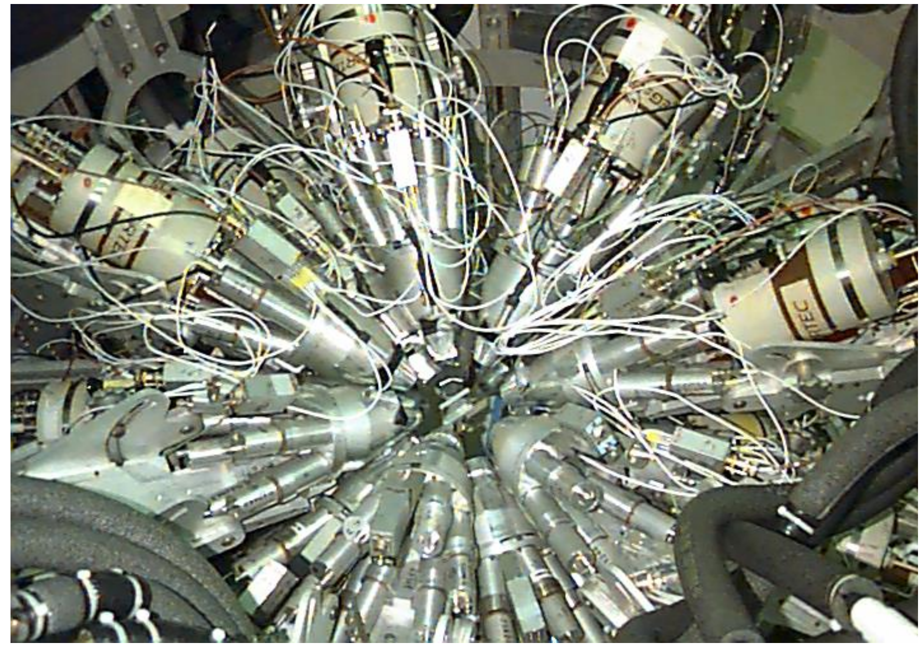


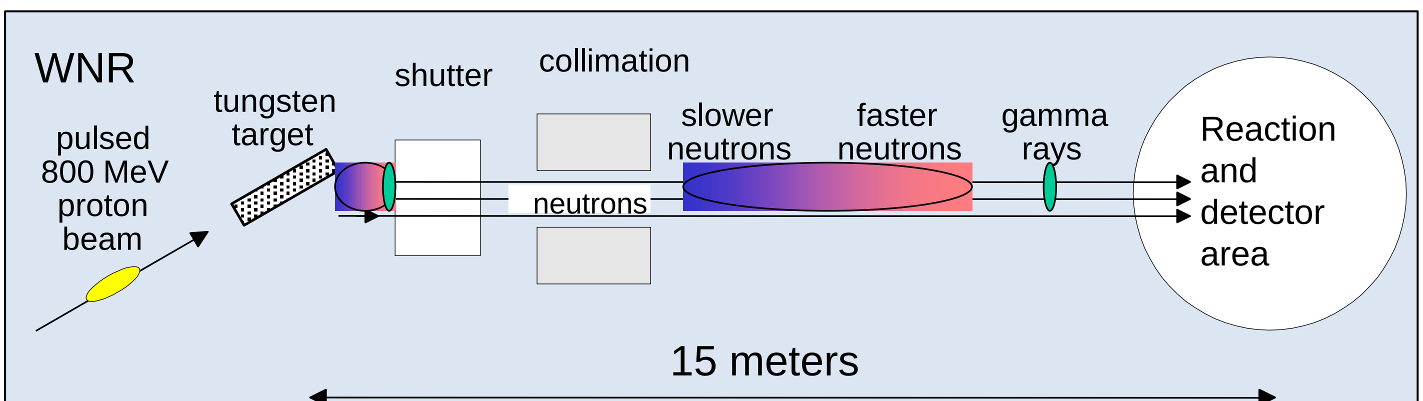
Before irradiation: A(^{238}Pu)≈ 0,004 Bq
Integrated fluence = 8,98.10^{17} n.cm^{-2}
After irradiation of
m= 10µg
σ=0,3 barn
Nat ^{238}Pu = 10^{9}
A(^{238}Pu) ≈ 2 Bq

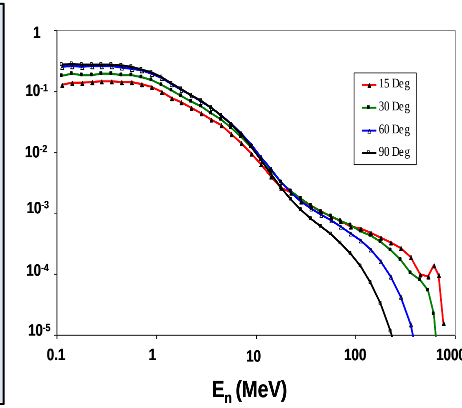
^{239}Pu(n,2n)^{238}Pu cross-section from partial γ-ray cross-sections (1)

- ❑ LANSCE (Los Alamos Neutron Science Center)
  - Spallation source
  - White neutron beam
  - Pulsed beam
- ❑ GEANIE
  - 26 high-resolution Ge detectors
  - BGO escape-suppression shields.

