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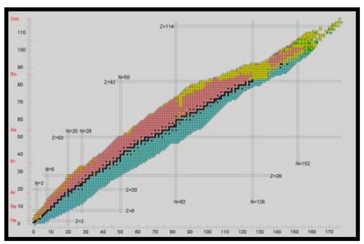
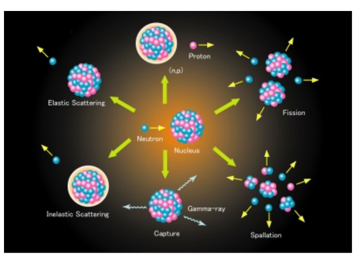
Experimental facilities and techniques





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What we are up to:

Detector

Sample

Some “source” where something is happening that you want to find out more about

In principle …

Sample

Detector arrangement

↓

Electronics and DAQ

In principle …

Detector arrangement

Electronics and DAQ

Analysis

Results

Fulfilling some needs

(the original reason …)

Sample

What then is “the source”?

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

- ^{252}Cf(SF),
- an environmental sample, or
- something that has been or is irradiated

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

In the latter cases you need some “**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

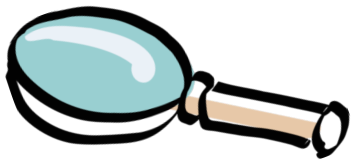
↓

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 …)

Time to narrow down:

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

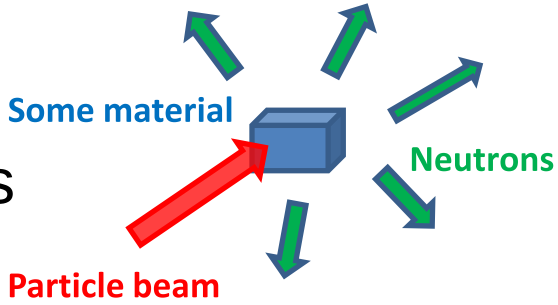
In many cases, especially related to nuclear data for application, this means a neutron field.

(we´ll talk about “nuclear data” later today …)

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

Outline

- Introduction (just done that)
- Overview on neutron sources and beams



- Characterization, monitoring, and general remarks on facilities


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

- Hitchhiker's guide to neutrons

Some resources on facilities

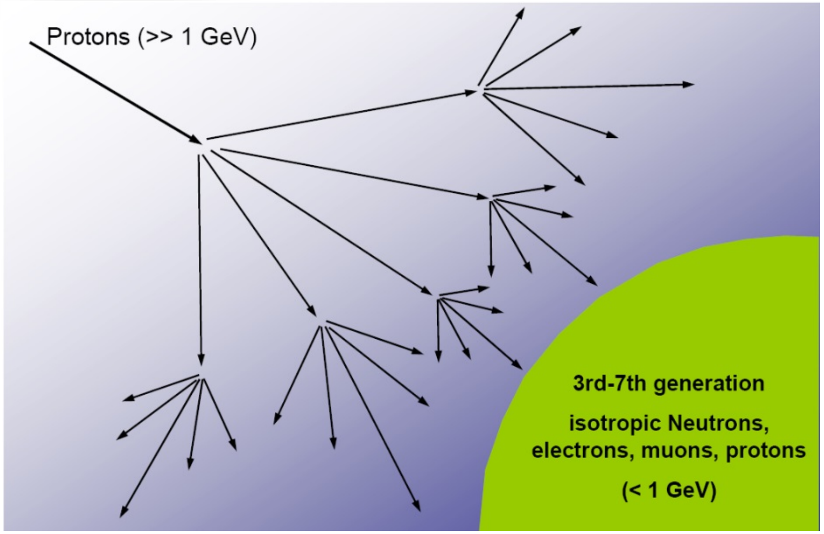
- IAEA-TECDOC-1743 "*Compendium of Neutron Beam Facilities for High Precision Nuclear Data Measurements*" (Vienna 2014)
- EURADOS Report 2013-02 "*High-energy quasi-monoenergetic neutron fields: existing facilities and future needs*" (Braunschweig 2013)
- OECD NEA "*Research and Test Facilities Required in Nuclear Science and Technology*" (OECD 2009)
- IUPAP Report 41 "*Research Facilities in Nuclear Physics*" (IUPAP 2006)

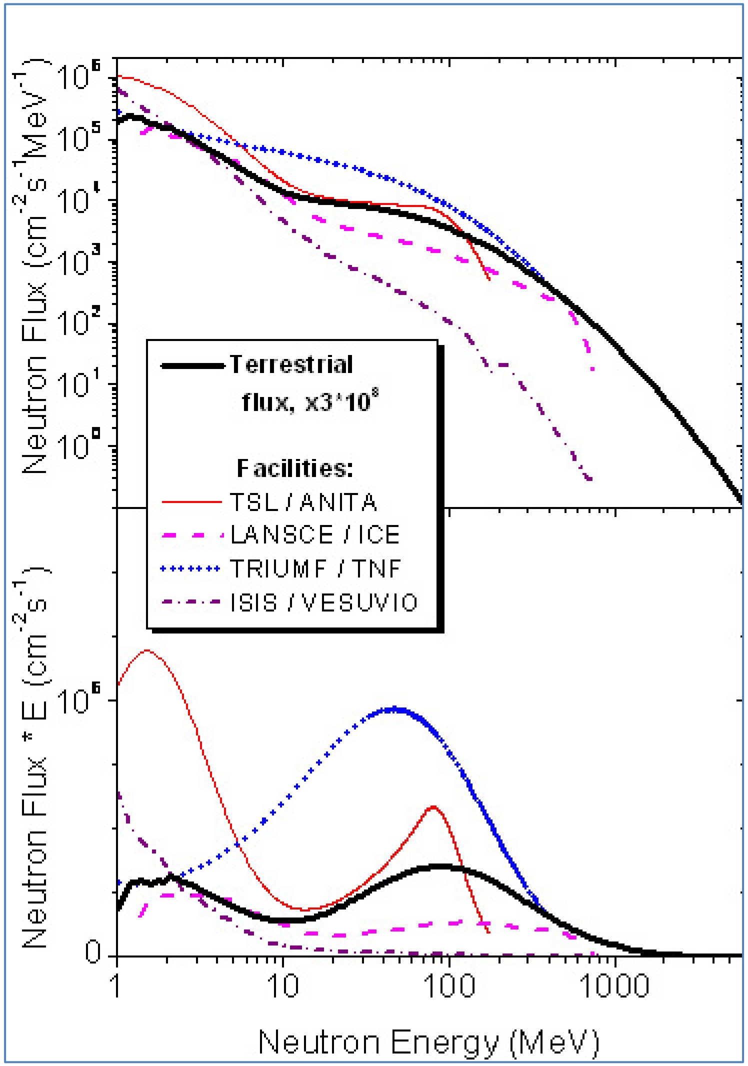
There is also a group on the Linkedin social network:
"Neutron beam facilities and users"
with over 500 members (research and industry)

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 used at reactors (inside and extracted from the core)
  - And neutrons are produced from ion or electron beams, e.g., at accelerator *facilities* (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



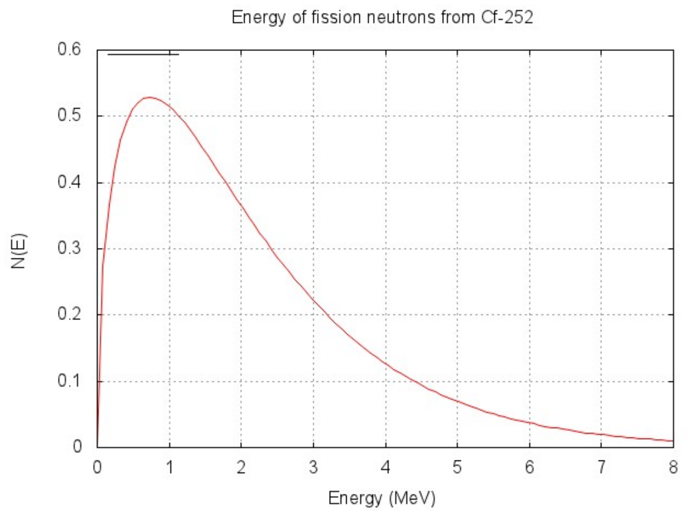


- Produced in the atmosphere by cosmics
- Dose to humans and SEE in electronics.
- High altitude facilities (e.g. Zugspitze) primarily monitor and measure the neutron spectrum
- Several accelerator-based facilities mimic atmospheric neutrons for accelerated testing (used by electronics industry)

Neutron sources I

Fission sources: $^{252}Cf(SF)$

- 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 %
  - 2.314×10^6 n/s/mg
  - 4,316 n/s/µCi



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

Neutron sources II

(α,n) sources: e.g. AmBe and PuBe

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

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

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

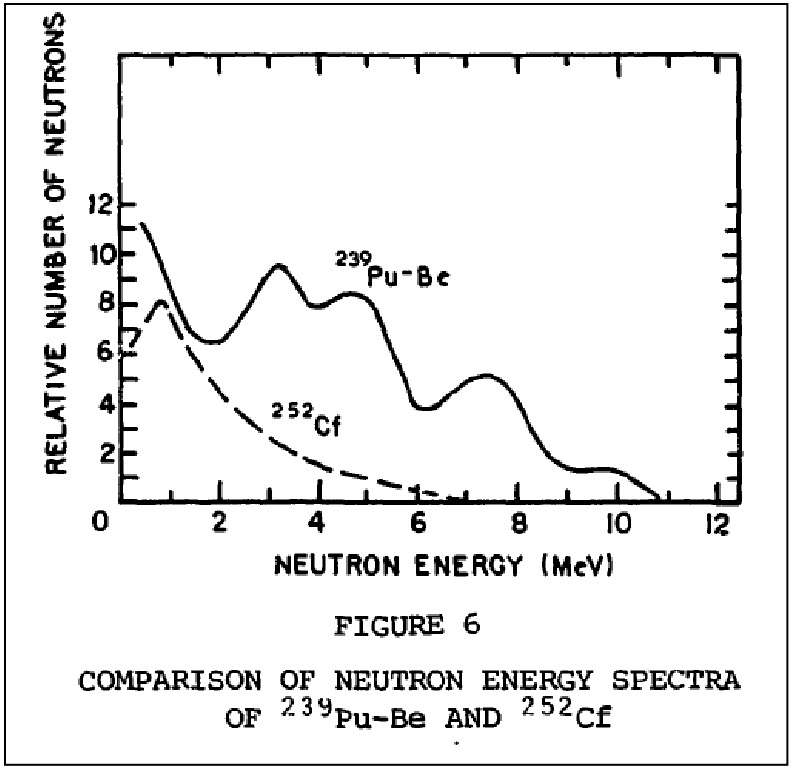


Fig. from “Gamma-ray and neutron soruces” by R.J. Holmes

In general:
neutron sources (Cf252, AmBe…) are used in reference fields.
See e.g. http://www.ptb.de

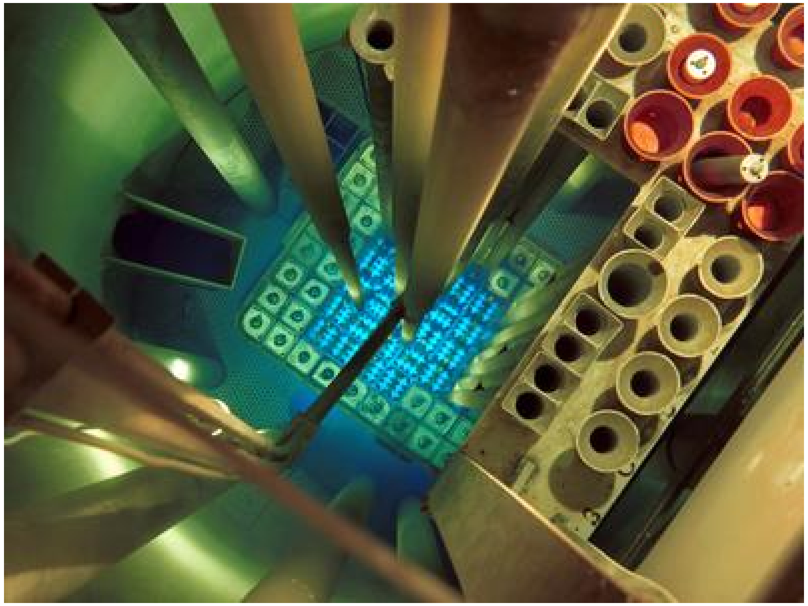
Neutrons from fission reactors

Research reactors can offer pneumatic systems for irradiation purposes.

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

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/research/training-reactor.html

Stationary neutron beam at a reactor: the Budapest research reactor

IAEA-TECDOC-1743 page 4

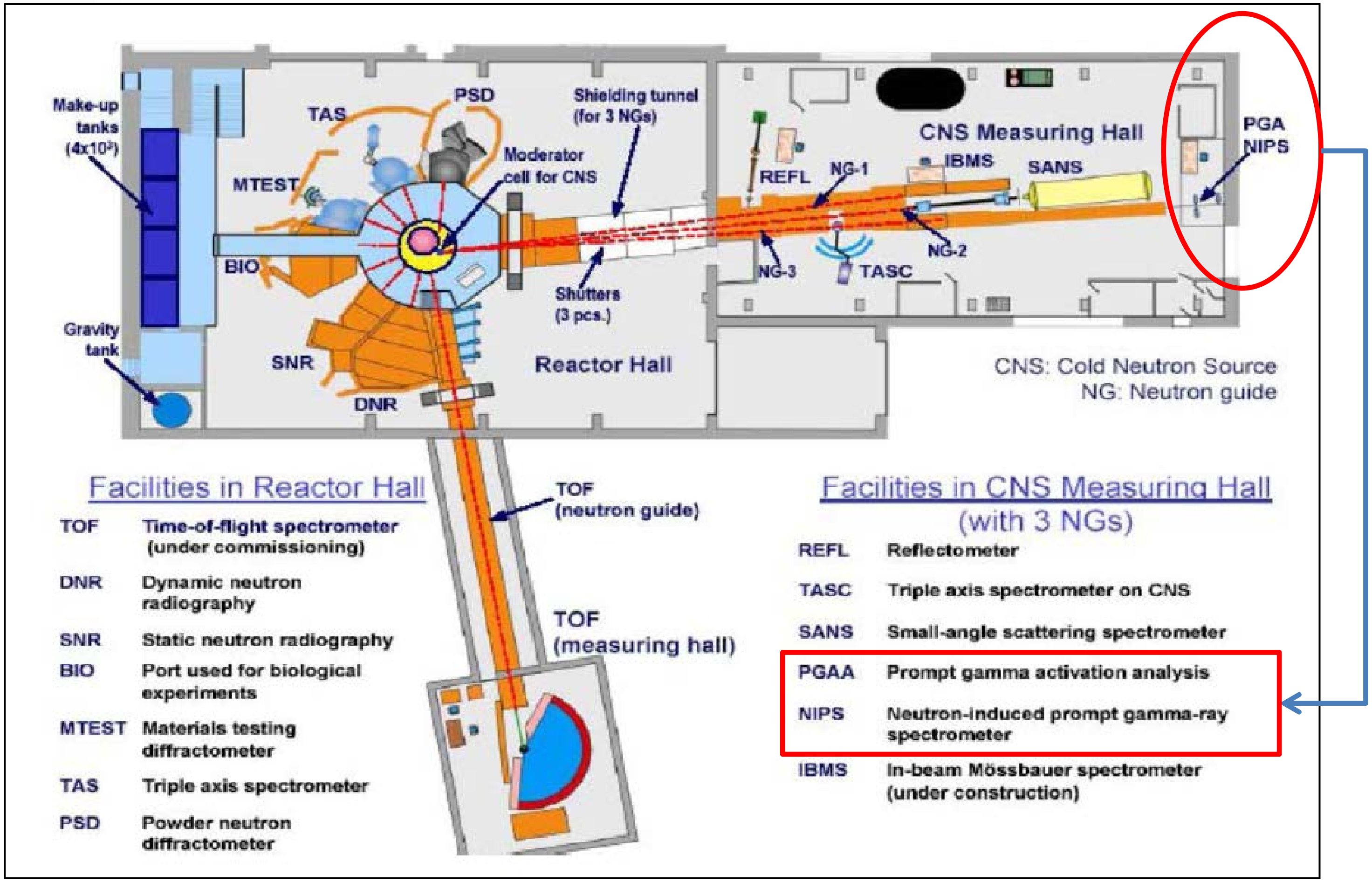


FIG. 1. Schematic drawing of the Budapest Research Reactor Hall; channels noted with PSD and the 3 neutron guides going to the right wall of the reactor hall are connected to tangential beam tubes. All others, drawn with red lines, are radial channels.

Pulsed neutron beam at a reactor: IBR-2 in Dubna

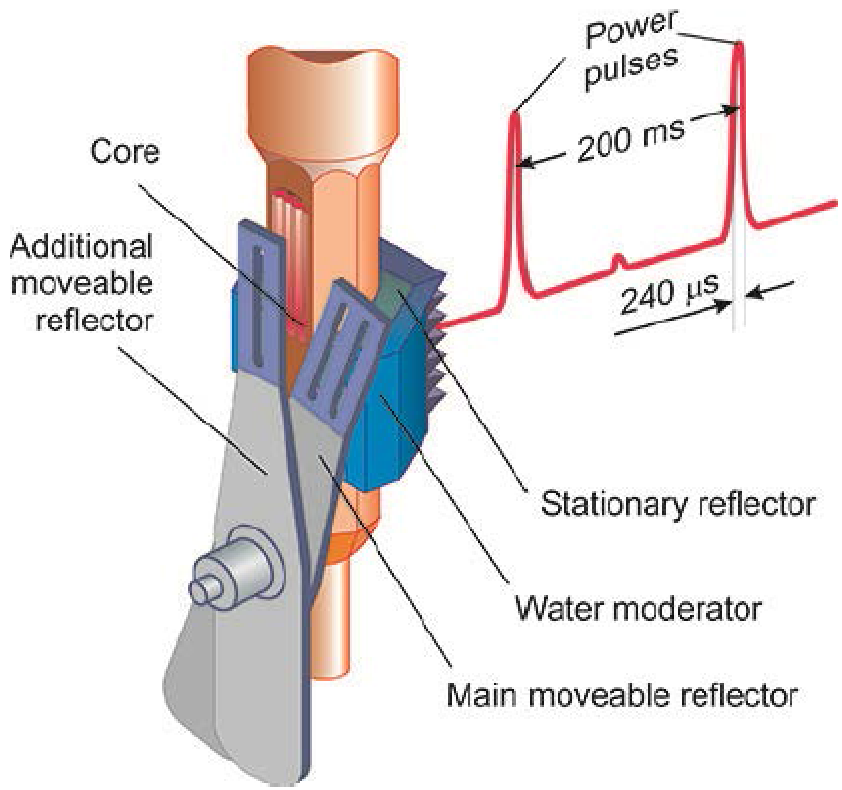


FIG.3. Schematic picture of IBR-2 pulsed reactor [5]

Reactivity modulation by two movable reflectors.

Reflectors rotate at different velocity. When they coincide near the reactor core a power pulse is generated.

