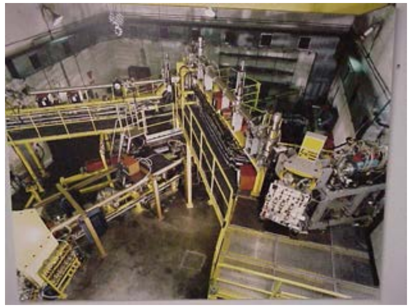
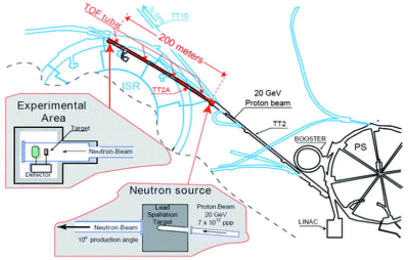
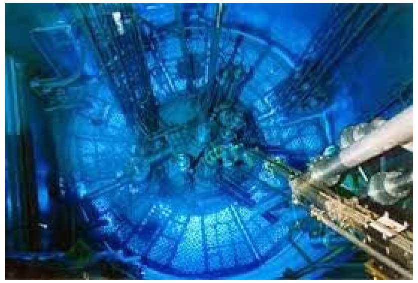
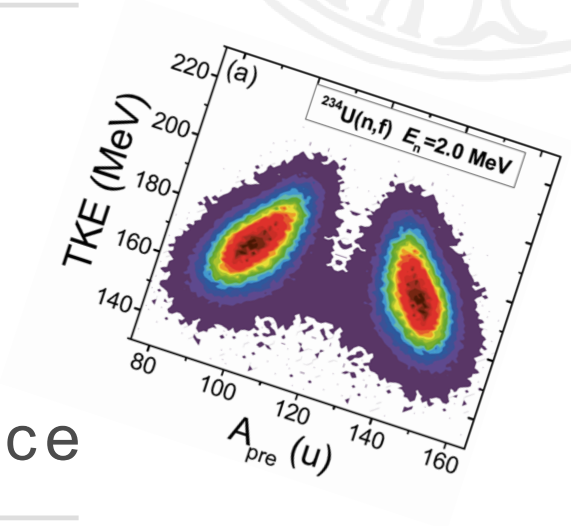






Nuclear data facilities and measurements

Experiments are the foundation of science



Stephan Pomp
Department of physics and astronomy
Uppsala University
Sweden
Contact: stephan.pomp@physics.uu.se

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Experiments are the foundation of the scientific method

“Therefore, the seeker after the truth is not one who studies the writings of the ancients […] but rather the one who suspects his faith in them and questions what he gathers from them, the one who submits to argument and demonstration […].”

Ibn al-Haytham (aka Alhazen), c. 965 – c. 1040

“The strongest arguments prove nothing so long as the conclusions are not verified by experience. Experimental science is the queen of sciences and the goal of all speculation.”

Roger Bacon, c. 1220 – c. 1292, *Opus Tertium*

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Overall goal of this lecture:

To give you some insights into

- **the used experimental methods for obtaining nuclear data, and**
- **the challenges and limitations faced by experiments.**

We must base models and evaluations on empirical evidence.

But the experimentalist needs to address a range of challenges and we can only study certain aspects of a nuclear reaction.

For example: we expose a sample to some irradiation and measure (some of) the outgoing particles.

What happens in-between is a question of modelling (or better experimental techniques!).
The models will then give predictions for unmeasured cases which one can try to test experimentally.

If we can test a prediction depends, e.g., on availability of suitable beams and target, and resolution of detectors (time, energy, …)

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Outline

Introduction

- General comments about experiments and challenges
- Nuclear data of interest

Facilities

- Overview
- Neutron sources
- Reactors
- Accelerator-based neutron facilities (DD/DT, QMN, White)
- Characterization and monitoring

Measurements

- Nuclear data of interest (reminder)
- Overview on measurement techniques for nuclear data
- Considerations for a possible experiment – an example

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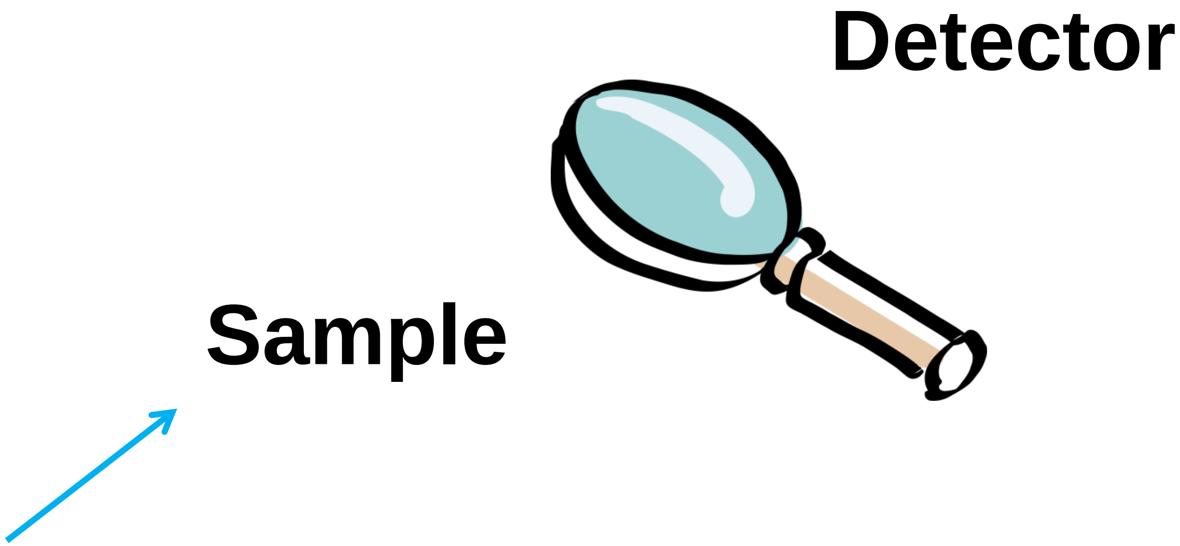
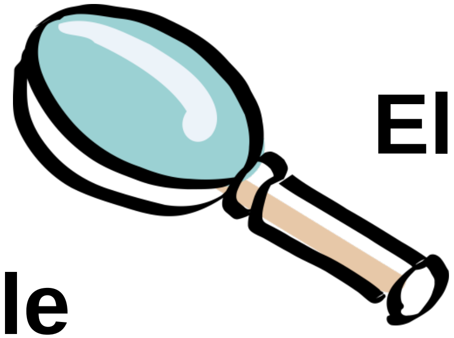
What do we want?



A **sample** where *something* is happening that you want to find out more about.

The sample might be a **source** of some radiation that the **detector** registers.

In principle:



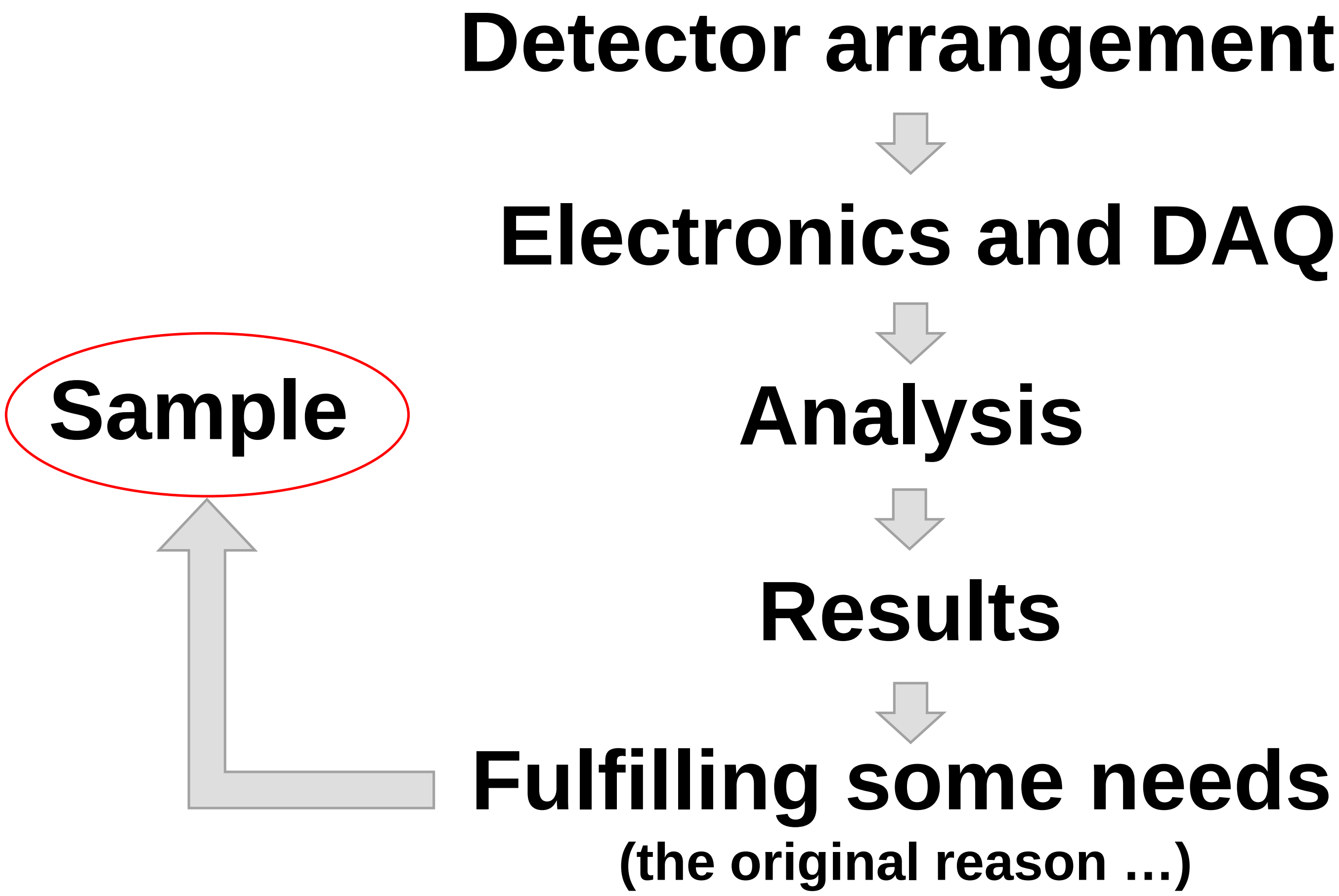
Detector arrangement

⇩

Electronics and DAQ

Sample

In principle:



Detector arrangement

Electronics and DAQ

Analysis

Results

Fulfilling some needs

(the original reason …)

Sample

In principle:

The **source** could be a radioactive sample you want to study, e.g.,

- ^{60}Co, ^{137}Cs, ^{252}Cf(sf), …
- an environmental sample (“unknown” source), or
- something that has been or is irradiated

  (e.g., activation analysis or in-beam experiment)

In the latter cases you need some kind of **facility** to provide the field that you expose a sample (or target) to in order to study a certain nuclear reaction.

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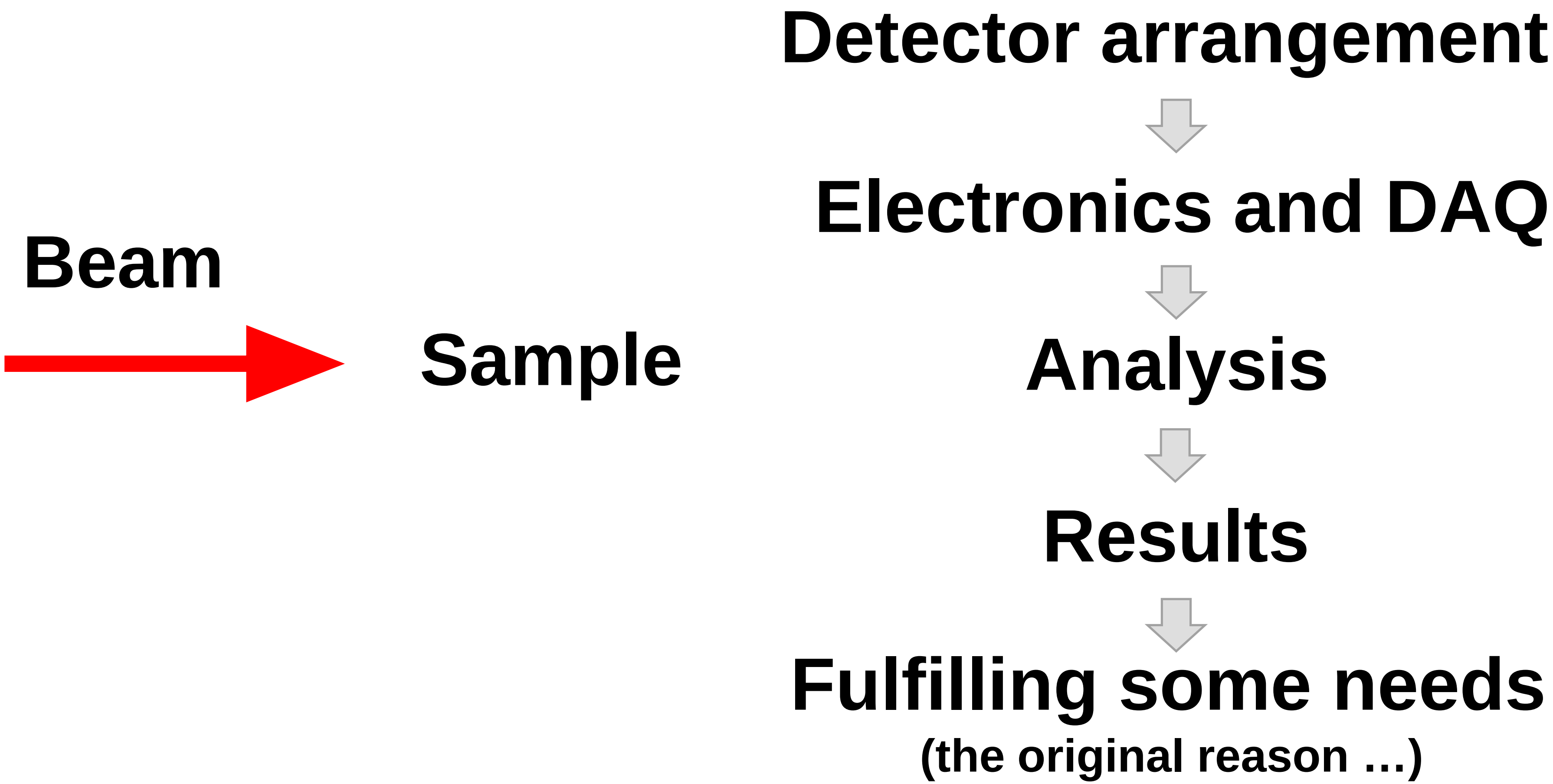
In principle:



Beam

Sample

Detector arrangement

Electronics and DAQ

Analysis

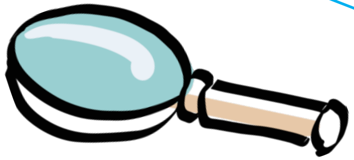
Results

Fulfilling some needs

(the original reason …)

In principle:

Beam monitor



Beam

Sample

Detector arrangement

⇩

Electronics and DAQ

⇩

Analysis

⇩

Results

⇩

Fulfilling some needs

(the original reason …)

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Experimental requirements

We need well characterized **detectors**. This means known responses, geometrical efficiencies, resolutions, etc.

This information is needed to correct the measured data and publish, e.g., cross sections with **well understood uncertainties.**

We also need:

- a characterized **source or beam facility** (also implying uncertainties and corrections)
- a **sample** with known amount, composition, etc.

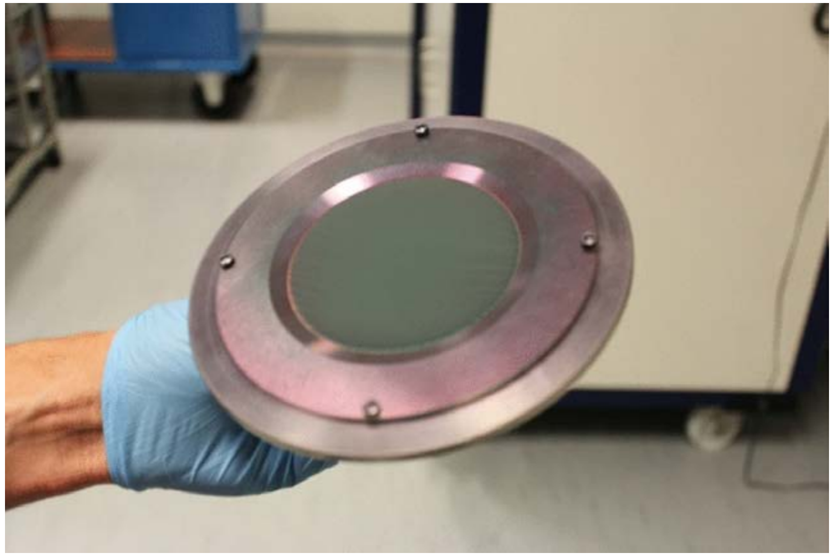

Fig. from N. Colonna et al., EPJ A **56**, 48 (2020)
https://doi.org/10.1140/epja/s10050-020-00037-8

In sum:

Many experiments need some sort of exposure of a sample (or target) to an external field.

In many cases, especially related to nuclear data for application,
this means a **neutron field**.

Hence we will focus on **neutron facilities**.

Before we do that: let’s have a look at the kind of experimental data needed.

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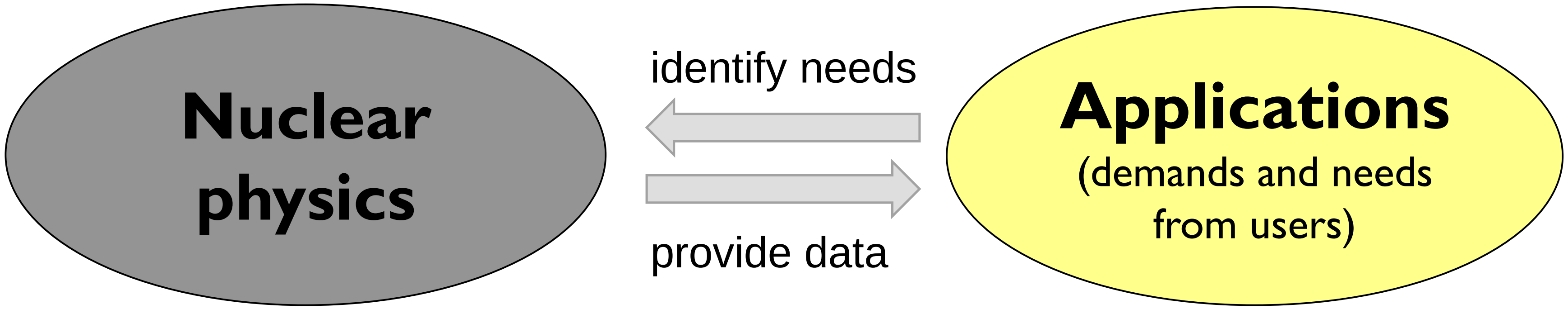

Theoretical:
- Nuclear reaction modelling (e.g. **TALYS**)

Experimental:
- Nuclear physics measurements
- Detection and measurement techniques

- **Computational:**
- Simulation codes
- Analysis methods

Nuclear data evaluation methodology

Medical:
- Nuclear medicine, Dosimetry, …
- Drug development, Regenerative medicine, …

Materials:
- Semiconductors, Radiation damage, …

Energy:
- Fission (GenIV, fuel cycle,…), Fusion, …

Safety and Security:
- Safeguards, …

Environment:
- Radioecology, …

Science:
- Archaeology, Astrophysics, Geology, …

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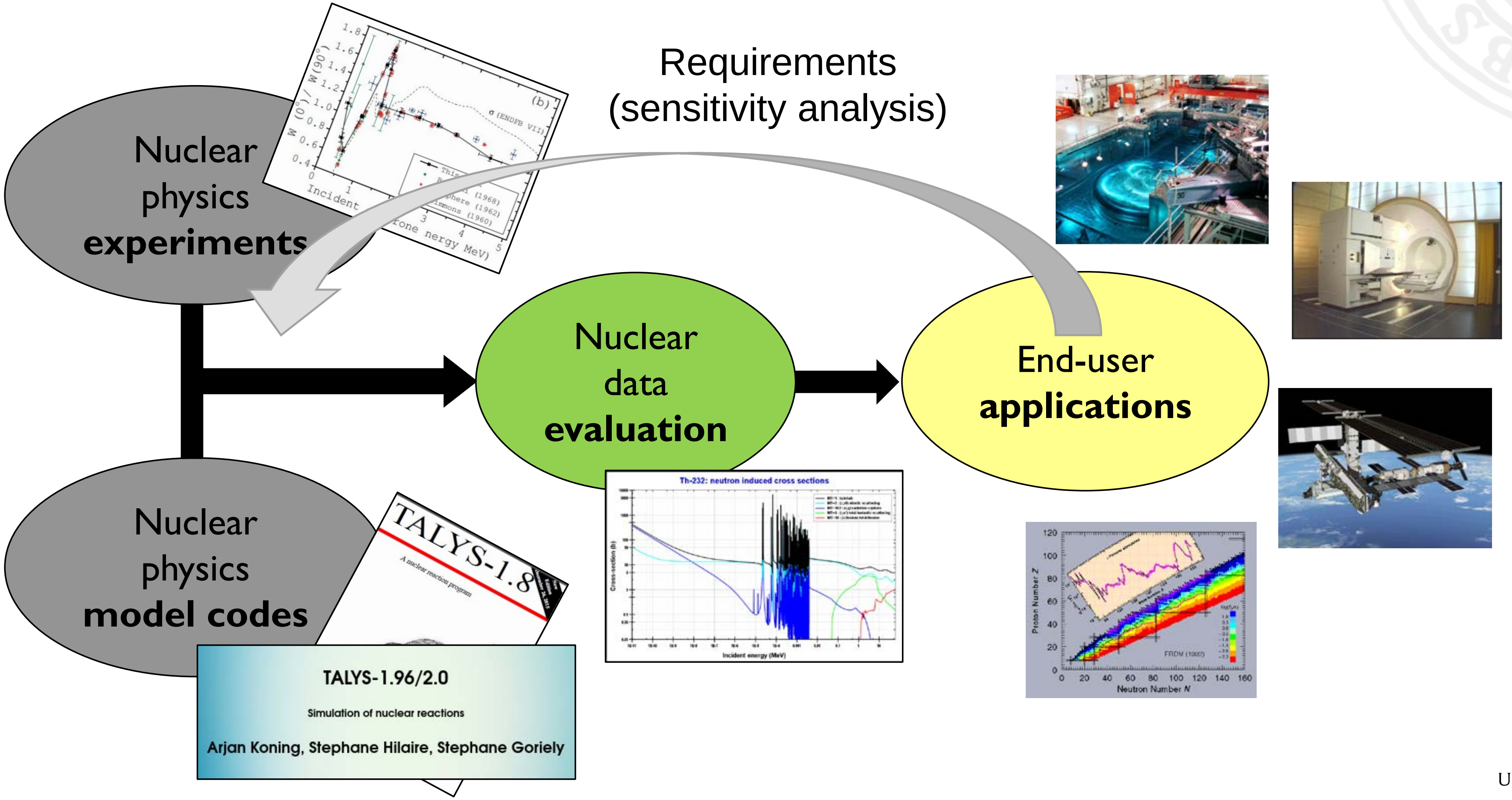
A sketch of the nuclear data cycle



Requirements
(sensitivity analysis)

Nuclear
physics
experiments

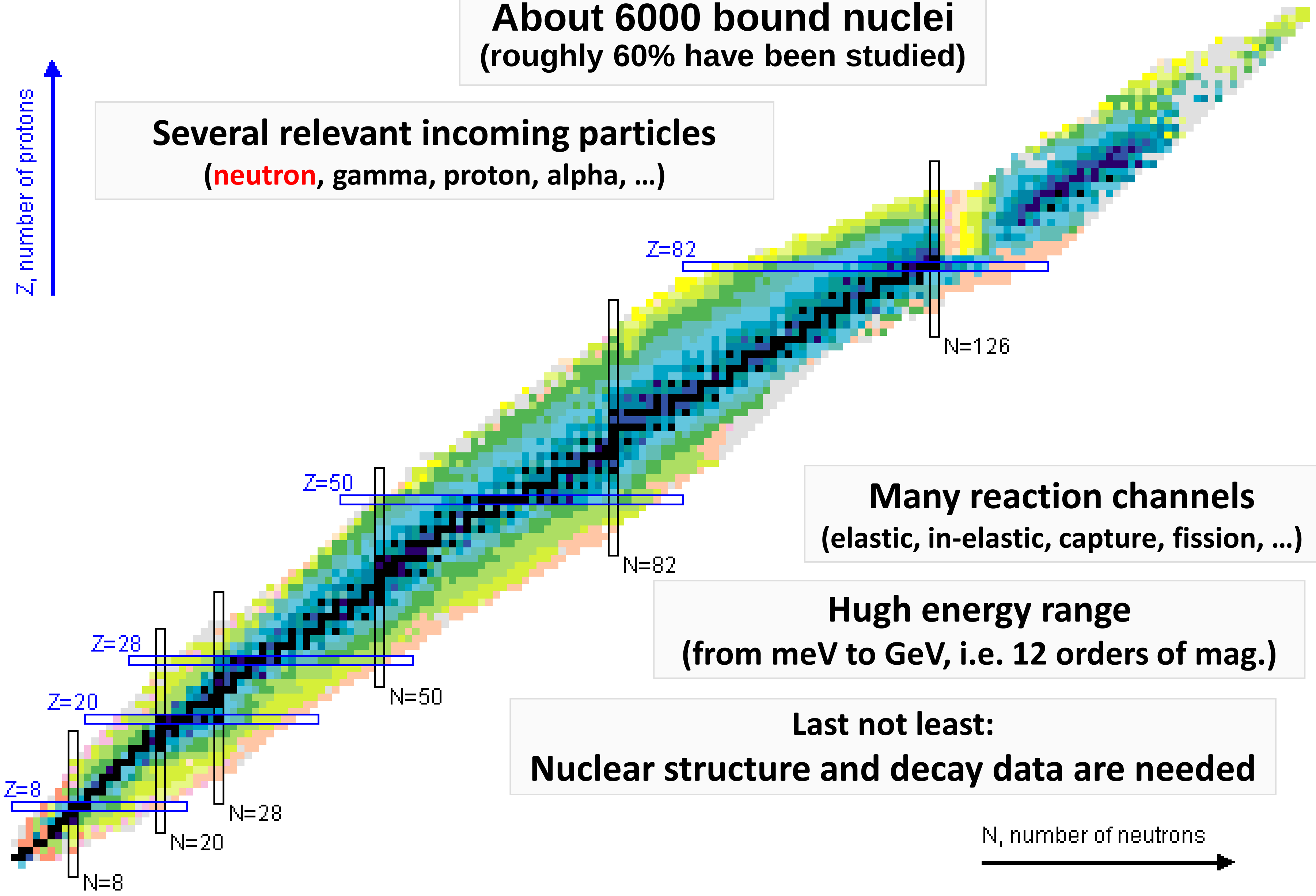
Nuclear
data
evaluation

End-user
applications

Nuclear
physics
model codes

TALYS-1.8
A nuclear reaction program

TALYS-1.96/2.0
Simulation of nuclear reactions
Arjan Koning, Stephane Hilaire, Stephane Goriely



About 6000 bound nuclei
(roughly 60% have been studied)

Several relevant incoming particles
(neutron, gamma, proton, alpha, …)

Many reaction channels
(elastic, in-elastic, capture, fission, …)

Hugh energy range
(from meV to GeV, i.e. 12 orders of mag.)

