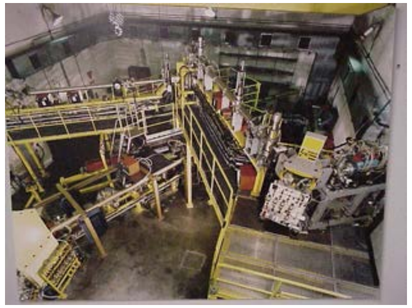
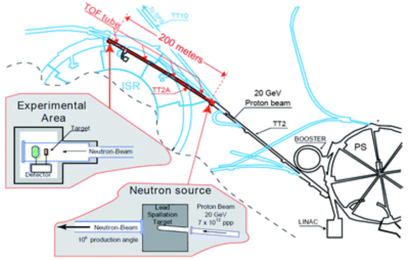
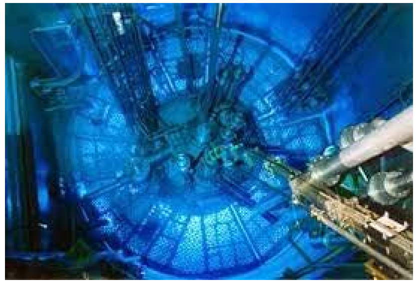
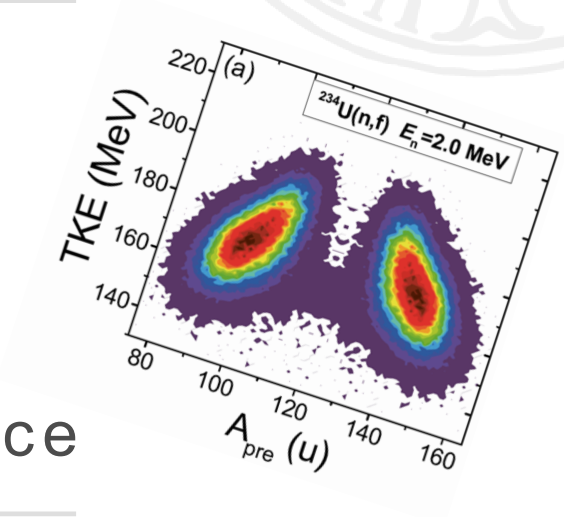






Nuclear data facilities and measurements

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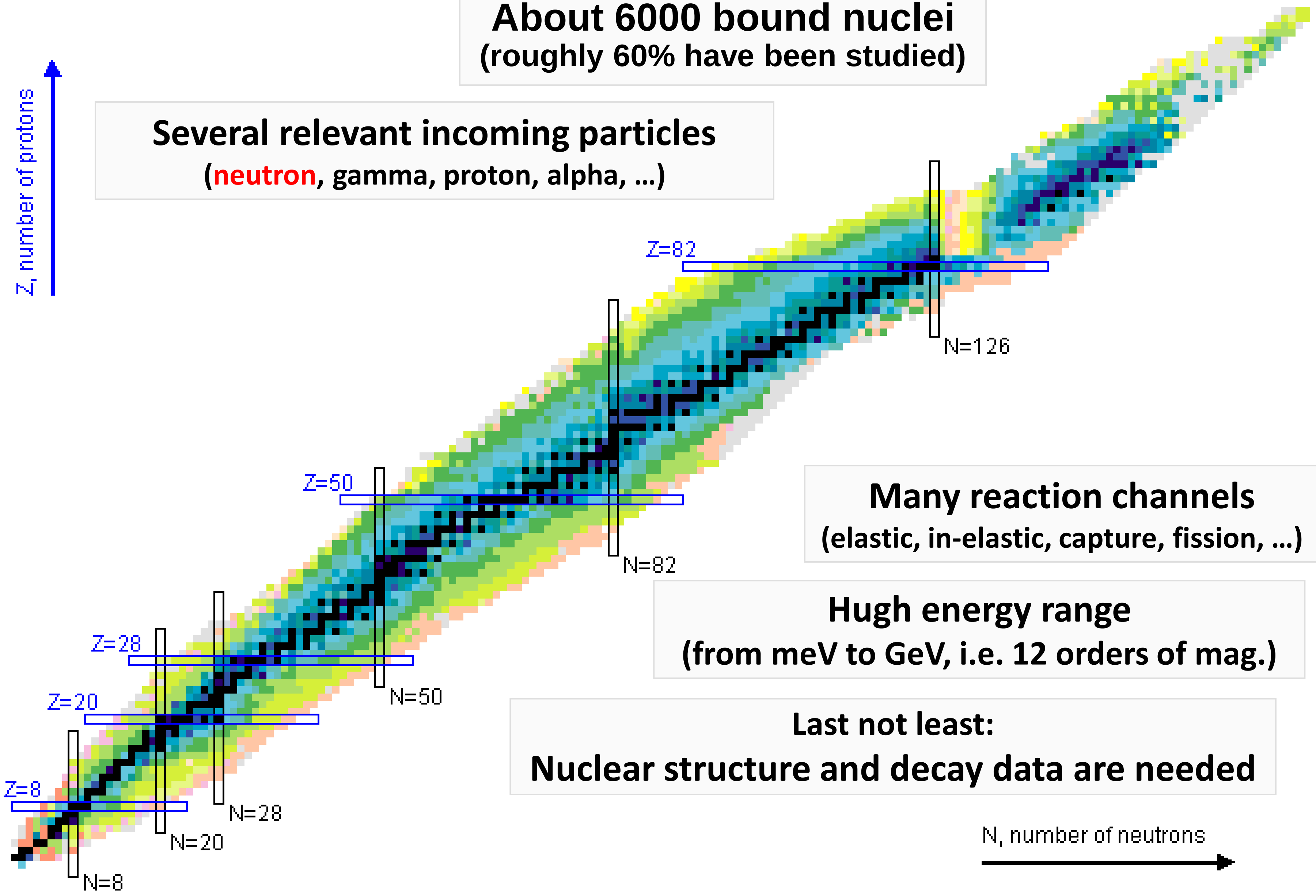
About 6000 bound nuclei
(roughly 60% have been studied)

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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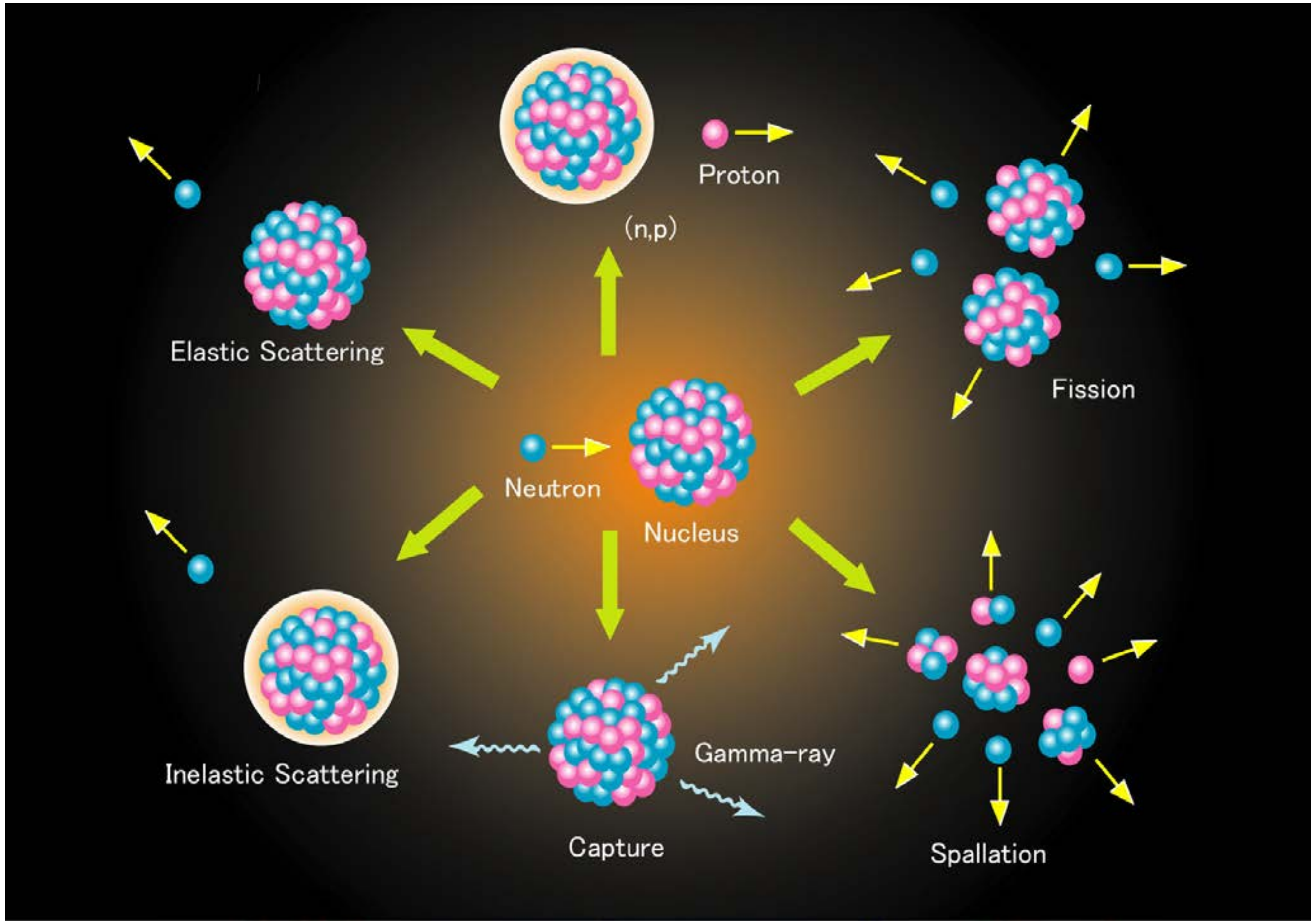
Many reaction channels to consider



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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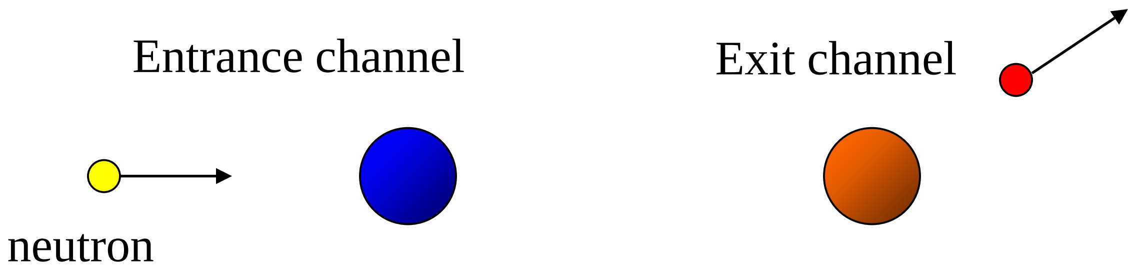
Nuclear reactions – overview



Scattering
- Elastic scattering : X(n,n)X
- Inelastic scattering : X(n,n')X* — Transition to excited states; De-excitation via γ-emission

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

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A walk through measurement techniques for ND

What are the most basic nuclear data ingredients in nuclear reaction modelling?

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Masses

See presentation by S. Goriely.
Data: AME 2020

Measurements of nuclear masses are needed to determine

- binding energies, and
- neutron and proton separation energies.

$$S_n(A,Z) = M(A-1,Z) + M_n - M(A,Z)$$

$$S_p(A,Z) = M(A-1,Z-1) + M_p - M(A,Z)$$

From these one can calculate Q-values for different reactions.

$$Q = M_{before} - M_{after}$$

e.g.: $Q(n,\gamma) = M(A,Z) + M_n - M(A+1,Z) = S_n(A+1,Z)$

```
Q-values for binary reactions:

Q(n,g):  7.22755
Q(n,n):  0.00000
Q(n,p):  0.69154
Q(n,d): -3.81821
Q(n,t): -6.19572
Q(n,h): -7.72140
Q(n,a):  4.93048
```

From TALYS test case on $^{93}Nb(n,x)$

Exo- or endothermic? Impact on shape of excitation function.

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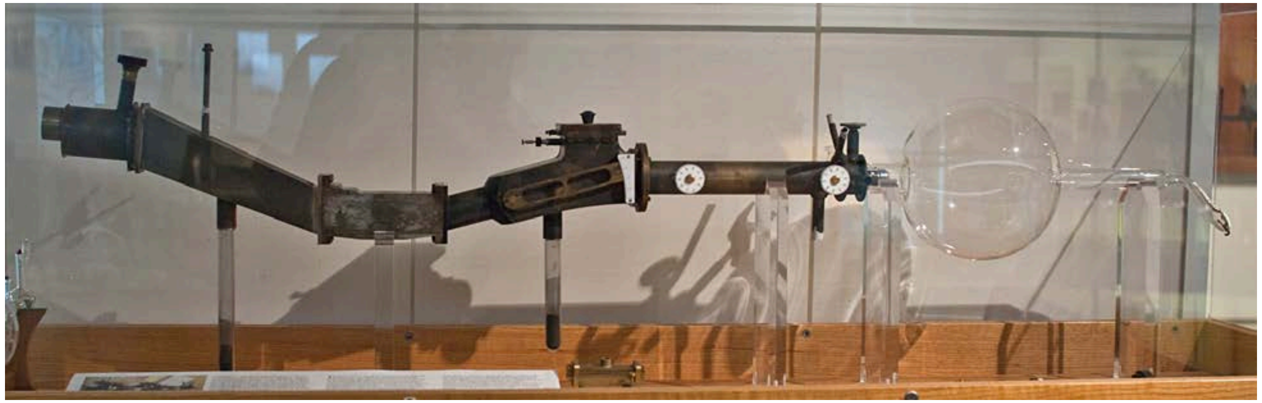
Mass measurement – first steps

Francis William **Astons first mass spectrograph** reported results in **1919**.
The mass resolving power (MRP) was about 1:130 and mass accuracy about 0.1%.
The instrument used **electromagnetic focusing**; Aston identified 212 naturally occurring isotopes.
Aston became a member of the International Committee on Atomic Weights (a section of IUPAC) in 1921 and received the Nobel Prize in **Chemistry** in 1922.

The exact mass of many isotopes was measured leading to the result that hydrogen has a 1% higher mass than expected by the average mass of the other elements. …



Replica of Astons thirds mass spectrograph.
By Jeff Dahl - Own work, CC BY-SA 3.0,
https://commons.wikimedia.org/w/index.php?curid=7870712

Sources:
- Wikipedia
- Technical details and history:
G. Squires, J. Chem. Soc., Dalton Trans. (1998) 3893
https://doi.org/10.1039/A804629H

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Mass measurement – first steps

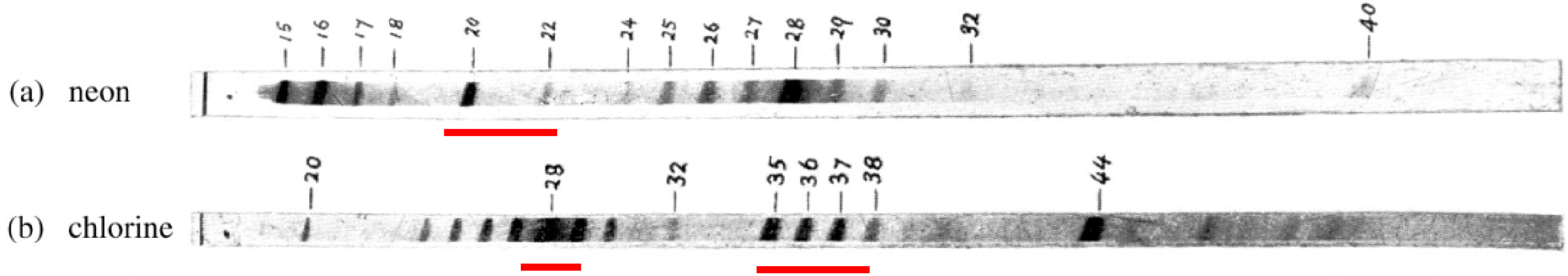

Fig. 8 Mass spectra obtained by Aston, 1919–1920, of (a) neon showing the 20 and 22 isotopes, and (b) chlorine showing the 35 and 37 isotopes.[14] A number of other ions are present in both spectra. For example, the line at 28, prominent in both spectra, is due to CO. The lines at 36 and 38, present in the chlorine spectrum, are due to $H^{35}Cl$ and $H^{37}Cl$.

G. Squires, J. Chem. Soc., Dalton Trans. (1998) 3893
https://doi.org/10.1039/A804629H

Abundances: ^{20}Ne: 90.48%, ^{21}Ne: 0.27%, ^{22}Ne: 9.25%, and ^{35}Cl: 75.76%, ^{37}Cl: 24.24%

Mass measurements today

The most precise (atomic) mass measurements (for unstable nuclei) are obtained at **Penning Traps**, e.g, ISOLTRAP (CERN), JYFLTRAP (Univ. of Jyväskylä), SHIPTRAP (GSI), and TITAN (TRIUMF). The achieved MRP are > 10^7., i.e., a few 10 keV.

The Penning trap usually connected to an **ISOL system** (Isotope Separation OnLine).

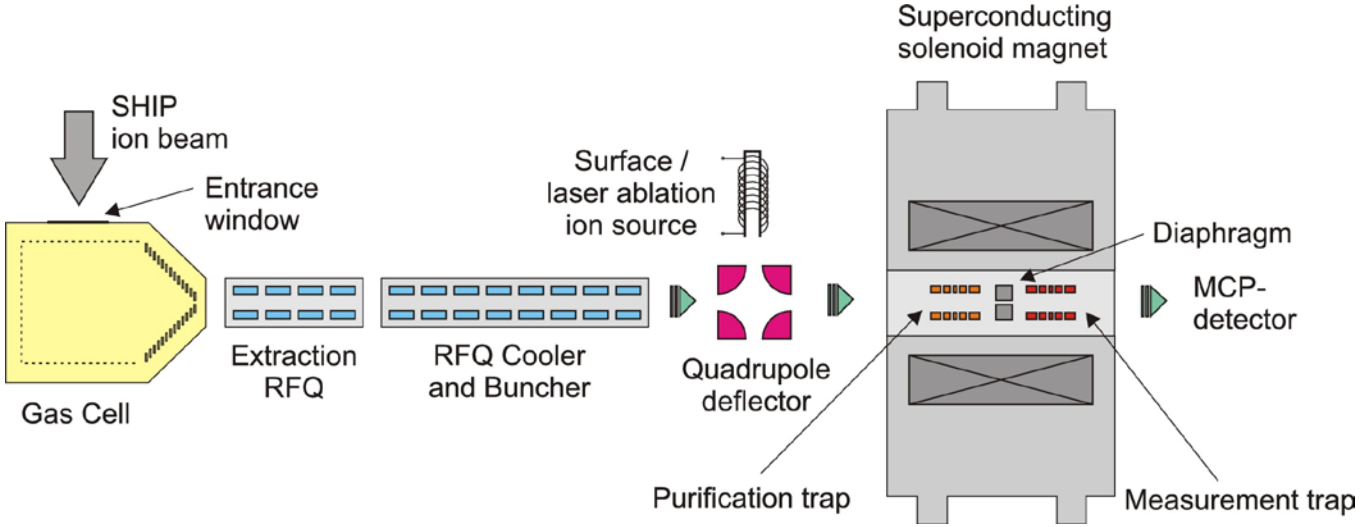

Figure: M. Block, Nuclear Physics A 944 (2015) 471–491, https://doi.org/10.1016/j.nuclphysa.2015.09.009

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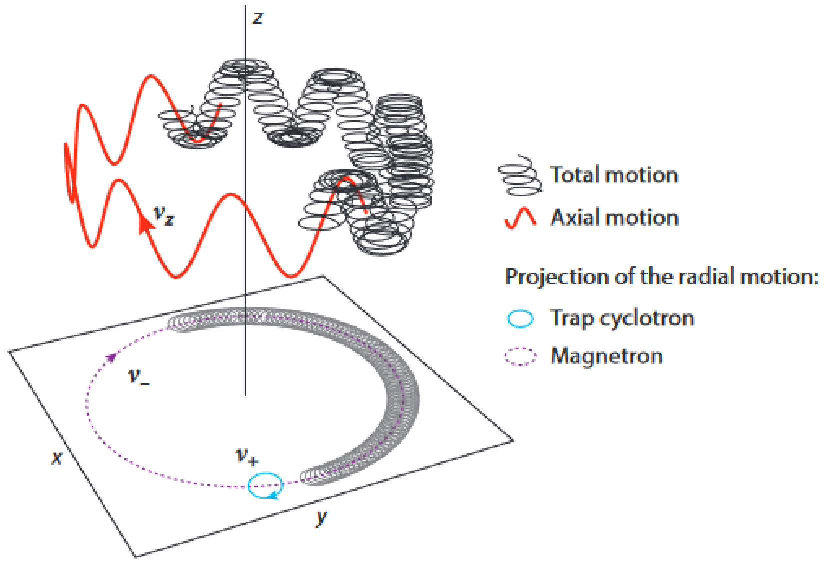
Mass measurements

The most precise (atomic) mass measurements (for unstable nuclei) are obtained at **Penning Traps**, e.g, ISOLTRAP (CERN), JYFLTRAP (Univ. of Jyväskylä), SHIPTRAP (GSI), and TITAN (TRIUMF).

$$\nu_c = \frac{1}{2\pi} \cdot \frac{q}{m} \cdot B.$$

"The determination of the mass m of an ion with electric charge q in a Penning trap is based on the measurement of its cyclotron frequency v_c (the frequency of the ion motion in a pure magnetic field)"



Mass excesses can measured to better than 10 keV.

[For stable and light nuclei, using various techniques: < 1 eV possible.]

J. Dillig et al., Annu. Rev. Nucl. Part. Sci. 2018. 68:45–74, https://doi.org/10.1146/annurev-nucl-102711-094939

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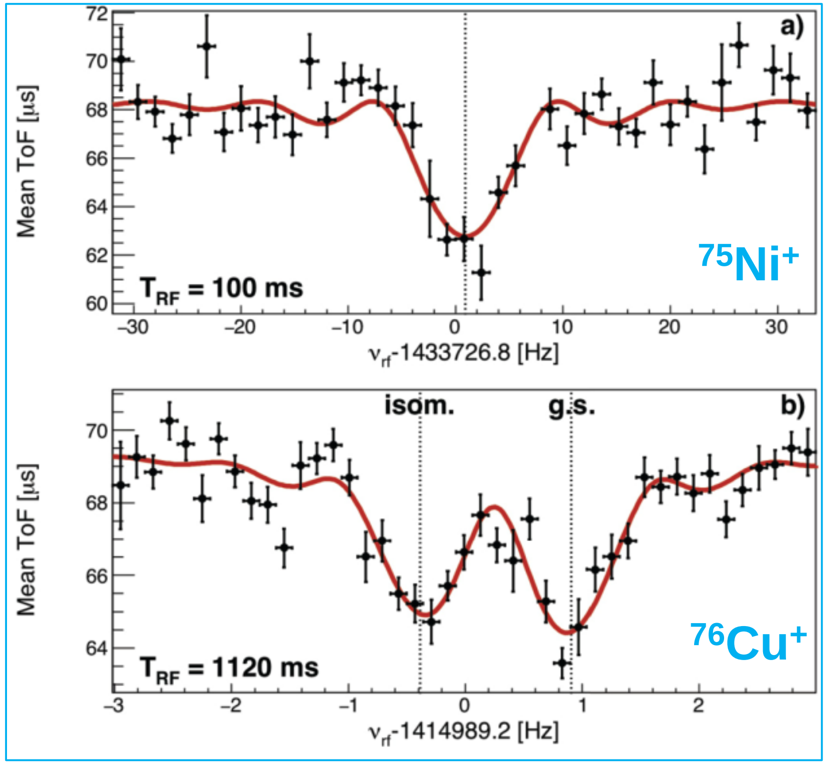
Example from JYFLTRAP



S. Giraud, et al., Phys. Lett. B 833 (2022) 137309.

Precision mass measurement at the double Penning Trap.

