Neutrons for nuclear technology: experiments

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ARIEL-H2020 International on-line school on nuclear data: the path from the detector to the reactor calculation -- NuDataPath - 2022

Accelerator and Research reactor Infrastructures for Education and Learning

ARIEL

Disclaimer:

I asume:

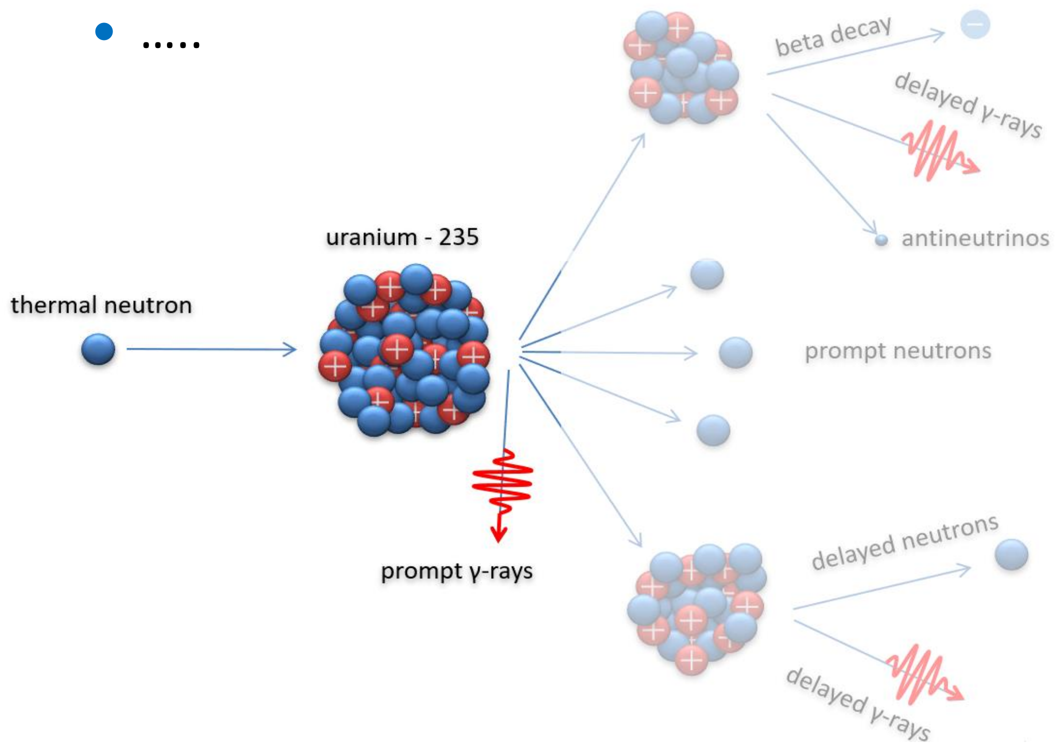
- You know now how neutron detectors work
- For other particles, at least ou know what are scintillators, gas detectors, semiconductors,...
- You know the principle of time-of-flight experiments
- You understand why the study of neutron reactions is important for Nucl. Tech.
- You know the role ofthe different reactions and neutron energies

Now let's "just" see a few examples of different type of measuremnts at some of the facilities that were mentioned yesterday .

Reactions and observables

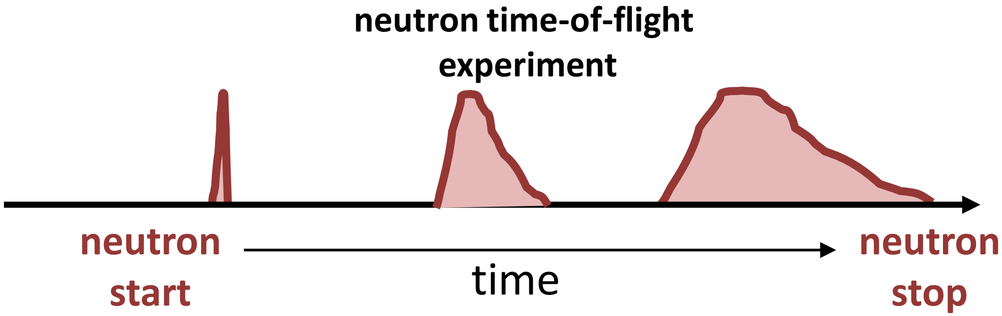
We need to detect different types of particles:

- g-rays from neutron neutron capture/fission: (n,g)/(n,f)
- g-rays from inelastic reactions: (n,n’), (n,xn), …
- Light charged particles from (n,lcp) reactions: (n,p), (n,a), …
- Heavy charged nuclei from fission: (n,f)
- Neutrons from many reactions: (n,f), (n,n), (n,n’), (n,xn)
- …..



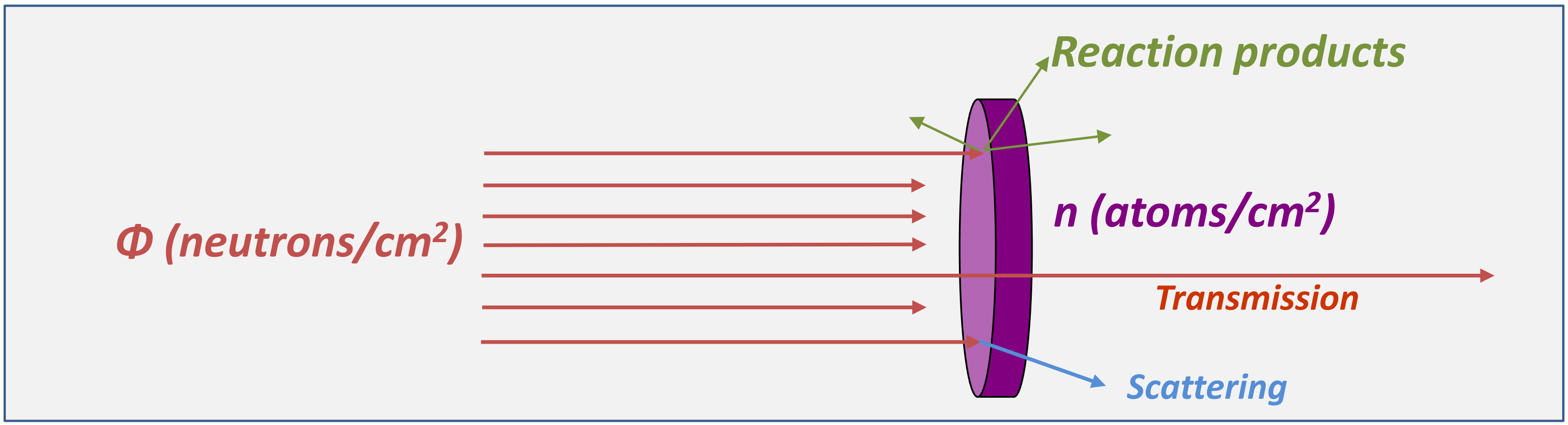
The types of **particles**, **processes**, **energies** and **observales** of interest are so different that their study requires a large variety of detector types and detection arrays.

The time-of-flight technique (again)