Last not least:
Nuclear structure and decay data are needed

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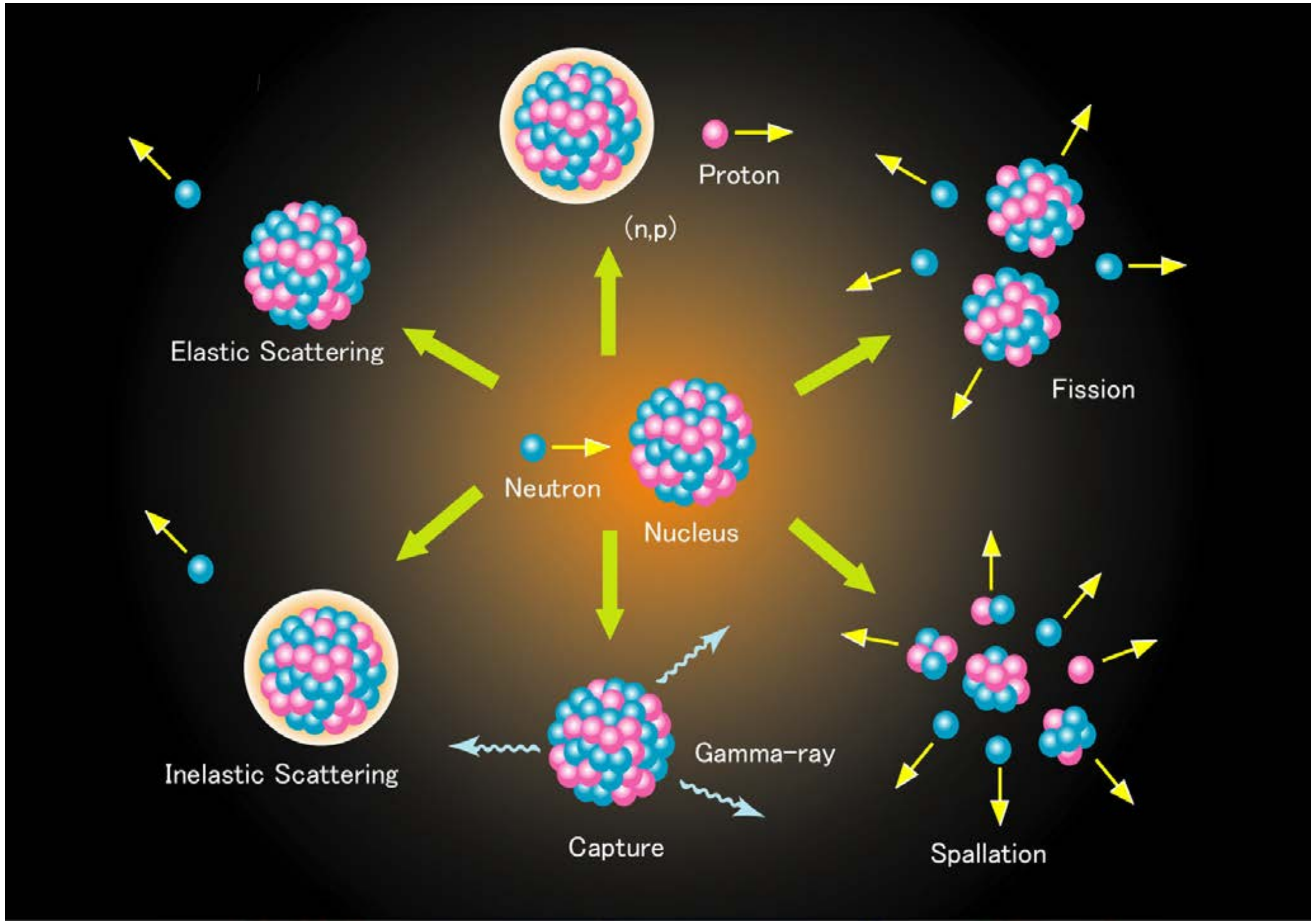
Many reaction channels to consider



With increasing energy of the incident neutron, more reaction channels open.

Elastic scattering and capture are energetically always possible.

Other channels: calculate Q-values.

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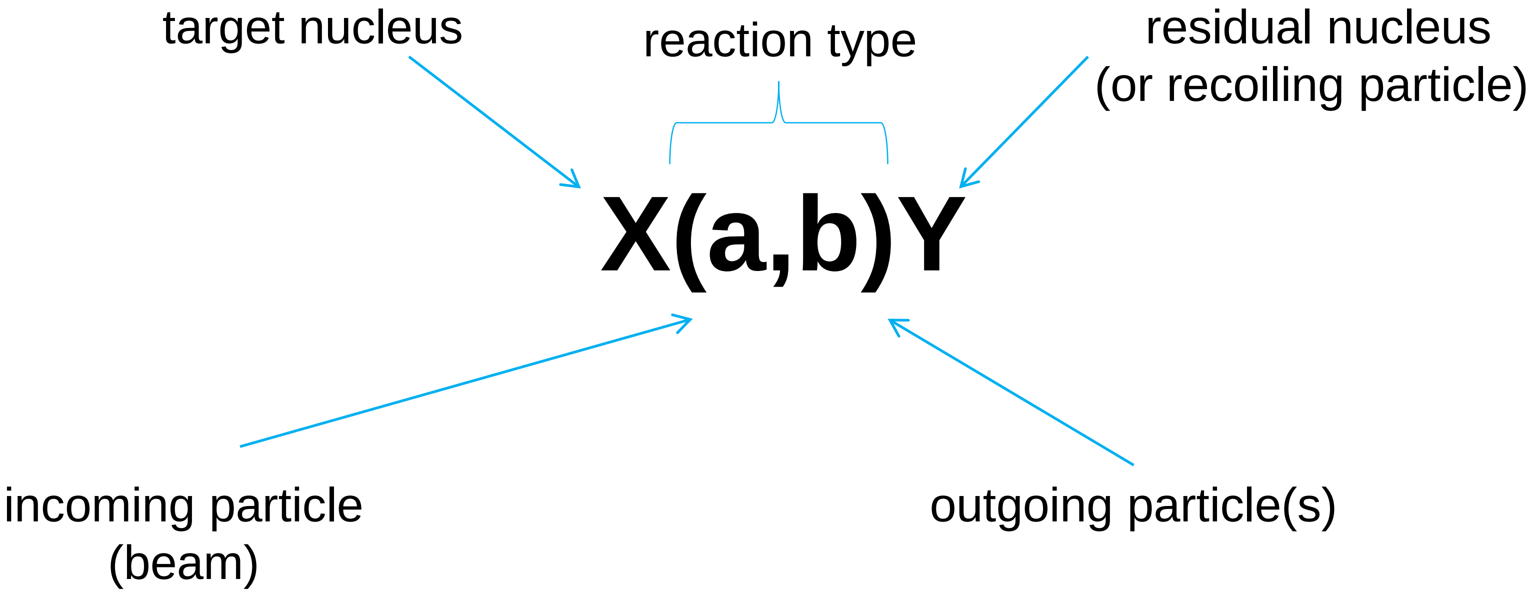
Nomenclature and possible approaches



target nucleus

reaction type

residual nucleus
(or recoiling particle)

X(a,b)Y

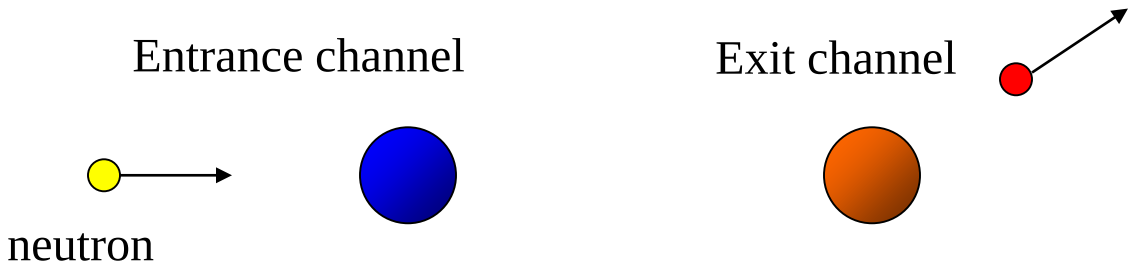
incoming particle
(beam)

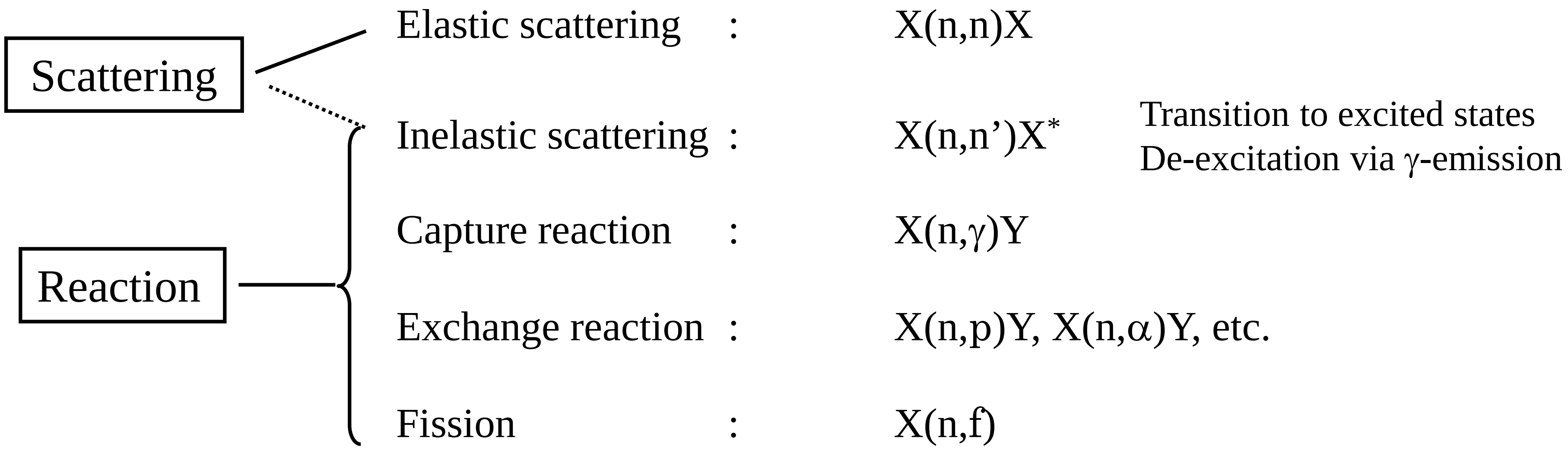
outgoing particle(s)

Experiments generally focus on either measuring

- Y (offline; e.g. neutron activation experiments), or
- b (online, detector setup, event trigger)

Nuclear reactions – overview





Scattering

Reaction

Elastic scattering : X(n,n)X

Inelastic scattering : X(n,n')X*

Transition to excited states
De-excitation via γ-emission

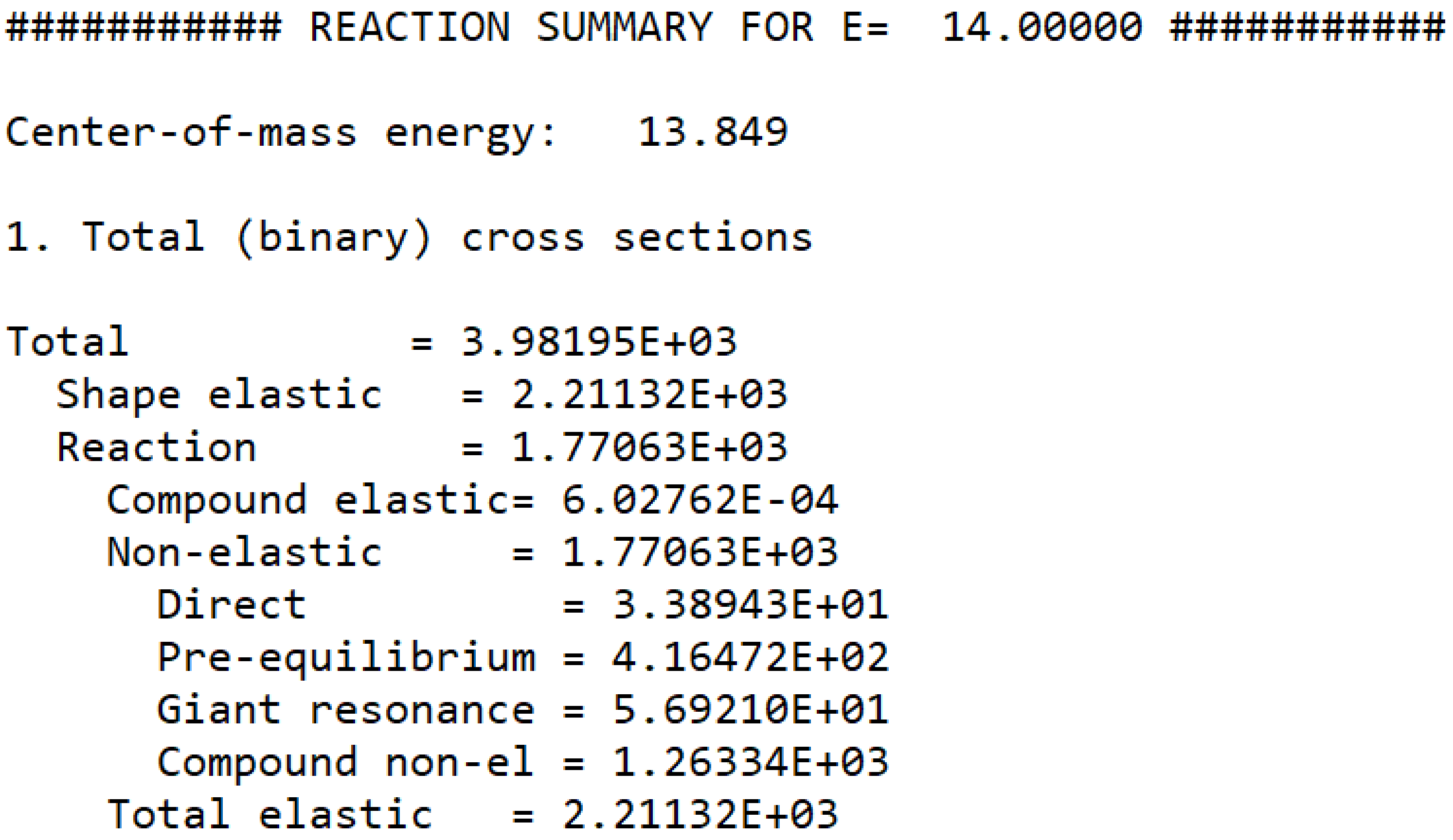
Capture reaction : X(n,γ)Y

Exchange reaction : X(n,p)Y, X(n,α)Y, etc.

Fission : X(n,f)

Elastic scattering cross section + Reaction cross section = Total cross section

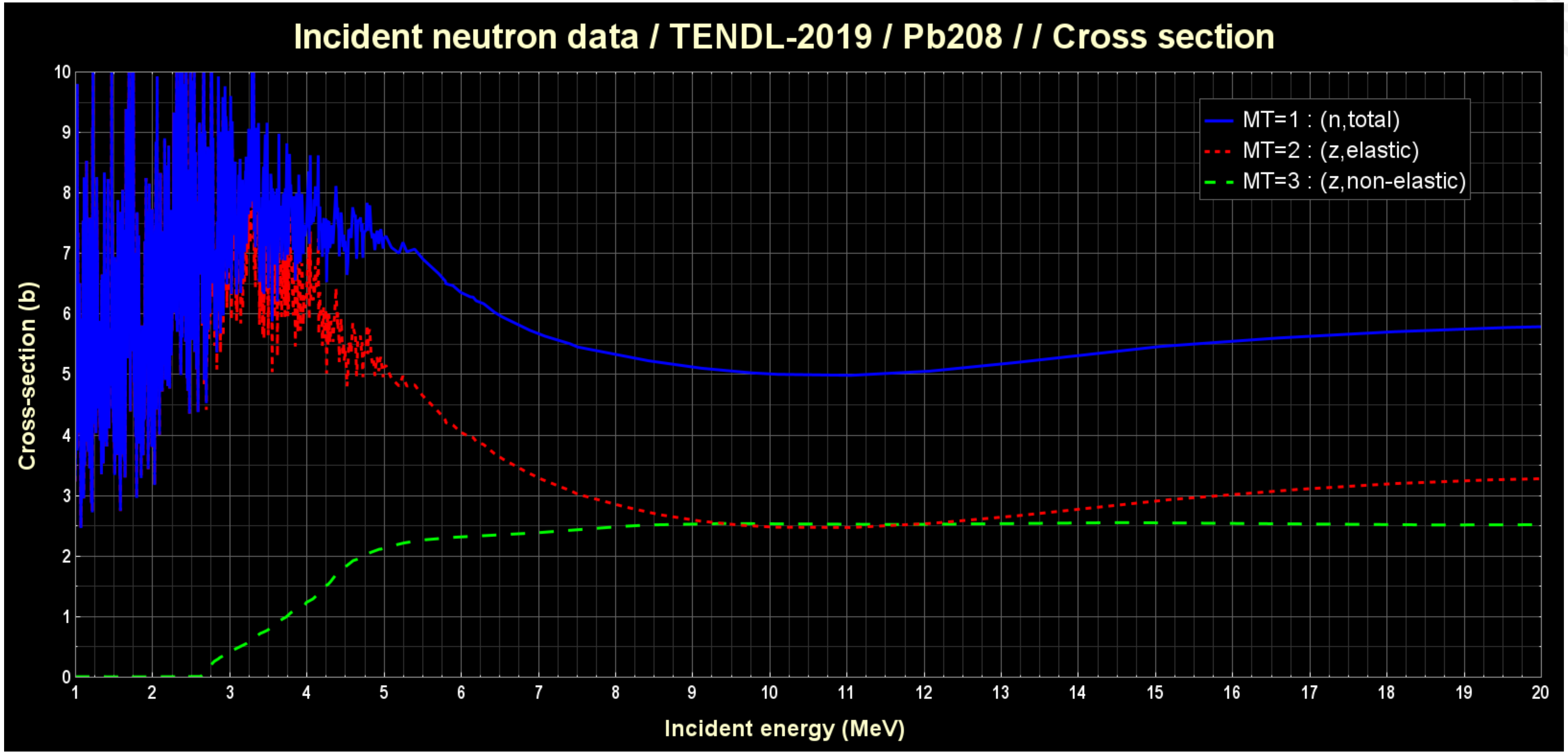
TALYS output – Test case:14 MeV neutrons on Nb93



```
########### REACTION SUMMARY FOR E=  14.00000 ###########

Center-of-mass energy:   13.849

1. Total (binary) cross sections

Total            = 3.98195E+03
  Shape elastic    = 2.21132E+03
  Reaction         = 1.77063E+03
    Compound elastic= 6.02762E-04
    Non-elastic      = 1.77063E+03
      Direct           = 3.38943E+01
      Pre-equilibrium = 4.16472E+02
      Giant resonance = 5.69210E+01
      Compound non-el = 1.26334E+03
    Total elastic    = 2.21132E+03
```

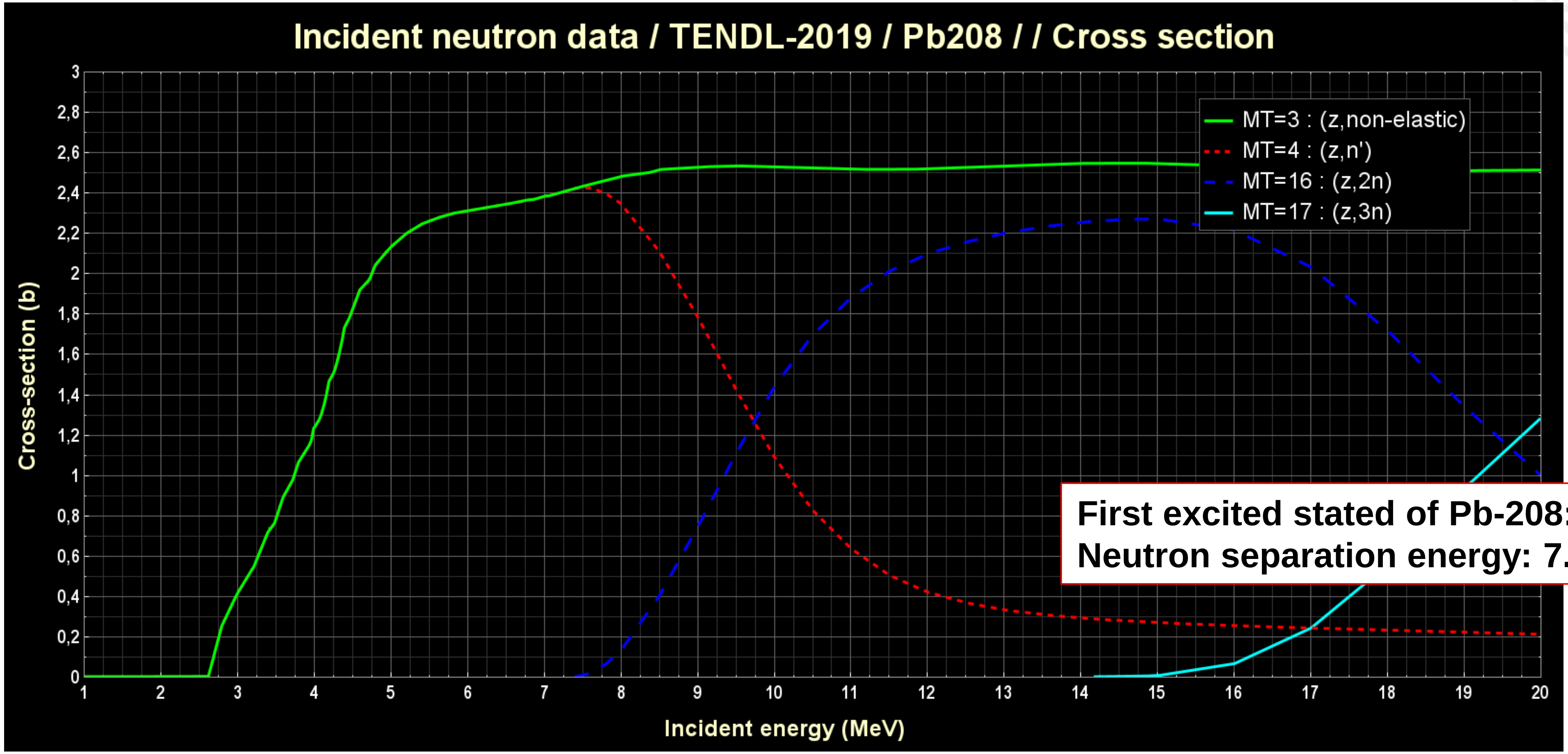
Example – Pb208 total, elastic, non-elastic

Retrieved with:
https://www.oecd-nea.org/jcms/pl_39910/janis



Example – Pb208 non-elastic, (n,n'), (n,2n), (n,3n)

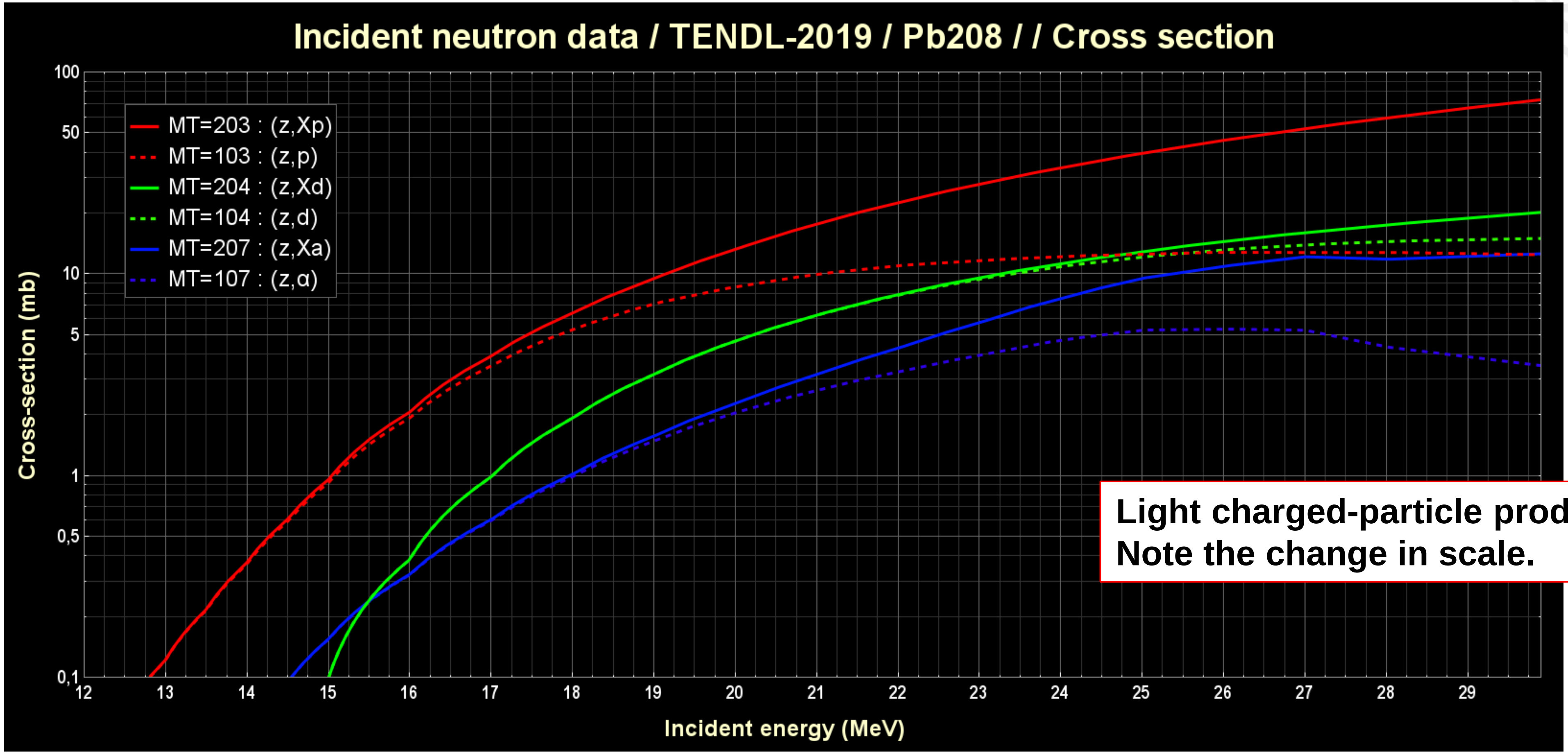
Retrieved with:
https://www.oecd-nea.org/jcms/pl_39910/janis



First excited stated of Pb-208: 2.6 MeV.
Neutron separation energy: 7.4 MeV.