Time-of-flight ion-cyclotron-resonance (TOF-ICR) technique:
Determine $\nu_c = \frac{1}{2\pi} \cdot \frac{q}{m} \cdot B$
by scanning over a quadrupolar excitation with ν_{rf}.

When $\nu_{rf} = \nu_c$, ions extracted from the trap have the shortest flight time to a detector (MCP).

Nuclide	$T_{1/2}$(ms)	I^{π}	r	ME_{JYFL} (keV)	ME_{lit} (keV)	Diff. (keV)
^{74}Ni	507.7 (4.6)	0^+	0.881260877(44)	-48451.4 (3.5)	-48700 (200)#	-249 (200)
^{75}Ni	331.6 (3.2)	$9/2^+$#	0.893234508(187)	-44055.9 (14.7)	-44240 (200)#	-184 (201)
^{76}Cu	637.7 (5.5)[a]	3^- [a]	0.905062917(26)	-51011.4 (2.0)	-50981.6 (0.9)	29.8 (2.2)

$r = \nu_{ref}/\nu$

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Nuclear level structure

See presentation by S. Hilaire.

Just in brief the example ^{83}As.

Measured with γ-spectroscopy,

e.g. AGATA, EUROBALL, EXOGAM, …

```
83As
  number of levels:                              33
  number of gamma-rays:                          57
  number of levels in a complete level scheme:   15
  number of levels with assigned spin and parity: 1
  neutron separation energy:                     7.635222 [MeV]
  proton separation energy:                      11.543227 [MeV]

------------------------------------------------------------------------------------------
 NL    EL[MeV]     S/P  F     T1/2[s] Ng  s unc               s-info  nd m        p       mode
                                          Nf     Eg[MeV]      Pg          Pe          Icc
------------------------------------------------------------------------------------------
  1   0.000000    2.5 -1  1.340E+01  0 u                  5/2-#  1 =  1.0000E+02 %B-
  2   0.306510    1.5 -1             1 u                 (3/2-)  0
                                          1     0.3065  9.912E-01  1.000E+00  8.900E-03
  3   0.711670    1.5  1             2 g                         0
                                          2     0.4052  7.865E-01  7.876E-01  1.386E-03
                                          1     0.7117  2.124E-01  2.124E-01  3.510E-04
  4   1.193700    1.5  1             2 g                         0
                                          2     0.8870  9.664E-02  9.666E-02  2.198E-04
                                          1     1.1938  9.032E-01  9.033E-01  1.673E-04
  5   1.196530    0.5  1             2 g                         0
                                          2     0.8900  9.344E-01  9.346E-01  2.183E-04
                                          1     1.1962  6.541E-02  6.544E-02  5.080E-04
  6   1.256760    2.5 -1             2 g                         0
                                          2     0.9501  2.125E-01  2.126E-01  4.090E-04
                                          1     1.2568  7.872E-01  7.874E-01  2.399E-04
```

https://www-nds.iaea.org/cgi-bin/ripl_levels.pl?Z=33&A=83

$^{83}_{33}As_{50}$-1 From ENSDF - Evaluated December 2014 $^{83}_{33}As_{50}$-1

Adopted Levels, Gammas

		History	
Type	Author	Citation	Literature Cutoff Date
Full Evaluation	E. A. Mccutchan	NDS 125, 201 (2015)	31-Dec-2014

https://www.nndc.bnl.gov/ensnds/83/As/adopted.pdf

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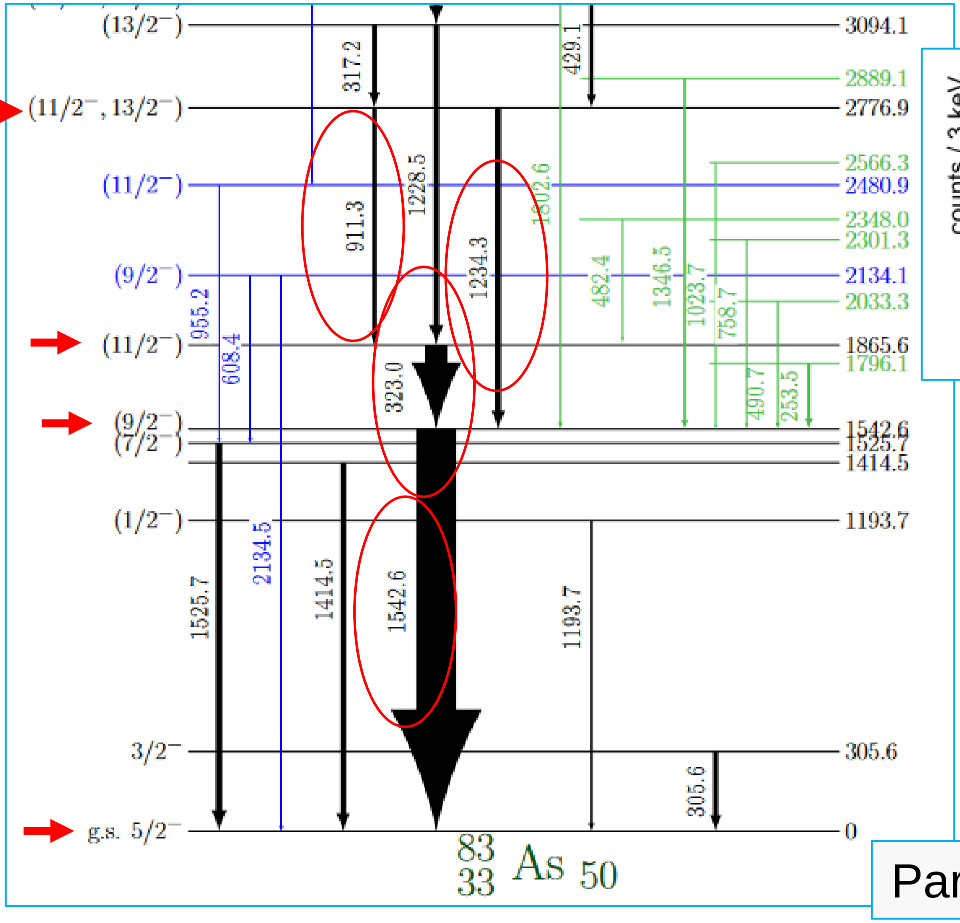
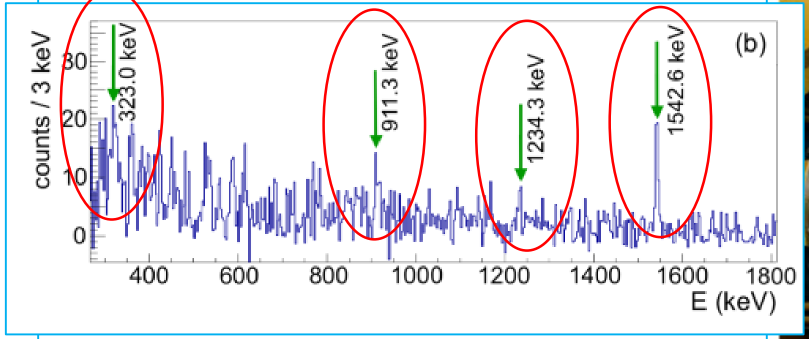
Measured with setups like AGATA (and many others)

https://www.agata.org/



K. Rezynkina *et al.* Phys. Rev. C **106**, 014320 (2020)



Partial level scheme

Correlate transitions to get level scheme.

Spin assignment e.g. from observed transitions and input from, e.g., angular distributions, beta decay, etc.

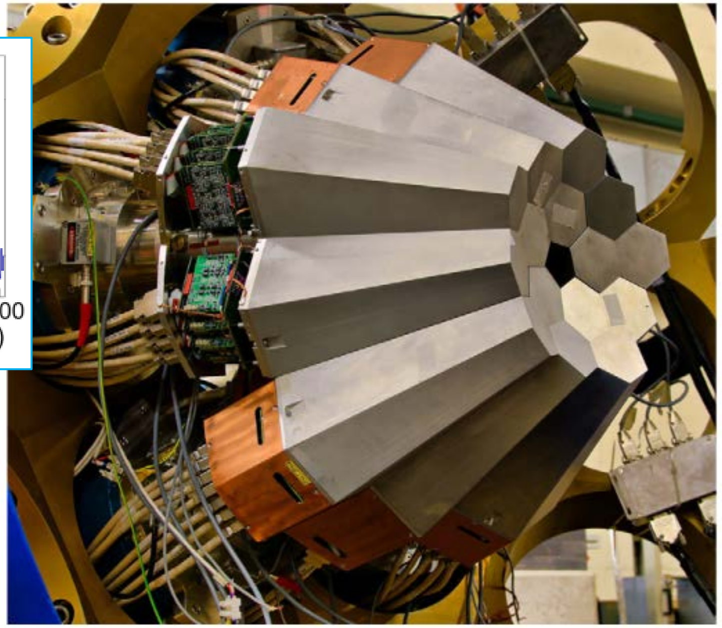


Fig. 6. (Colour online) Photograph of the setup with five AGATA triple cluster detectors installed at LNL in Italy.

S. Akkoyun et al. / NIM A **668** (2012) 26–58

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Levels: ^{83}As

E(level)†	J^{π}‡	$T_{1/2}$	XREF	Comments
0.0	(5/2⁻)	13.4 s *4*	ABC	$\%\beta^-=100$ $T_{1/2}$: weighted average of 14.1 s *11* (1968De19), 13.3 s *4* (1969ScZY), 13.3 s *6* (1974KrZG). J^{π}: the first two orbitals located above the Z=28 shell closure are πf5/2 and πp3/2, thus the low-lying levels are expected to have J^{π}=3/2⁻,5/2⁻. ^{85}Br (Z=35) has J^{π}(g.s.)=3/2⁻, suggesting that the f5/2 orbital is filled first; therefore, ^{83}As(Z=33) should have J^{π}(g.s.)=5/2⁻. Non observation of the 306-keV level in ^{208}Pb(^{18}O,Xγ) further suggests the spin of the ground state is higher than that of the 306-keV level.
306.51 *4*	(3/2⁻)		A C	J^{π}: see comment on J^{π} of ground state.
711.67 *5*			A	
1193.70 *10*			A	
1196.53 *14*			A	
1256.76 *9*			A	
1329.87 *10*			A	
1415.11 *10*			A	
1434.92 *9*			A	
1525.48 *13*			A	
1543.41 *15*	(9/2)		ABC	J^{π}: Q 1543γ to (5/2⁻).
1804.78 *11*			A	
1866.21 *25*	(11/2)		BC	J^{π}: D 323γ to (9/2).

https://www.nndc.bnl.gov/ensnds/83As/adopted.pdf

```
83As
  number of levels:                                 33
  number of gamma-rays:                             57
  number of levels in a complete level scheme:      15
  number of levels with assigned spin and parity:   1
  neutron separation energy:                        7.635222 [MeV]
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----------------------------------------------------------------------------------------------
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                                            Nf        Eg[MeV]     Pg              Pe            Icc
----------------------------------------------------------------------------------------------
   1   0.000000    2.5  -1   1.340E+01   0  u                      5/2-#   1  =   1.0000E+02 %B-
   2   0.306510    1.5  -1               1  u                     (3/2-)   0
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   3   0.711670    1.5   1               2  g                              0
                                              2    0.4052   7.865E-01   7.876E-01   1.386E-03
                                              1    0.7117   2.124E-01   2.124E-01   3.510E-04
   4   1.193700    1.5   1               2  g                              0
                                              2    0.8870   9.664E-02   9.666E-02   2.198E-04
                                              1    1.1938   9.032E-01   9.033E-01   1.673E-04
   5   1.196530    0.5   1               2  g                              0

   6   1.256760    2.5  -1
```

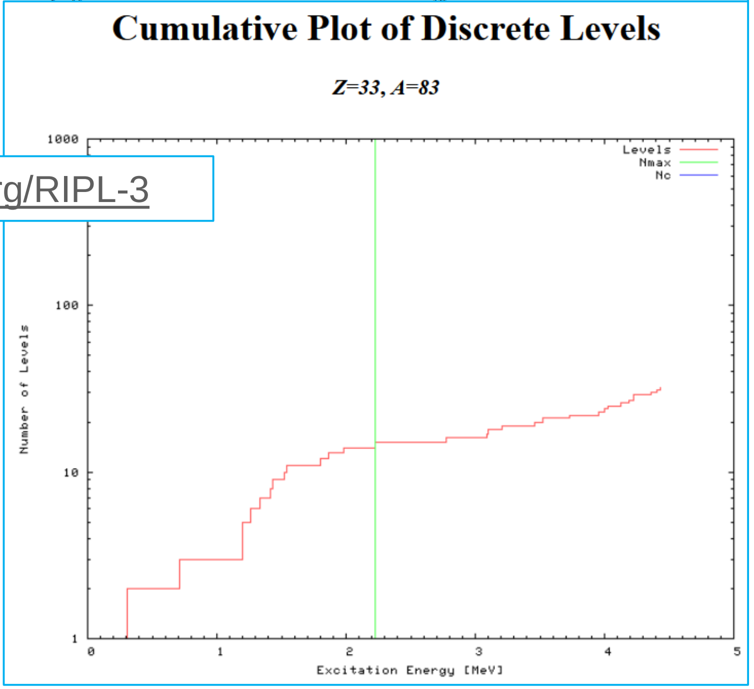

https://www-nds.iaea.org/RIPL-3

In this example case, ENSDF is from 2014 and RIPL-3 has more up-to-date information.
If a particular level scheme has a large impact on your work: **check the literature**.
You can update the level (and decay) schemes used by TALYS.

Level densities – Oslo method

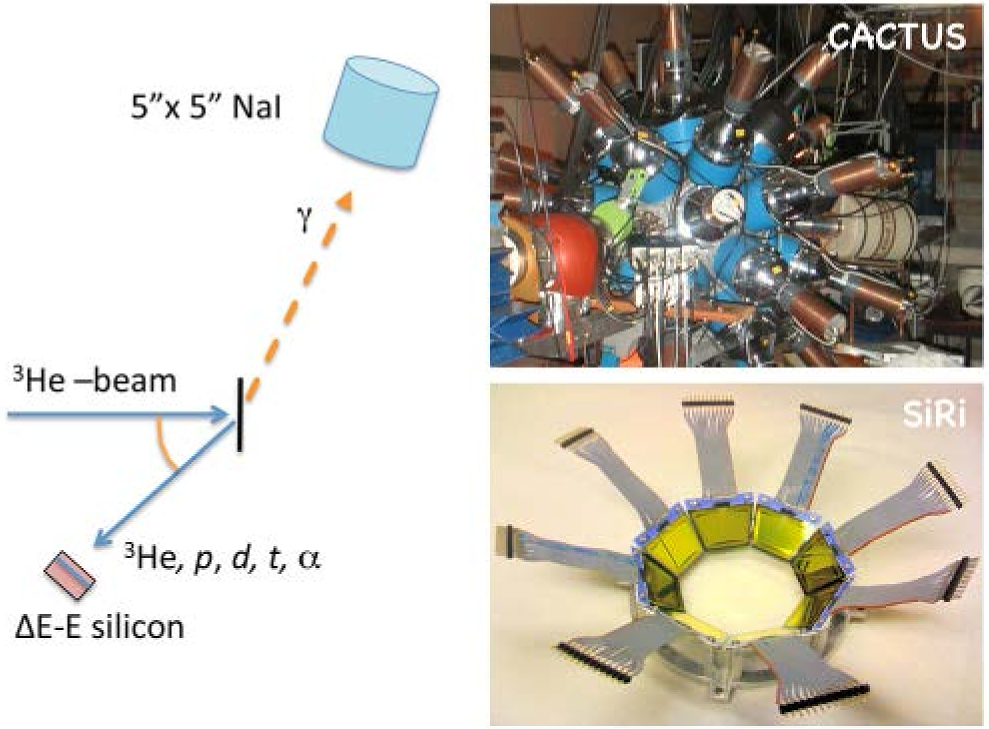

Fig. 2. (Color online) Typical particle-γ coincidence set-up for the Oslo method. The 64 silicon particle telescopes of SiRi are placed in the vacuum chamber at the center of CACTUS.

The Oslo cyclotron delivers a charged particle beam.

"The excitation of the nucleus is performed by light ion reactions, e.g. (d,$p\gamma$), (p,$p'\gamma$) and (^{3}He,$\alpha\gamma$) where the **energy of the charged ejectile determines the excitation energy**."

The CACTUS setup measures the γ-rays.

M. Guttormsen et al., EPJ A **51**, 170 (2015).
https://doi.org/10.1140/epja/i2015-15170-4

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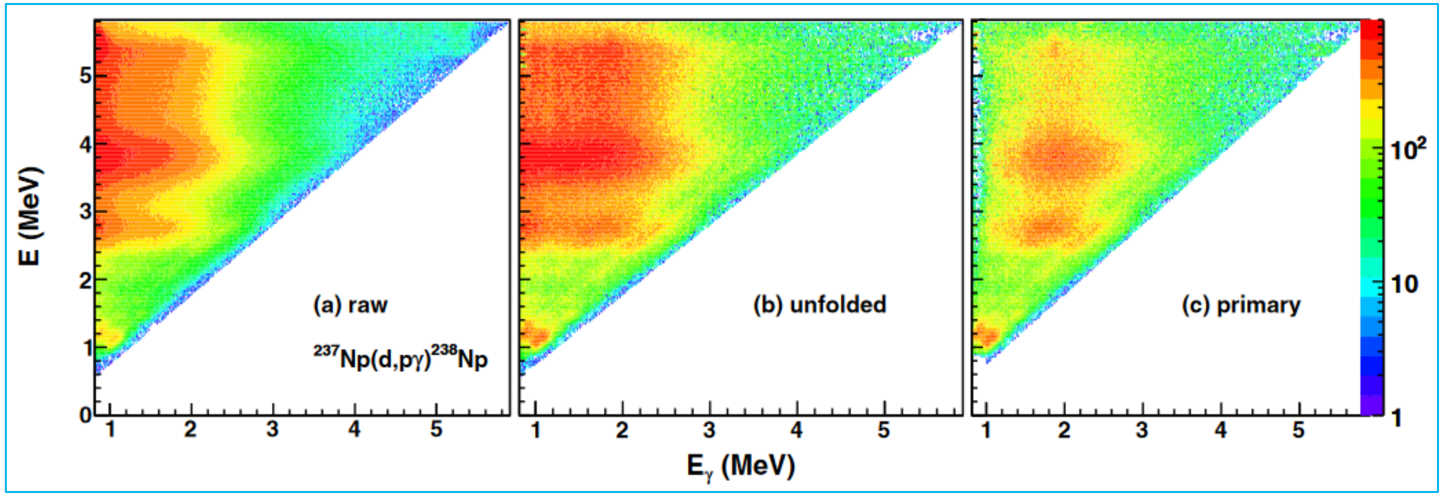
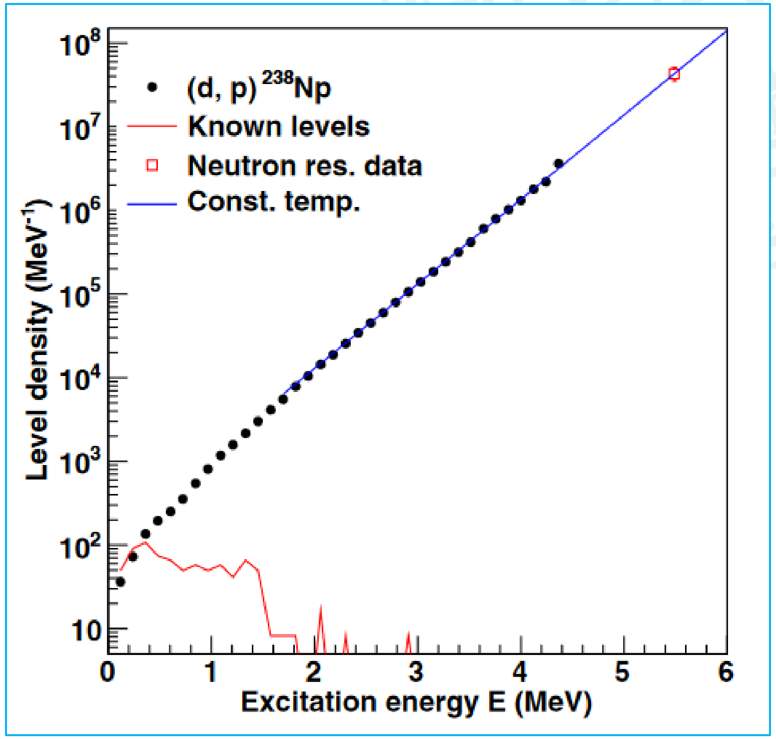
Level densities – Oslo method

excitation energy





T. G. Tornyi et al., PRC **89**, 044323 (2014)
http://dx.doi.org/10.1103/PhysRevC.89.044323

The figure shows measured γ-spectra as function of excitation energy (left).
An unfolding procedure yields **primary γ-rays** (right).
From these, the level densities can be derived.
(for details see, e.g., A. Schiller et al., NIM A **447**, 494 (2000))

These are found to be almost independent of particle reaction and beam energy. I.e. the compound nucleus has only “memory” of spin and parity distribution.

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Excursion: Surrogate reactions

Note that in the previous example of a nuclear data measurement a technique is used that is often called **surrogate reaction**.

"The Surrogate Nuclear Reaction technique *combines experiment with theory* to obtain cross sections for **compound-nuclear reactions**, **a + A -> B* -> c + C**, **involving difficult-to-produce targets, A**." (J. Escher et al., NIM B **261** (2007) 1075.)

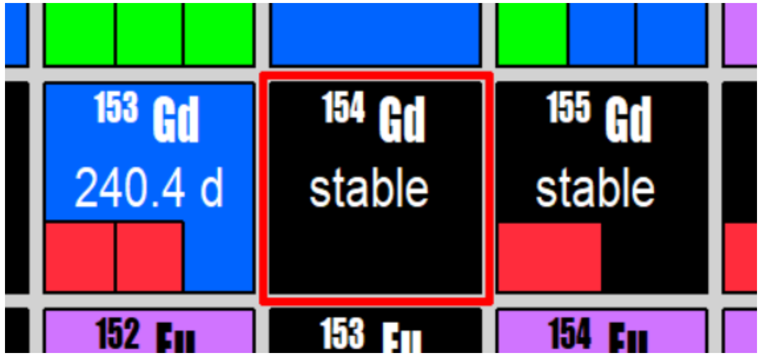
Example:

Goal: study neutron capture in $^{153}Gd(n,\gamma)^{154}Gd$

Use instead:

$^{155}Gd(^{3}He,\alpha)^{154}Gd$

(pick-up of one neutron)



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Surrogate reactions

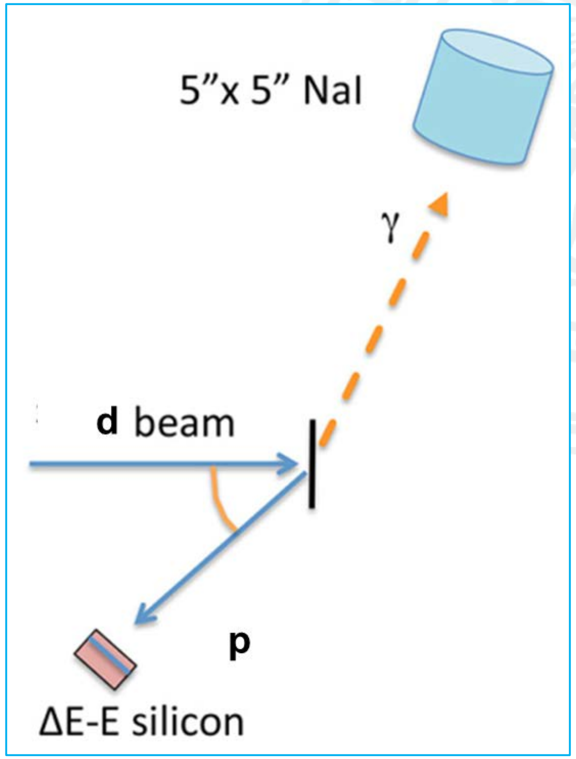
In the shown example from the Oslo cyclotron, however, the challenge is different.