Burst maximum: 10^{16} $cm^{-2}s^{-1}$

Using accelerators

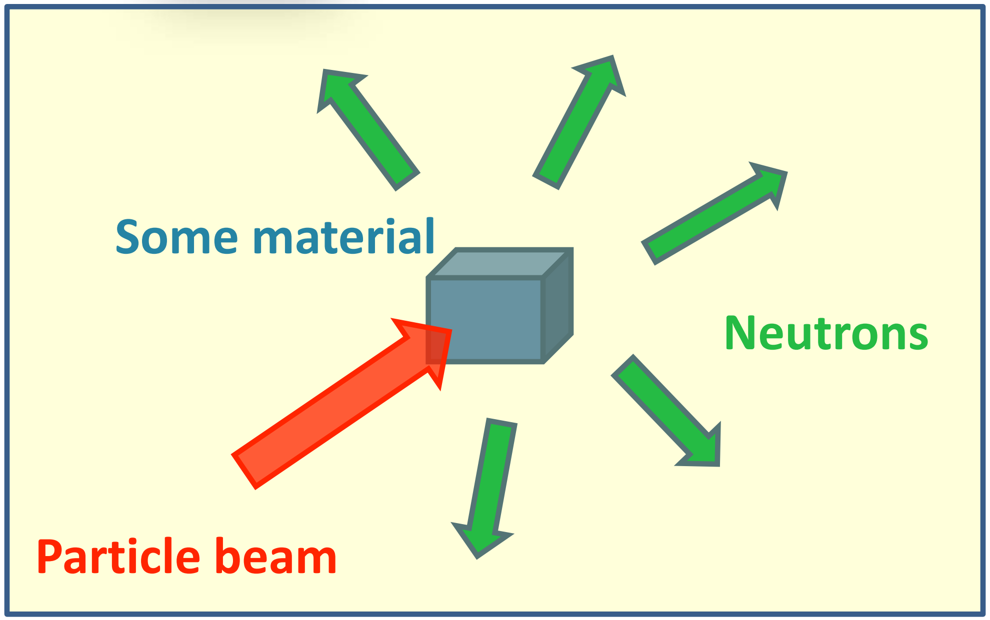
Electrostatic accelerators (Van de Graaff, Tandem)
Cyclotrons (e.g. TSL in Sweden)
Linear accelerators (e.g. the future NFS at GANIL)
Synchrotrons (e.g. PS at CERN)

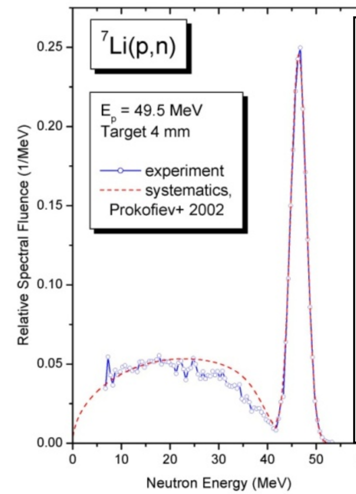
One of many uses of a Van de Graaff …

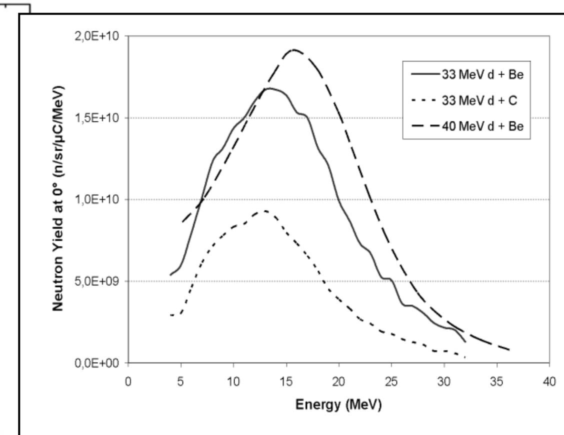
Different combinations of
primary particles (ions – p,d,α, …– and electrons) + suitable **target**

A wide range of different neutron beams …

Getting neutrons is easy ...





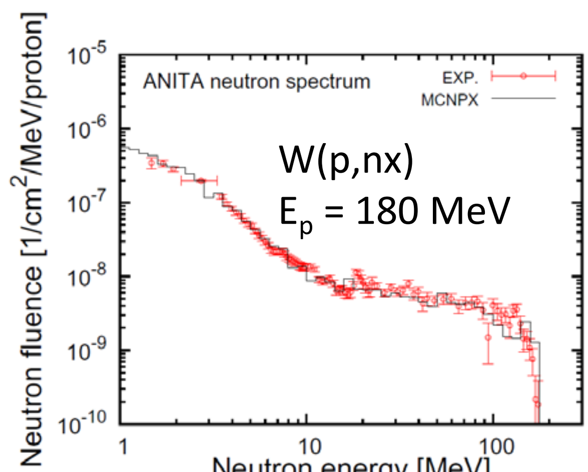


(Quasi-)monoenergetic beams
White beams + TOF

→ "PHYSICS"

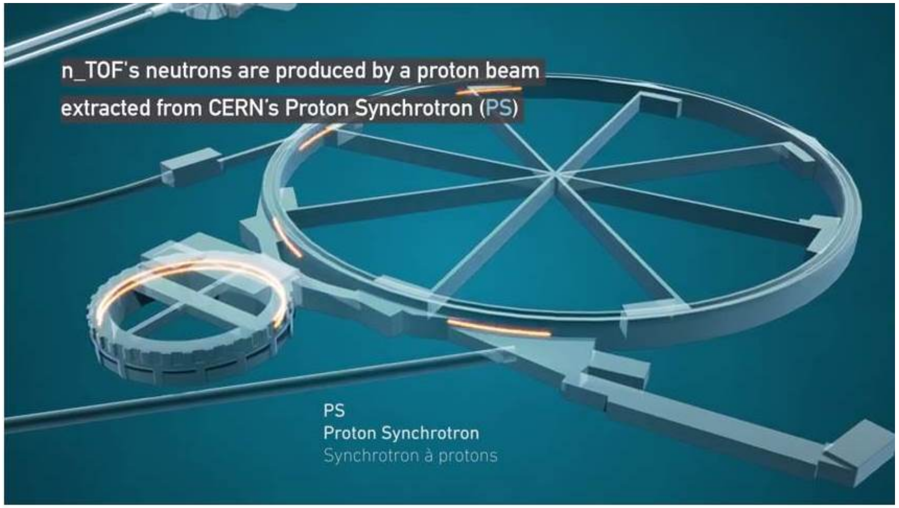
Neutron fields simulate
- Cosmic ray neutrons
- Reactor environment
- ...

→ "APPLICATIONS"



A movie to relax a bit …

… and get an impression of n_TOF:
https://www.youtube.com/watch?v=atJNBaDUmIU



The Neutron Time-of-Flight Facility (n_TOF) at CERN

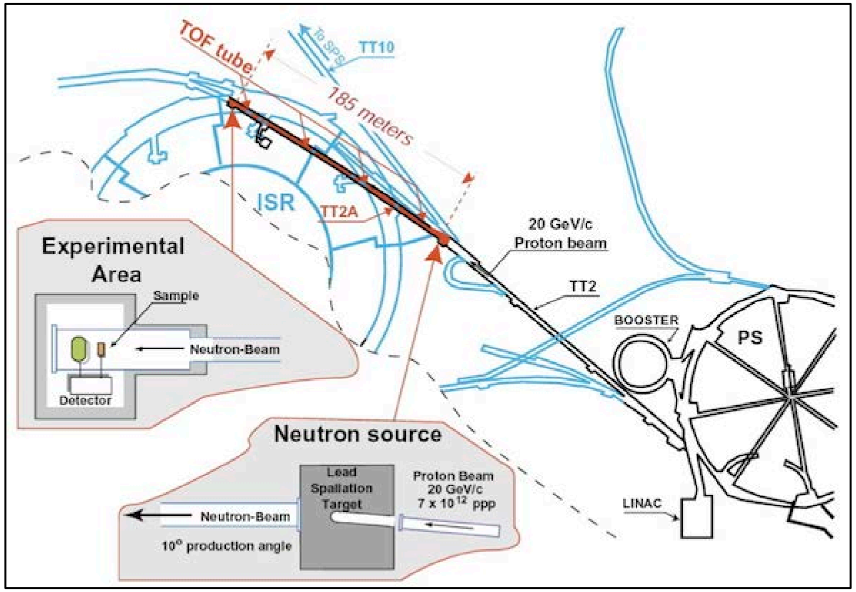
Other movies that might interest you:

- Short presentation of the ISIS facility
  https://www.isis.stfc.ac.uk/Pages/A-video-tour-of-the-ISIS-facility.aspx
- Talk on NFS https://media.medfarm.uu.se/play/video/5975

White beams

Proton beams:

- 20 GeV on Pb (n_TOF@CERN)
- 800 MeV on W (WNR@LANL)
- 180 MeV on W (ANITA@TSL)



Deuteron beam:

- 40 MeV on Be (NFS@GANIL)

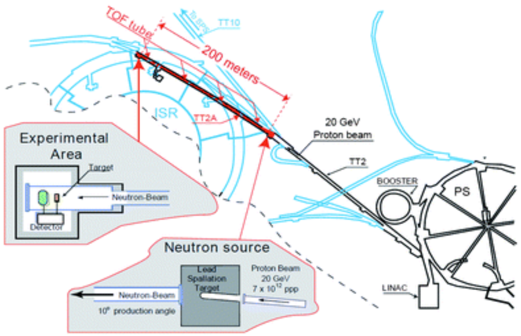
Electrons beams:

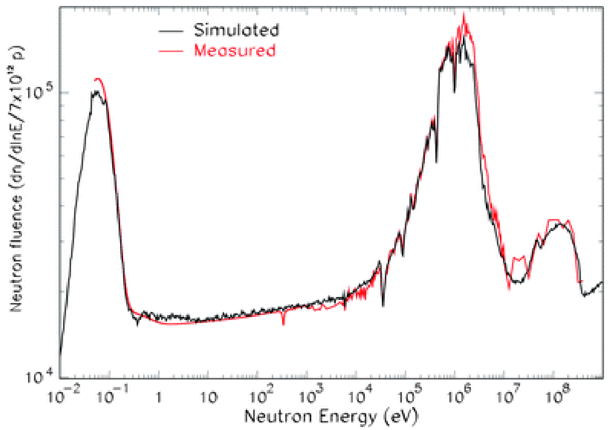
- 100 MeV on U (Gelina@JRC)
- 40 MeV on Pb (nELBE@HZR Dresden)

Usage of a pulsed beam allows for time-of-flight method to determine the neutron energy on an event-by-event basis (see lecture by Peter Schillebeeckx).

"White" neutron sources

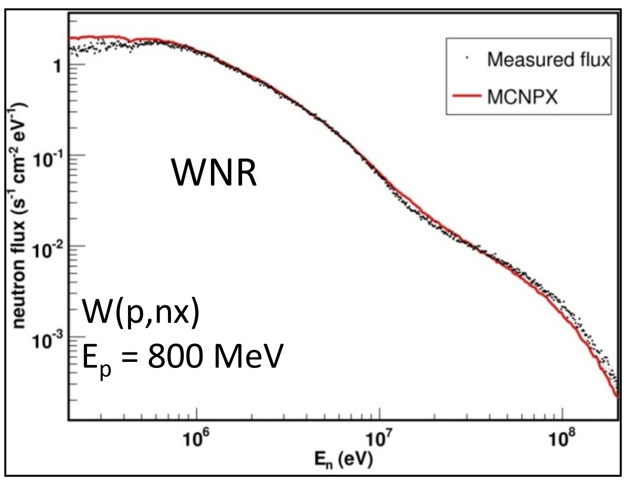
n_TOF

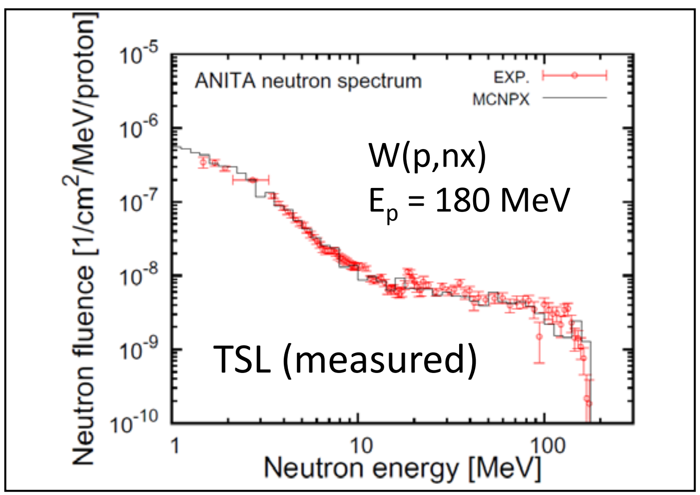




Lethargy representation shows three "peaks":

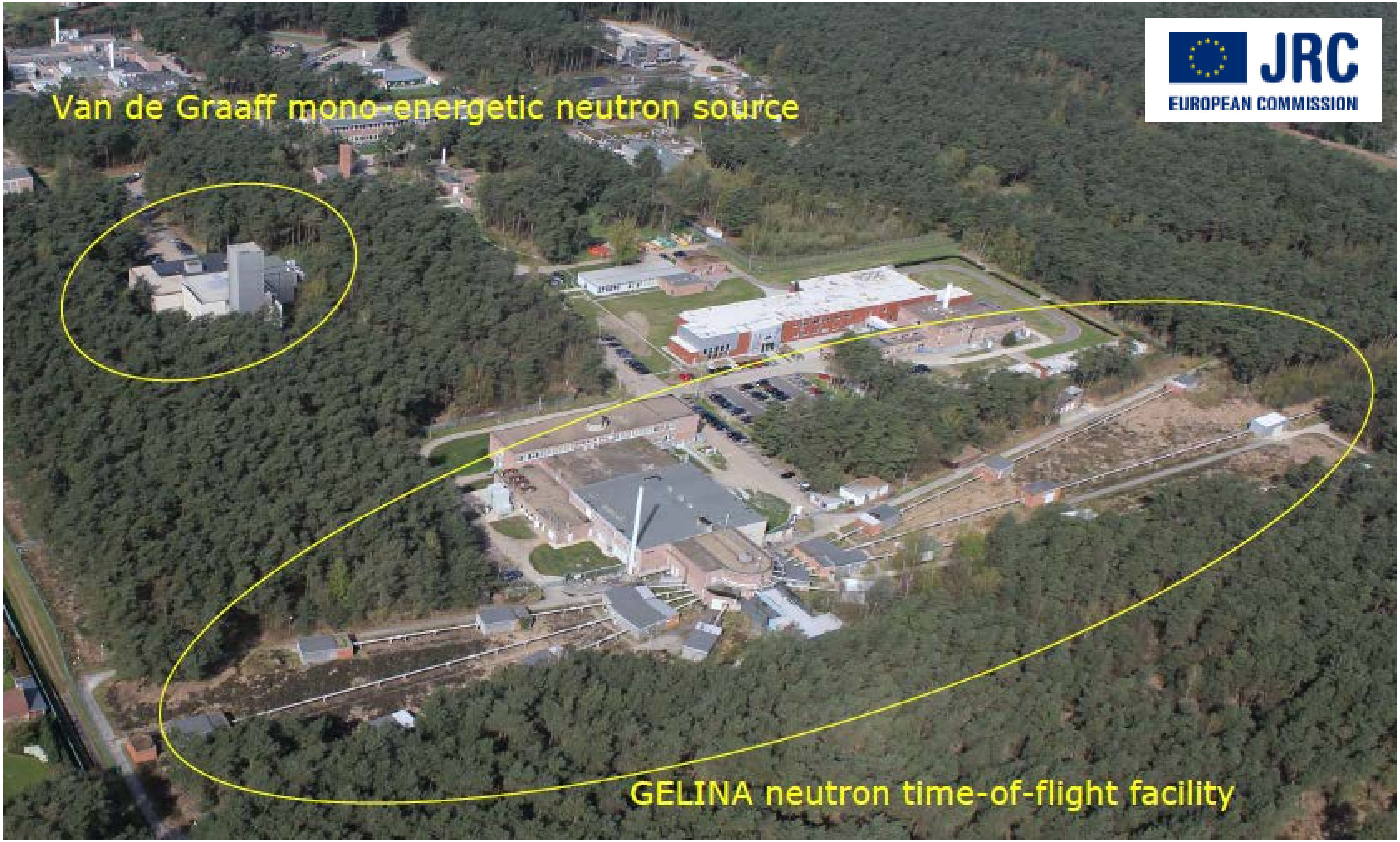
- Spallation (high E)
- Evaporation (medium E)
- Thermal (low E)





Atmospheric-like spectra

A view of JRC with two neutron facilities



Mono-energetic neutrons

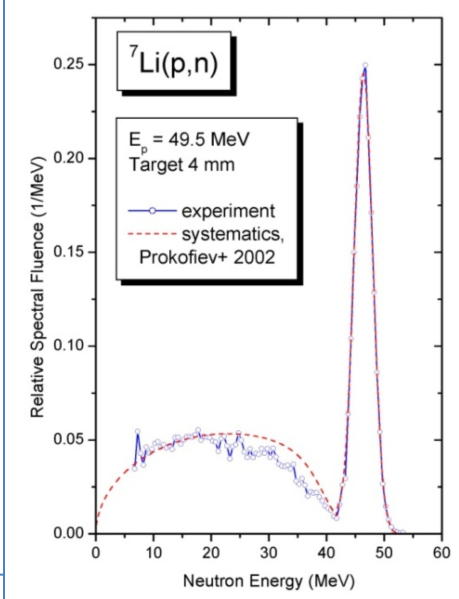
Other than 0 deg for some purposes … (use kinematics!)

Neutron “beam” normally used **0 deg** 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 deg

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.