Example – Pb208 (n,lcp)

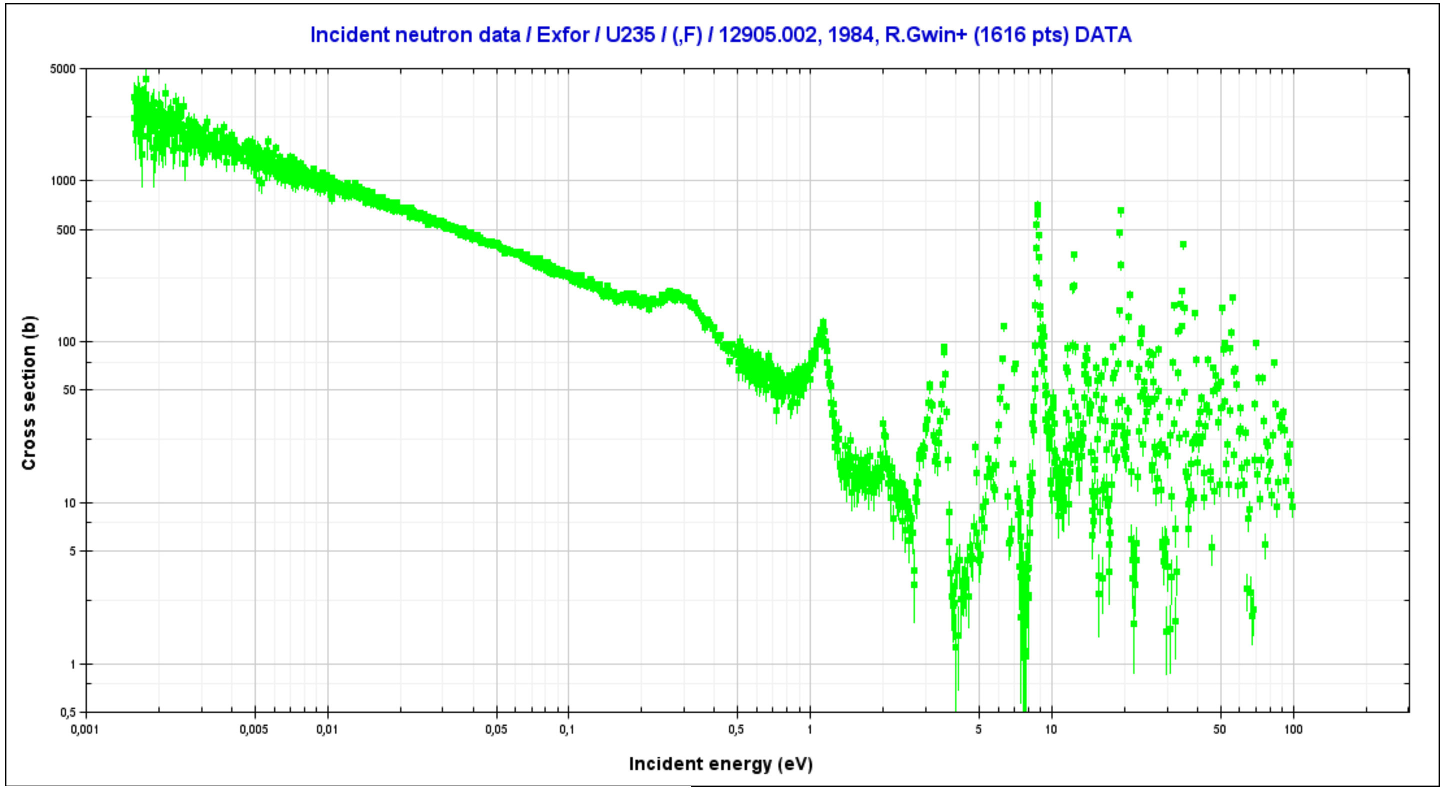
Retrieved with:
https://www.oecd-nea.org/jcms/pl_39910/janis



Light charged-particle production. Note the change in scale.

How do underlying experimental data look like?

Example: a cross section measurement for neutron-induced fission of ^{235}U



EXFOR data retrieved with JANIS

- One isotope (U-235),
- one reaction channel (fission),
- one incoming particle (neutron),
- one data set

  (Gwin et al. (1984), 1616 data points)

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Models and evaluations …

… have to make sense of a wide variety of **experimental data obtained** with

- a range of experimental methods,
- at a variety of facilities, and
- normalized, efficiency corrected, etc., in different ways that are not always properly documented .

Nevertheless: Experimental results are forever, models change ☺

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Physical quantities of interest
(to be stored in nuclear data files)

basic

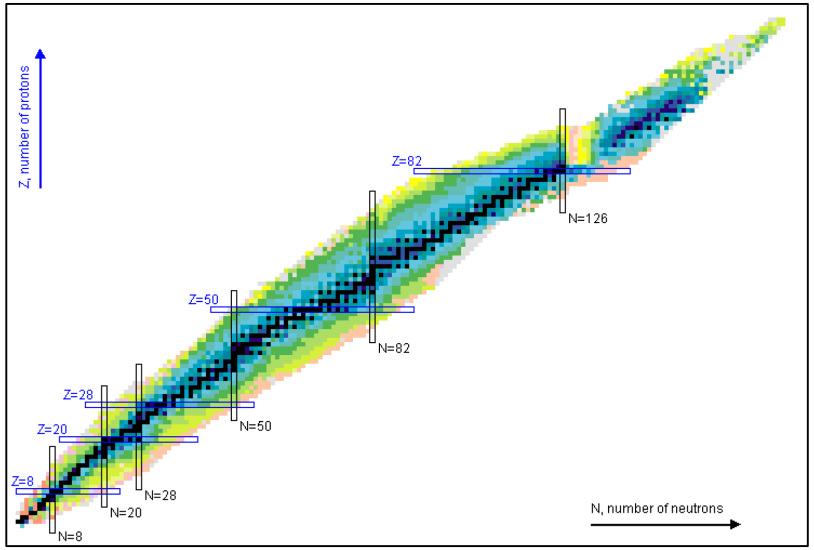
- Cross sections $\sigma(E)$
- Angular distributions (emitted particles) $d\sigma/d\Omega$
- Energy spectra (emitted particles) $d\sigma/dE'$
- Energy-Angle correlated spectra $d^2\sigma/dE'd\Omega$

  (Double-differential cross section, DDX)

practical

- Resonance parameters
- Neutrons per fission, Fission energy spectrum, Fission product yields, …

- Covariance data



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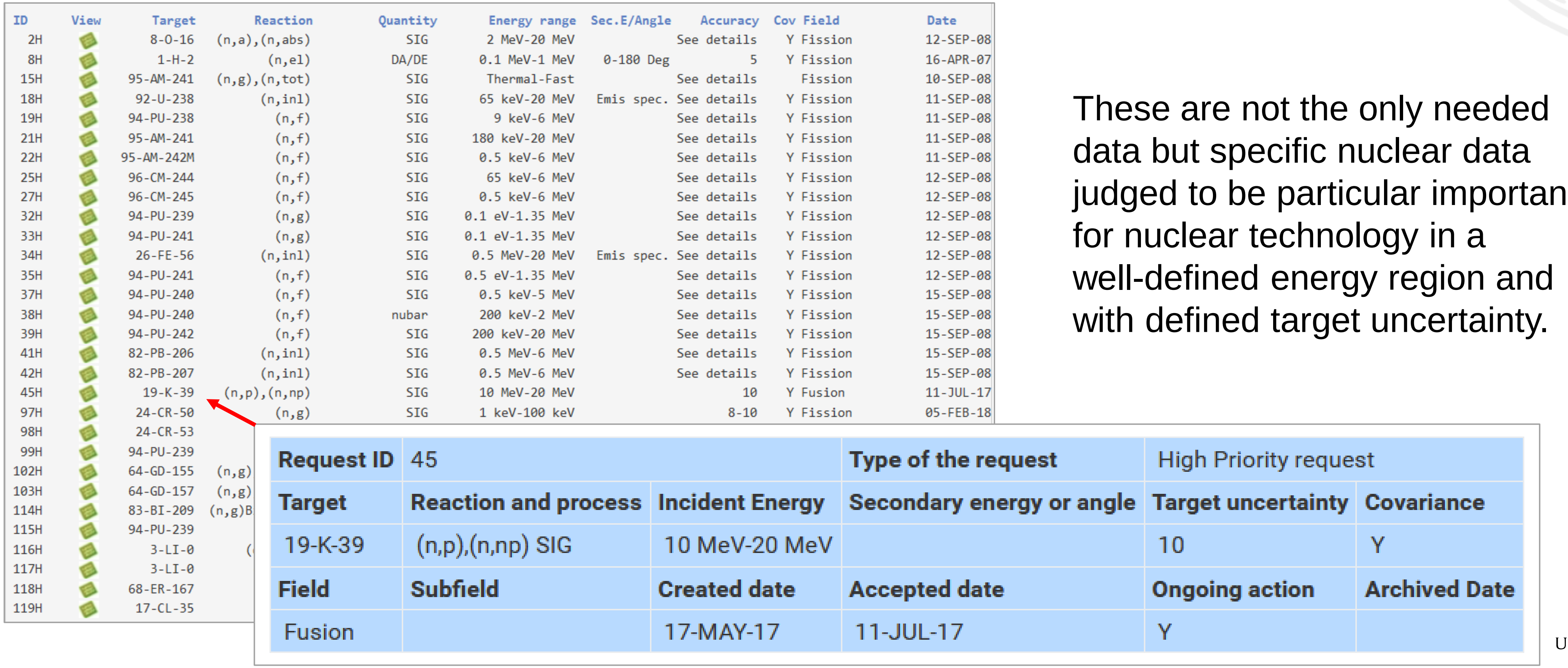
Example for nuclear data needs: HPRL

https://www.oecd-nea.org/dbdata/hprl/index.html



ID	View	Target	Reaction	Quantity	Energy range	Sec.E/Angle	Accuracy	Cov	Field	Date
2H	🟩	8-O-16	(n,a),(n,abs)	SIG	2 MeV-20 MeV		See details	Y	Fission	12-SEP-08
8H	🟩	1-H-2	(n,el)	DA/DE	0.1 MeV-1 MeV	0-180 Deg	5	Y	Fission	16-APR-07
15H	🟩	95-AM-241	(n,g),(n,tot)	SIG	Thermal-Fast		See details		Fission	10-SEP-08
18H	🟩	92-U-238	(n,inl)	SIG	65 keV-20 MeV	Emis spec.	See details	Y	Fission	11-SEP-08
19H	🟩	94-PU-238	(n,f)	SIG	9 keV-6 MeV		See details	Y	Fission	11-SEP-08
21H	🟩	95-AM-241	(n,f)	SIG	180 keV-20 MeV		See details	Y	Fission	11-SEP-08
22H	🟩	95-AM-242M	(n,f)	SIG	0.5 keV-6 MeV		See details	Y	Fission	11-SEP-08
25H	🟩	96-CM-244	(n,f)	SIG	65 keV-6 MeV		See details	Y	Fission	12-SEP-08
27H	🟩	96-CM-245	(n,f)	SIG	0.5 keV-6 MeV		See details	Y	Fission	12-SEP-08
32H	🟩	94-PU-239	(n,g)	SIG	0.1 eV-1.35 MeV		See details	Y	Fission	12-SEP-08
33H	🟩	94-PU-241	(n,g)	SIG	0.1 eV-1.35 MeV		See details	Y	Fission	12-SEP-08
34H	🟩	26-FE-56	(n,inl)	SIG	0.5 MeV-20 MeV	Emis spec.	See details	Y	Fission	12-SEP-08
35H	🟩	94-PU-241	(n,f)	SIG	0.5 eV-1.35 MeV		See details	Y	Fission	12-SEP-08
37H	🟩	94-PU-240	(n,f)	SIG	0.5 keV-5 MeV		See details	Y	Fission	15-SEP-08
38H	🟩	94-PU-240	(n,f)	nubar	200 keV-2 MeV		See details	Y	Fission	15-SEP-08
39H	🟩	94-PU-242	(n,f)	SIG	200 keV-20 MeV		See details	Y	Fission	15-SEP-08
41H	🟩	82-PB-206	(n,inl)	SIG	0.5 MeV-6 MeV		See details	Y	Fission	15-SEP-08
42H	🟩	82-PB-207	(n,inl)	SIG	0.5 MeV-6 MeV		See details	Y	Fission	15-SEP-08
45H	🟩	19-K-39	(n,p),(n,np)	SIG	10 MeV-20 MeV		10	Y	Fusion	11-JUL-17
97H	🟩	24-CR-50	(n,g)	SIG	1 keV-100 keV		8-10	Y	Fission	05-FEB-18
98H	🟩	24-CR-53								
99H	🟩	94-PU-239								
102H	🟩	64-GD-155	(n,g)							
103H	🟩	64-GD-157	(n,g)							
114H	🟩	83-BI-209	(n,g)B							
115H	🟩	94-PU-239								
116H	🟩	3-LI-0	(							
117H	🟩	3-LI-0								
118H	🟩	68-ER-167								
119H	🟩	17-CL-35								

Request ID	45		**Type of the request**	High Priority request	
Target	**Reaction and process**	**Incident Energy**	**Secondary energy or angle**	**Target uncertainty**	**Covariance**
19-K-39	(n,p),(n,np) SIG	10 MeV-20 MeV		10	Y
Field	**Subfield**	**Created date**	**Accepted date**	**Ongoing action**	**Archived Date**
Fusion		17-MAY-17	11-JUL-17	Y	

These are not the only needed data but specific nuclear data judged to be particular important for nuclear technology in a well-defined energy region and with defined target uncertainty.

Challenge to experimentalist

Provide the requested data with highest possible accuracy and well-characterized uncertainties.

This needs a suitable methods for the specific task and facilities that can provide the relevant beams with reasonable intensities.

So let’s look at some **facilities**.

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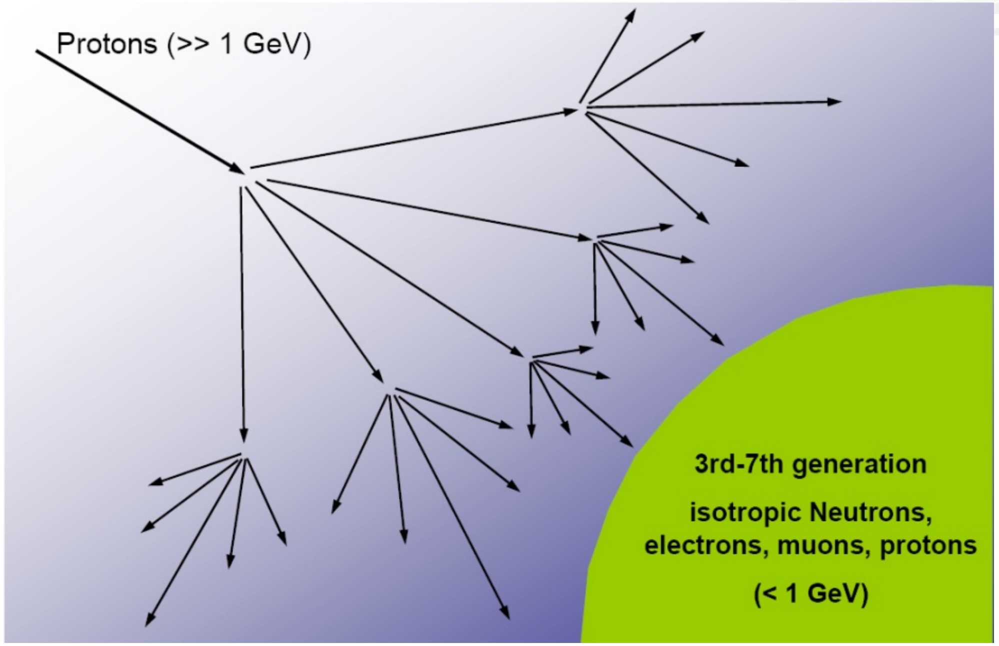
So how to obtain neutrons?

- Actually, they are everywhere and often the problem is the reverse, i.e., to get rid of them.
- This means getting neutrons is, in principle, easy:
  - Neutrons created in the atmosphere by cosmic radiation.
  - Neutrons can be provided via sources (Cf-252, PuBe, AmBe, …).
  - Neutrons can be provided by reactors (inside and extracted from the core).
  - And neutrons are produced from ion or electron beams, e.g., at accelerators (from small scale DD or DT reactions or large accelerators that produce “white” or QMN beams).
- The challenge is to “know” the field, i.e., to properly characterize the field that your sample/target is exposed to.

Atmospheric neutrons

- Produced in the atmosphere from cosmic radiation.
- Dose to humans and SEE in electronics.
- High altitude facilities (e.g. Zugspitze) primarily monitor and measure the neutron spectrum, e.g., for monitoring solar activity.
- Several accelerator-based facilities mimic atmospheric neutrons for especially accelerated testing of electronics.



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Atmospheric neutrons

Some facilities create (white) neutron-energy spectra aiming at mimicking the energy spectrum of atmospheric neutrons.

Goal:

accelerated testing of electronics.

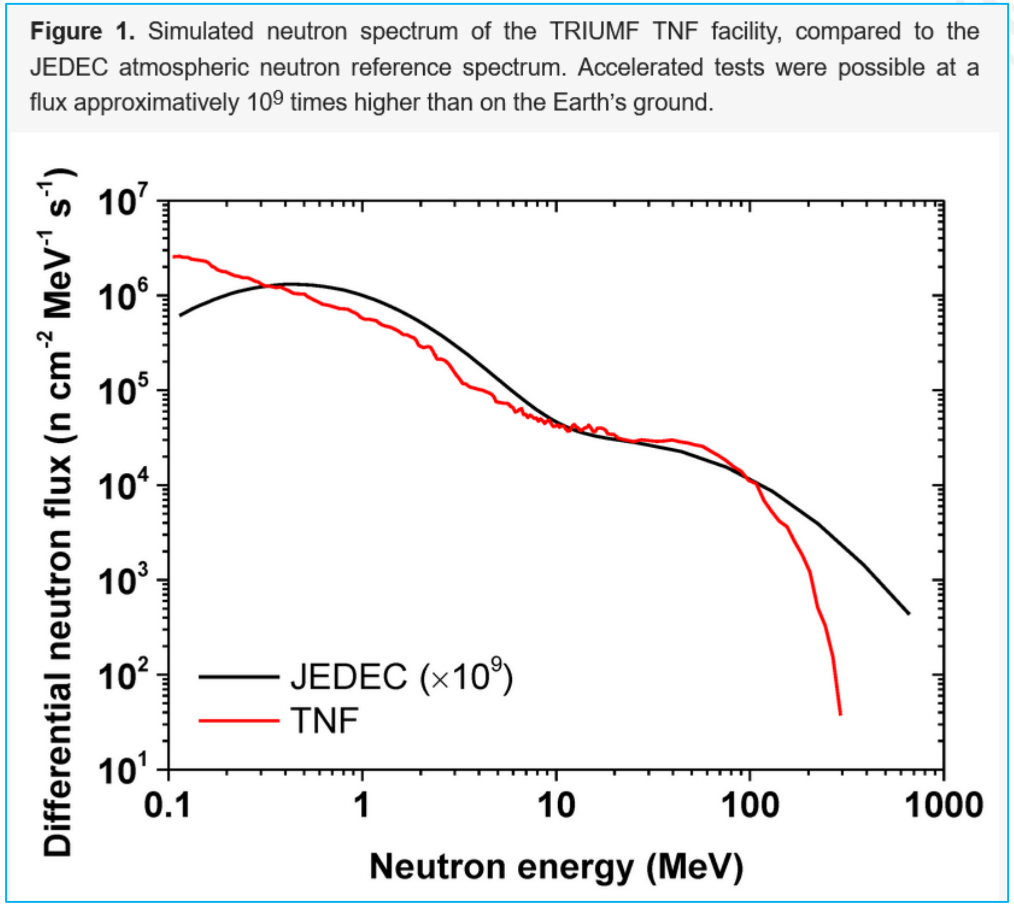

Figure 1. Simulated neutron spectrum of the TRIUMF TNF facility, compared to the JEDEC atmospheric neutron reference spectrum. Accelerated tests were possible at a flux approximatively 10^9 times higher than on the Earth's ground.

Sensors **2020**, *20*(16), 4510;
https://doi.org/10.3390/s20164510

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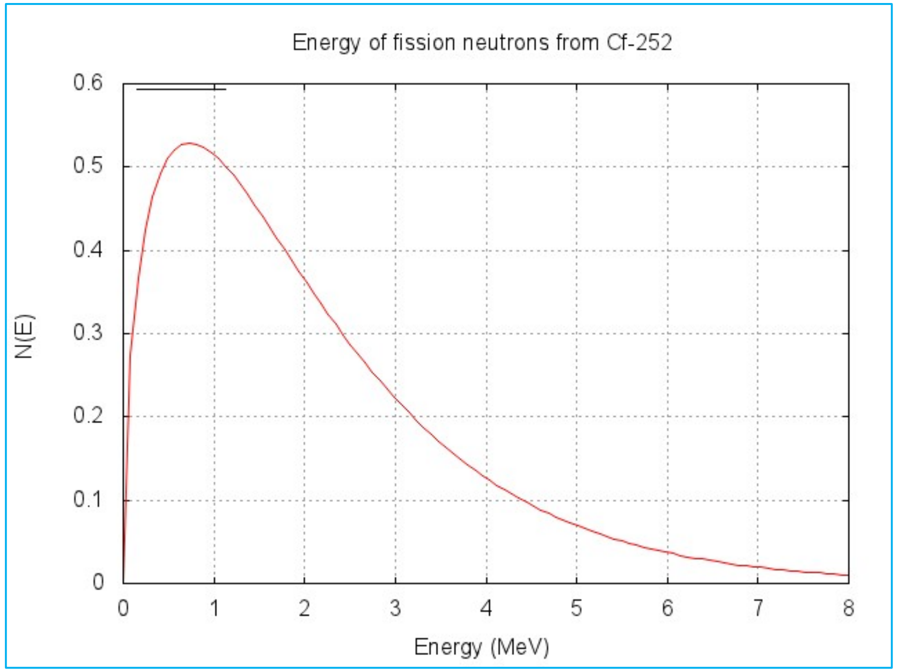
Neutron sources I

Fission sources: ^{252}Cf(SF)

Advantage: no accelerator needed. *In principle* same neutron spectrum for all such sources, i.e. good for standardization.

- Prompt neutrons from spontaneous fission:
  - 3.768 neutrons per fission
  - Watts spectrum: $N(E) = e^{-E/a} \cdot \sinh\sqrt{bE}$
    (a= 1.18 MeV; b = 1.03419 MeV^{-1})
  - $T_{1/2}$ = 2.645 years
  - BR(SF) = 3.09 %
  - 2.314x10^{6} n/s/mg
  - 4,316 n/s/µCi



Source: Radev and McLean, “Neutron-sources for standard testing”, LLNL-TR-664160

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Neutron sources II

(α,n) sources: e.g. AmBe and PuBe

- α-emitter mixed with light element
- often Be is used:

$$\alpha + {}^{9}\text{Be} \rightarrow {}^{12}\text{C} + n + \gamma$$

- source intensity typ. $10^6 - 10^8$ n/s

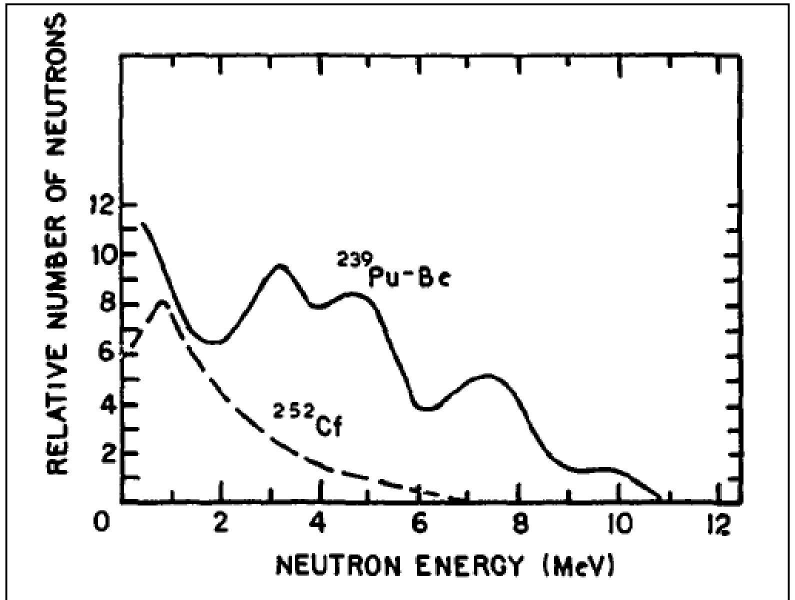

FIGURE 6

COMPARISON OF NEUTRON ENERGY SPECTRA OF ^{239}Pu-Be AND ^{252}Cf

Fig. from “Gamma-ray and neutron soruces” by R.J. Holmes

In general: neutron sources (^{252}Cf, AmBe…) are used in reference fields, e.g., for dosimetry. See, e.g., PTB in Germany http://www.ptb.de or NIST in USA https://www.nist.gov/

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Outline

Introduction

- General comments about experiments and challenges
- Nuclear data of interest

Facilities

- Overview
- Neutron sources
- **Reactors**
- Accelerator-based neutron facilities (DD/DT, QMN, White)
- Characterization and monitoring

Measurements

- Nuclear data of interest (reminder)
- Overview on measurement techniques for nuclear data
- Considerations for a possible experiment – an example

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Neutrons from fission reactors

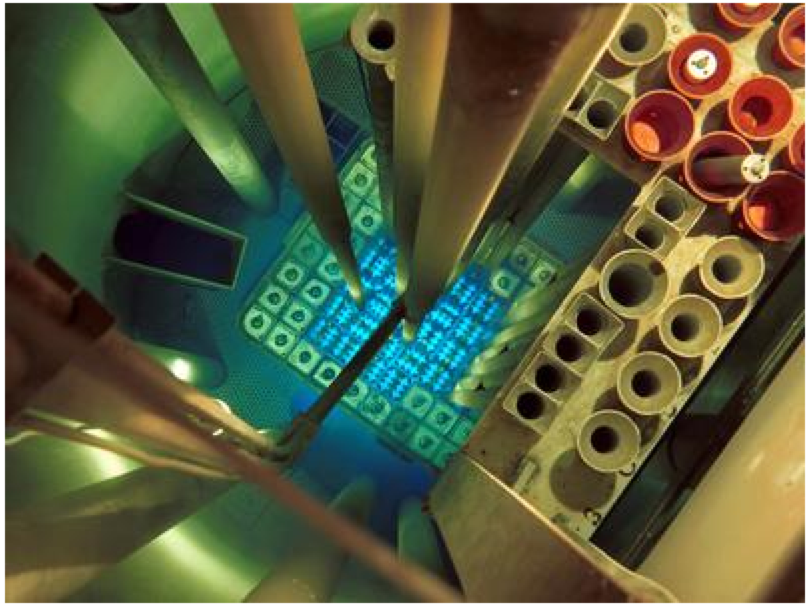
Research reactors can offer pneumatic systems for irradiation purposes.

E.g. the pool-type reactor at BME in Budapest:
max thermal neutron flux: 2.7•10^{12} n/cm^2s

Usage: e.g. in-core irradiation (activation)
plus fast-transfer system to γ-spectroscopy setup.

⇩

Measurement of average cross sections
for (n,γ) in a thermal field.