GErmanium Array for Neutron Induced Excitations

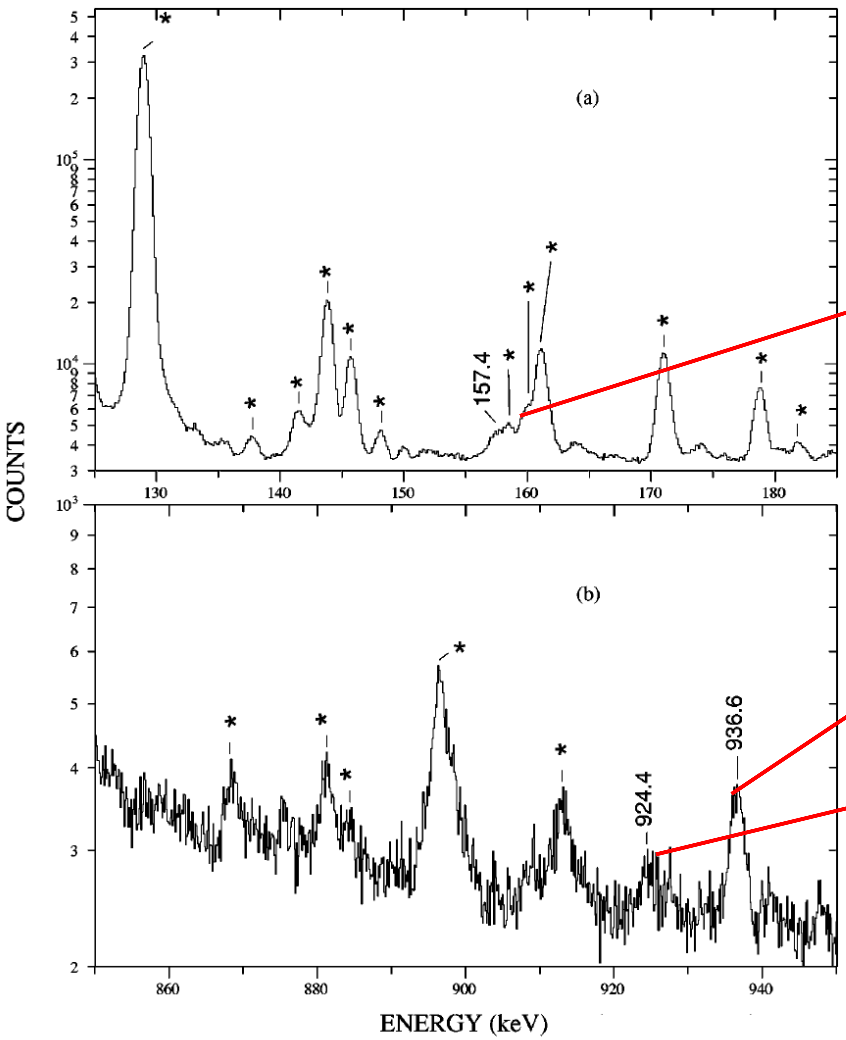


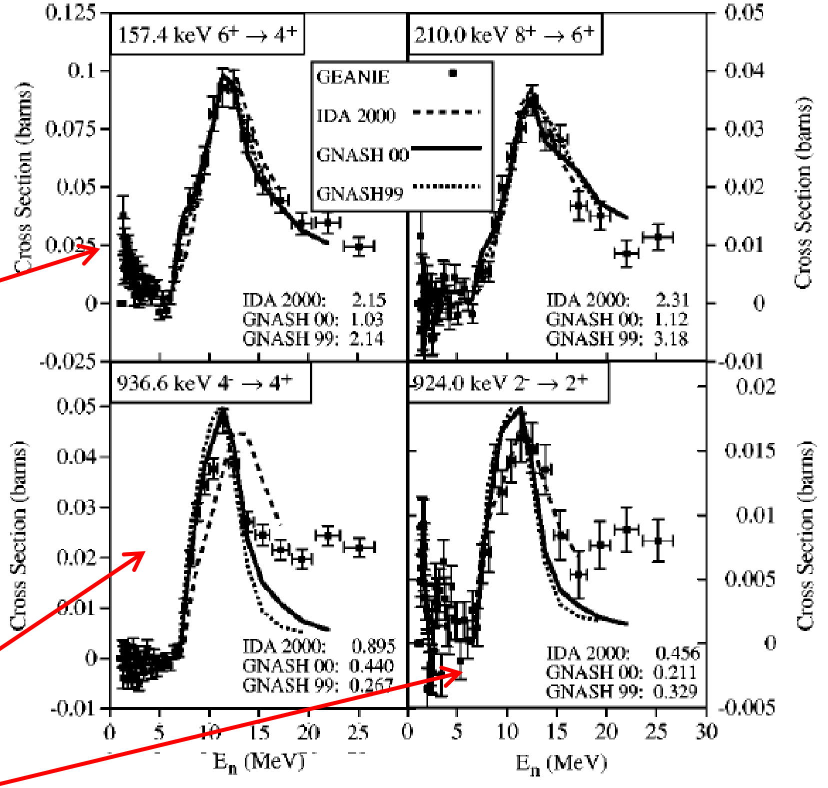




$^{239}Pu(n,2n)^{238}Pu$ cross-section from partial γ-ray cross-sections (2)