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

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

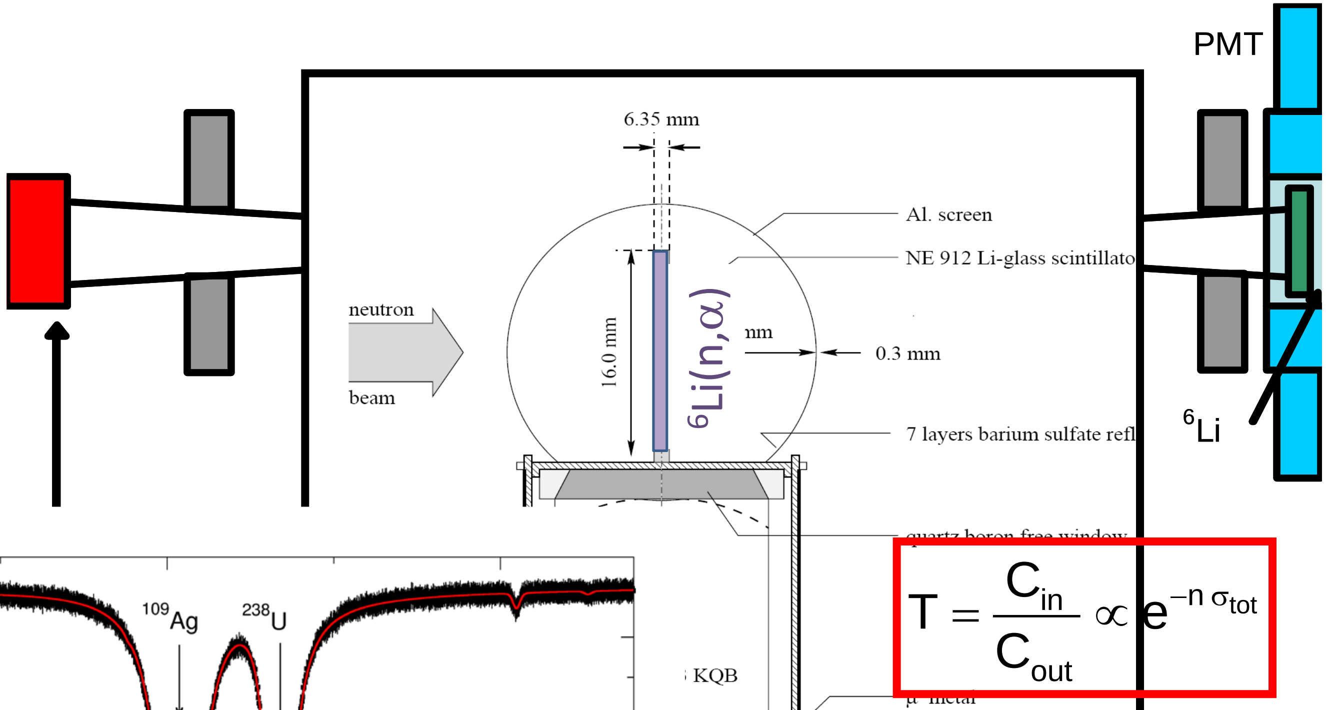


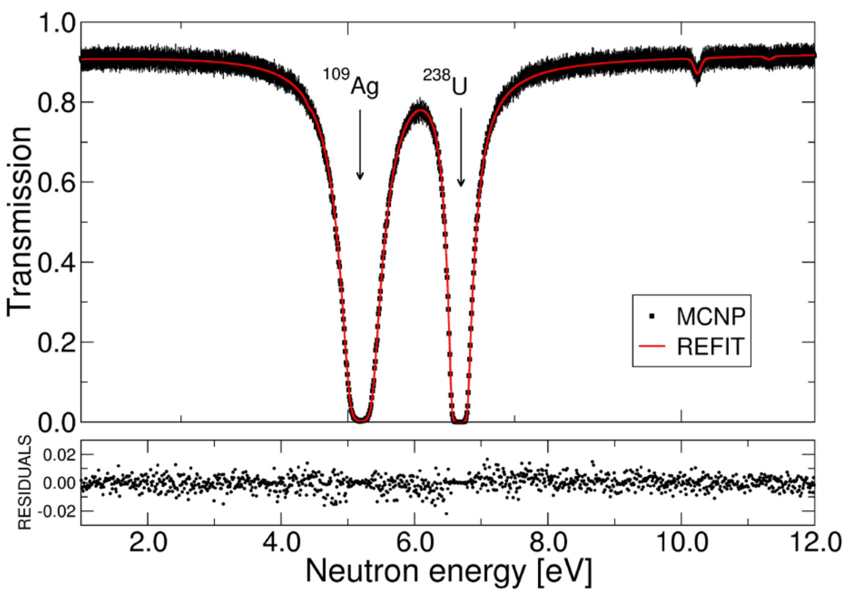
$$Transmission\ probability: \qquad T = e^{-n\sigma_{n,tot}}$$

$$Reaction\ probability\ (Yield): \quad Y_{n,x} = \left(1 - e^{-n\sigma_{n,tot}}\right)\frac{\sigma_{n,x}}{\sigma_{n,tot}} \quad (1^{st}\ order\ approx.)$$

Measuring transmission: total cross sections (n,tot)

Transmission measurement



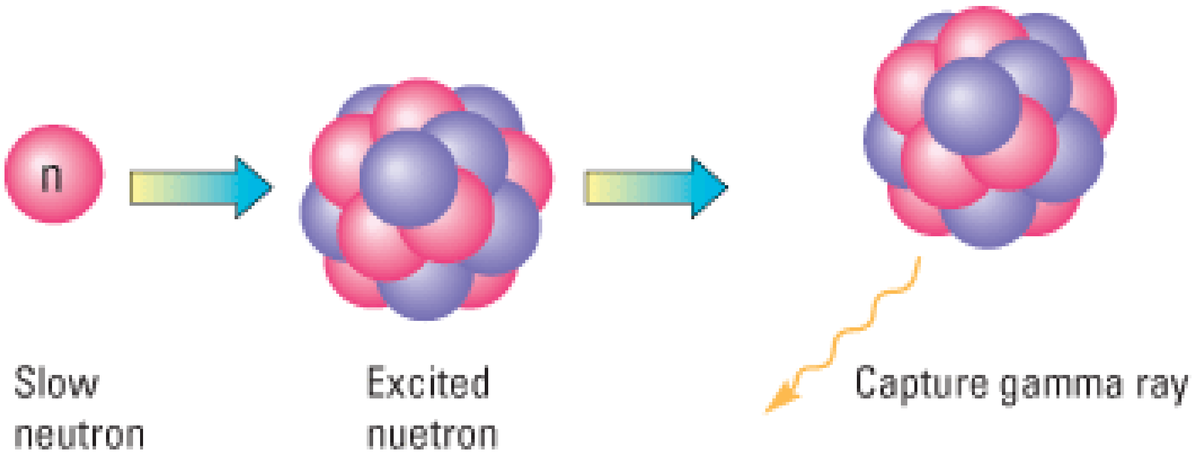


$$T = \frac{C_{in}}{C_{out}} \propto e^{-n\,\sigma_{tot}}$$

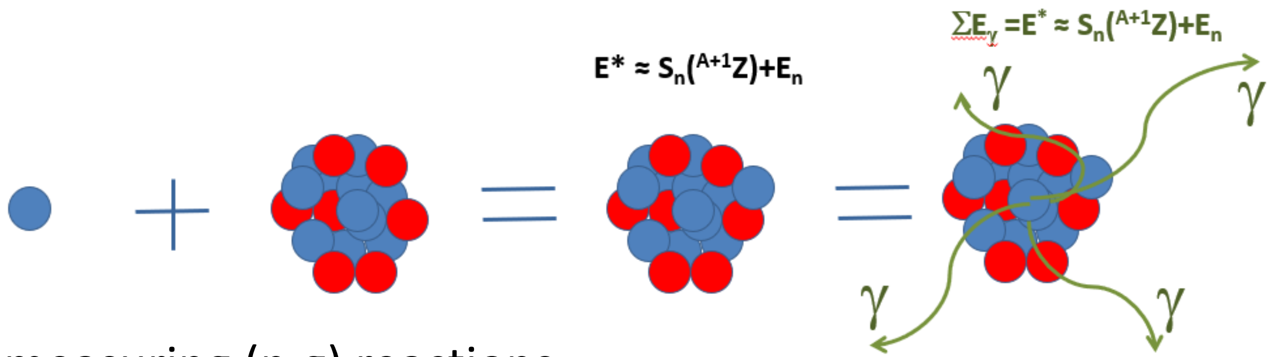
It may seem simple but:

- Background needs to be measured carefully (black resonances)
- Sample inhomogeneities important (powder's grain size)
- Thick targets needed (difficult for radiact.)
- Resoluton broadeding to be considered
- ....

Measuring capture (n,γ)



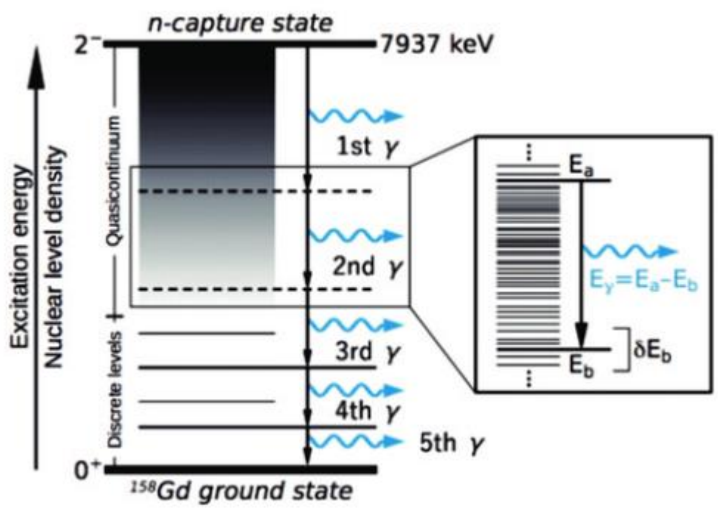
Observables in neutron capture

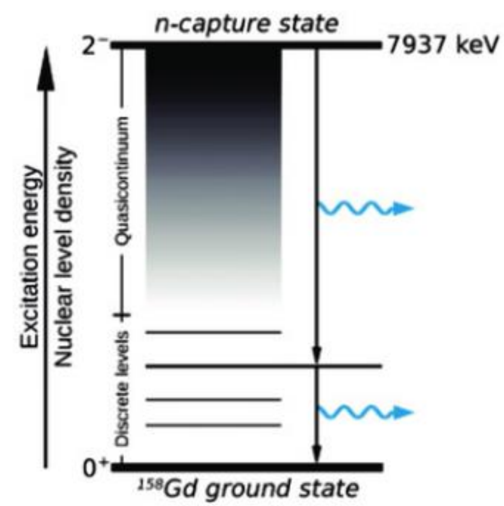


Strategies for measuring (n,g) reactions:

- Detect **a "characteristic"** g-ray from the cascade (PGA, prompt gamma analysis)
- Detect **only one** g-ray of the cascade (TED, Total Energy Detectors)
- Detect **all** (ideally) g-rays of the cascade (Calorimetry)

