Principles and examples of neutron production

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Accelerator and Research reactor Infrastructures for Education and Learning

ARIEL

[H2020-ARIEL] "HISPANOS Hands-On school on the production, detection and use of neutron beams"

September 21st, 2022

What will we see today?

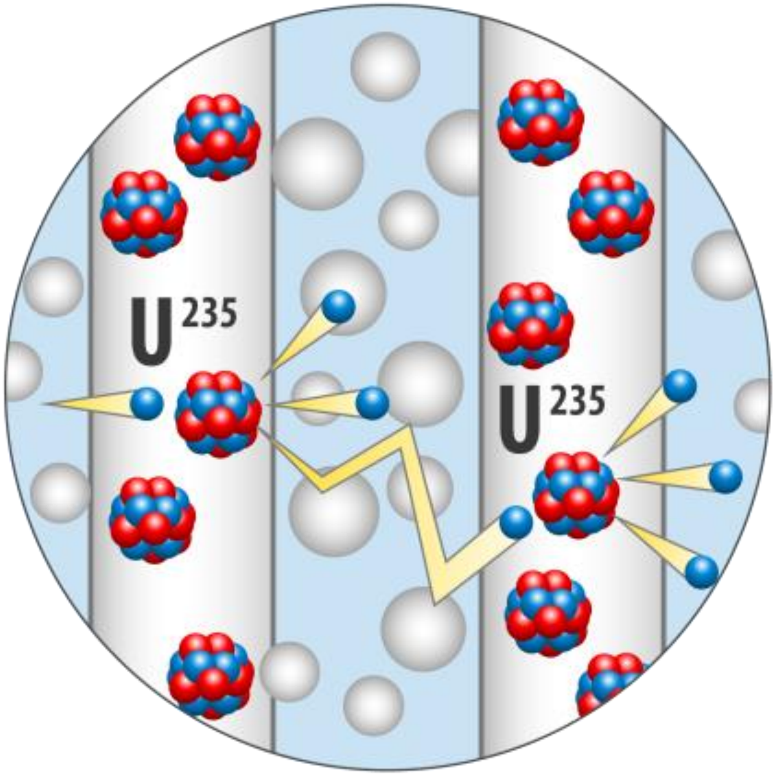
- Some general considerations
  - Neutron moderation process
  - Neutron energy ranges
  - Continuous vs. pulsed neutron beams

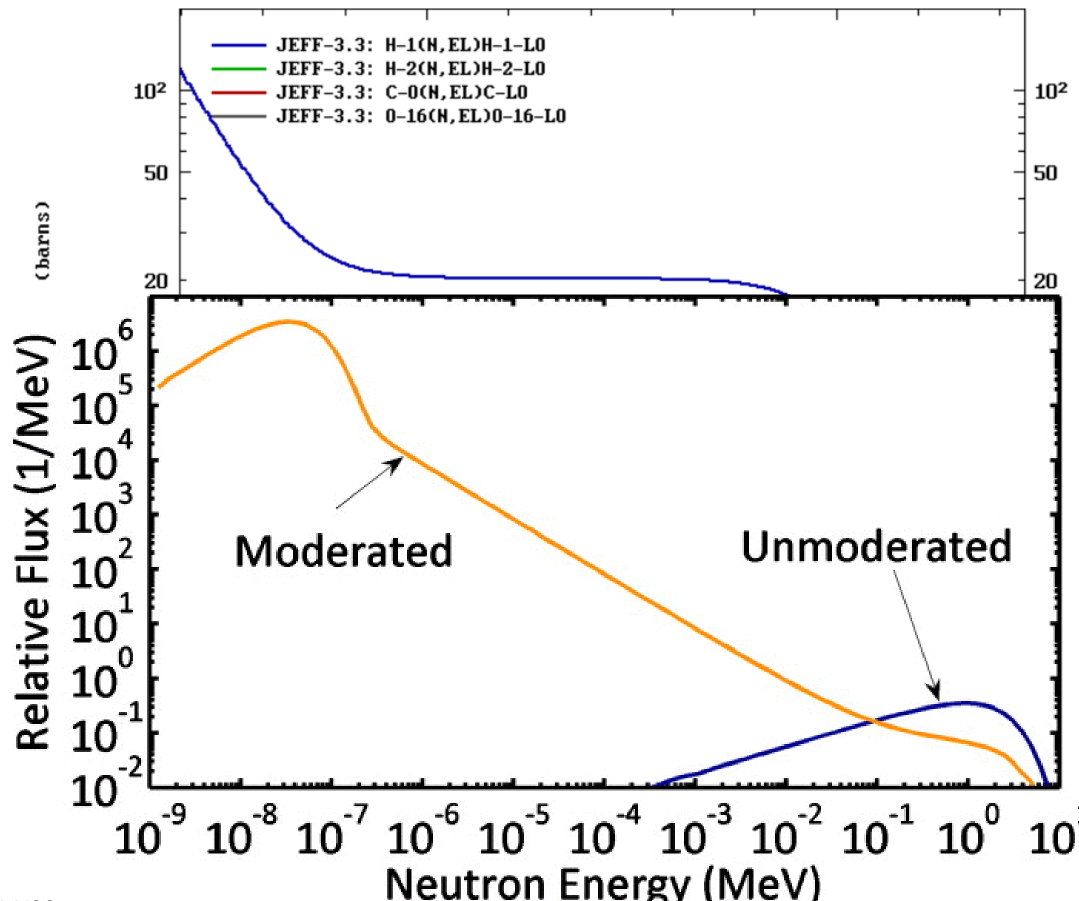
- Fission in nuclear reactors
- Nuclear reactions with ion accelerators of:
  - low energy (few MeV)
  - high energy (tens of MeV)
  - very high energy (GeV)
- Photoproduction with electron accelerators
- Laser-driven neutron sources

- ARIEL Transnational Access

Some general considerations

Neutron moderation process



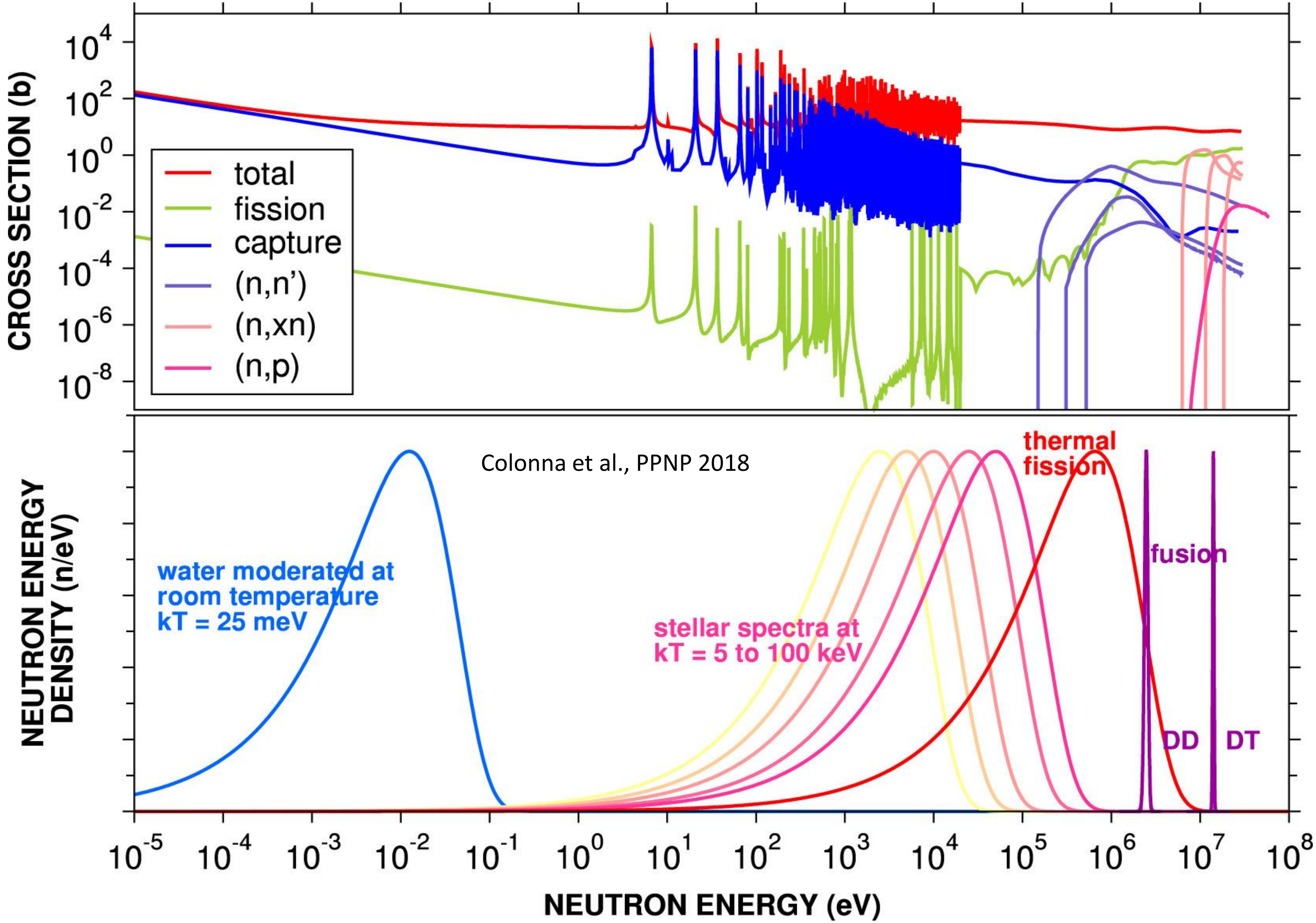


Continuous neutron scattering end up with the neutrons in thermal equilibrium with the medium:

<u>MB distrib. with characteristic *k*T</u>

^{2}H	0,56	30
^{12}C	0,86	116
^{16}O	0,89	15

Neutron energy ranges



Continuous vs. pulsed beams: time-of-flight

- Continuous: Neutrons of all energies "together":

  => integral effects (not a problem if spectrum adequate)

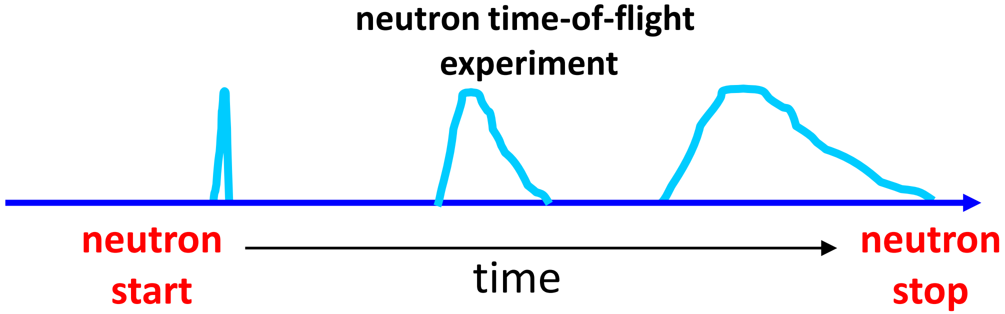
  Examples:

  - Irradiation (thermal, atmospheric, etc.)
  - Production of radioisotopes
  - Activation for a given spectrum

- Pulsed: allows for time-of-flight

  => time of arrival provides neutron kinetic energy

  => differential experiments => X(E_n)

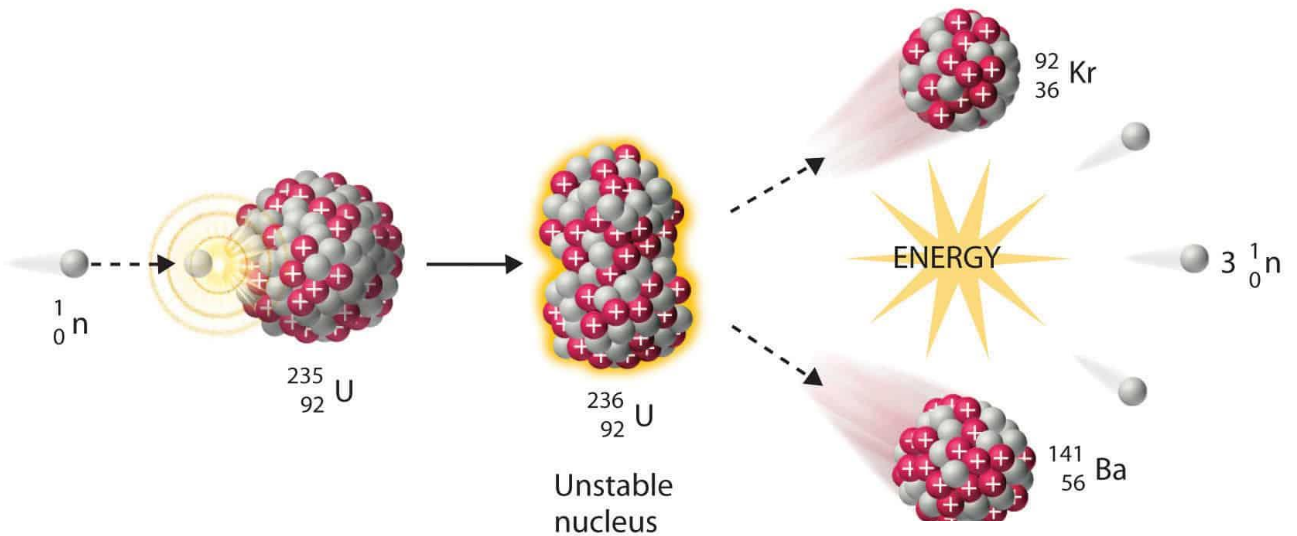


Time-of-Flight to E_n relation (non-rel.):

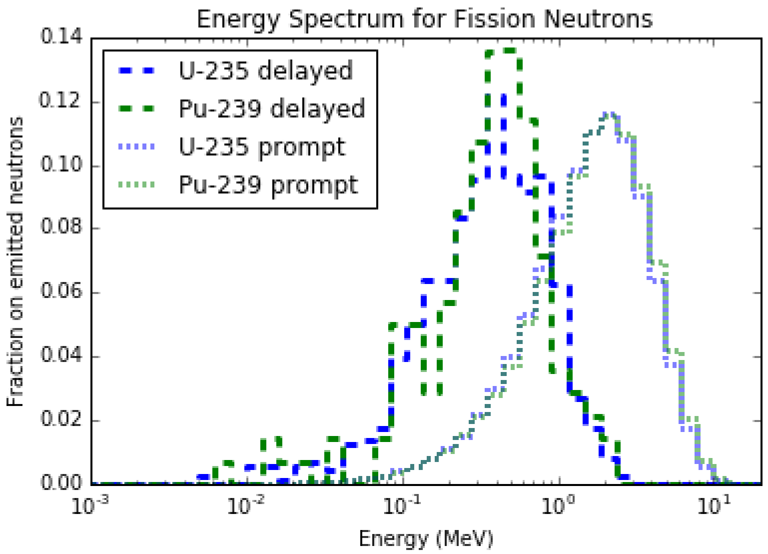
$$ToF \propto \frac{L}{\sqrt{E_n}}$$

=> E_n resolution increases with L

Fission in nuclear reactors



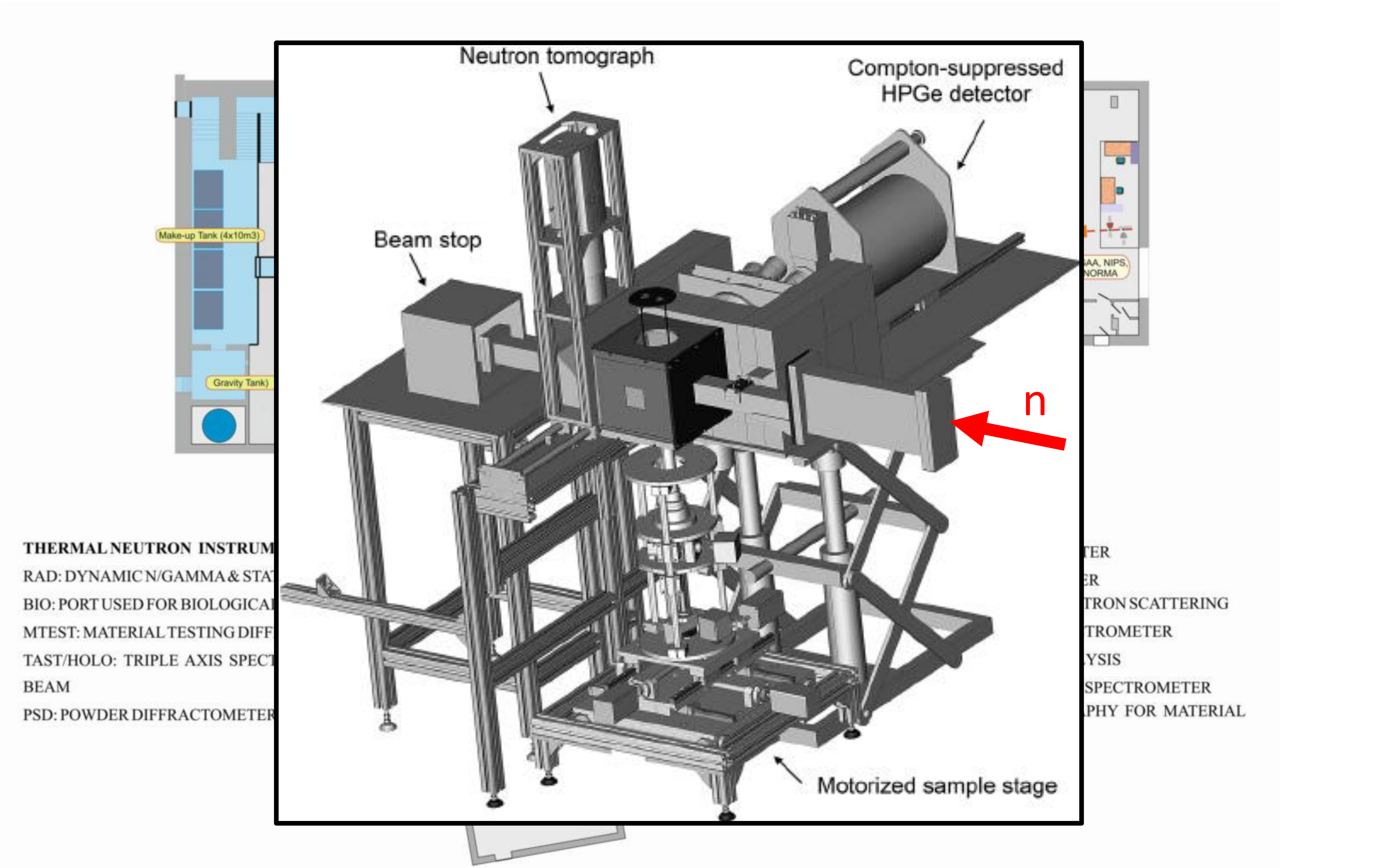
1
0 n
235
92 U
236
92 U
Unstable
nucleus
92
36 Kr
ENERGY
3 1
0 n
141
56 Ba



Energy Spectrum for Fission Neutrons
U-235 delayed
Pu-239 delayed
U-235 prompt
Pu-239 prompt
Fraction on emitted neutrons
Energy (MeV)
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
10-3
10-2
10-1
100
101

ILL: 1.5×10^{15} n/cm^2/s @core

BRR: $2x10^{14}$ n/cm^2/s @core, $8x10^7$ @PGAA



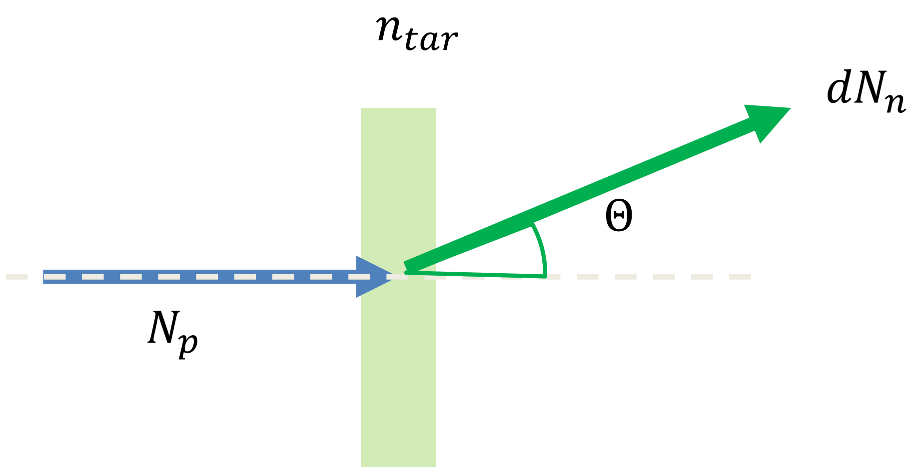
Nuclear reactions with low energy (few MeV) ion accelerators

See:
- R. Nolte and D. J. Thomas, "*Monoenergetic fast neutron reference fields: I. Neutron production*", Metrologia 48 (2011) S263
- D. L. Chichester, "*Production and Applications of Neutrons Using Particle Accelerators*", INL/EXT-09-17312 (2009)