BME Budapest:
http://www.reak.bme.hu/en/training-reactor.html

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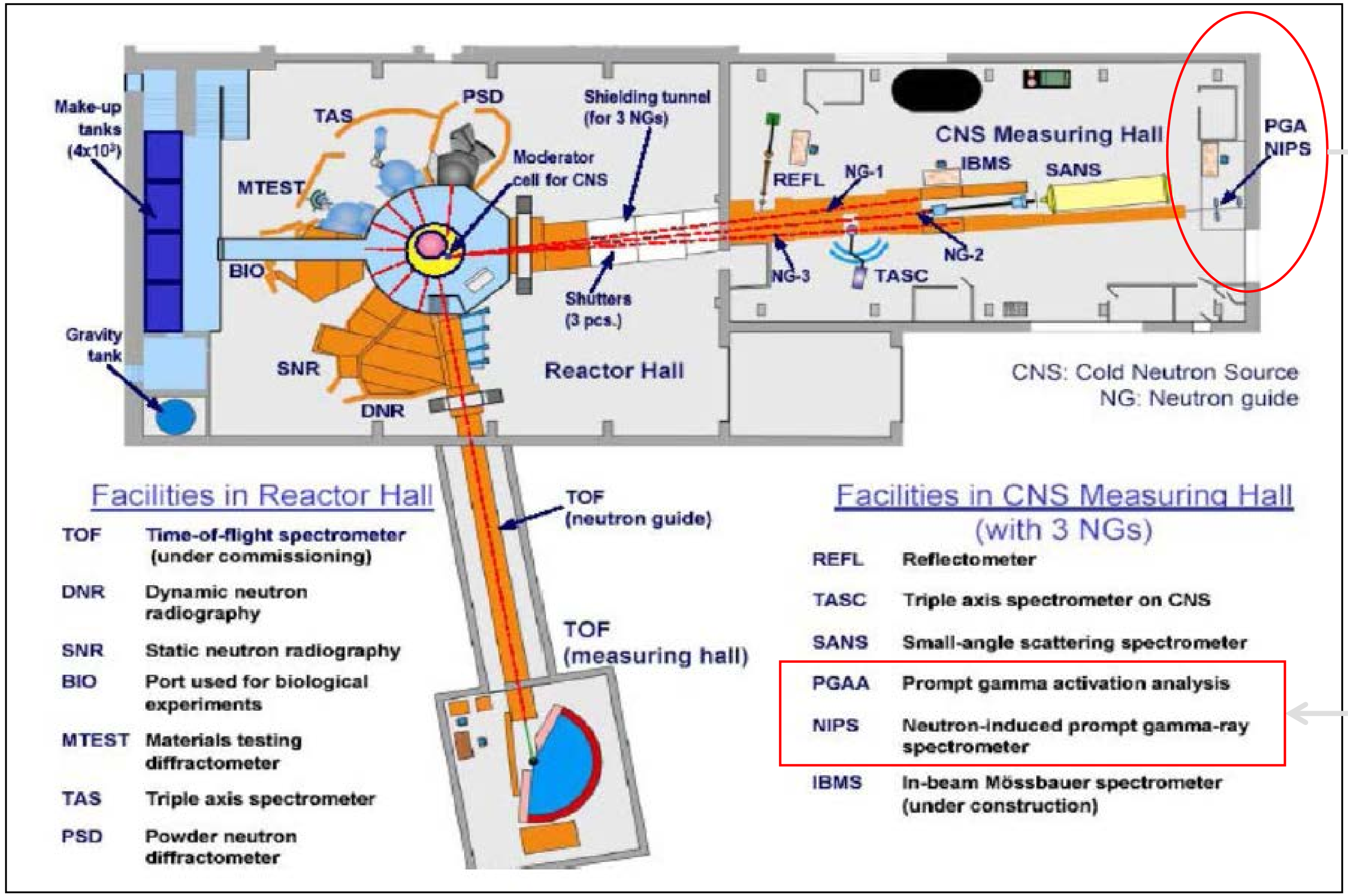
Neutron beams at a reactor: the Budapest research reactor

IAEA-TECDOC-1743 page 4



CNS: Cold Neutron Source
NG: Neutron guide

Facilities in Reactor Hall

TOF	Time-of-flight spectrometer (under commissioning)
DNR	Dynamic neutron radiography
SNR	Static neutron radiography
BIO	Port used for biological experiments
MTEST	Materials testing diffractometer
TAS	Triple axis spectrometer
PSD	Powder neutron diffractometer

Facilities in CNS Measuring Hall (with 3 NGs)

REFL	Reflectometer
TASC	Triple axis spectrometer on CNS
SANS	Small-angle scattering spectrometer
PGAA	Prompt gamma activation analysis
NIPS	Neutron-induced prompt gamma-ray spectrometer
IBMS	In-beam Mössbauer spectrometer (under construction)

Some reactors offer external beams.

Use for, e.g.,

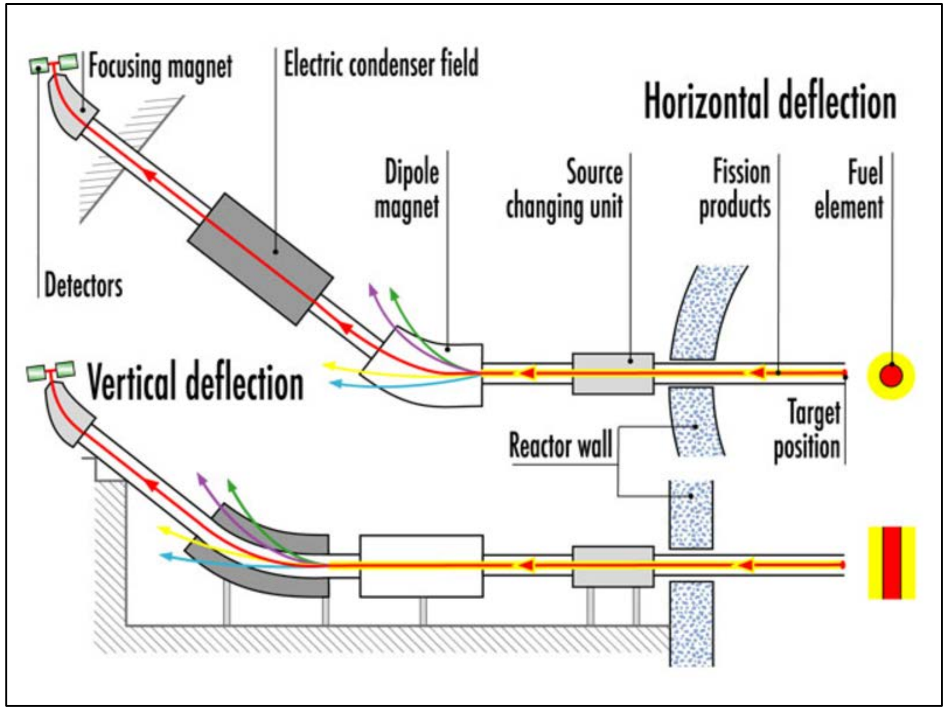
- prompt-gamma activation analysis

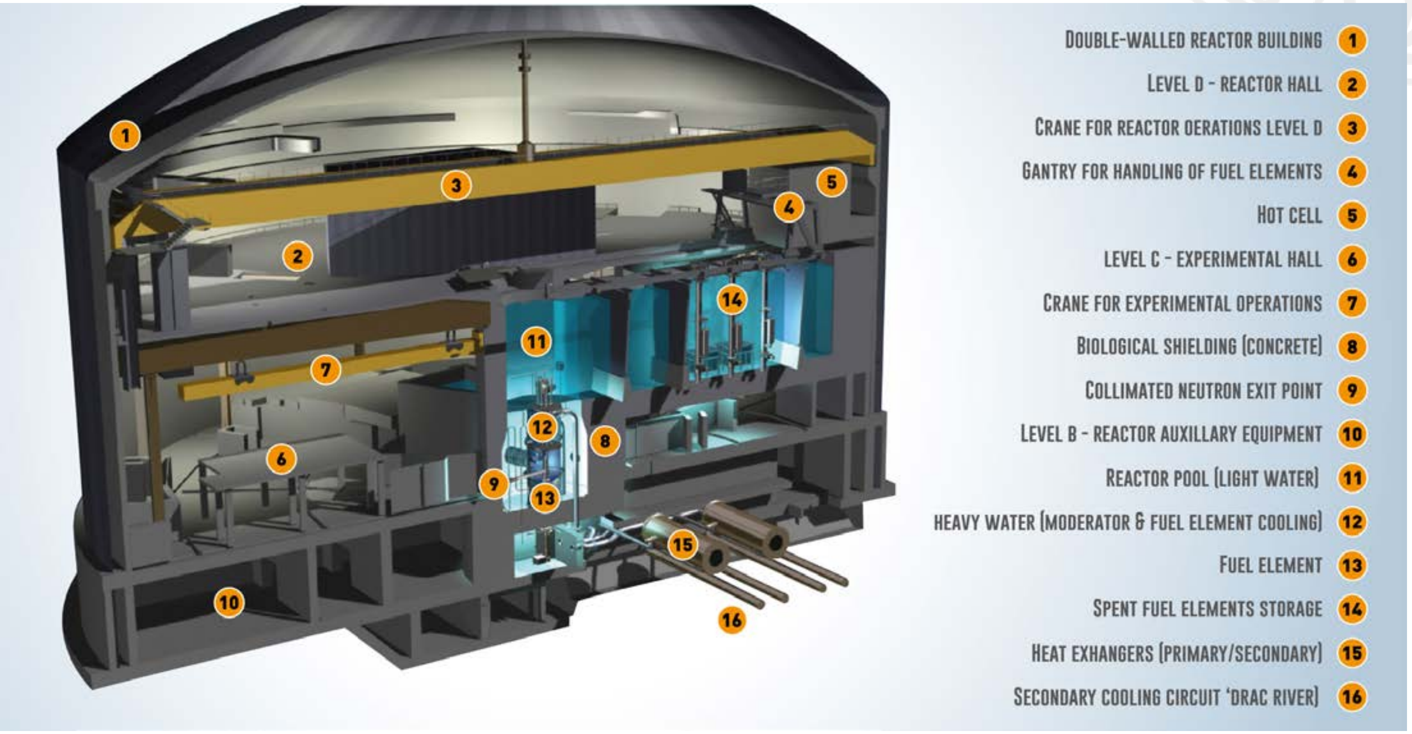
https://www.iki.kfki.hu/nuclear/instruments/pgaa_en.shtml

- measurements of fission yields

ILL in Grenoble, France: Neutrons for Society

Here: target close to core: extract products





Images from https://www.ill.eu

The LOHENGRIN spectrometer at ILL: a recoil mass spectrometer for studying the properties of the exotic isotopes produced during the fission process.

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Using accelerators for neutron production

Electrostatic accelerators (Van de Graaff, Tandem, e.g. at JRC-Geel)

Cyclotrons (e.g. former TSL in Sweden)

Linear accelerators (e.g. NFS at GANIL and GELINA at JRC-Geel)

Synchrotrons (e.g. PS at CERN and n_TOF)

One of many uses
of a Van de Graaff …

Different combinations of

primary particles (ions – p, d, … – and electrons) + suitable **target**

↓

A wide range of different neutron beams …

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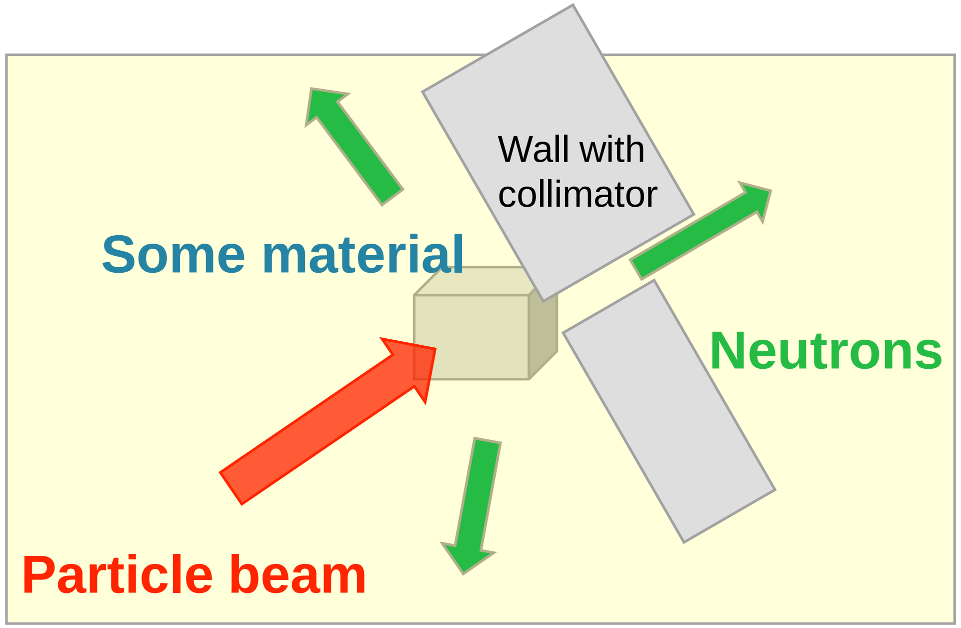
Getting neutrons is easy



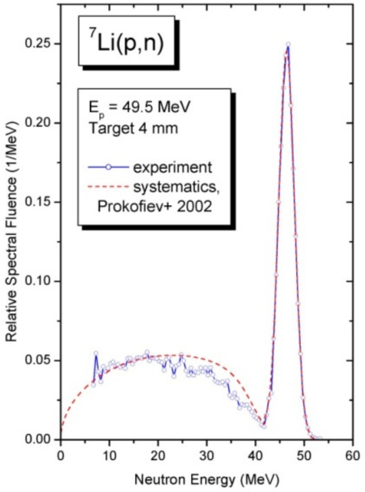
- (Quasi-)monoenergetic beams
- "White" beams + TOF

⇨ "PHYSICS"

Neutron fields simulate
- Cosmic ray neutrons
- Reactor environment
- …

⇨ "APPLICATIONS"

Some types of neutron energy spectra



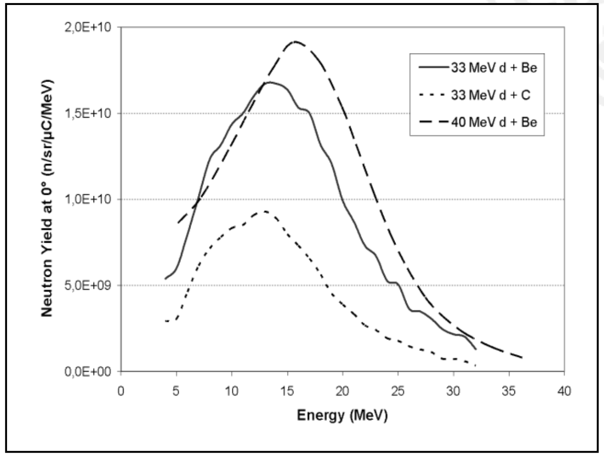
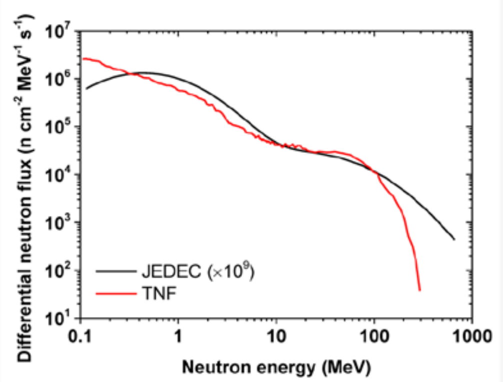


Figure 1. Simulated neutron spectrum of the TRIUMF TNF facility, compared to the JEDEC atmospheric neutron reference spectrum. Accelerated tests were possible at a flux approximatively 10^9 times higher than on the Earth's ground.

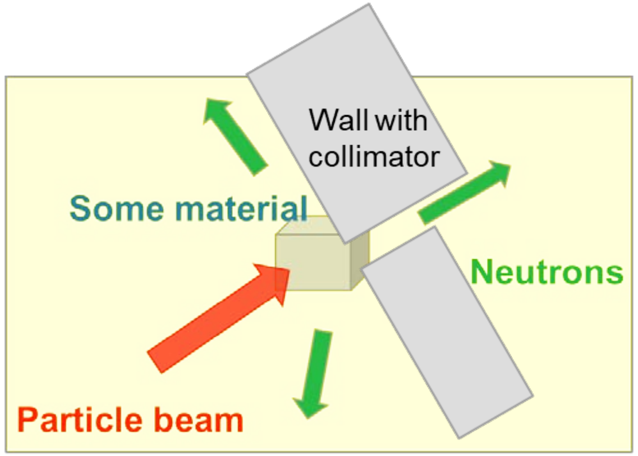


Mono-energetic and quasi-monoenergetic beams

A typical reaction used is: **^{7}Li(p,n)^{7}Be**

Neutron “beam” normally used **0 degree** emission angle relative to the direction of the ion beam:

- small variation of differential neutron emission cross section
- simple kinematic
- neutrons are unpolarized, and
- yield has an (normally) absolute maximum at 0 degress



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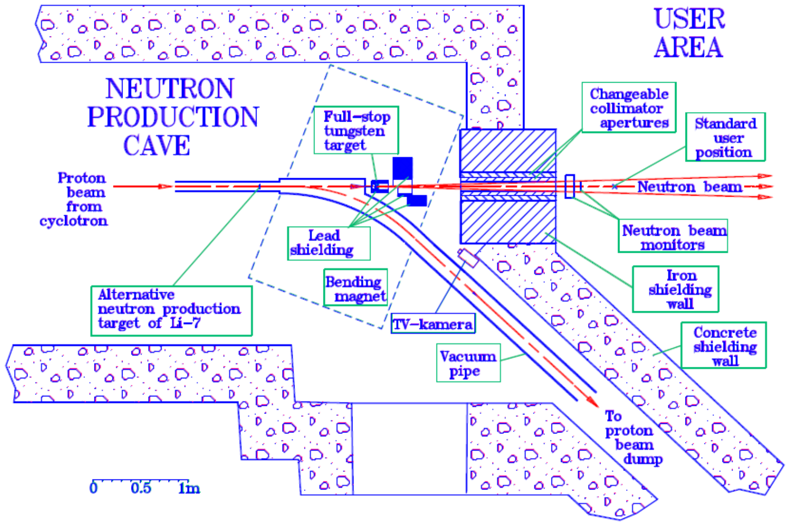
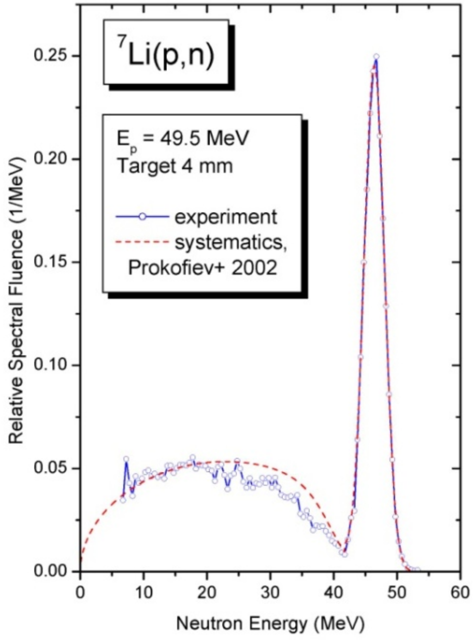
Mono-energetic and quasi-monoenergetic beams

Despite energy spread due to, e.g., energy loss of projectile ions in target a beam is called ‘**mono-energetic**‘ if only one neutron production channel contributes.

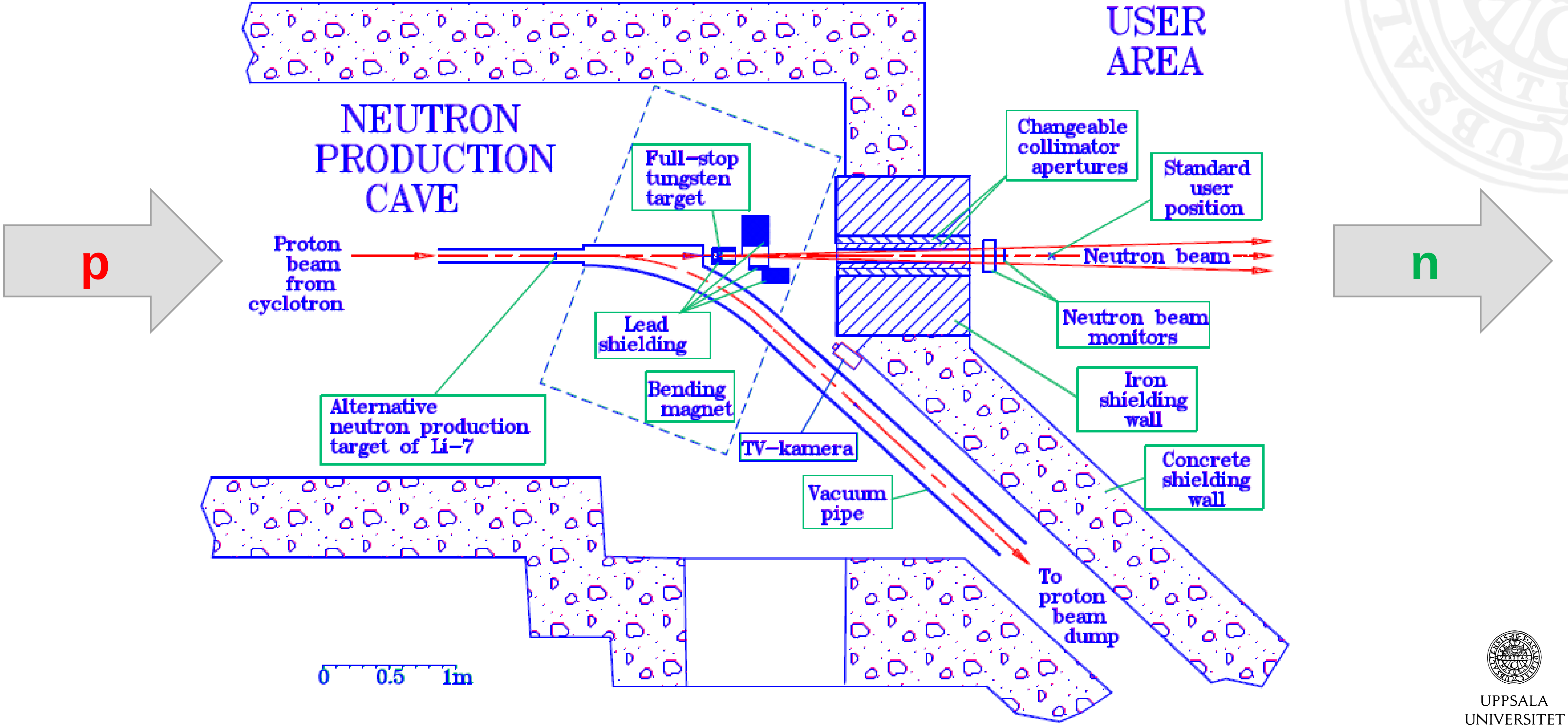
Otherwise, the term ‘**quasi-monoenergetic**’ is used.

Extra neutrons occur due to, e.g.,break-up reactions or from neutron emission via excited states.





Typical layout; example: The Svedberg Laboratory (now closed) in Uppsala



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Mono-energetic neutrons

The “big four”:

- D(d,n)^{3}He Q = 3.2689 MeV
- T(p,n)^{3}He Q =-0.7638 MeV
- **T(d,n)^{4}He Q = 17.589 MeV**
- **^{7}Li(p,n)^{7}Be Q =-1.6442 MeV**

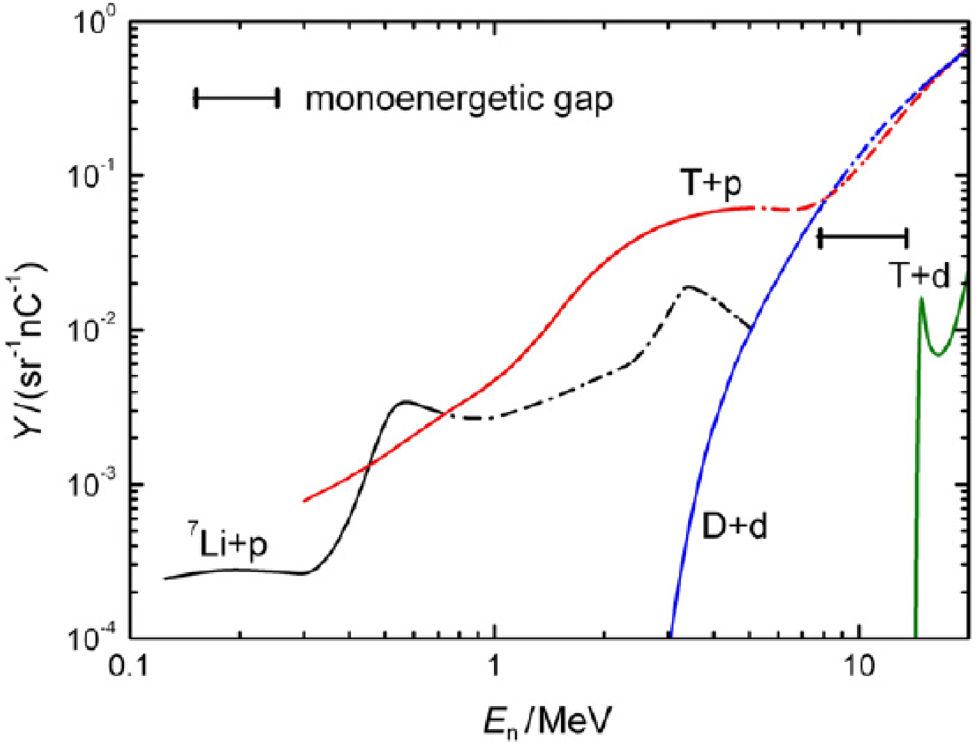


Figure 1. Neutron emission yield Y at 0° for the four most important neutron-producing reactions as a function of the neutron energy E_n. The dashed line indicates the energy range where the reactions are accompanied by break-up reactions (T(p, n)^{3}He, D(d, n)^{3}He) or neutron groups from excited states (^{7}Li(p, n)^{7}Be).