En=11,37 MeV





Use of theoretical calculations to deduce (n,2n) cross-section

L. A. Bernstein at al., PHYSICAL REVIEW C **65 021601(R)**

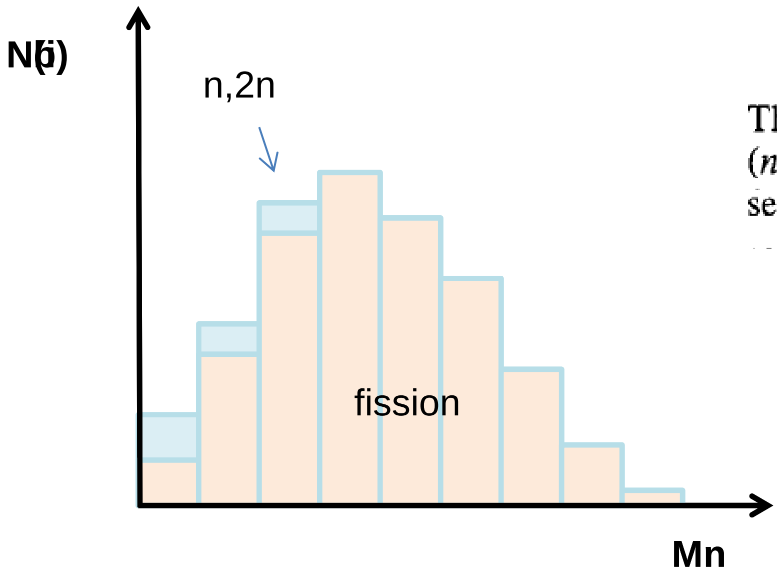
Direct measurement of secondary neutrons

Difficulty : distinguishing fission neutrons from (n,2n)

- Total neutrons multiplicity measurement (n,fis) + (n,2n) + (n,n')
  - Neutron ball
  - Thick target
  - Trigger on prompt peak
- For Mn≥ 4 only fission contribution
- Mn=2

$$N_F = \frac{\sum_{i\geqslant 4} N(i)}{\sum_{\nu\geqslant 4} P(\nu)} \; .$$

P(i) fission multiplicity probability



$$N_2 = N(2) - N_F P(2) \; ,$$

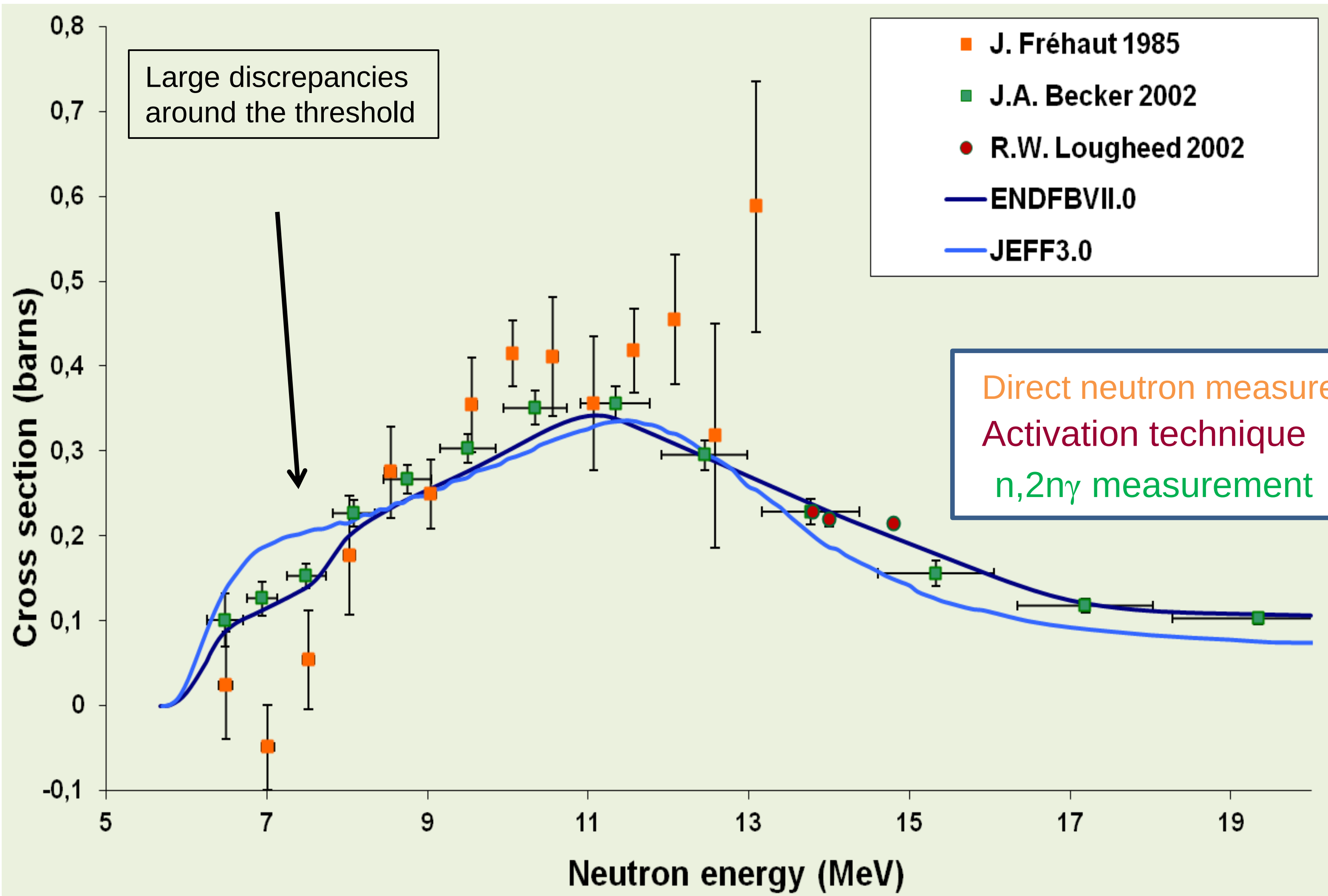
$$N_3 = N(3) - N_F P(3) \; . \qquad (2)$$