- "Classical" facilities:
  - PTB, NPL as metrology laboratories
  - Frascatti (14 MeV)
  - More humble facilities: DEMOKRITOS, CNA (HISPANOS), …

Neutron producing nuclear reactions (I)

- In two-body reactions monoenergetic neutrons can be produced, e.g. DT-reaction: T(D,n)^{4}He, Q = 17.16 MeV
- Kinematics determines the angular distribution and energy spectrum
- The yield (neutrons /primary particles) is determined by the differential cross section $\frac{d\sigma}{d\Omega}(E_{proyectile}, \Theta)$
- Realistic yield determination by integration over the target thickness and angular range (slowing down of the beam in the target material)

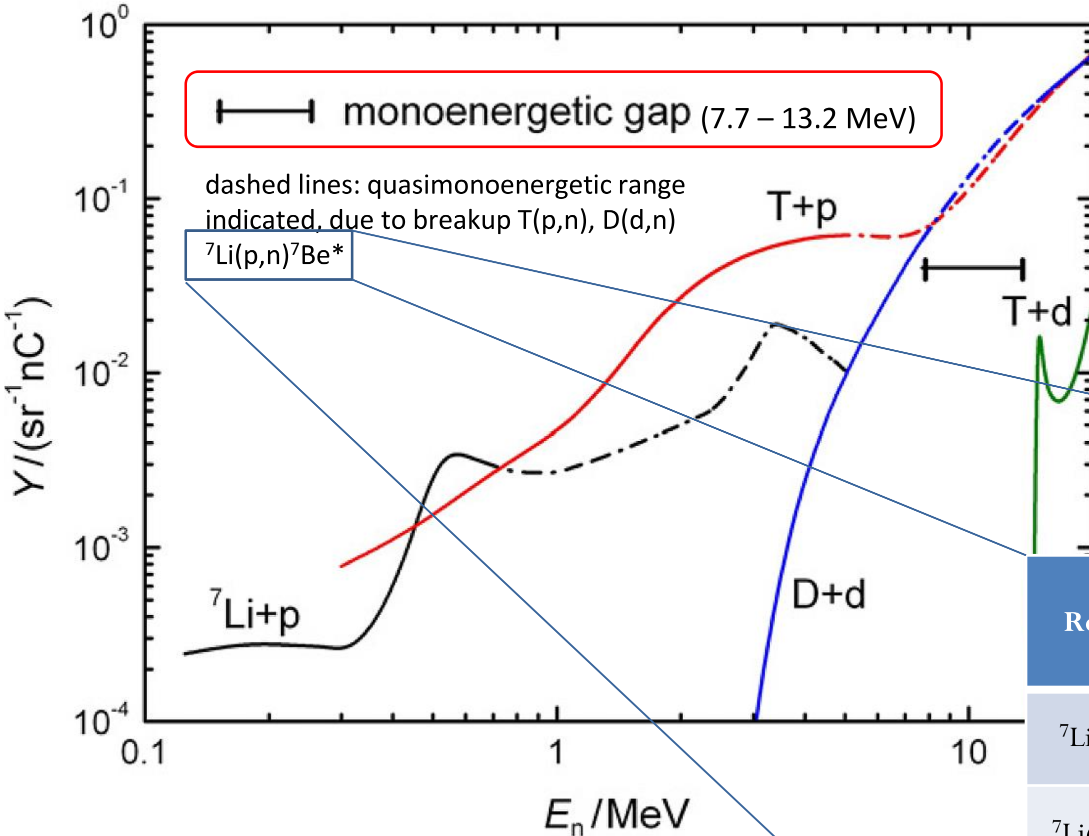


Neutron producing nuclear reactions (II)

Table 2 Common nuclear reactions particle accelerators use to produce neutrons.

Reaction	Shorthand	Q Value [MeV]	Threshold Energy [MeV]	Minimum Product Energies [MeV]
$^{2}H + ^{2}H \rightarrow ^{3}He + n$	$^{2}H(d,n)^{3}He$	+3.269	NA	^{3}He: 0.82 n: 2.45 *
$^{2}H + ^{3}H \rightarrow ^{4}He + n$	$^{3}H(d,n)^{4}He$	+17.589	NA	^{4}He: 3.54 n: 14.05
$^{1}H + ^{7}Li \rightarrow ^{7}Be + n$	$^{7}Li(p,n)^{7}Be^{\dagger}$	-1.644	1.880	^{7}Be: 0.21 n: 0.03
	$^{1}H(^{7}Li,n)^{7}Be^{\dagger}$	-1.644	13.094	^{7}Be: 10.0 n: 1.44
$^{2}H + ^{7}Li \rightarrow ^{8}Be + n$	$^{7}Li(d,n)^{8}Be$	+15.031	NA	^{8}Be: 1.68 n: 13.35
$^{1}H + ^{9}Be \rightarrow ^{9}B + n$	$^{9}Be(p,n)^{9}B$	-1.850	2.057	^{9}B: 0.18 n: 0.023
$^{2}H + ^{9}Be \rightarrow ^{10}Be + n$	$^{9}Be(d,n)^{10}B$	+4.361	NA	^{10}B: 0.40 n: 3.96

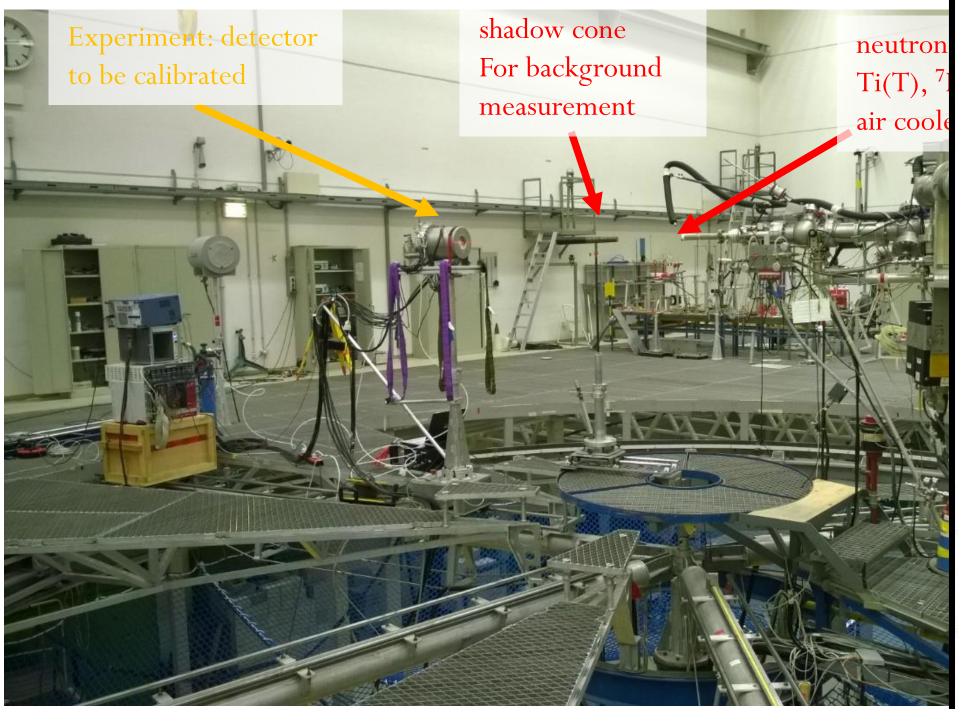
Monoenergetic (& quasi) neutron beams



Reaction	^{7}Be* Exc. Energy (MeV)	Q-value (MeV)	Threshold (MeV)
^{7}Li(p,n)^{7}Be	0	-1.644	1.881 forward 1.920 backward
^{7}Li(p,n)^{7}Be*	0.429	-2.073	2.371 forward 2.421 backward
^{7}Li(p,n^{3}He)^{4}He	break-up	-3.229	3.692
^{7}Li(p,n)^{7}Be**	4.57	-6.214	7.110 forward 7.260 backward

The PTB (& NPL) metrology facility

- 2 MV tandem accelerator with up to 50 uA
- p(^{7}Li,n), p(^{3}H,n), d(^{2}H,n) and d(^{3}H,n) reactions
- Large hall minimizes neutron scattering background



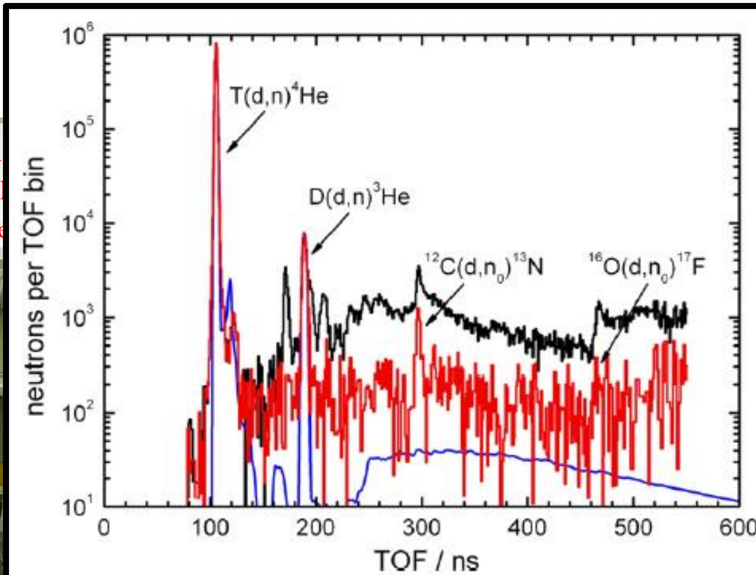
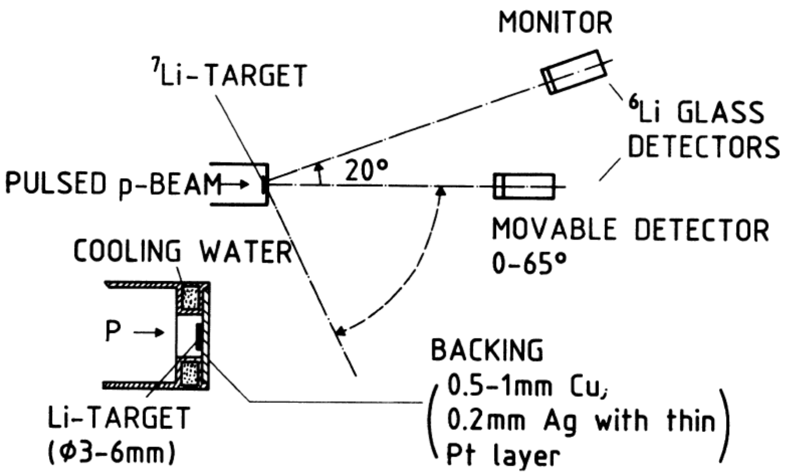
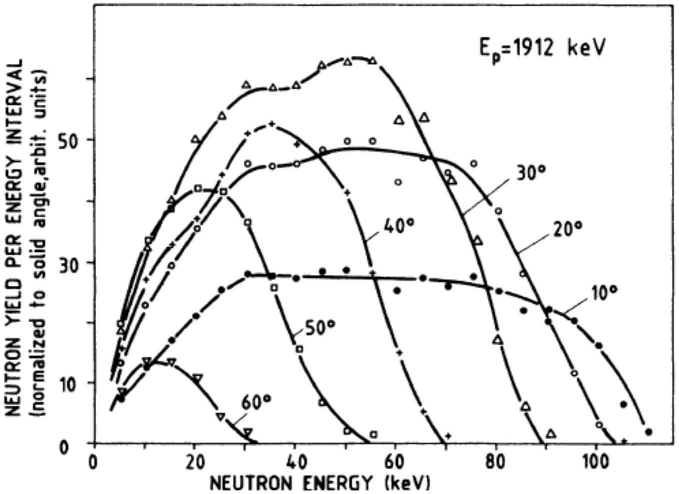


Figure 7. TOF distribution for neutrons produced by bombarding a Ti(T) and an unloaded Ti target with 2.682 MeV deuterons. The areal titanium mass of the two targets was 1.91 mg cm^{-2}. The T/Ti loading ratio of the Ti(T) target was 1.42. The upper and the lower histograms show the neutron distributions measured using the Ti(T) target before and after subtraction of the distribution measured using the unloaded Ti target, respectively. The solid line is a simulation carried out using the TARGET code [23].

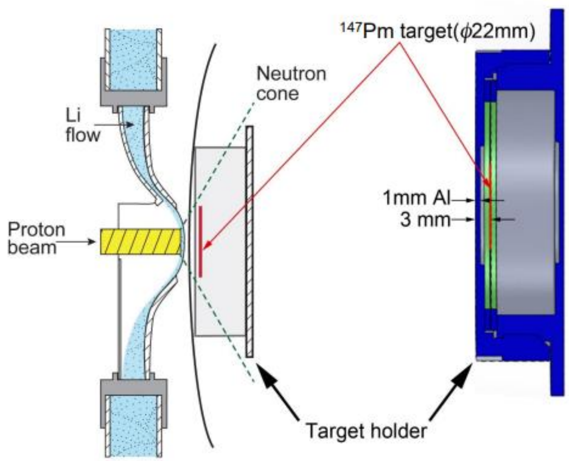
30 keV quasi-Maxwellian neutron beam

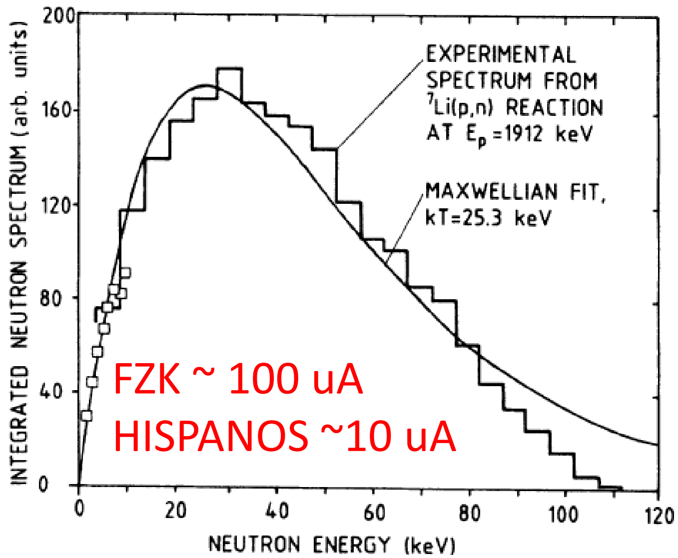
Ratynski and Käppeler., "*A standard for stellar nucleosynthesis*", Phys. Rev. C 37(1988)





LiLiT ~ 1 mA (liquid Li target)





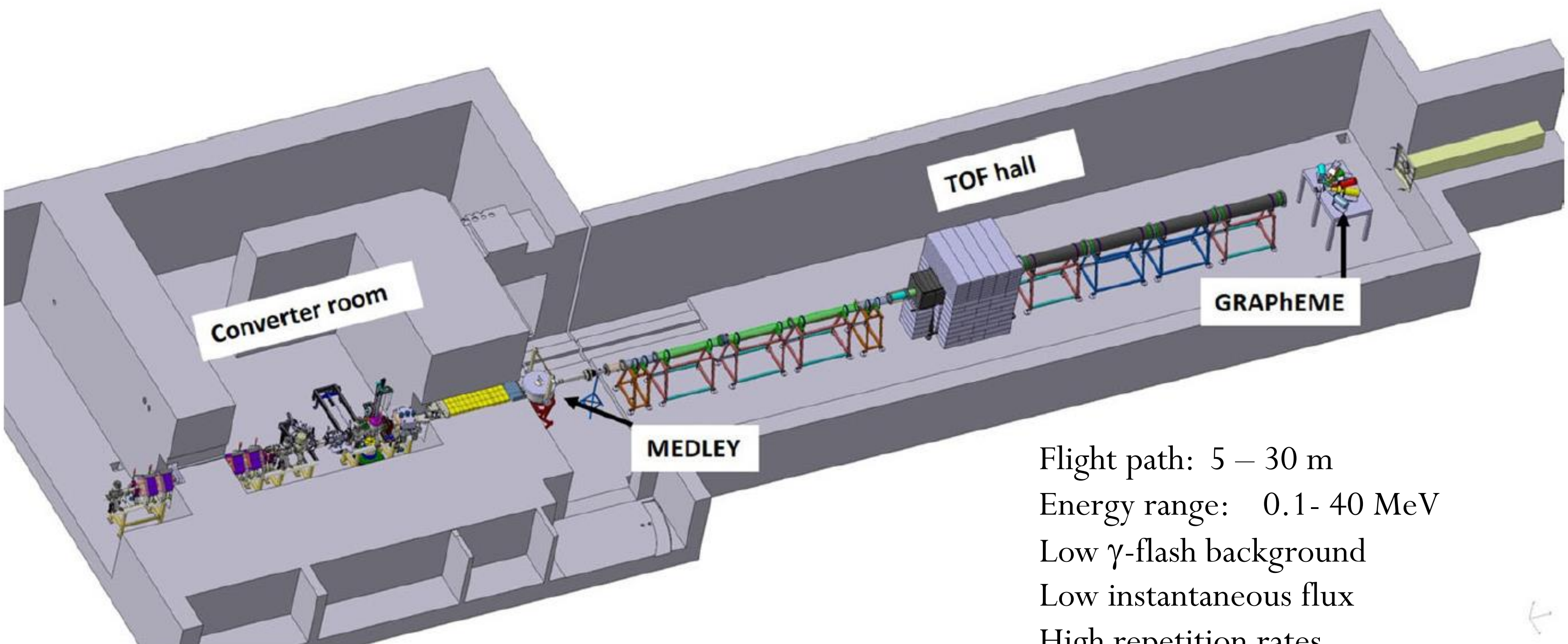
FZK ~ 100 uA
HISPANOS ~10 uA

Nuclear reactions with high energy (few tens of MeV) ion accelerators

Neutrons for Science (NFS) @GANIL's SPIRAL2

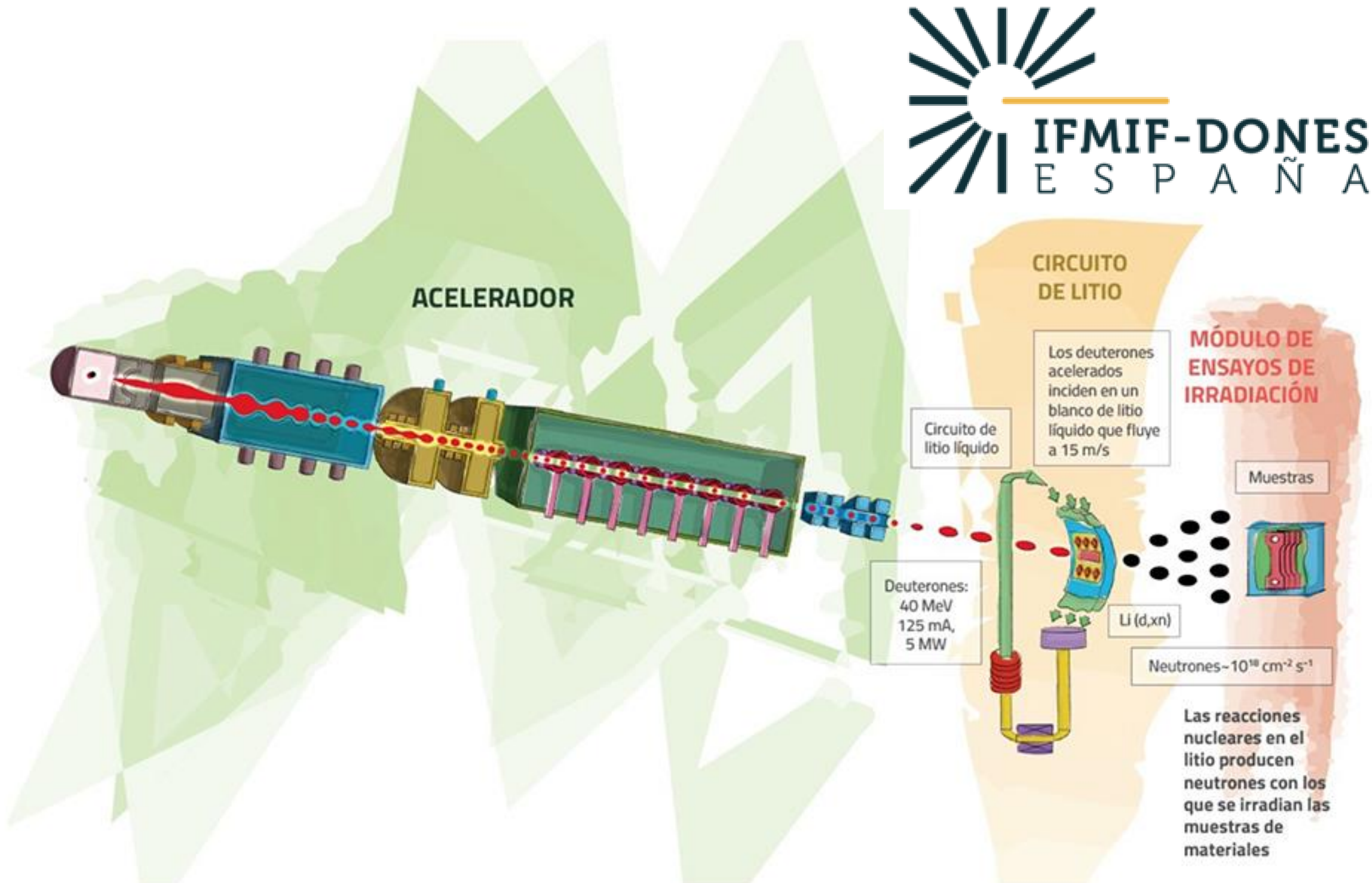
GANIL's SPIRAL-2, a Superconducting Linear Accelerator:

- 40 MeV deuteron and 33 MeV protons
- Beam current 5 mA, i.e. rotating target
- Flight path 5 to 10 meters
- Frequency=0.25-1 MHz



Flight path: 5 – 30 m
Energy range: 0.1- 40 MeV
Low γ-flash background
Low instantaneous flux
High repetition rates

IFMIF-DONES: DEMO Oriented Neutron Source

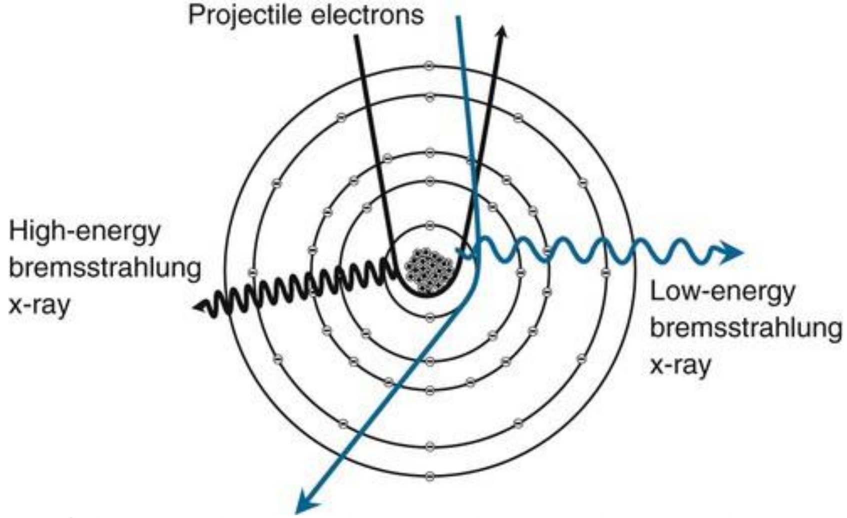


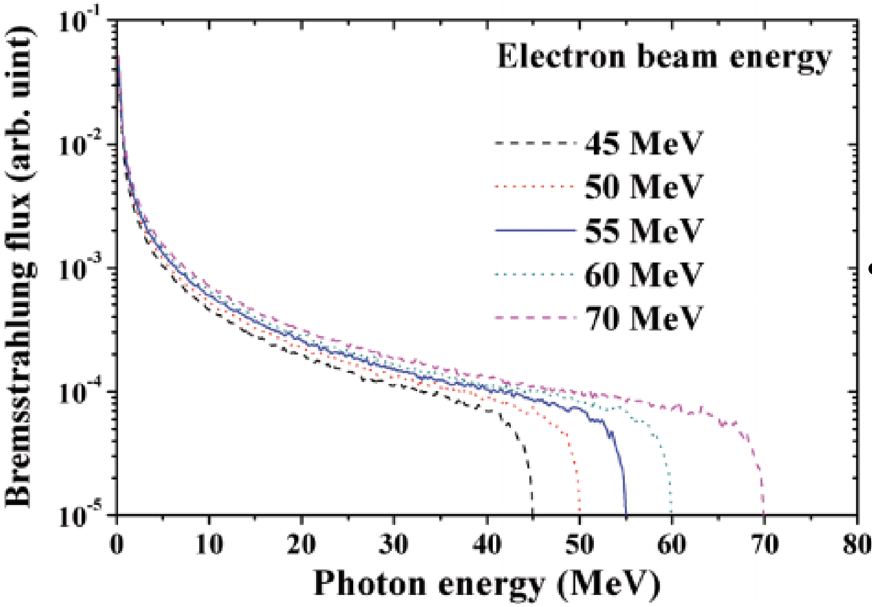
Upgrades for complementary experiments under study

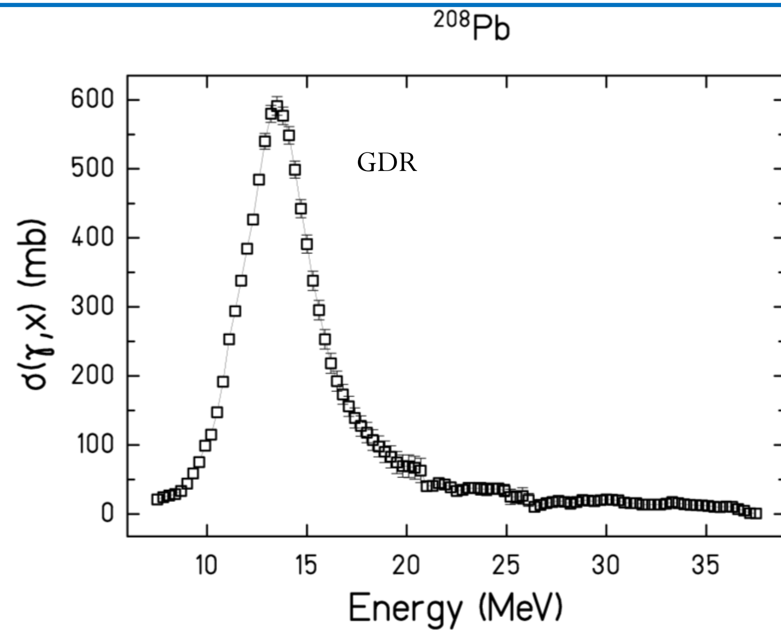
Photoproduction with e^- accelerators

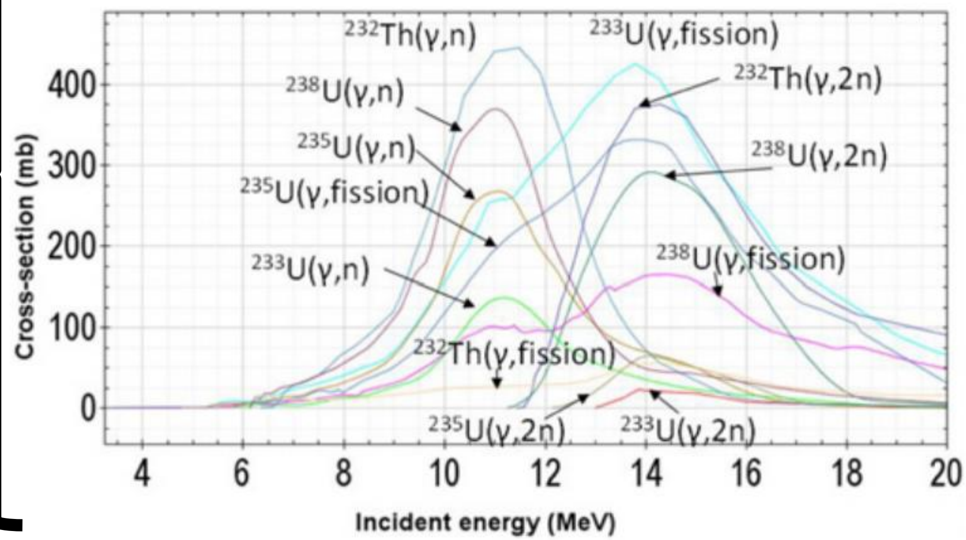
- Historical facilities:
  - ORELA @ORNL
  - GELINA @JRC-Geel
  - More recently, nELBE @HZDR, ALTO@IPN-Orsay, …

Photoproduction of neutrons with Bremsstrahlung

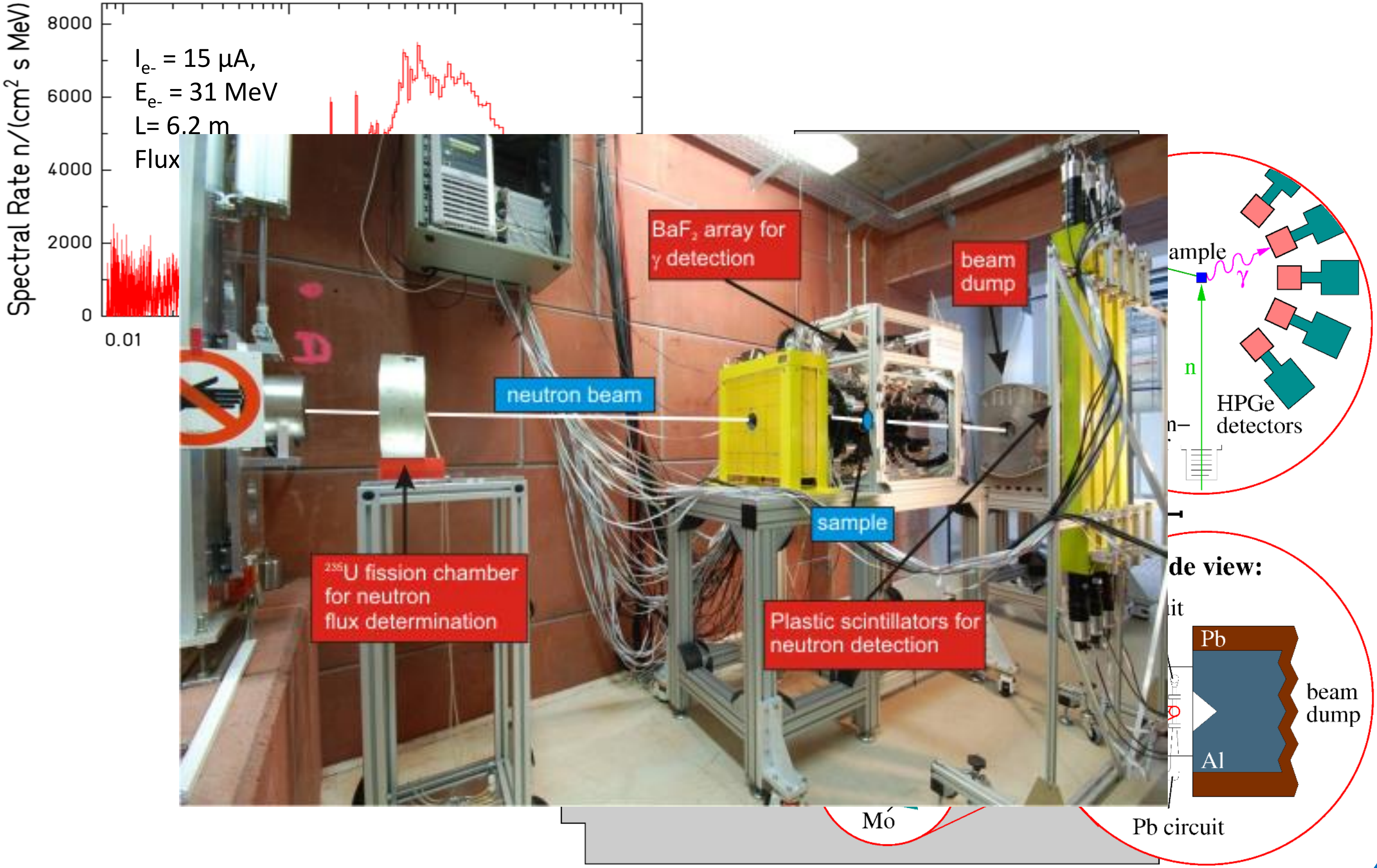






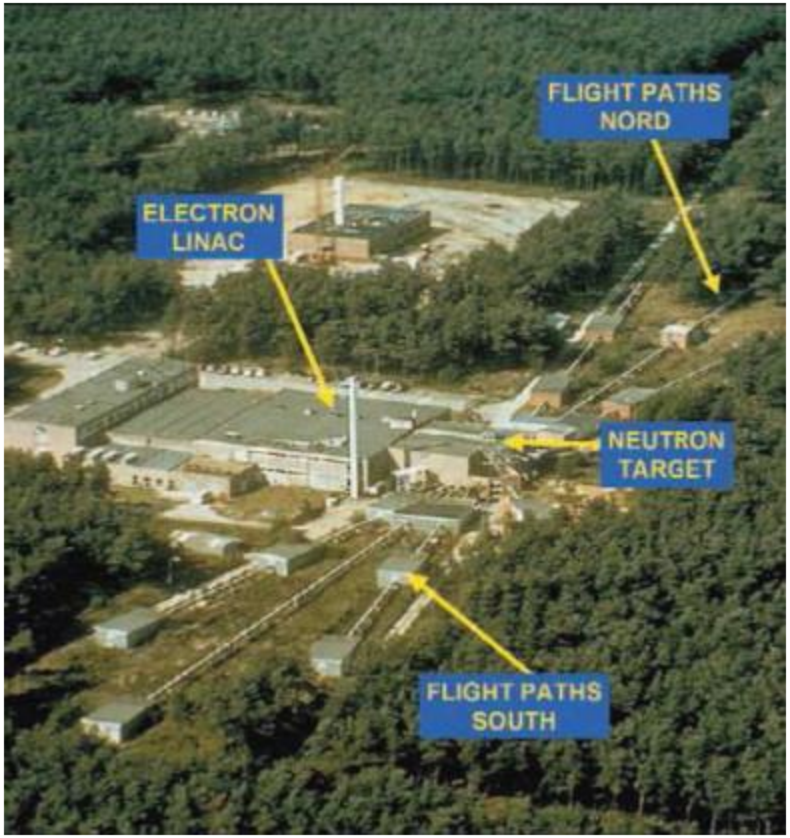


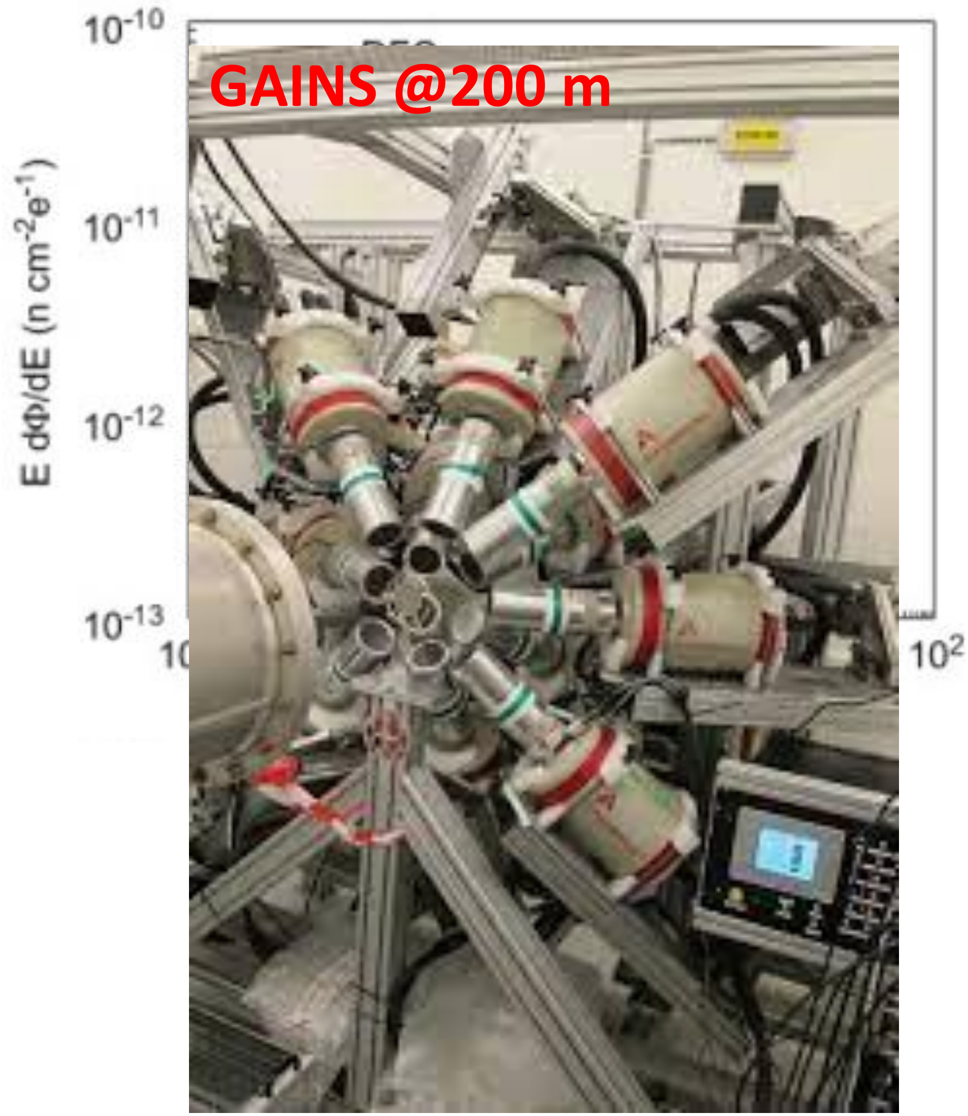
nELBE@HZDR



Spectral Rate n/(cm² s MeV)
8000
6000
4000
2000
0
0.01
I_{e-} = 15 μA,
E_{e-} = 31 MeV
L= 6.2 m
Flux
BaF₂ array for γ detection
beam dump
neutron beam
sample
²³⁵U fission chamber for neutron flux determination
Plastic scintillators for neutron detection
ample
γ
n
HPGe detectors
de view:
Pb
Al
beam dump
Pb circuit
Mo

GELINA@JRC-Geel



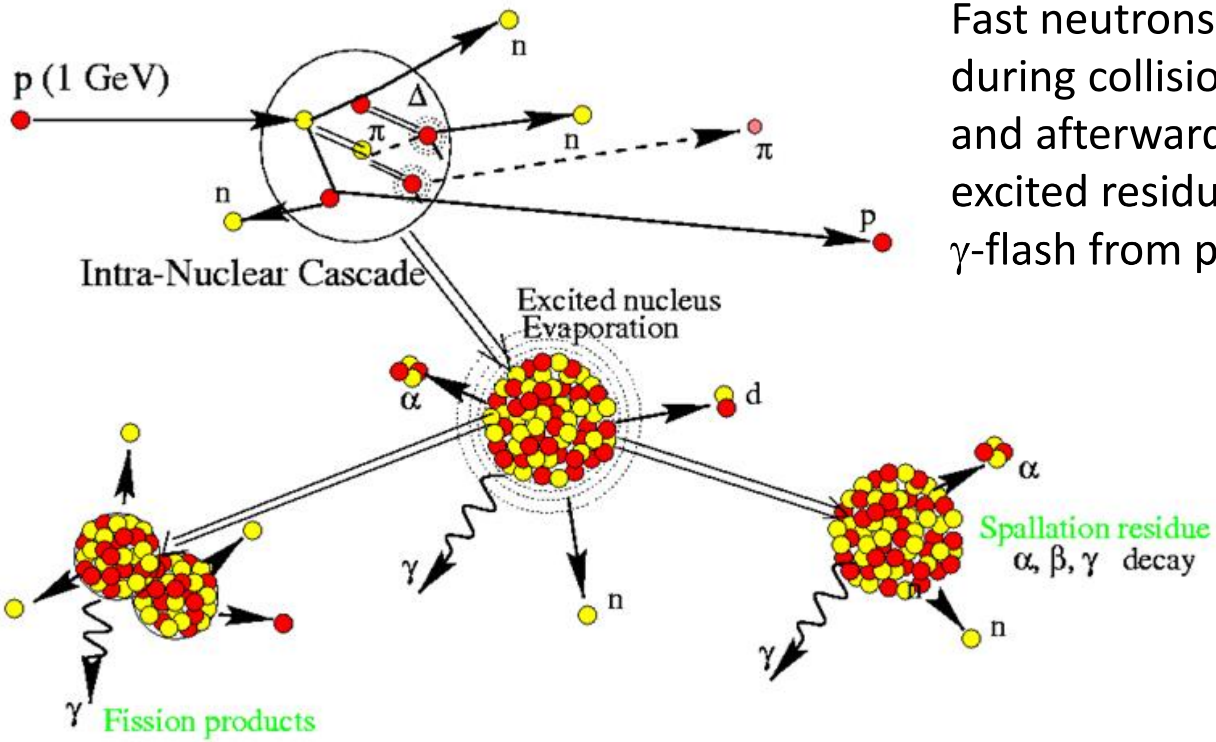


Spallation with very high (GeV) ion accalerators

- nTOF@CERN (Europe)
- DANCE@LANL (USA)
- MLF@J-PARC (Japan)
- Back-n@CSNS (China)

Neutron production by spallation

Relativistic protons impinging on heavy target nuclei



Fast neutrons emitted during collision and afterwards from excited residual nuclei γ-flash from pion decay

Nucleon-Nucleus collisions at relativistic energies

- $T_{coll} < 10^{-22}$s : Collisions of the projectile nucleon with nucleons in the target (Intranuclear Cascade, emission of **fast** particles π,**n**,p,…)
- $T_{equil} > 10^{-21}$s – 10^{-16}s Reorganisation of the residual nuclei, thermalization, **particle evaporation** (**n**,p,d,α,…), gamma ray emission