How to produce excited states below S_n ?

This is, obviously, not possible with a neutron beam.

Here coincidence of a proton and a γ-ray means that a **(d,pγ)** reaction occurred, corresponding to the transfer of a neutron into the ^{237}Np target nucleus.
Due to the *binding energy of the neutron in deuterium*, excitation energies below S_n can be populated.

E* is derived from the Q-value of the reaction and the measured kinetic energy of the **spectator proton**. Rather precise determination of E* is possible in this way.



Adapted from
M. Guttormsen et al., EPJ A **51**, 170 (2015).
https://doi.org/10.1140/epja/i2015-15170-4

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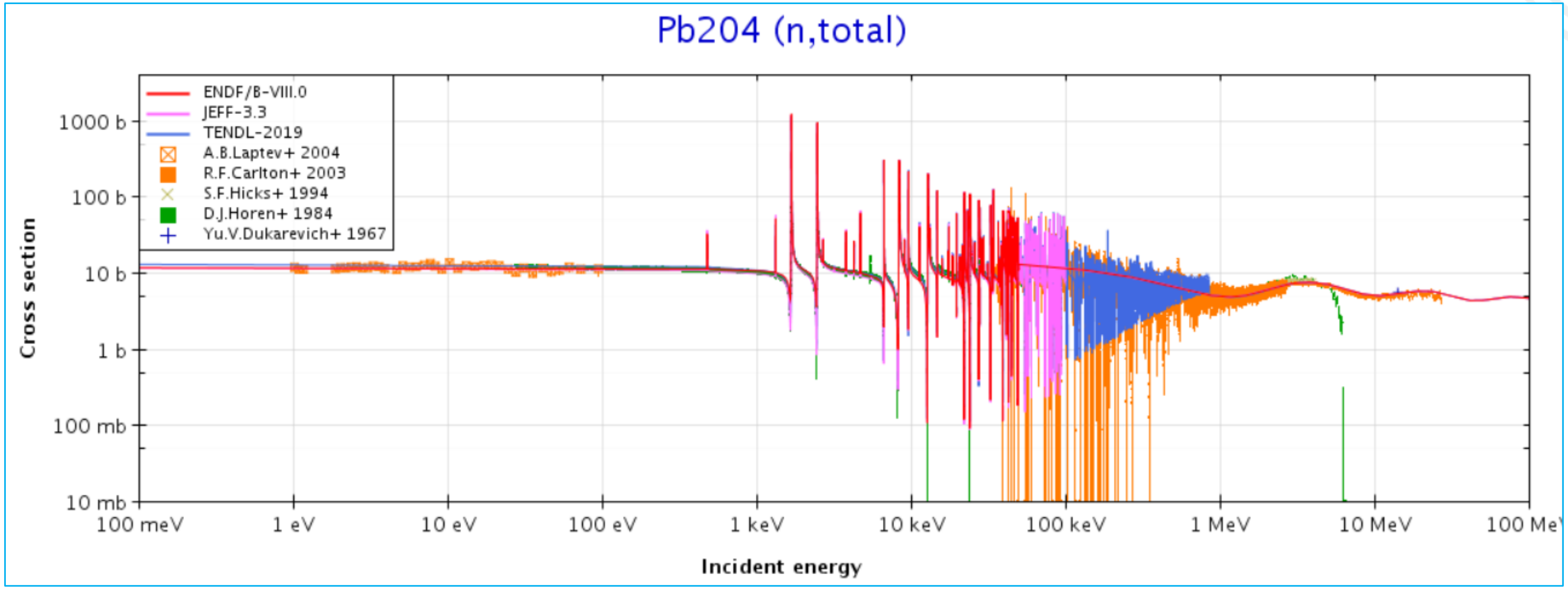
Total cross section



Plotted using: https://www.oecd-nea.org/janisweb

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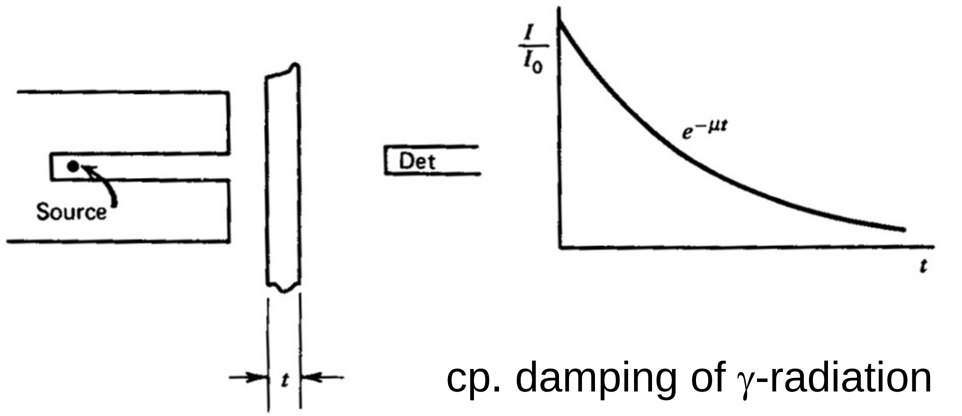
Total cross section measurements - Principle

Common method: transmission measurements.

$$T(x) = \frac{\Phi}{\Phi_o} = e^{-\sigma_T n_x}$$

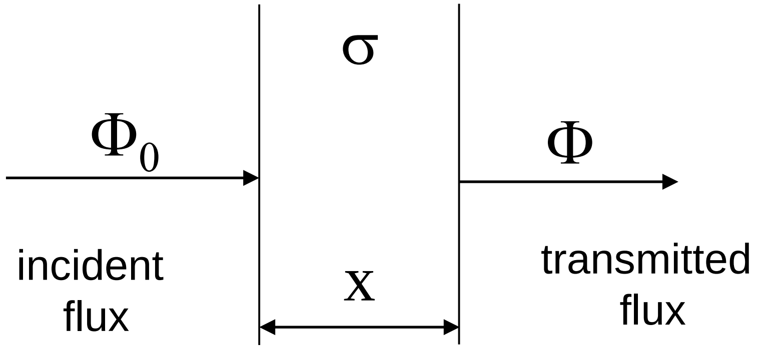
Number density ρx
(atoms per barn)



cp. damping of γ-radiation

Effective total cross section

$$\sigma_T = -\frac{1}{n_x}\, T(x)$$



Total neutron cross section for x -> 0

(“infinitely” thin absorber)

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Total cross section measurements

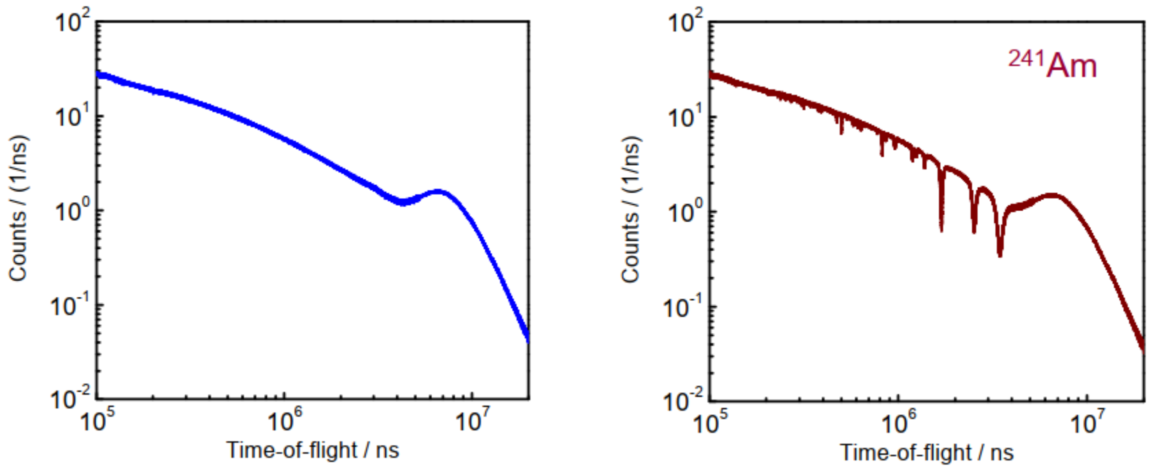
Challenges:

- Detected neutrons passed through the sample (good control of background)
- Neutrons scattered in the target do not reach detector
- Good transmission geometry (collimation, target orientation, …)
- Homogeneous target

Often measured

at **time-of-flight facilities**

like GELINA.



Neutron time-of-flight without (left) and with target (right)

Figs:
P. Schillebeecks

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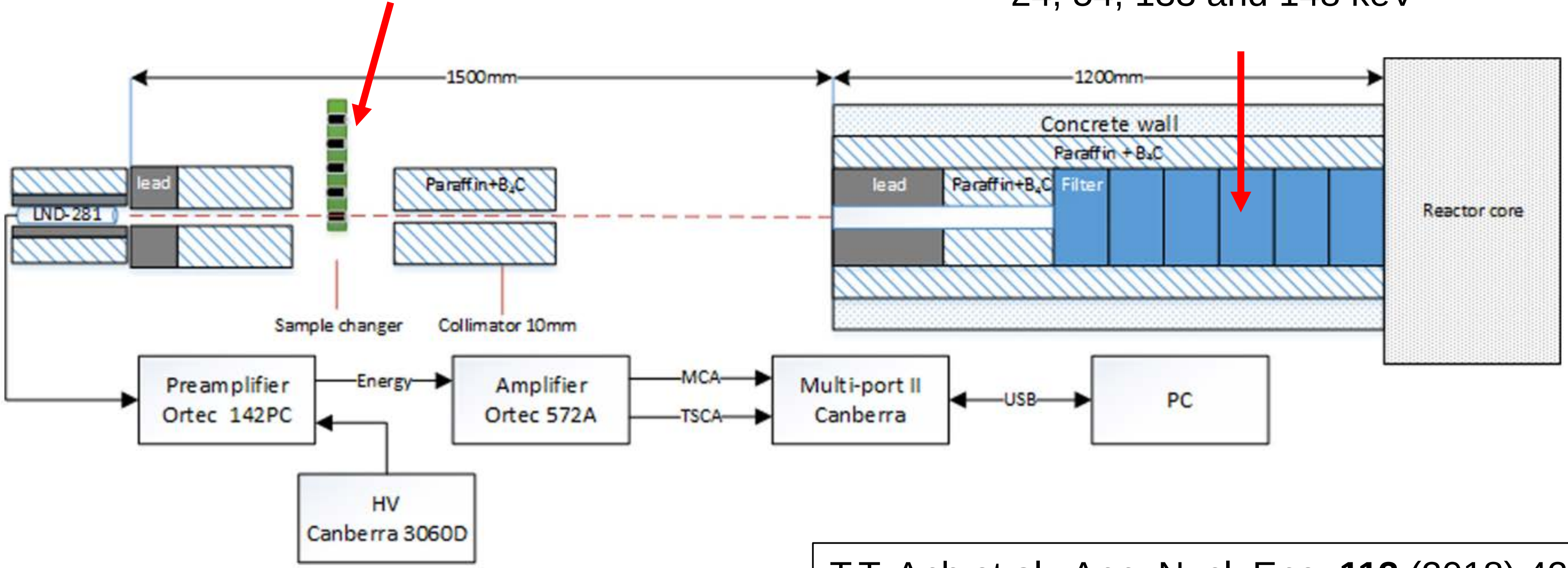
Total cross section measurements - Example

93Nb samples with
Different thicknesses

Filters to achieve beams with
24, 54, 133 and 148 keV

Neutron detector



Research reactor in Dalat, Viet Nam

T.T. Anh et al., Ann. Nucl. Ene. **113** (2018) 420

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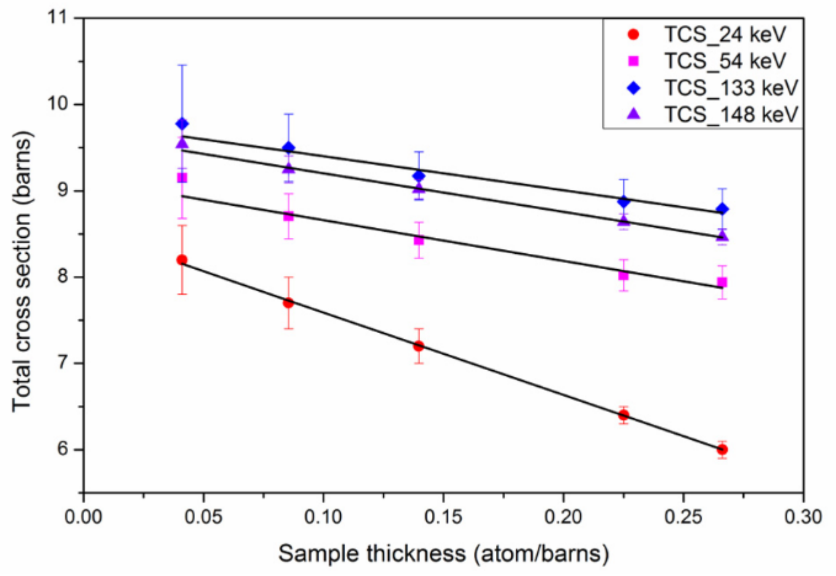
Total cross section measurements - Example

Table 4
Total neutron cross sections of ^{93}Nb in keV region (in barns).

#	$N_x \pm \Delta N_x$ (at/b)	24 keV $\sigma_t \pm \Delta\sigma_t$ (b)	54 keV $\sigma_t \pm \Delta\sigma_t$ (b)	133 keV $\sigma_t \pm \Delta\sigma_t$ (b)	148 keV $\sigma_t \pm \Delta\sigma_t$ (b)
1	0.0411 ± 0.0001	8.17 ± 0.44	9.15 ± 0.47	9.78 ± 0.68	9.54 ± 0.28
2	0.0854 ± 0.0002	7.68 ± 0.25	8.71 ± 0.26	9.50 ± 0.39	9.25 ± 0.16
3	0.1397 ± 0.0004	7.16 ± 0.21	8.43 ± 0.21	9.17 ± 0.28	9.02 ± 0.11
4	0.2251 ± 0.0007	6.45 ± 0.12	8.02 ± 0.18	8.88 ± 0.26	8.64 ± 0.09
5	0.2662 ± 0.0009	5.99 ± 0.09	7.94 ± 0.19	8.79 ± 0.24	8.47 ± 0.09
σ_t		**8.50** ± **0.29**	**9.13** ± **0.29**	**9.79** ± **0.41**	**9.60** ± **0.17**



Total neutron cross section for x -> 0 (“infinitely” thin absorber)

T.T. Anh et al., Ann. Nucl. Ene. **113** (2018) 420

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Transmission and interaction ("reaction")

Everything that is not transmitted has interacted in the target:

$$T = e^{-\sigma_T n}$$

$$T = \frac{\Phi}{\Phi_o} = \frac{C_{in}}{C_{out}}$$

Absolute flux and

detection efficiency cancel;

σ_T can be measured

with **low uncertainties** (<1%)

$$Y_r \cong (1 - e^{-\sigma_T n})\frac{\sigma_r}{\sigma_T} + \ ...$$

$$Y_{r,exp} = \frac{C_r}{\varepsilon_r \ \Omega_r \ \Phi_n \ A_r}$$

Detection efficiency and solid angle coverage

Neutron flux and target area

More complex relation

between experimental yield

and σ_r. Larger uncertainties.

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Interactions ("Reactions")

These include

- Elastic scattering (n,n)
- Inelastic scattering (n,n'γ)
- Capture (n,γ)
- Fission (n,f)
- Neutron production (n,xn)
- Charged-particle production (n,xp), (n,xd), …

We will now look at measurement examples for some of these observables.

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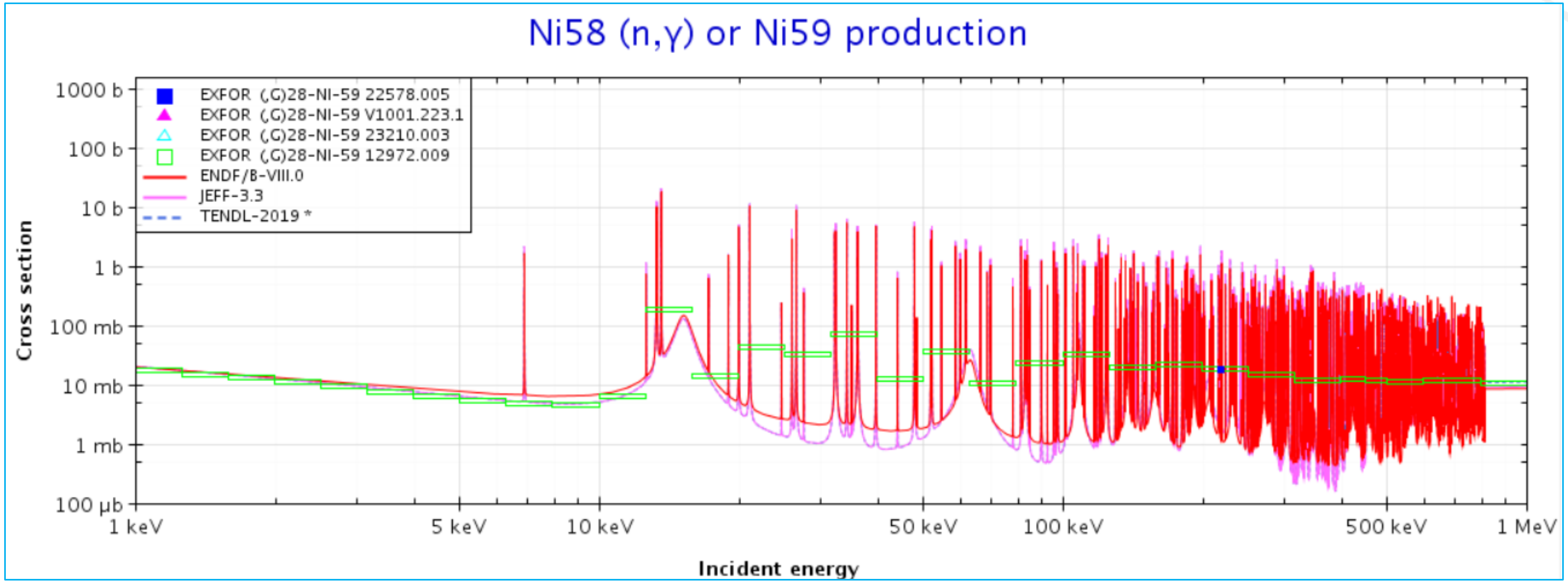
Capture cross section



Plotted using: https://www.oecd-nea.org/janisweb

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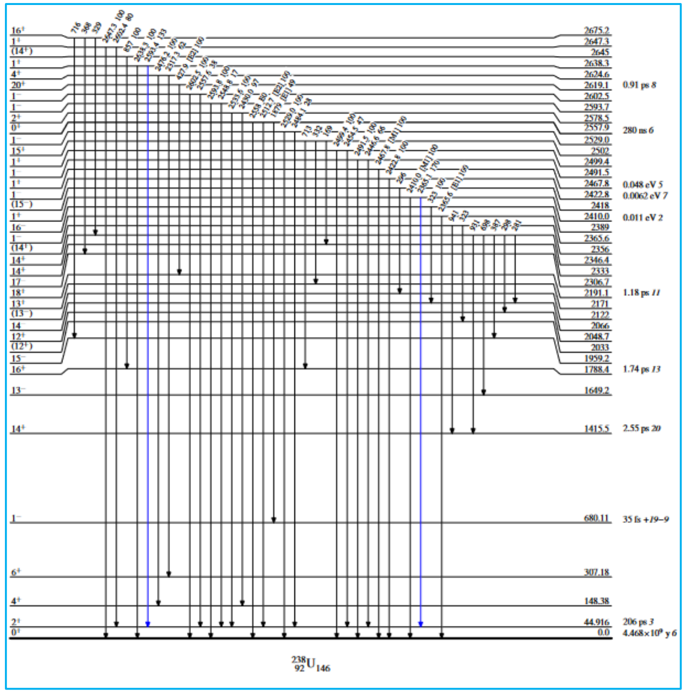
Capture cross section

Especially in the resonance region best measured at time-of-flight facilities (GELINA, LANSCE, n_TOF, …)

Ideally:

- Detection efficiency independent of the γ-ray cascade
- Low sensitivity to scattered neutrons
- Good time response of detectors

(see, e.g., A. Borella et al., NIM A **577** (2007) 626 and references therein)



Partial level scheme for 238U
https://www.nndc.bnl.gov/ensnds/238/U/adopted.pdf

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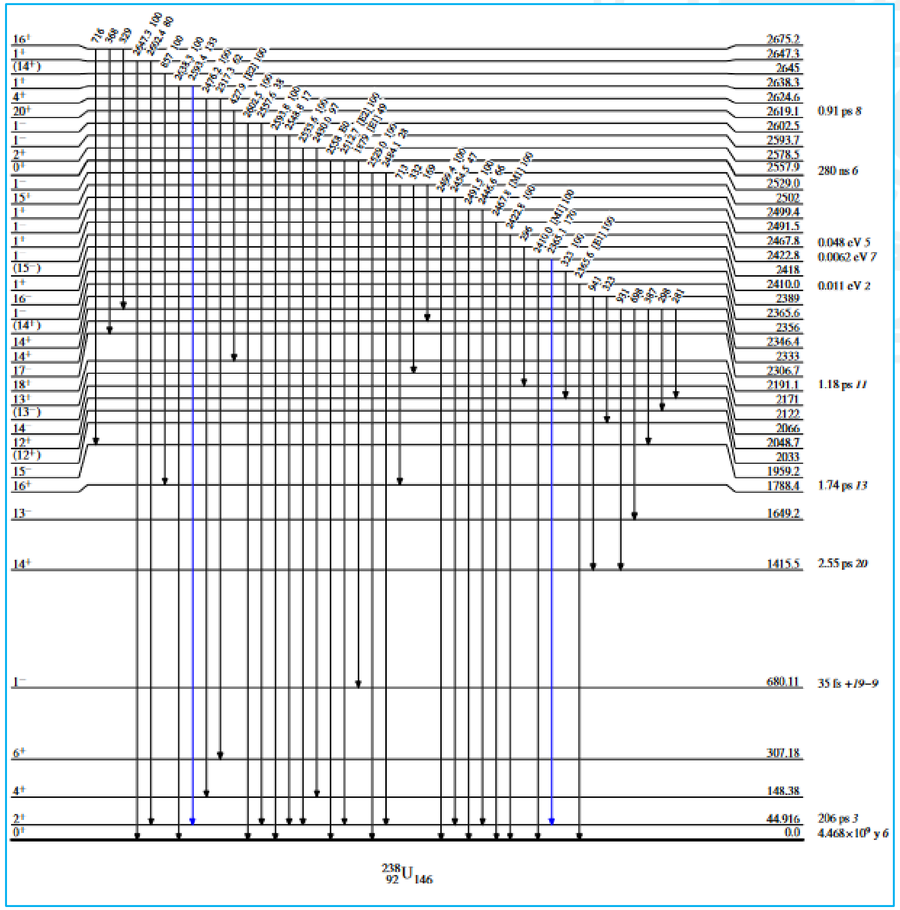
Capture cross section

Options:

- γ-ray spectroscopy using Ge-detectors
  - Determine spin and parity of populated states.
  - Can distinguish isotopes if ^{nat}X samples are used.
  - Needs good knowledge of level scheme.
  - Sensitive to neutrons and no good time resolution.

- Total absorption detectors
  - Need 4π coverage and near 100% efficiency (e.g. BaF_2).
  - Used e.g. at n_TOF

- Total energy detection principle
  - Needs: efficiency low and proportional to E_γ.
  - Used at GELINA with C_6D_6 liquid scintillators.
  - With the pulse weighting technique, efficiency becomes independent of the γ-ray cascade.



Partial level scheme for 238U
https://www.nndc.bnl.gov/ensnds/238/U/adopted.pdf

Sources: P. Schillebeeckxs, ICTP School 2017, A. Borella et al., NIM A **577** (2007) 626

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Capture cross section measurement at GELINA

H.I. Kim et al., EPJ A (2016) **52:** 170 as example

Total energy detection principle and pulse weighting technique is used to measured $^{238}U(n,\gamma)$ in the resonance region.