This method therefore provided the ratio of the $(n,2n)$ or the $(n,3n)$ cross section to the fission cross section:

$$\frac{\sigma_2}{\sigma_F} = \frac{N_2}{N_F} \quad \text{and} \quad \frac{\sigma_3}{\sigma_F} = \frac{N_3}{N_F} \; . \qquad (3)$$

J. Fréhaut et al. NUCLEAR SCIENCE AND ENGINEERING: **74, 29-33 (1980)**

Results on the $^{239}Pu(n,2n)^{238}Pu$ cross-section measurements

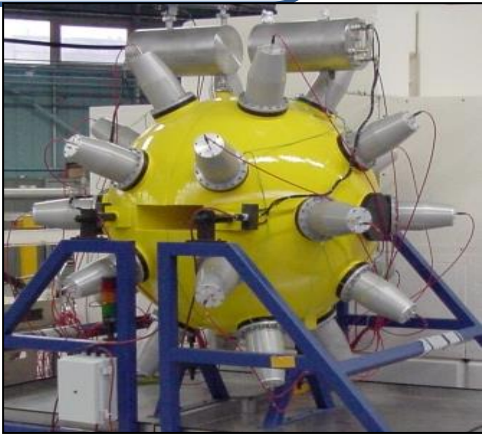


Direct neutron measurement
Activation technique
n,2nγ measurement

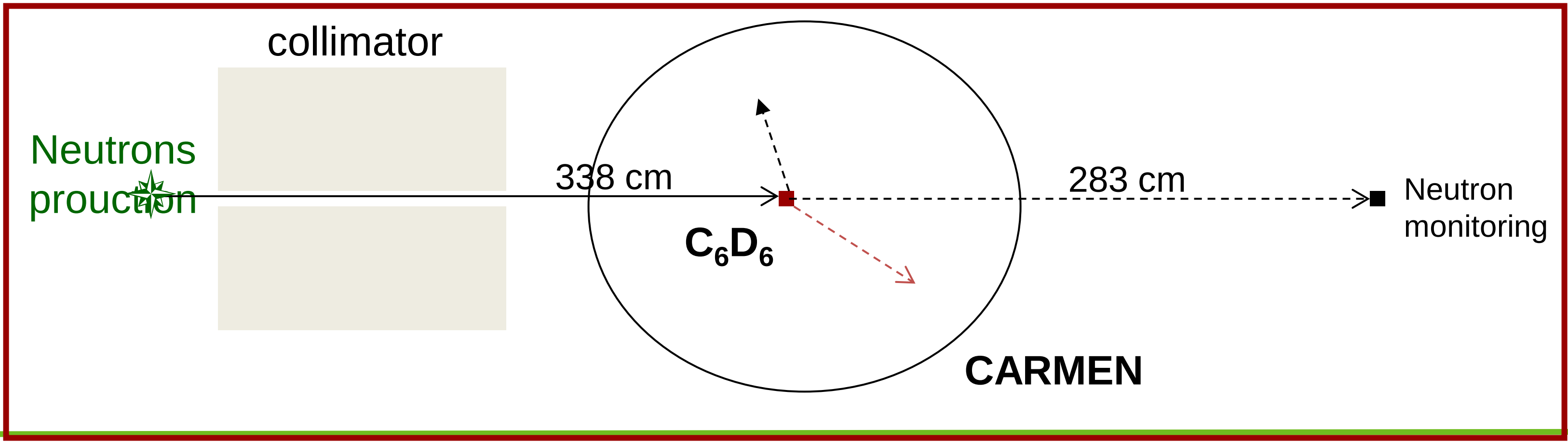
Cross-section measurement of the D(n,2n) reaction (1)

n + D → p + n + n Eth=3.34 MeV

- Three bodies system in the exit channel
- The emission of the 2 neutrons cannot be treated like evaporated neutrons
- Theoretical model based on the resolution of the Faddeev equations (J. Carbonell et B. Morillon)