Spallation neutron yield

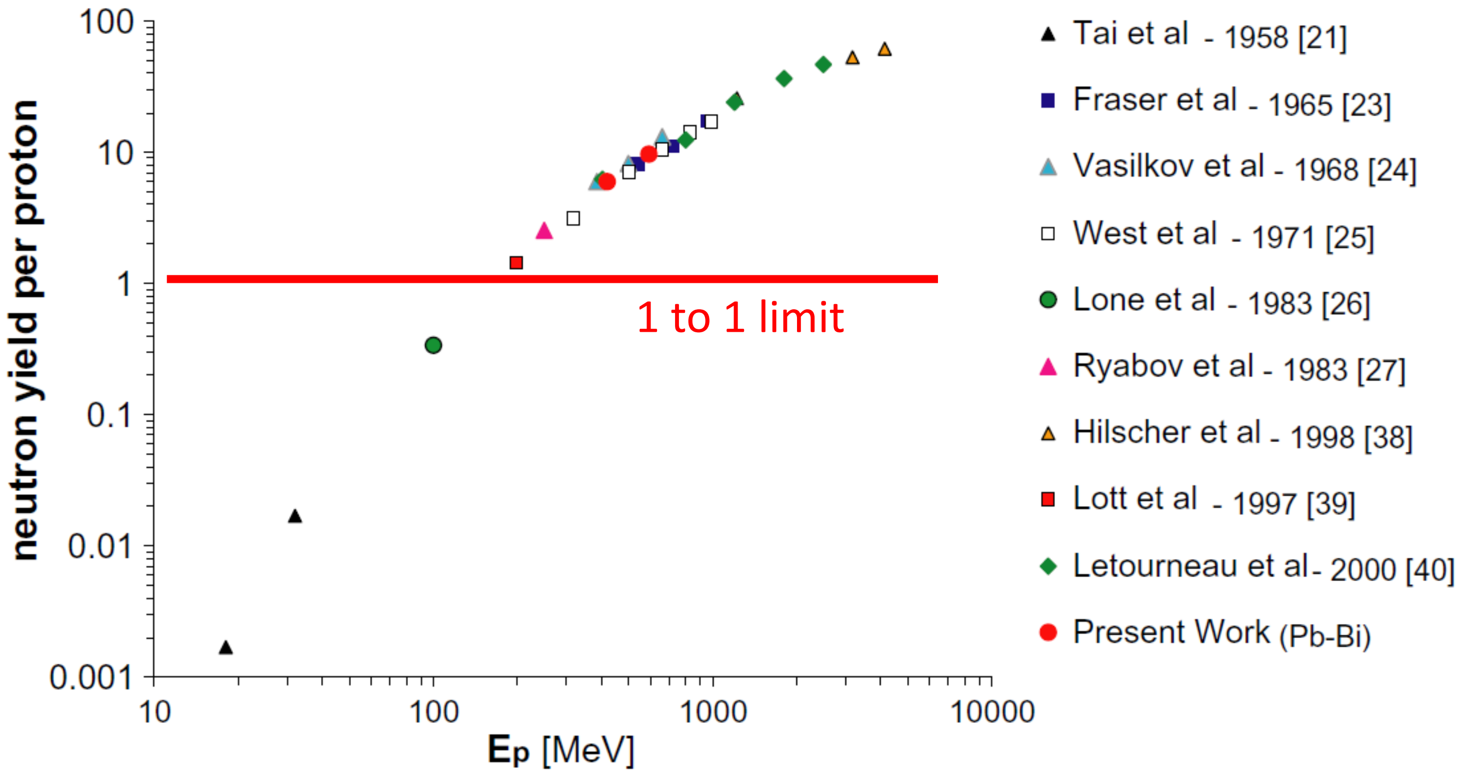
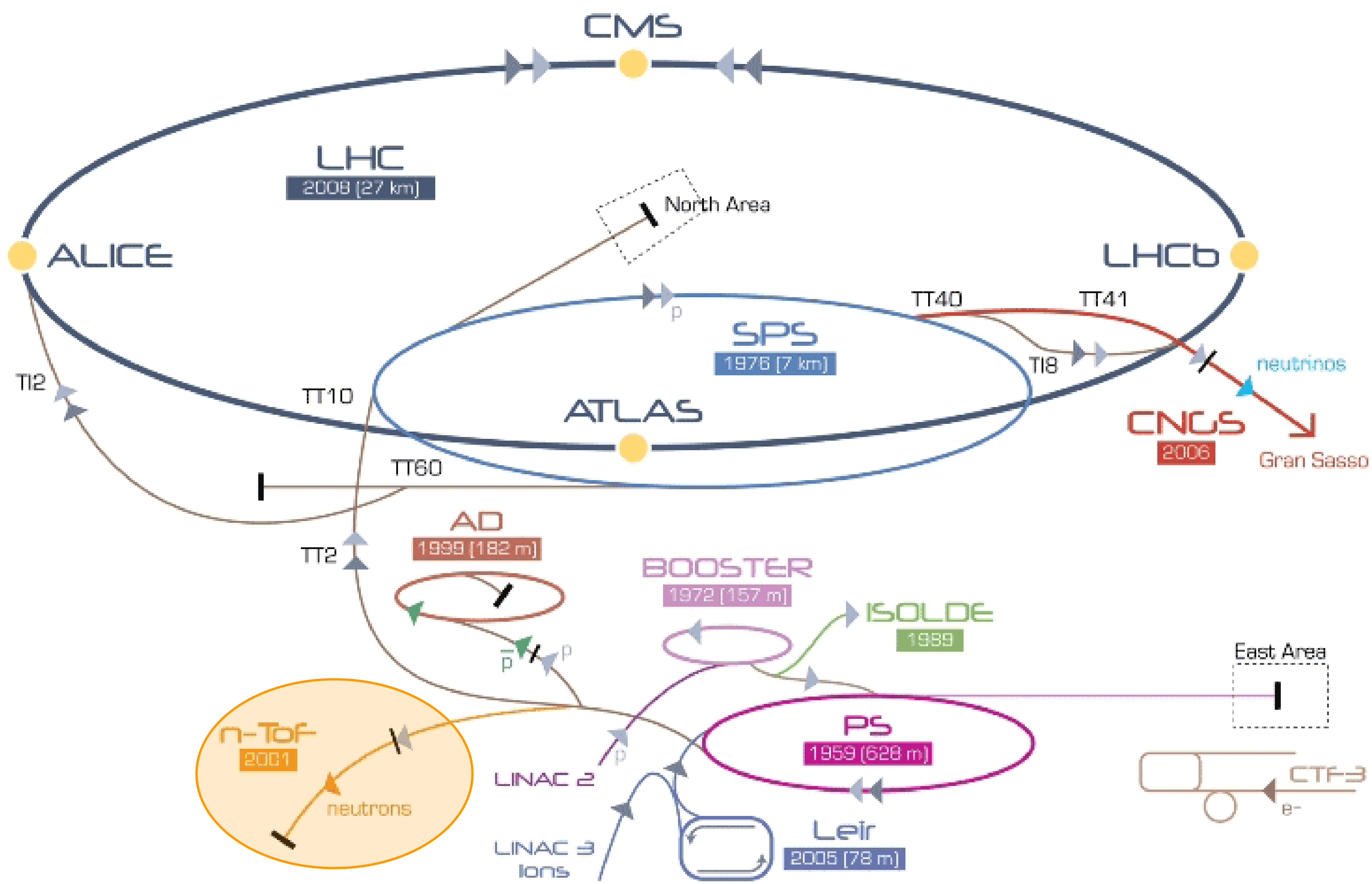


Fig. 10. Compilation of thick-target n/p values for p + Pb and Pb/Bi measured to date at all incident energies.

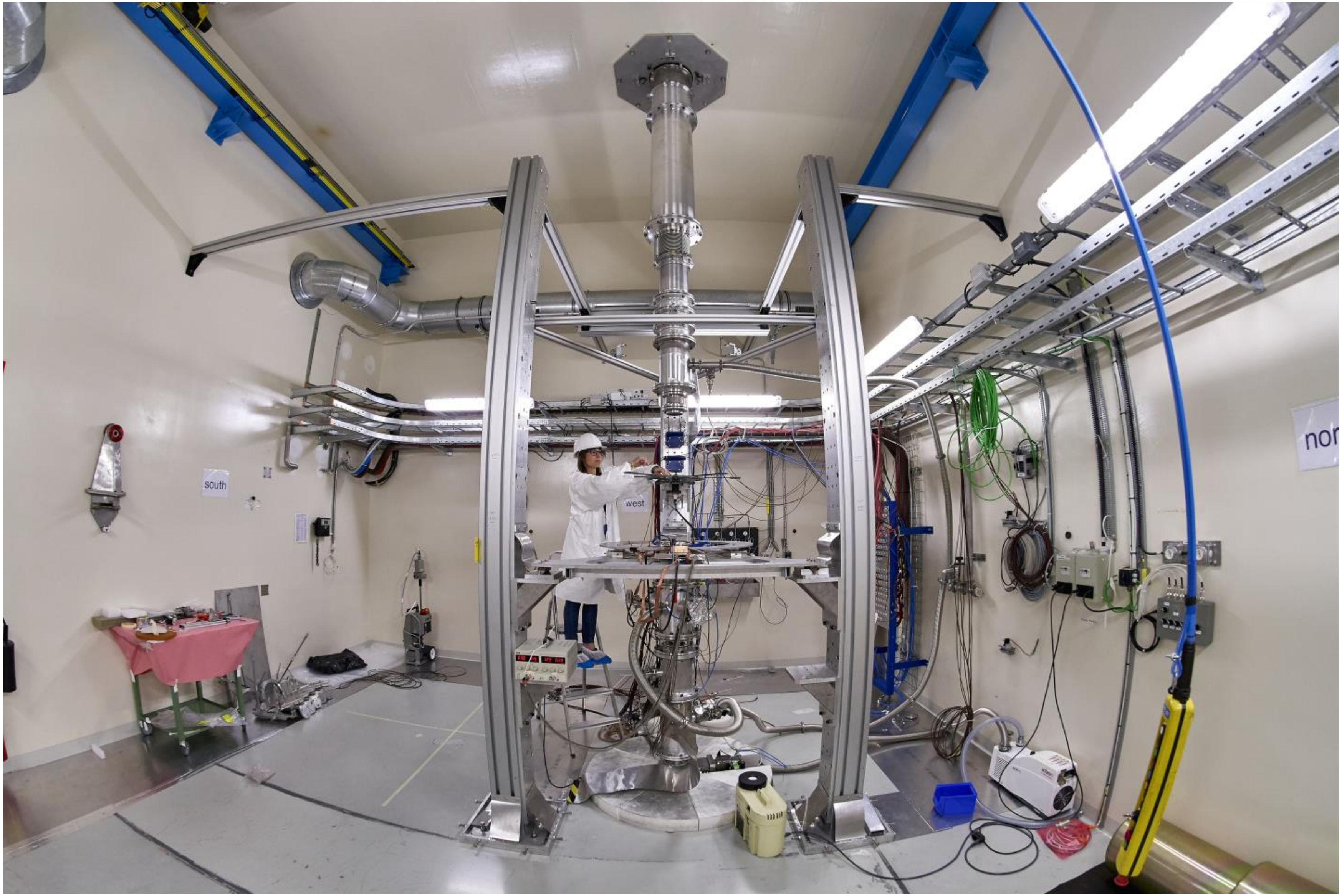
CERN nTOF ca. **300 n/p 20 GeV protons on Pb**