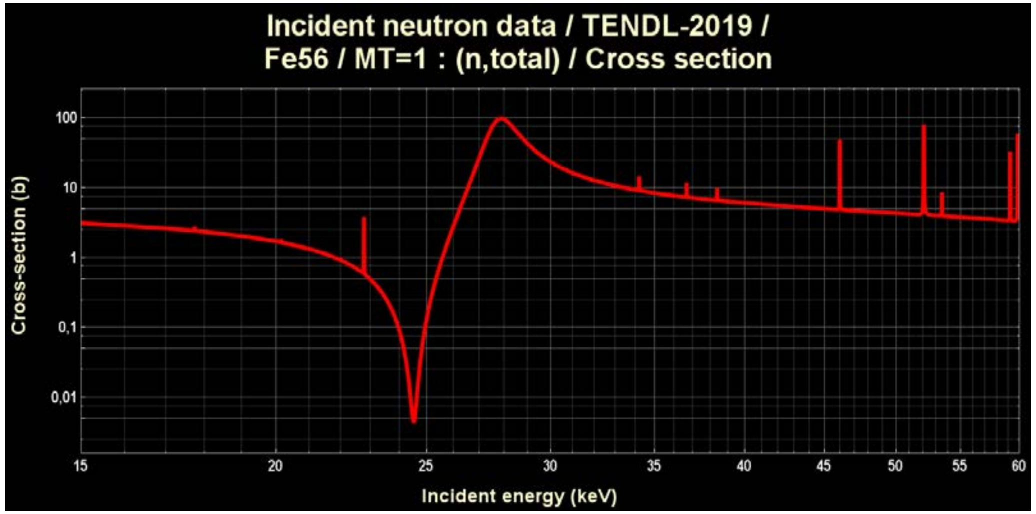
References:

H. Harano et al., *Radiation Measurements* **45** (2010) 1076-1082
V. Lacoste, *Radiation Measurements* **45** (2010) 1083-1089
R. Nolte et al., *Metrologia* **48** (2011) S263-S273
H. Harano et al., *Metrologia* **48** (2011) S292-S303

Other mono-energetic neutron sources

Using resonances:

- Directly, e.g., ${}^{45}Sc(p,n){}^{45}Ti$, or
- filtered beams, e.g., with ${}^{56}Fe$ (24 keV)



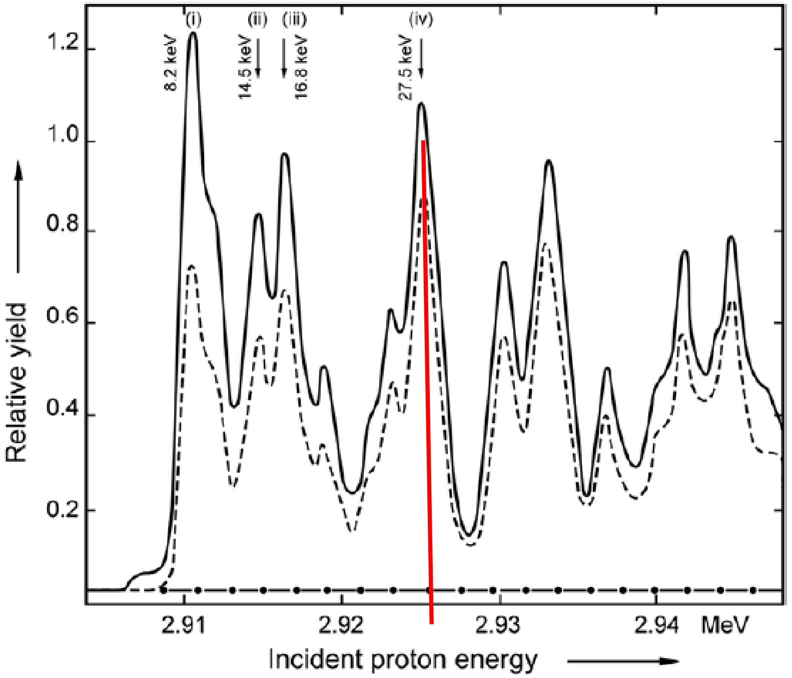
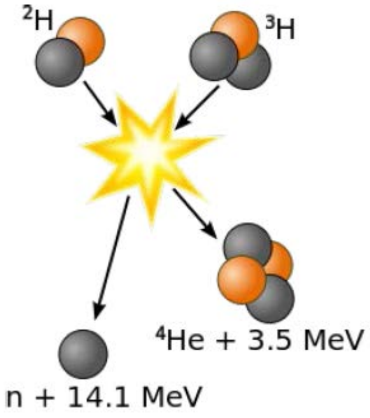


Figure 4. Excitation function for the reaction ${}^{45}Sc(p, n){}^{45}Ti$ measured using a long counter and a metallic scandium target with an areal mass corresponding to a proton energy loss of about 300 eV. The solid and dashed lines show the excitation functions at neutron emission angles of 0° and 60°, respectively. The figure is taken from [28].

E.g.
2.926 MeV for
27.5 keV neutrons

R. Nolte et al., *Metrologia* **48** (2011) S263-S273

Neutrons from DD and DT reactions

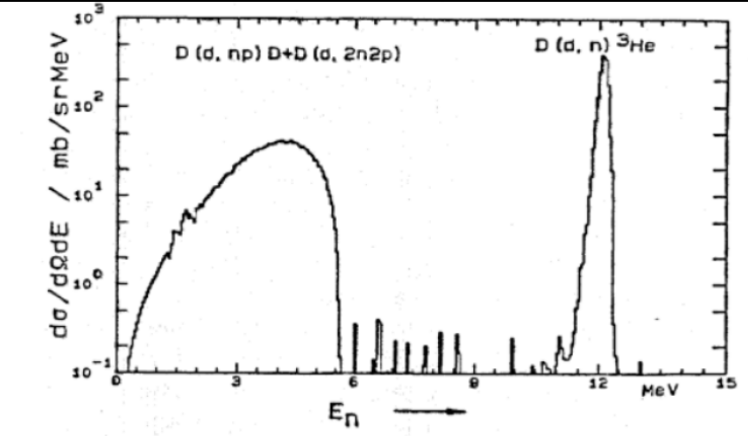


Very commonly used to produce 2.5 MeV and 14.1 MeV fields.

Possible to use as small portable (sealed tube) device.

Normally with a primary beam of a few hundred keV.

- DT yields typically 100 times larger than DD
  - “Standard” DT: 10^8 n/s; up to 10^{11} n/s commercial availble.
- Target: typically metal hydrates (TiT)
- In combination with, e.g., a Tandem, higher energies can be reached (possibly at the expense of breakup reactions)



Neutron production cross section at 0° in D+D reaction at deutron energy 9 MeV.

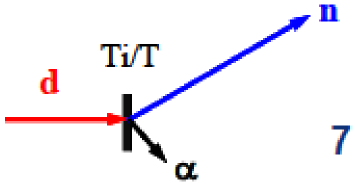
H. Conde et al, Nuclear Data for Science and Technology: Proceedings of an International Conference, held at the Forschungszentrum Jülich, Fed. Rep. of Germany, 13–17 May 1991, pp. 386-394

More info NG and their use: IAEA (2012) “Neutron Generators for Analytical Purposes”

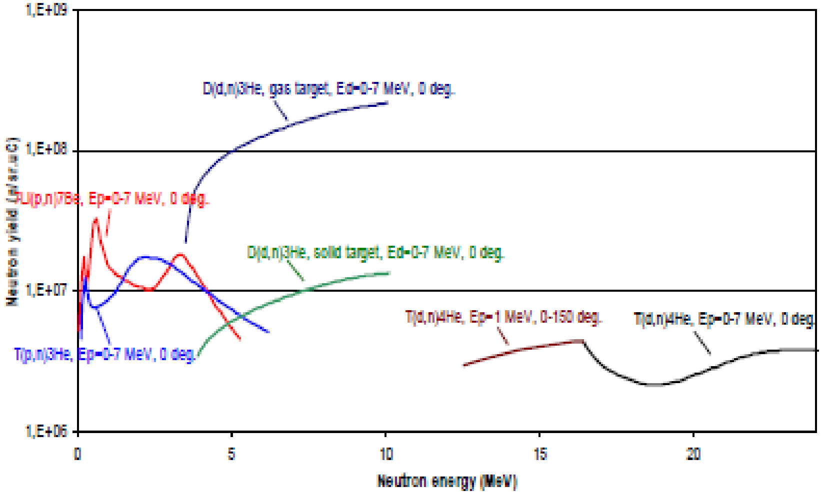
MONNET at JRC-Geel, Belgium

measurements with quasi mono-energetic neutrons produced via nuclear reactions

e.g.: T(d,n)^{4}He



7 MV



Neutron energy ~

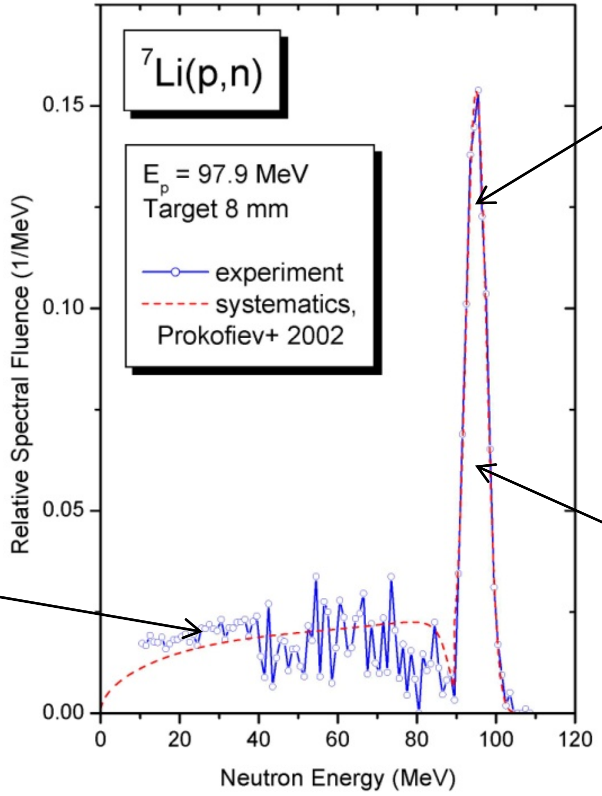
- nuclear reaction,
- target nucleus,
- impinging ion type,
- ion beam energy,
- neutron emission angle

^{7}Li(p,n)^{7}Be	E_n: 0 - 5.3 MeV
T(p,n)^{3}He	E_n: 0 - 6.2 MeV
D(d,n)^{3}He	E_n: 1.8 - 10.1 MeV
T(d,n)^{4}He	E_n: 12.1 - 24.1 MeV

QMN energy spectrum – case of ^{7}Li(p,n)

Most commonly used:

^{7}Li(p,n)



Peak (~50%) from
^{7}Li(p,$n_{0,1}$)^{7}Be (Q$_0$=1.644 MeV)

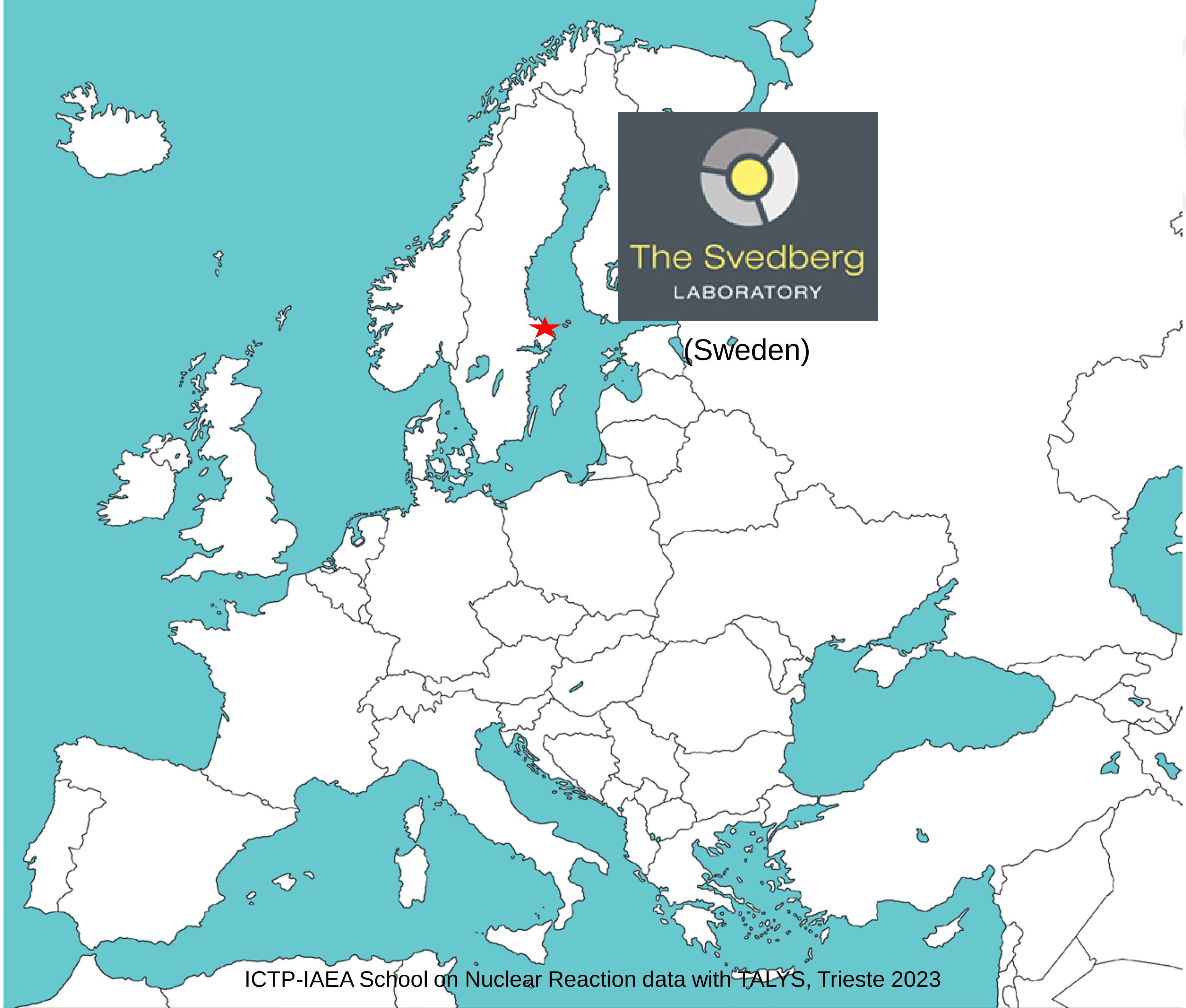
0.429 MeV

Width dependend
on Li target thickness
(here: limited exp. res.)

Break-up continuum
^{7}Li(p,nx)

can be suppressed
by TOF techniques
in pulsed beam

Figure: S. Pomp et al., AIP Conf. Proc. 769 (2005) 780



The Svedberg LABORATORY

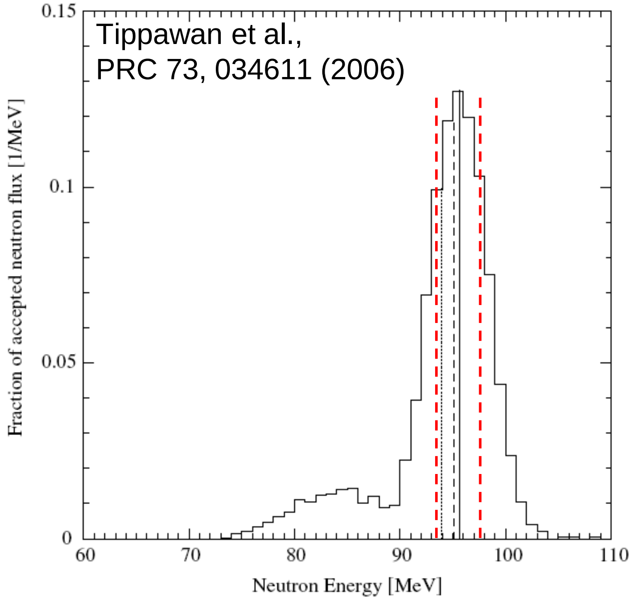
(Sweden)

QMN beam @ TSL

Cyclotron of The Svedberg Laboratory (TSL) offered proton beams up to 180 MeV.
Using **^{7}Li(p,n)** quasi monoenergetic neutron beams were produced.

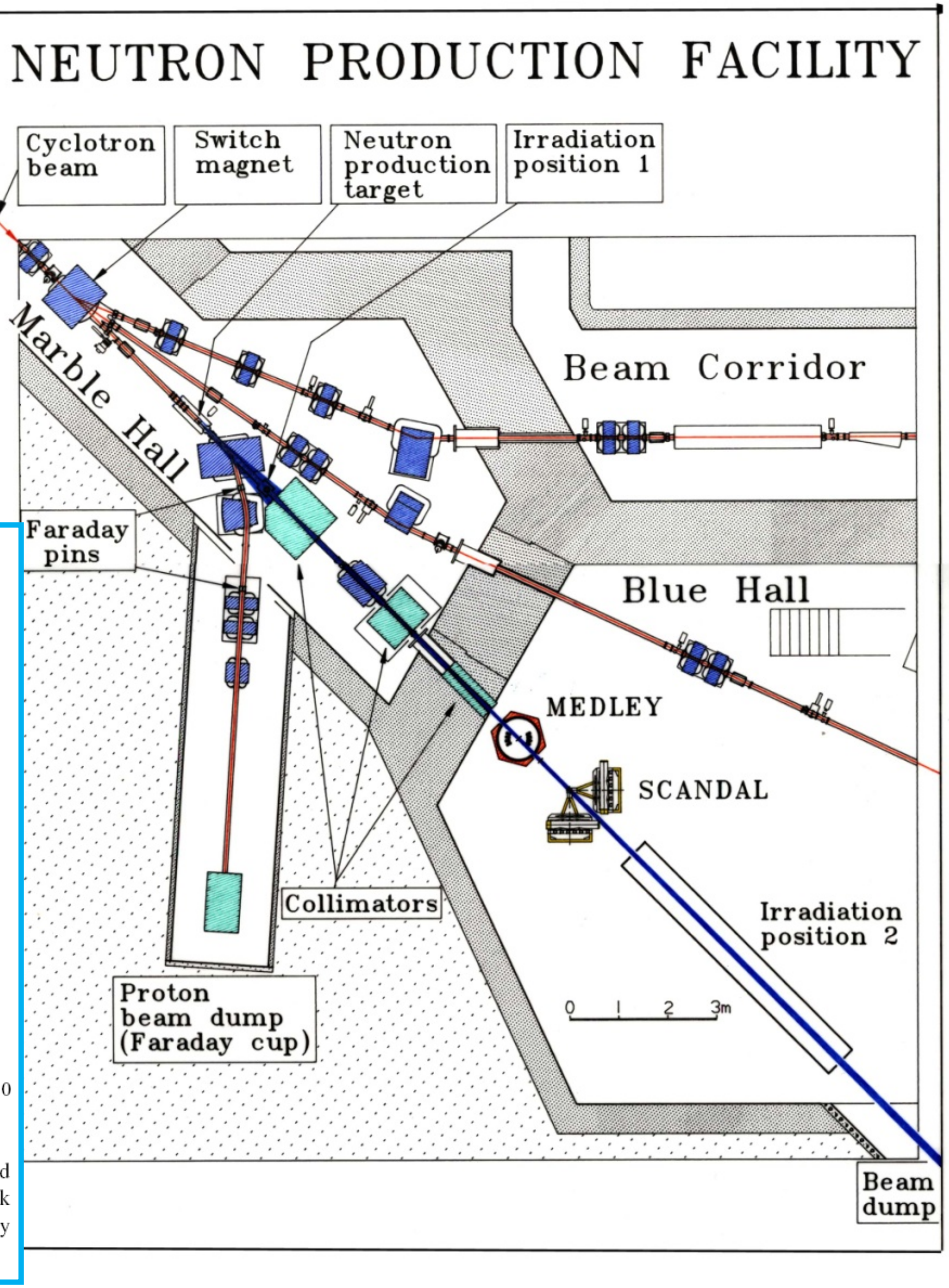
- 20-180 MeV neutrons
- 10^6 neutrons/sec @ 100 MeV
- 10^5 neutrons/sec @ 180 MeV
- beam size: 7 to 25 cm in diameter

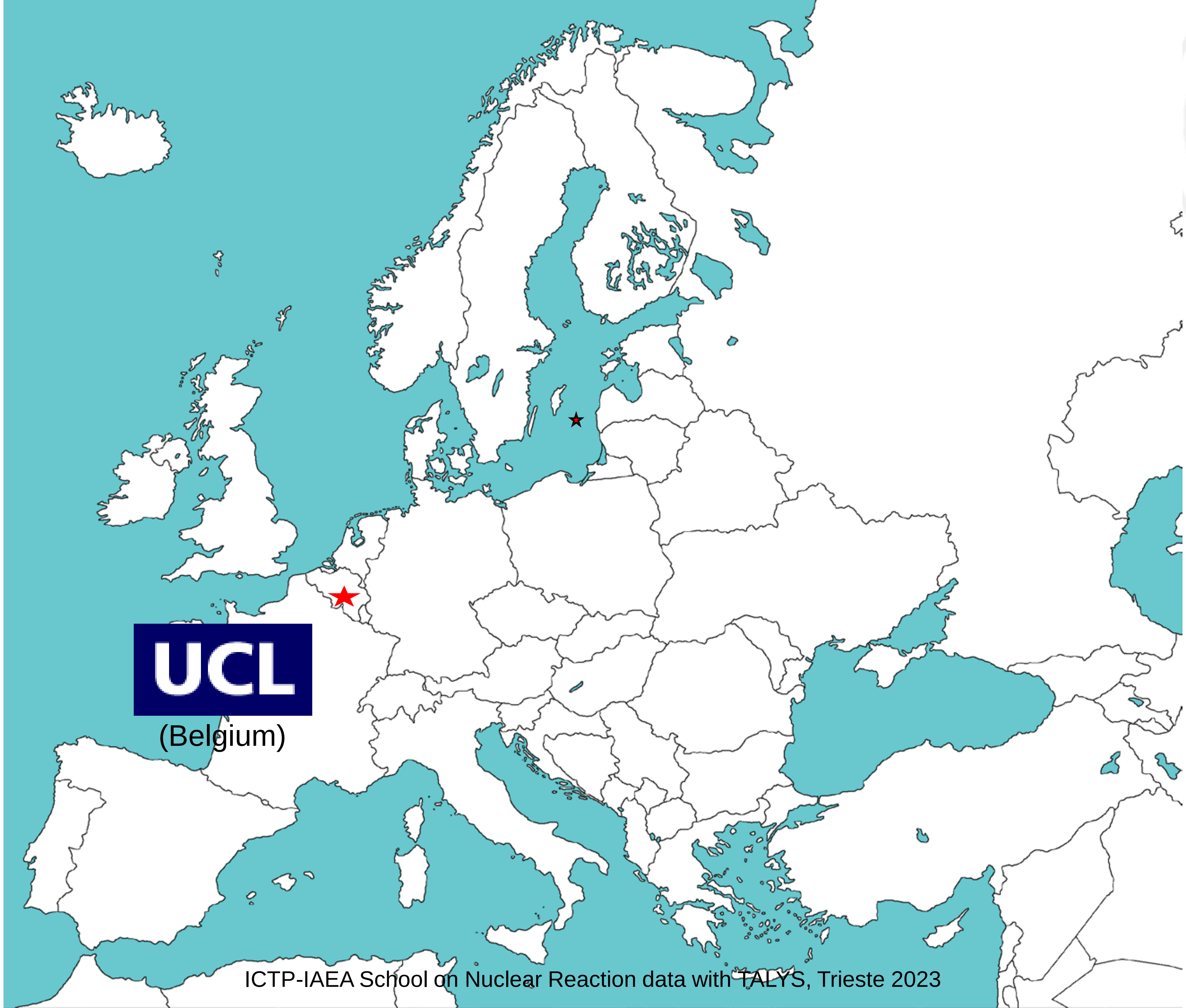
Suppression of neutrons outside the QMN peak using time-of-flight.



Tippawan et al., PRC 73, 034611 (2006)

FIG. 1. Neutron energy distribution with TOF criterion applied derived from *np* scattering data at an angle of 20°. The peak (95.6 MeV), median (95.1 V), and average (94.0) are indicated by solid, dashed, and dotted vertical lines, respectively.

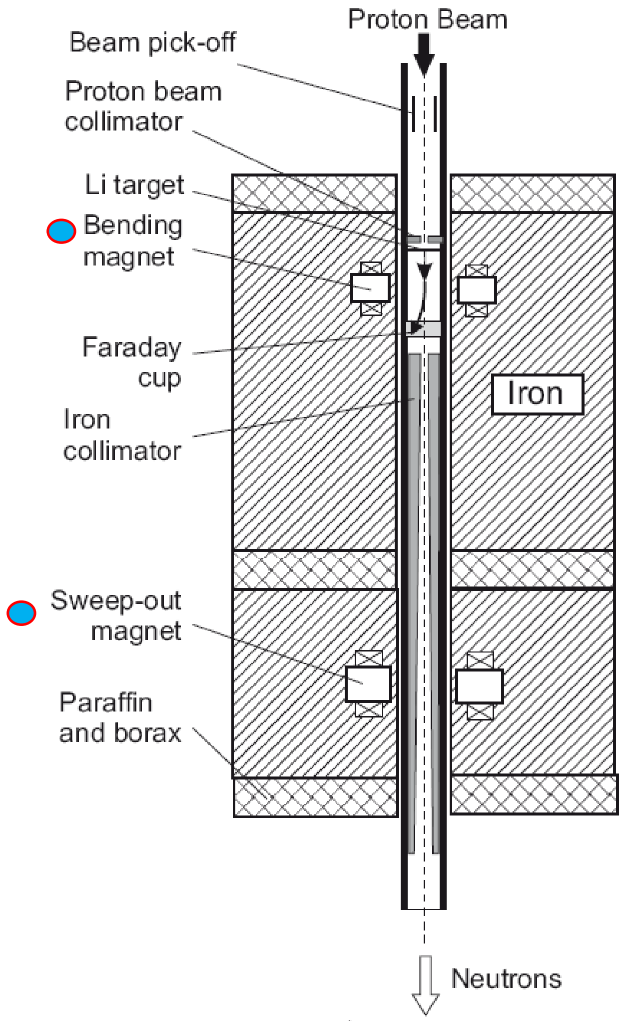




UCL

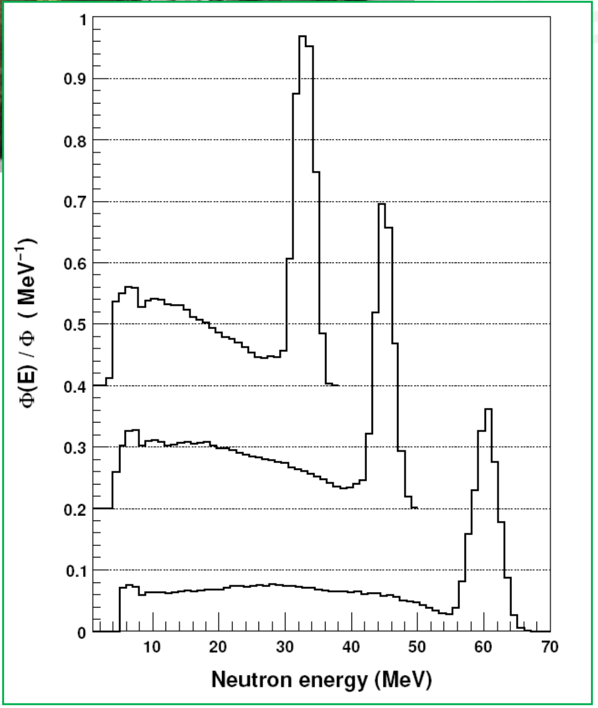
(Belgium)

Louvaine-la-Neuve, Belgium



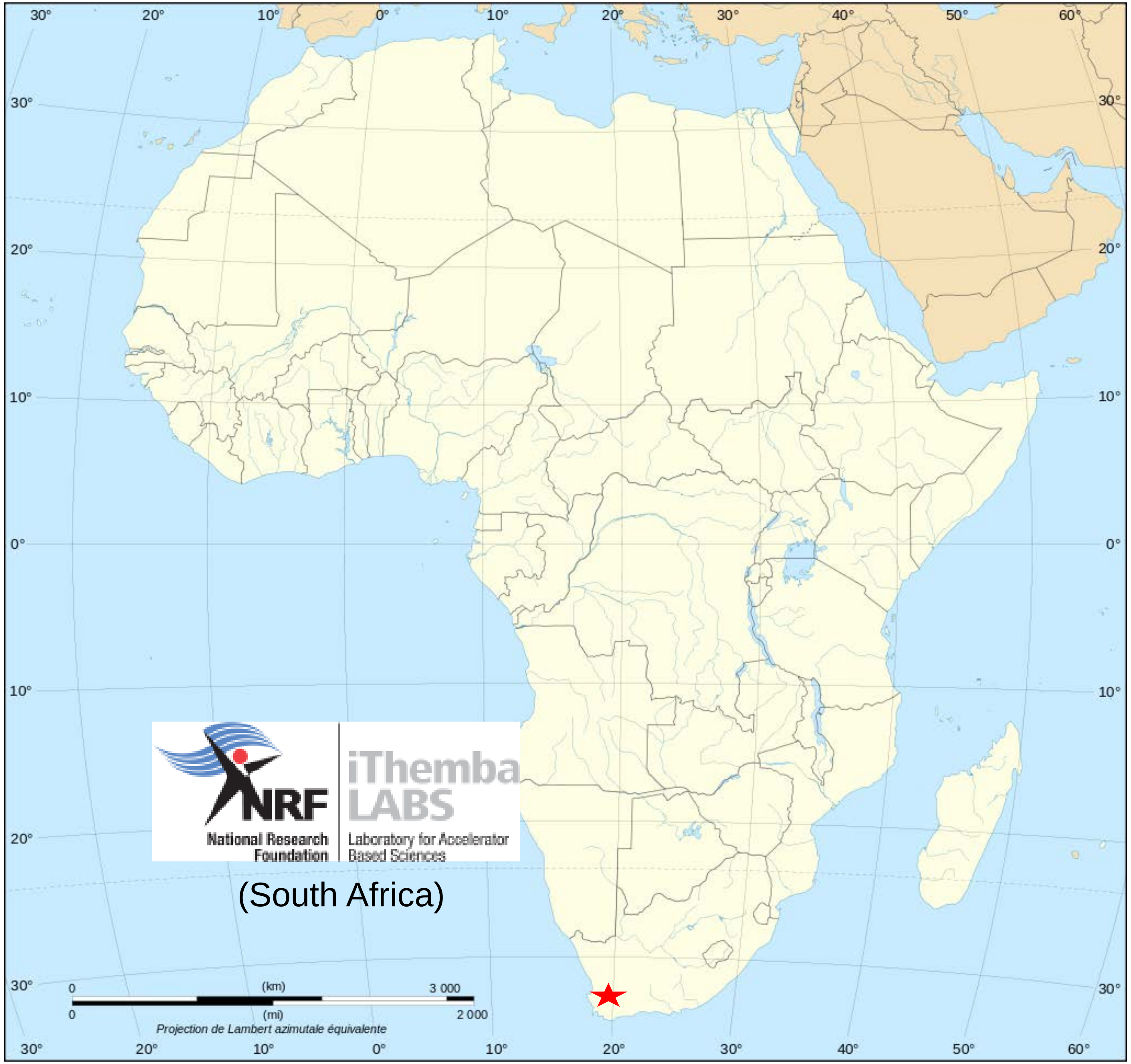
- neutron peak: 25-70 MeV
- pulse selection from cyclotron
- short proton pulses on ^{7}Li target

Characterised by PTB (Germany):
H.Schuhmacher *et al.*, NIM A 421 (1999) 284-295.