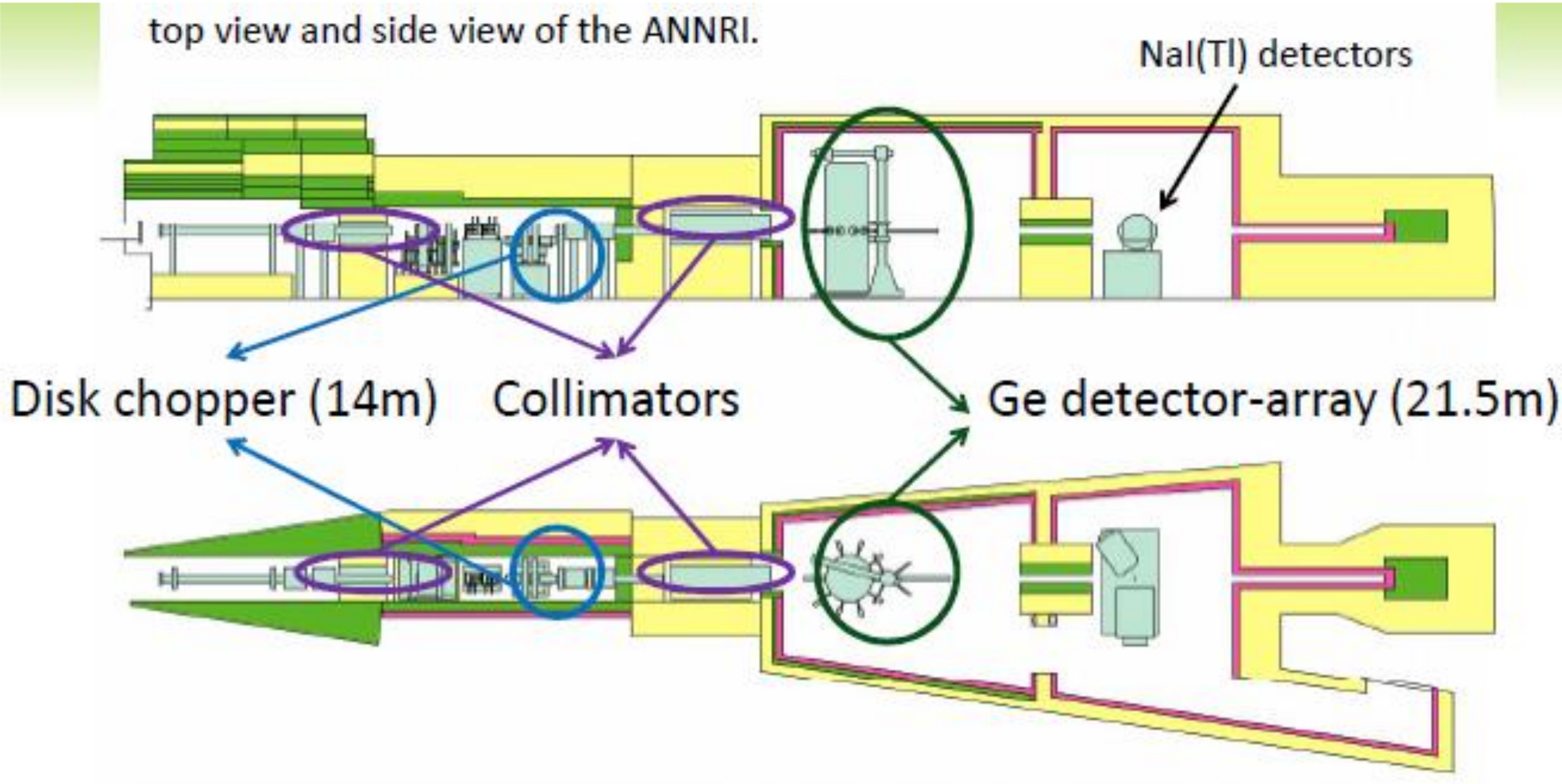
Main challenge:





PGA: Detecting a "characteristic" γ-ray (I)

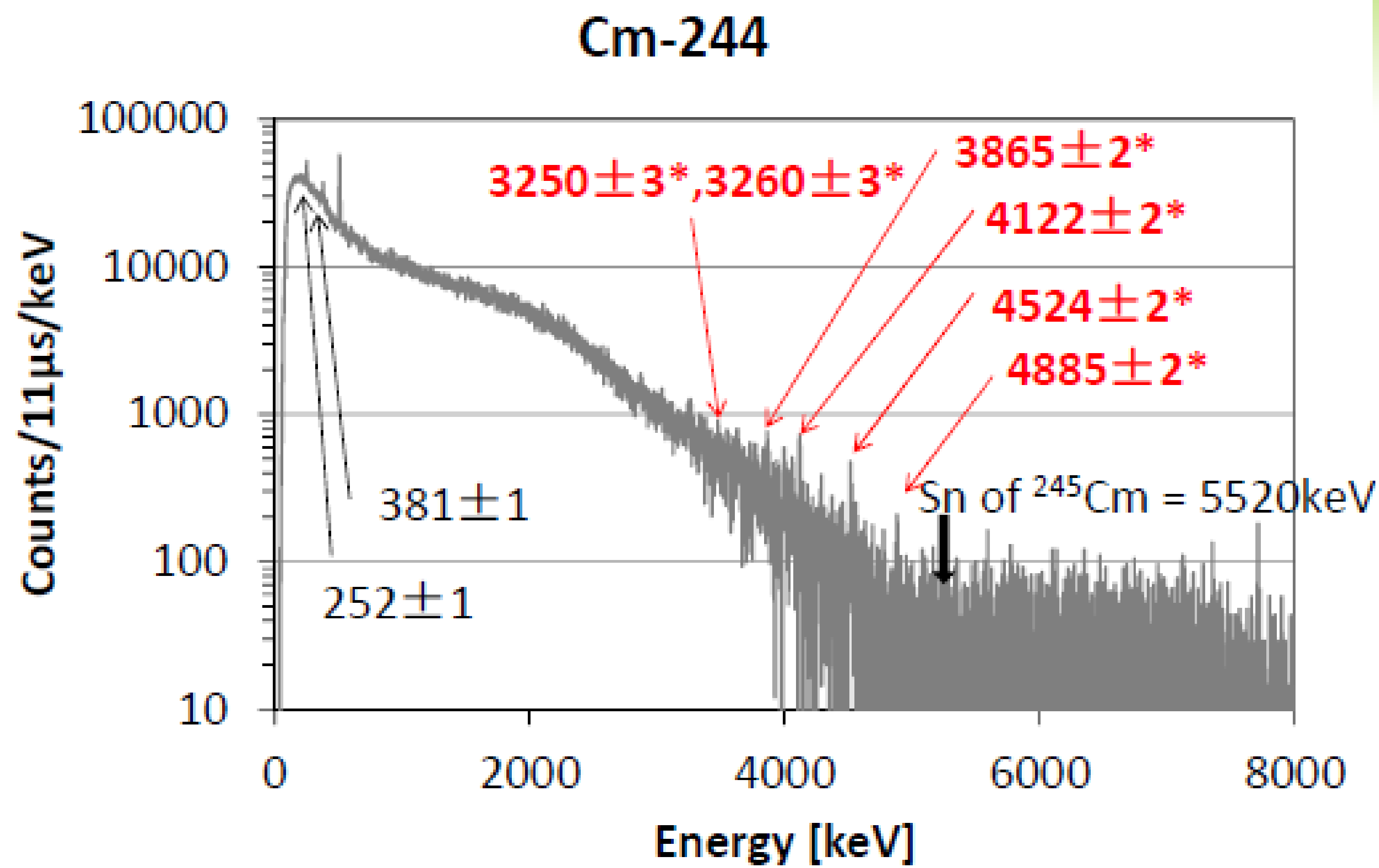
- ANNRI @ J-PARC (Japan)



PGA: Detecting a “characteristic” γ-ray (II)

Limitation in accuracy:

One needs to know the “intensity” of the characteristic(s) γ-ray line(s)



Brief TED: why detecting a "single" γ-ray?

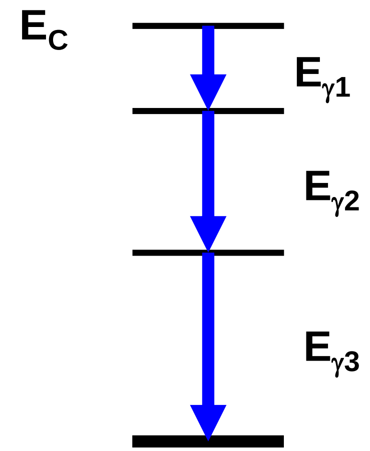
Every decay cascades is different,

then the efficiency to detect each one is different,

how to measure then?

if $\varepsilon_{\gamma i}$: total efficiency for γ-ray of energy $E_{\gamma i}$

then: Total efficiency of the cascade : $\varepsilon_c = 1 - \Pi(1 - \varepsilon_{\gamma i})$

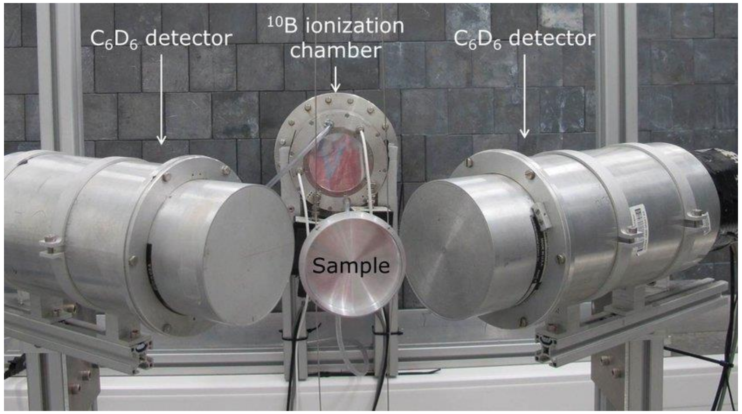


But if ($\varepsilon_{\gamma i} << 1$) then $\varepsilon_c = \Sigma \varepsilon_{\gamma i}$