K. Van der Meer, NIM B 217 (2004) 202–220

The n_TOF facility at CERN

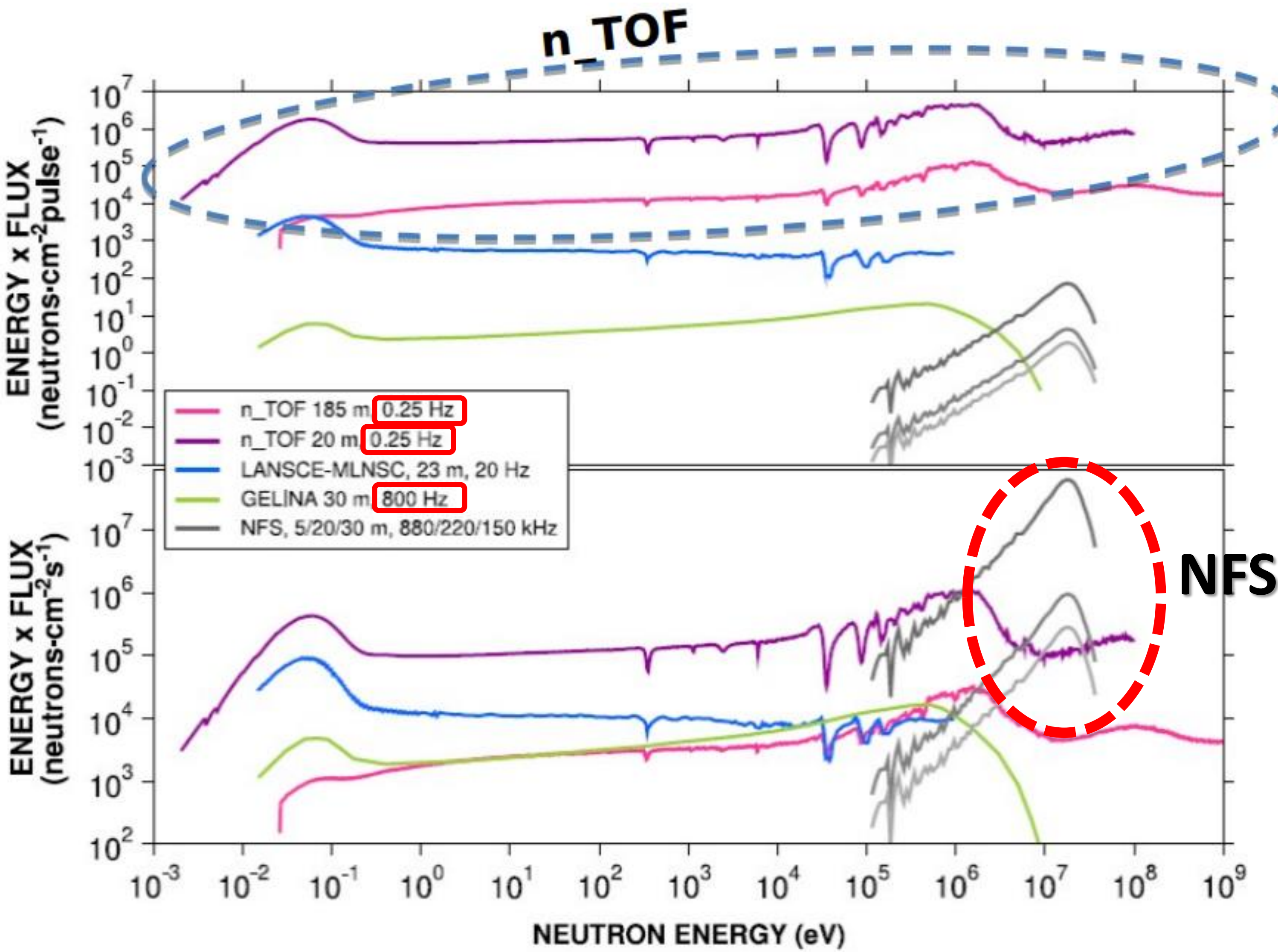


The n_TOF Facility at CERN: a Google™ view

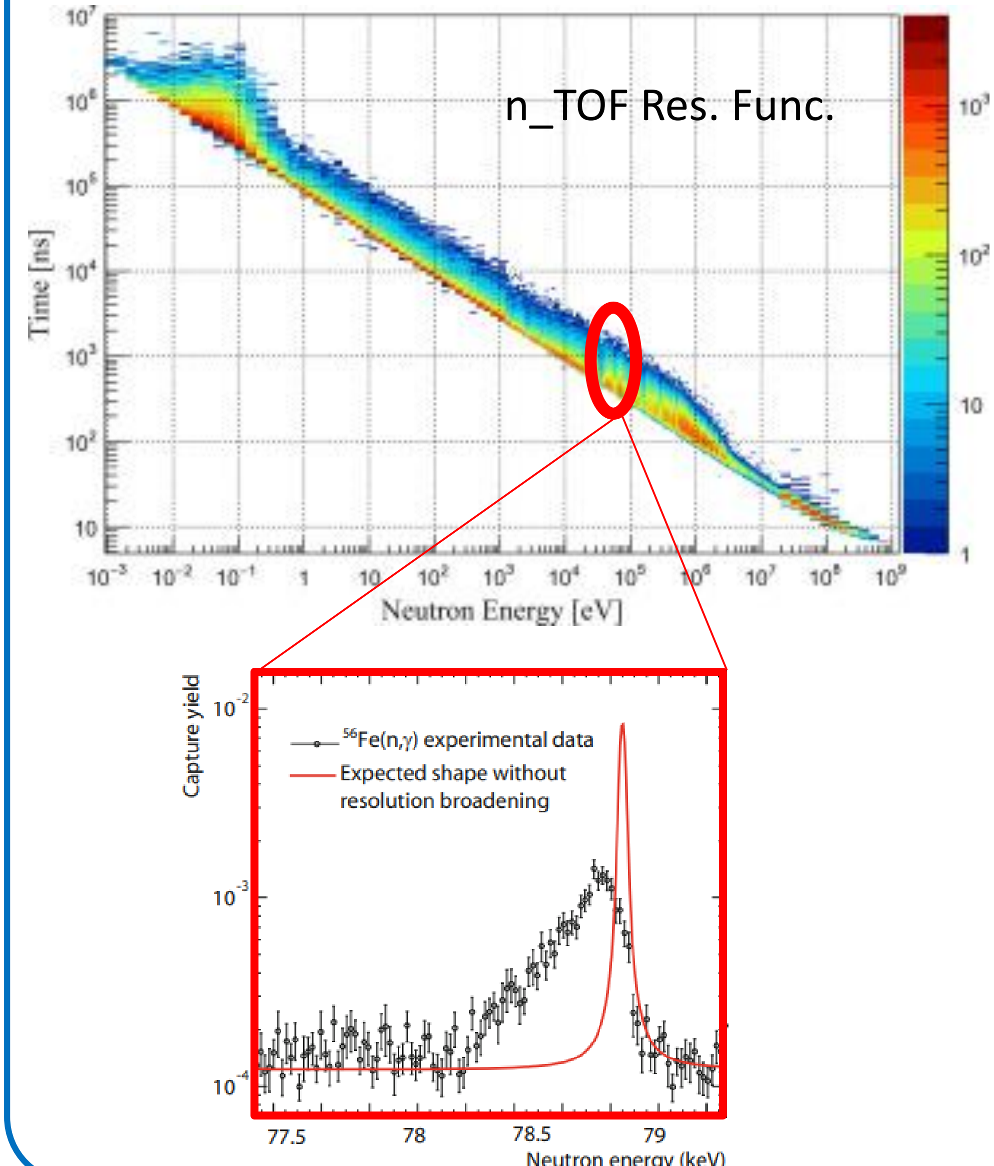


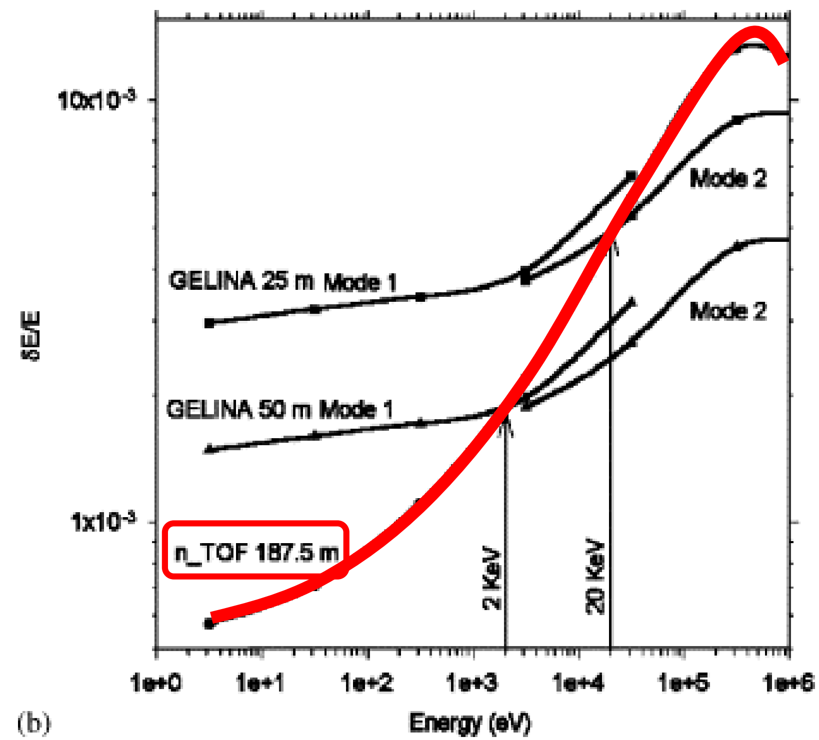
(back to) Some general considerations

Neutron flux: average vs. instantaneous



Neutron resolution function



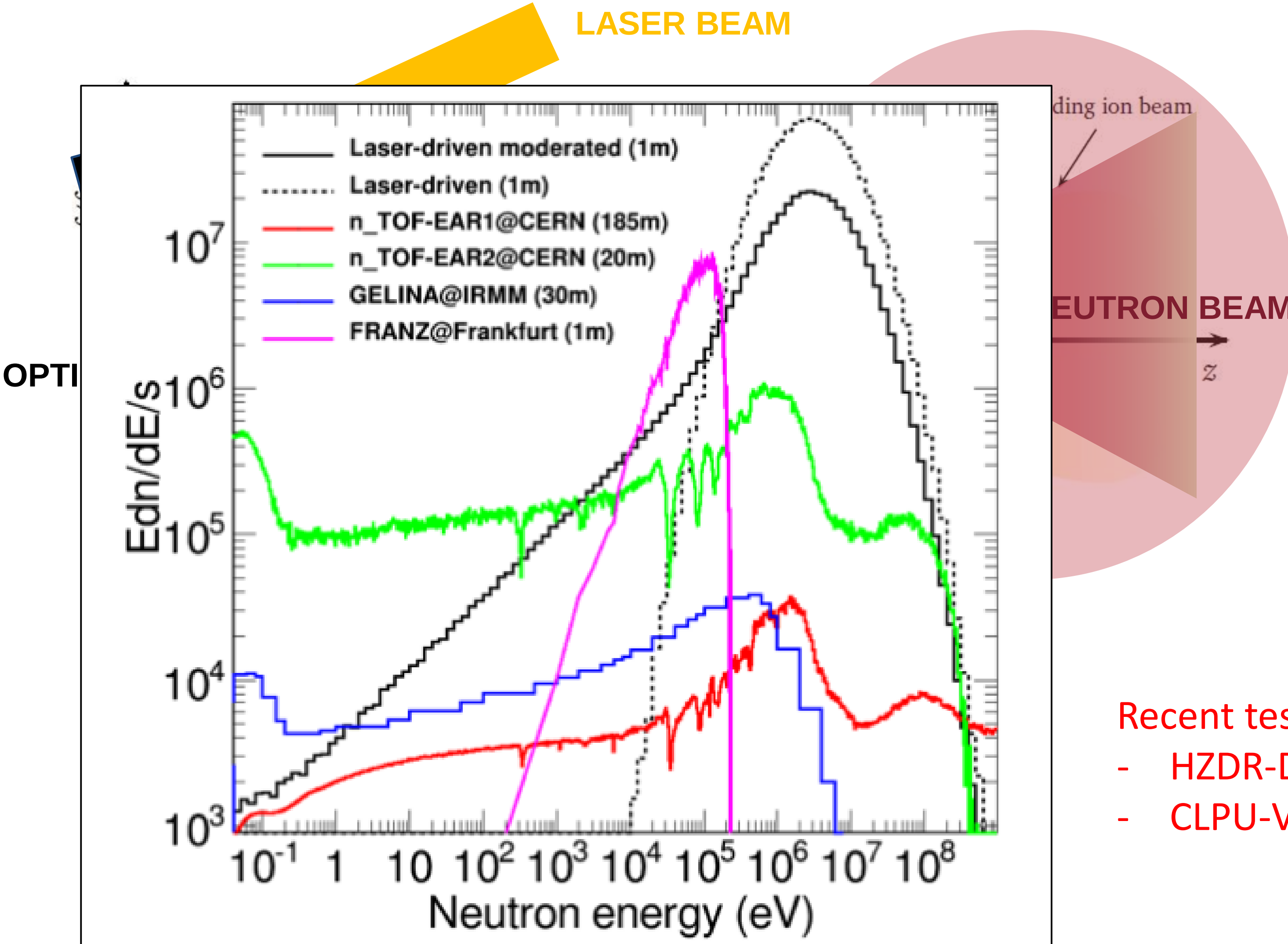


Resolution function affected by:

- Flight path length
- Pulse width
- Target geometry/size
- Moderaor size/geometry

Laser-driven neutron sources

A future LDNS for time-of-flight?



Recent test experiments at:
- HZDR-DRACO (Germany)
- CLPU-VEGA3 (Spain)

H2020-ARIEL Transnational Access

H2020-ARIEL Transnational Access

summary of the ARIEL facilities available for TAA		accelerators																				research reactors				
		e^- beams		ion beams																						
		nELBE@HZDR	GELINA@JRC	MONNET@JRC	n_TOF@CERN	AIFIRA@CNRS	ALTO@CNRS	GENESIS@CNRS	NFS@GANIL	CEA-DAM	FNG@ENEA	PTB	FNG@NPI	HISPANOS@CNA	NESSA@UU	U. Oslo	NPL	IFIN-HH	JYU	IRSN	AGOR@UMCG	BRR@mtaEK	BR1@SCK·CEN	TRIGA@JGU	LR-0/LVR-15 @CVR	RHF@ILL
neutrons	cold (<25 meV)																					■		■		■
neutrons	thermal (‹E_n›=25 meV)		■	■										■			■			■		■	■	■	■	■
neutrons	epithermal (25 meV – 100 keV)		■		■	■	■			■				■			■			■		■	■	■	■	■
neutrons	fast (0.1-20 MeV)	■	■	■	■	■	■	■	■	■	■	■	■	■	■		■			■		■	■	■	■	■
neutrons	very fast (>20 MeV)				■				■				■													
neutrons	pulsed beam	■	■	■	■				■	■		■	■	■	■					■				■		
neutrons	time-of-flight	■	■	■	■				■	■		■	■	■						■						
charged particles						■	■									■		■			■					
radioactive beam							■												■							■

Priority is given to PhD students and young postdocs!

Summary

- Neutron energies of interest:
  - meV to hundreds of MeV (9 orders of magnitud)
- Main characteristics:
  - pulsed vs. continuous
  - “monoenergetic” vs. “broad” vs. “white”
  - neutron energy (meV to hundreds of MeV)
  - neutron flux
  - for pulsed sources: flight path and resolution function
- Nuclear reactors
  - @core and external beam lines (cold, thermal & fast)
- Accelerator-based neutron sources
  - low energy ion accalerators (nuclear reactions)
  - high energy ion accalerators (nuclear reactions)
  - medium energy electron accelerators (photoproduction)
  - very high energy ion accalerators (spallation)
- Many Open Access facilities, priority to new users & students

Neutron sources in nature

- Neutron sources in nature:
  Neutrons can be formed in nuclear reactions of high-energetic cosmic particles in the upper atmosphere. The flux is inversely proportional to the solar activity
  (high solar activity deformes the earth‘s magnetic field)
  and strongly dependend on the geographical latitude and altitude.

Gordon et. al. IEEETNS 51 (2006) 3427

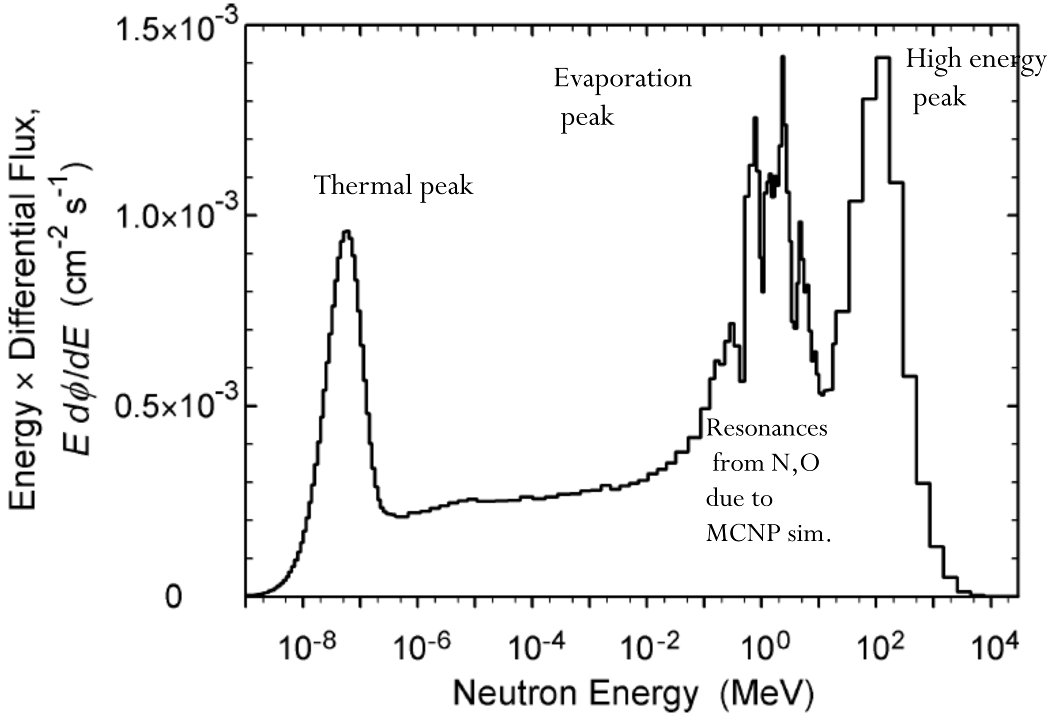
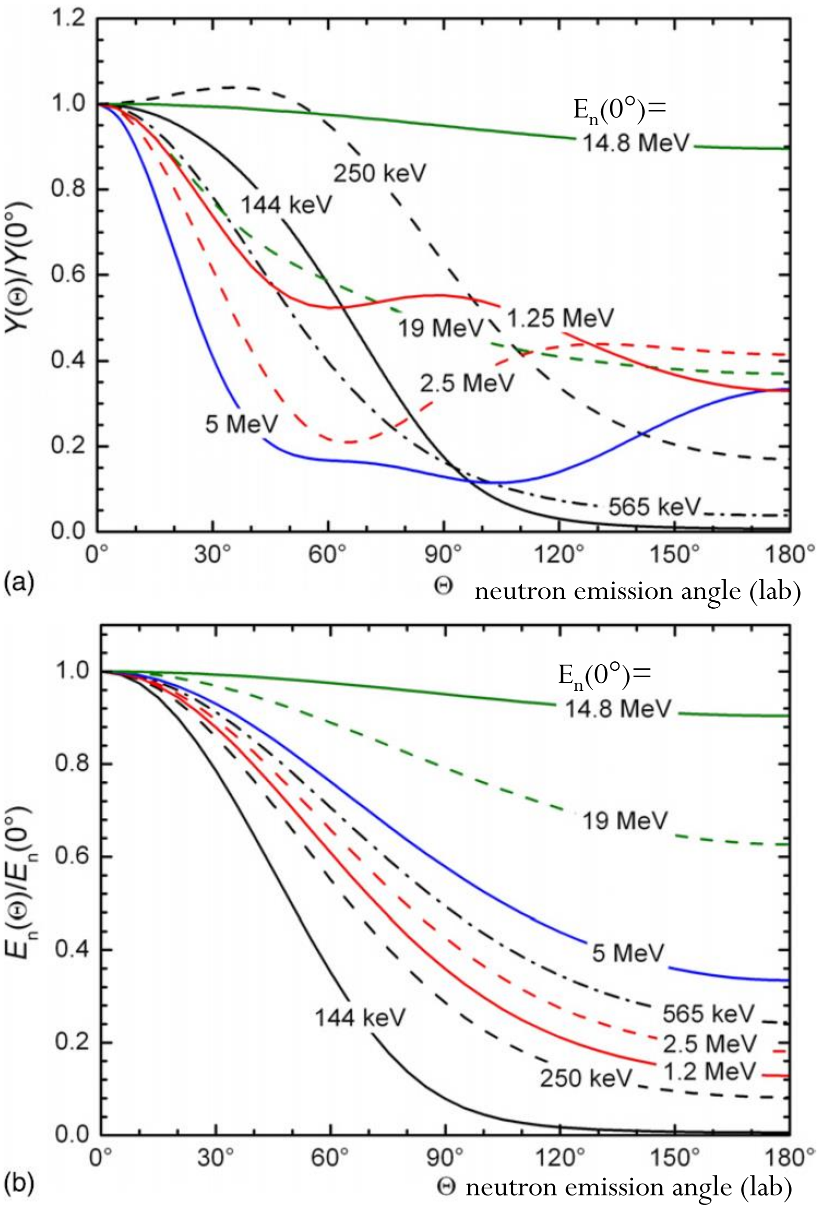


Fig. 4. Neutron spectrum measured on the roof of the IBM T. J. Watson Research Center in Yorktown Heights, NY.

Setup:
Extended range Bonner spheres
14 different size PE moderators
with ^{3}He proportional counters

G. Heusser, Low-radioactivity background techniques

Monoenergetic neutron reference fields



$T(d,n)^4He$ — relative Yield

$^7Li(p,n)^7Be$ — $Y(0°)$ calculated for $\Delta E_n = 10$ keV

$T(p,n)^3He$

$D(d,n)^3He$

$T(d,n)^4He$:
rather isotropic

$^7Li(p,n)^7Be$:
production of keV neutrons at backw
(reduced yield)

Parameters of reference fields
(E_n, Y, target, beam properties)
see table 2 of
R. Nolte, D.J. Thomas, Metrologia 48 (2011) S263

DROSG 2000 neutron source reactions code:
https://www-nds.iaea.org/public/libraries/drosg2000/

Relativistic two-body kinematics:

- Lorentz-Transformation in beam direction with rapidity $Y = \ln \frac{p_{cm} + \sqrt{m_1^2 + p_{cm}^2}}{m_1}$

…

$$p_{3,4} = \frac{\sqrt{m_{3,4}^2 + p_{cm}'^2}\,\cos\Theta_{3,4}\sinh Y \pm \cosh Y \sqrt{p_{cm}'^2 - m_{3,4}^2 \sin^2\Theta_{3,4}\sinh^2 Y}}{1 + \sin^2\Theta_{3,4}\sinh^2 Y}$$

- Two solutions of $p_{3,4} = f\left(\Theta_{3,4}\right)$!
- For endothermic reactions $Q = m_1 + m_2 - m_3 - m_4 < 0$ MeV
  Forward threshold (minimum kinetic energy for the reaction to occur)
  derived from $E_{3,cm} + E_{4,cm} \geq \mathrm{m}_3 + \mathrm{m}_4$

$$T_f = -Q[1 + \left(\frac{m_2}{m_1}\right) - \left(\frac{Q}{2m_1}\right)]$$

- If the ejectile is slower than the c.m. velocity E_3 is a double-valued function of the lab angle Θ_3 . Equivalent: Θ_3 is a double-valued function of Θ_{cm} up to the back threshold $T_b = -Q[1 + \frac{m_2}{m_1 - m_3} - \frac{Q}{2(m_1 - m_3)}]$

Energy range for neutron production

- „Monoenergetic" neutrons from reactions with only one neutron group
- „Quasi-monoenergetic" neutrons from reactions with a second group of neutrons from reactions to excited states of the recoil or nuclear break up
- Example: $^{7}Li(p,n)^{7}Be$

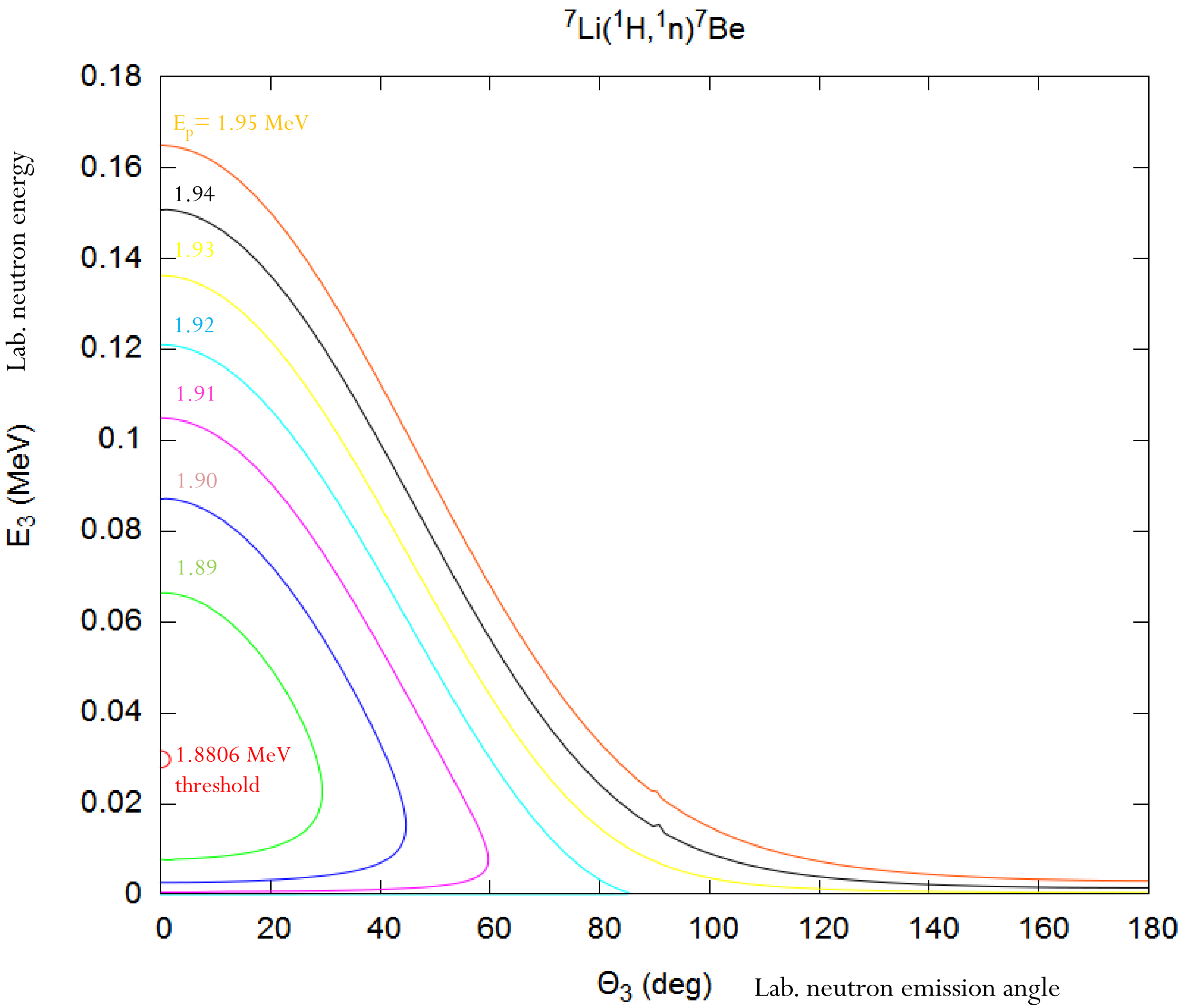
Reaction	$^{7}Be^{*}$ Exc. Energy (MeV)	Q-value (MeV)	Threshold (MeV)
$^{7}Li(p,n)^{7}Be$	0	-1.644	1.881 forward 1.920 backward
$^{7}Li(p,n)^{7}Be^{*}$	0.429	-2.073	2.371 forward 2.421 backward
$^{7}Li(p,n^{3}He)^{4}He$	break-up	-3.229	3.692
$^{7}Li(p,n)^{7}Be^{**}$	4.57	-6.214	-7.110 forward -7.260 backward

- Energy levels of light nuclei, see http://www.tunl.duke.edu/nucldata/index.shtml

- Monoenergetic neutrons from E_p =1.920 MeV – 2.371 MeV
  E_n = 121 keV – 649 keV

$^7Li(p,n)^7Be$: neutron energy vs. angle

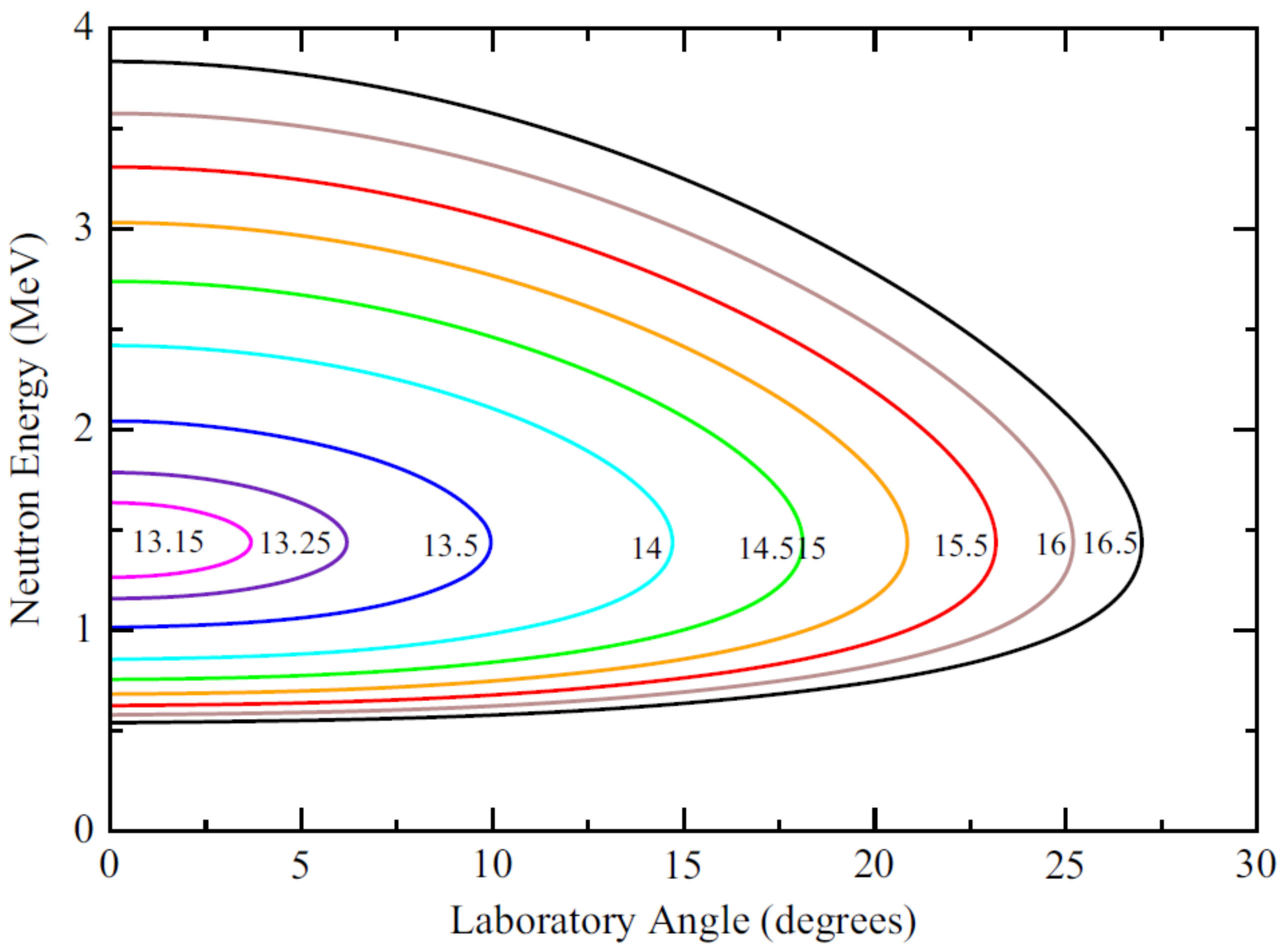
- $Q = -1.644$ MeV ; $T_f = 1.881$ MeV ; $T_b = 1.920$ MeV



Two neutron energy groups below T_b

Neutron production in inverse kinematics

- light-ion beam required with higher energy (beam heating) e.g. $^{1}H(^{7}Li,n)^{7}Be$



M. Lebois et al. NIM A735(2014)145–151

Fig. 1. Kinematic curves relating the angle of neutron emission to neutron energy in the laboratory frame for different ^{7}Li bombarding energies from 13.15 to 16.5 MeV, calculated using two-body relativistic kinematics.