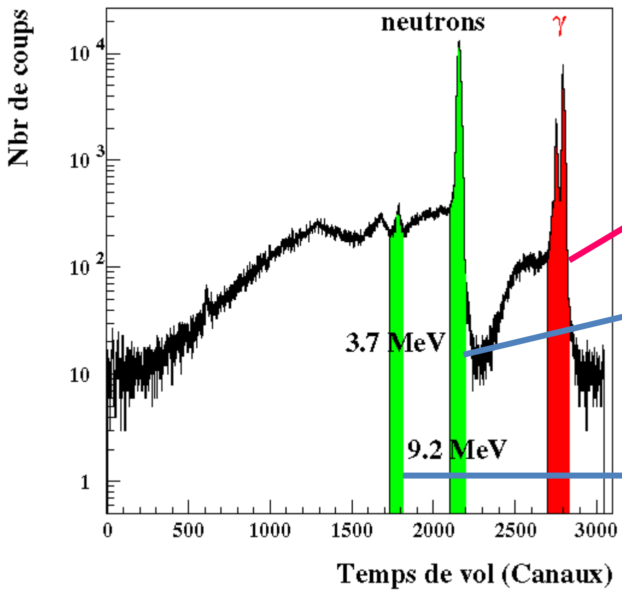


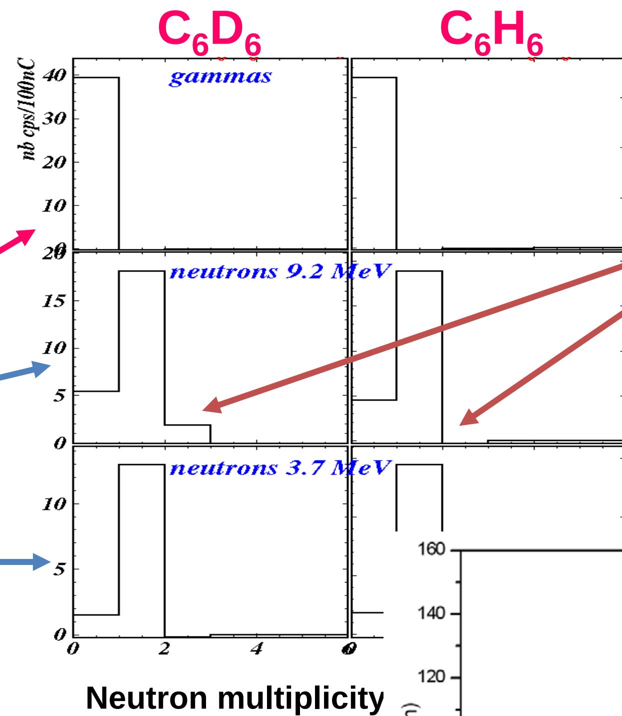
- Measurement of the 2 neutrons emitted -> Neutron ball
- Active target made of C_6D_6 :
  - reaction tagged by the recoil of the proton
  - incident neutron energy measured by time of flight
- Measurement with C_6H_6 target to subtract the carbon contribution



Cross-section measurement of the D(n,2n) reaction (2)

Incident neutron TOF





Number of events of multiplicity 2

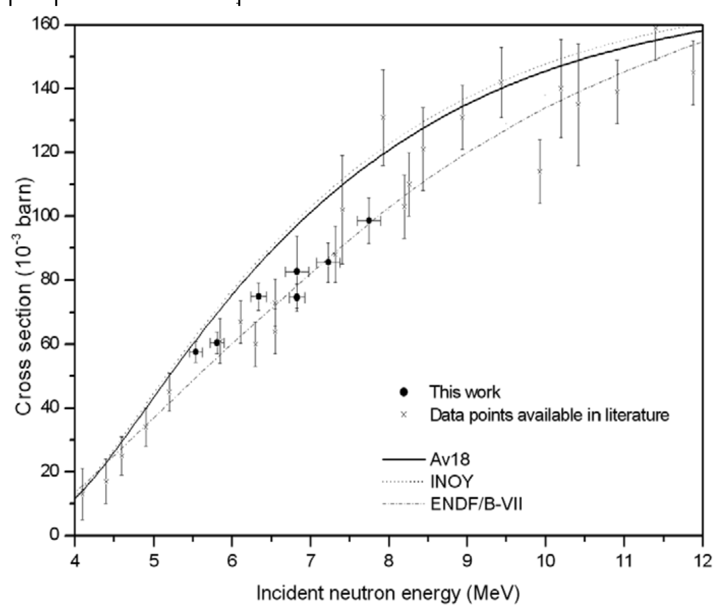
$$\sigma_{n,2n} = \frac{M_{C_6D_6}(2) - M_{C_6H_6}(2)}{\Phi \varepsilon N_{at}}$$

Φ flux on the target

N_{at} number at D nuclei in the target

ε detection efficiency of 2 neutrons

ε must take into account the correlation between the 2 neutrons



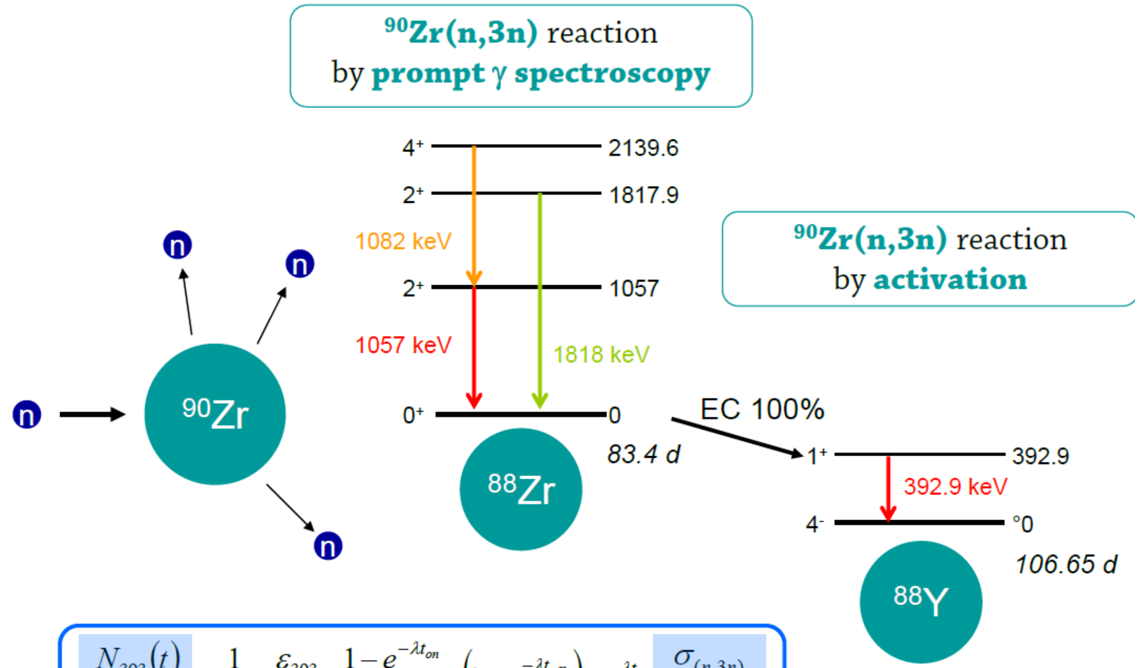
J. M. Laborie et al, EPJA (2012)