Total Energy Detector (TED)

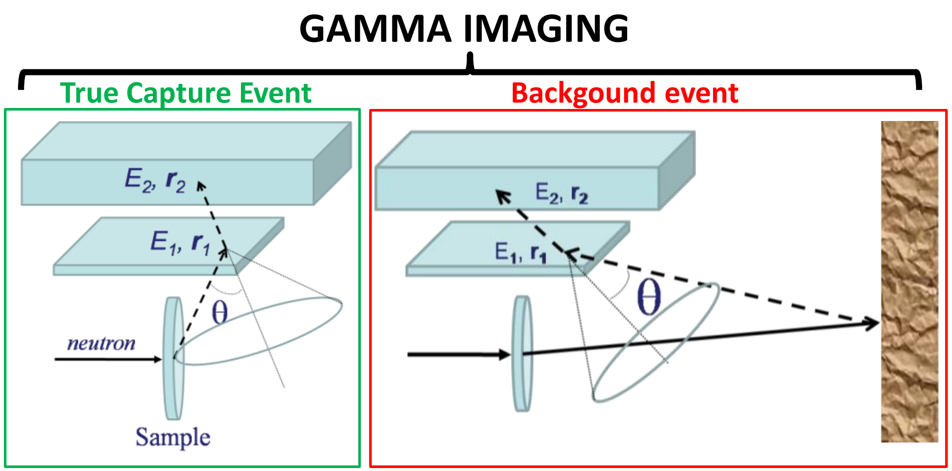
Now, if we had a detector for which $\varepsilon_{\gamma i} = kE_{\gamma i}$

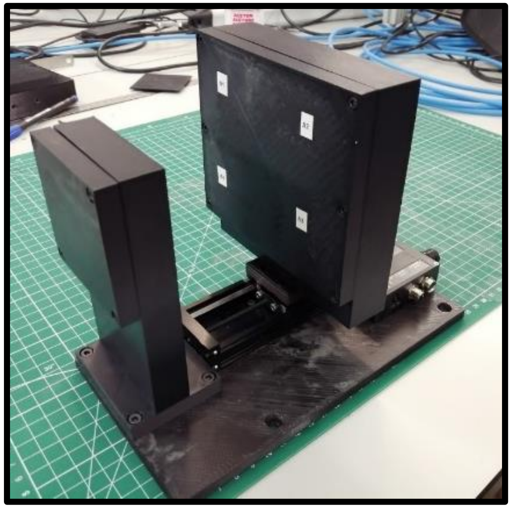
then $\varepsilon_c = \Sigma \varepsilon_{\gamma i} = \Sigma kE_{\gamma i} = k\Sigma E_{\gamma i} = kE_c$

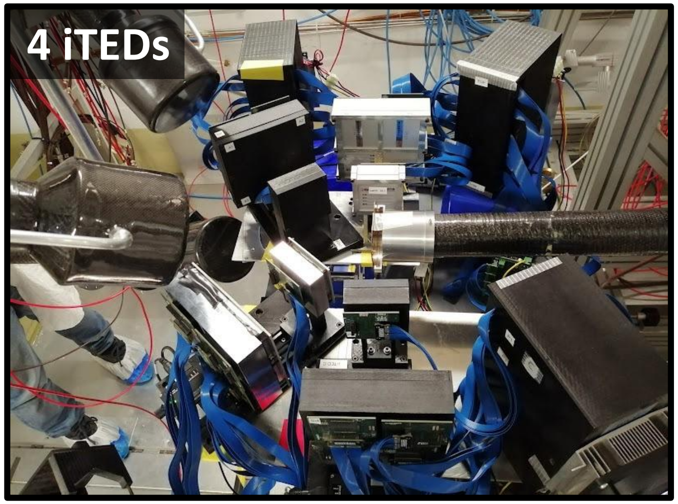


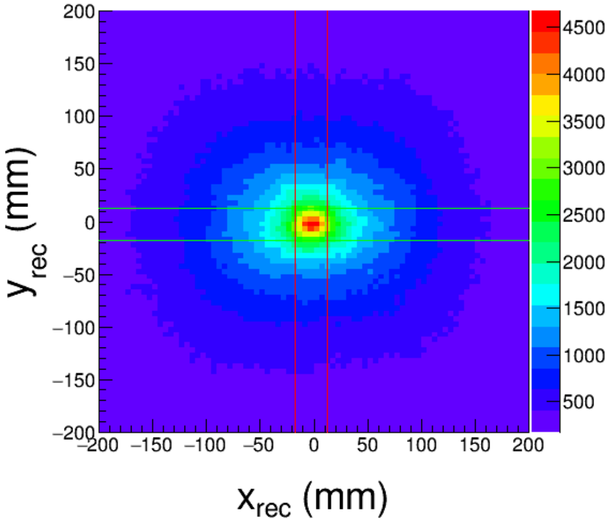
This type of detector can be constructed (Moxon-Rae detectors), but the proportionality is only approximate => MC used instead

The latest: TED + Imaging







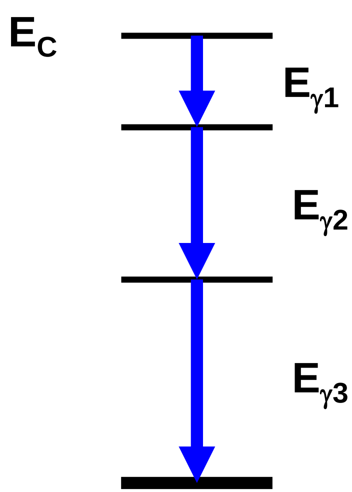


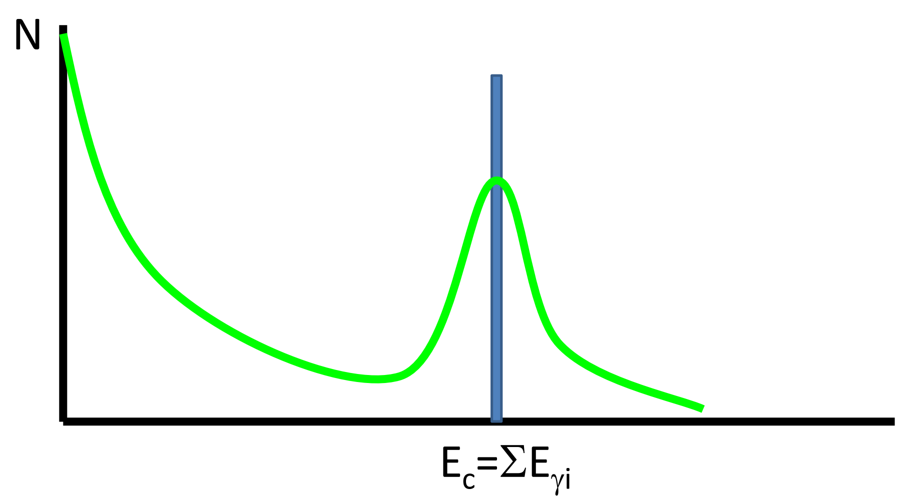
Total Absorption technique

If intrinsic and solid angle efficiencies are large:

- Total efficiency of the cascade : $\varepsilon_c = 1 - \Pi(1 - \varepsilon_{\gamma i})$
- Peak efficiency : $\varepsilon^p{}_c = \Pi \varepsilon^p{}_{\gamma i}$

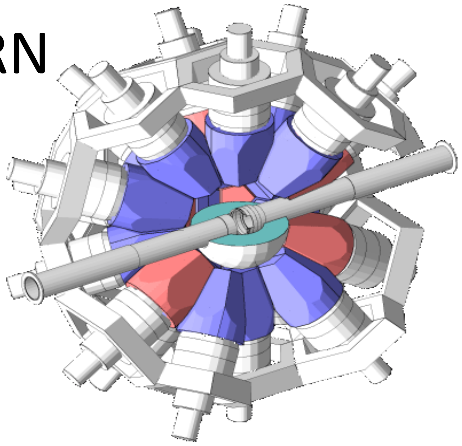
If $\varepsilon^p{}_{\gamma i} = \varepsilon_{\gamma i} = 1$ THEN $\varepsilon_c = \varepsilon^p{}_c = 1$