The good time-structure of the cyclotron allowed using “QMN neutrons” in the tail by time-of-flight.

See, e.g.,
N Nica et al 2002 J. Phys. G: Nucl. Part. Phys. 28 2823



NRF
National Research Foundation

iThemba LABS
Laboratory for Accelerator Based Sciences

(South Africa)

iThemba LABS, South Africa

https://tlabs.ac.za/

^{7}Li(p,$n_{0,1}$), up to 200 MeV neutrons

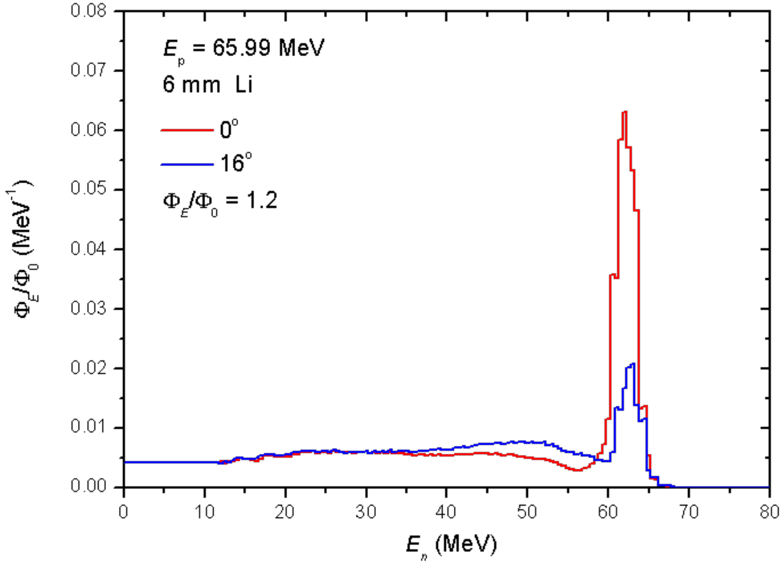
pulsed with 33 ns between pulses (option: 1 in 3, 5, or 7)

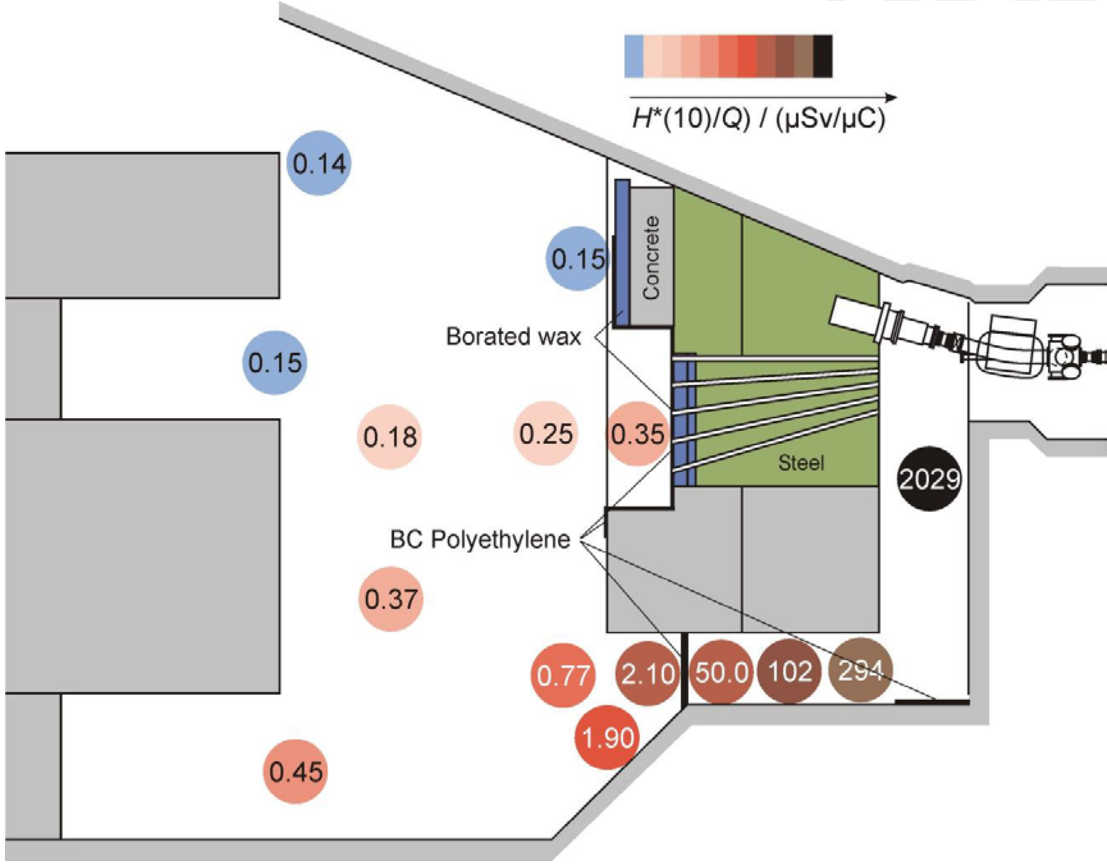
5 beam lines (0° – 16°)

metrology traceable to PTB

(see e.g. Nolte *et al.*, Rad. Prot. Dosim. 110 (2004) 97)

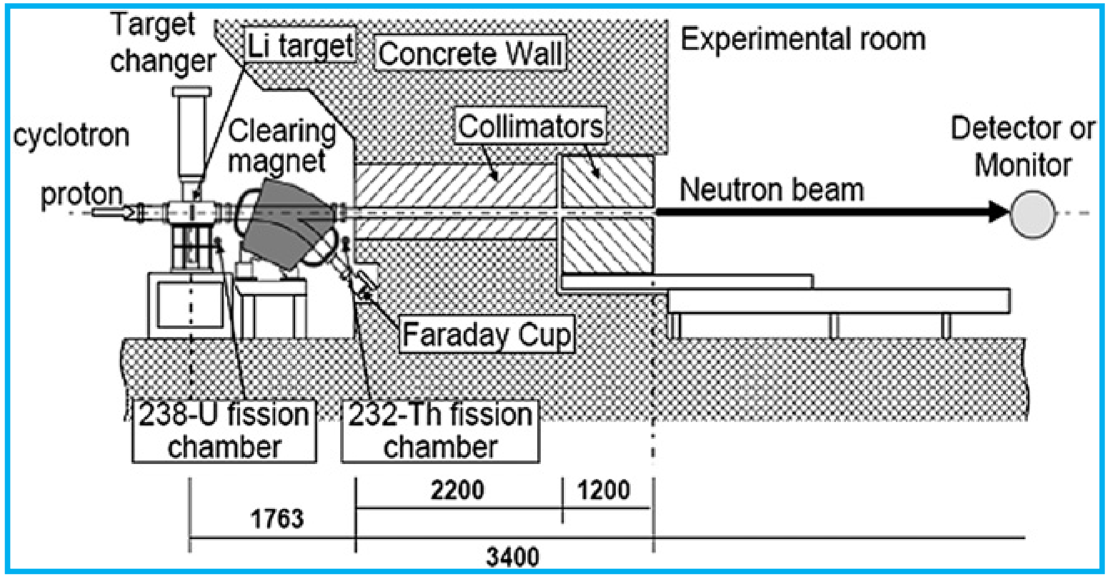
Option to subtract tail in even in a passive measurement






東北大学
TOHOKU UNIVERSITY
JAEA
RCNP
大阪大学　核物理研究センター

TIARA at JAEA and CYRIC at Tohoku University, Japan

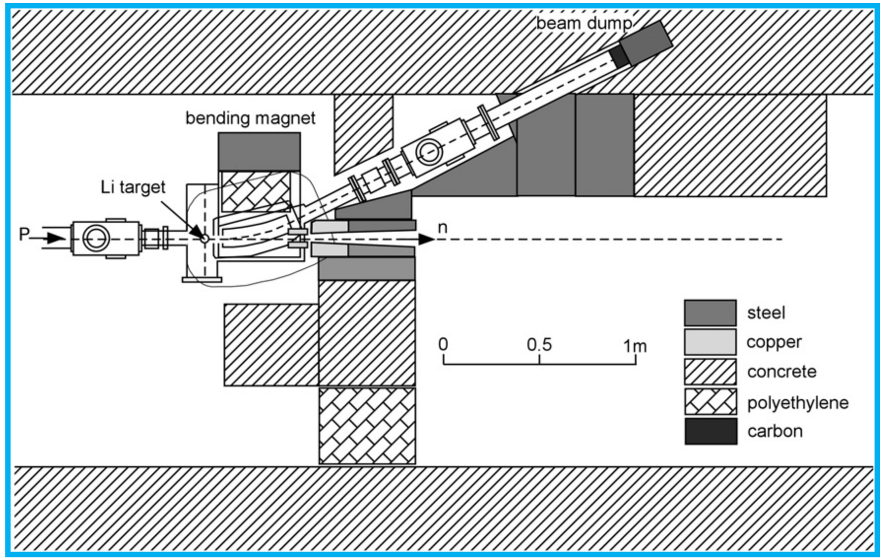


^{7}Li(p,n$_{0,1}$)

40- 90 MeV neutrons

up to 18 m flight path

ref. fields 45, 60, 75 MeV



^{7}Li(p,n$_{0,1}$)

20- 90 MeV neutrons

high intensity

See: Harano *et al,* Rad. Meas. 45 (2010) 1076.

S. Pomp, et al., “High-energy quasi-monoenergetic neutron fields: existing facilities and future needs.” EURADOS Report 2013-02, and
Radiation protection dosimetry 161 1-4 (2014): 62-6.

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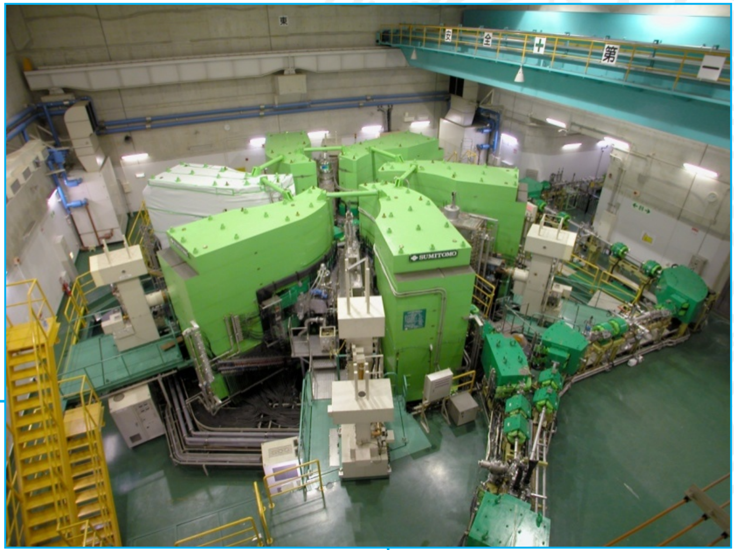
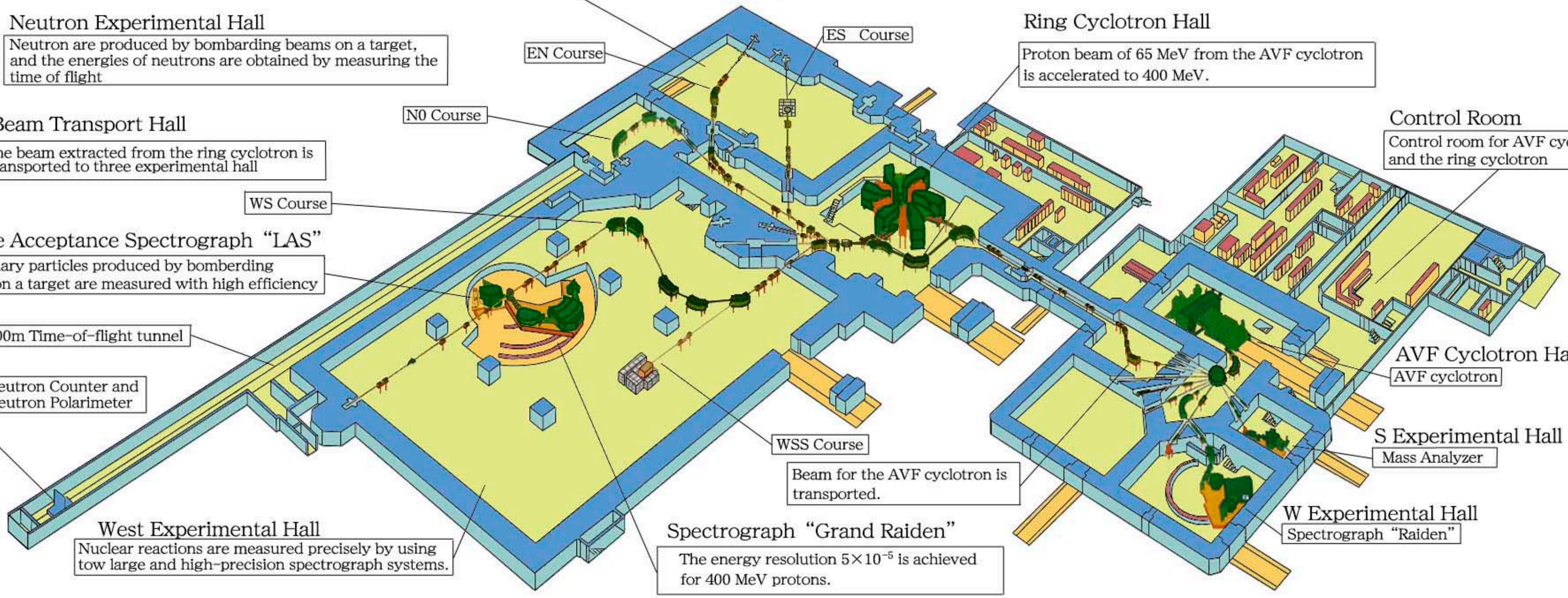
RCNP Osaka, Japan

https://www.rcnp.osaka-u.ac.jp/Divisions/np1-a/RCF/RCNPCF-Facility_e.html





East Experimental Hall
By bombarding heavy ions on target,beams of unstable nuclei which do not exist on earth are supplied.

Neutron Experimental Hall
Neutron are produced by bombarding beams on a target, and the energies of neutrons are obtained by measuring the time of flight

Beam Transport Hall
The beam extracted from the ring cyclotron is transported to three experimental hall

Large Acceptance Spectrograph "LAS"
Secondary particles produced by bomberding beam on a target are measured with high efficiency

100m Time-of-flight tunnel

Neutron Counter and Neutron Polarimeter

West Experimental Hall
Nuclear reactions are measured precisely by using tow large and high-precision spectrograph systems.

EN Course

ES Course

N0 Course

WS Course

WSS Course

Beam for the AVF cyclotron is transported.

Spectrograph "Grand Raiden"
The energy resolution 5×10^{-5} is achieved for 400 MeV protons.

Ring Cyclotron Hall
Proton beam of 65 MeV from the AVF cyclotron is accelerated to 400 MeV.

Control Room
Control room for AVF cyclotron and the ring cyclotron

AVF Cyclotron Hall
AVF cyclotron

S Experimental Hall
Mass Analyzer

W Experimental Hall
Spectrograph "Raiden"

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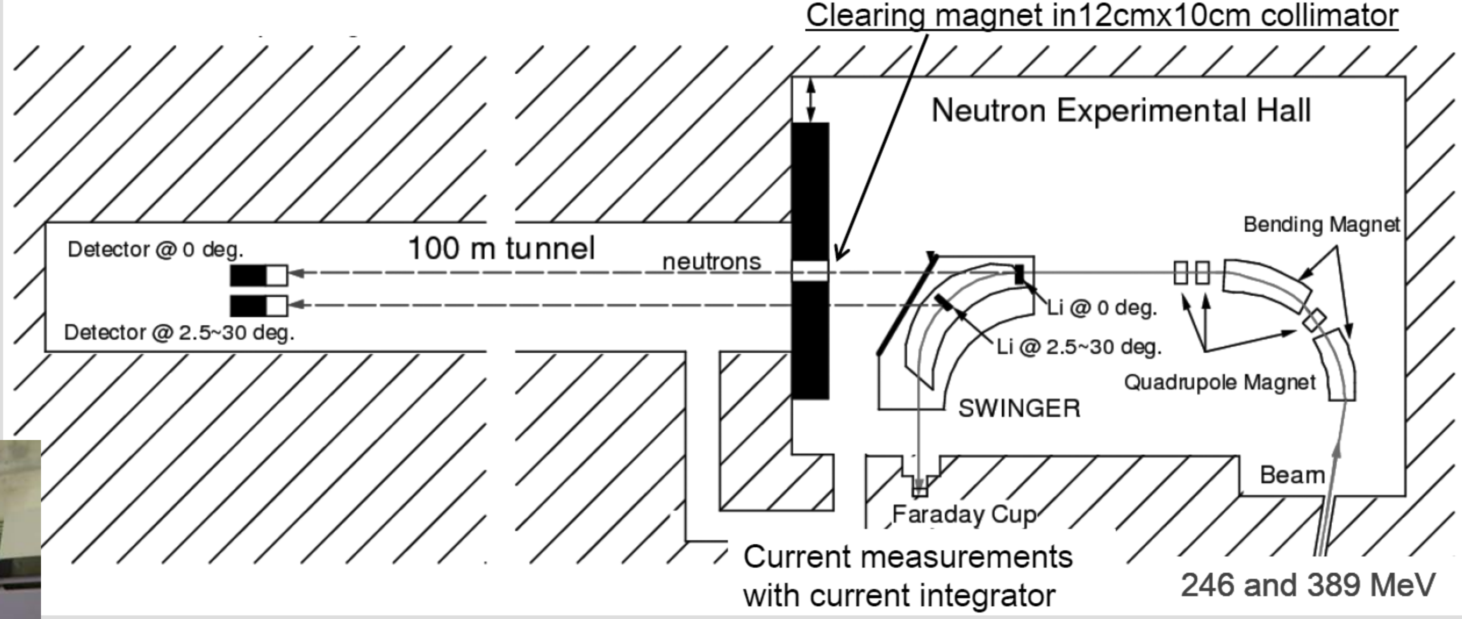
RCNP Osaka, Japan



$^7Li(p,n_{0,1})$

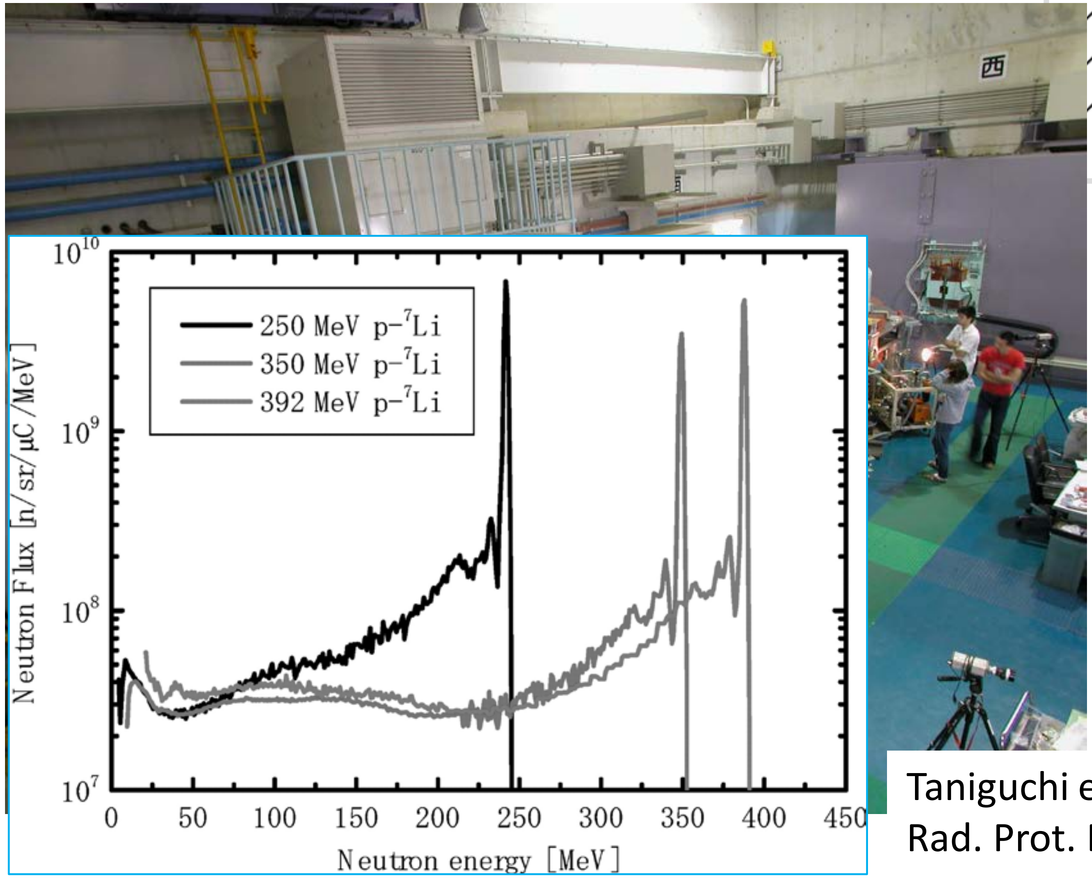
140-**400** MeV neutrons

variable beam angle

100 m flight path

S. Pomp, et al., "High-energy quasi-monoenergetic neutron fields: existing facilities and future needs."
EURADOS Report 2013-02, and
Radiation protection dosimetry 161 1-4 (2014): 62-6.

cp. iThemba LABS;
good for passive measurements



Taniguchi et al.
Rad. Prot. Dosim. 126 (2007), 23-27

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"White" neutron beams

Principle:

- **Pulsed** charged-particle beam on a target.
- Use of **time-of-flight** method to determine the **neutron energy on an event-by-event** basis for nuclear data measurements.

The achievable neutron-energy resolution depends on

- the time structure of the primary beam,
- the size of the primary target, and
- the length of flight patch.

In addition, the time-resolution of the detectors used in the experiment are of course relevant.