Kinematical focussing increases neutron intensity in a forward cone.

Licorne Facility at IPNO

$$T_f = 13.096 \text{ MeV}$$

Realistic source yield

The differential neutron spectrum

$$\frac{d^2N}{dE_n d\Omega} = N_p n_{tar}\left(\frac{d\sigma}{d\Omega^{cm}}\right)\left(\frac{d\Omega^{cm}}{d\Omega}\right)\left(\frac{dE_p}{dx}\right)^{-1}\left(\frac{dE_p}{dE_n}\right)$$

$$Y = \int \frac{d^2N}{dE_n d\Omega}\frac{1}{N_p}dE_n$$

$\frac{dE_p}{dx}$ linear stopping power,
$\frac{d\Omega^{cm}}{d\Omega}$ solid angle element ratio c.m to laboratory system,
$\frac{dE_p}{dE_n}$ kinematic factor

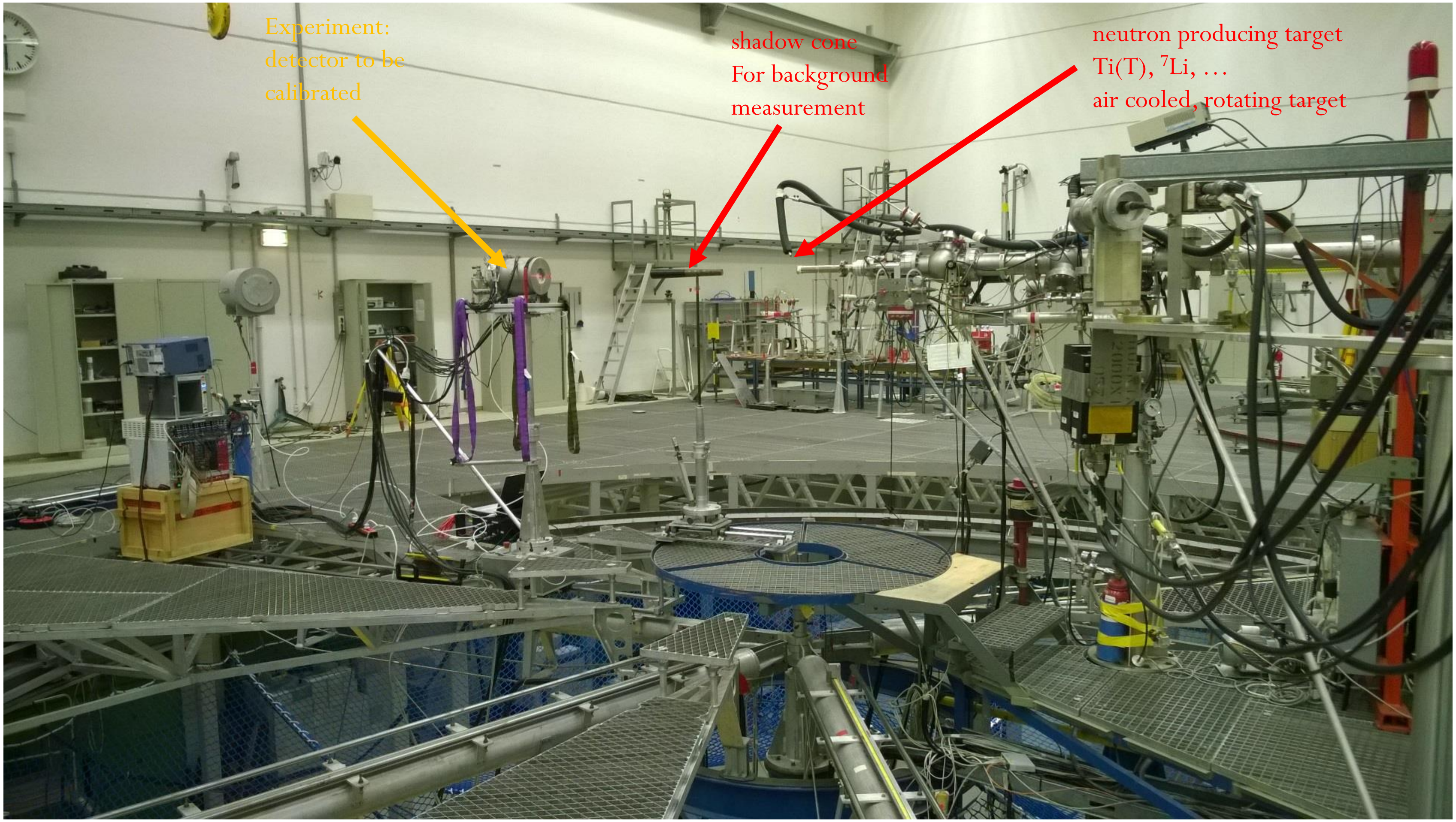
- Neutron yield depends on target thickness and purity:
  Energy loss of the beam in the neutron producing target layer
  ➔ beam heating of the target
  Thermal motion of target atoms e.g. in gaseous targets

  ➔ neutron energy spread
- Neutron scattering in target materials, backings, windows
- Opening angle and source and detector counting geometry
- Kinematic focussing for reactions in inverse kinematics

➔ Monte Carlo neutron transport simulation to describe the neutron spectrum of quasimonoenergetic neutron sources

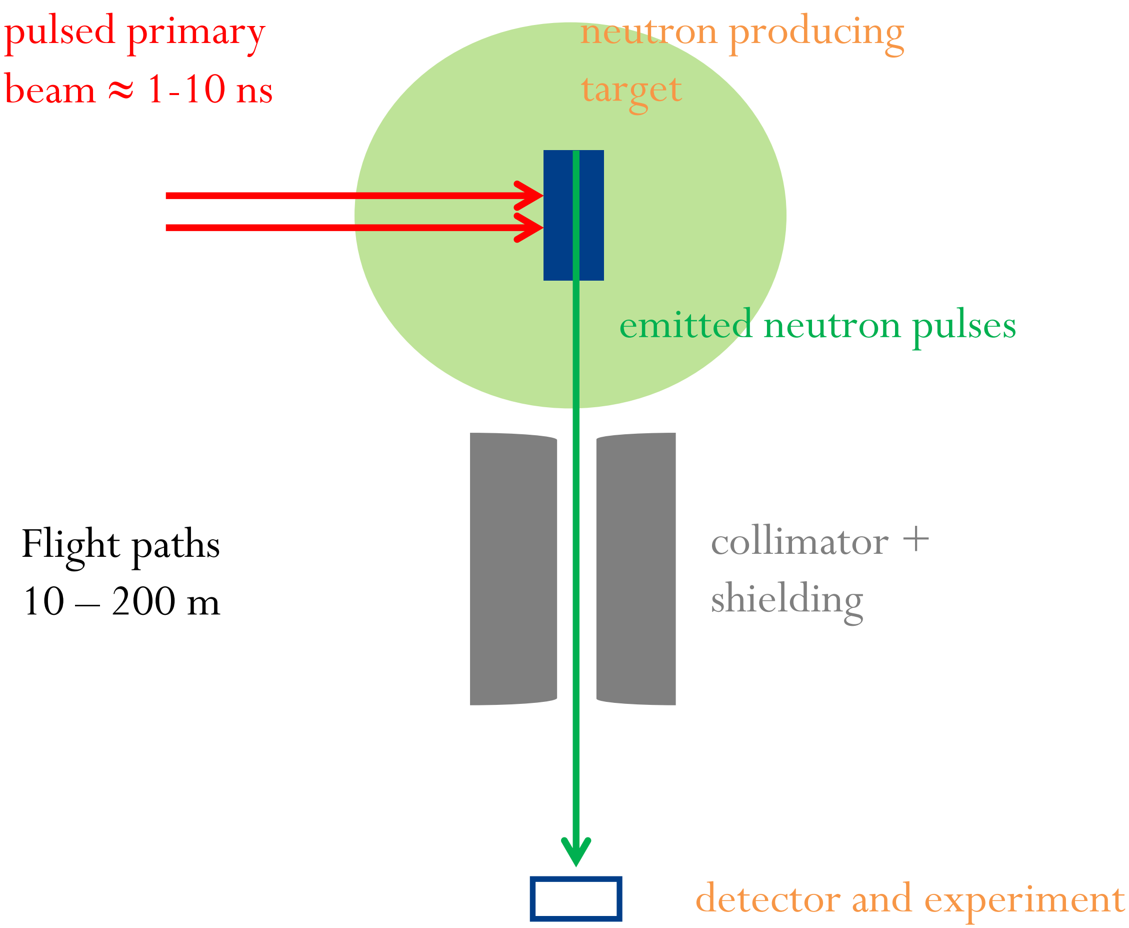
Time correlated associated particle method
➔ neutron yield measured independent from $\frac{d\sigma}{d\Omega^{cm}}$

PTB neutron reference facility



Neutron reference fields are produced in open geometry without collimation
Very low room return due to large free space around source and detectors
Van der Graaff Ion accelerator for 1 – 4 MeV protons, deuterons
with DC beam and pulsed beam Δt = 1-2ns, $\nu \approx$ 1 MHz

measurement



primary beams:

light charged particles with >100 MeV energy
➔ spallation neutron source

electrons 10 – 150 MeV
➔ photoneutron source

Deuteron beams on Be/C converters
deuteron break up

quasimonoenergetic neutron sources e.g. ^{7}Li(p,n)
➔ pulsed beam
background identification

Energy resolved measurements by time of flight:

- Measurement of time-of-flight t and flight path l

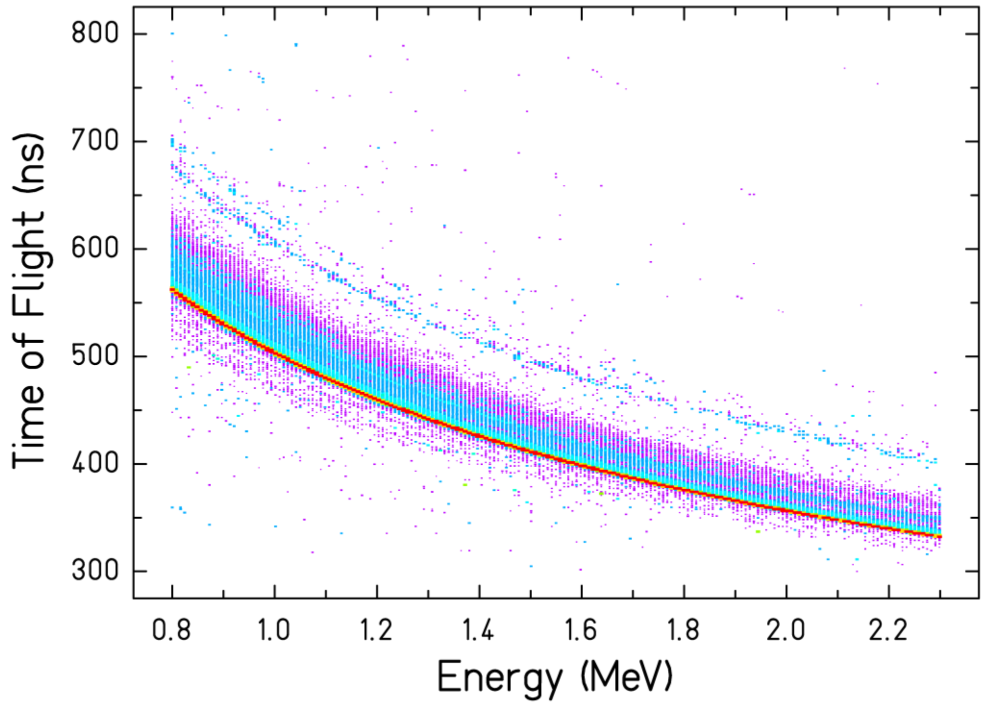
1. $v = \frac{l}{t}$
2. $\gamma = \frac{1}{\sqrt{1-\left(\frac{v}{c}\right)^2}}$
3. $E = mc^2(\gamma - 1)$ *(E is the neutron kinetic energy)*

- Energy resolution

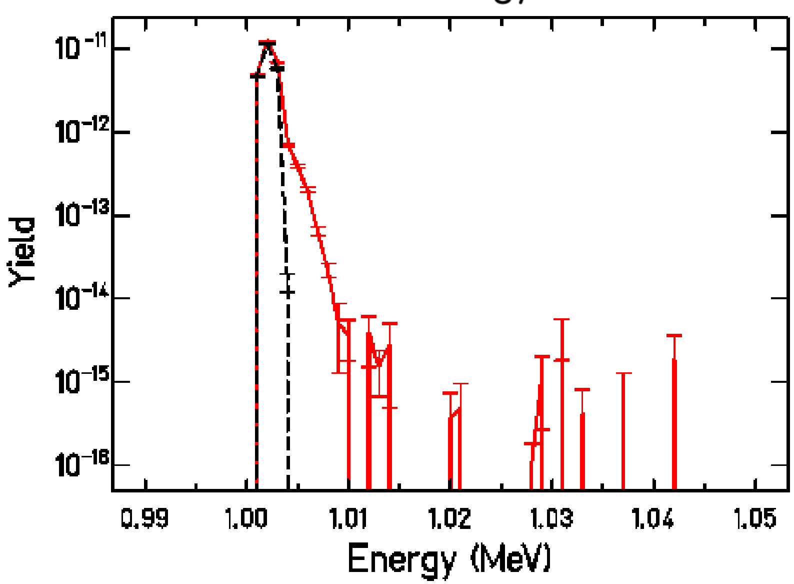
1. $\frac{\Delta E}{E} = (\gamma + 1)\gamma\frac{\Delta v}{v}$
2. $\frac{\Delta v}{v} = \sqrt{\left(\frac{\Delta t}{t}\right)^2 + \left(\frac{\Delta l}{l}\right)^2}$

- accelerator pulse length, time resolution of detectors,
  neutron transport in the neutron producing target and detector or sample
  Schillebeeckx et al. NDS 113 (2012) 3054

Time-of-flight to Energy correlation



- Neutron transport code MCNP: Simulation of **neutron scattering** inside the neutron source and all surrounding materials e.g. collimators
- **Neutron scattering can change the correlation of time of flight and neutron energy ➔ multiple scattering corrections**



- Unscattered neutrons can be identified
  (in the simulation)

Neutron evaporation spectrum from Compound Nucleus decay

CN decay probability:

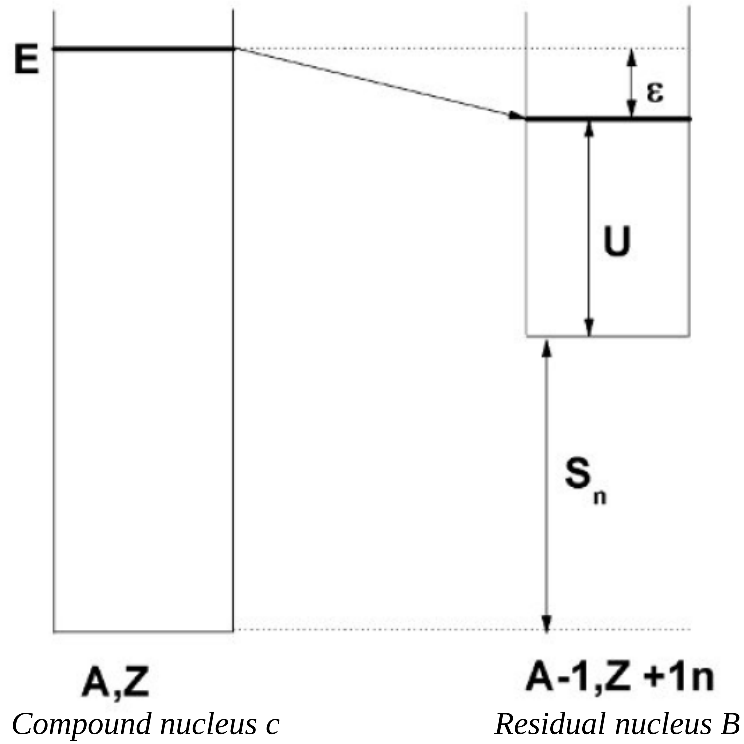
$$W_{c\beta}(\epsilon_\beta) = \frac{\rho_B(U)}{\rho_c(E)} \frac{m_\beta \epsilon_\beta \sigma_{\beta c}(\epsilon_\beta)}{\pi^2 \hbar^3}$$

$$\rho_c \propto \frac{1}{T} e^{E/kT}$$

$$\rho_B \propto \frac{1}{T} e^{U/kT} = \frac{1}{T} e^{(E-\epsilon-S_n)/kT}$$

$$\frac{\rho_B(U)}{\rho_c(E)} = const \cdot e^{-\epsilon/kT}$$

$$W(\epsilon_\beta) = const \cdot \sigma_{\beta c} \epsilon_\beta e^{-\epsilon/kT}$$



$U = E - \varepsilon - S_n$

At ε close to max. transitions to discrete excited states of the residual nucleus B

The emission spectrum depends on:

The **level density** of the compound nucleus ρ_c

The **level density** of the residual nucleus ρ_B

and the inverse cross section of compound nucleus formation

For neutron emission $\sigma_{\beta c}$ is not strongly energy depend. ➔ Maxwellian energy spectrum

For charged particle emission: Transmission through the Coulomb-Barrier

Neutron evaporation spectra

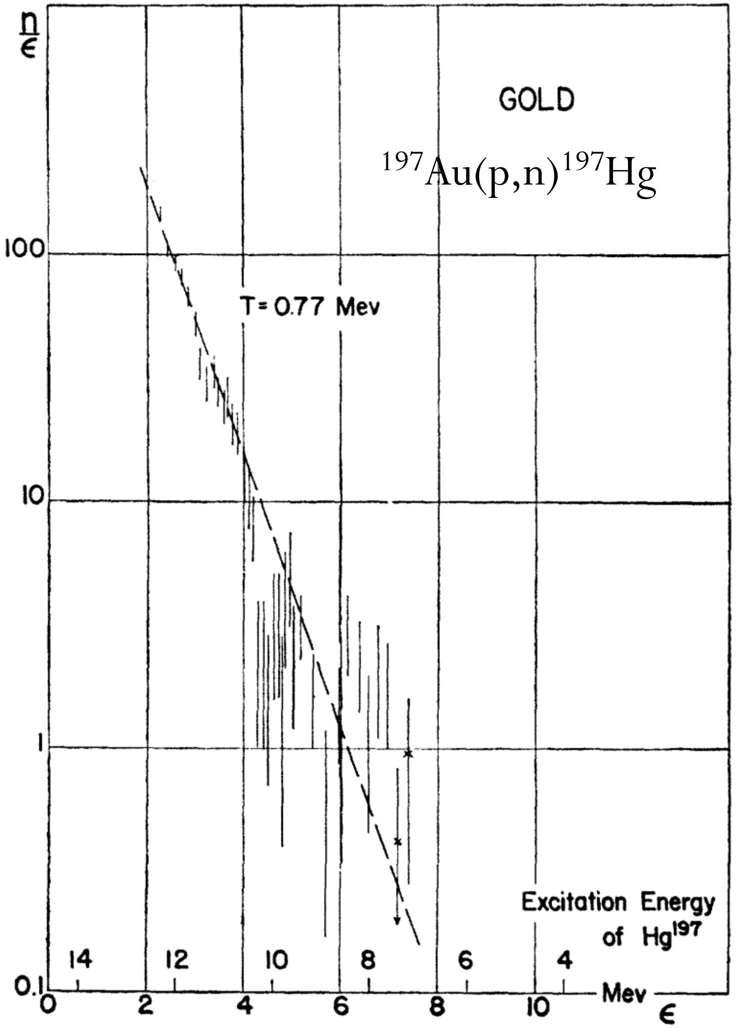


FIG. 11. Relative level density of Hg^{197}.