(n,g) calorimeters worldwide

n_TOF Total Absorption Calorimeter (TAC) at CERN



40 BaF_2 crystals covering 4π
(based on the original at FZK)

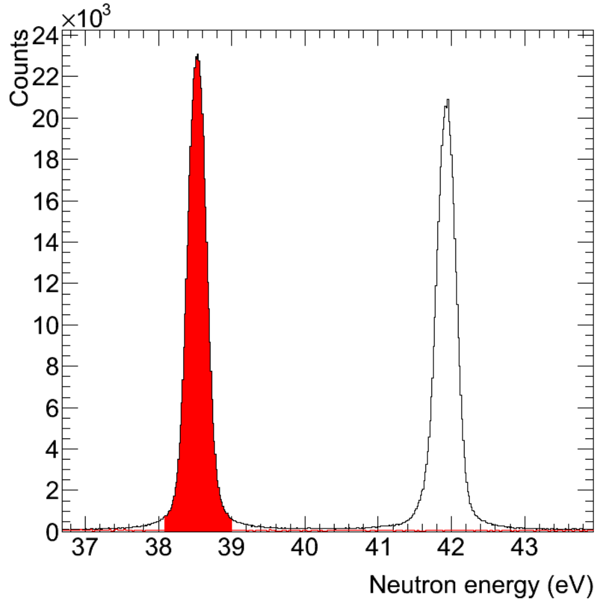
Similar one at the Back-n at CSNS

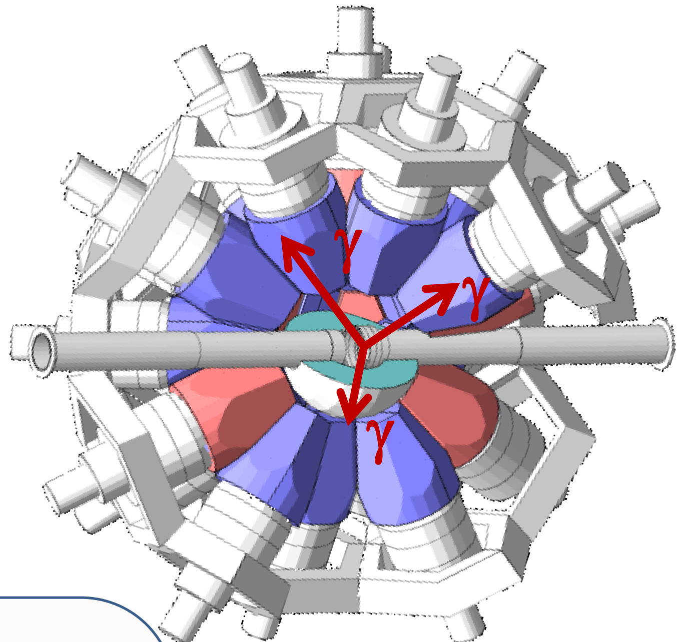
DANCE (Detector for Advance Neutron Capture Experiments) at Los Alamos (USA)

162 BaF_2 crystals covering 4π

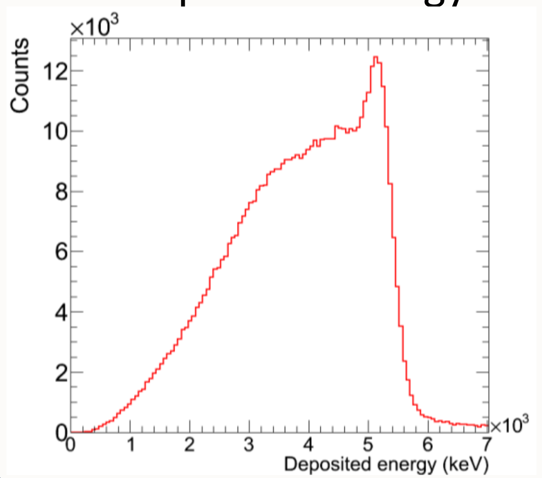
Future: a lot going on within the n_TOF collaboration

Brief TAC: observables (E_n, E_{sum}, m_{cr})

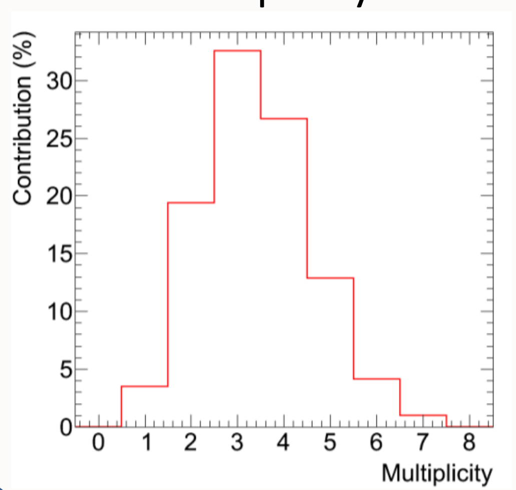




Deposited energy

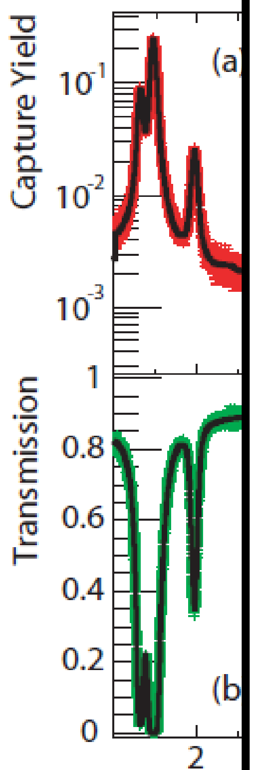


Multiplicity



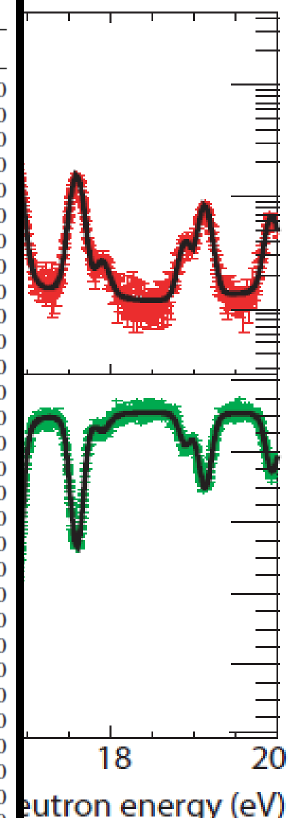
(n,tot)&(n,g) cross sections: resonance analysis

$$Transmission:\ T = \frac{C_{in}}{C_{out}} \propto e^{-n\ \sigma_{tot}} \qquad Capture\ yield:\ Y = \frac{C-B}{\varepsilon\ \Phi} = (1 - e^{-n\ \sigma_{tot}})\frac{\sigma_{n,g}}{\sigma_{tot}}$$