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**

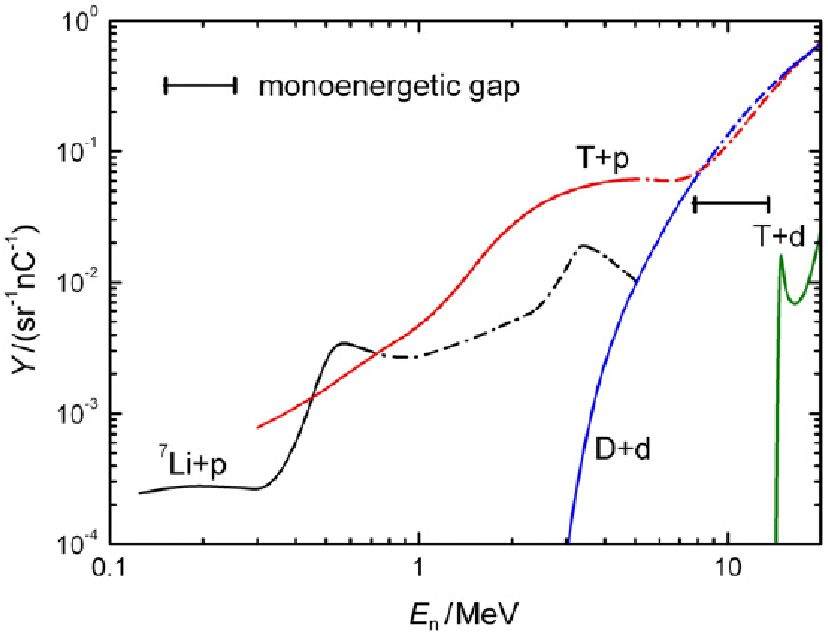


Figure 1. Neutron emission yield Y at 0° for the four most important neutron-producing reactions as a function of the neutron energy E_n. The dashed line indicates the energy range where the reactions are accompanied by break-up reactions (T(p, n)^{3}He, D(d, n)^{3}He) or neutron groups from excited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

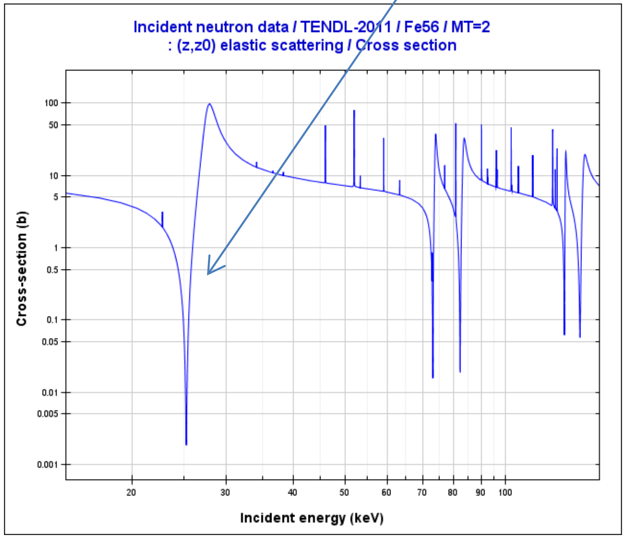
R. Nolte et al., *Metrologia* **48** (2011) S263-S273

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 for
- filtered beams, e.g., using ^{56}Fe (24 keV)



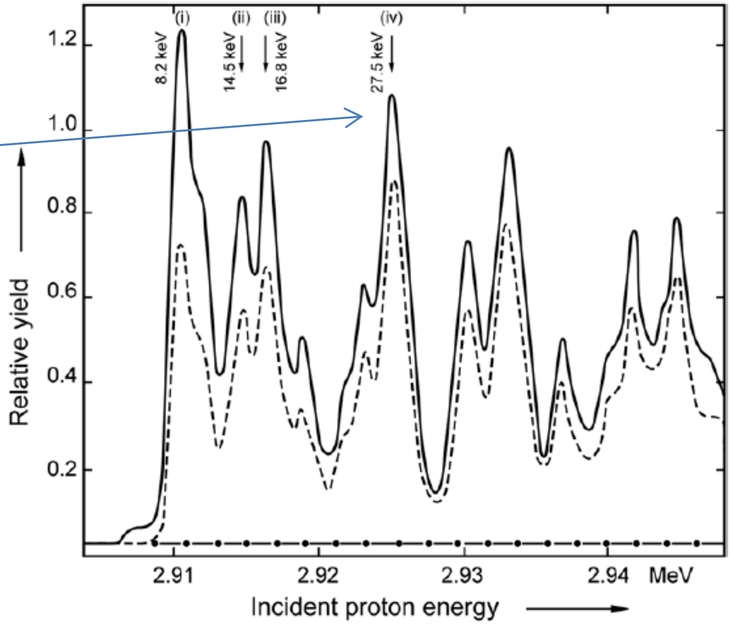
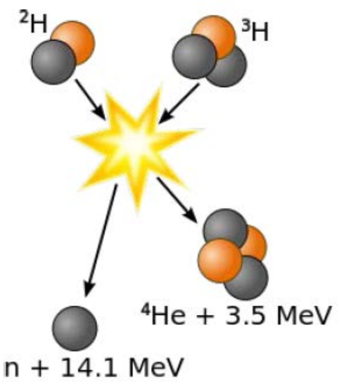


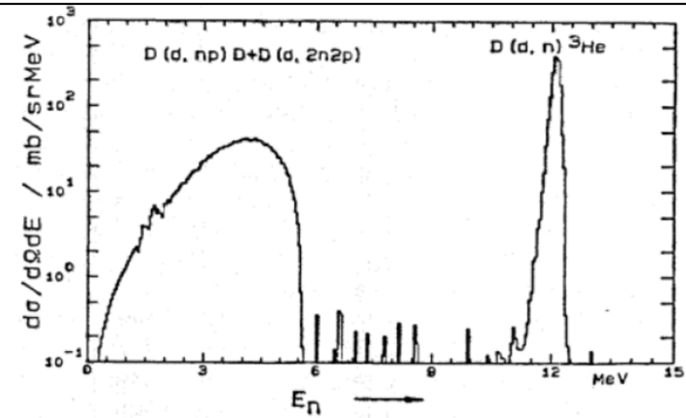
Figure 4. Excitation function for the reaction $^{45}Sc(p,n)^{45}Ti$ measured using a long counter and a metallic scandium target with an areal mass corresponding to a proton energy loss of about 300 eV. The solid and dashed lines show the excitation functions at neutron emission angles of 0° and 60°,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

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

DD and DT



- Very commonly used to produce 2.5 MeV and 14.1 MeV fields
- Possible to use as small portable (sealed tube) device
- Normally 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 commercially avail.
- 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"

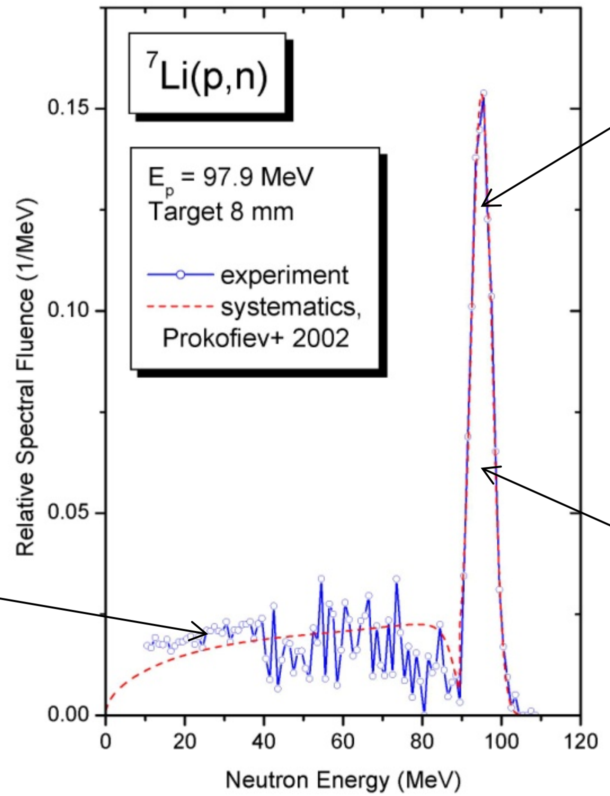
Quasi-monoenergetic beams

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



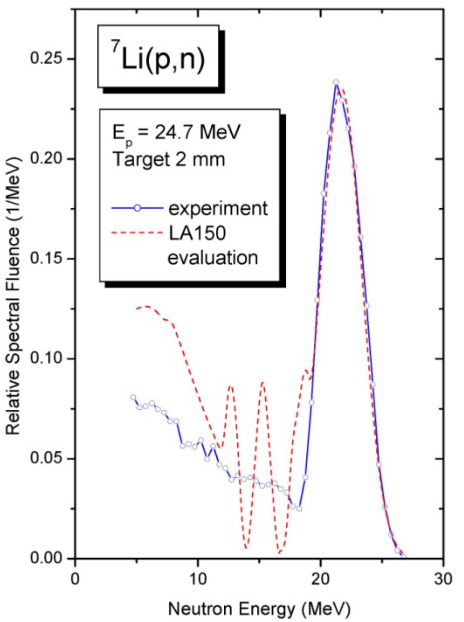
Break-up continuum
^{7}Li(p,nx)

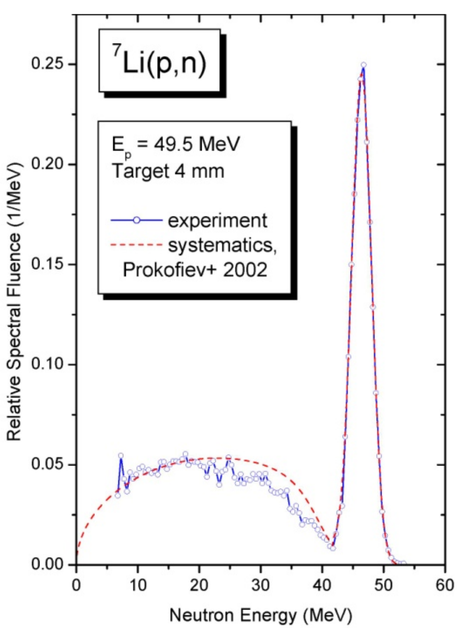
can be suppressed
by TOF techniques
in pulsed beam

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

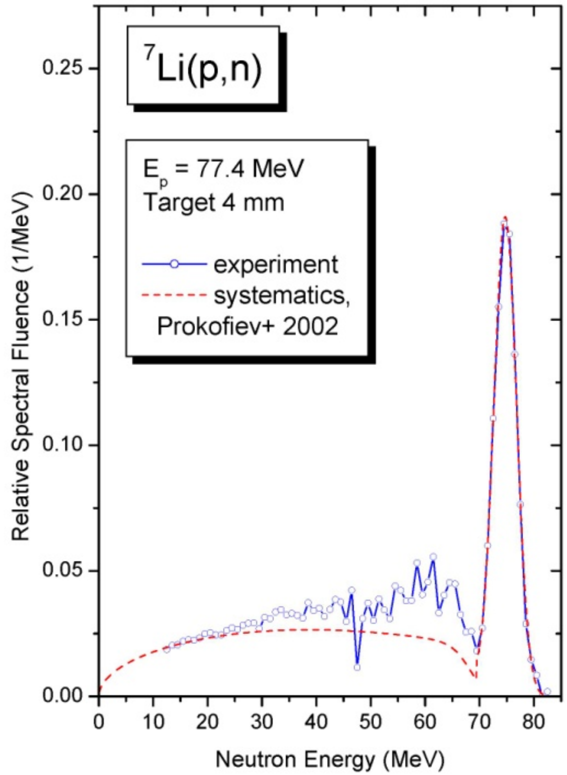
Dashed line: systematics by Prokofiev et al. J Nucl Sci Tech **39** (2002) 112.

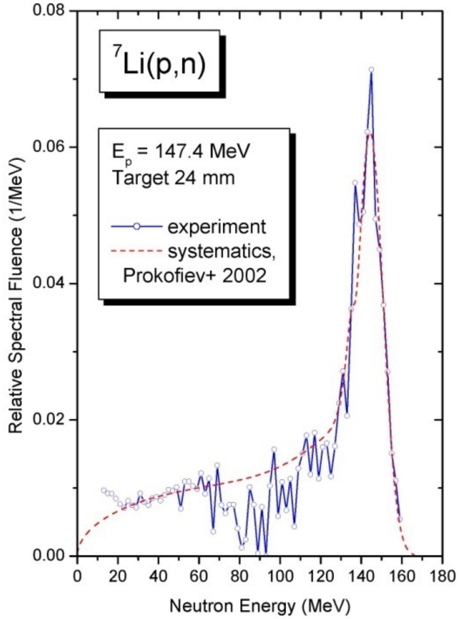
neutron spectra at TSL as measured from proton-recoil with the MEDLEY setup

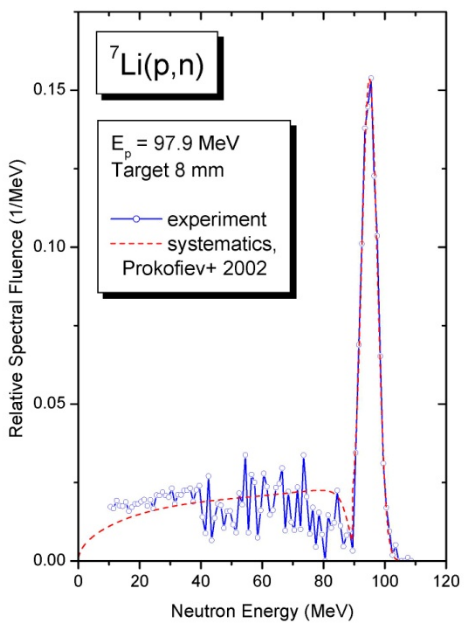




Note: different Li-target Thicknesses have been used







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

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Characterization and monitoring

For a successful measurement you need to know

- the neutron energy spectrum to which the sample has been exposed,
- 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 often 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) .

How to count neutrons?

Problem:

- charged particles ionize → "100 %" detection efficiency → just count
- neutrons: only nuclear interaction → << 100 % efficiency
- catch 22: to know the efficiency you need to know the cross section
  and for that you need to know the number of incoming neutrons …

Way out?

1 – Tagging

Example: $D(d,n)^3He$ — 2-body reaction, one final state
detect ^3He → neutron "tagged"
low intensity but now known

2 – Use total/reaction/elastic cross section obtained from attenuation measurements

Example: total (n,p) cross section well known (1%)
measure (n,p) angular distribution and normalize to total cross section

3 – Theoretical relations

Example: $np \rightarrow d\pi^0$ is half of $pp \rightarrow d\pi^+$ which is known
→ measure relative to $np \rightarrow d\pi^0$

Define set of reference cross sections and measure relative to them
(n,p); $^{238}U(n,f)$; …

Neutron detection

(e.g. for monitoring)

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 (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 postive, high Q-values at low energies

<u>Examples:</u>

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

Cross section (efficiency) varies as 1/v for these examples

Neutron energy

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

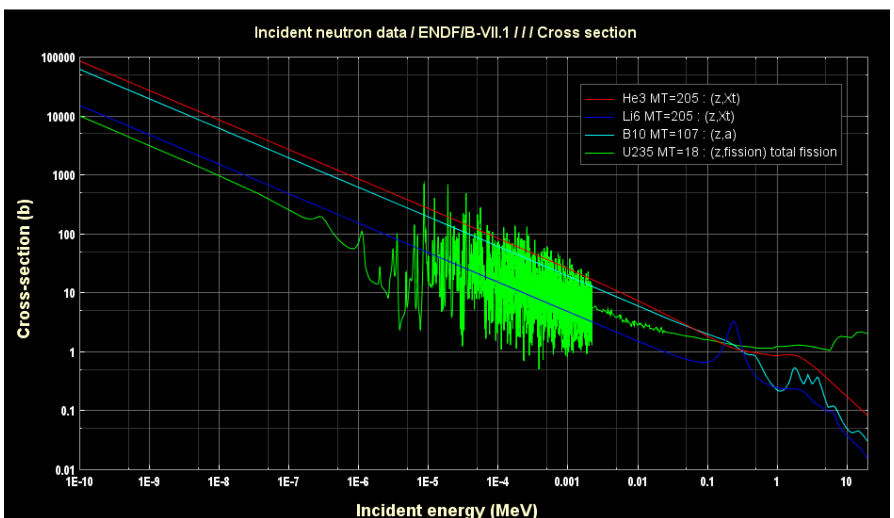
Bonner sphere spectrometers

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

Set of several polyethylene spheres with diameters Typically ranging from 1 to 20 inches.

With known response functions for each sphere spectra can be unfolded from a series of measurements

Active BSS usually use the ^{3}He(n,p)T reaction:



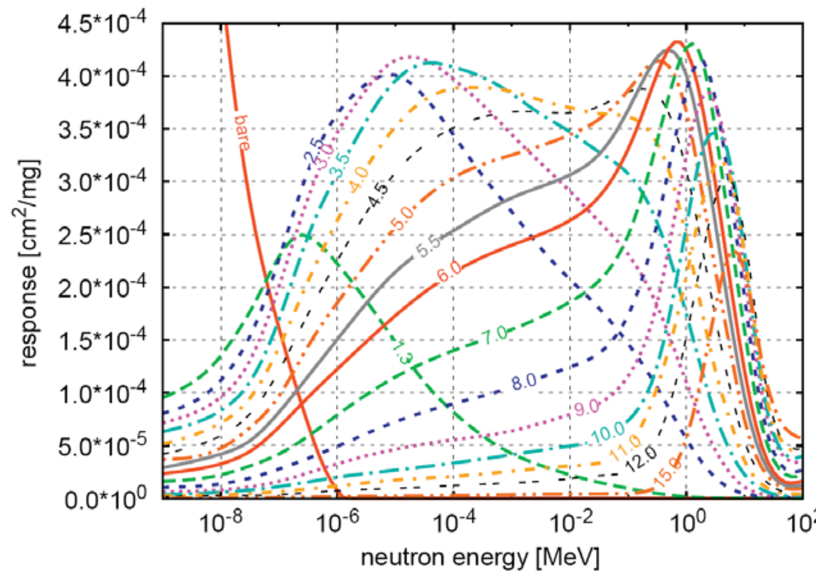


Fig. 7. Response functions of the whole Bonner sphere spectrometer with gold foils inside calculated with GEANT4; sphere size in inch is indicated on each line.

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

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Reference cross sections

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

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

Requirements for standard? Besides very well-known cross section: good experimental reproducibility (example ^{197}Au: just one isotope …)

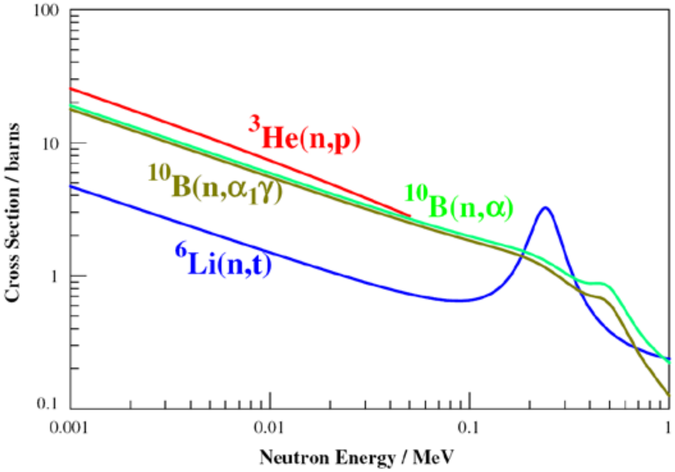

Figure 2. The low neutron energy cross section standards. Data below 1 keV are not shown.

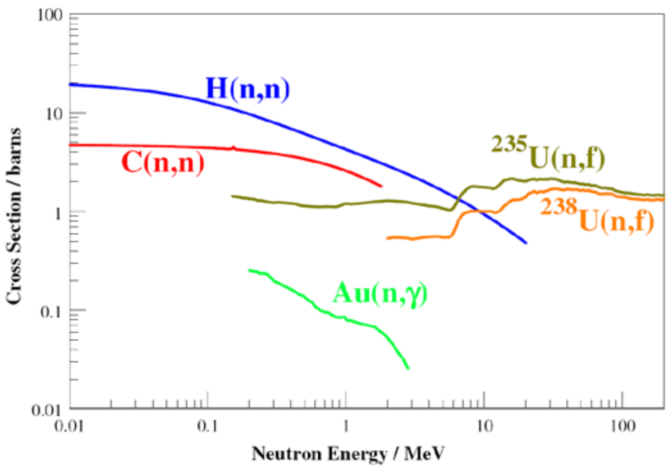

Figure 3. The high-energy neutron cross section standards. Data below 10 keV are not shown.