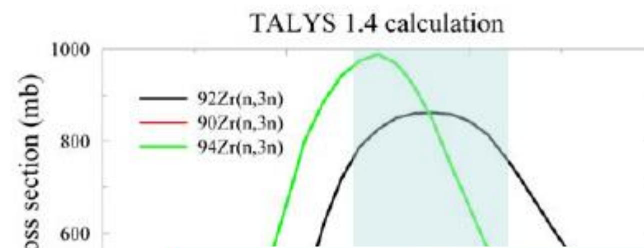
(n,3n) cross section measurement by two techniques

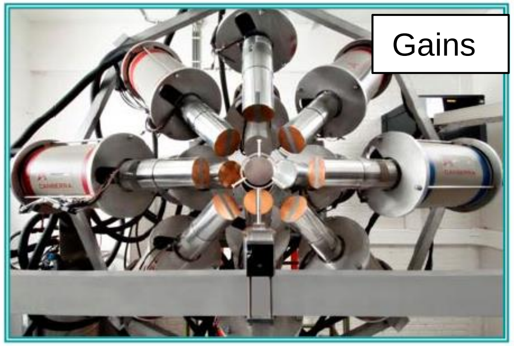
The (n,xnγ) cross-section measurements are used to extract (n,xn) cross section-> need of theoretical model

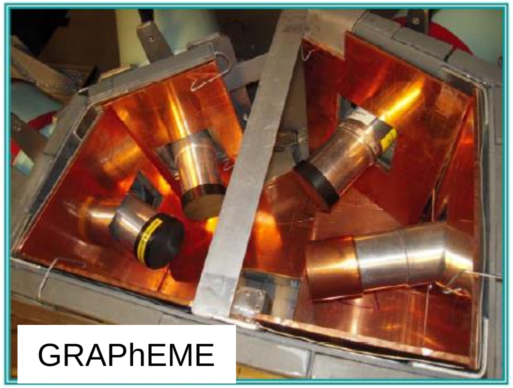
At NFS the $^{90}Zr(n,3n)$ cross-section can be measured by prompt γ spectroscopy and by activation technique at the same time

→validation of the theoretical models









$$\frac{N_{393}(t)}{N_{1057}(t)} = \frac{1}{t_{on}} \cdot \frac{\varepsilon_{393}}{\varepsilon_{1057}} \cdot \frac{1-e^{-\lambda t_{on}}}{\lambda} \cdot \left(1-e^{-\lambda t_{off}}\right) \cdot e^{-\lambda t_d} \cdot \frac{\sigma_{(n,3n)}}{\sigma_{(n,3n\gamma)}}$$

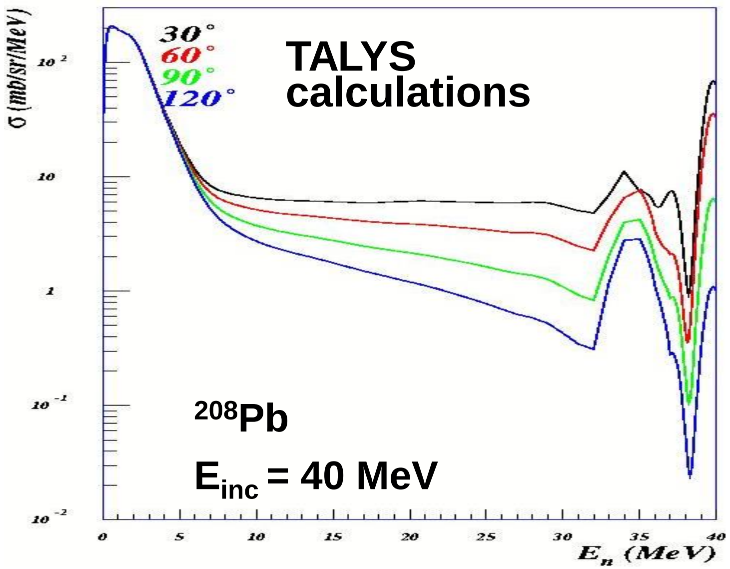
Quasi-mono-energetic neutrons from 26 to 32 MeV

M. Kerveno et al., Letter of Intents for NFS facility

Study of pre-equilibrium process in (n,xn) reaction

Measurement of (n,xn) double differential cross section in coincidence with neutron multiplicity.

Validation of pre-equilibrium models



Method :

- measurement of energy and angle of one neutron
- count of the (x-1) neutrons emitted simultaneously.