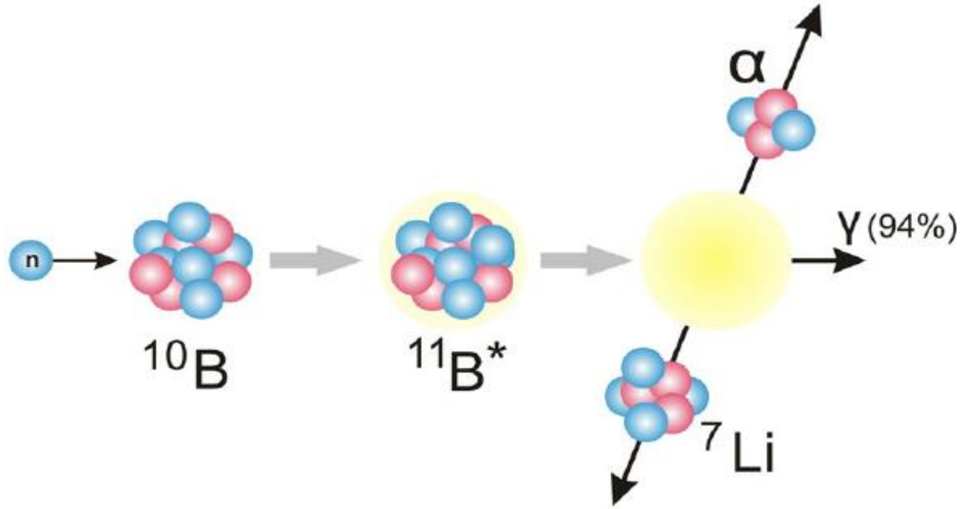


Resonance parameters from RSA with SAMMY

Energy (eV)	J^π	This work Γ_γ(meV)	This work Γ_n(meV)	JENDL-4.0 Γ_γ(meV)	JENDL-4.0 Γ_n(meV)	Noguere Γ_γ(meV)	Noguere Γ_n(meV)
1.321 ± 0.001	3	40.9 ± 1.8	0.0317 ± 0.0012	40.3	0.0320	37.9 ± 0.4	0.0310 ± 0.0010
1.478 ± 0.001	2	40.9 ± 1.8	0.181 ± 0.007	40.5	0.1840	41.6 ± 0.9	0.1840 ± 0.0040
1.969 ± 0.001	3	40.9 ± 1.8	0.0140 ± 0.0005	39.5	0.0140	37.2 ± 0.6	0.0140 ± 0.0010
3.865 ± 0.002	3	40.9 ± 1.8	0.207 ± 0.008	39.7	0.2120	40.4 ± 0.6	0.2110 ± 0.0020
4.264 ± 0.003	2	40.9 ± 1.8	0.0323 ± 0.0012	40.4	0.0330	40.0 ± 0.9	0.0330 ± 0.0010
4.863 ± 0.003	2	40.9 ± 1.8	0.0396 ± 0.0015	40.0	0.0420	40.1 ± 1.2	0.0430 ± 0.0010
5.777 ± 0.004	3	40.9 ± 1.8	0.524 ± 0.019	41.9	0.5280	42.1 ± 0.8	0.5330 ± 0.0090
6.378 ± 0.004	3	40.9 ± 1.8	0.0779 ± 0.0029	39.6	0.0790	38.8 ± 1.2	0.0790 ± 0.0010
6.677 ± 0.004	2	40.9 ± 1.8	0.0136 ± 0.0005	40.1	0.0130	39.3 ± 1.0	0.0140 ± 0.0010
7.189 ± 0.005	2	40.9 ± 1.8	0.00823 ± 0.00030	40.0	0.0090	39.3 ± 1.0	0.0100 ± 0.0010
7.423 ± 0.005	3	40.9 ± 1.8	0.119 ± 0.004	38.4	0.1220	39.0 ± 1.5	0.1240 ± 0.0010
7.678 ± 0.007	2	40.9 ± 1.8	0.00176 ± 0.00012	40.0	0.0020	39.3 ± 1.0	0.0030 ± 0.0010
8.307 ± 0.006	3	40.9 ± 1.8	0.0879 ± 0.0033	37.6	0.0900	39.7 ± 1.4	0.0930 ± 0.0010
8.978 ± 0.006	3	40.9 ± 1.8	0.101 ± 0.004	37.0	0.1020	37.2 ± 1.3	0.1040 ± 0.0010
9.299 ± 0.006	2	40.9 ± 1.8	0.585 ± 0.022	41.4	0.6020	41.8 ± 0.9	0.6110 ± 0.0060
10.231 ± 0.007	2	40.9 ± 1.8	0.0275 ± 0.0010	40.0	0.0280	39.3 ± 1.0	0.0300 ± 0.0010
10.682 ± 0.007	3	40.9 ± 1.8	0.422 ± 0.016	40.0	0.4320	39.3 ± 1.0	0.4390 ± 0.0050
10.845 ± 0.008	3	40.9 ± 1.8	0.683 ± 0.025	40.0	0.6890	39.3 ± 1.0	0.7010 ± 0.0110
11.097 ± 0.008	2	40.9 ± 1.8	0.996 ± 0.037	43.8	1.0100	42.2 ± 1.1	1.0320 ± 0.0130
12.202 ± 0.009	3	40.9 ± 1.8	0.0487 ± 0.0018	40.0	0.0490	39.3 ± 1.0	0.0480 ± 0.0010
12.618 ± 0.009	2	40.9 ± 1.8	0.888 ± 0.033	40.2	0.9110	38.9 ± 1.2	0.9250 ± 0.0100
13.139 ± 0.009	3	40.9 ± 1.8	0.0178 ± 0.0007	40.0	0.0170	39.3 ± 1.0	0.0170 ± 0.0010
14.282 ± 0.031	2	40.9 ± 1.8	0.000962 ± 0.000099	40.0	0.0020	39.3 ± 1.0	0.0020 ± 0.0010
15.796 ± 0.012	3	40.9 ± 1.8	0.0671 ± 0.0025	40.0	0.0690	39.3 ± 1.0	0.0690 ± 0.0010
15.949 ± 0.012	3	40.9 ± 1.8	0.0374 ± 0.0018	40.0	0.0380	39.3 ± 1.0	0.0380 ± 0.0010
16.089 ± 0.012	2	40.9 ± 1.8	1.01 ± 0.04	40.0	1.0520	38.1 ± 1.8	1.0690 ± 0.0120
16.860 ± 0.012	2	40.9 ± 1.8	0.290 ± 0.011	37.8	0.2990	39.3 ± 1.0	0.3040 ± 0.0020
17.597 ± 0.013	3	40.9 ± 1.8	0.151 ± 0.006	39.1	0.1560	39.3 ± 1.0	0.1590 ± 0.0010
17.908 ± 0.013	2	40.9 ± 1.8	0.0155 ± 0.0007	40.0	0.0180	39.3 ± 1.0	0.0180 ± 0.0010
17.935 ± 0.039	3	40.9 ± 1.8	0.00299 ± 0.00029	40.0	0.0030	39.3 ± 1.0	0.0030 ± 0.0010
18.892 ± 0.014	2	40.9 ± 1.8	0.0418 ± 0.0015	40.0	0.0480	39.3 ± 1.0	0.0480 ± 0.0010
19.126 ± 0.014	3	40.9 ± 1.8	0.0838 ± 0.0031	40.0	0.0880	39.3 ± 1.0	0.0890 ± 0.0010
19.932 ± 0.015	3	40.9 ± 1.8	0.0622 ± 0.0023	40.0	0.0700	39.3 ± 1.0	0.0690 ± 0.0010



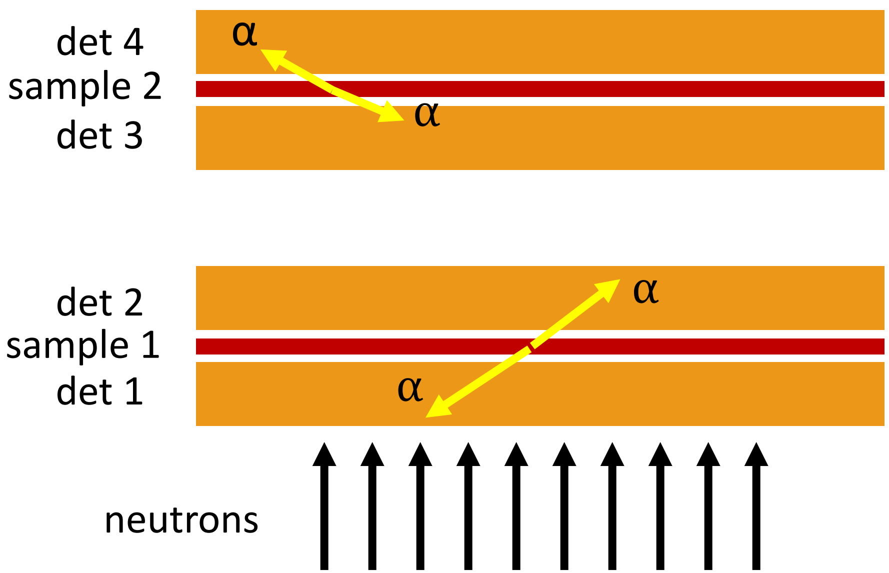
Measuring light charged particle production (n,chp)



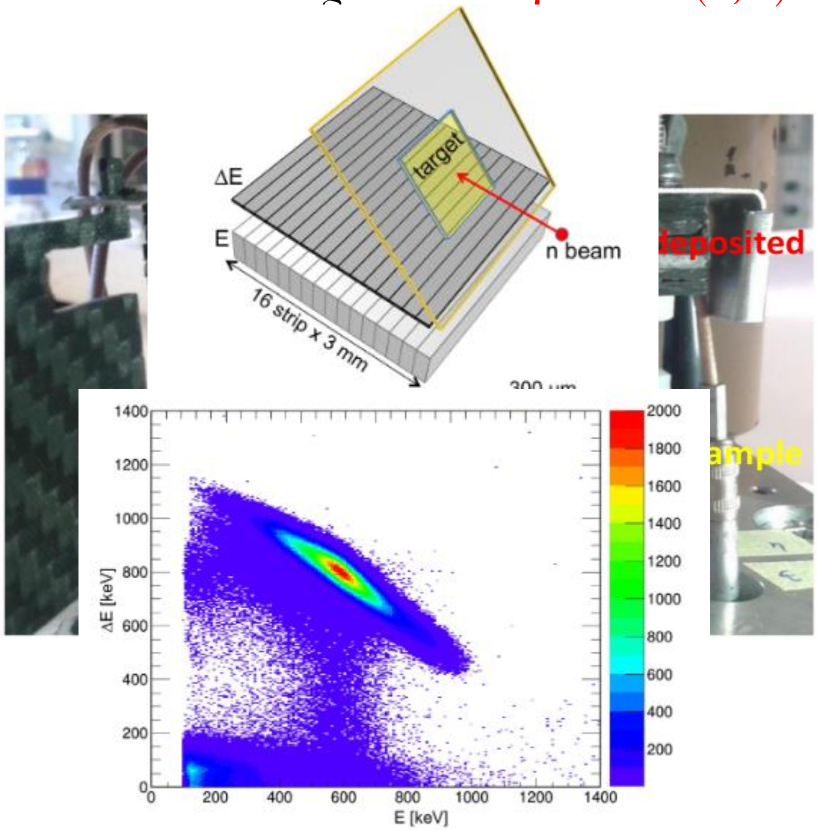
(n,α/p) with high radioactive (GBq) targets

7Be(n,a)/(n,p) at CERN n_TOF => Unambiguous identification!

Discriminate background ^{7}Be γ and ^{7}Be(n,p)



Discriminate background ^{7}Be γ and ^{7}Be(n,α)



Silicon detectors in the neutron beam
3x3 cm^2 active area, 140 μm thickness
2 ^{7}Be targets with ~18 GBq each (~1.4 μg)

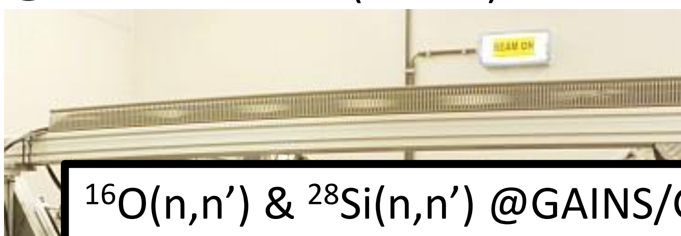
Silicon detectors OFF the neutron beam
3x3 cm^2 active area, 20 and 140 μm thickness
^{7}Be target with ~1 GBq each (~0.1 μg)

Measuring inelastic scattering (n,xn)

Detectors for inelastic reactions (I)