Gugelot, Phys. Rev. 81 (1951) 51

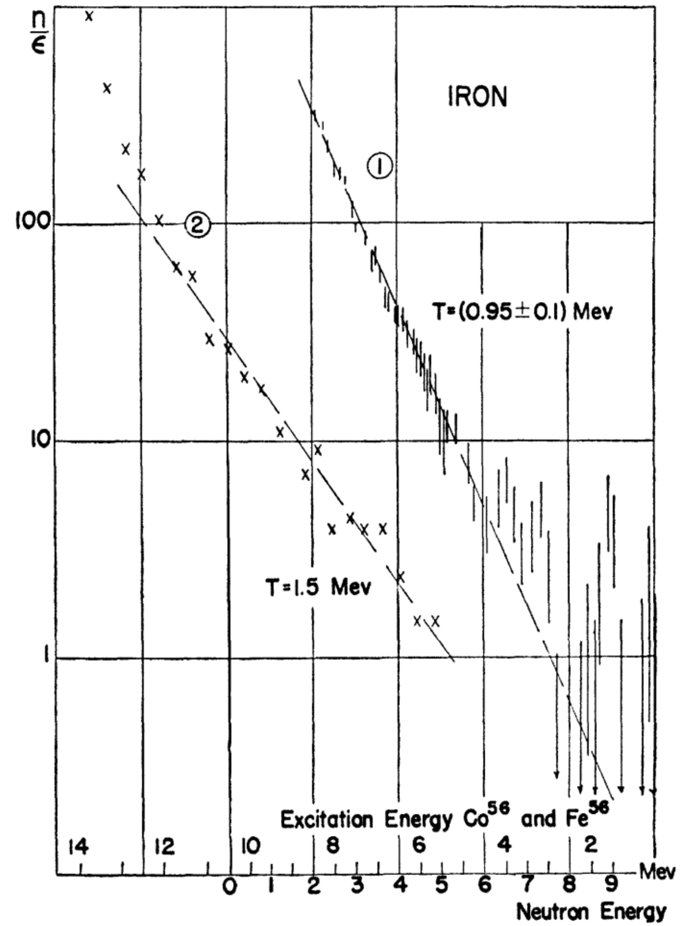
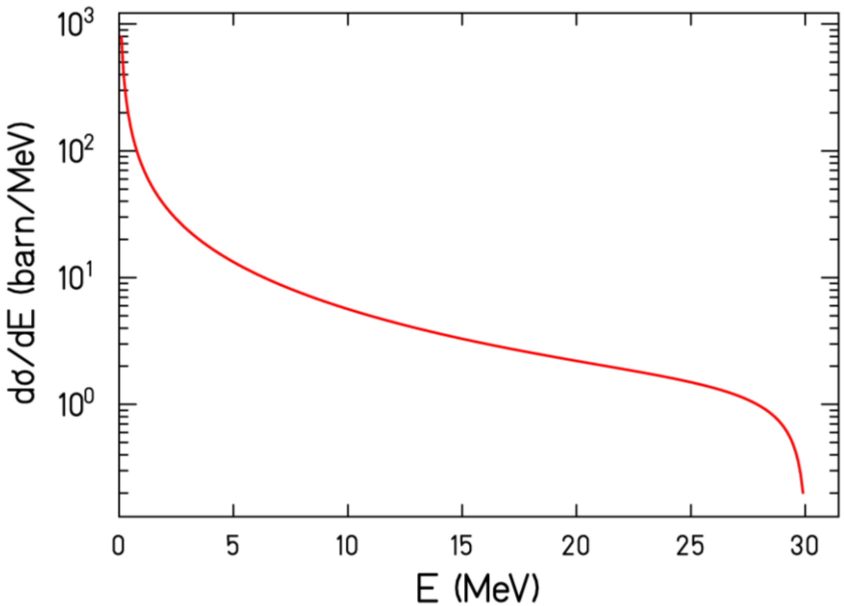
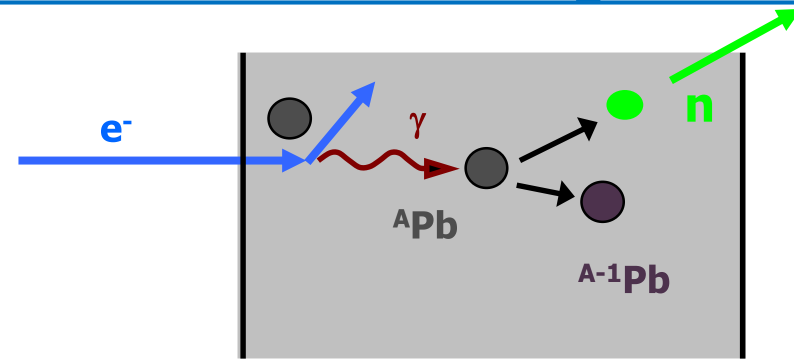


FIG. 9. Relative level density of Co^{56} and Fe^{56}. Curve 1: represents the relative level density for Co^{56} obtained from the neutron spectrum; curve 2: shows the relative level density of Fe^{56} as observed from the inelastic scattering of 16-Mev protons by iron (reference 38).

Photoproduction of neutrons with bremsstrahlung

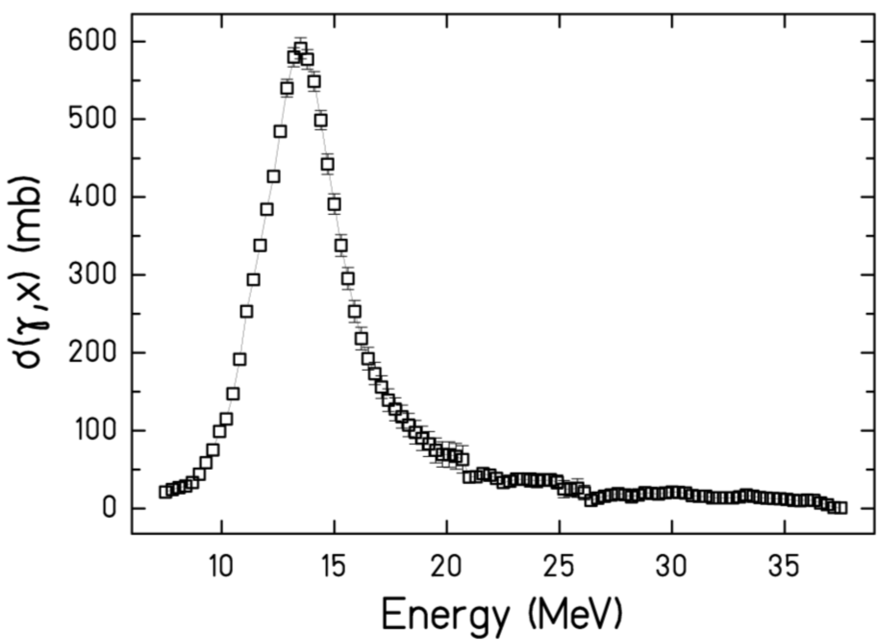




Bremsstrahlung spectrum ➔ Photonuclear excitation of Pb through the Giant D

Neutron pro
(γ,xn) react

nELBE yield
30 MeV 15μ
200 kHz
GELINA yie
100 MeV 96
800 Hz



Veyssiere et al., NPA 159 (1970) 561

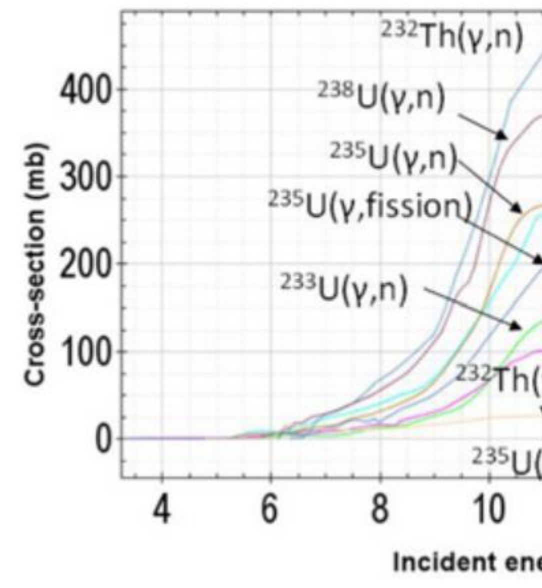
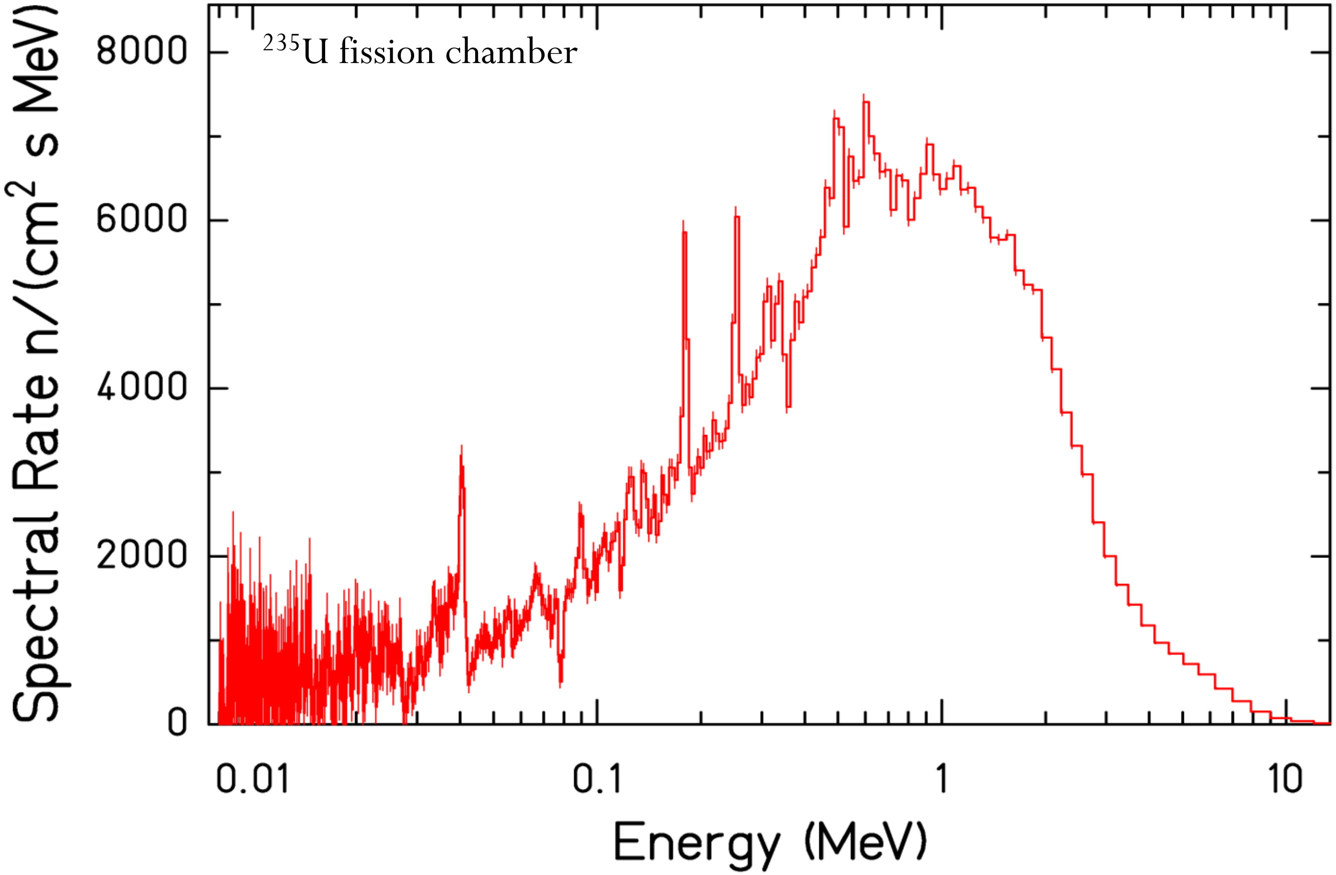


Photo neutron spectrum from nELBE



Measurement time : 49.4 h I_{e-} = 15 µA, E_{e-} = 31 MeV

Flight path 618 cm

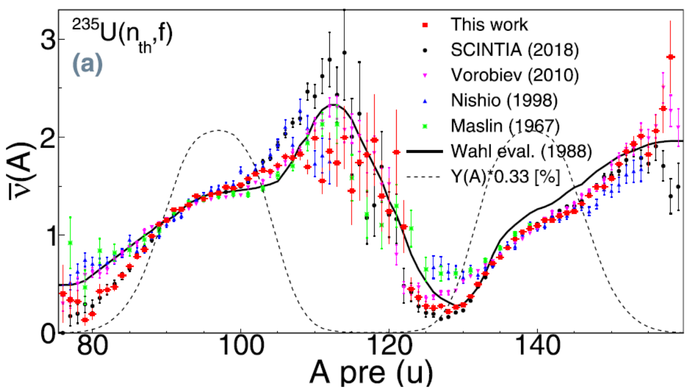
Absorption dips : 78,117, 355, 528, 722, 820 keV ^{208}Pb scatttering resonances

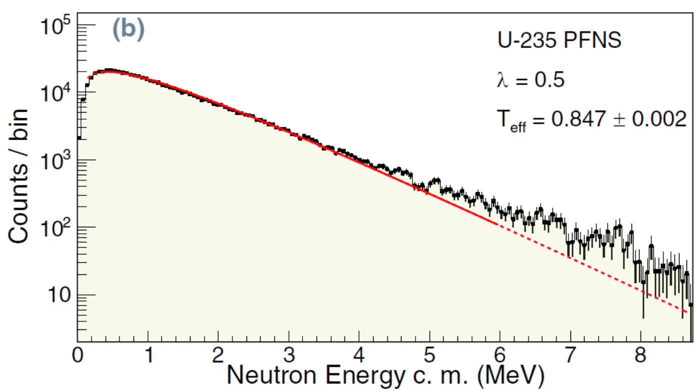
Emission peaks: 40,89,179, 254, 314, 605 keV near threshold photoneutron emission

In ^{208}Pb (strong capture resonances of ^{207}Pb)

R. Beyer et al., NIM A723 (2013) 151

Prompt neutron production by fission





- Neutrons are mostly emitted from the accelerated fission fragments.
- Low energy fission shows saw-tooth behaviour of the average number of neutrons emitted from each fission fragment with mass number A

- Fission fragments are excited neutron-rich compound nuclei that deexcite by neutron and gamma-ray emission
- Neutron evaporation in statistical model

Van de Graaff accelerator, JRC Geel
TFGIC + liquid scintillators
A. Al-Adili, Phys. Rev. C102 (2020) 064610

e.g. Los Alamos Model for prompt fission neutrons
D.G. Madland, Nuclear Physics A 957 (2017) 289–311

Accelerator-based Neutron Sources

- **Time-of-flight neutron sources**
- High energy resolution for resolved resonance region:
  Gelina JRC Geel, nELBE HZDR Dresden, n_TOF CERN
- Quasimonoenergetic and ‘white’ beams < 40 MeV: **NFS Ganil**
- Dedicated detector systems for (n,n’ γ) and (n,tot) measurements

New!

NFS (GANIL), n_TOF lead target 3 (CERN) + NEAR station

- **Ion accelerators**
- Quasimonoenergetic and ‘white’ neutrons for unresolved resonance region
  - Electrostatic accelerators :
    CNRS-AIFIRA Bordeaux, CEA Bruyeres le Chatel, PTB Braunschweig, NPL London, CAN Sevilla, CNRS-ALTO Paris
  - Cyclotrons: **PTB , NPI Rez**
- 14 MeV generators for high intensities:
  ENEA Frascati, UU Uppsala, CNRS-GENESIS Grenoble
- Ion beams for surrogate method, ISOL and IBA: **UO Oslo, JYU Jyväskylä, IFIN Budapest**

New!

HISPANoS D+d source CAN Sevilla, NESSA 14 MeV generator UU, TANJA 2 MV Tandetron PTB, MR-TOF mass separator JYU Jyväskyla

Research Reactors

- Thermal cross sections, fission neutron spectra, fundamental physics with neutrons
- Dedicated instruments: Penning traps, fission fragment and gamma spectrometers, cold neutron sources
- Ultracold, cold and thermal neutrons:
  MTA-EK Budapest, SCK CEN Mol, CVŘ, Řez
- High-flux reactor: **ILL Grenoble**
- Pulsed source: **JGU TRIGA Mainz**
- Instruments for nuclear data:
  Prompt Gamma Activation Analysis
  Neutron induced Prompt gamma-ray spectroscopy
  Fission product prompt gamma-ray spectrometer
  Fission Yield measurements
  Fission fragment spectrometer

Beam properties of the ARIEL facilities

summary of the ARIEL facilities available for TAA		accelerators																				research reactors				
		e^- beams		ion beams																						
		nELBE@HZDR	GELINA@JRC	MONNET@JRC	n_TOF@CERN	AIFIRA@CNRS	ALTO@CNRS	GENESIS@CNRS	NFS@GANIL	CEA-DAM	FNG@ENEA	PTB	FNG@NPI	HISPANOS@CNA	NESSA@UU	U. Oslo	NPL	IFIN-HH	JYU	IRSN	AGOR@UMCG	BRR@mtaEK	BR1@SCK·CEN	TRIGA@JGU	LR-0/LVR-15 @CVR	RHF@ILL
neutrons	cold (<25 meV)																					■		■		■
neutrons	thermal (‹E_n›=25 meV)		■	■										■			■			■		■	■	■	■	■
neutrons	epithermal (25 meV – 100 keV)		■		■	■	■			■				■			■			■		■	■	■	■	■
neutrons	fast (0.1-20 MeV)	■	■	■	■	■	■	■	■	■	■	■	■	■	■		■			■		■	■	■	■	■
neutrons	very fast (>20 MeV)				■				■				■													
neutrons	pulsed beam	■	■	■	■				■	■		■	■	■	■					■				■		
neutrons	time-of-flight	■	■	■	■				■	■		■	■	■						■						
charged particles						■	■									■		■			■					
radioactive beam							■												■							■

LOHENGRIN Fission Fragment Spectrometer

FF recoil spectrometer

$$\frac{A}{\Delta A} \cong 400;\ \frac{E}{\Delta E} \cong 100$$

-separation of ionic charge states ➔ fission yields

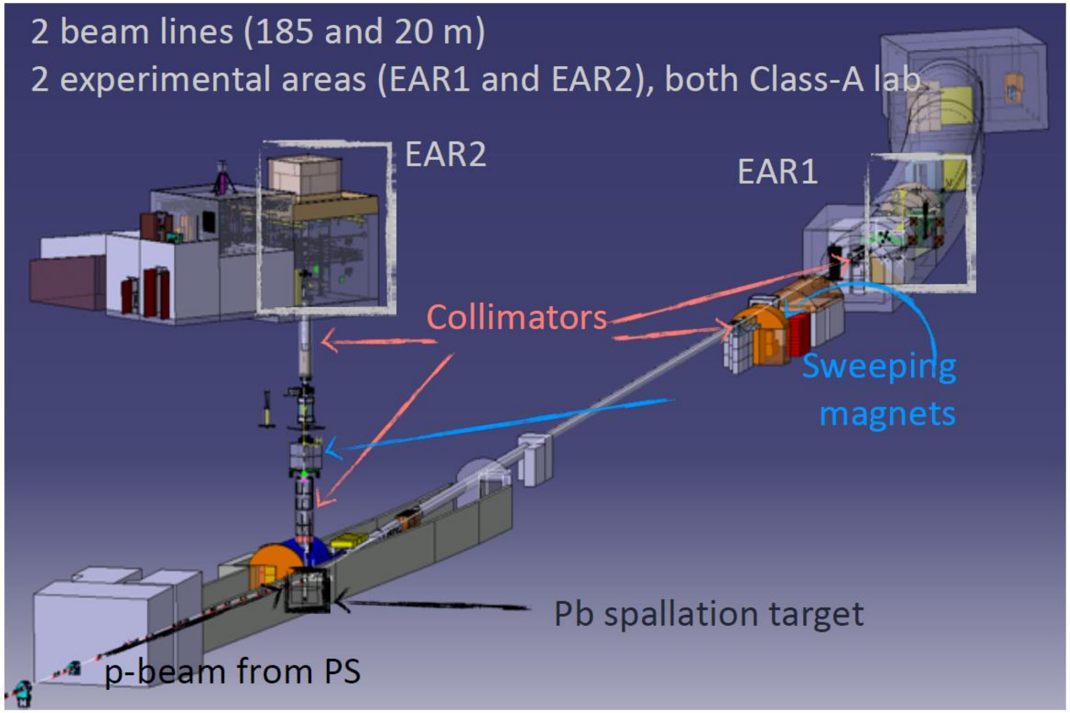
A. Chebboubi, Eur. Phys. J. A (2021) 57:335

PGAA's modular neutron flight tube applications

Removable modules enable to accommodate user supplied set up:

- Measurement of prompt fission gamma spectra of ^{233}U(n$_{cold}$, f γ) with users from JRC Geel in 2018
- Fission chamber + gamma ray detectors (4 $LaBr_3$:Ce + HPGe)
- Relative (n, γ) Xsection measurement (^{242}Pu(n, γ) Univ. Sevilla, 2018)
- Isotopic analysis of samples (CERN, EFNUDAT)
- Gamma strength function (^{242}Pu(n, γ) Univ. Sevilla, 2018) and (^{232}Th(n, γ) Univ. Osmangazi, 2017, 2018)
- Gamma-gamma coincidence (^{94}Nb(n, $\gamma\gamma$), Univ. Novi Sad, 2016 and 2017)
- Etc.