Beam request:

- Quasi-monkinetic beam
- Pulsed
- Well collimated

Experimental set-up :

- NE213 detectors
- CARMEN detector

X. Ledoux et al., Letter of Intents for NFS facility

Summary

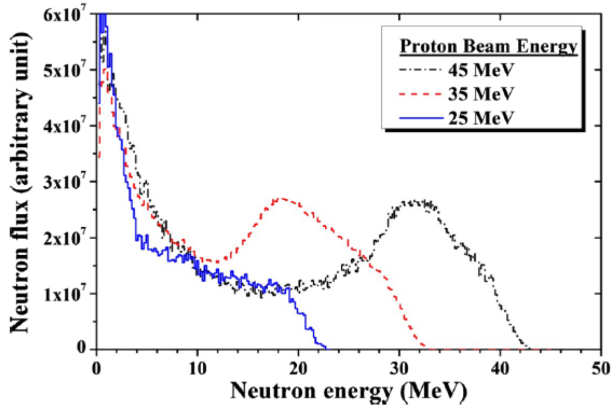
- n,xn reactions play an important role in the 1 MeV – 50 MeV range
  - Reactor
  - Waste production in high neutron flux
  - Accurate library of nuclear data
- Several techniques exist
  - Activation
  - n,xnγ reactions
  - Direct outgoing neutron measurement
- All the techniques cannot be used in all cases
  - Specific detection set-up
  - Specific neutron facilities

Yttrium

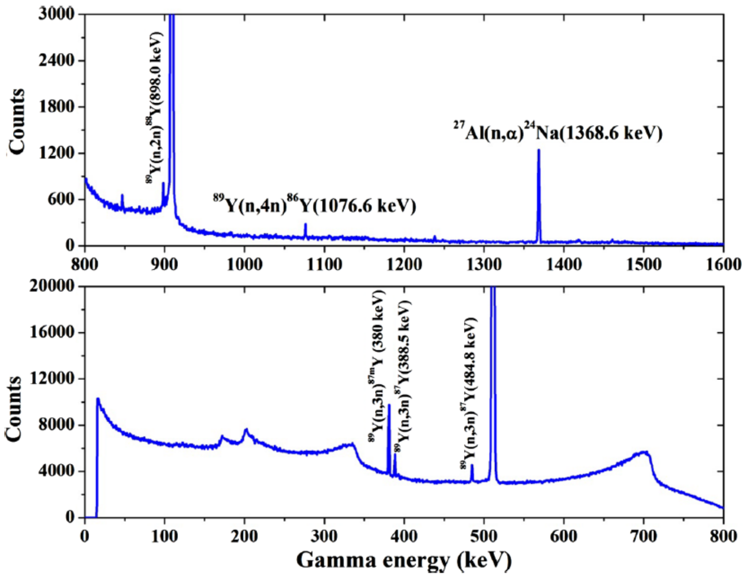
Thus the (n, xn) reaction of 89Y is important, when the superconductor is used in the neutron field of higher energy such as in the fast reactor and accelerated driven sub-critical system (ADSs).

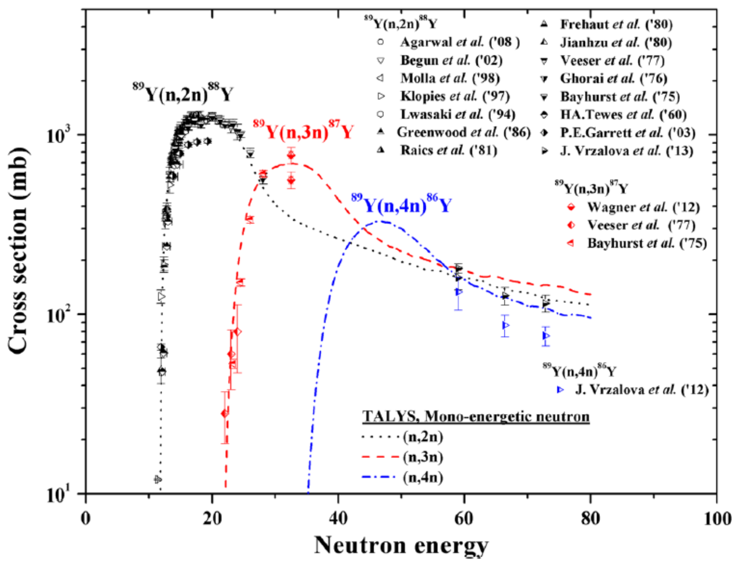
Measurement of cross-sections for 89Y(n,xn) reaction at average neutron energies of 15–36 MeV