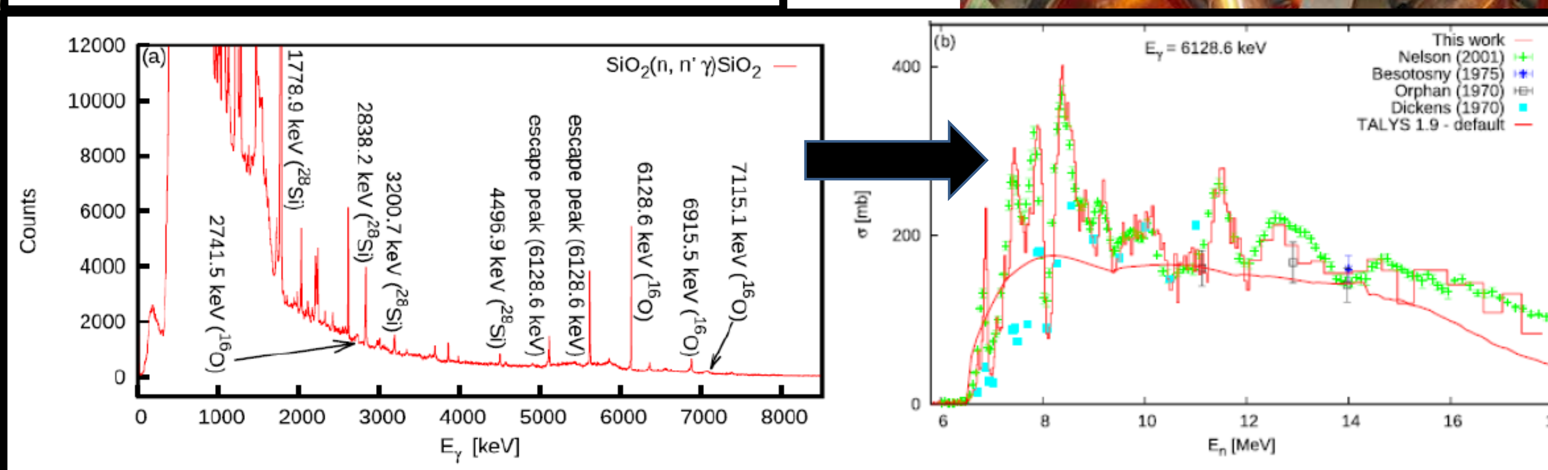
The γ-rays from (n,n’) reactions are measured by HPGe detectors

GAINS (Gamma Array for Inelastic Neutron Scattering) @ IRMM GELINA (100 m)



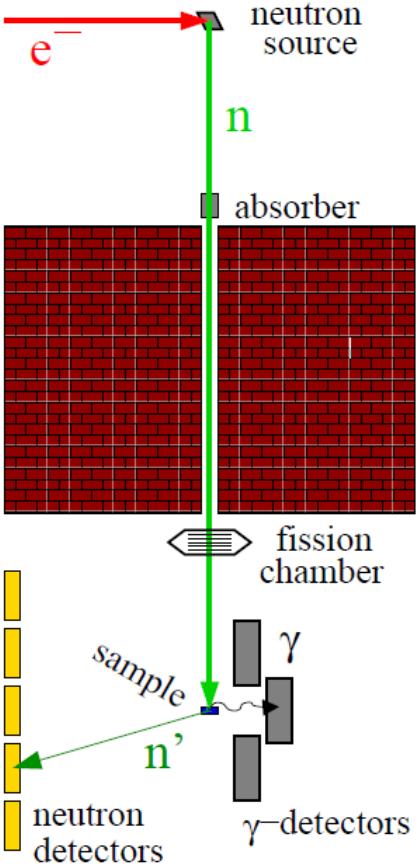
GRAPhEME (Germanium array for actinides precise measurements) @ IRMM GELINA (30 m)

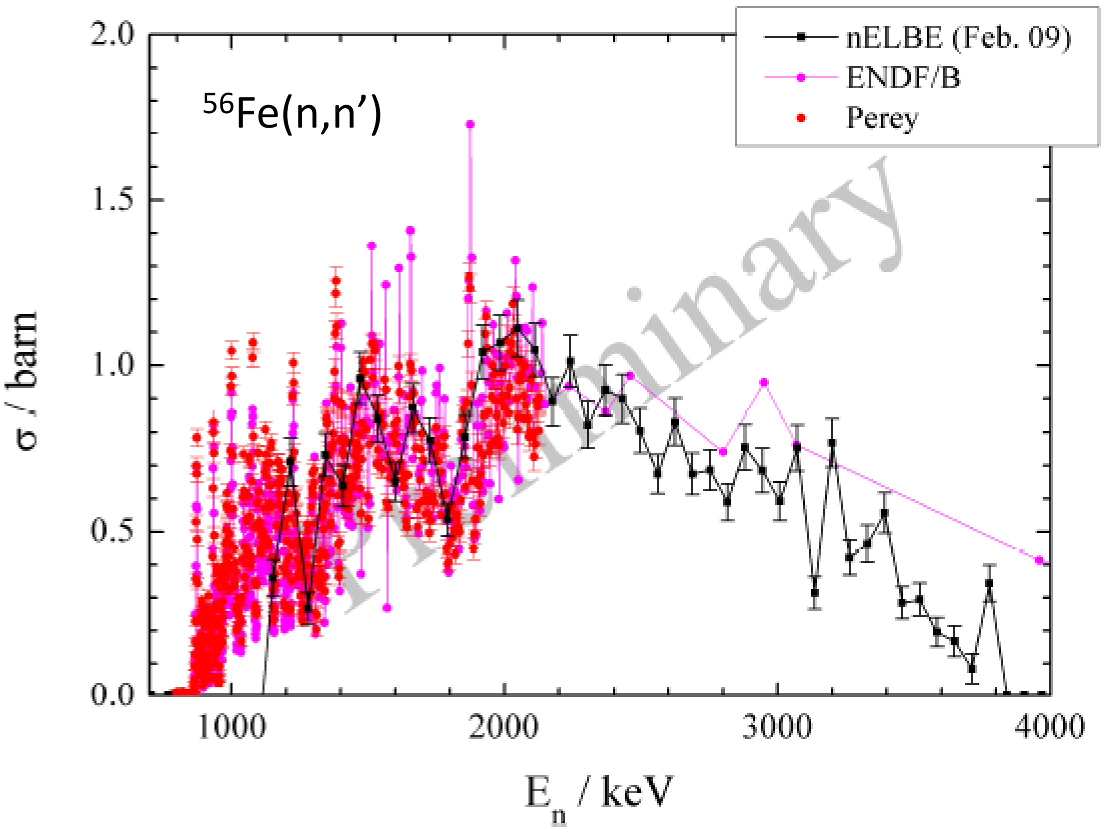
$^{16}O(n,n')$ & $^{28}Si(n,n')$ @GAINS/GELINA



Detectors for inelastic reactions (II)

At nELBE, the HPGe are replaced by 16 BaF2 (lower resolution but faster and with higer efficiency) and 5 neutron detectors (fast plastic scintillators) are added.