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“White” neutron beams

Proton beams:

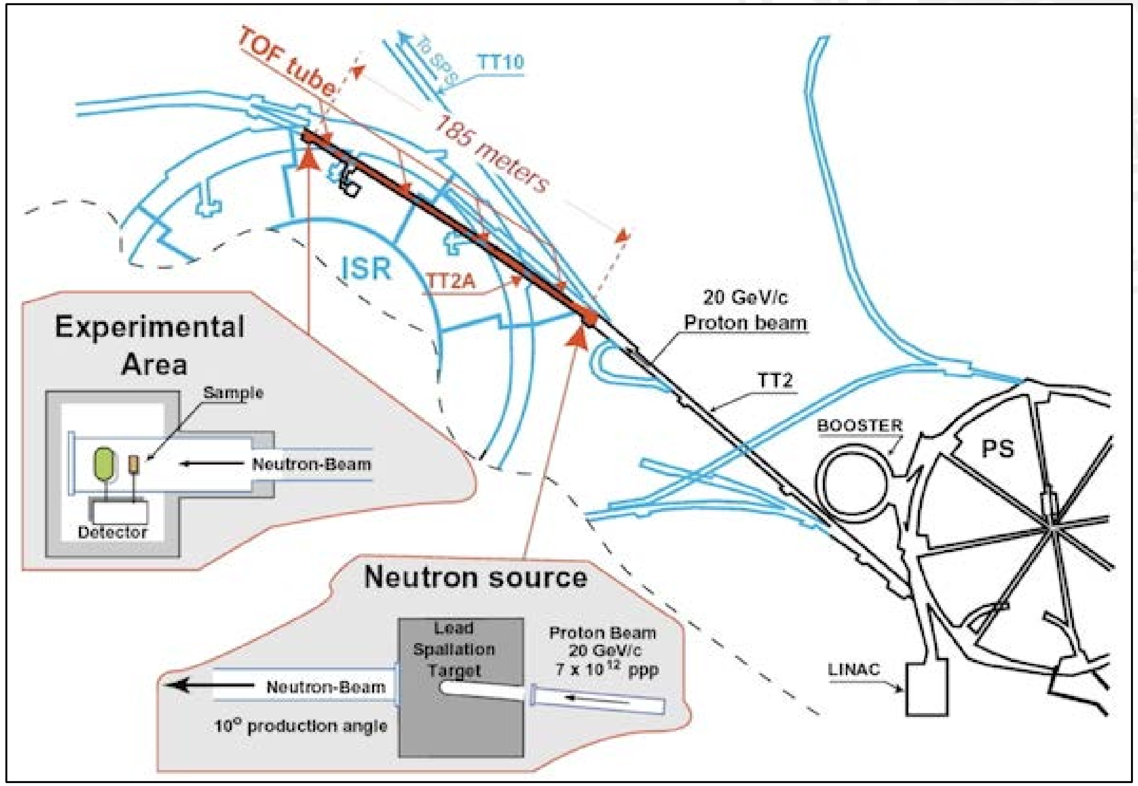
- 20 GeV on Pb (n_TOF@CERN, Switzerland) →
- 800 MeV on W (WNR@LANL, USA)
- [180 MeV on W (ANITA@TSL, Sweden)]

Deuteron beam:

- 40 MeV on Be (NFS@GANIL, France)

Electrons beams:

- 100 MeV on U (Gelina@JRC, Belgium)
- 40 MeV on Pb (nELBE@HZR Dresden, Germany)



https://ntof-exp.web.cern.ch/index.php?page=FacilityDescription

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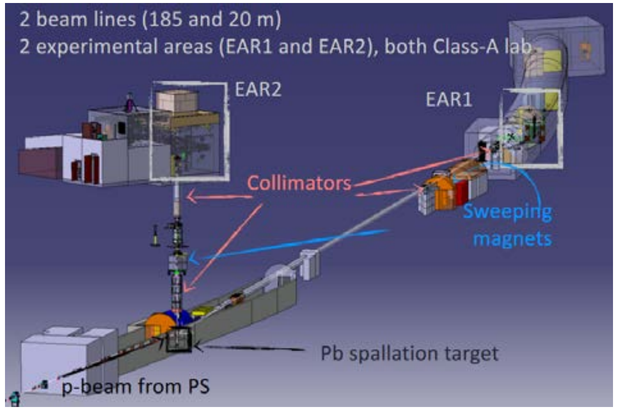
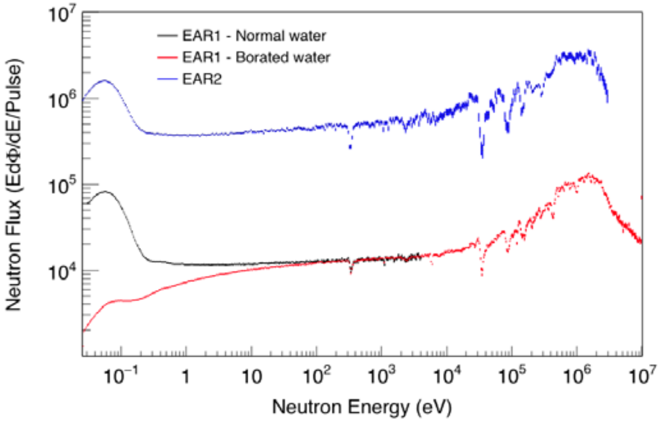
“White” neutron beams at CERN and LANSCE

n_TOF
CERN
Switzerland



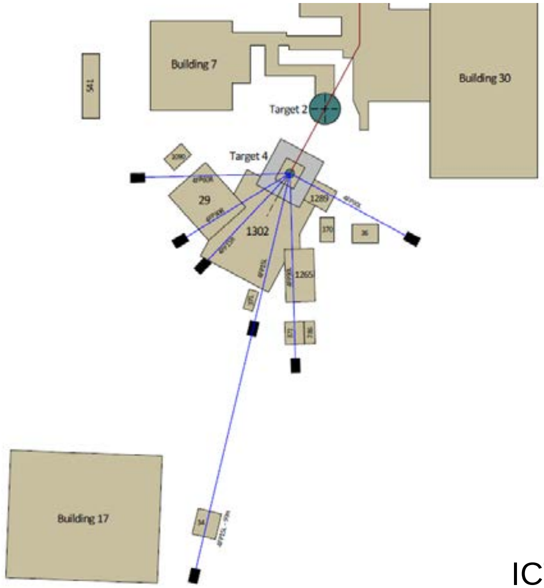


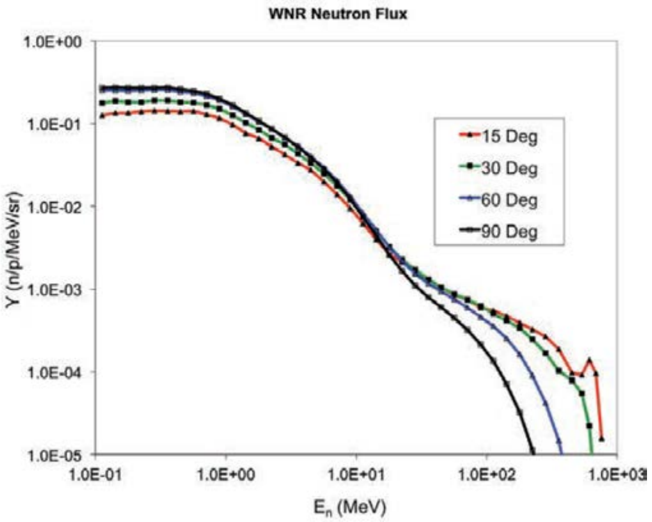
Pb(p,nx)
E_p = 20 GeV

https://ntof-exp.web.cern.ch/index.php?page=FacilityDescription
E. Chiaveri et al., EPJ Web of Conf **239**, 17001 (2020)

Careful: different units on y-axis!

WNR
LANSCE
USA





W(p,nx)
E_p = 800 MeV

https://lansce.lanl.gov/facilities/wnr/flight-paths/index.php
S.F. Nowicki, et al., Phys. Proc. **90** (2017) 374.

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GELINA at JRC, Belgium

https://joint-research-centre.ec.europa.eu/laboratories-and-facilities/jrc-neutron-time-flight-facility_en

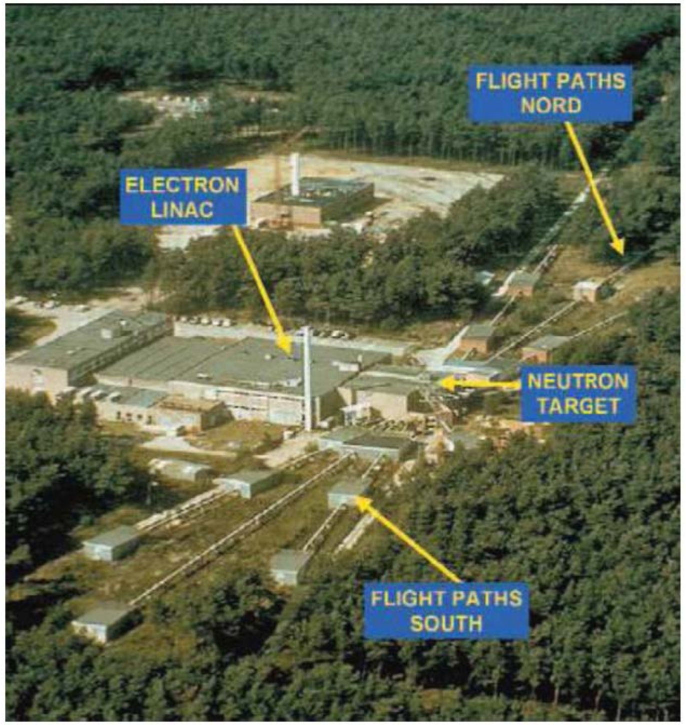

Fig. 1. Aerial view of the GELINA time-of-flight facility.

- Pulsed electron beam (0.67 ns FWHM) on uranium.
- Neutrons from bremsstrahlung via (γ,xn) and (γ,f).
- Neutron energy spectrum (meV – ~15 MeV), depending on angle and moderation.

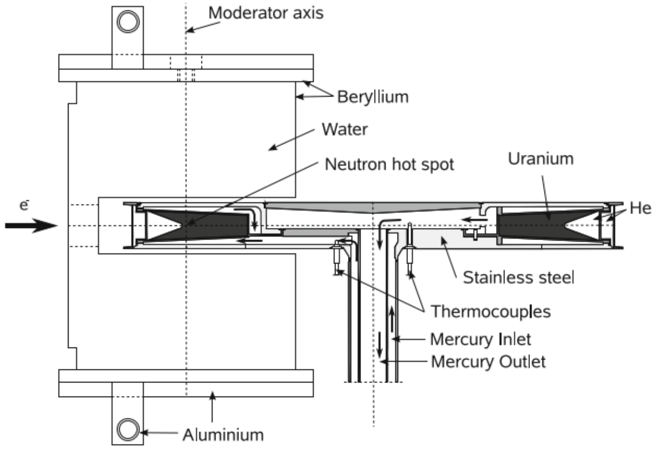

Fig. 2. Neutron-producing target.

D. Ene, et al., NIM A **618** (2010) 54–68
https://doi.org/10.1016/j.nima.2010.03.005

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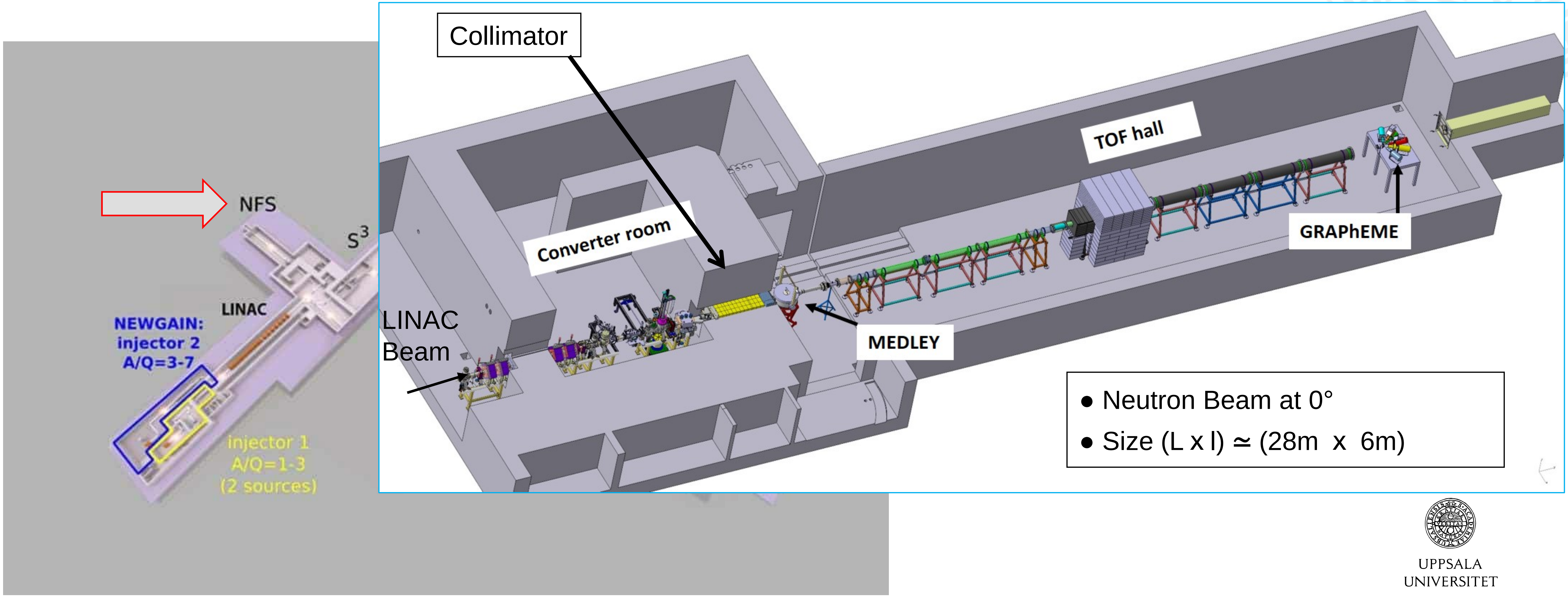
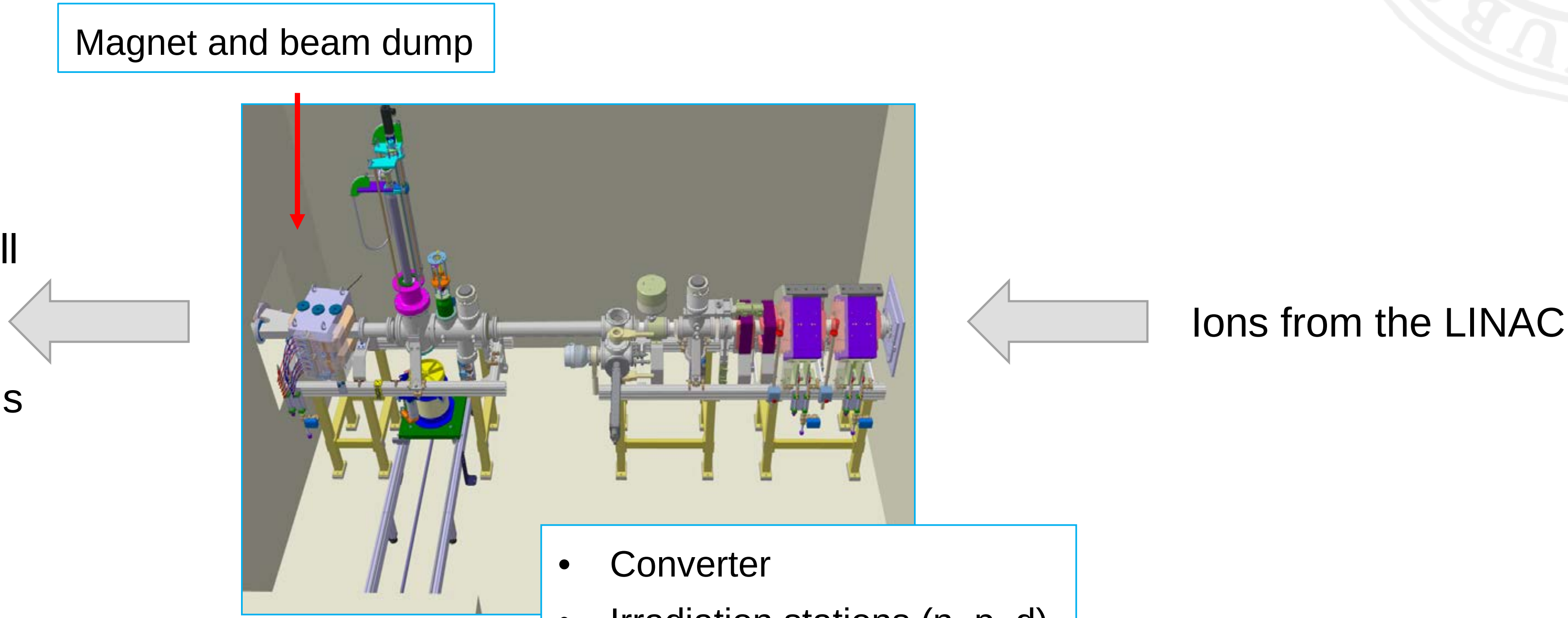
Neutrons For Science (NFS), GANIL, France

https://www.ganil-spiral2.eu/scientists/ganil-spiral-2-facilities/experimental-areas/nfs/



- Neutron Beam at 0°
- Size (L x l) ≃ (28m x 6m)

NFS – Converter room



Magnet and beam dump

Neutron to TOF hall

QMN and
white neutron beams
possible

Ions from the LINAC

- Converter
- Irradiation stations (n, p, d)
  with “rabbit” system
  (pneumatic transfer)

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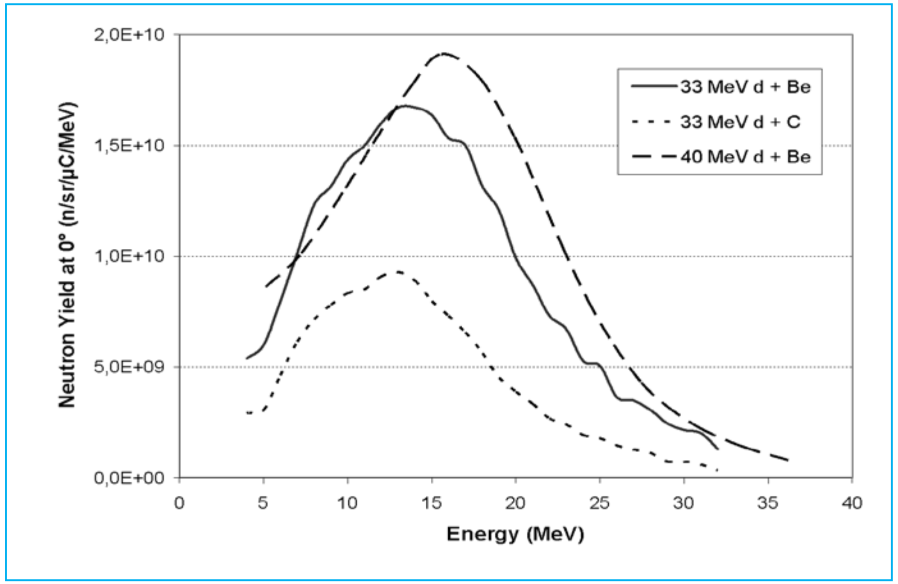
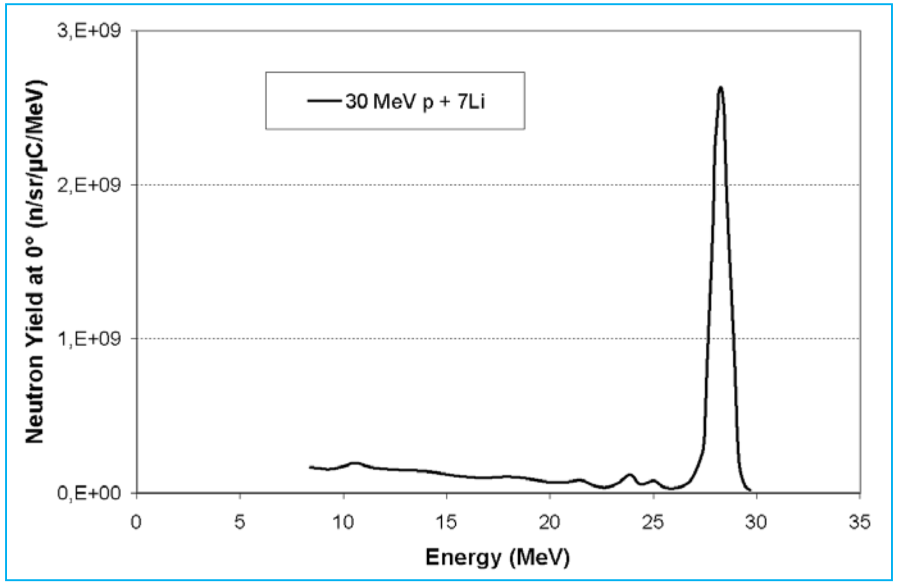
Continuous "white" spectrum and QMN at NFS

Expected neutron energy spectra (so far only preliminary experimental data)



40 MeV deuterons on thick Be target
Max current: 50 µA (design)



30 MeV protons on thin Li target (1 mm)
Max current: 20 µA (design)

Comparison of some neutron energy spectra

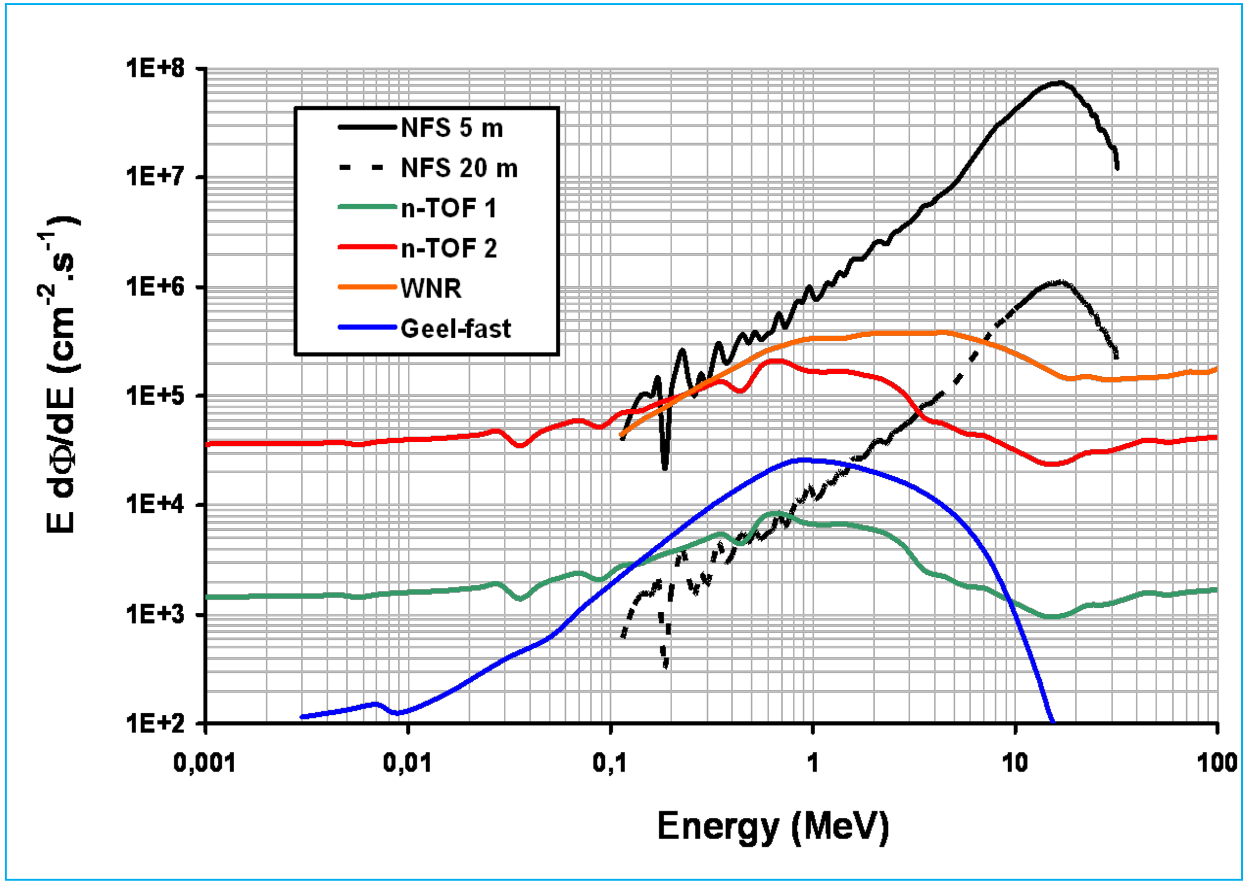


Figure courtesy of X. Ledoux

NFS : 40 MeV d + Be

WNR : Los Alamos

n-TOF 2 : CERN

n-TOF 1 : CERN

GELINA : Geel

1-30 MeV range

Large energy range,
High energies

Low energy,
Good energy resolution

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Outline

Introduction

- General comments about experiments and challenges
- Nuclear data of interest

Facilities

- Overview
- Neutron sources
- Reactors
- Accelerator-based neutron facilities (DD/DT, QMN, White)
- **Characterization and monitoring**

Measurements

- Nuclear data of interest (reminder)
- Overview on measurement techniques for nuclear data
- Considerations for a possible experiment – an example

Characterization and monitoring

For a successful measurement you need to know

- the neutron **energy spectrum** to which the sample has been exposed to,
- the neutron **fluence** during the experiment (possibly with flux variations),
- and also the **size and uniformity** of the field.

Last not least: good knowledge of the (ambient) **background** is normally needed.

On units:

- **Flux** is a rate, e.g. number of neutrons per second. Flux can additionally be given, e.g., per area, energy bin, incoming primary particles or current, etc.
- **Fluence** is given by area (e.g., a time integrated flux) .

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Topical issue Metrologia **48** (2011)
on **neutron metrology**
https://iopscience.iop.org/issue/0026-1394/48/6

How to count neutrons?

Problem:

- charged particles ionize → “100 %” detection efficiency → “just count” (e.g., measure current)
- neutrons: only nuclear interactions → << 100 % detection efficiency
- catch 22: to know the detection efficiency of a neutron detector, you need to know the cross section … and for that you need to know the number of incoming neutrons …

Way out?

1 – Neutron tagging
2 – Use total/reaction/elastic cross section
3 – use theoretical relations between cross sections

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How to count neutrons?

1 – Tagging

Example: T(d,n)^{4}He

2-body reaction, one final state
detect ^{4}He → neutron "tagged", direction of flight known
low, but known intensity; use for efficiency calibration …

2 – Use total/reaction/elastic cross sections

Example:

- total H(n,p) cross section well known (transmission measurements) over a wide energy range (uncertainty <1%)

> measure H(n,p) angular distribution and normalize to total cross section

3 – Theoretical relations

Example:

The np $\rightarrow d\pi^0$ cross section is half of the pp $\rightarrow d\pi^+$ cross section, which is known
→ measure relative to np $\rightarrow d\pi^0$

Define a set of
cross section standards
and measure relative to them:
(n,p); ^{238}U(n,f); …

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Neutron detection (e.g. for monitoring)

Review on neutron detection techniques:
A. Pietropaolo, et al., Phys. Rep. 875 (2020), 1-65
https://doi.org/10.1016/j.physrep.2020.06.003

Generally: **convert to charged particle**
need to know cross section for conversion reaction
need to know neutron energy

Problem: normally no correspondence between energy of incoming neutron
and detected charged particle → no energy information

Exception: **elastic H(n,p) scattering** (two-body kinematics with Q-value = 0 MeV)

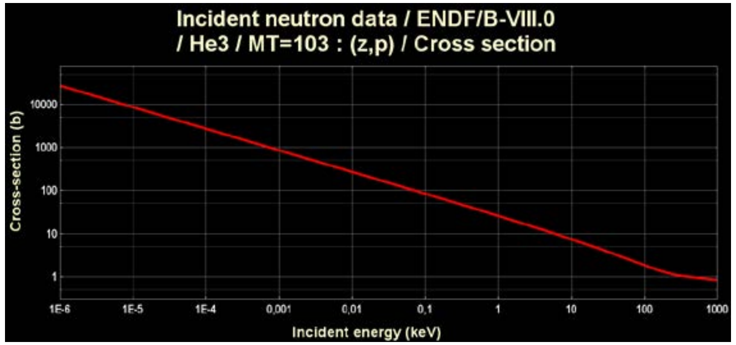
Very nice, but this only works good at high energies …

Hence we need reactions with positive, high Q-values at low energies

<u>Examples:</u>

fission	($Q \approx 200$ MeV)
$^{10}B(n,\alpha)^{7}Li$	($Q = 2.3$ MeV)
$^{6}Li(n,\alpha)^{3}H$	($Q = 4.8$ MeV)
$^{3}He(n,p)^{3}H$	($Q = 0.8$ MeV)

At low energies, the cross section (detection efficiency) varies as 1/v for these examples



Cross section standards

Wanted characteristics for a standard. Nuclide should be

- usable in elemental form (not in a compound),
- chemically inert and not radioactive,
- easy to fabricate into various shapes,
- readily available and not expensive,
- mono-isotopic, and have
- few (or no) other channels open that could cause interference with the reaction of interest.
- In the standards energy region, the cross section should be large with a minimal amount of structure.

+ further requirements for some specific measurement situations.

After: A.D. Carlson, Metrologia **48** (2011) S328-S345

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Cross section standards

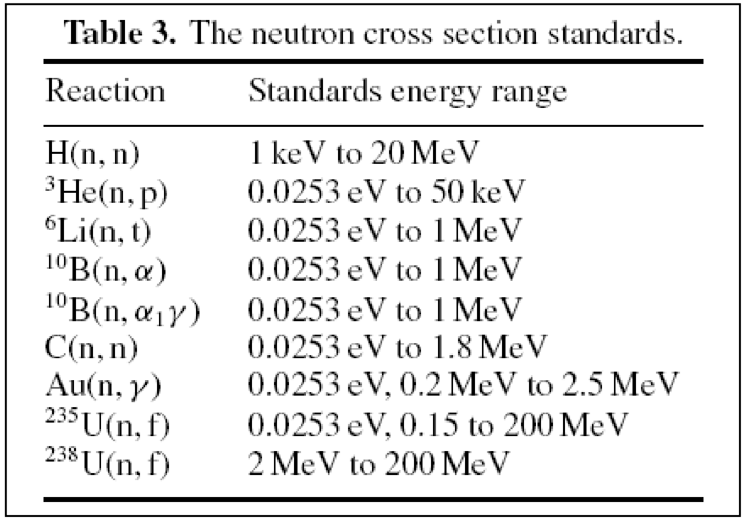

Table 3. The neutron cross section standards.