12.5 m and 60 m capture measurement stations of GELINA were used.

Only s- and p-wave neutrons contribute.

For **compound spin J = 1/2**:
primary γ-rays are emitted isotropically.

For **compound spin J = 3/2**:
the impact of anisotropic emission of the primary γ-rays is avoided by placing the detectors at 125°.

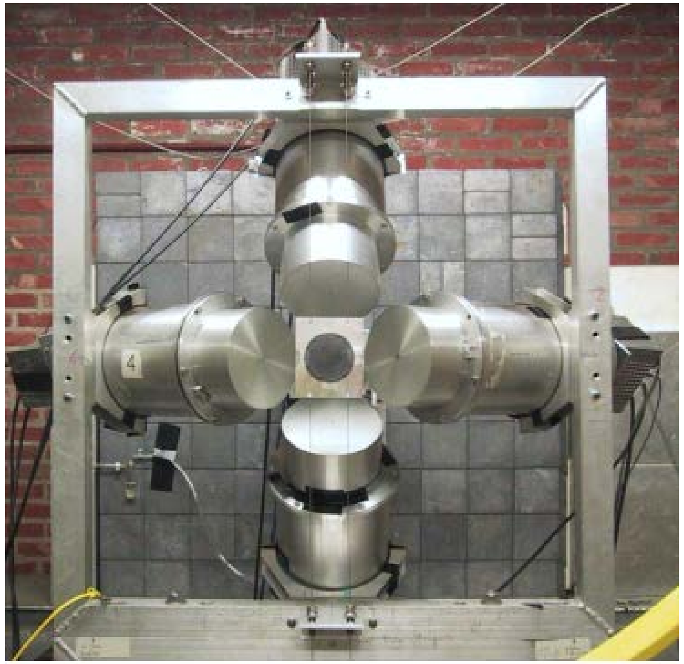

Figure: P. Schillebeeckxs, ICTP School 2017

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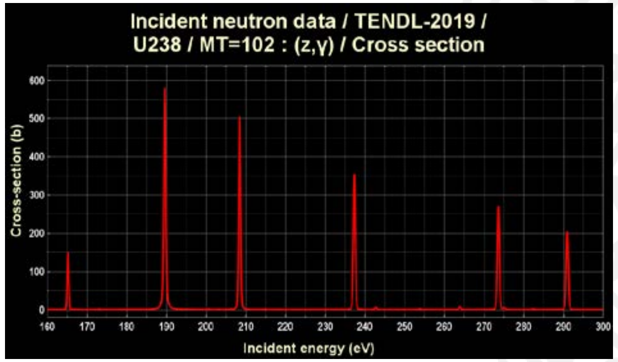
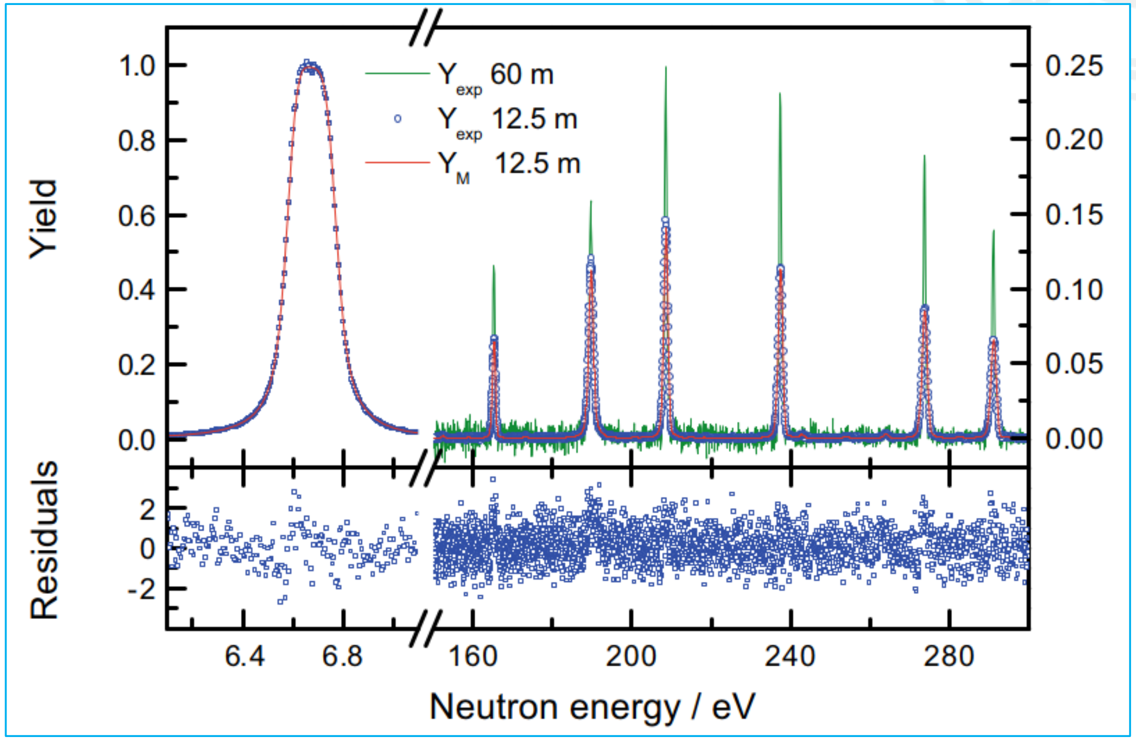
Capture cross section measurement at GELINA



First excited state of 238U is at 45 keV. Hence no contribution from (n,n'γ).

The total uncertainty due to the weighting function, normalization, neutron flux and sample characteristics is about 1.5%.

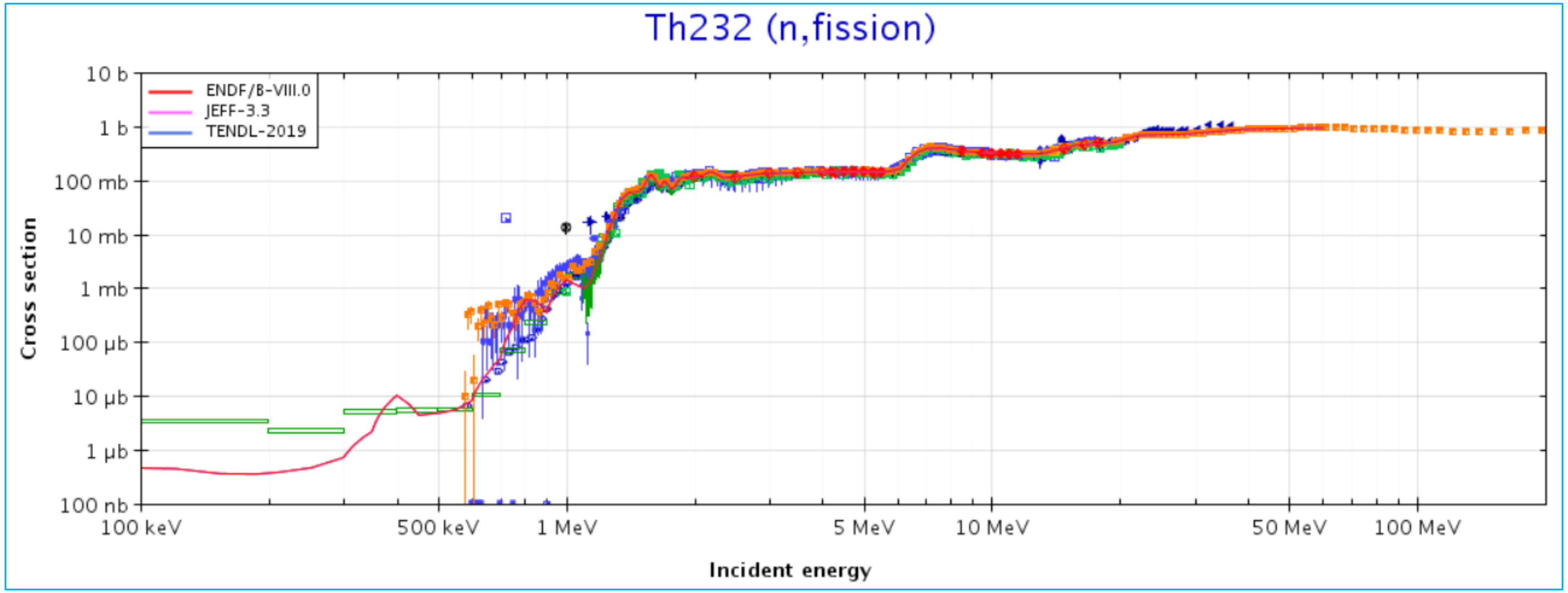
Example of experimental data:



H.I. Kim et al., EPJ A (2016) **52:** 170

Note the higher neutron-energy resolution that is obtained at the 60 m station.

Fission



Plotted using: https://www.oecd-nea.org/janisweb

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Fission cross section measurement (at n_TOF)

What we need:

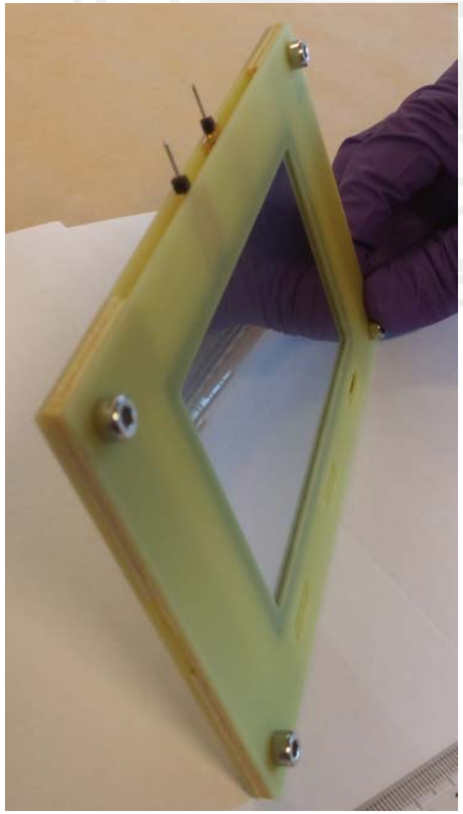
A detector for **registering fission products** and identifying that a fission event has occurred. Preferably insensitive to other types of radiation (e.g. α particles).

Detector should have **good timing** to allow determination of the incident neutron energy from a time-of-flight measurement.

One option: **Parallel Plate Avalanche Counters** (PPACs); gas-filled detectors with low mass (stopping power), relatively simple structure, and comparatively easy to maintain.

Suitable design (position sensitive PPAC) allows even measurement of angular distribution of the fission product.

Measure **relative to a reference cross section**, e.g., ^{238}U(n,f).



M. Carlsson, Master thesis, UU 2018

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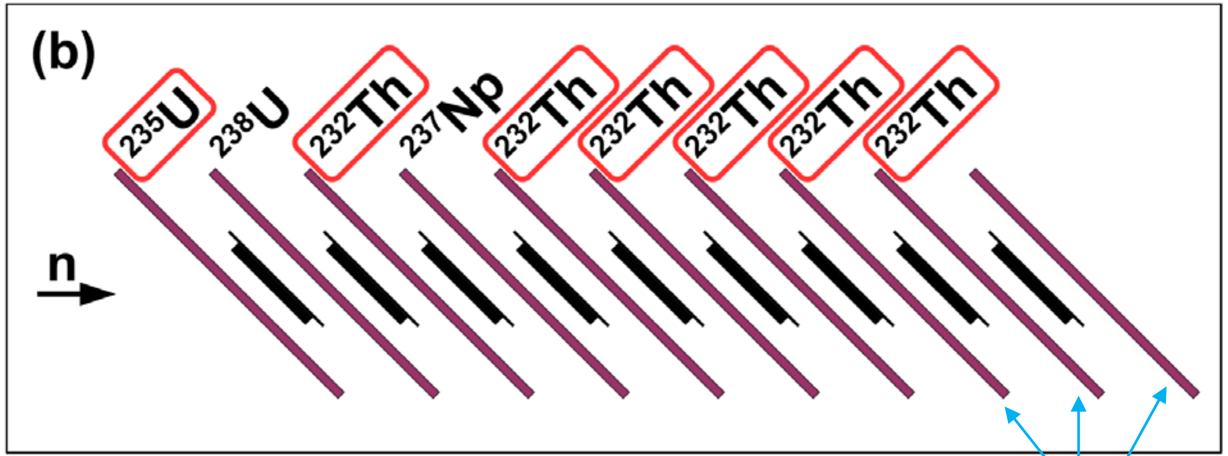
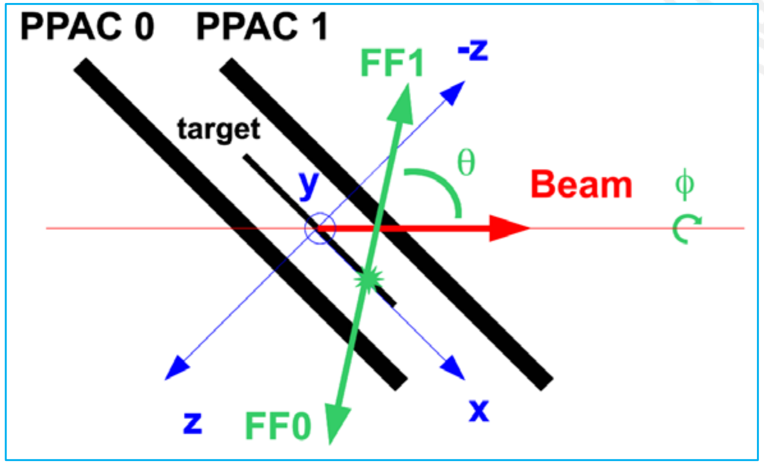
Fission cross section measurement at n_TOF

PPAC – Target – PPAC – Target …



Figures: D. Tarrío et al., PRC **107**, 044616 (2023)

Fission ID: 2 PPACs “fire”



Simultaneous measurement relative to another cross section.

The neutron fluence cancels:

$$\frac{\sigma_i(E_n)}{\sigma_j(E_n)} = \frac{C_i(E_n)}{C_j(E_n)} \frac{\cancel{\Phi(E_n)}}{\cancel{\Phi(E_n)}} \frac{N_j}{N_i} \frac{\varepsilon_j(E_n)}{\varepsilon_i(E_n)}$$

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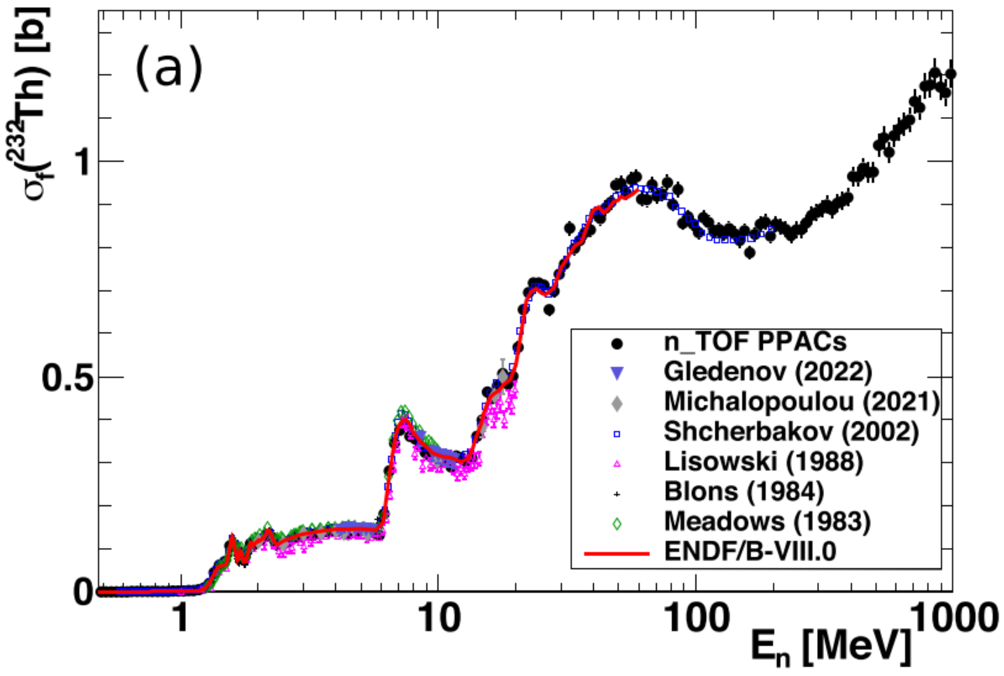
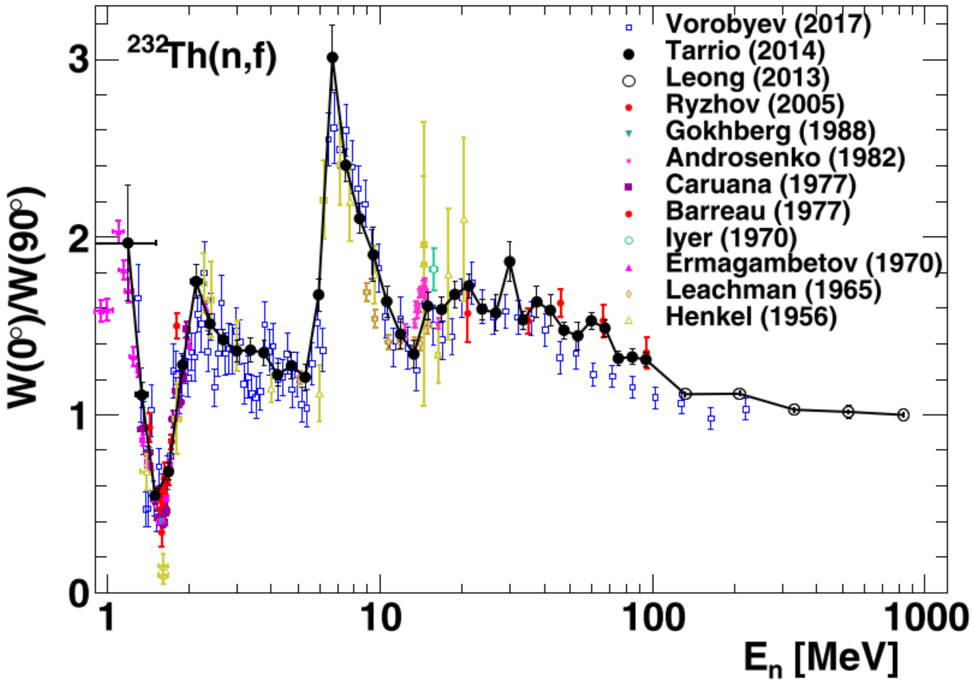
As example: Results for $^{232}Th(n,f)$

Cross section



Anisotropy



D. Tarrío et al., PRC **107**, 044616 (2023)

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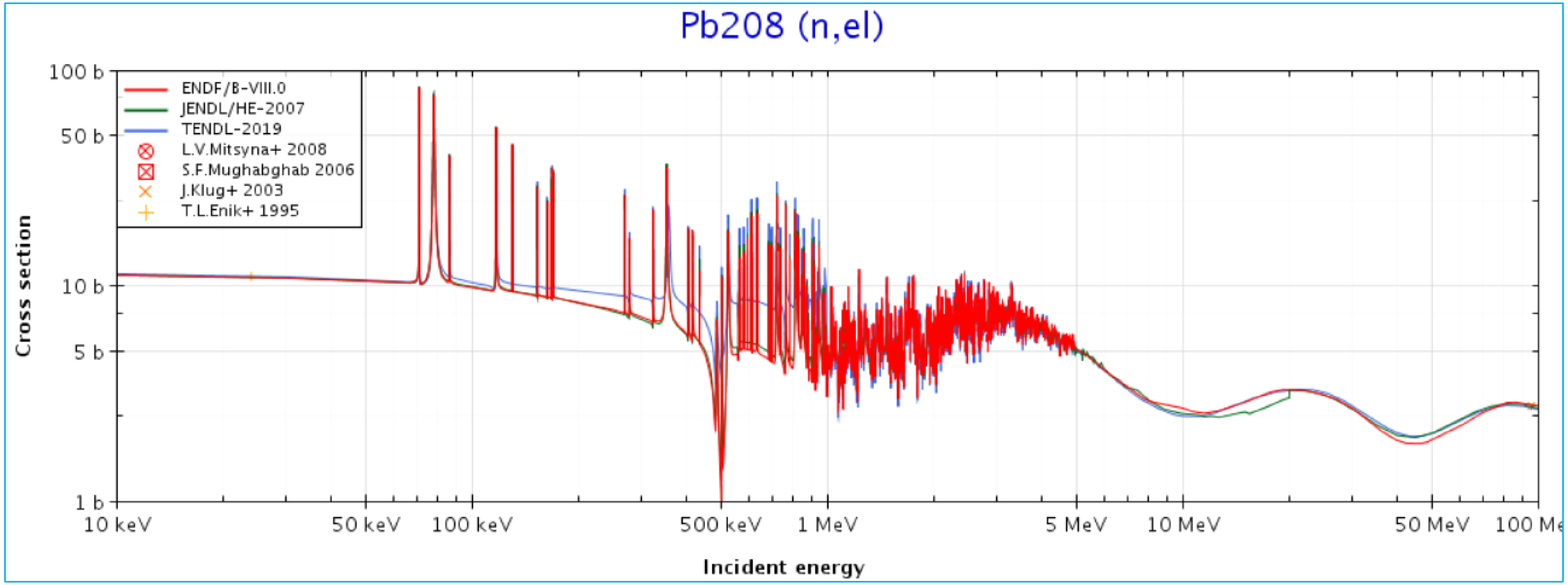
Elastic



Plotted using: https://www.oecd-nea.org/janisweb

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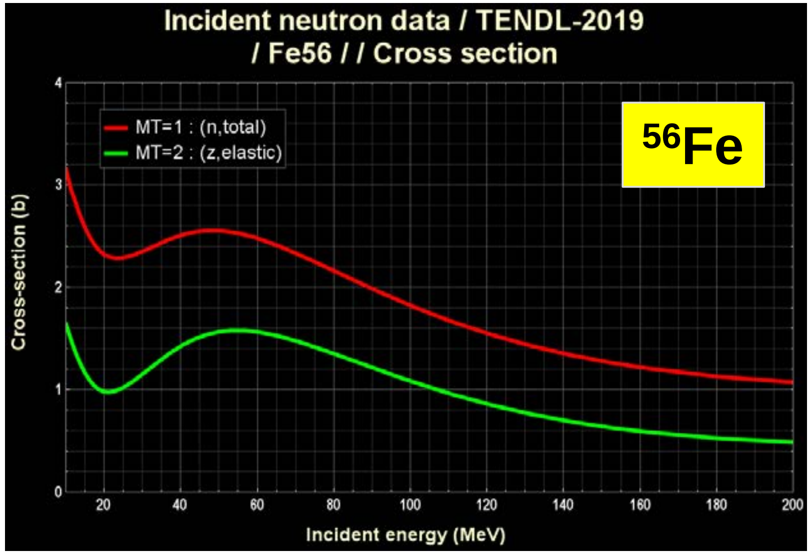
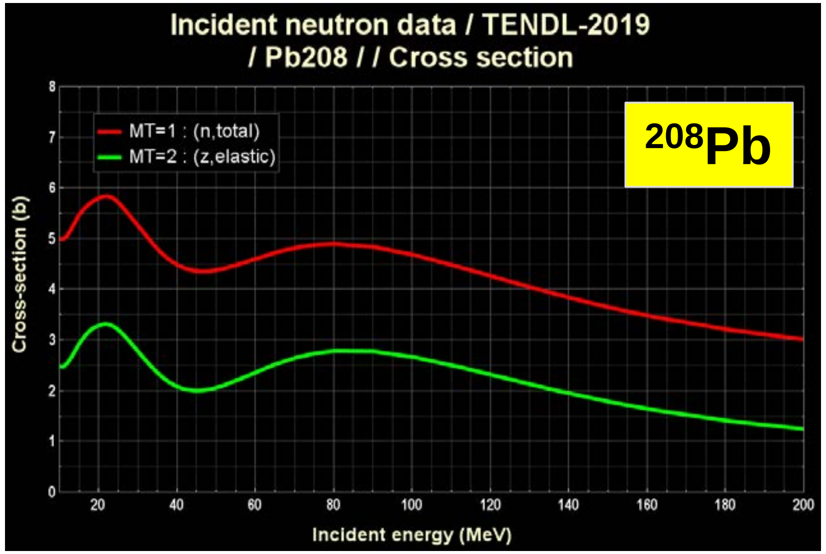
Elastic scattering of neutrons (n,n)

- Incident particle's direction of motion (and state of polarization) is changed **without loss of energy** (in CM), by interaction with a target nucleus.
- Important way to study the nuclear potential and obtain optical model parameters.
  See, e.g., A. Koning and J.P. Delaroche, Nucl. Phys A **713** (2003) 231.