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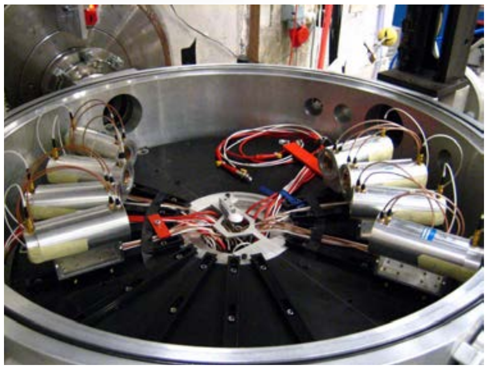
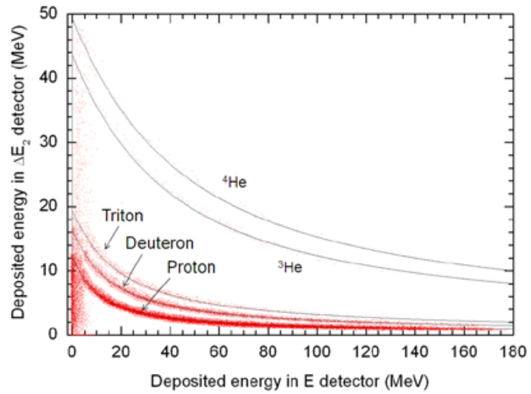
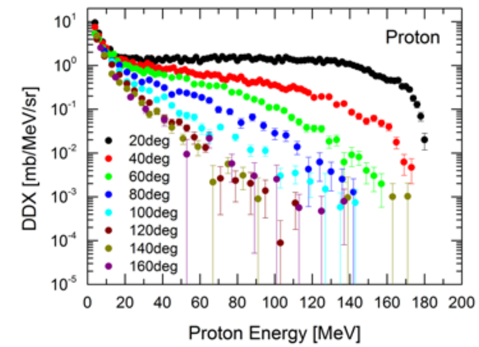
Example: ddx with Medley







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

Neutron “monitor”

Relative neutron flux

Detection efficiency (of the CsI scintillator)

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

CH_2 ⟶ No. of recoil protons

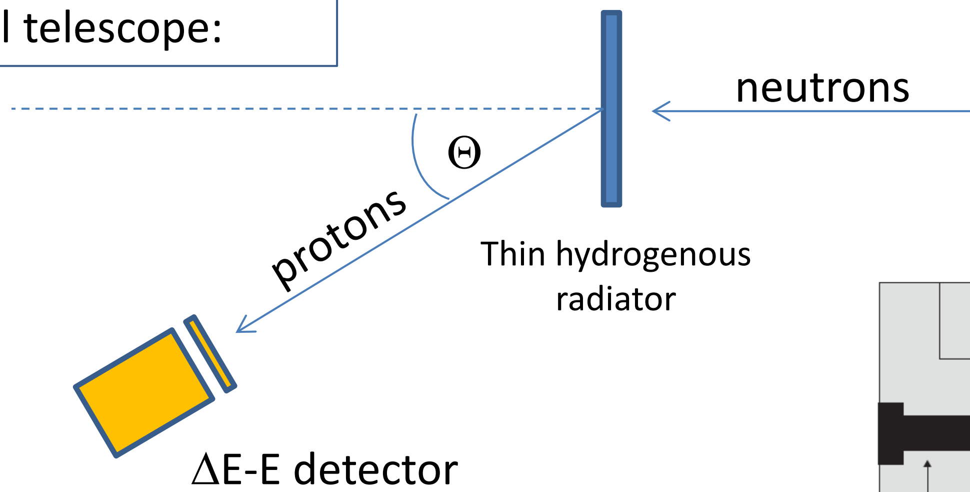
No. of target atoms

Solid angle

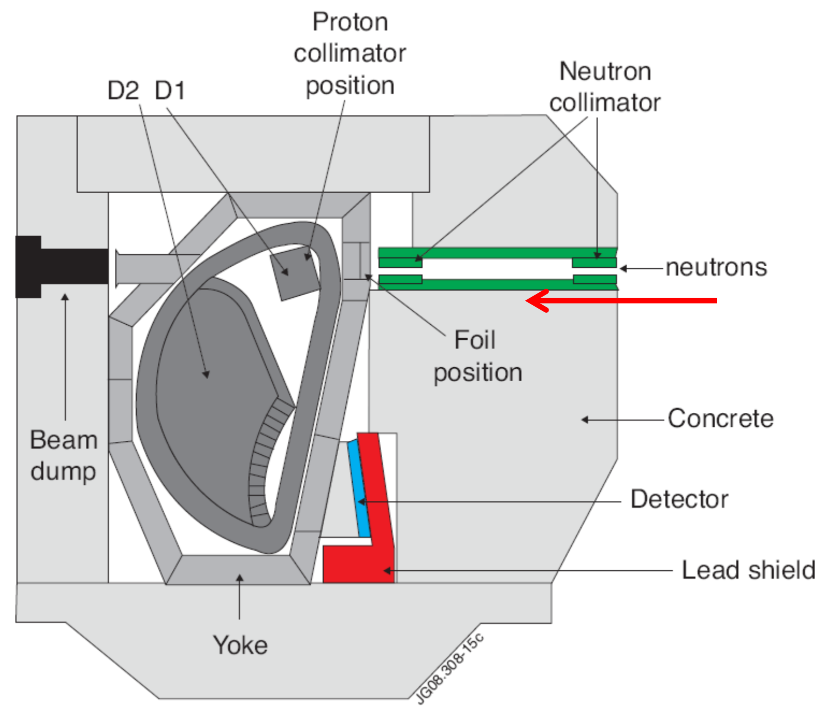
H(n,p) cross section

Using H(n,p) – proton recoil (1)

Principle of a proton recoil telescope:



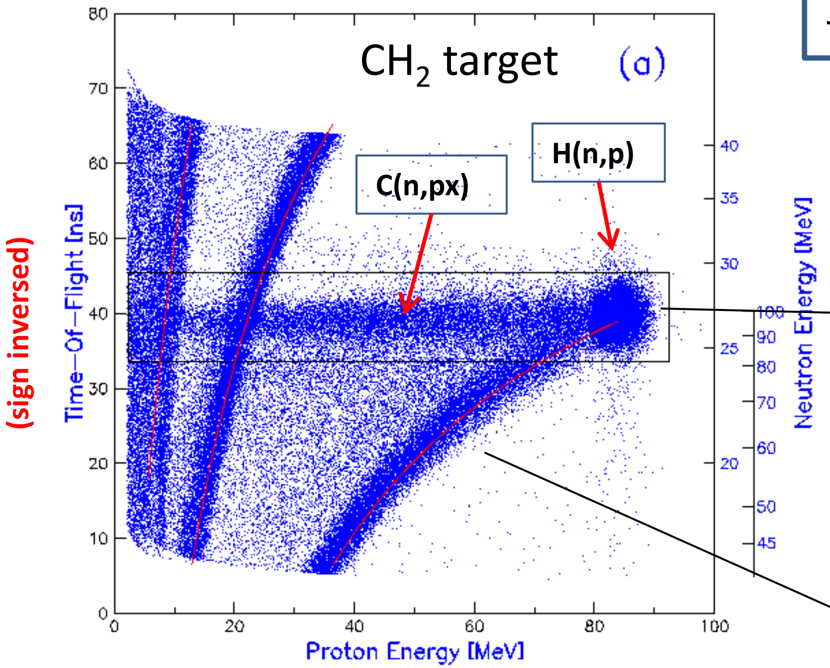
The MPR (Magnetic Proton Recoil) spectrometer at JET:



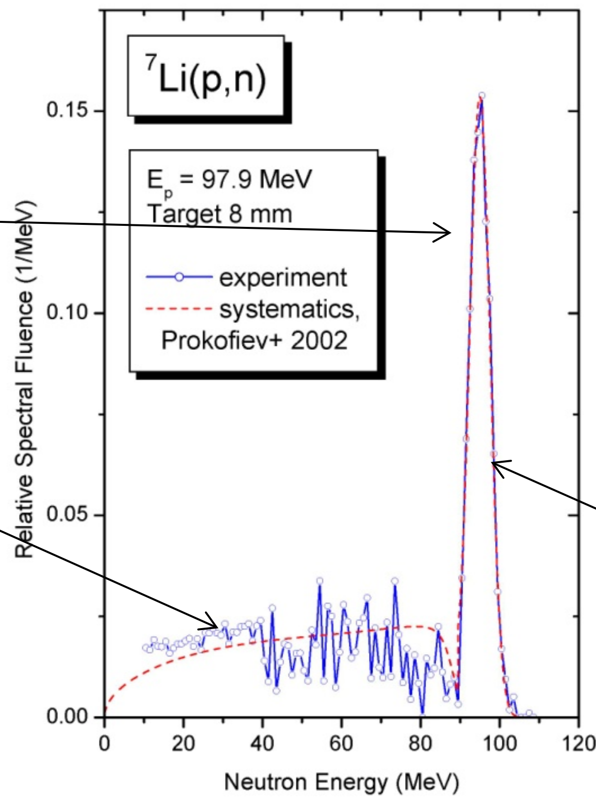
http://www.iop.org/Jet/fulltext/EFDP08052.pdf

Using H(n,p) – proton recoil (2)

Protons from (n,p) are detected at a specific scattering angle (here 20 degrees)
→ the neutron energy follows from kinematics



Repetition rate from cyclotron: about 58 ns → wrap around



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

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

Monitors

- 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?

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?

Technical limitations:

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

See example in lecture on nuclear data measurements

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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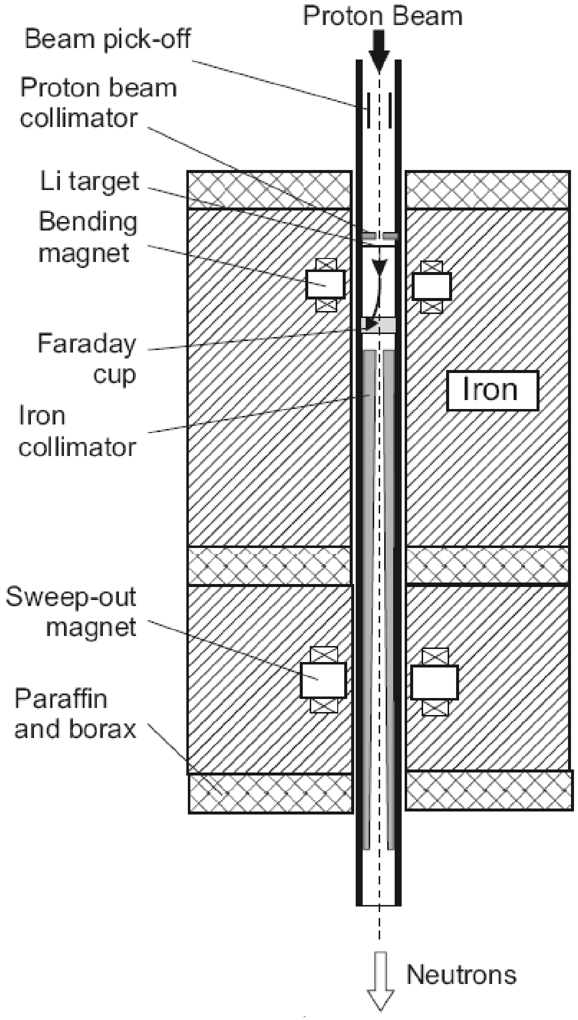
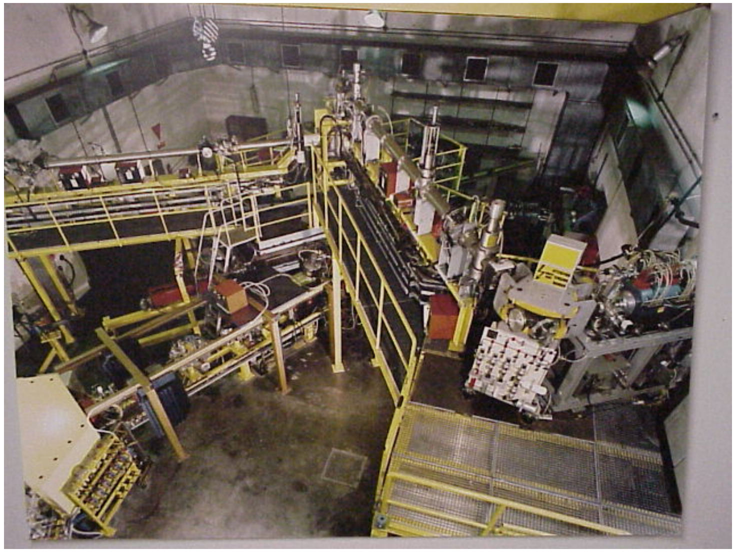
Hitchhiker's guide to neutrons …

Some former and some existing neutron facilities in the world


UCL
(Belgium)

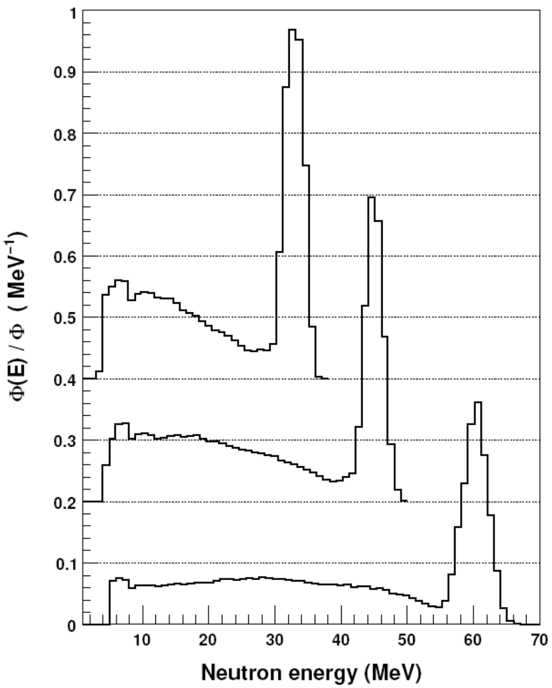
UCL (Belgium)

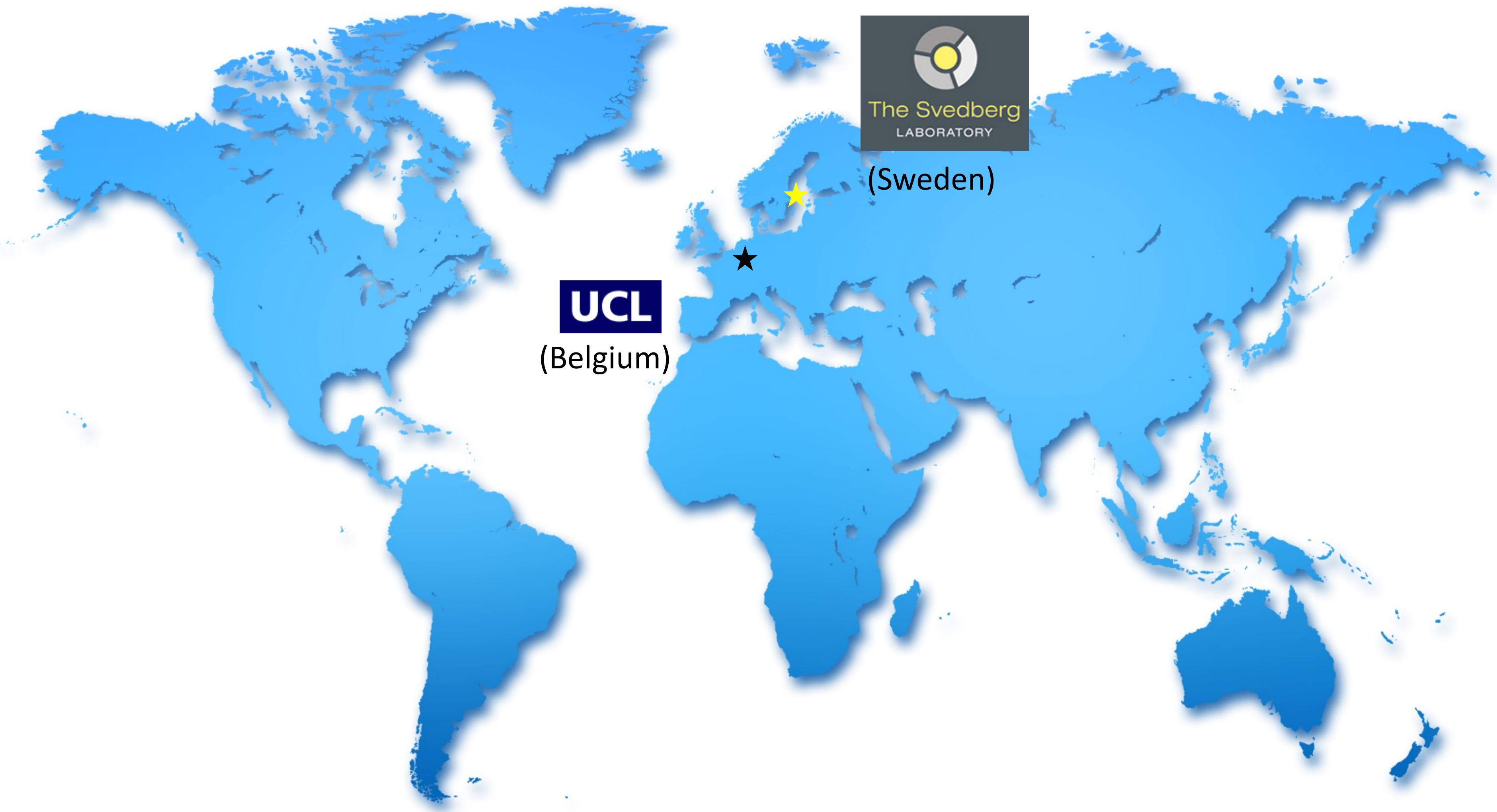




- 25-70 MeV
- pulse selection
- short pulses

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

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(Belgium)