CERN n_TOF Experiment



EAR-2:
short flight path 20 m for higher intensity
90° to the proton beam ➔ Background reduction

E.Chiaveri, EPJ Web of Conferences 239, 17001 (2020)

- Spallation source using 20 GeV/c proton beam from CERN proton synchrotron

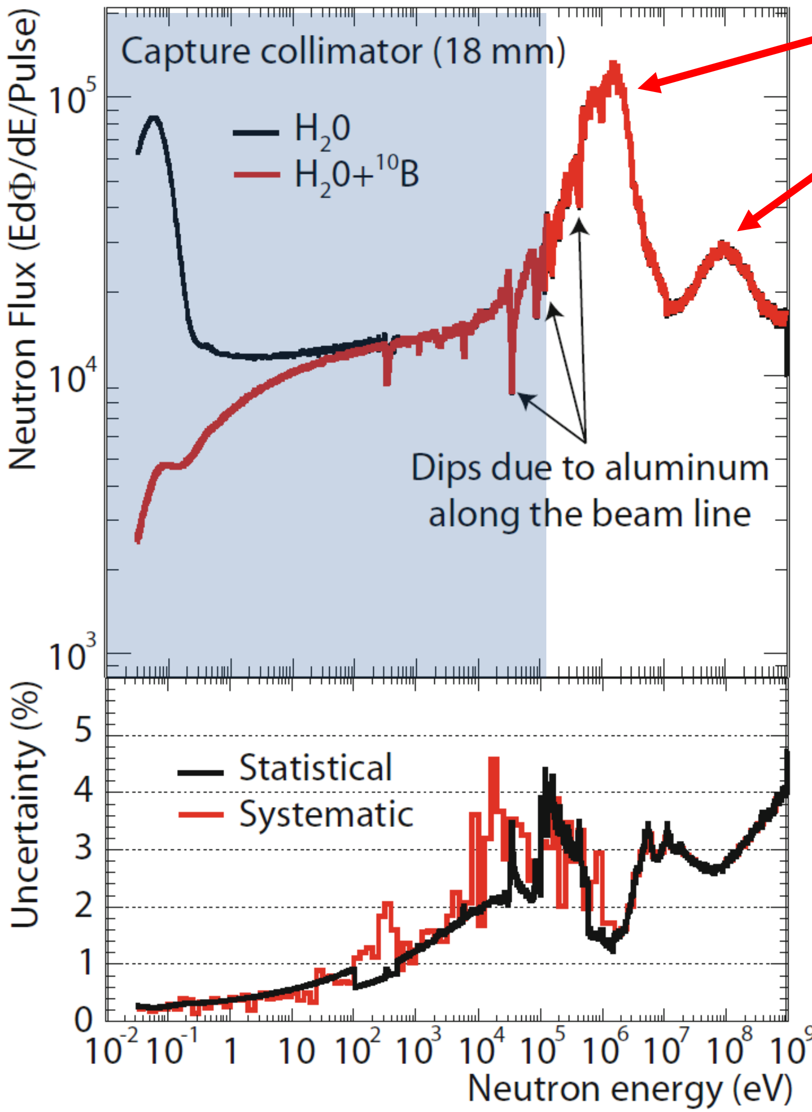
- New spallation target in 2021 > 10^6 n / PS pulse

- Radioactive target capability at experimental stations (high instantaneous flux ➔ use of small number of target atoms)

Experimental capabilities:
radiative neutron capture (n,γ)
neutron induced fission (n,f)
Neutron induced light charged particle emission (n,p) (n,α)

NEAR station for irradiation

Spallation neutron spectrum at CERN nTOF



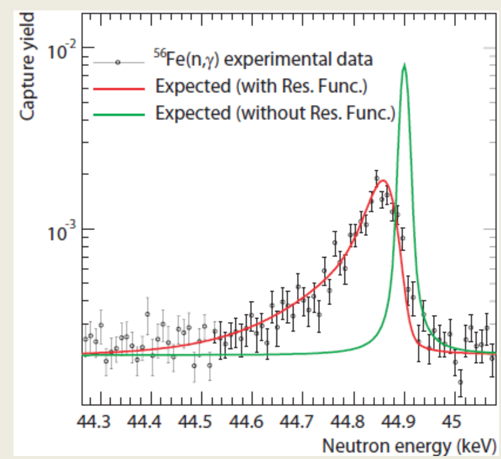
Neutron evaporation (0.1 – 10 MeV)

Fast neutrons from intranuclear cascade stage > 10 MeV

Shaded range < 0.1 MeV
Neutrons slowed down by hydrogeneous materials

ENERGY RESOLUTION

E_n (eV)	$\Delta E_n/E_n$
1	$4.3\cdot10^{-4}$
10	$4.3\cdot10^{-4}$
10^2	$4.3\cdot10^{-4}$
10^3	$7.5\cdot10^{-4}$
10^4	$1.7\cdot10^{-3}$
10^5	$5.4\cdot10^{-3}$
10^6	$2.8\cdot10^{-3}$



C. Guerrero et al., EPJA49 (2013) 27

GELINA pulsed neutron source

Electron accelerator

- 150 MeV electron accelerator
- 10 ns burst, 10 A peak
- 800 bursts/s

Compression magnet

- Pulse compression magnet
- <1 ns burst, >100 A peak

Electron-neutron conversion target

- Uranium target – rotating, mercury cooled
- 4 10^{10} neutrons / burst

water-filled Be moderators

12 Flight paths
8 to 400 m

moderated or fast neutron spectrum
24 h/d, 100 h/w

GELINA neutron spectrum and energy resolution

Flaska et al., NIM A531 (2004) 394

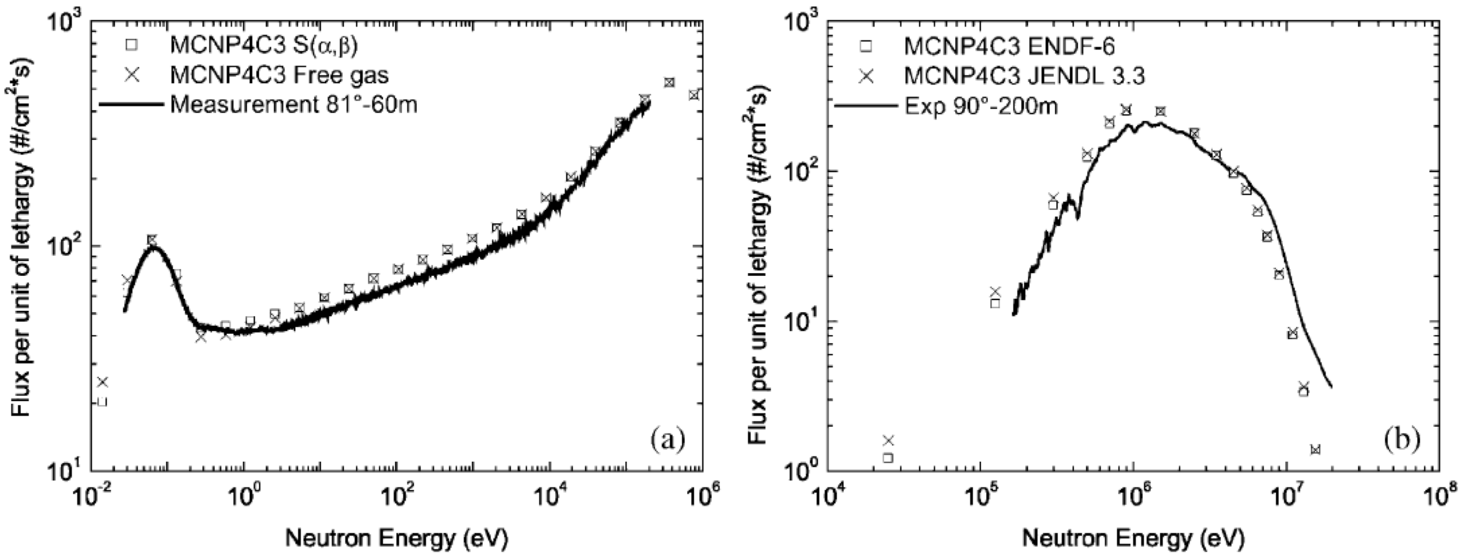
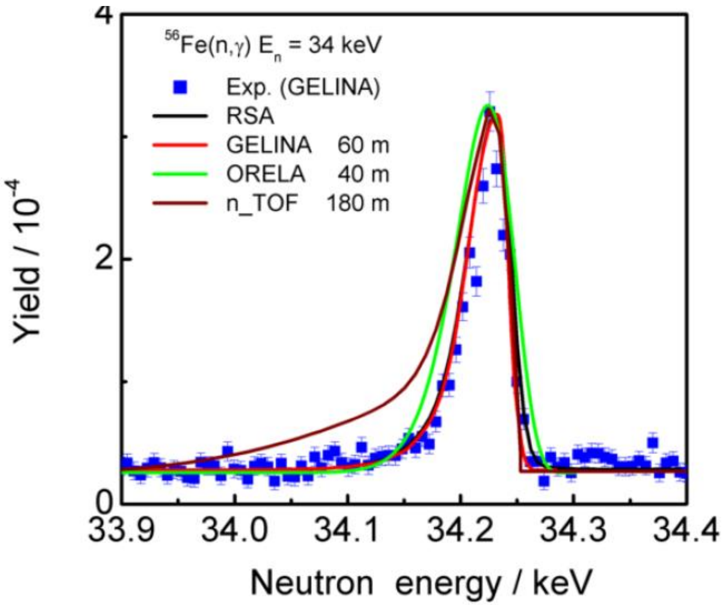


Fig. 4. Neutron flux per unit of lethargy in the flight-path. (a) 81°—60 m of the moderated neutron spectrum; (b) 90°—200 m of the fast neutron spectrum.

Fast neutron spectrum from 0.1 – 18 MeV

Schillebeeckx et al. NDS 113 (2012) 3054

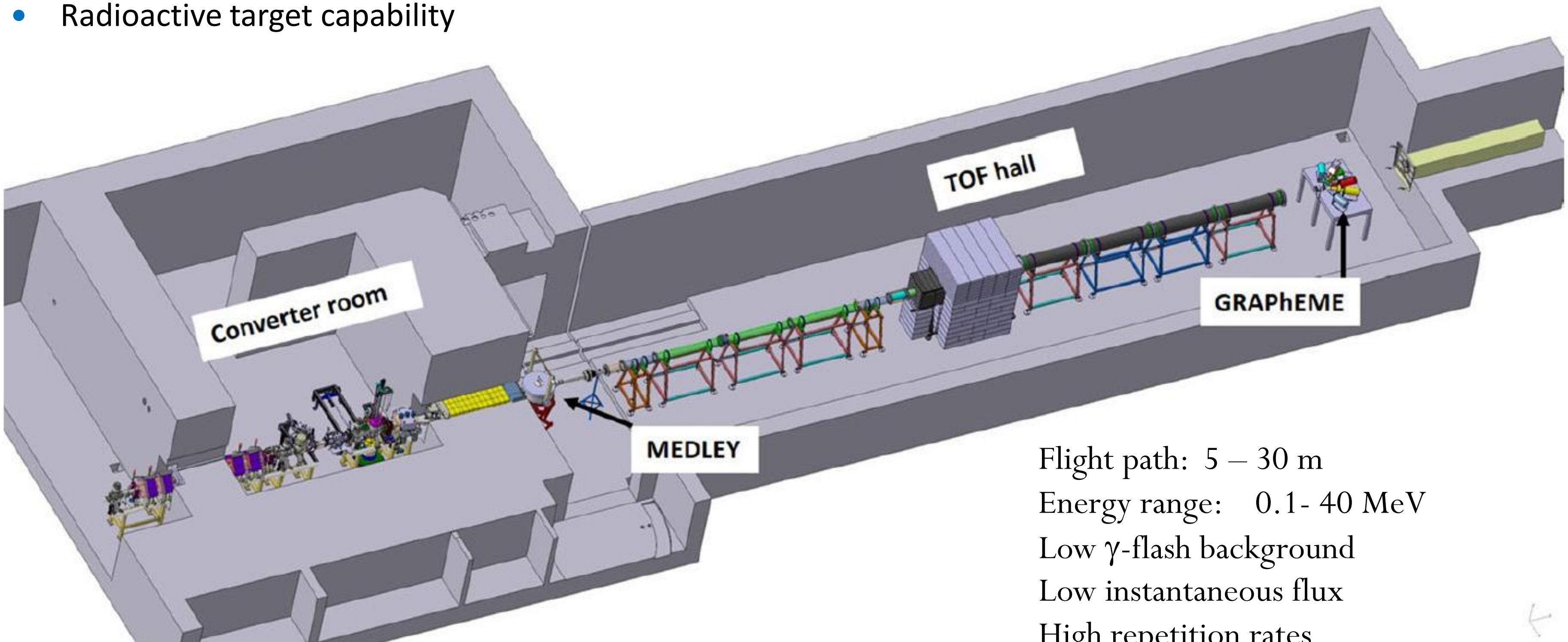


GELINA:

- width is dominated by the tof-resolution
  resonance total $\Gamma \approx 2$ eV
  Doppler width (FWHM) ≈ 13 eV
  ToF resolution (FWHM) ≈ 40 eV
- photoneutron sources tend to have a higher resolution than spallation neutron sources (larger target-moderators required)

Neutrons For Science at GANIL

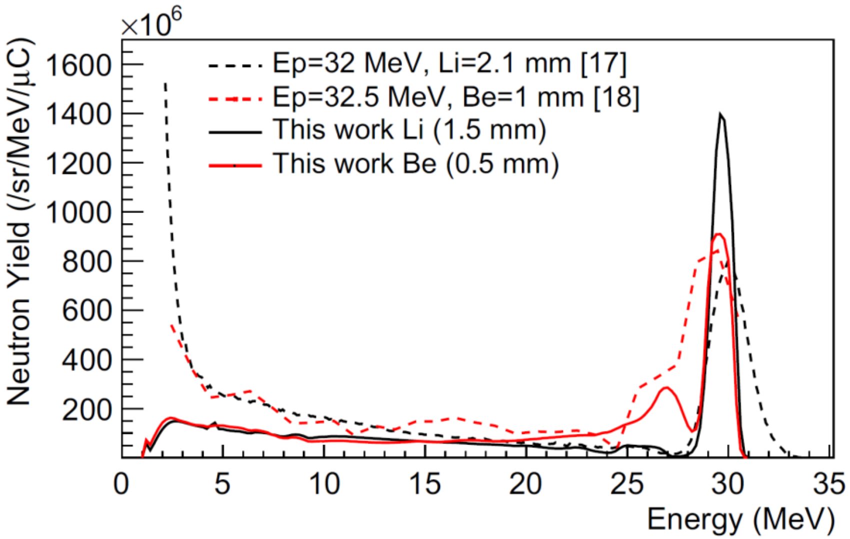
- First facility at SPIRAL-2 superconducting LINAC
  proton (33 MeV), deuteron (40 MeV), helium (80 MeV) beams for neutron production
- F_0= 88 MHz with single bunch selector for ToF measurements 150 kHz – 1 MHz
  beam current 5 mA / N up to < 50 μA
- Thin and thick converter targets Li, C, Be
  quasimonoenergetic and continuous neutron spectra
- Irradiation station
- Radioactive target capability



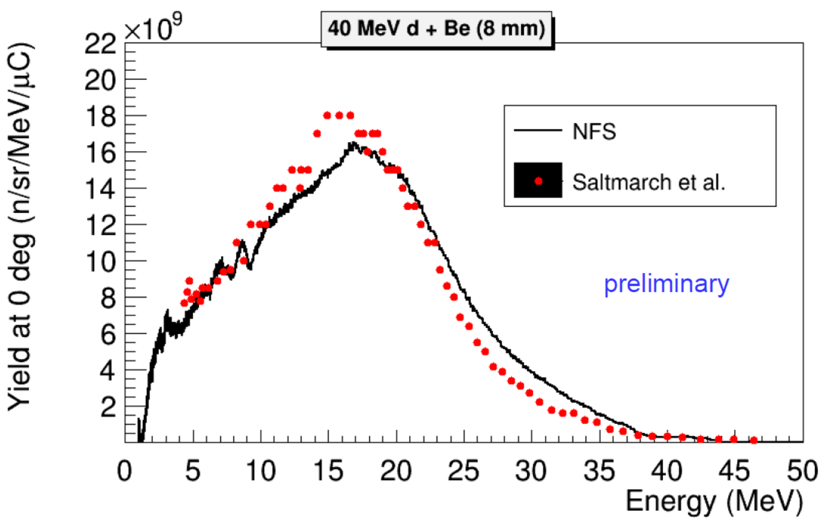
Flight path: 5 – 30 m
Energy range: 0.1- 40 MeV
Low γ-flash background
Low instantaneous flux
High repetition rates

X. Ledoux, Eur. Phys. J. A (2021) 57:257

NFS neutron spectra



- Quasimonoenergetic neutrons $p + {}^7Li$, ${}^9Be$ thin converters



Flux at 5 meters : 8.10^7 n/s/cm²
at 15 MeV : 5.10^6 n/s/cm²/MeV
at 30 MeV : 6.10^5 n/s/cm²/MeV

- White spectrum 40 MeV deuterons on thick Be converter

Fast neutron range up to 40 MeV:
Reaction studies:
(n,n'γ),(n,xn), (n,f), (n,p), (n,α), (n,tot)

X. Ledoux, Colloque Ganil 2021

Neutron time-of-flight facilities for cross section measurements

Facility	Type	particle energy (MeV)	Target	Pulse width (ns)	Frequency (Hz)	Flight Path Length (m)
GELINA	e-	80-140	U(Hg cooled)	1	40-800	10-400
nELBE	e-	40	Pb	0.01	100000-250000	4-10
NFS(GANIL)	d	40	Be,C	0.2	150000- 1000000	5-30
n_TOF (CERN)	p	20000	Pb	6	0.4	20,185
RPI	e-	60	Ta	7 - 5000	500	10-250
LANSCE - MLNSC	p	800	W	135	20	7-60
LANSCE -WNR	p	800	W	0.2	13900	8-90
JPARC/MLF - ANNRI	p	3000	Hg	600	25	21,28
CSNS back-n	p	1600	W(H2O cooled)	50 (double pulse)	25	55, 76
KURRI	e-	20-46	Ta	2,5,..100	1-300	10,13,24
KURRI	e-	7-32	Ta	100-4000	1-100	10,13,24
ORELA	e-	140	Ta	2 - 30	1-1000	10-200
POHANG	e-	75	Ta	2000	12	11

Literature

- Reference:
  J.B. Marion, J.L. Fowler, Fast Neutron Physics Part I+II, Interscience New York, 1960 (kinematics in chapter I.b)

- Quasimonoenergetic neutrons:
  R. Nolte, D.J. Thomas, Metrologia 48 (2011) S263

- Neutron sources and resonance parameter determination
  P. Schillebeeckx, Nuclear Data Sheets 113 (2012) 3054–3100

- ARIEL webpage with links to many neutron beam facilities

ENDE