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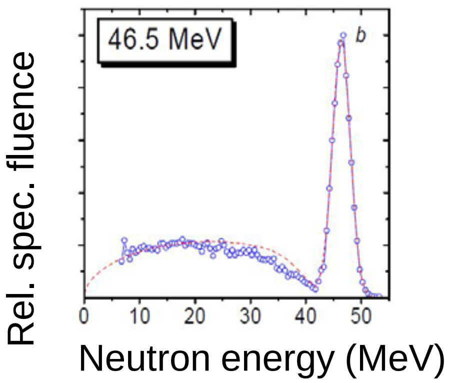
General questions – not specific to elastic scattering

- Beam?
  - reactor (fission neutrons)
  - mono-energetic (DD, DT, …)
  - **quasi-monoenergetic (usually ^{7}Li(p,n))**
  - so-called white sources (spallation, W(p,nx))
- Target?
  - **normally solid (count rate)**
  - composite ? (e.g. SiO_2)
  - contamination ? (how “clean” – isotopic composition ?)
  - activity ?
  - normalization ? (relative measurements)
- Detectors?
  - charged particle ? (gas-filled, solid state, scintillators)
  - **neutrons ? (conversion,** liquid scintillator, …**)**
  - gamma ? (Ge, NaI, $LaBr_3$, …)



Measuring (n,n) with SCANDAL (with focus on $d\sigma/d\Omega$)

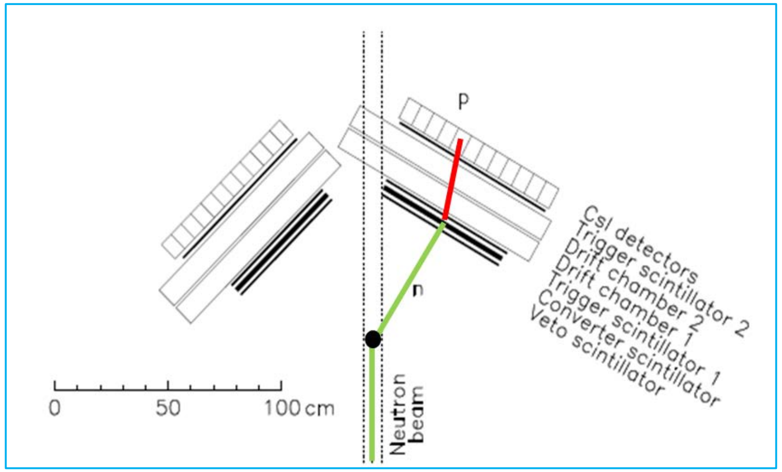
- **QMN neutron beam**, suppression of the low-energy tail using TOF.
- **Convert scattered neutron** to proton (using CH_2) and measure the energy of the proton.
- **Reconstruct** both scattering angle and energy of the scattered neutron

Challenge:

- Make sure the event was (n,n) and not (n,nx)
  - Conversion in CH_2 -> both H(n,p) and ^{12}C(n,p)
  - Detection of proton in scintillators

Solutions:

- Veto on incoming charged particle on converter
- Use kinematic cuts



Sketch of the SCAttered Neutron Detection Assembly (SCANDAL) detector setup

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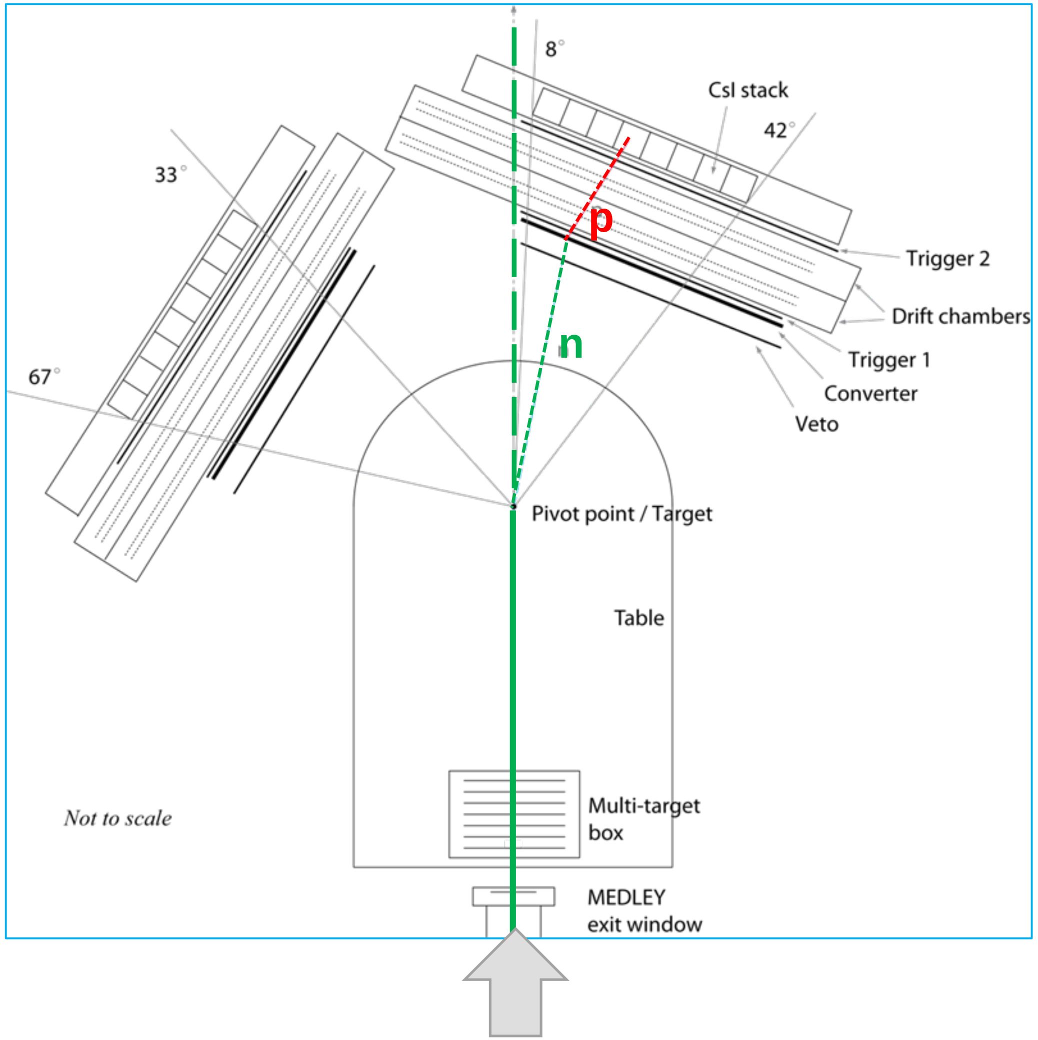
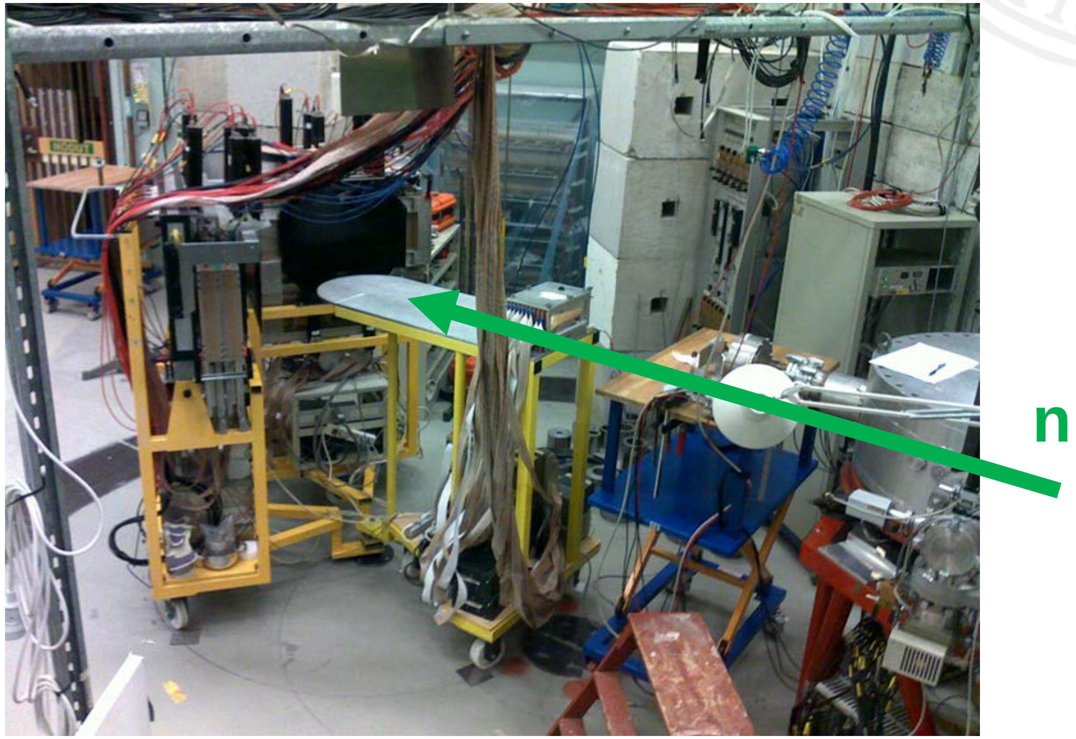
SCANDAL – drawing and IRL





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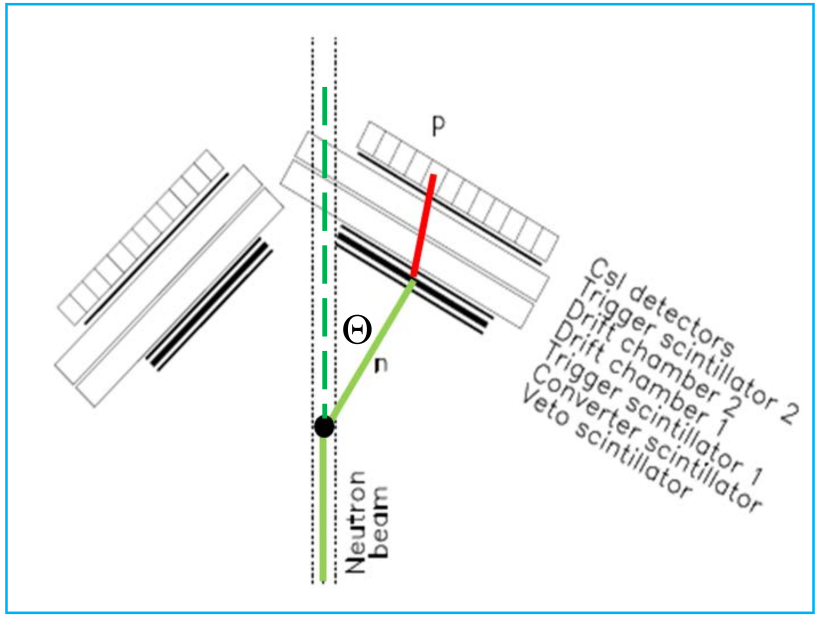
SCANDAL- More details about how it works



Data sets at **96 MeV**:
H, D, C, O, Fe, Y, Pb (n,n)
See e.g. Klug et al., PRC **68**, 064605 (2003)
C, Fe, Y, Pb (n,xn)
See e.g. Sagrado Garcia et al., PRC **84**, 044619 (2011)
,

Active plastic converter: CH_2

- H(n,p)
- C(n,p) Q-value: -12.6 MeV
- Overlap in proton energy from around 20°.
- Hence: Opening angle criterion 10°.

The proton track is registered via hits in gas filled drift chambers and the proton energy measured in scintillator (CsI).

For **elastic** scattering analysis, the analysis is straight forward. Always choose events with maximum energy.

For **inelastic** scattering it cannot be determined event-by-event if energy was lost in the target or in conversion on ^{12}C in the converter.

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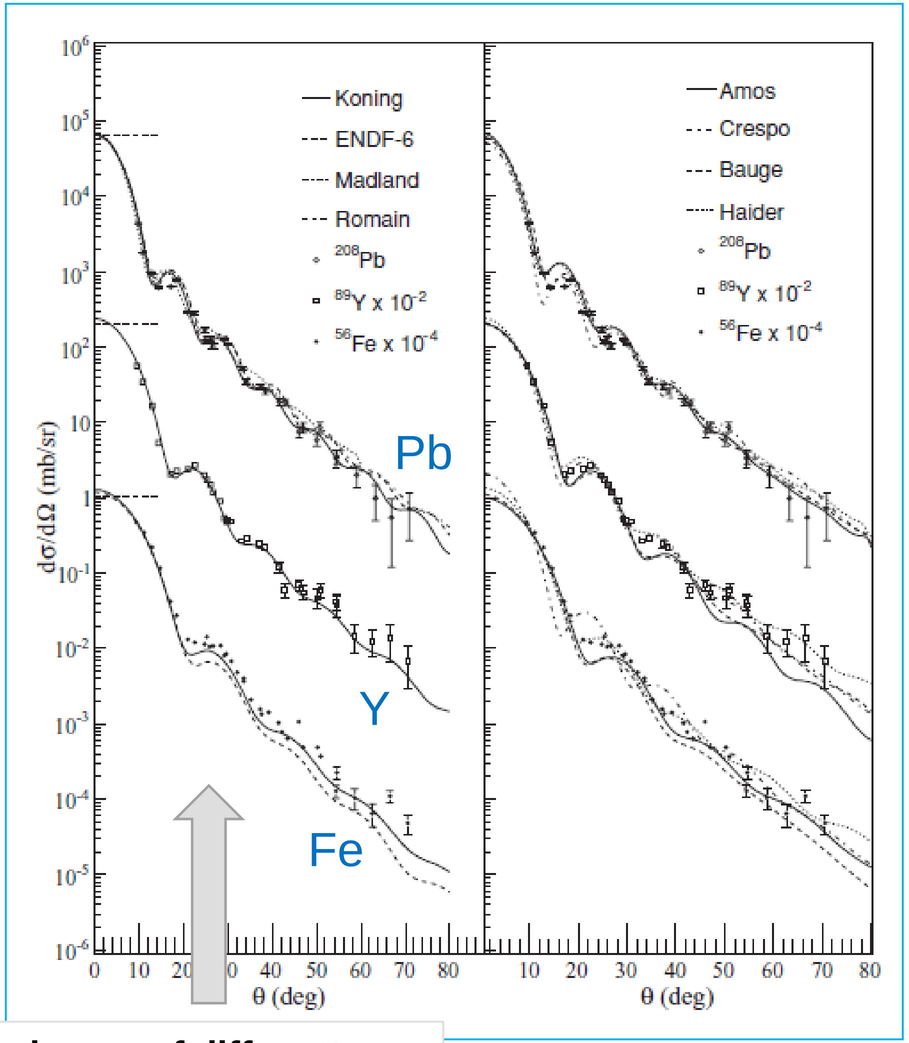
Example of measurement results dσ/dΩ for (n,n)

A. Öhrn et al., PRC **77**, 024605 (2008)



change of diff. pattern with incr. nuclear radius

Some further analysis steps and corrections:

- Particle ID (PID) via ΔE-E (scint – CsI)
- CsI detection efficiency
- corrections for multiple scattering (the target has several cm diameter; finite probability for second scattering -> washes out structures)

Absolut normalization:
integrate dσ/dΩ and normalize to

$$\sigma_{elastic} = \sigma_{total} - \sigma_{reaction} = \int_0^{4\pi} \left(\mathrm{d}\sigma/\mathrm{d}\Omega\right)\mathrm{d}\Omega$$

using literature data.

Alternative: careful studies of flux, efficiency …

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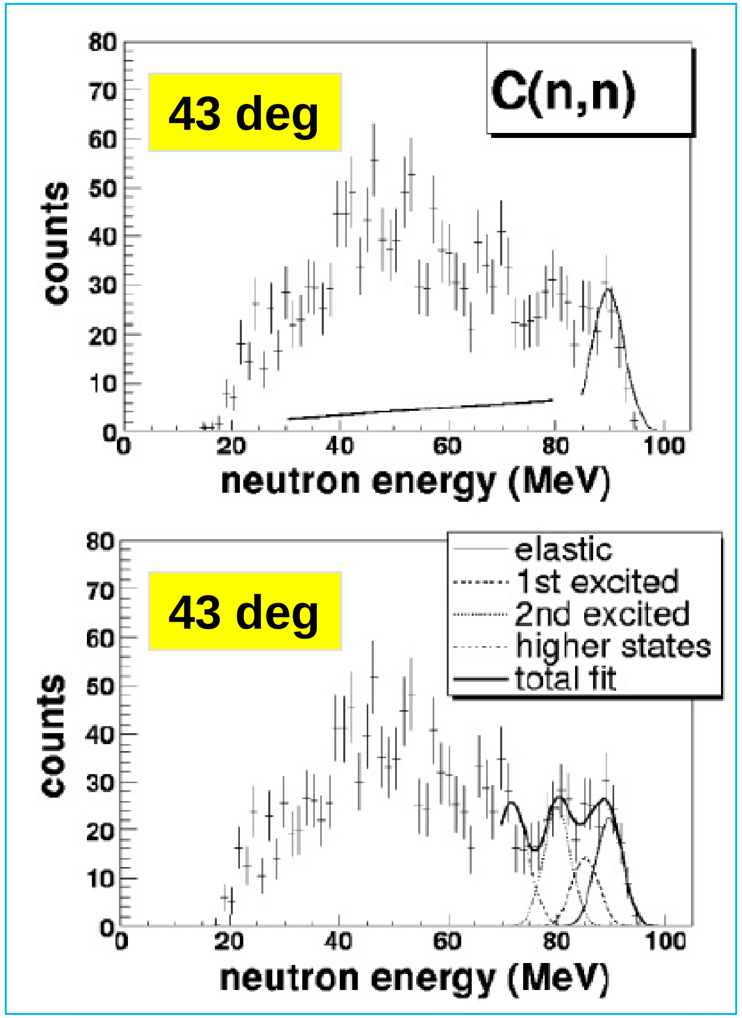
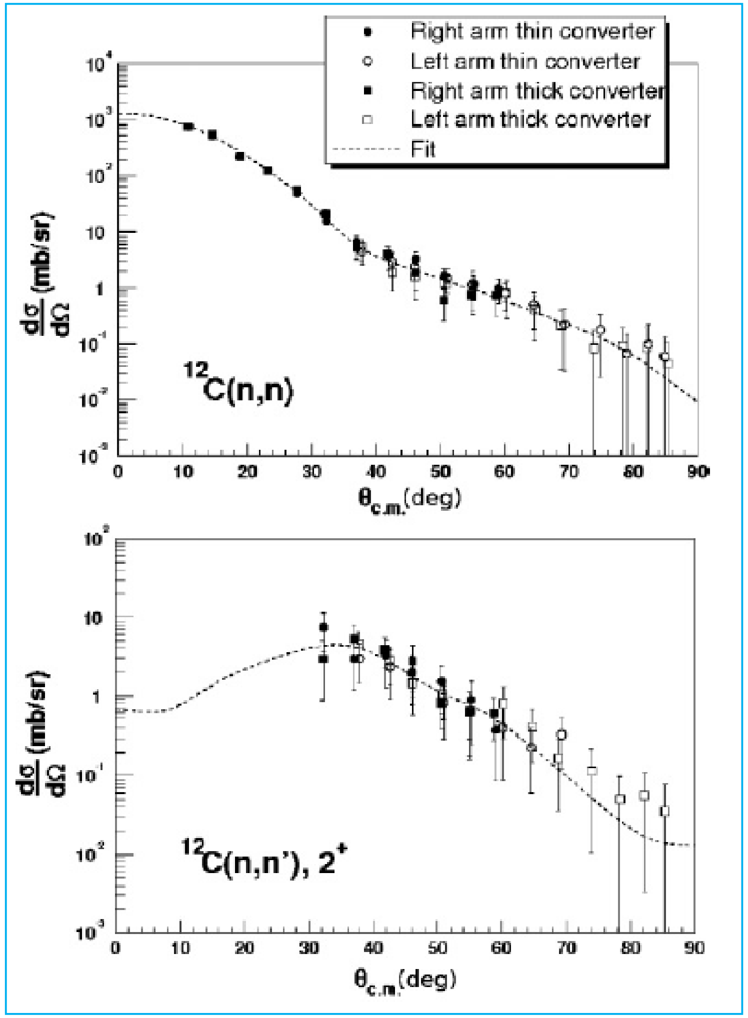
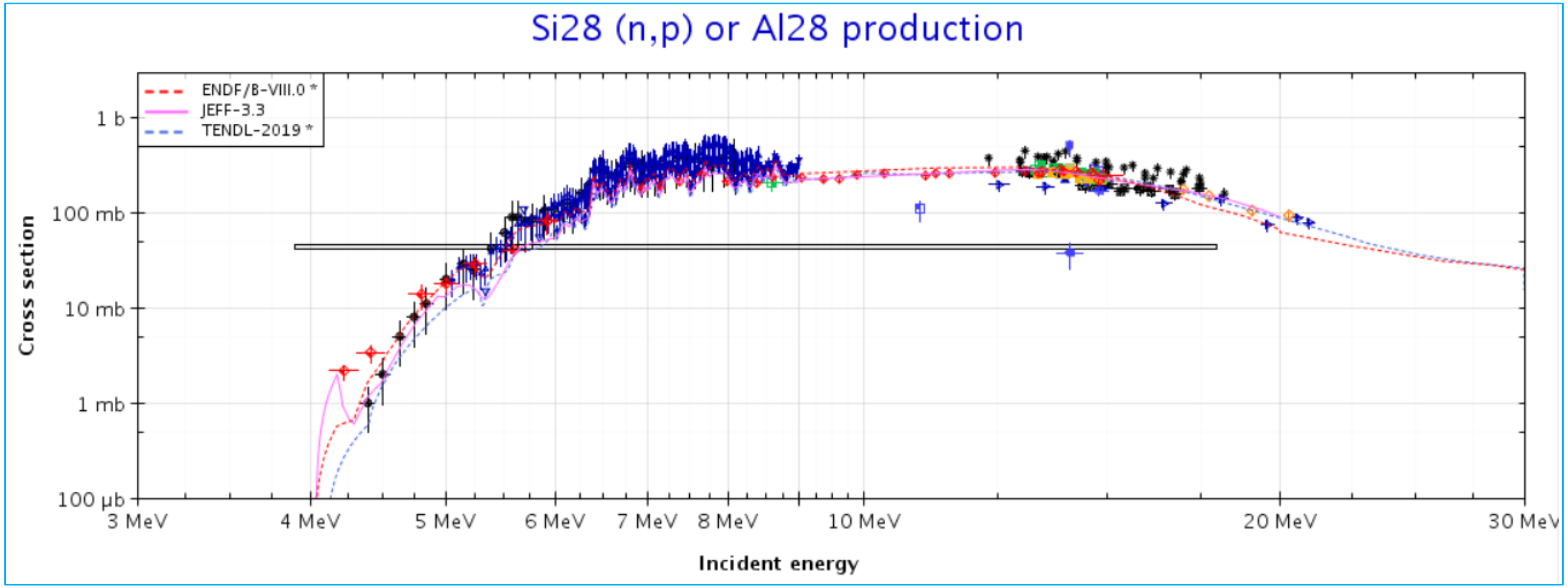
Example of measurement results for (n,n')

P. Mermod et al., PRC **74**, 054002 (2006)





Charged-particle production



Plotted using: https://www.oecd-nea.org/janisweb

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Use of neutron activation technique

Principle: Expose sample to a neutron field and then studying the reaction product by γ-spectroscopy.