The first neutron beam @ TSL

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

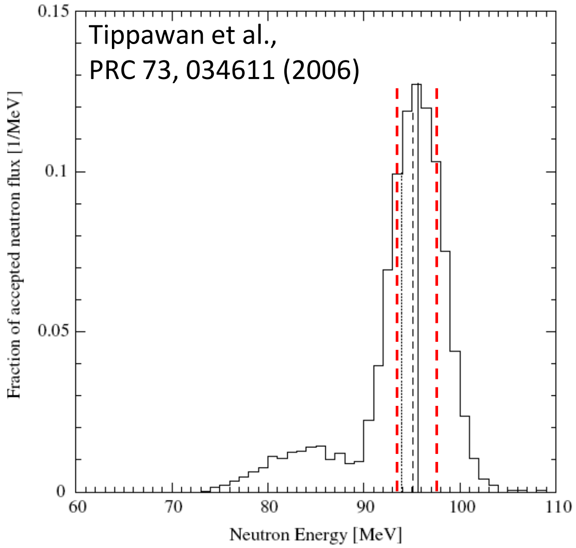
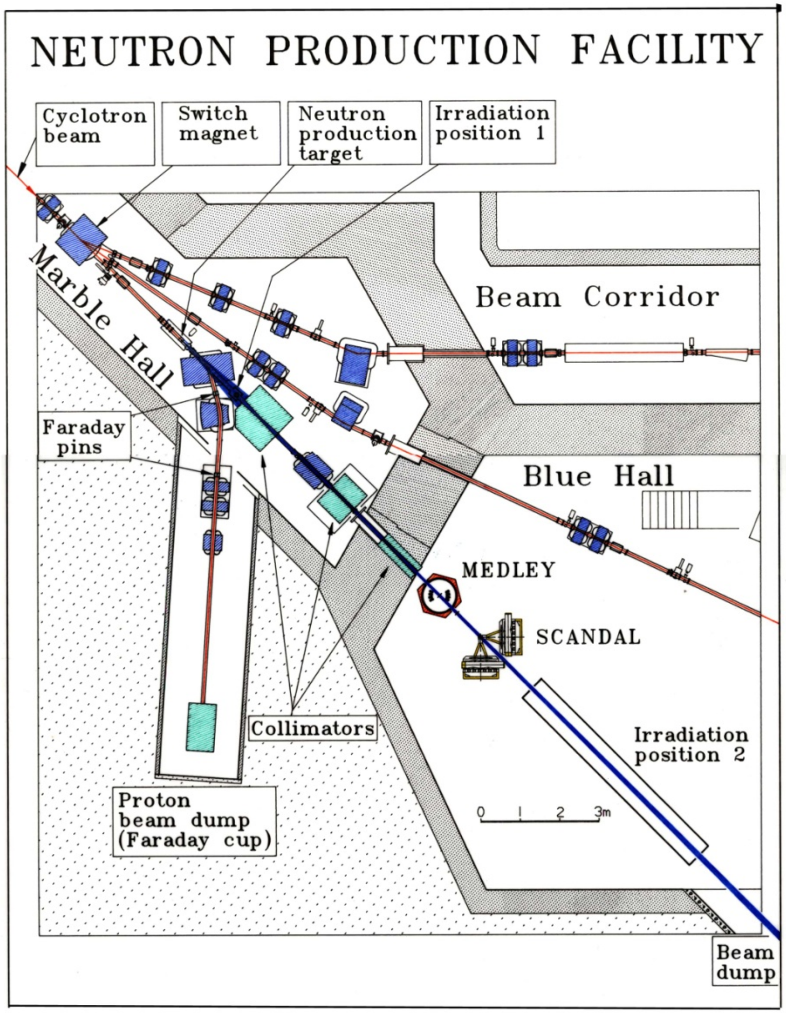
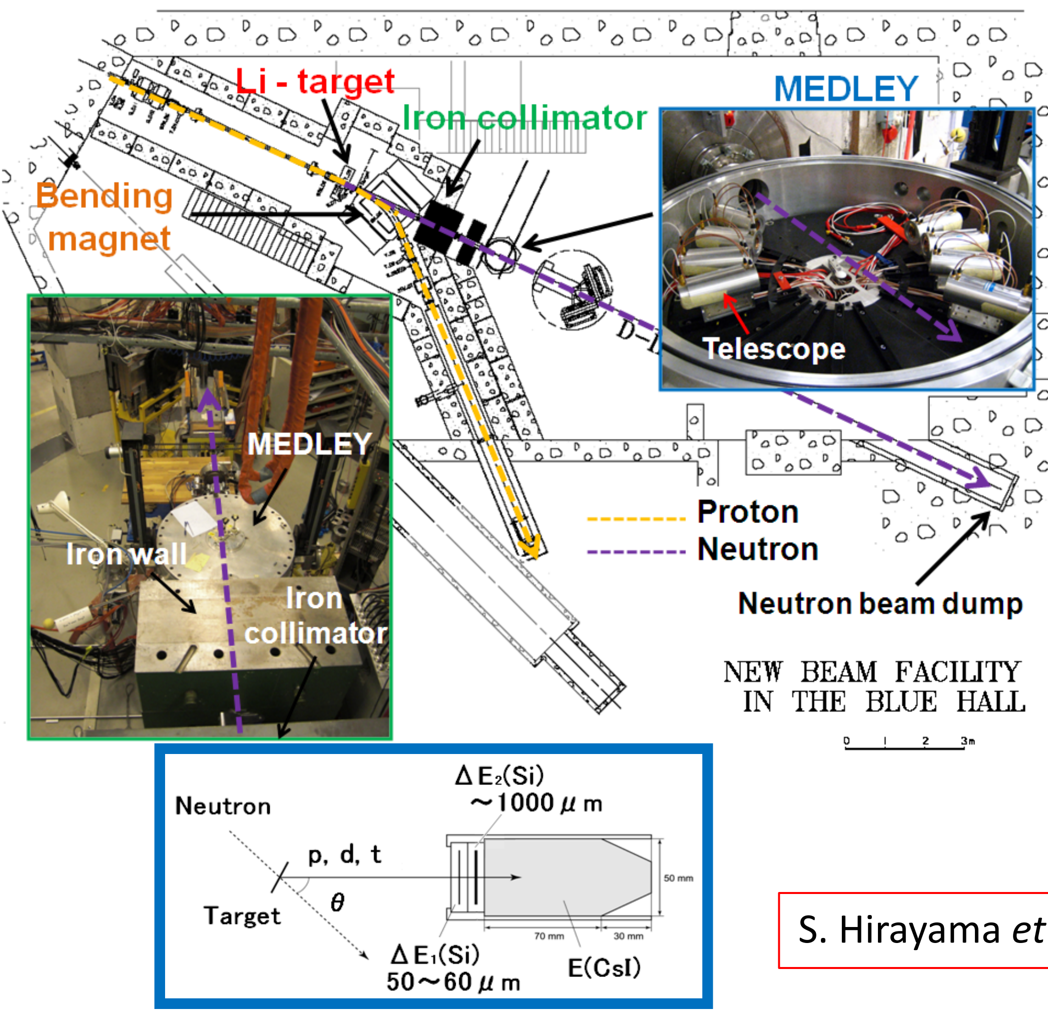
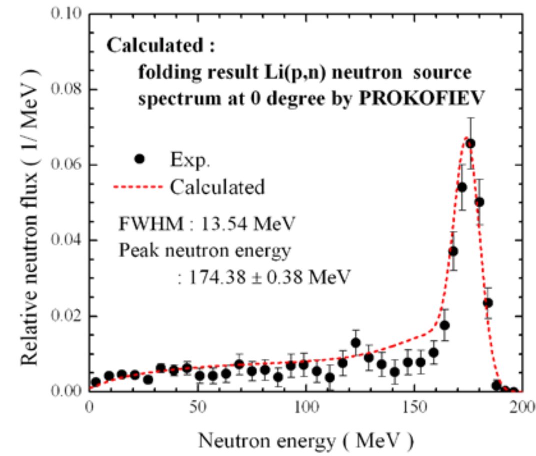


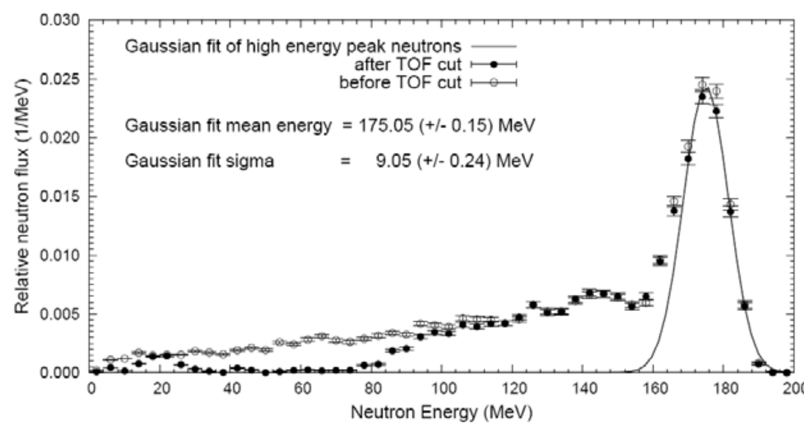
FIG. 1. Neutron energy distribution with TOF criterion applied derived from *np* scattering data at an angle of 20°. The peak (95.6 MeV), median (95.1 V), and average (94.0) are indicated by solid, dashed, and dotted vertical lines, respectively.



The second beam: up to 175 MeV







S. Hirayama *et al.* and R. Bevilacqua *et al.*, ND2010

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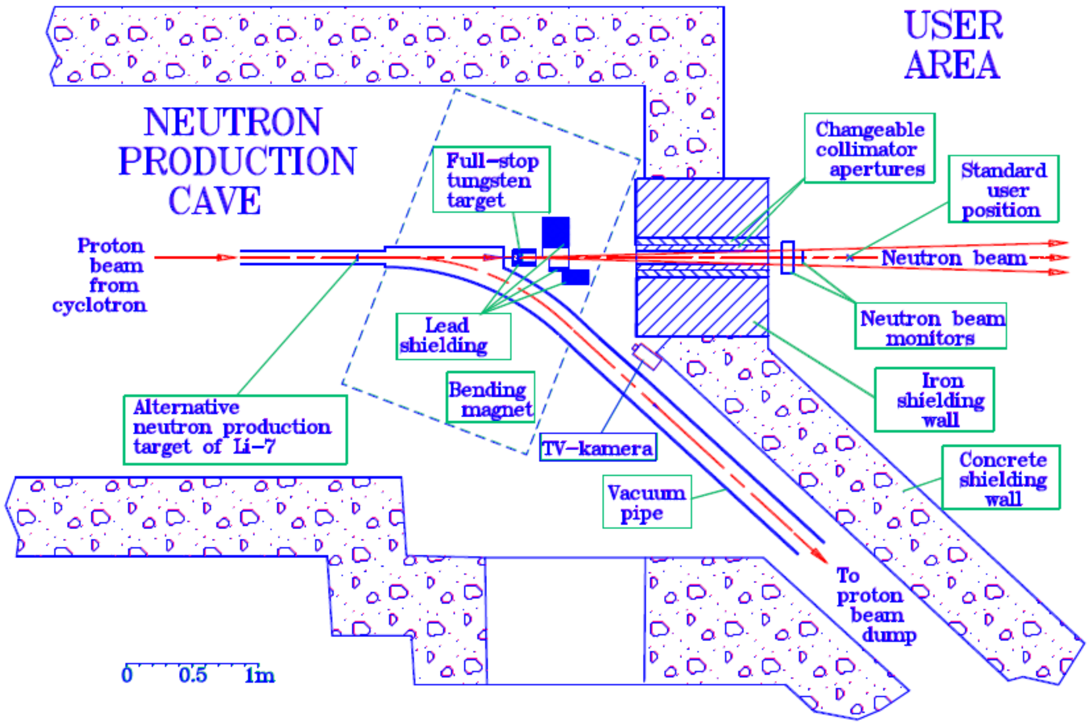
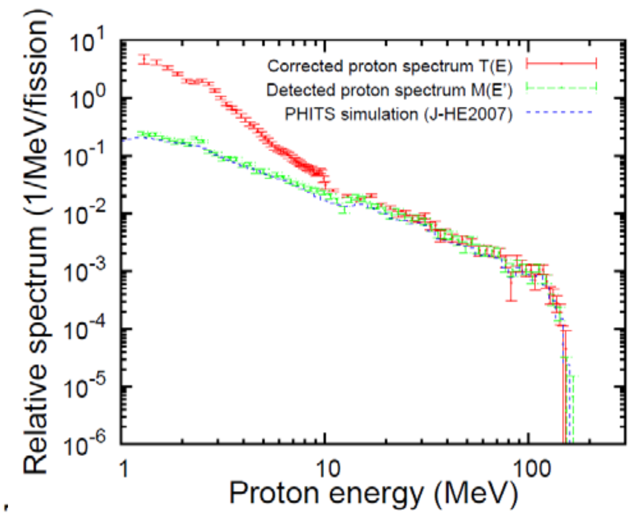
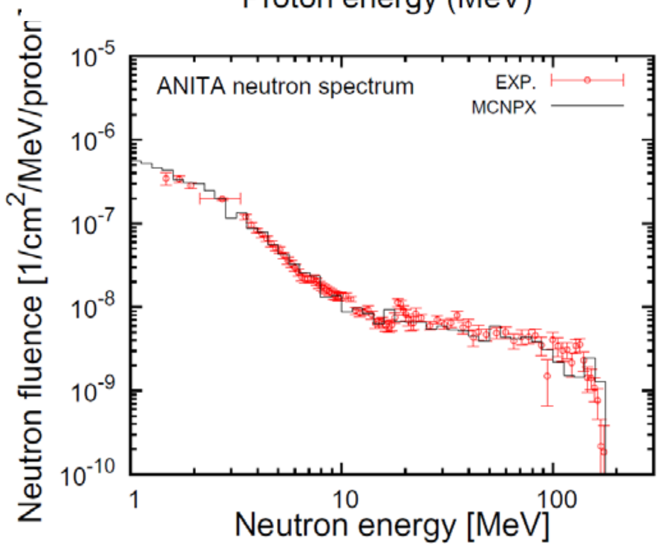
ANITA – a (former) white neutron source in Uppsala

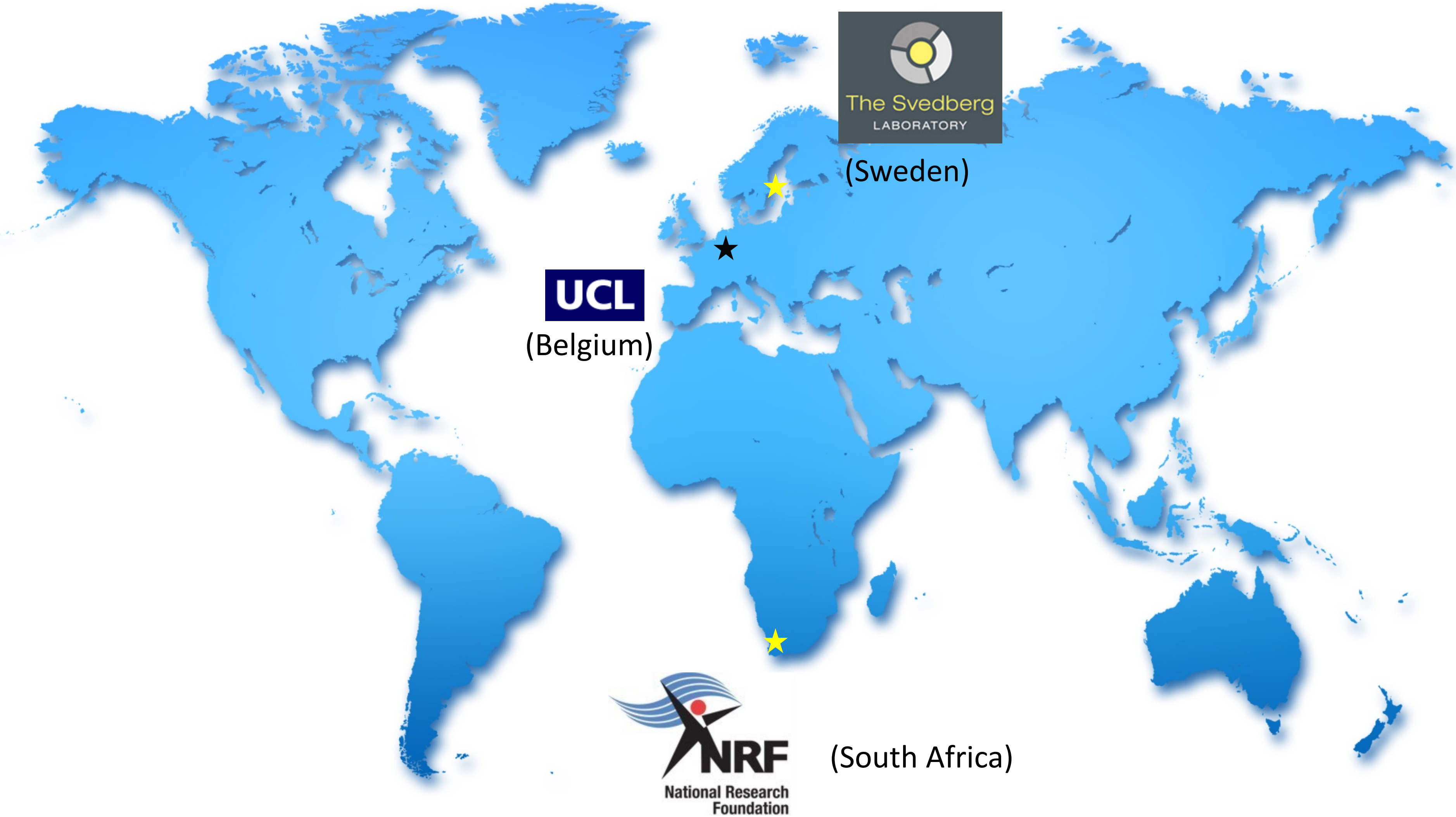






- Neutron spectrum via H(n,p) @ 20 degree
- Measurement extends to $E_n \approx 1.5$ MeV

Y. Naitou et al.,SND2009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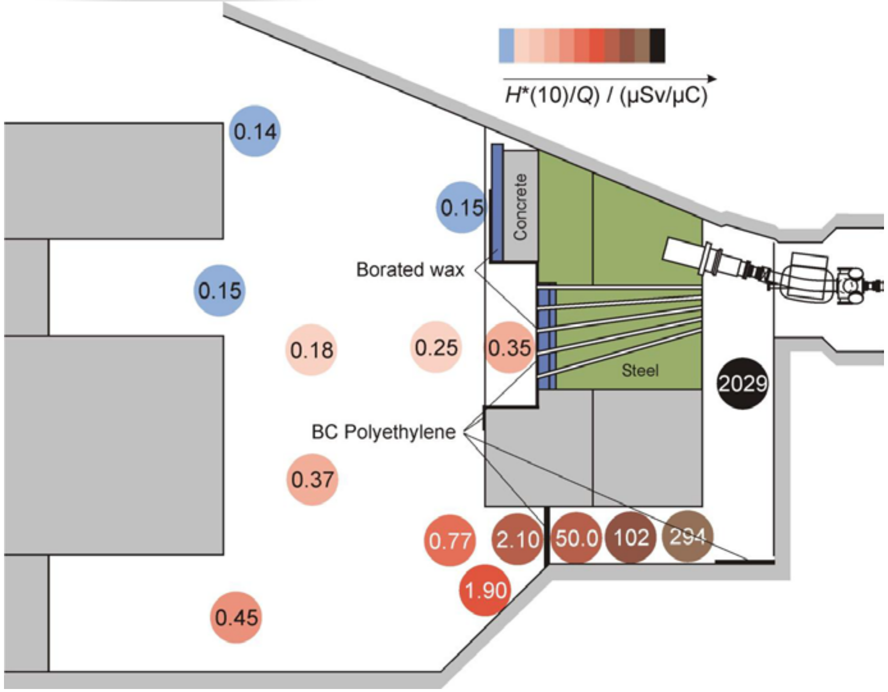
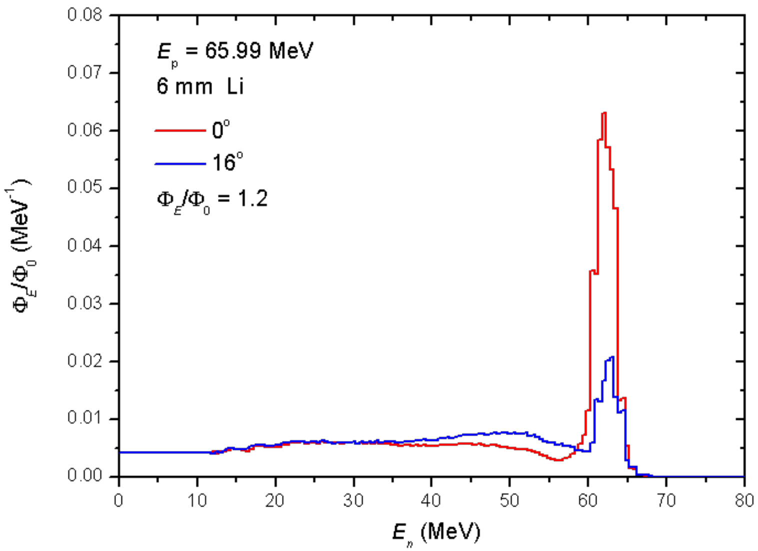