Reaction	Standards energy range
H(n, n)	1 keV to 20 MeV
^{3}He(n, p)	0.0253 eV to 50 keV
^{6}Li(n, t)	0.0253 eV to 1 MeV
^{10}B(n, α)	0.0253 eV to 1 MeV
^{10}B(n, $\alpha_1\gamma$)	0.0253 eV to 1 MeV
C(n, n)	0.0253 eV to 1.8 MeV
Au(n, γ)	0.0253 eV, 0.2 MeV to 2.5 MeV
^{235}U(n, f)	0.0253 eV, 0.15 to 200 MeV
^{238}U(n, f)	2 MeV to 200 MeV

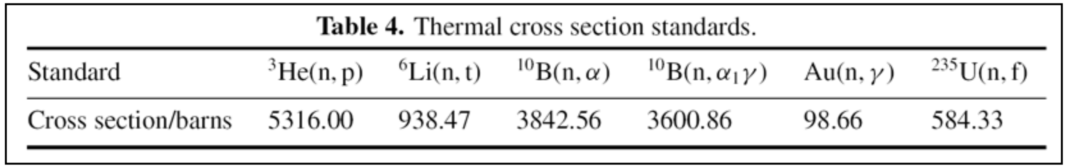

Table 4. Thermal cross section standards.

Standard	^{3}He(n, p)	^{6}Li(n, t)	^{10}B(n, α)	^{10}B(n, $\alpha_1\gamma$)	Au(n, γ)	^{235}U(n, f)
Cross section/barns	5316.00	938.47	3842.56	3600.86	98.66	584.33

Ref: A.D. Carlson, Metrologia **48** (2011) S328-S345

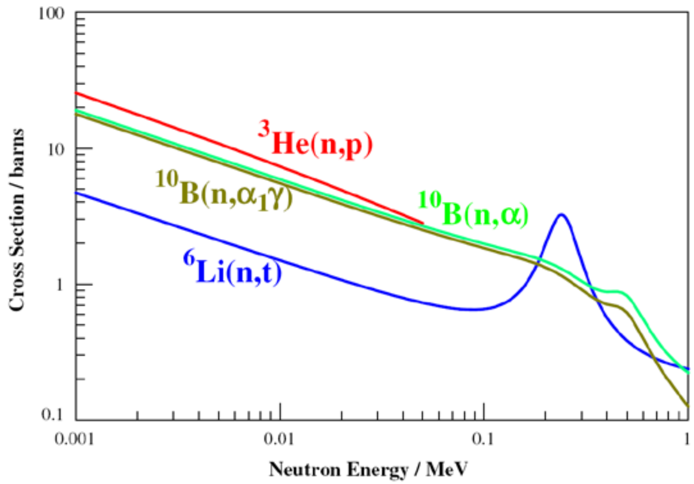

Figure 2. The low neutron energy cross section standards. Data below 1 keV are not shown.

Low energies

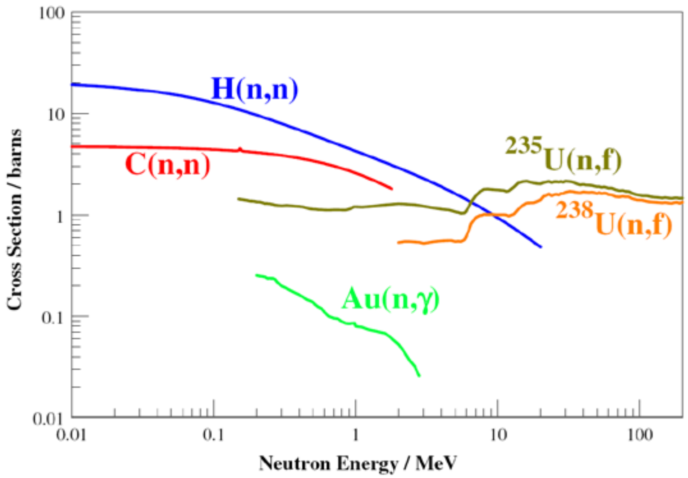

Figure 3. The high-energy neutron cross section standards. Data below 10 keV are not shown.

Medium and high energies

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Neutron energy measurement

Generally:	**time-of-flight (TOF)** needs pulsed source works best at low energies can be done event-by-event
High-energy:	**proton recoil, i.e., H(n,p) scattering** measure proton energy and angle → neutron energy follows from 2-body kinematics
Alternative:	**spectrum unfolding** (Bonner spheres, liquid scintillators) needs response functions from well defined source statistics instead of event-by-event
Low energy:	**diffraction** sub eV range, e.g. materials research

We look at these methods a bit closer

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Bonner sphere spectrometers (BSS)

Set of several polyethylene spheres with diameters as moderators.
Typically ranging from 1 to 20 inches.
Detection of neutrons in the center (e.g., using ^{3}He(n,p)T reaction).

With known response functions for each sphere (!),
spectra can be unfolded from a series of measurements.

Image source: http://www.npl.co.uk/

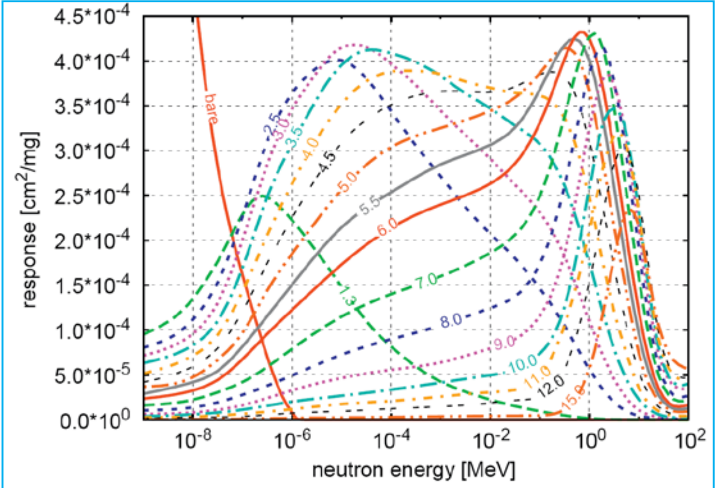

Fig. 7. Response functions of the whole Bonner sphere spectrometer with gold foils inside calculated with GEANT4; sphere size in inch is indicated on each line.

Simulated responses for different sizes of a BS.
Larger -> Better moderation of higher energies -> increased response, and vice versa.
Measure? Reference fields, QMN beams, …

from: S. Garny et al. ,Nucl. Inst. Meth. **A 604** (2009) 612–617

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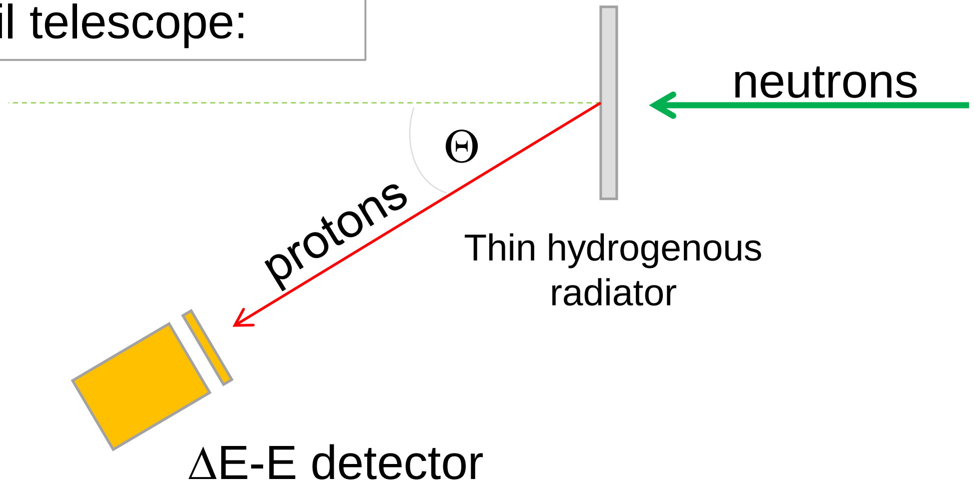
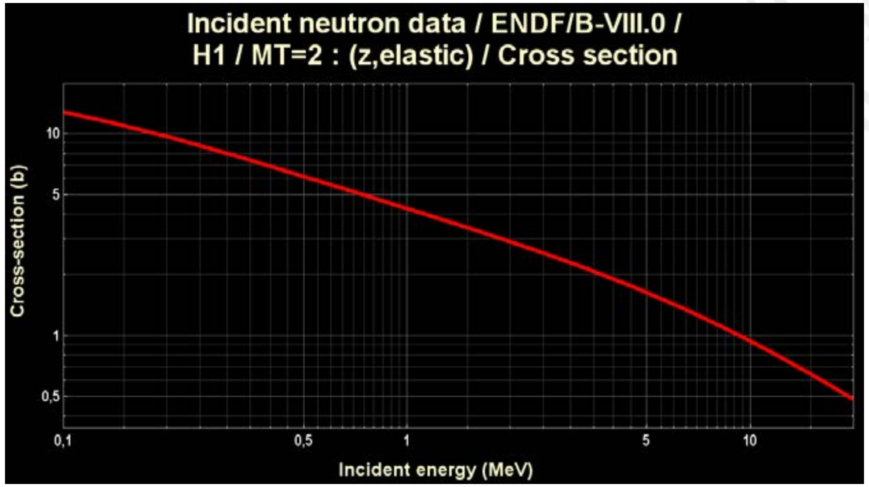
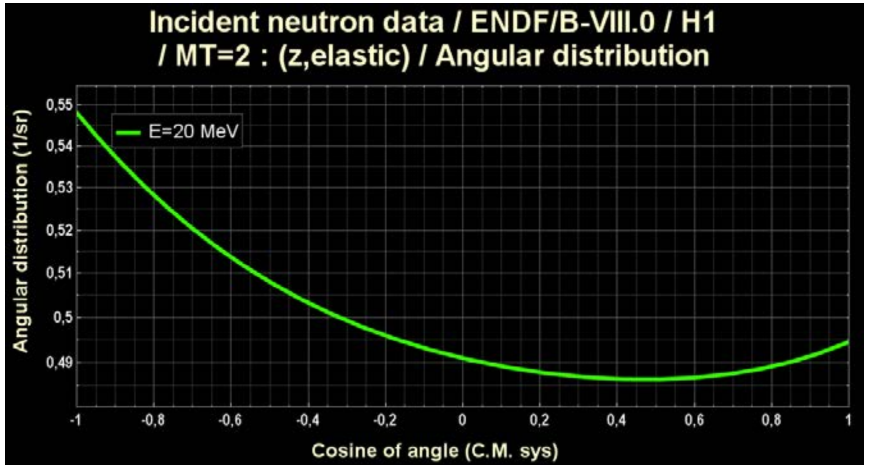
Using H(n,p) – proton recoil technique

Principle of a proton recoil telescope:




Incident neutron data / ENDF/B-VIII.0 / H1 / MT=2 : (z,elastic) / Cross section


Incident neutron data / ENDF/B-VIII.0 / H1 / MT=2 : (z,elastic) / Angular distribution

Using H(n,p) for fusion plasma diagnostics

The MPR (Magnetic Proton Recoil) spectrometer at JET:

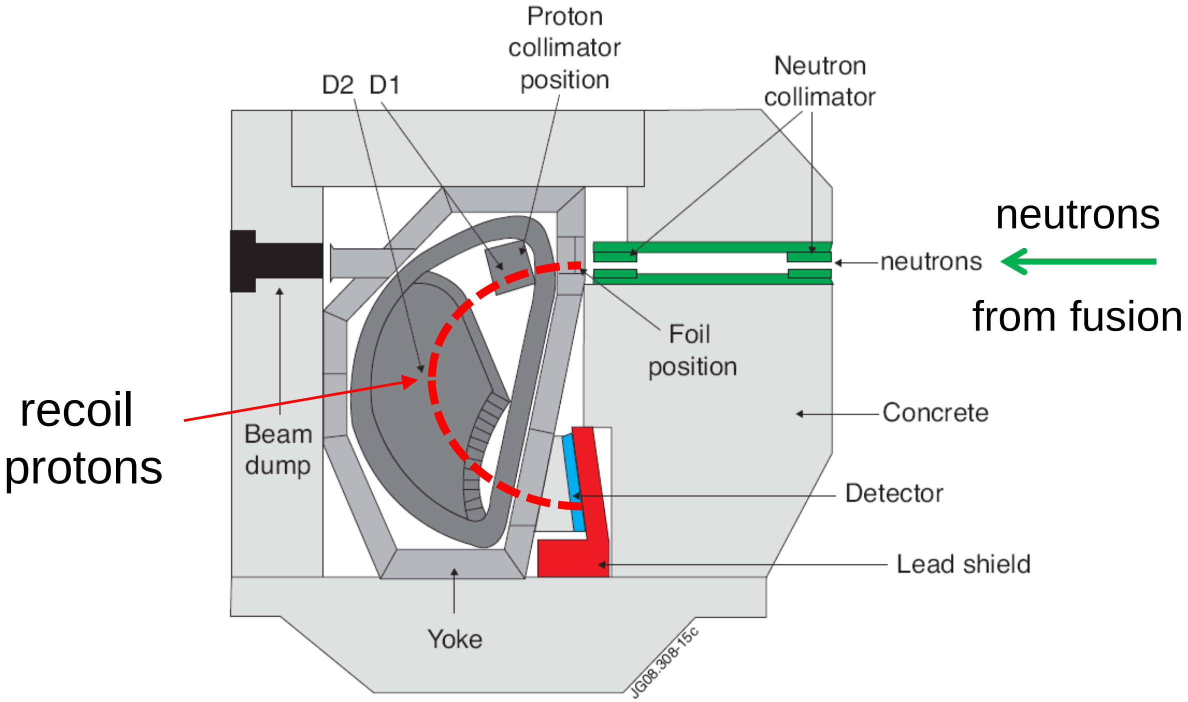
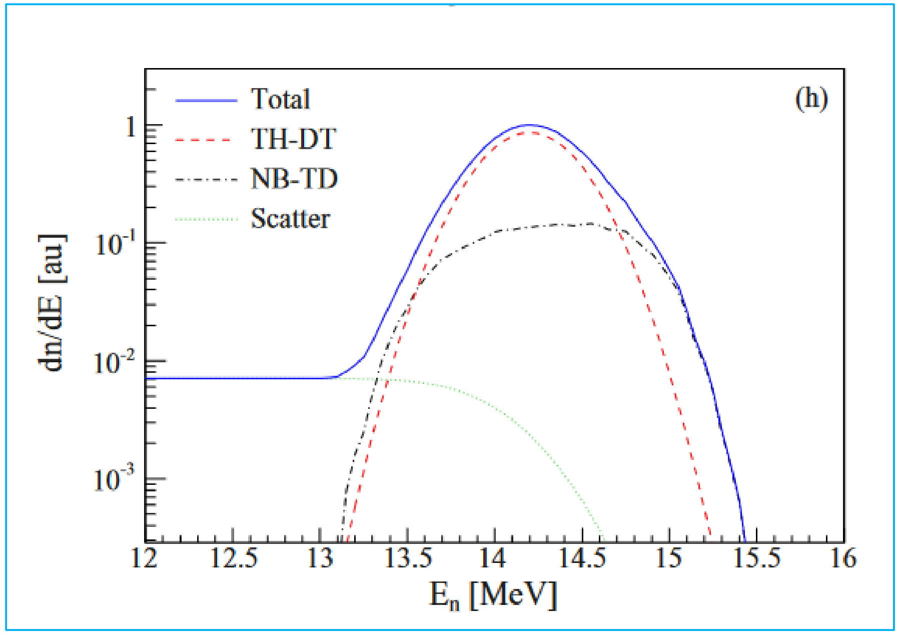


Figure adapted from E. Anderssson Sundén, et al, NIM A **610** (2009) 682.

Measured neutron spectrum at JET and fit to plasma components (thermal, heating)



C. Hellesen, et al., Nucl. Fusion Energy **55** (2015) 023005

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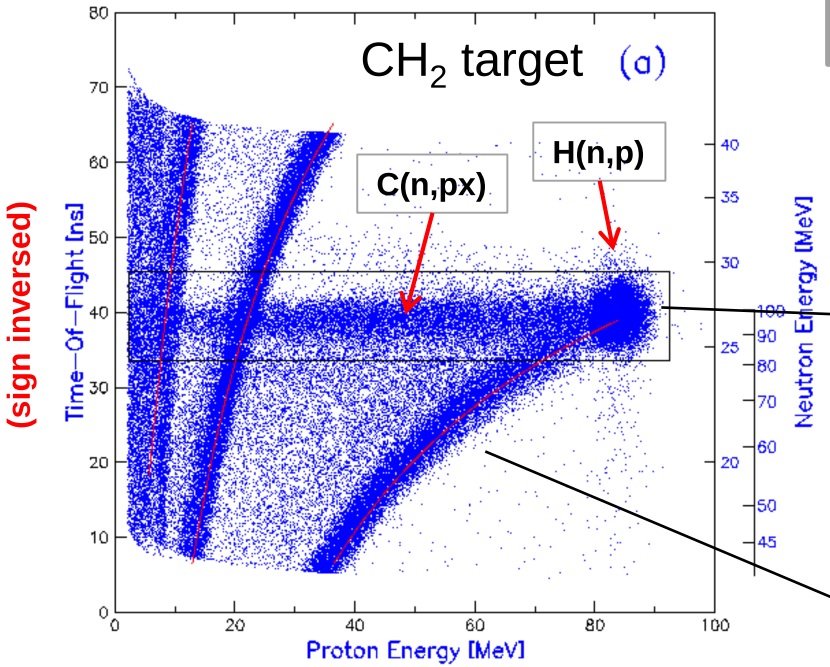
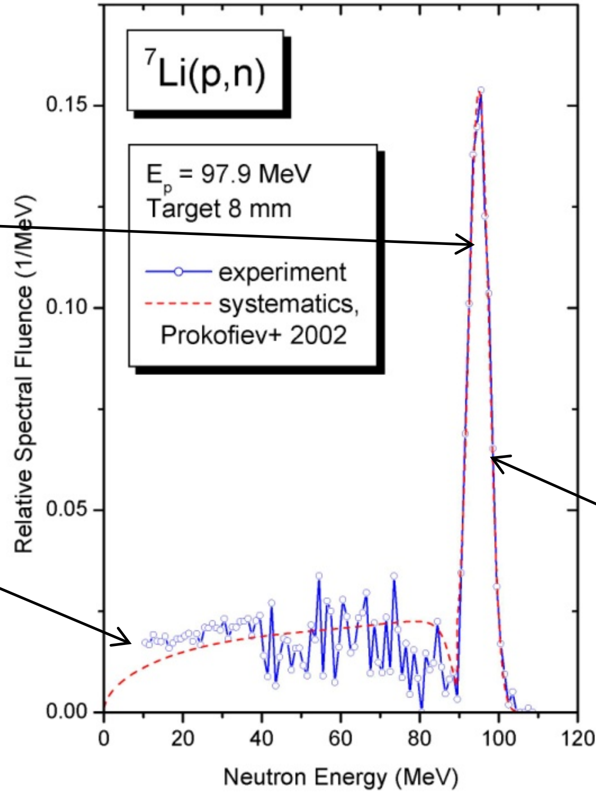
Using H(n,p) at a neutron beam facility

Experimental “raw” data:

Method: Protons from H(n,p) are detected at a specific scattering angle (here 20 degrees) → the neutron energy follows from kinematics.
Neutron TOF serves as a check of kinematics and background reduction.



Repetition rate from cyclotron:
about 58 ns → wrap around



Derived neutron energy spectrum

Note: H(n,p)
Cross section
changes with energy…

Width
dependent
on Li target
thickness
and limited
exper. res.

Figures: S. Pomp et al., AIP Conf. Proc. 769 (2005) 780

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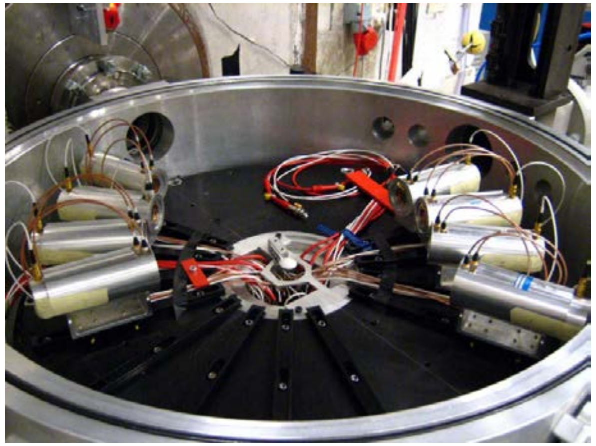
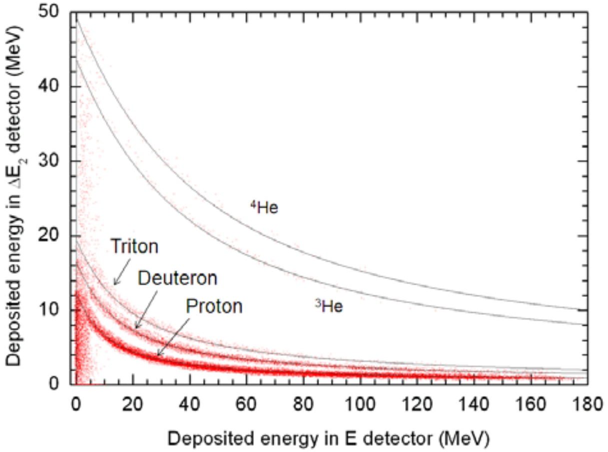
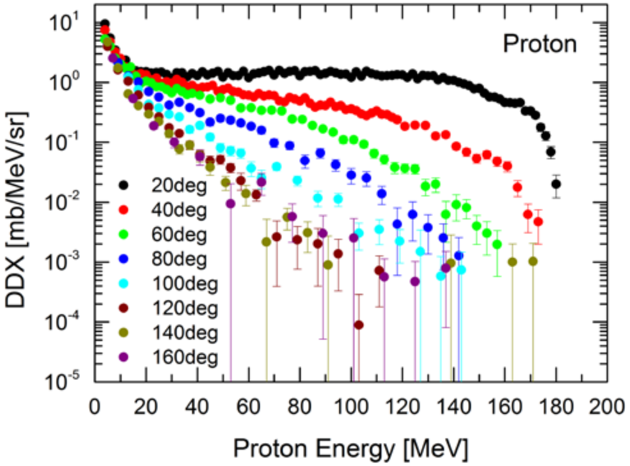
Normalization of experimental data - Example



Instrument (Medley) for measuring neutron-induced light-ion production



Experimental data in one of the detector telescopes (ΔE-E plot)



Published cross section data

$$\boxed{\sigma = \frac{\text{number of reactions per unit time}}{\text{beam particles per unit time and area x scattering centres}}}$$

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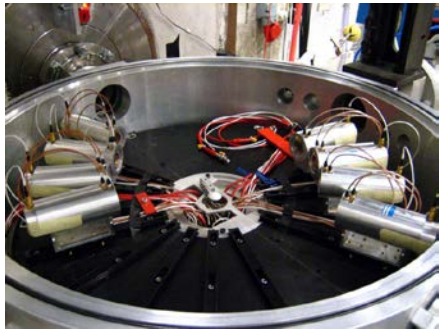
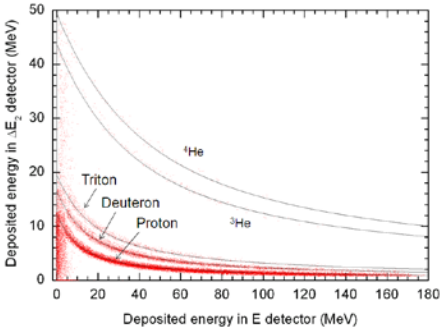
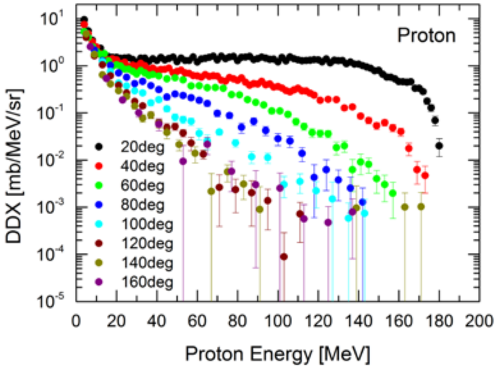
Normalization of experimental data - Example







$$\sigma = \frac{\text{number of reactions per unit time}}{\text{beam particles per unit time and area x scattering centres}}$$

Double-differential cross section measured relative H(n,p) standard using CH_2 target

Neutron "monitor"

Relative neutron flux

Detection efficiency (of the CsI scintillator)

$$\frac{d^2\sigma(\theta,E)}{dEd\Omega} = \frac{Y_{\text{target}}(\theta,E)}{\boxed{Y_H}}\boxed{\frac{N_H}{N_{\text{target}}}}\boxed{\frac{\Phi_{CH_2}}{\Phi_{\text{target}}}}\boxed{\frac{\Omega_{CH_2}}{\Omega_{\text{target}}}}\frac{d\sigma_H}{d\Omega}\boxed{\frac{f_{CH_2}(E)}{f_{\text{target}}(E)}}\frac{1}{\Delta E}$$

CH_2 ⟶ No. of recoil protons

No. of target atoms

Solid angle

H(n,p) cross section

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Beam monitors (measure relative neutron flux)

Primary beam (indirect monitoring)

- e.g. Faraday cup in beam dump at QMN facilities

Neutron beam (direct monitoring, using neutron-induced reactions)

- Fission chambers
- Thin-film breakdown counters (TFBC)

Reference measurements during experiment

- e.g. simultaneous exposure of standard sample
- Usage of standard reaction of same type:

Reaction under study	**^{52}Cr(n,p)**	**^{239}Pu(n,f)**	**^{nat}W(n,f)**
Recommended monitor reaction	H(n,p)	^{235}U(n,f)	^{209}Bi(n,f)

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How to choose the right facility for an experiment?

Critical parameters:

- Energy and energy range
- Flux
- Size of beam spot
- Available space
- Structure of beam (temporal, energy resolution, …)
  - Need for beam kicker?
- Background situation and presence of other particles in beam

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How to choose the right facility for an experiment?

Technical limitations:

- Sufficient beam intensity? Amount of beam time needed?
- Enough available space?
- Can you obtain the necessary target?

Organisational limitations:

- Different priorities at the respective organization
- Target material or quantity not allowed by facility
- Limited access

Other limitations:

- Economical (cost of beam time)
- Cultural and language

**Contact facility in due time
if you plan for an experiment!**

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Facilities – Some resources

Online and interactive:

- **IAEA Accelerator Knowledge Portal:** https://nucleus.iaea.org/sites/accelerators
- **Research Reactor Database (RRDB):** https://nucleus.iaea.org/rrdb

Print:

- IAEA-TECDOC-1743 "*Compendium of Neutron Beam Facilities for High Precision Nuclear Data Measurements*" (Vienna 2014) https://www-pub.iaea.org/MTCD/Publications/PDF/TE-1743_web.pdf
- EURADOS Report 2013-02 "*High-energy quasi-monoenergetic neutron fields: existing facilities and future needs*" (Braunschweig 2013) https://eurados.sckcen.be/sites/eurados/files/uploads/Publications/25_EURADOSReport201302_complete.pdf
- OECD NEA "*Research and Test Facilities Required in Nuclear Science and Technology*" (OECD 2009) https://www.oecd-nea.org/jcms/pl_14330

Plus the papers mentioned in the slides and references therein.

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