Plus: In principle a relatively easy and accessible measurement technique.
Large acceptance ("100%") of the reaction products (often low systematic uncertainties).

Minus: Not always applicable: needs radioactive residual with suitable half-life.
Needs well-known neutron spectrum and might need corrections (e.g. using unfolding).
No knowledge on reaction path, only on the residual (e.g., (n,np) or (n,d)).
No knowledge on event-by-event basis to deduce e.g. angular distribution, energy spectra of emitted particles, etc.

On the other hand: experiments that do measure the emitted particles generally have no or limited information on the residual nucleus (i.e., on measures, e.g., X(n,xp))

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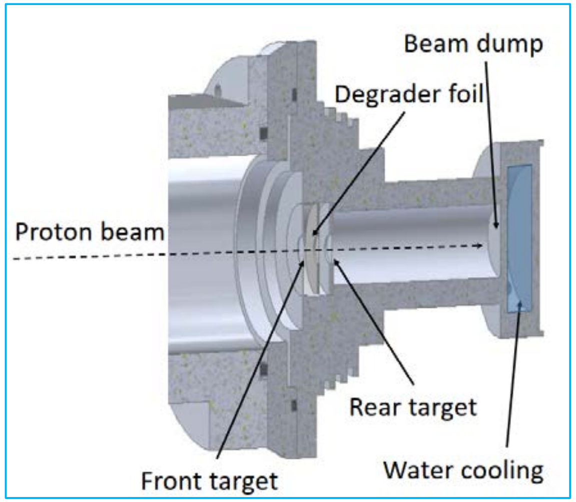
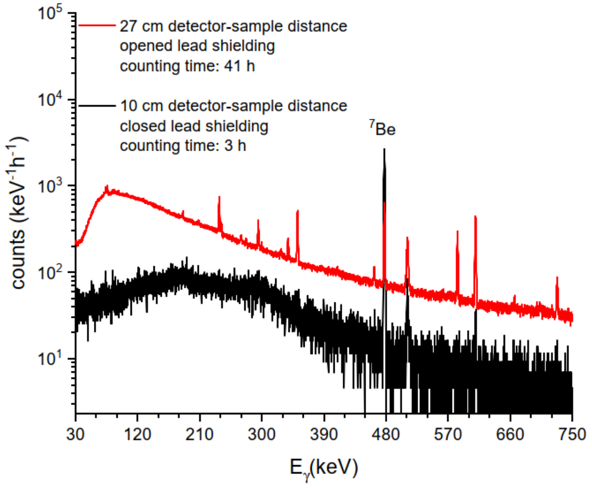
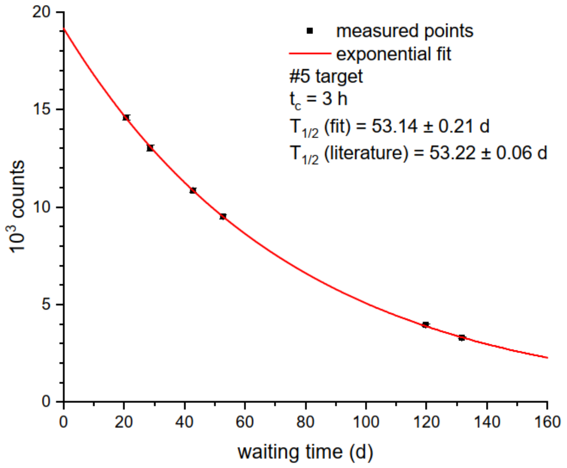
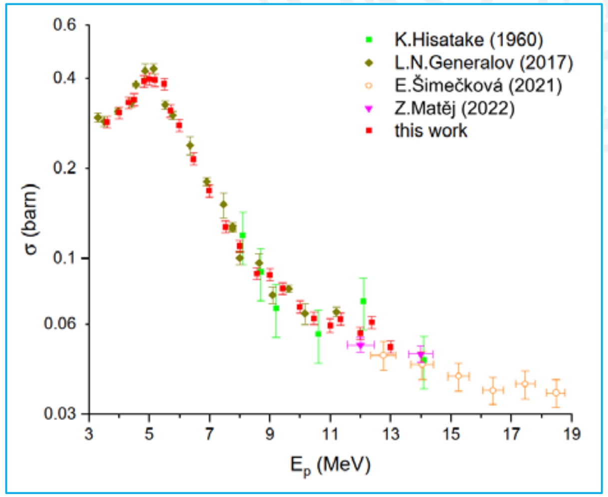
Example 1 – ^{7}Li(**p**,n)^{7}Be at Atomki, Debrecen, Hungary









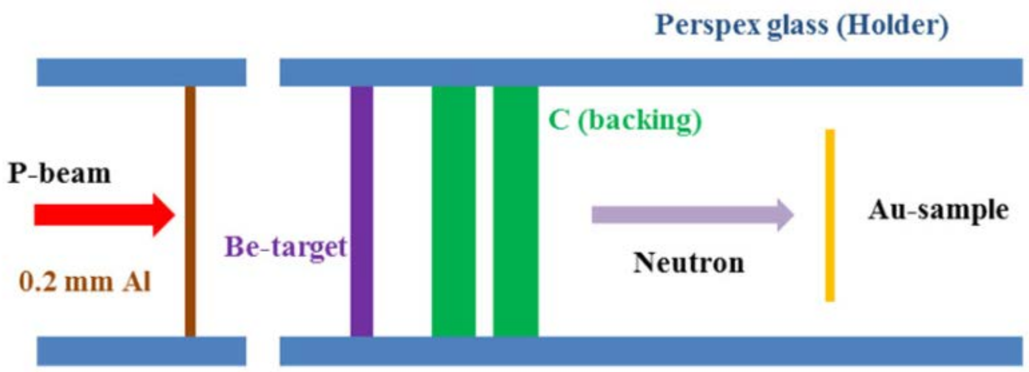
Á. Tóth, et al.,
https://arxiv.org/pdf/2310.08219.pdf

- Expose thin ^{7}LiF samples with Al backing (to stop ^{7}Be) to a proton beam with well-known energy.
- Monitor integrated beam current.
- Measure 477 keV γ-line from β-decay of ^{7}Be to determine the number of ^{7}Li(p,n) ^{7}Be reactions that have occured.
- Repeat at different beam energies and measure several foils simultaneous.

Example 2 – high energy neutrons at KIRAMS, Korea

Measurement of the cross-sections for the

- ^{209}Bi(n, 4n) ^{206}Bi and ^{209}Bi(n, 5n) ^{205}Bi,
- ^{nat}Pb(n,xn) ^{204m,203,202m,201,200}Pb,
- ^{nat}Pb(n, αxn) ^{203}Hg, and
- ^{nat}Pb(n, pxn) ^{202}Tl reactions.



Measured at the Korean Institute of Radiological and Medical Sciences.

Use of the activation and off-line γ-ray spectrometric technique.

The quasi-monoenergetic neutron from the ^{9}Be(p,n) reaction in the energy range 15 – 37 MeV from 25, 35 and 45 MeV proton beams.

M. Zaman, et al., Eur. Phys. J. A (2015) **51**:104
https://link.springer.com/article/10.1140/epja/i2015-15104-2

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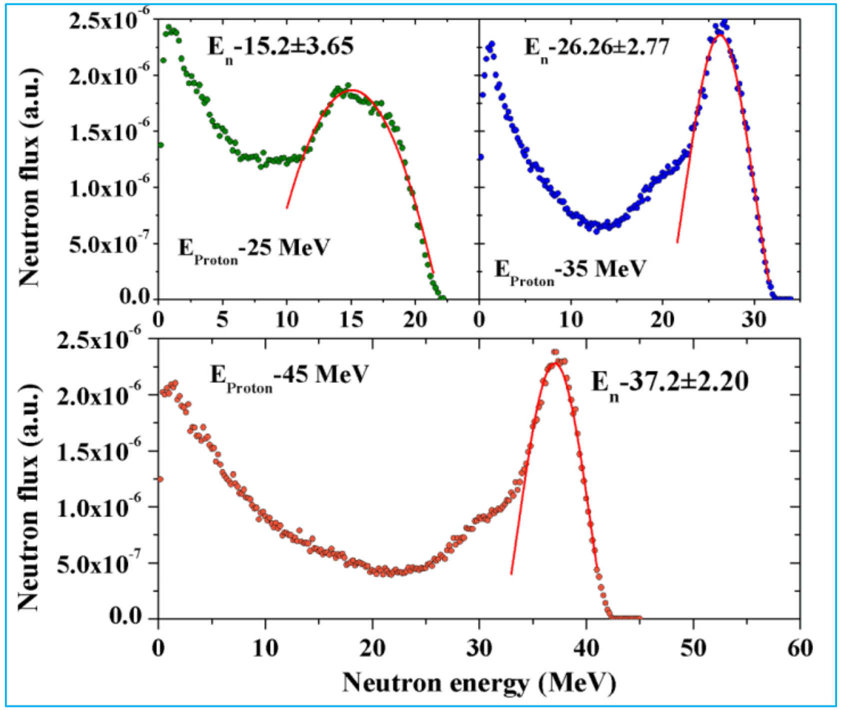
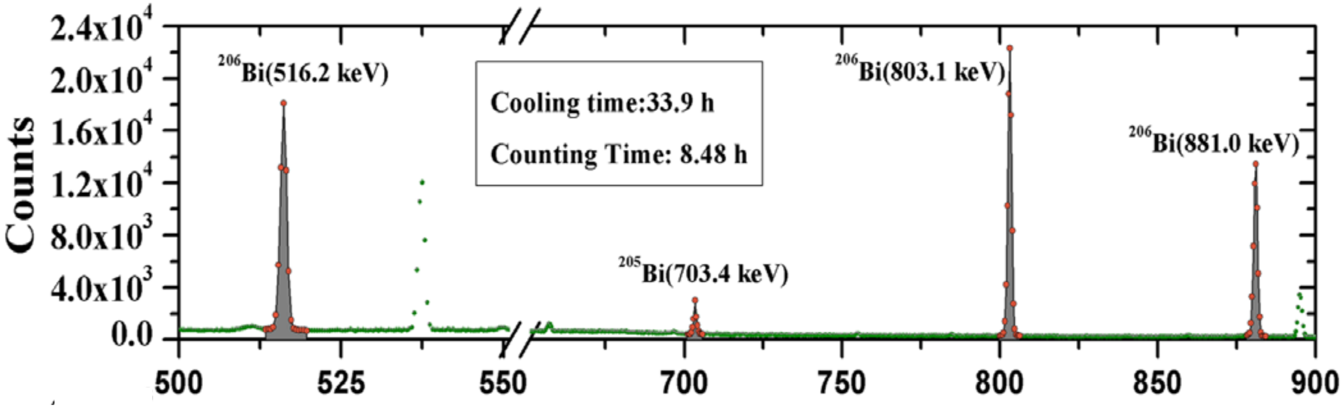
Example 2 – high energy neutrons at KIRAMS, Korea



The incident neutron spectra at the different proton energies are obtained from MCNPX/LA-150h calculations. Unfolding is necessary to derive cross sections.

Irradiations lasted for 30-60 minutes. Monitor: ^{197}Au.



M. Zaman, et al., Eur. Phys. J. A (2015) **51**:104
https://link.springer.com/article/10.1140/epja/i2015-15104-2

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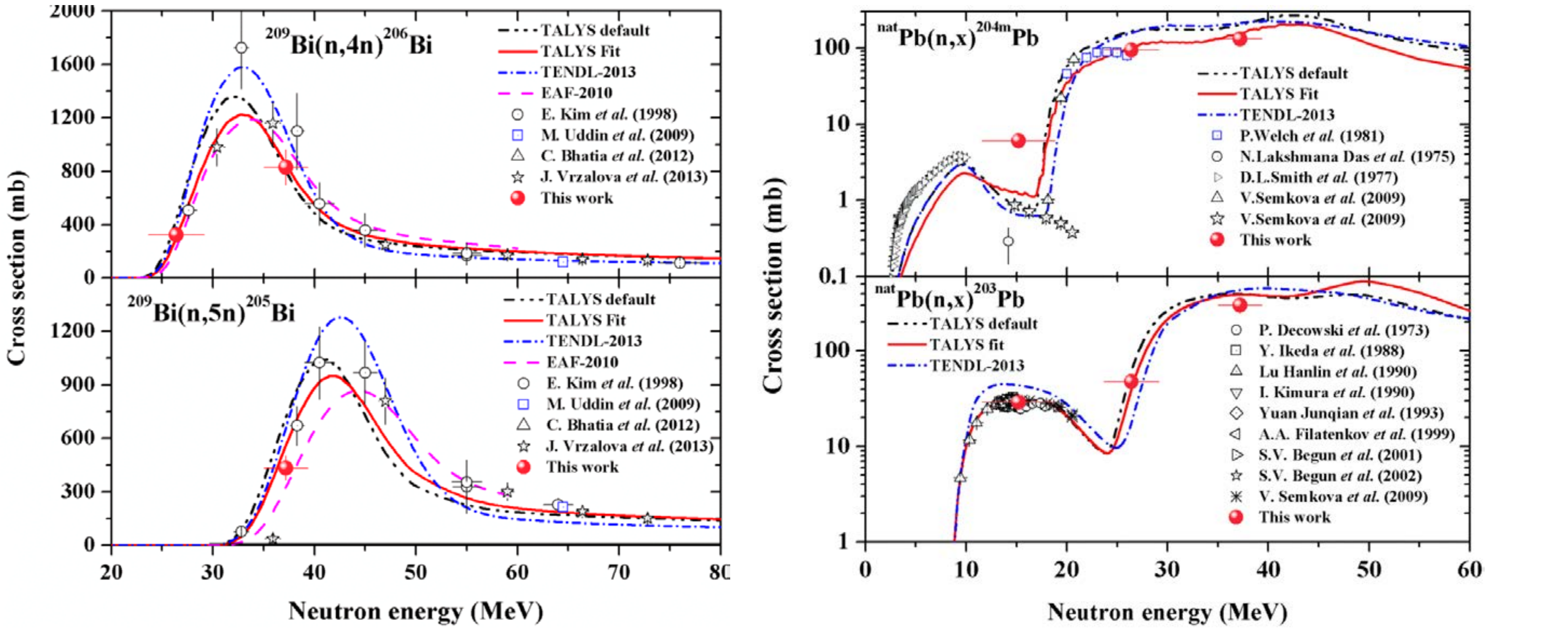
Example 2 – high energy neutrons at KIRAMS, Korea



Note:
Relatively wide horizontal uncertainties from the neutron spectrum (and the unfolding).

M. Zaman, et al., Eur. Phys. J. A (2015) **51**:104
https://link.springer.com/article/10.1140/epja/i2015-15104-2

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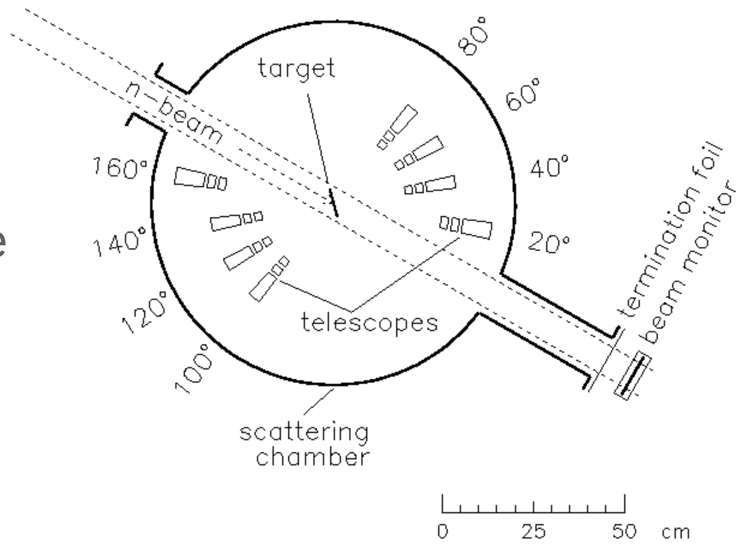
Event-by-event measurement of (n,xp), (n,xd), ...

Measure (some of the) emitted particles:

- Protons from (n,px), etc., which means we do a so-called **inclusive** measurement (exclusive: all outgoing particles are measured).
- Generally needs **particle identification** capabilities since there are several open reaction channels at high energies. Hence one needs to use, e.g., **ΔE-E techniques**.



Sketch of the Medley setup, currently at NFS, GANIL.

Plus:

Possibility to measure **energy spectra and angular distributions,**

Minus:

Often **limited geometric acceptance**.

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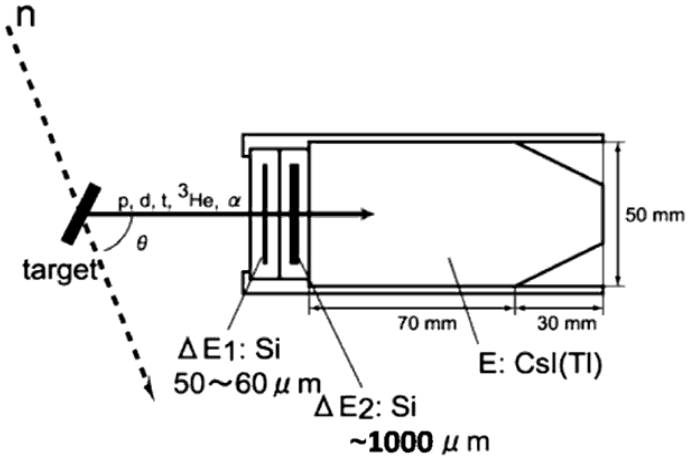
Example: Medley using ΔE–ΔE–E

detect and identify light ions: *p*, *d*, *t*, ^{3}He and α

- but may also detect (but not identify) heavier ions or fission products

use the ΔE-ΔE-E technique –> wide dynamic range (1-160 MeV)

- Combine two silicon detectors with suitable thicknesses (all 450 mm^2) for ΔE–ΔE …
  - 20 µm, 50-60 µm, 400-550 µm, 1000 µm.
- … with CsI(Tl) for E measurement
  - Small (5 cm long) or large (10 cm) depending needed stopping power.



low threshold for particle ID:

- With ultrathin silicon detector (20 µm):
  - About 1,2 MeV for p, and 4.5 MeV for α

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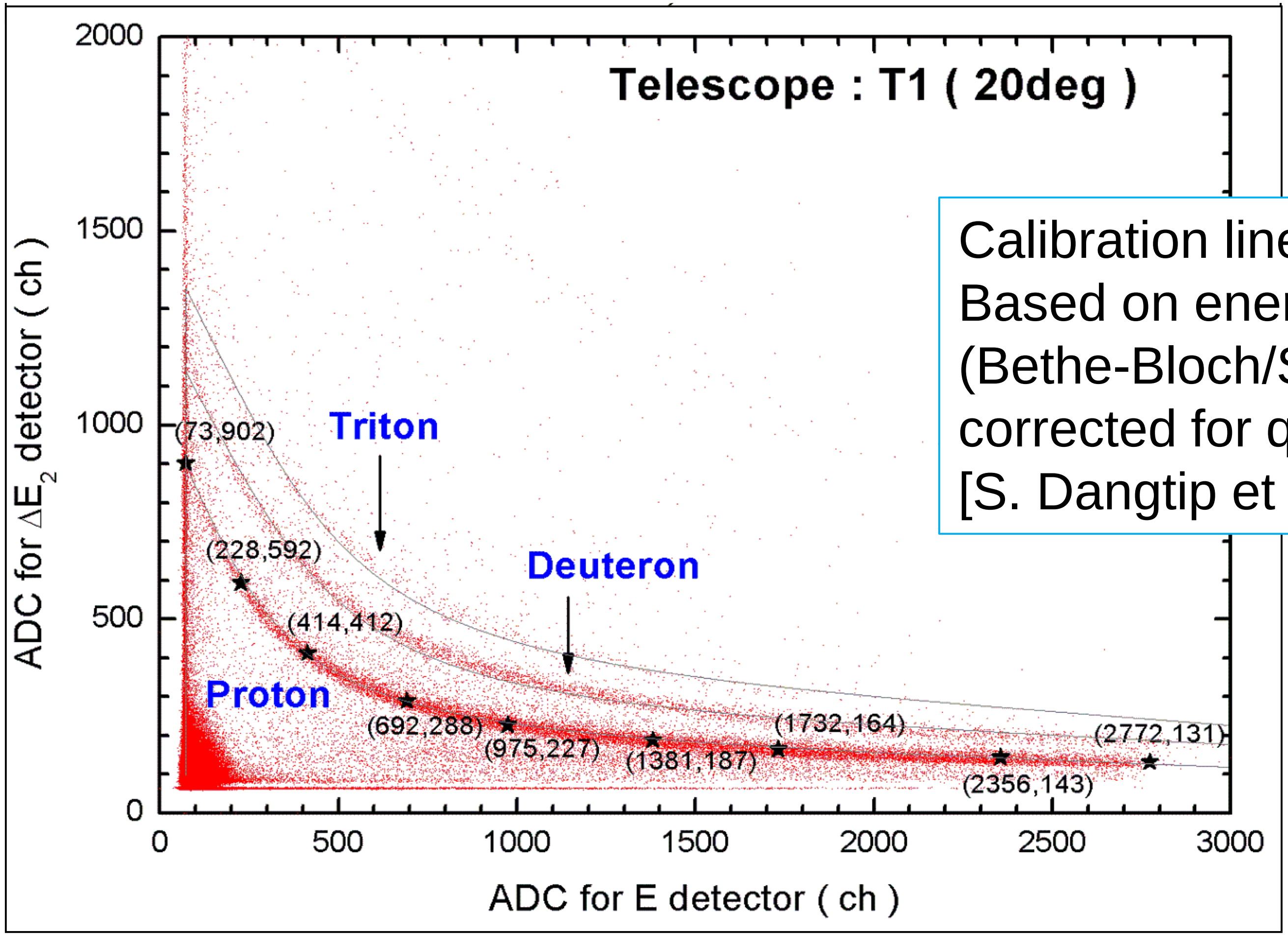
Medley ΔE-E plot: Raw data and calibration



Calibration lines:
Based on energy loss calculations (Bethe-Bloch/SRIM) and pulse height corrected for quenching (Birks formula …)
[S. Dangtip et al., NIM A **452** (2000) 484]

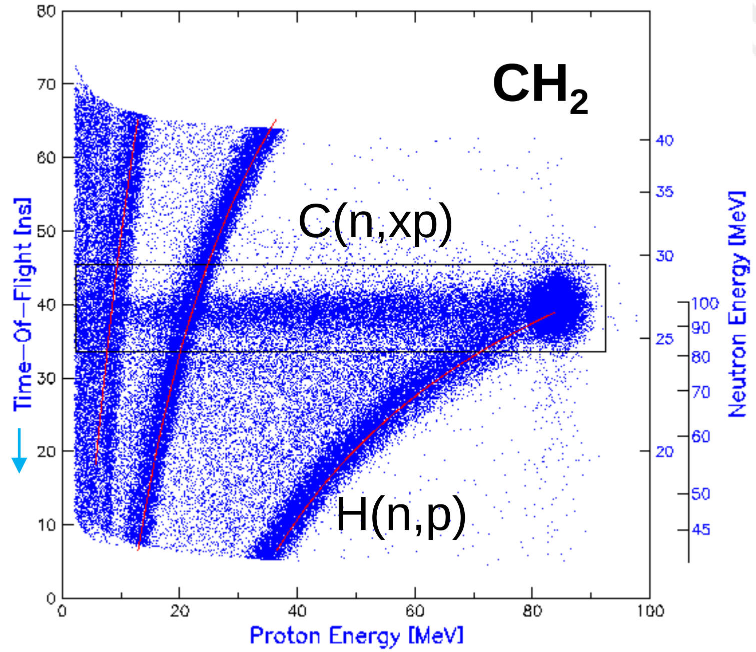
Main corrections

- Wrap around
  - i.e. correct for frame overlap
  - Proton beam from cyclotron pulsed with 45-75 ns (width 1-2 ns)
- CsI efficiency correction
  - Incorrect measured energy due to nuclear interactions in CsI.
- Thick target correction
  - Produced particles suffer energy loss inside target

„easy“

„unambigeous“

„tricky … “



Use of a CH_2 target for cross section normalization, and estimation of the amount of low energy neutrons within TOF window.