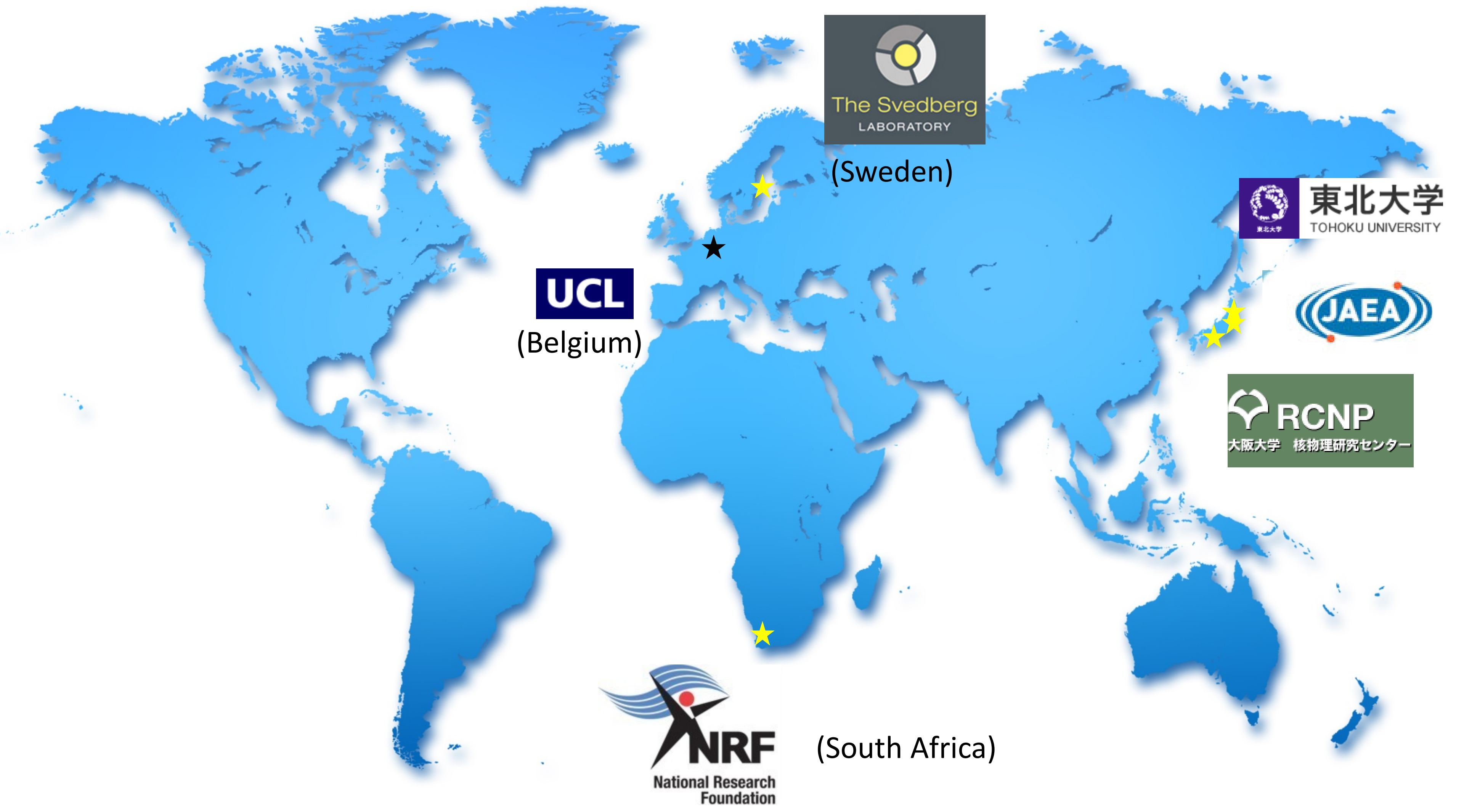


^{7}Li(p,n$_{0,1}$), up to 200 MeV neutrons

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)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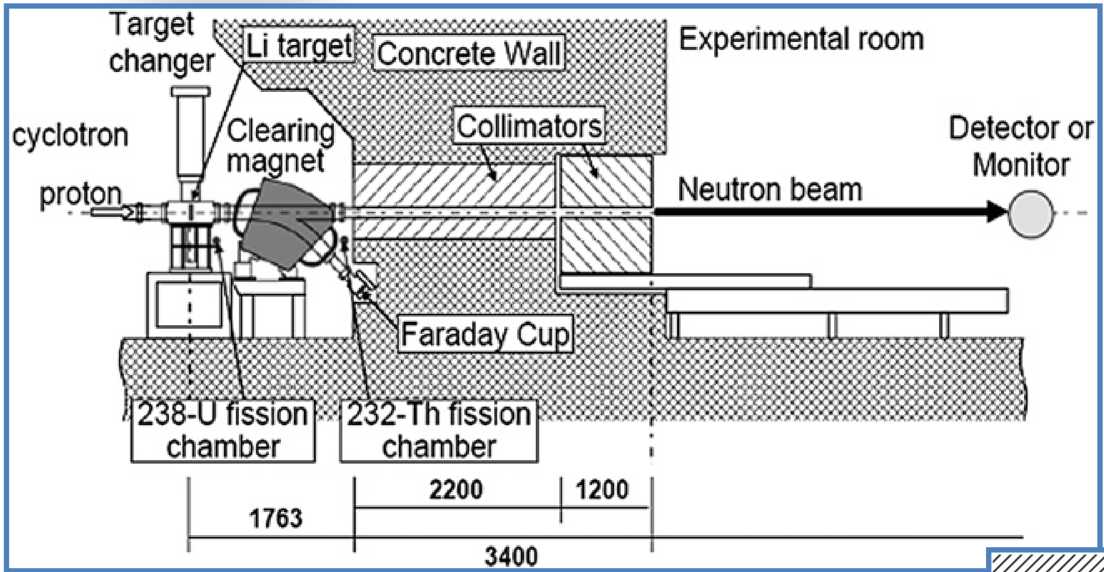
TIARA at JAEA and CYRIC at Tohoku University



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

40- 90 MeV neutrons

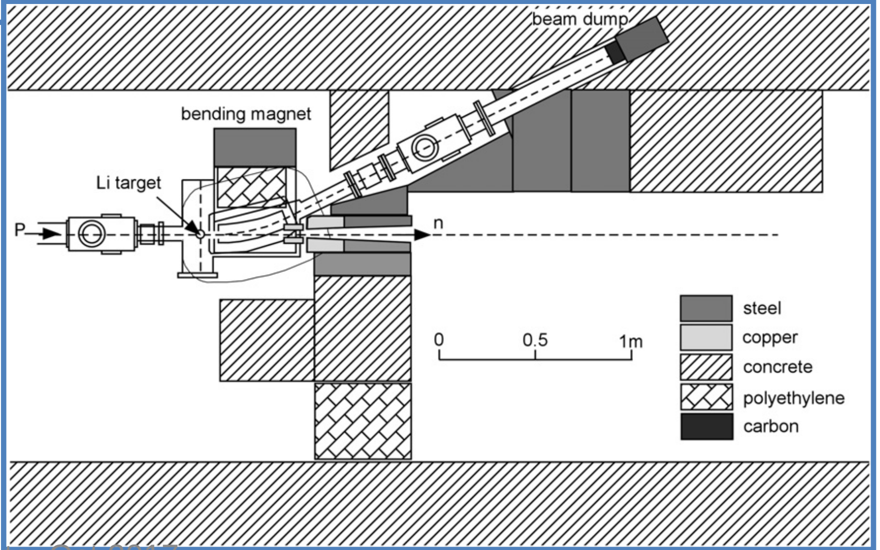
up to 18 m flight path

ref. fields 45, 60, 75 MeV

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

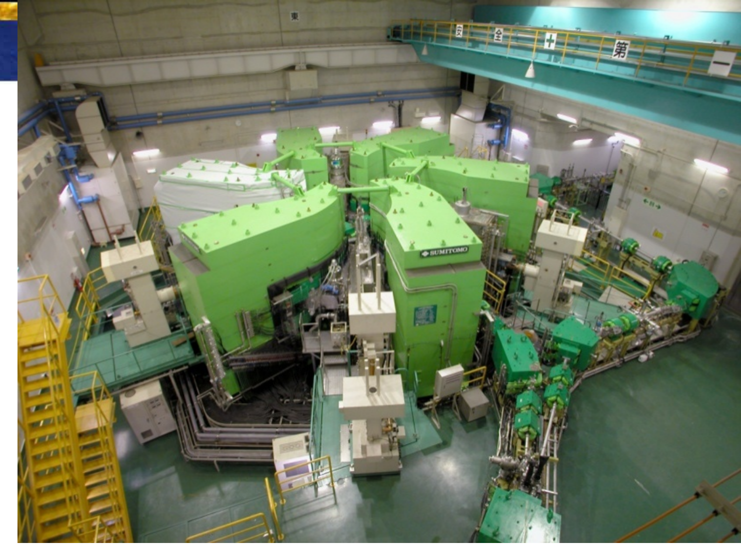
20- 90 MeV neutrons

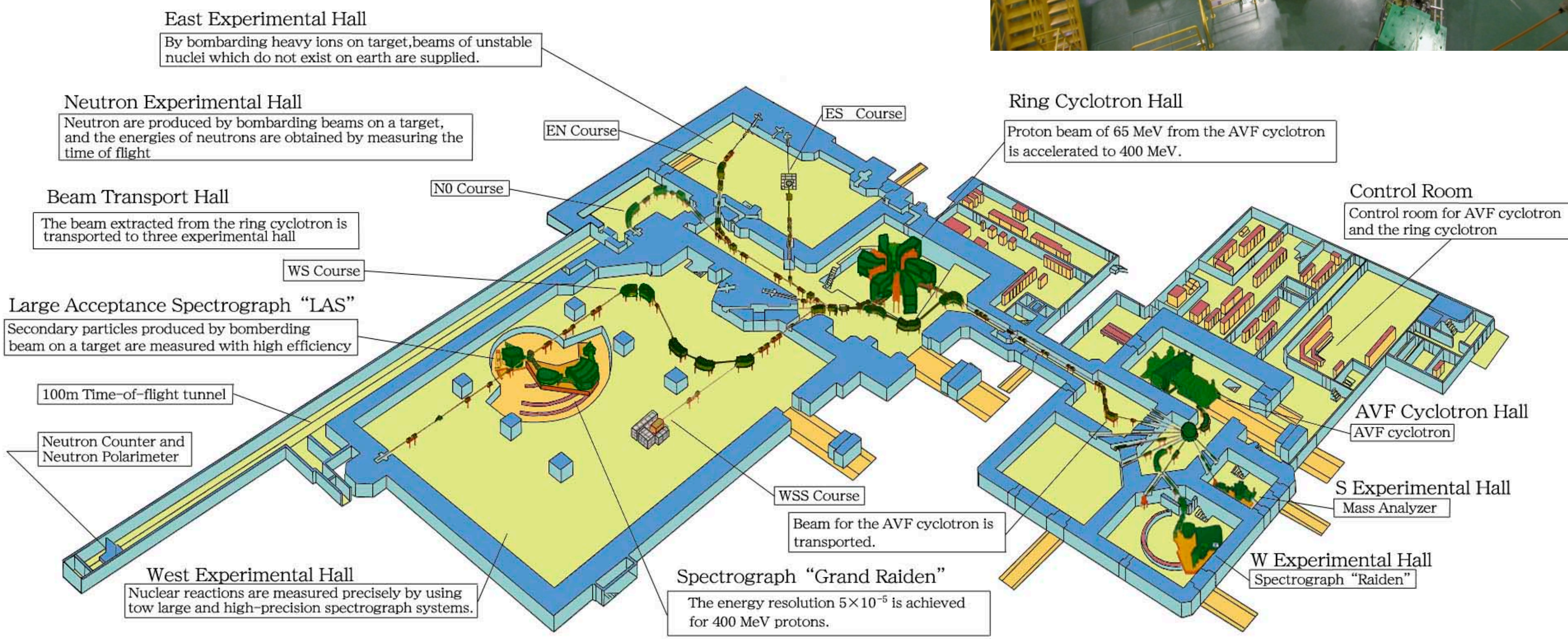
high intensity



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

RCNP at Osaka





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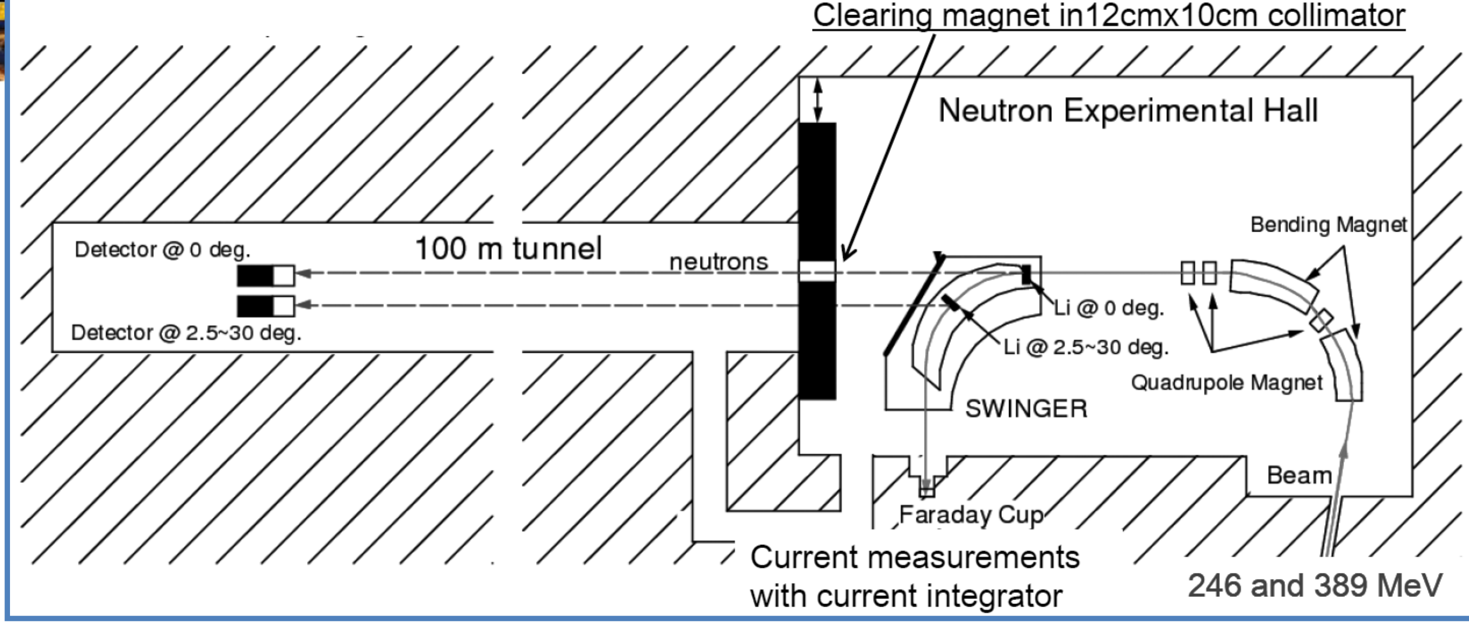

$^{7}Li(p,n_{0,1})$

140- 400 MeV neutrons

variable beam angle

100 m flight path

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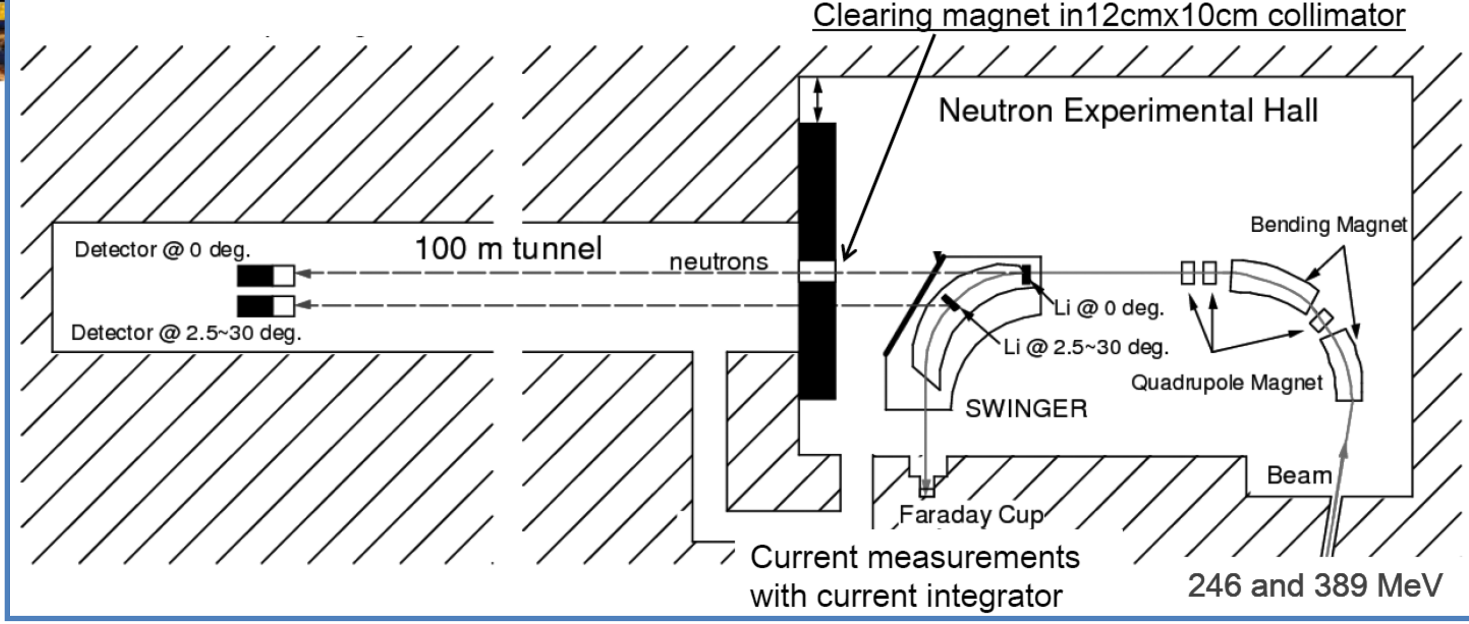
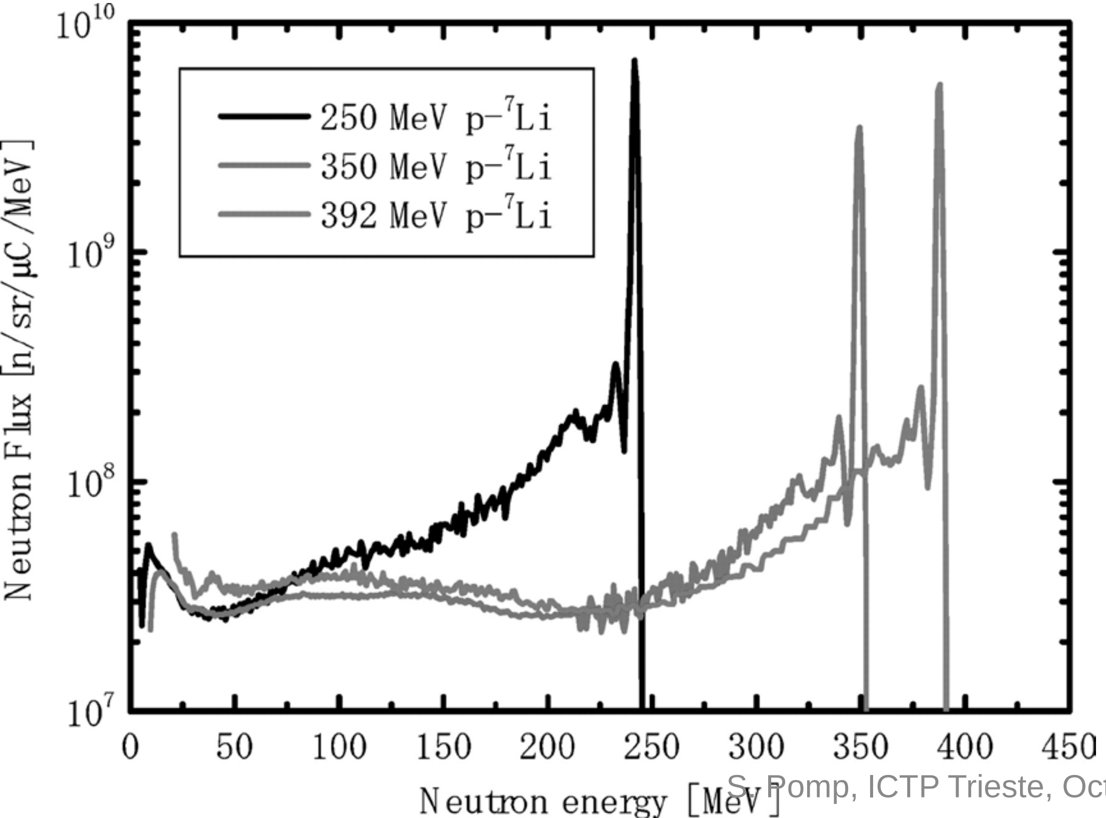