Monitoring : activa

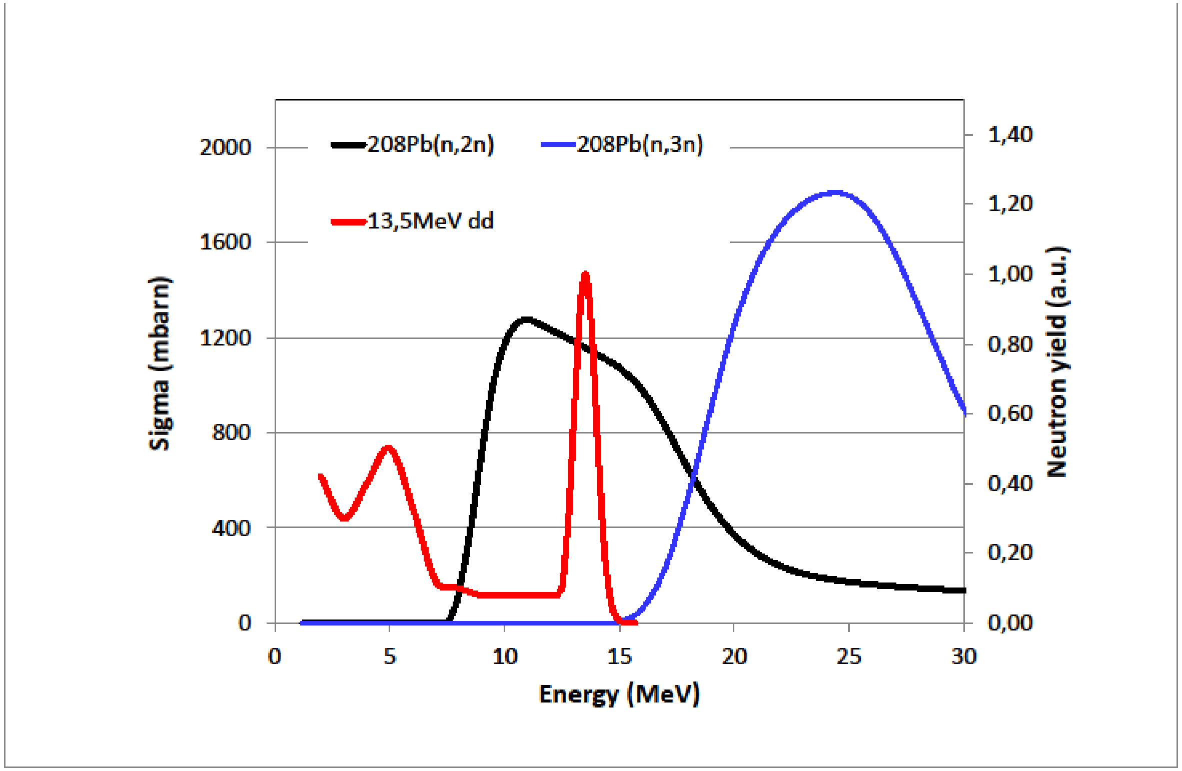


$$\langle\sigma\rangle = \frac{N_{obs}(CL/LT)\lambda}{n\,\Phi_n\,I_\gamma\,\varepsilon\,(1 - e^{-\lambda T_I})\,e^{-\lambda T_C}\,(1 - e^{-\lambda CL})}$$





(n,2n) and (n,3n) measurements



D(d,n)3He produces purely mono-energetic neutrons up to 7 MeV
But The low energy component is below the (n,2n) threshold
D(d,n)3He can be used up 10 MeV

Numerical application

Measurement on Carbon sample

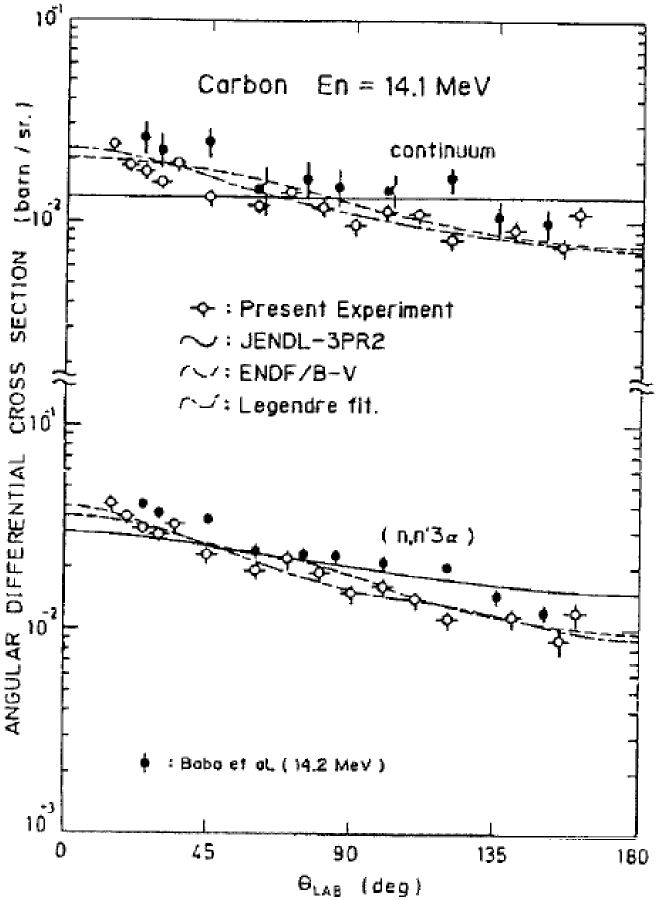
Flux : Φ (n.cm^{-2}.s^{-1})

Differential cross section : dσ/dΩ (barn.sr^{-1})

Intrinsic efficiency : 20%

Sample : A=12, Φ=3cm, h=3cm, m=15g

$$N_{\det}(s^{-1}) = \Phi\left(\frac{m}{A}N_{avo}\right)\varepsilon\frac{d\sigma}{d\Omega}d\Omega$$



Φ = 10^{6} n.cm^{-2}.s^{-1}

dσ/dΩ = 0,001 barn.sr^{-1}

Ndet = 0,02 count.s^{-1}