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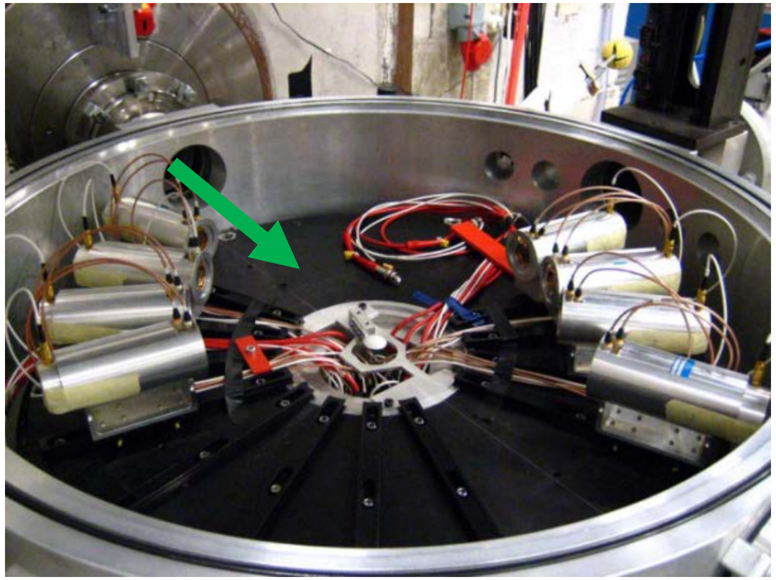
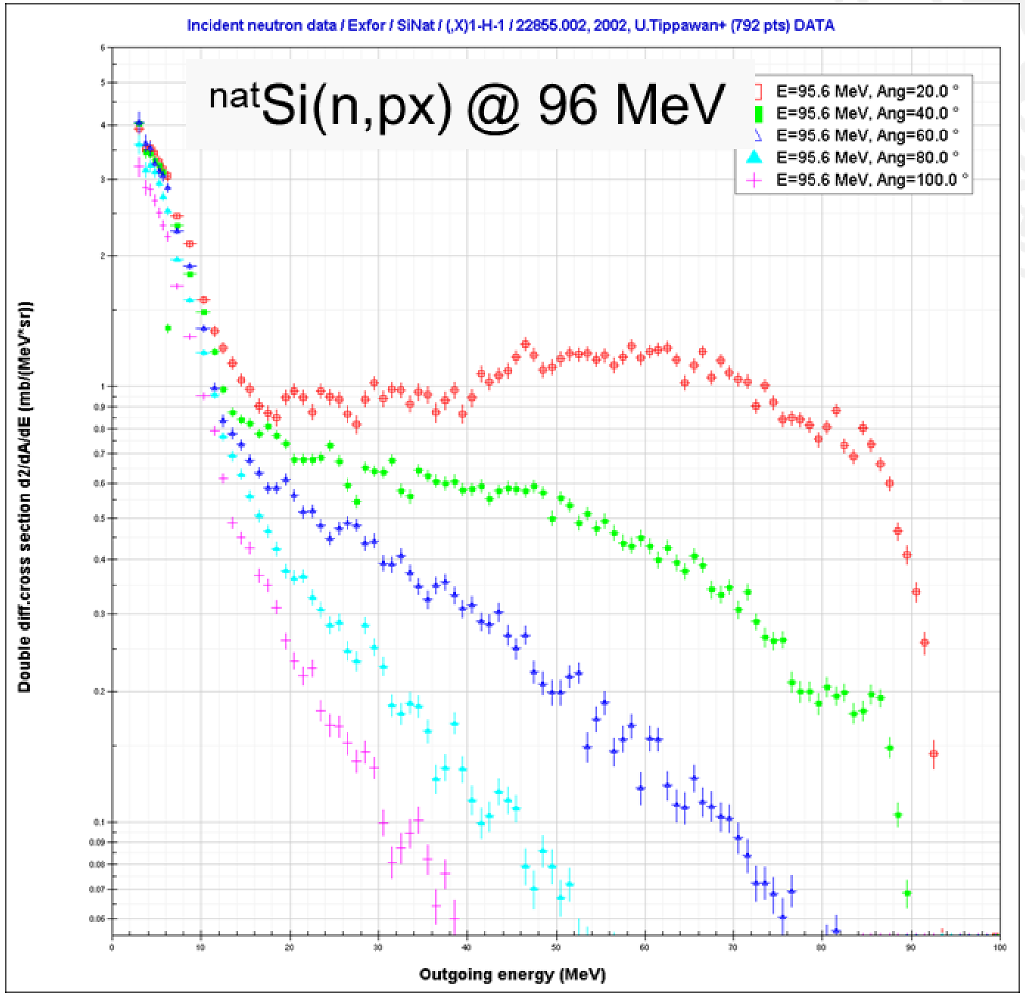
Several telescopes





Measure: $d^2\sigma/d\Omega dE$ (double-differential xs)

Derive: $d\sigma/dE$, $d\sigma/d\Omega$, and σ_{prod}

EXFOR data for
U. Tippawan, et al., Phys. Rev. C **69**, 064609 (2004)

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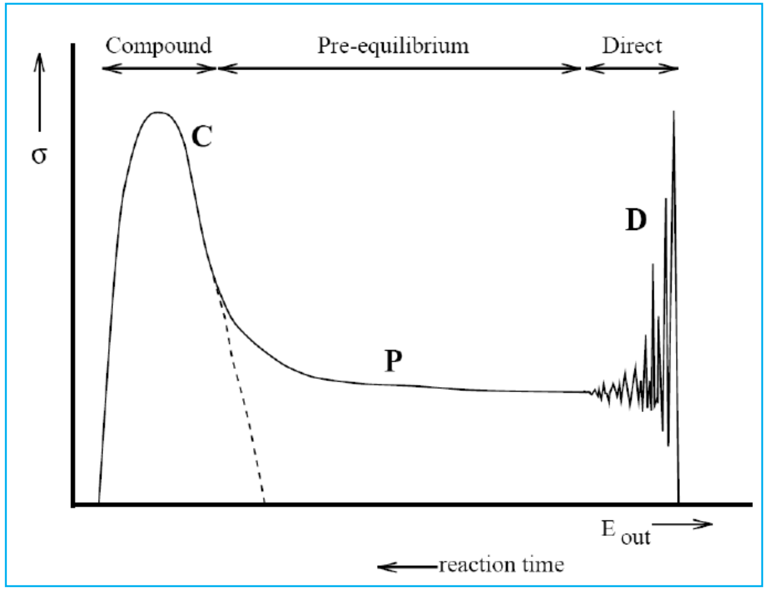
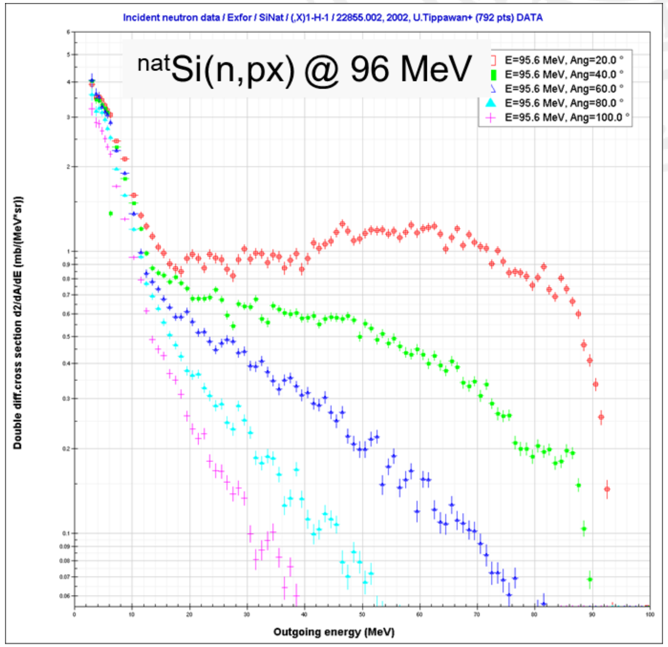
What could you learn?

Figure from the TALYS manual



Measurement of energy spectra of outgoing particle reveals information on various reaction mechanisms (and their competition).



Tippawan et al., PRC 69, 064609 (2004)

← number of neutron – nucleon interactions

”information-loss”

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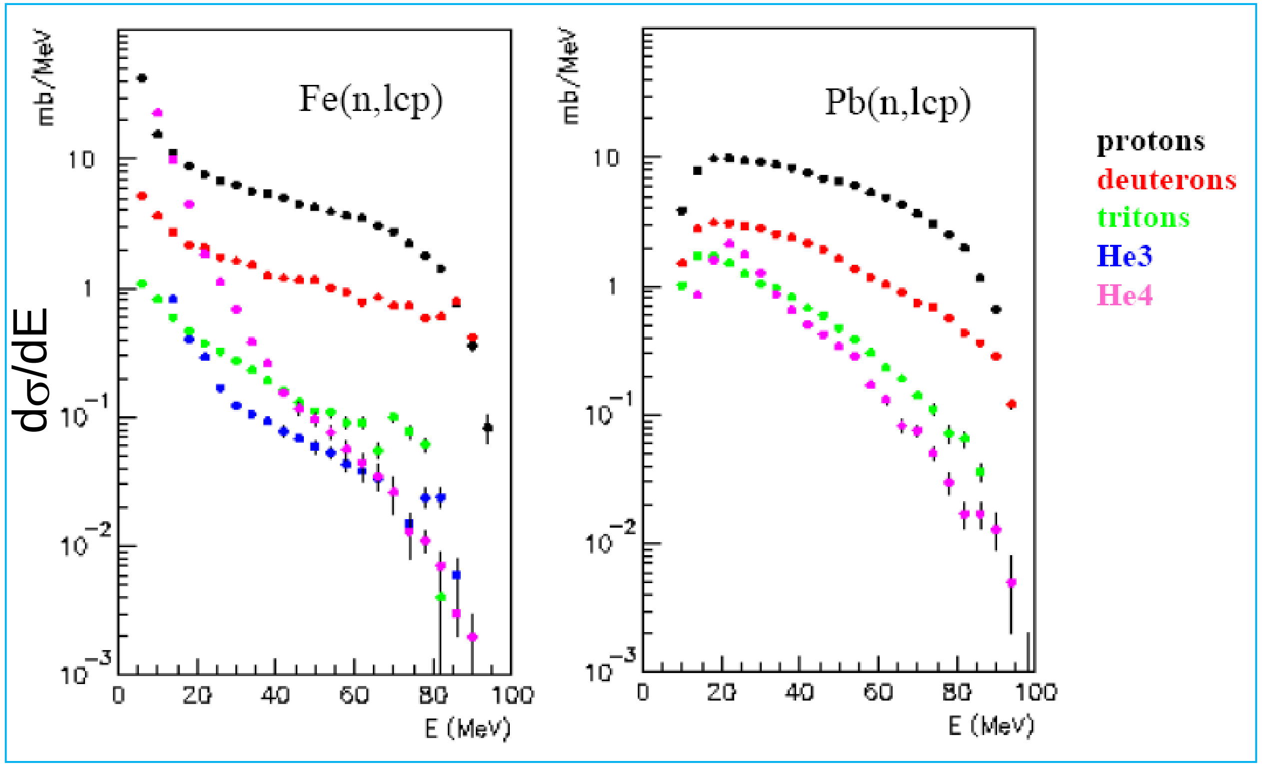
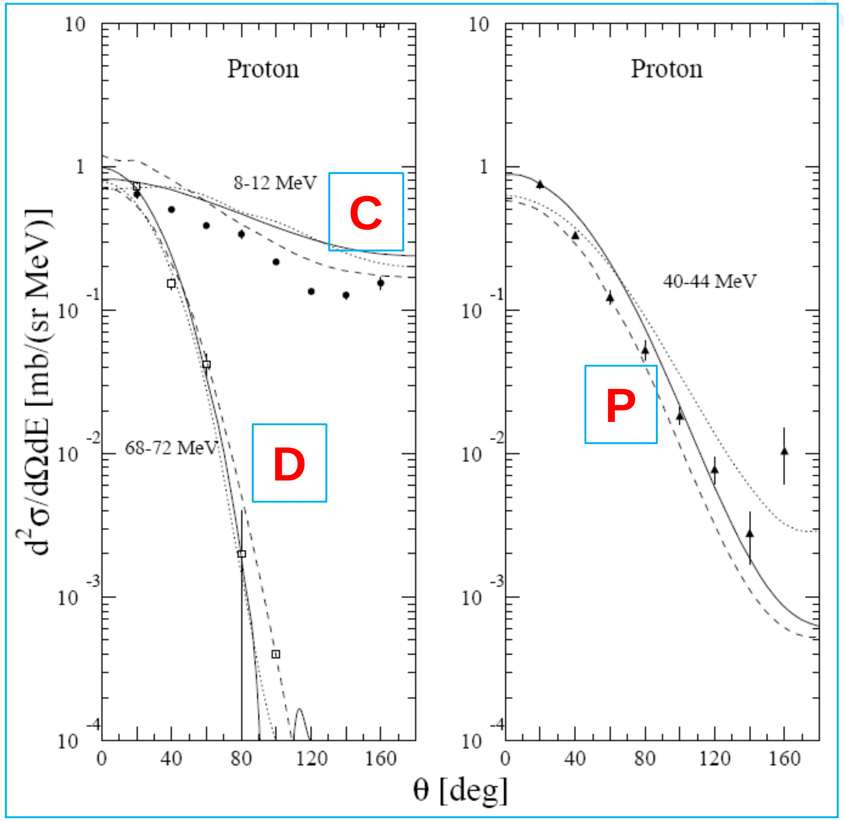
Examples for dσ/dE, dσ/dΩ

Fe and Pb @ 96 MeV



C(*n,px*) @ 96 MeV



Mostly
Compound
Pre-eq.
Direct

Data from V. Blideanu, et al., Phys. Rev. C **70**, 014607 (2004).

Tippawan et al., Phys. Rev. C **79**, 064611 (2009)

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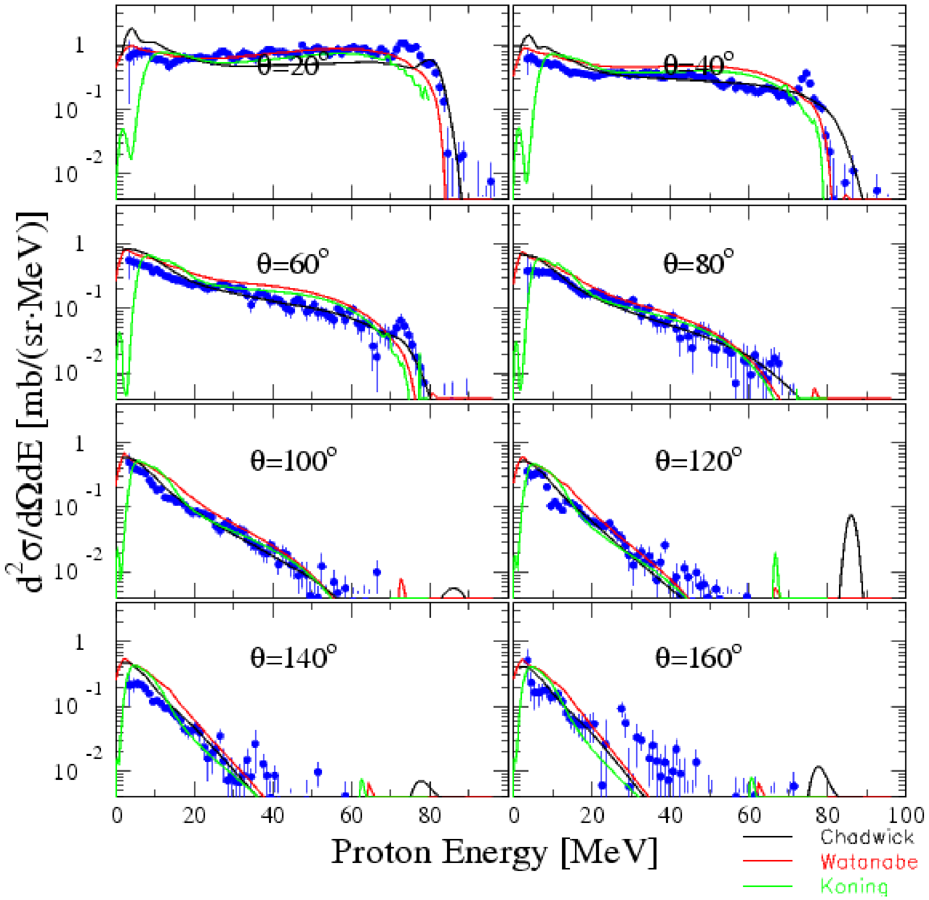
Integral data from C(n,px) @ 96 MeV: Kerma



U. Tippawan et al., PRC **79**, 064611 (2009)

Kerma: Kinetic energy of the secondary charged particles released by the primary neutron per unit mass (cp. dose: *absorbed* energy).

$$K = \Phi \cdot k_{\Phi}$$

Φ : fluence of uncharged particles at the same point

k_{Φ} : kerma coefficient; unit: [J m^2 kg^{-1}] or [fGy m^2]

$$k_{\Phi}(E_n) = N \sum_i \int E \int \left(\frac{d^2\sigma_i(E_n)}{d\Omega\, dE} \right) d\Omega\, dE$$

Medley data for Kerma:
M. Göttsche et al., Rad. Meas. **45** (2010) 1139

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That was …

… a walk through some experimental techniques to measure nuclear reaction data.

We shall now look at a case and start planning an experiment.

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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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A test case – let’s think about a possible experiment

Starting point: some data needs, e.g., from the HPRL:

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)							
15H		95-AM-241	(n,g),(n,tot)							
18H		92-U-238	(n,inl)							
19H		94-PU-238	(n,f)							
21H		95-AM-241	(n,f)							
22H		95-AM-242M	(n,f)							
25H		96-CM-244	(n,f)							
27H		96-CM-245	(n,f)							
32H		94-PU-239	(n,g)							
33H		94-PU-241	(n,g)							
34H		26-FE-56	(n,inl)							
35H		94-PU-241	(n,f)							
37H		94-PU-240	(n,f)							
38H		94-PU-240	(n,f)							
39H		94-PU-242	(n,f)							
41H		82-PB-206	(n,inl)	SIG						
42H		82-PB-207	(n,inl)	SIG	0.5					
45H		19-K-39	(n,p),(n,np)	SIG	10					
97H		24-CR-50	(n,g)	SIG	1					
98H		24-CR-53	(n,g)	SIG	1 keV-100 keV		8-10	Y	Fission	05-FEB-18
99H		94-PU-239	(n,f)	nubar	Thermal-5 eV		1	Y	Fission	12-APR-18
102H		64-GD-155	(n,g),(n,tot)	SIG	Thermal-100 eV		4	Y	Fission	09-MAY-18
103H		64-GD-157	(n,g),(n,tot)	SIG	Thermal-100 eV		4	Y	Fission	09-MAY-18
114H		83-BI-209	(n,g)Bi-210g,m	BR	500 eV-300 keV		10	Y	ADS,Fission	09-NOV-18
115H		94-PU-239	(n,tot)	SIG	Thermal-5 eV		1	Y	Fission	08-APR-19
116H		3-LI-0	(d,x)Be-7	SIG	10 MeV-40 MeV		10	Y	Fusion	31-MAY-21
117H		3-LI-0	(d,x)H-3	SIG,TTY	5 MeV-40 MeV		10	Y	Fusion	31-MAY-21
118H		68-ER-167	(n,g)	SIG,RP	0.01 eV-100 eV		2	Y	Fission	30-AUG-21
119H		17-CL-35	(n,p)	SIG	100 keV-5 MeV		5-8	Y	Fission	17-APR-22

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	

^{39}K(n,p) and ^{39}K(n,np) in the energy range between 10 and 20 MeV.

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

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Requester: Dr Stanislav SIMAKOV at KIT, GER
Email: intersurfen@gmail.com

Project (context): IFMIF and DONES material test facilities, and fusion power plants

Impact:
The 39K(n,p) reaction produces 39Ar with decay half-life of 269 years and makes the dominant contribution to the long-lived radioactive inventories in NaK. The latter is considered as a coolant of specimens in the accelerator driven irradiation facilities that are designed now for the fusion material testing (IFMIF [1], DONES [2] ...). Together with the competing reaction 39K(n,np)38Ar they also determine the total amount of Argon gas which impact on the thermal and mechanical properties of sealed specimens containers [3]. The current poor knowledge of these two reactions questions whether NaK could be used in the IFMIF and DONES design. Additionally, since potassium is present in cement and concrete, the 39K(n,p)39Ar reaction impacts on the long-term radioprotection and shielding issues in IFMIF/DONES testing vaults and future fusion power plants.

Accuracy:
The continuous Argon gas leakage through cracks in the welding of sealed containers or their accidental rupture is a complex process. Because of this complexity, the sensitivity analyses quantifying the required accuracy of the cross sections have never been done. However, considering the potentially high impact and the poor knowledge of these cross sections, a request for 10% accuracy is a reasonable requirement that will be practically achievable by utilizing the current techniques. This requirement is supported by the fusion and general nuclear data users.

Justification document:

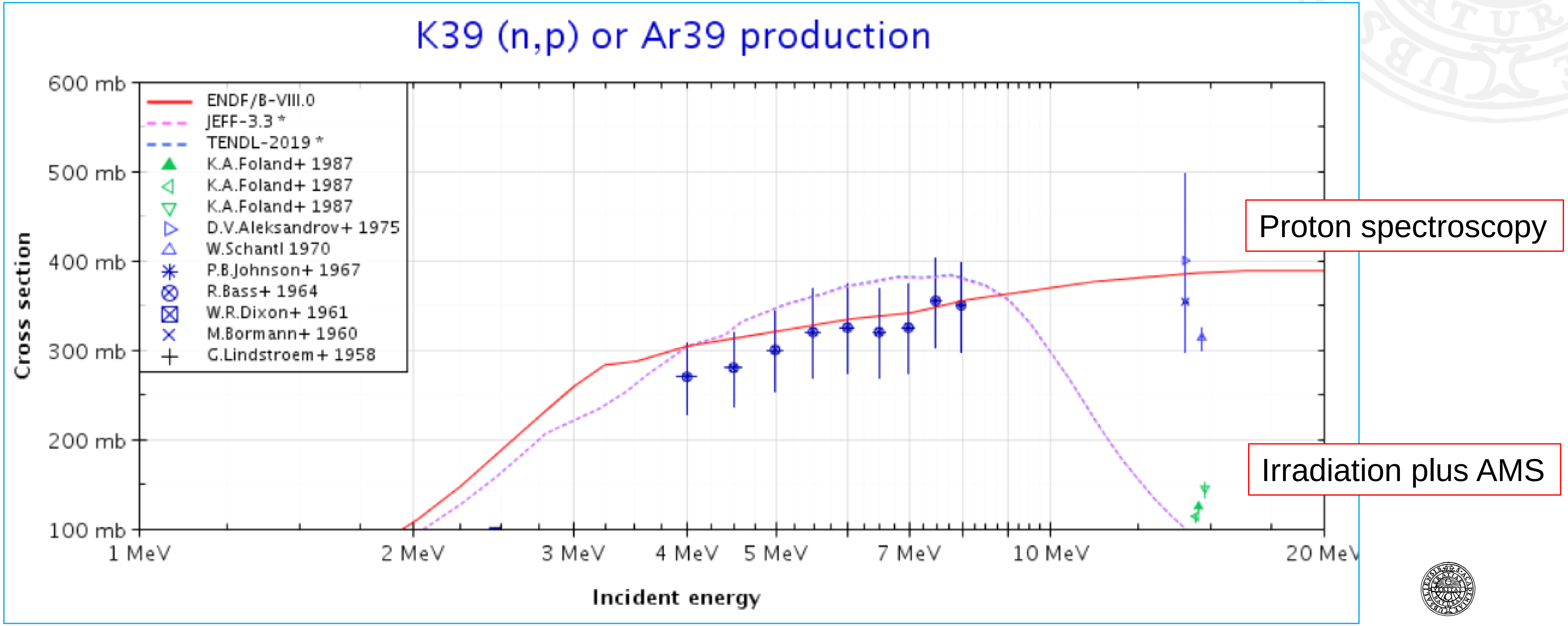
https://www.oecd-nea.org/dbdata/hprl/hprlview.pl?ID=466

At 14 MeV neutron energy 3 measurements by proton spectroscopy and activation [4-6] reported 3 times larger value for 39K(n,p)39Ar reaction cross section than measurement by AMS [7]. For competing reaction 39K(n,np)38Ar the situation is vice versa. See Ref. [3] for more information.