$^{7}Li(p,n_{0,1})$

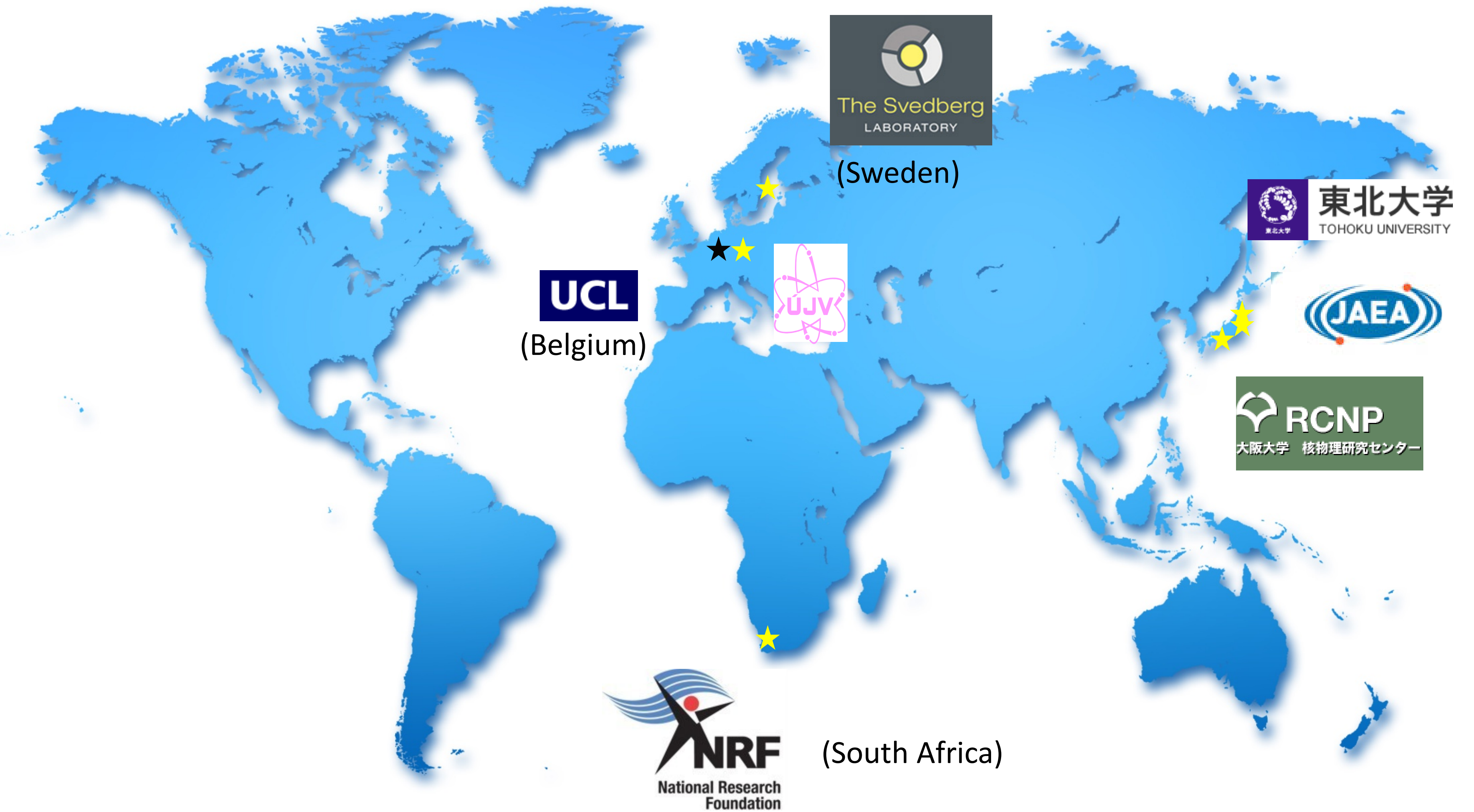
140- 400 MeV neutrons

variable beam angle

100 m flight path

Taniguchi et al.

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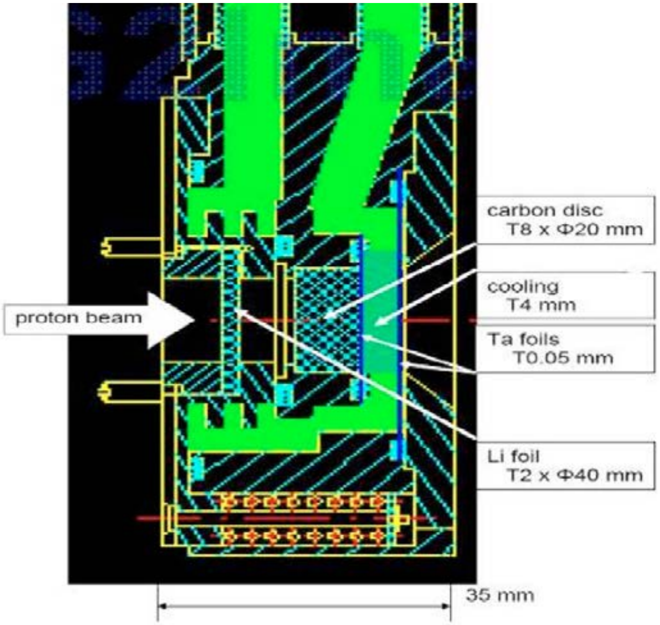

Target station of the neutron source and drawing of the reaction chamber

(M. Honusek, et al., EPJ Web of Conferences, Vol. 8, 07004, EFNUDAT – Measurements and Models of Nuclear Reactions)

- uses Li-7 but with carbon disc as beam dump directly behind target. (cp ATOMKI)
- hence target samples can be as close as 48 mm from the Li target.
- and a neutron flux density of about 10^9 n/cm^2/s in the QMN peak at 30 MeV can be achieved.
- peak energies up to 36 MeV.
- Standards beams are 18, 21.6, 24.8, 27.6, 30.3, 32.9 and 35.6 MeV


GANIL spiral2
laboratoire commun CEA/DSM CNRS/IN2P3
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SPIRAL-2

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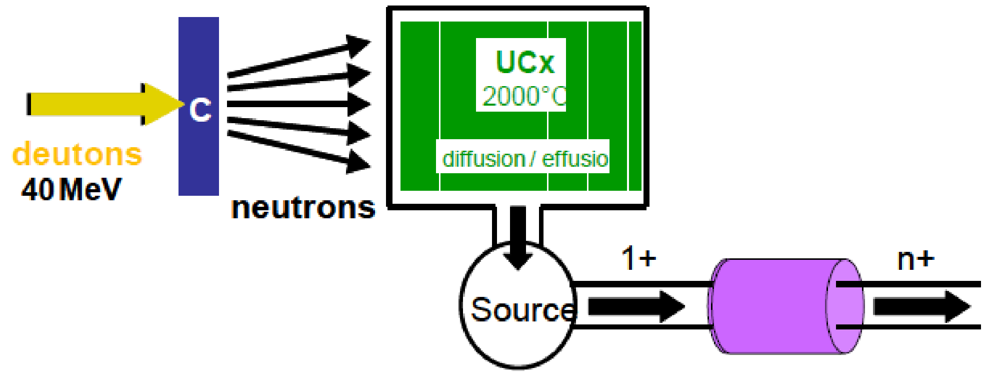
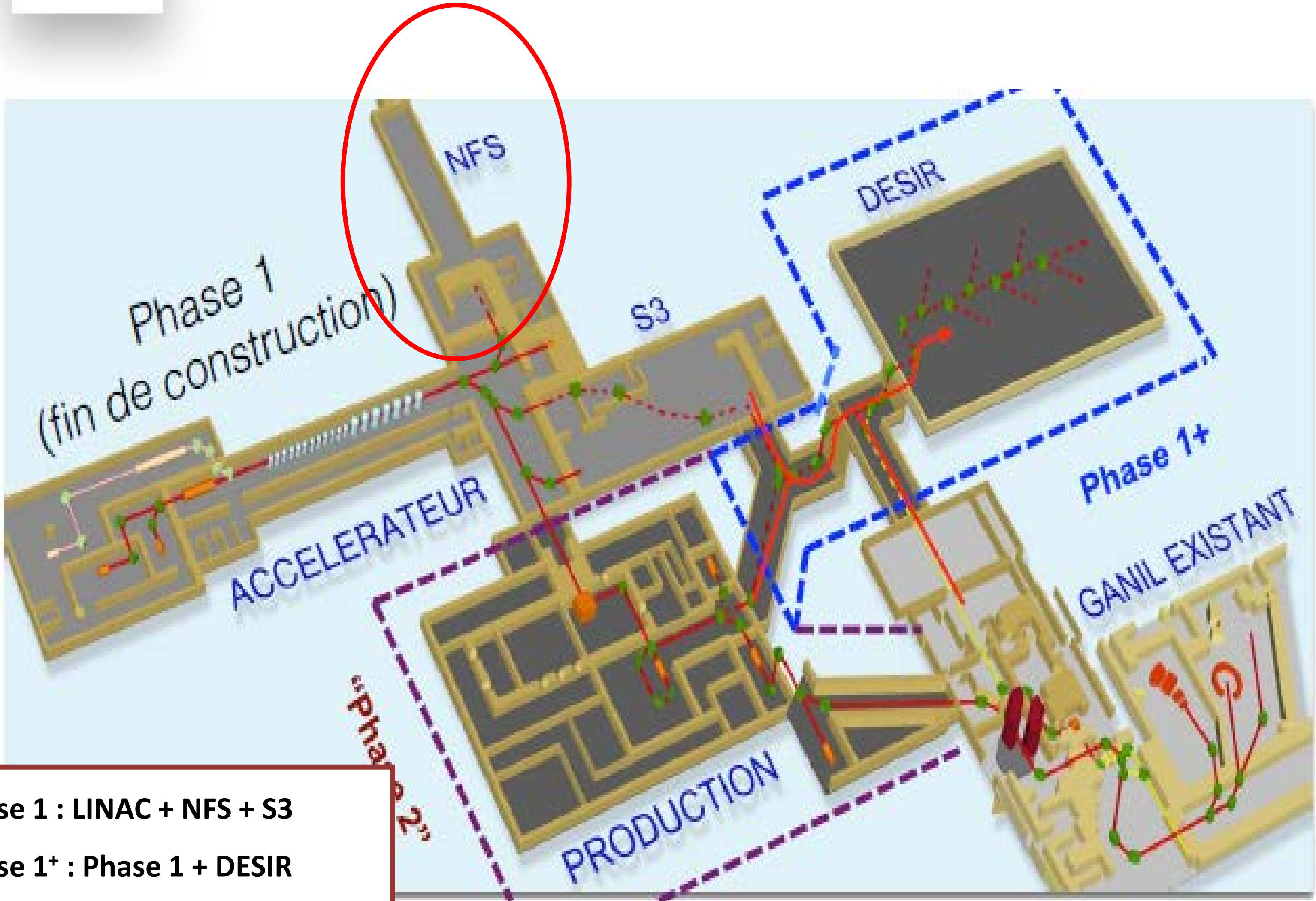
- The final goal of SPIRAL-2 is to produce intense Radioactive Ions Beams
  - Radioactive ions are produced by $^{238}U(n,f)$ with fast neutrons
  - Neutrons are produced by 40MeV d + C using a LINAC delivering 5mA



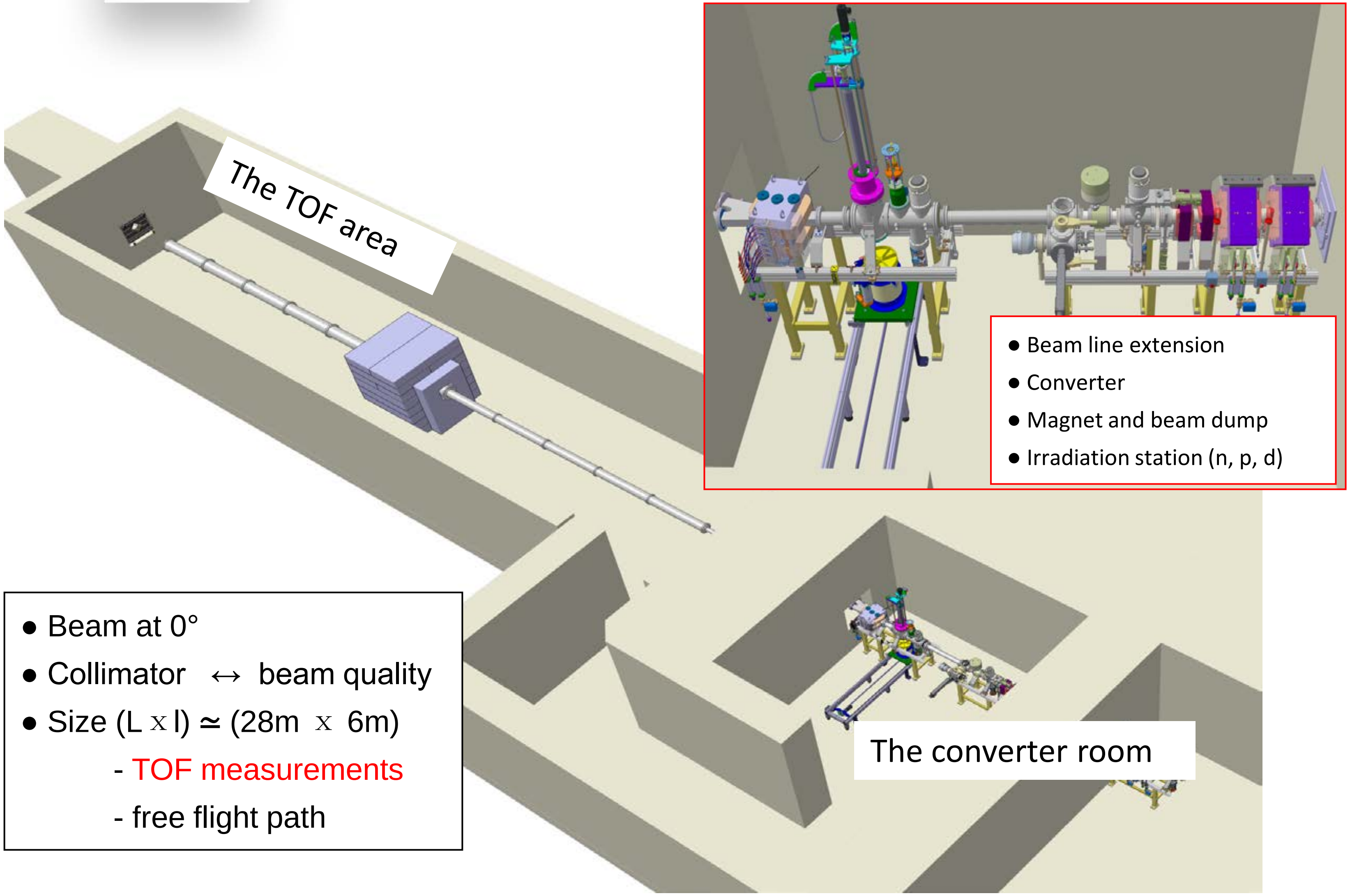
- LINAC Experimental areas :
  - S3 (Super Spectrometer Separator) : Heavy ions beams , super heavy nuclei
  - NFS **Neutrons For Science**
- DESIR facility

This and following slide (in part adapted): courtesy X. Ledoux



- Phase 1 : LINAC + NFS + S3
- Phase 1^{+} : Phase 1 + DESIR
- Phase 2 : RIB

The NFS facility



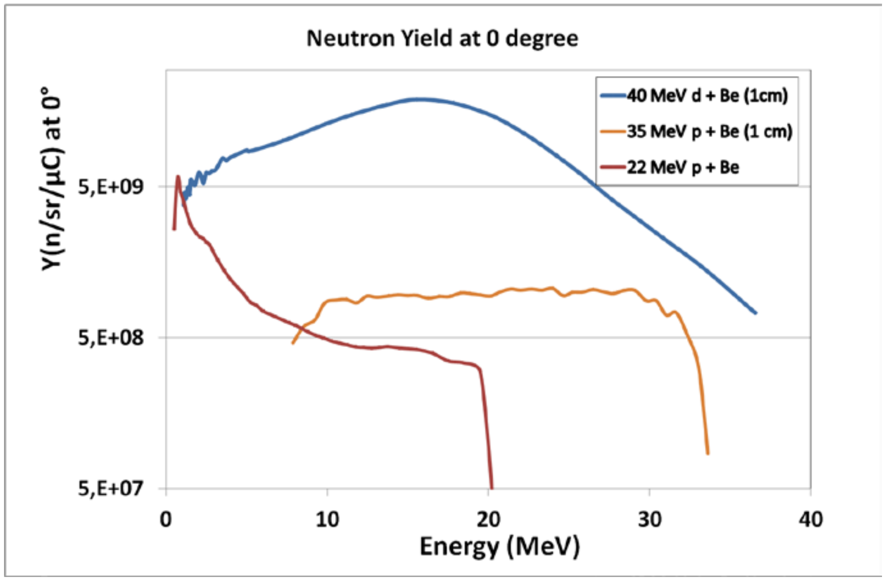
- Beam at 0°
- Collimator ↔ beam quality
- Size (L x l) ≃ (28m x 6m)
  - TOF measurements
  - free flight path