The main evaluated libraries are similarly discrepant depending on which experiment they follow.

The new measurement is needed first at 14 MeV to resolve this contradiction.

Data situation for ^{39}K(n,p)



Plotted using: https://www.oecd-nea.org/janisweb

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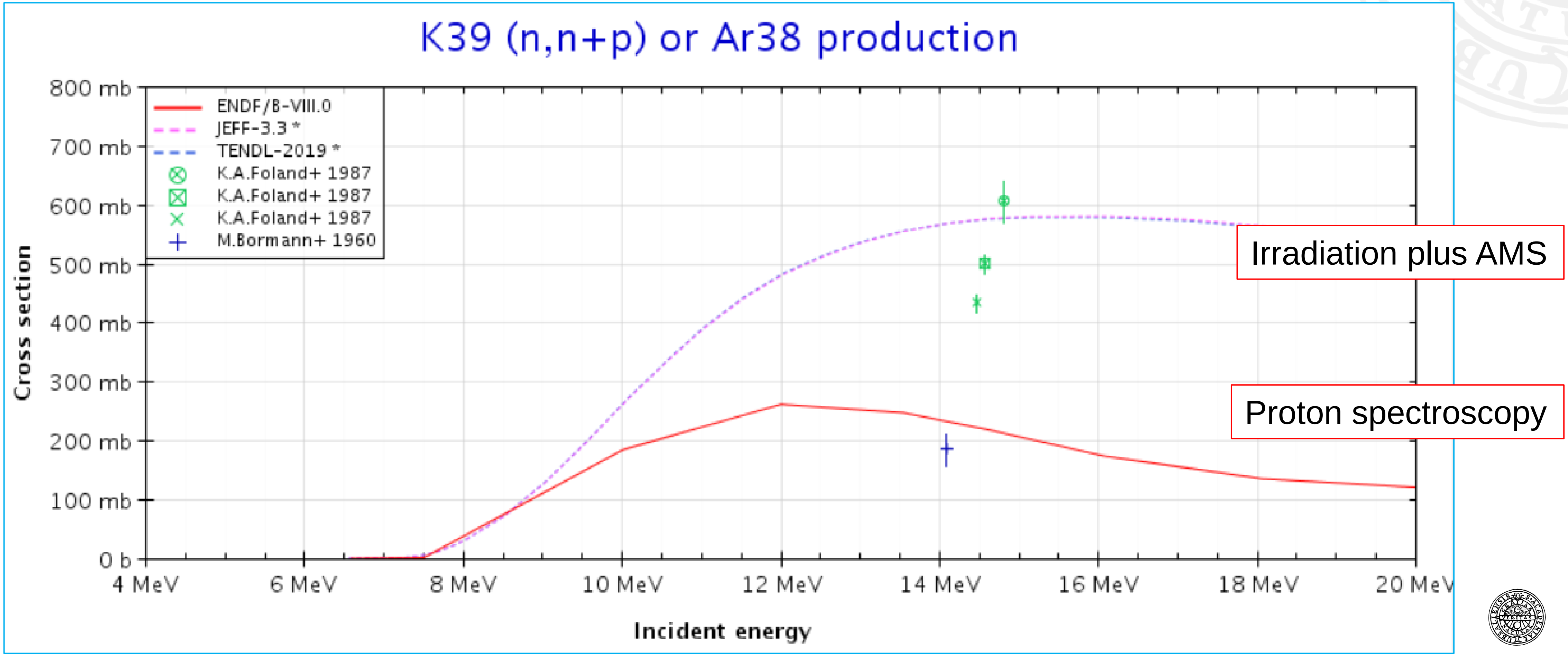
Data situation for ^{39}K(n,np)



Plotted using: https://www.oecd-nea.org/janisweb

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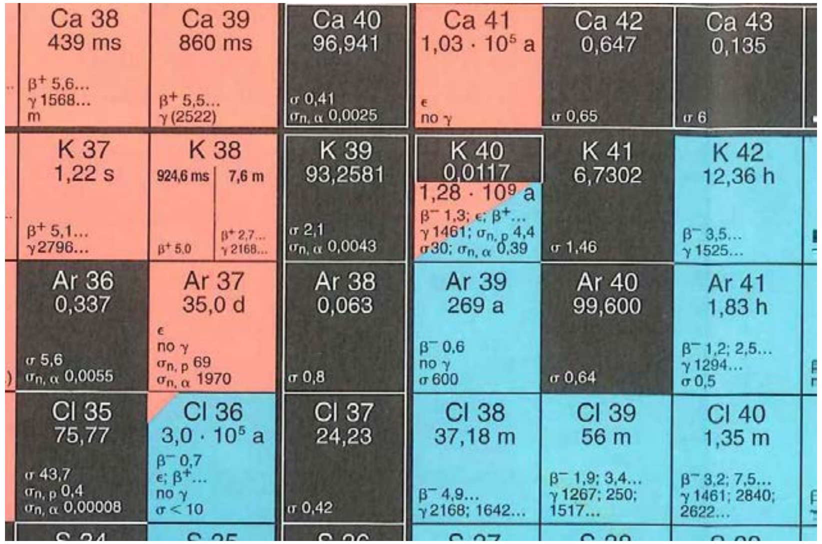
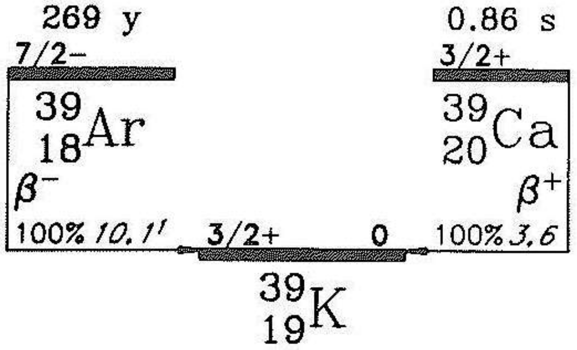
Look at some basics first



Isotopic compostion of ^{nat}K:

^{39}K	93.26%
^{40}K	0.01%
^{41}K	6.73%

^{38}Ar	stable
^{39}Ar	β^-



β^--decay goes to g.s.

γ-spectroscopy not possible ☹

(Note: for $^{41}K(n,p)$, γ-spectroscopy would be an option)

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Options?

Either use proton spectroscopy (e.g. with active detector),

200 M. BORMANN, H. JEREMIE, G. ANDERSSON-LINDSTRÖM, H. NEUERT UND H. POLLEHN

Über die Wirkungsquerschnitte einiger von 14 MeV-Neutronen in den Szintillationskristallen NaJ(Tl), KJ(Tl), CsJ(Tl) und $Li^6J(Eu)$ ausgelösten Kernreaktionen*

Von M. BORMANN, H. JEREMIE **, G. ANDERSSON-LINDSTRÖM, H. NEUERT und H. POLLEHN

Aus dem Physikalischen Staatsinstitut, I. Institut für Experimentalphysik, Hamburg

(Z. Naturforschg. **15 a**, 200—210 [1960]; eingegangen am 20. Januar 1960)

http://zfn.mpdl.mpg.de/data/Reihe_A/15/ZNA-1960-15a-0200.pdf

or use mass measurement techniques of products

The Production of ^{38}Ar and ^{39}Ar by 14-MeV Neutrons on ^{39}K

K. A. Foland, R. J. Borg, M. G. Mustafa

Nuclear Science and Engineering / Volume 95 / Number 2 / February 1987 / Pages 128-134
Technical Paper / dx.doi.org/10.13182/NSE87-A20423

https://doi.org/10.13182/NSE87-A20423

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Target

Tricky:

- Potassium is a highly reactive metal
- Either treat under vacuum or inert gas or
- Use a composite (which needs background subtraction)

For the sake of this discussion:

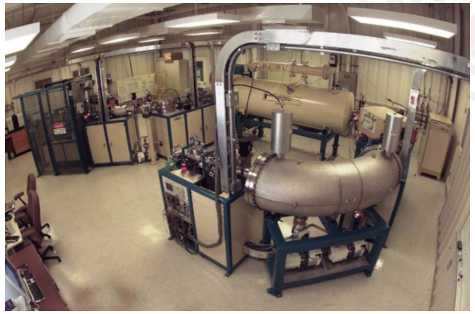
let’s assume we found a way to handle thin K sheets

(e.g., sealed between mylar foils) as a target …

Passive or active?

Out-of-beam measurement

- activation technique; e.g. irradiation plus AMS
- needs either mono-energetic beam (e.g., DT), or
  QMN + unfolding/low-E-tail subtraction methods
- Pro: Measures product (independent of reaction channel)
- Con: Limited number of available beam energies



In-beam measurement

- neutron beam plus online detection
- Pro: measurements at many incoming energies possible
- Con: possible ambiguity on reaction product (e.g., (n,xp) measurement)

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Let’s say we opt for proton detection

Method?

- Active target (target = part of detector)
  - Pro: 4π coverage
  - Con: careful response analysis necessary
- Target + Telescope (ΔE-E)
  - Pro: PID, energy spectra, angular distributions
  - Con: small $\Delta\Omega$ coverage

Beam?

- DT source: one mono-energetic beam
- QMN beams (Li(p,n)): several beams but low-E tail
- White beam: “all in one”

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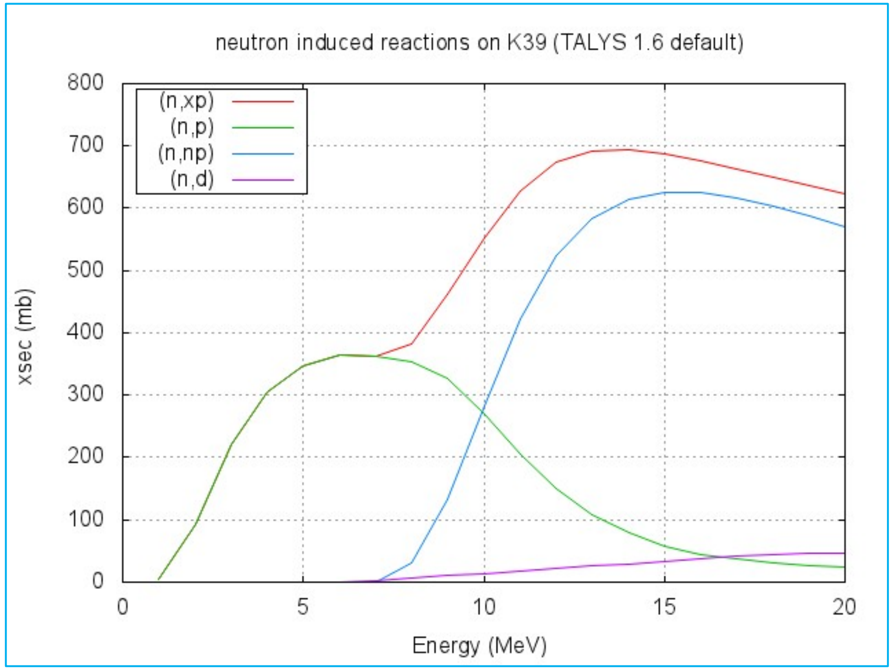
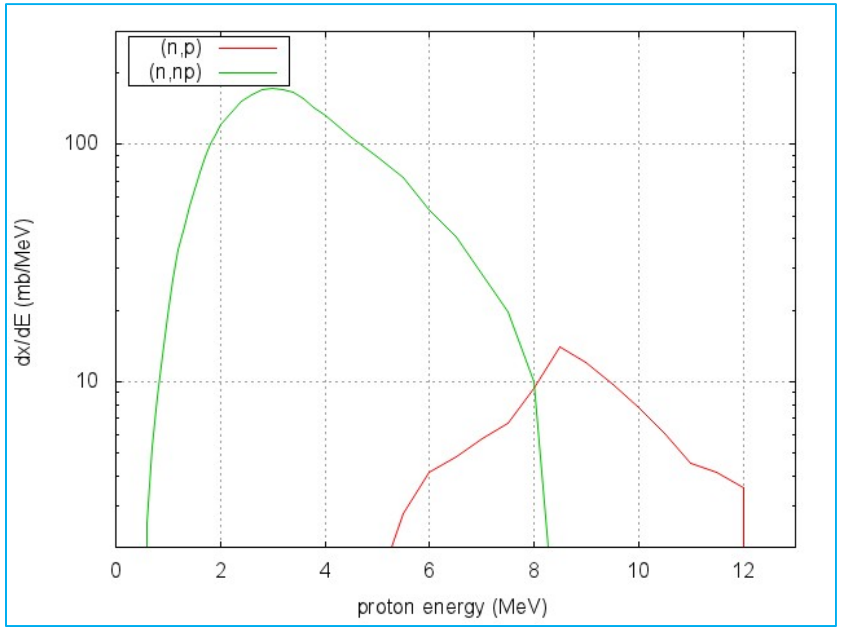
One problem though …



What we would measure is (n,xp).
According to TALYS (1.6 so outdated …) this xs is,
in the 10-20 MeV region, heavily dominated by (n,np).



Possible way out?
Study the energy of the emitted proton:
(Problem: bias from model)

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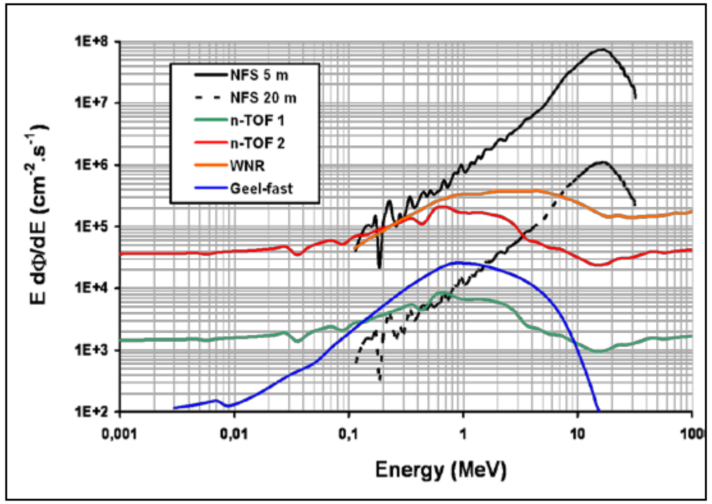
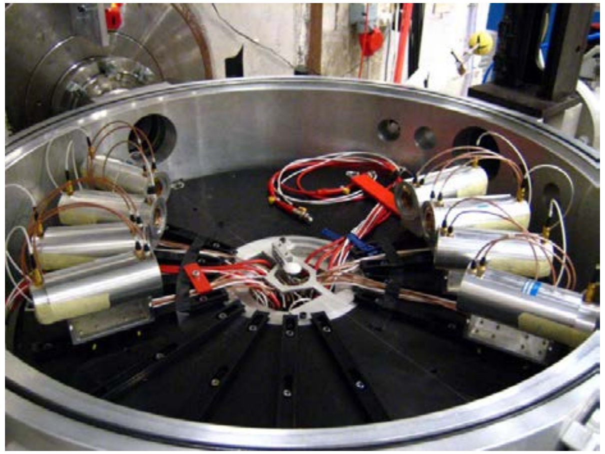
Anyway, we go ahead and …

… decide that we want to use a **white neutron beam** with good intensity in the interesting energy range (NFS) and that we use a setup like Medley:





The HRPL asks for an uncertainty for the measured cross section below 10%.
Typically systematic uncertainties dominate (normally larger than 5%).
Let's try to get a **statistical uncertainty** of, say, **better than 1%** (10,000 events).

Question: how much beam time would we need?

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Reaction rate estimation

$$R = \sigma_{(n,p)} \cdot \Phi_{beam} \cdot N_{target}$$

Reaction rate per unit time and energy bin

1/s/MeV

Cross section

$1/cm^2$

Beam flux per unit time, unit area and energy bin

$1/cm^2/s/MeV$

Number of target nuclei within the beam

Let's use 1 MeV bins

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Reaction rate estimation

$$R = \sigma_{(n,p)} \cdot \Phi_{beam} \cdot N_{target}$$

The cross section is roughly 200 mb.
(200 mb = **2 · 10^{-25} cm^2**)

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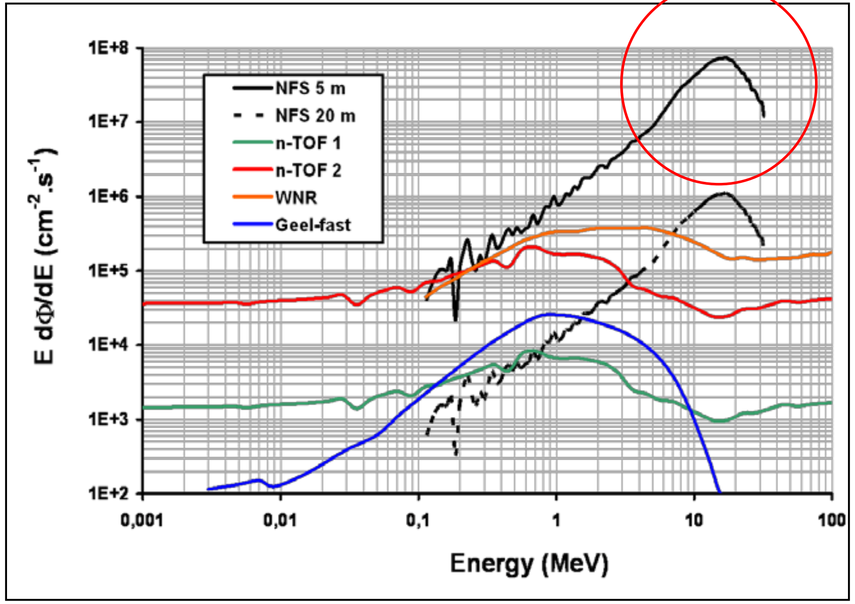
Reaction rate estimation

$$R = \sigma_{(n,p)} \cdot \Phi_{beam} \cdot N_{target}$$

NFS flux at 5 m according to the figure:

E_n [MeV]	E dΦ/dE [cm^{-2} s^{-1}]	dΦ/dE [cm^{-2} s^{-1} MeV^{-1}]
5	$1 \cdot 10^7$	$2 \cdot 10^6$
10	$4 \cdot 10^7$	$3 \cdot 10^6$
15	$7 \cdot 10^7$	$5 \cdot 10^6$
20	$5 \cdot 10^7$	$2.5 \cdot 10^6$

Let as use an average of **$3 \cdot 10^6$ cm^{-2} s^{-1} MeV^{-1}**



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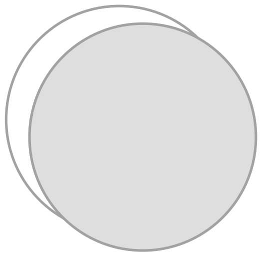
Reaction rate estimation

$$R = \sigma_{(n,p)} \cdot \Phi_{beam} \cdot N_{target}$$



Target:
assume a disc of metallic potassium (yes, it is tricky …) with

- diameter 3 cm, i.e., $A_{target} \approx 7\ \mathrm{cm}^2$
- thickness t = 100 µm, and
- density ρ = 0.89 g/cm^3 (areal density is then 8.9 mg/cm^2).

$$N_{target} = \rho \cdot t \cdot A_{target} \cdot \frac{N_A}{M_a} \approx 10^{21}$$

Reaction rate estimation

$$R = \sigma_{(n,p)} \cdot \Phi_{beam} \cdot N_{target}$$

Using

$\sigma_{(n,p)}$ = 2 · 10^{-25} cm^{2}

Φ_{beam} = 3 · 10^{6} cm^{-2} s^{-1} MeV^{-1}

N_{target} = 1 · 10^{21}

we get *R* = 600 s^{-1} MeV^{-1}

Assuming further we have **an arrangement of 10 detector telescopes** with Si detectors (100% efficiency for protons) with an opening are of **450 mm^{2} each** and placed at a **distance of 10 cm**, we **cover about 3.6% of 4π**.

This finally gives that we register 20 events per second and would need (only) 500 seconds to collect 10,000 events.

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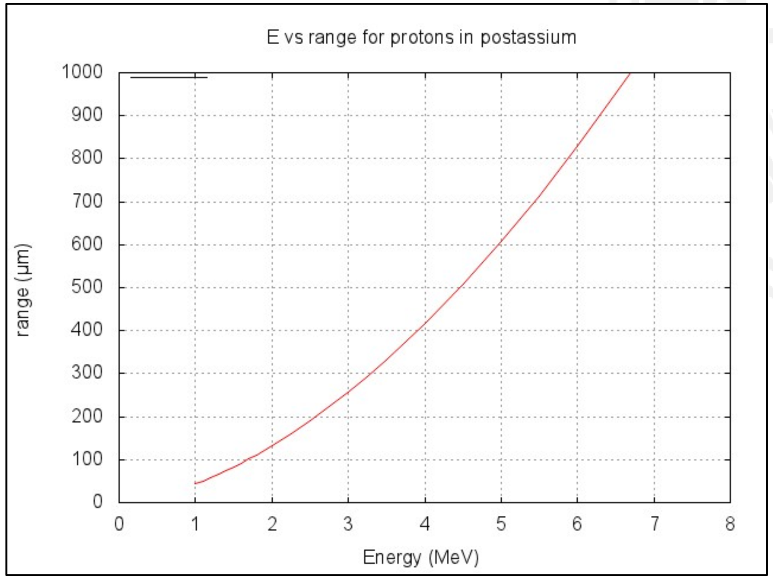
What more …

… do we need to consider?

We need to correct for energy and particle losses in the target. But 100 µm thickness seems quite ok:



Calculated with SRIM; see srim.org

Furthermore:
what we would measure with a setup of telescopes placed at different angles is in fact **dσ/dΩ(Θ)**.

To get σ we need to **integrate over the scattering angle**, probably needing proper interpolation/extrapolation, i.e., a theoretical description of the **shape of the angular distribution**.

But we stop this discussion here …

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Conclusion

We looked at the case of measuring the cross sections for
^{39}K(n,p) and ^{39}K(n,np) in the 10 to 20 MeV range.

Using a white neutron beam as in the future NFS facility and an arrangement of detector telescopes, we estimated that enough statistics could be collected within far less than one hour of beam time.
I.e. even if we made some optimistic assumptions, the experiment is feasible (in that respect).

Main problems that one needs to solve:

- How to get a suitable target (potassium is chemically highly reactive). Maybe one can use a compound. But these would need advance background subtraction.
- How to distinguish between (n,p) and (n,np)? Following the present discussion we would measure (n,xp). However, with input from model calculations this might be good enough.
- Probably something else that we did not think of yet …

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Summary

- Experiments are the foundation of science.
- The large variety of needed nuclear data calls for use of a range of different experimental techniques.
- This includes use of different facilities, which need careful characterisation.
- For this neutron cross sections standards are key. And many measurements are relative to some reference (ratios, …).
- Producing a good experimental data set with well characterized uncertainties (and made available in EXFOR) needs often many years of work.
- We cannot measure everything ….
- … so we need models and good codes like TALYS ☺

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