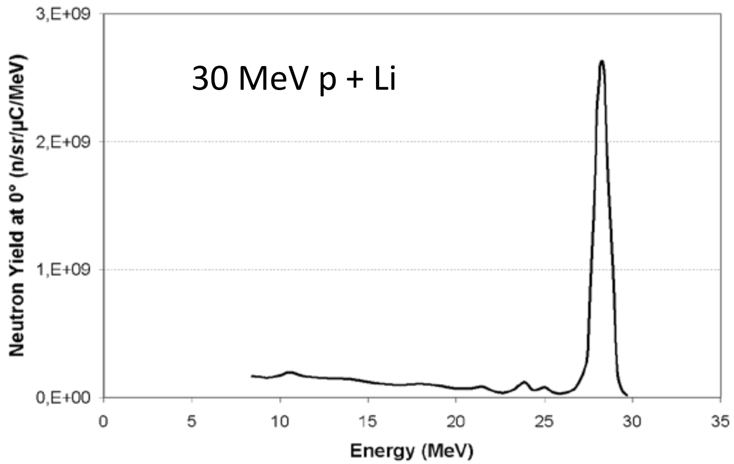
- Beam line extension
- Converter
- Magnet and beam dump
- Irradiation station (n, p, d)

NFS: “white beam” and QMN

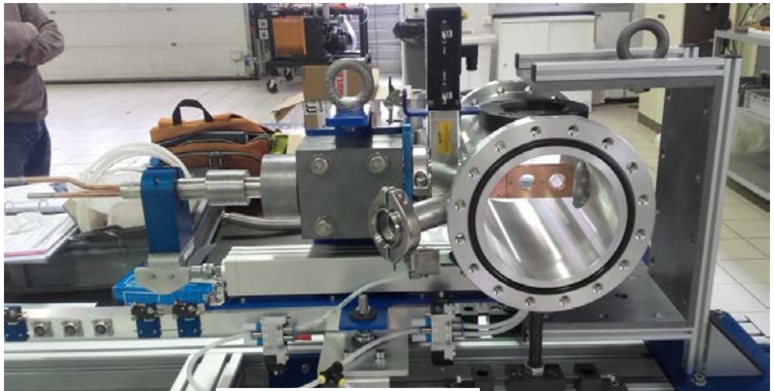
40 MeV d+ Be (6 mm)

p+^{7}Li -> n + ^{7}Be   Q= -1.64 MeV



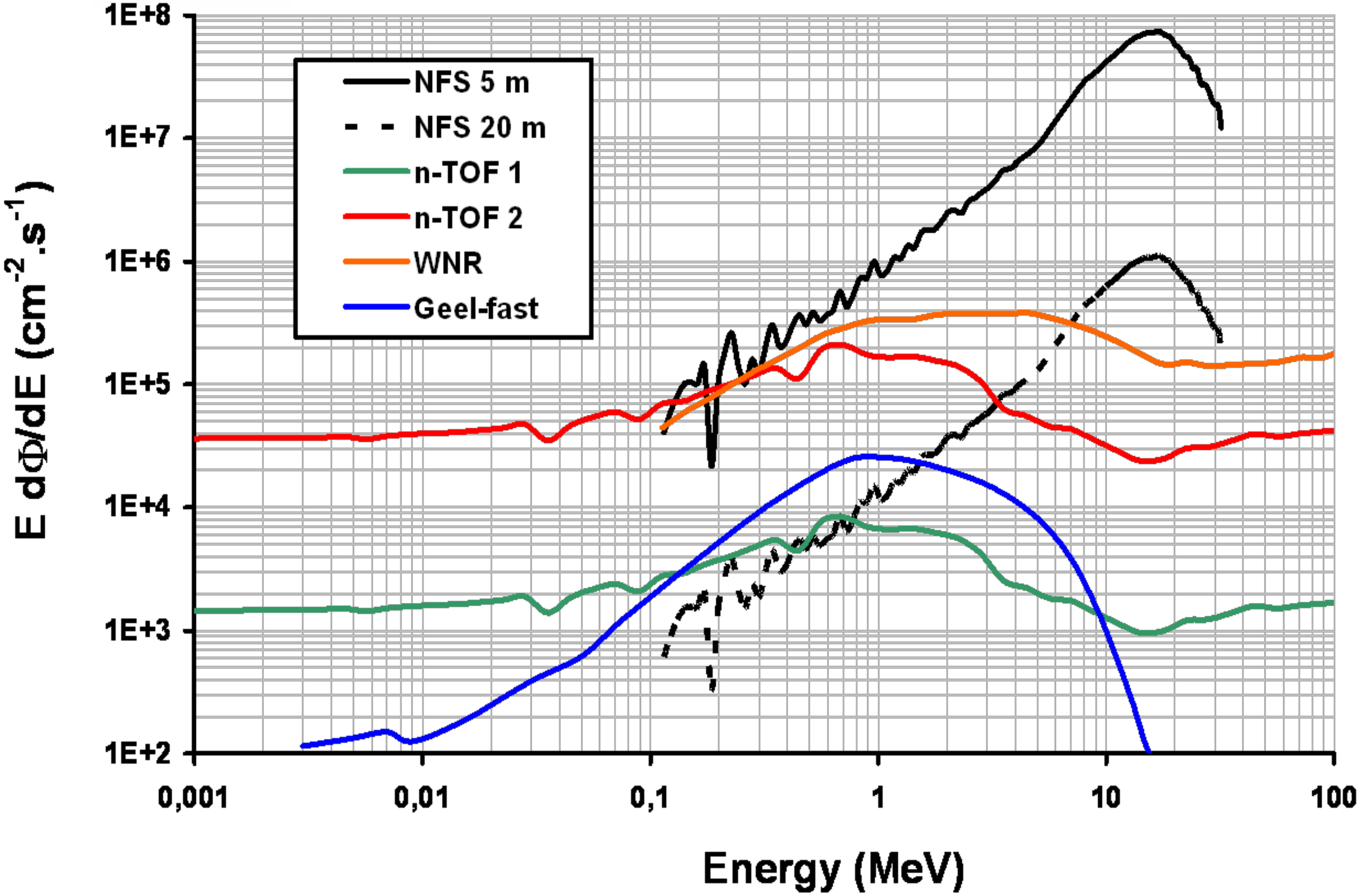


Rotating thick converter



Thin converter

Comparison with other Neutron TOF facilities



NFS : 40 MeV d + Be

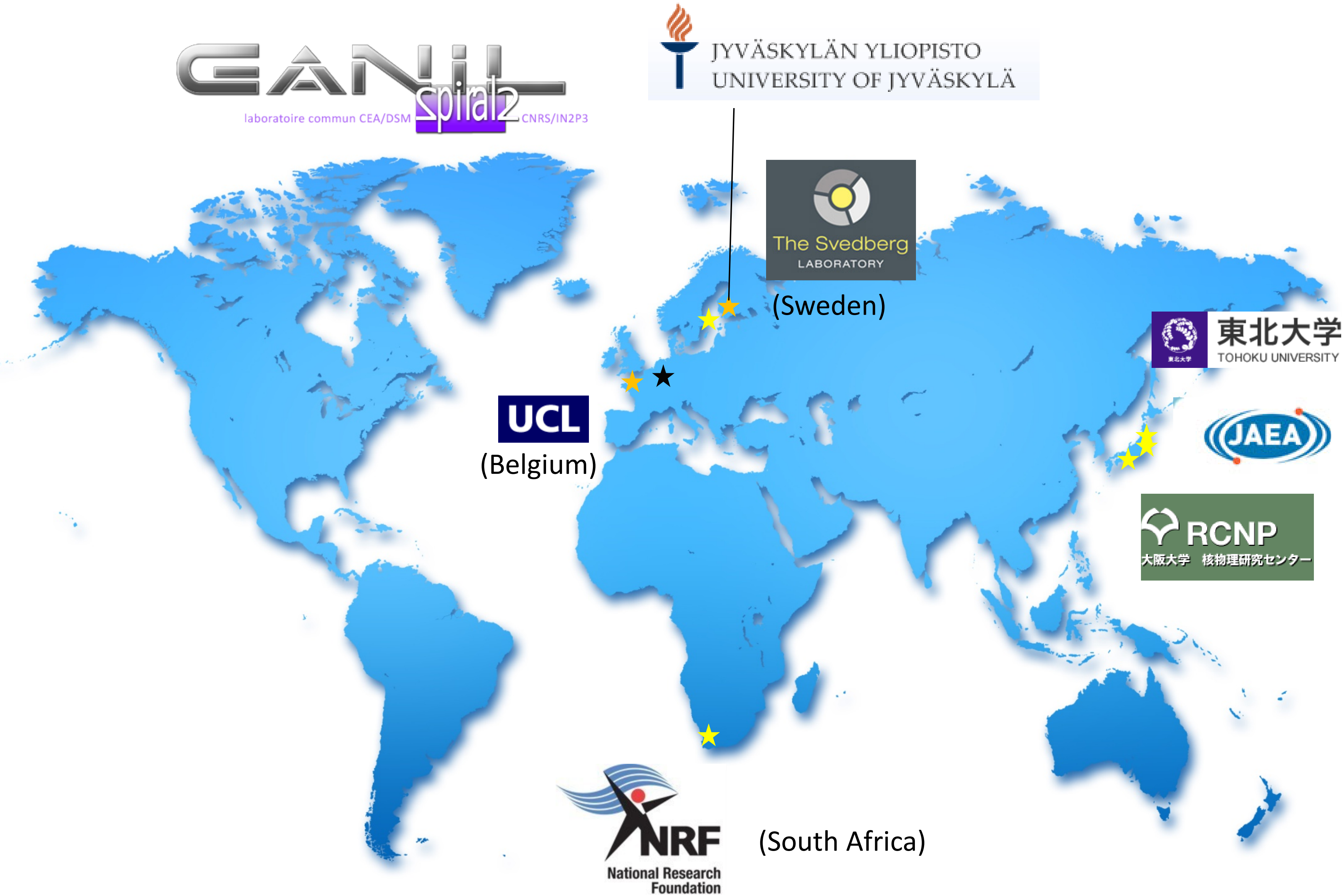
WNR : Los Alamos

n-TOF 2 : CERN

n-TOF 1 : CERN

GELINA : Geel

Complementary to the existing facilities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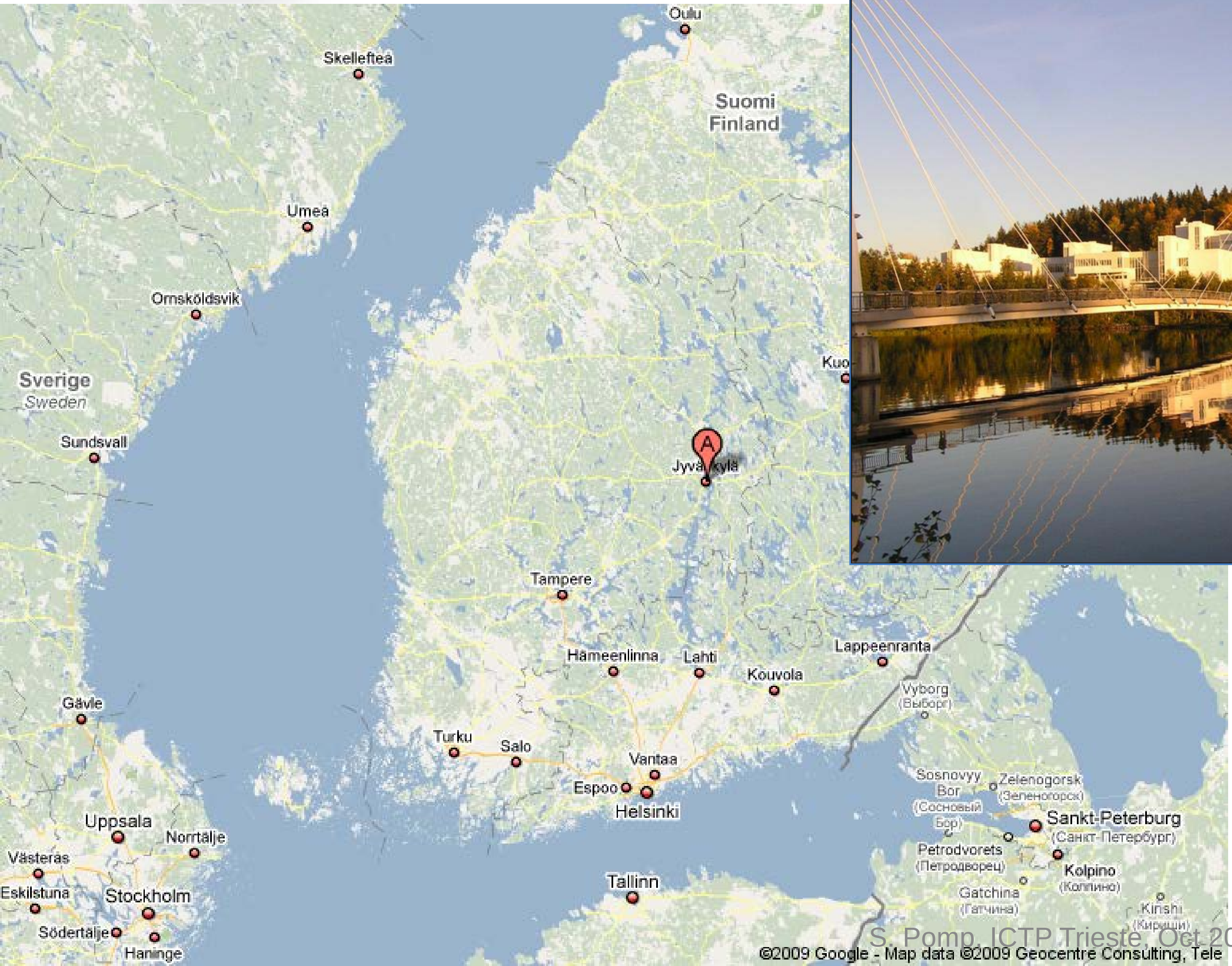
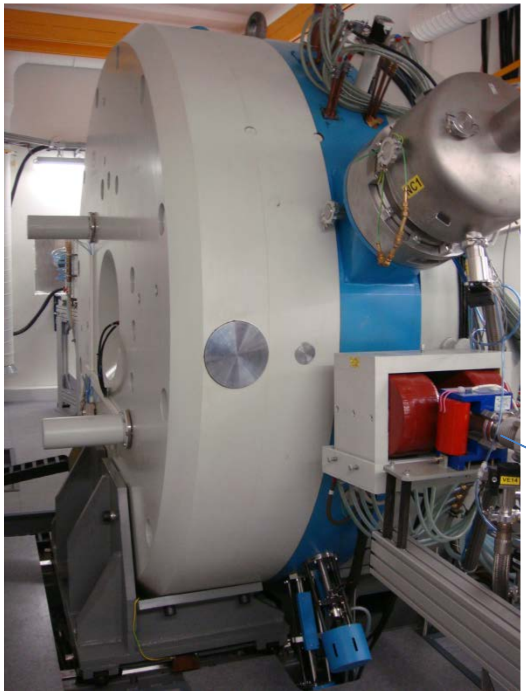
Tervetuloa Jyväskylään

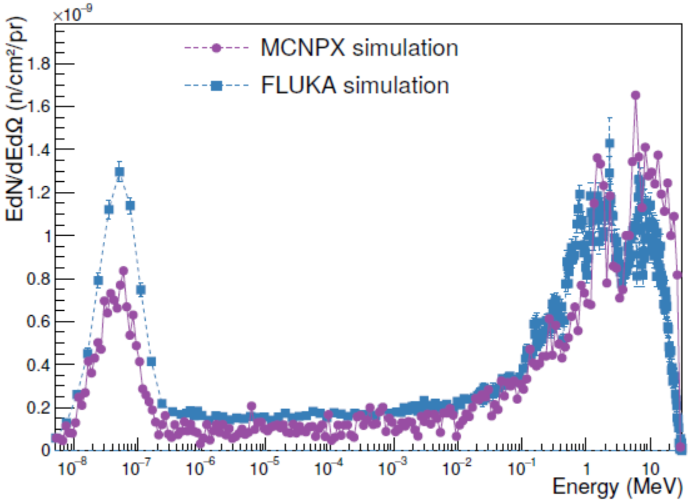


Neutrons for fission@IGISOL

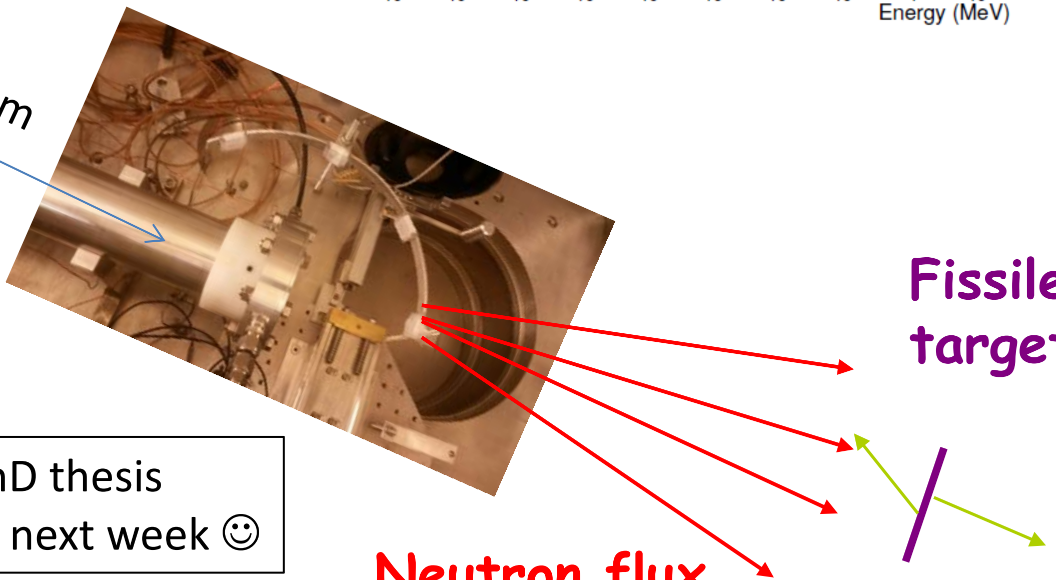


MCC30/15 cyclotron:
18 - 30 MeV p
9 - 15 MeV D
I ~ 100 µA

Protons on Be target



p-beam



Fissile target

Neutron flux

See PhD thesis
A. Mattera next week ☺

More on IGISOL in the lecture on fission yields …

Acknowledgements

Several colleagues from different labs have provided material to these slides, especially the section on different facilities.
Thanks in particular to:
Alexander Prokofiev (UU) and Xavier Ledoux (GANIL).