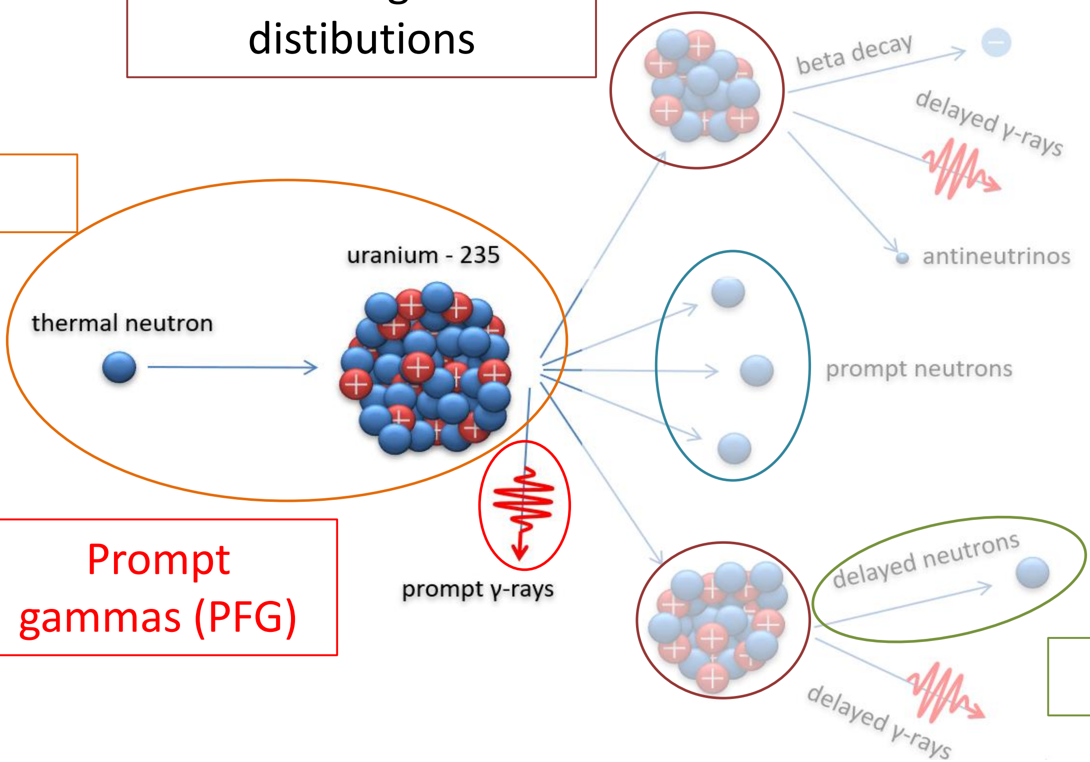




Measuring fission

Fission fragments distibutions

Fission



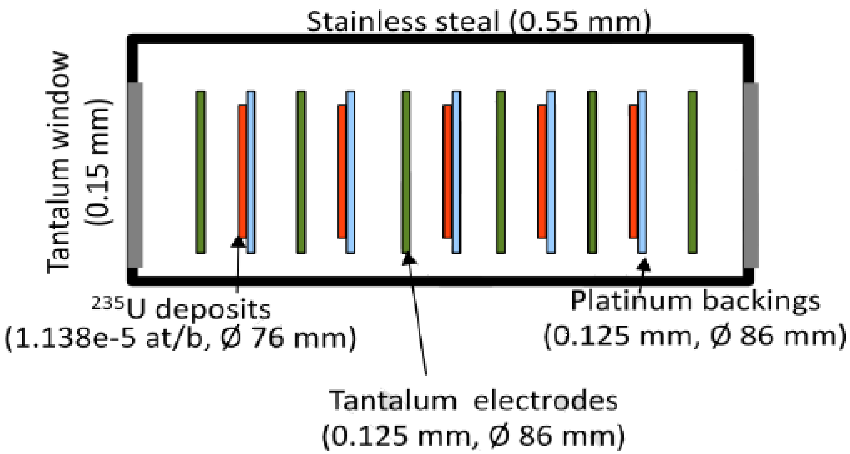
Neutron multiplicities

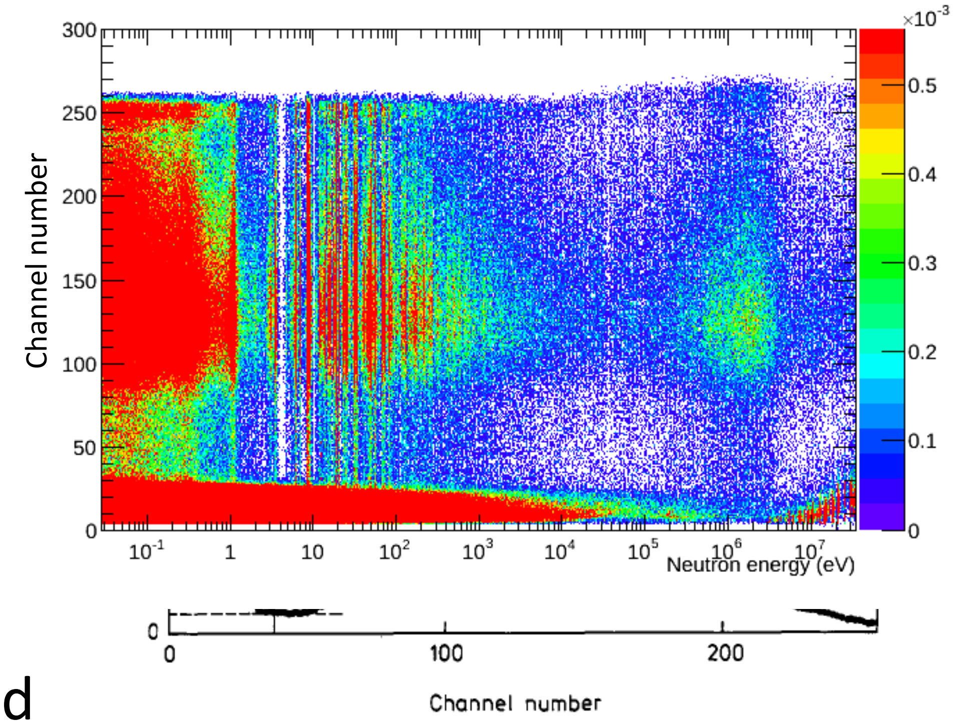
Prompt gammas (PFG)

β delayed neutrons

A “reference” fission chamber (PTB)

A pair of multiplate fission chambers loaded with ^{235}U and ^{238}U were developed in 1990 and can, still today, be used for flux measurements and intercomparisson experiments.

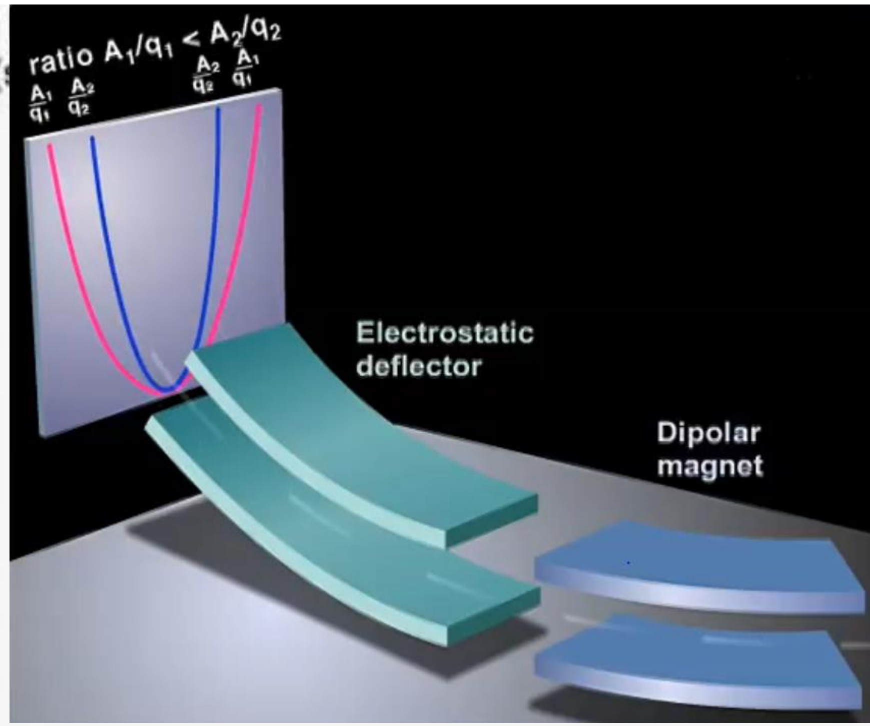


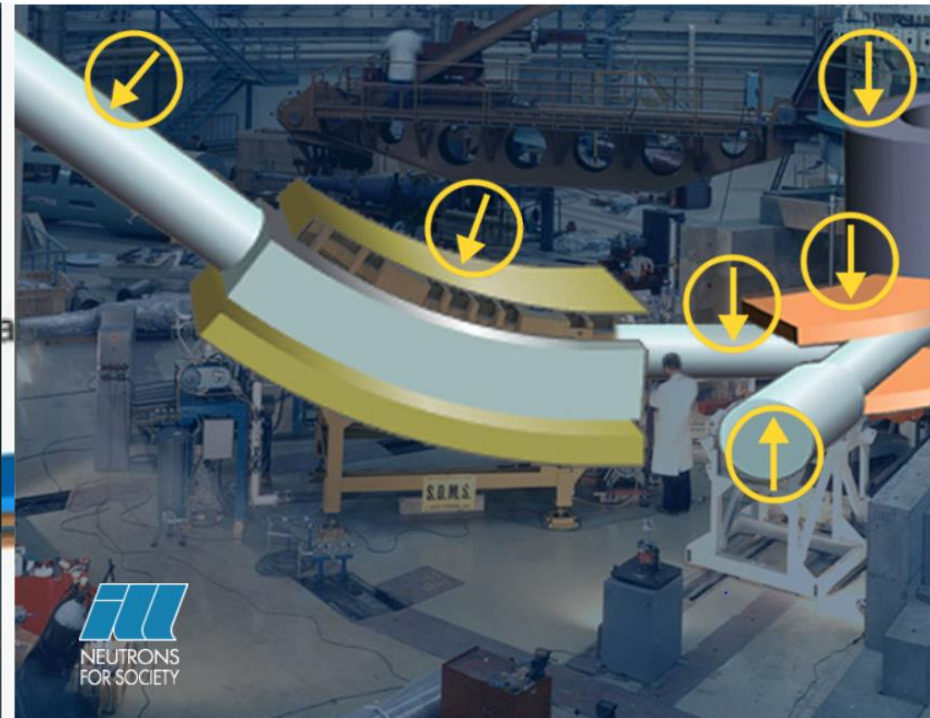


The key:

- Samples very well charecterized
- Efficiency very well characterized: 98% for E>0,45P

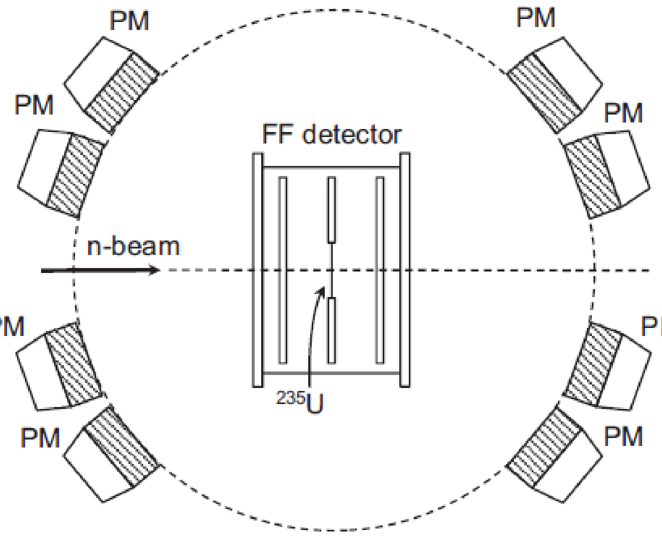
Fission fragments with a fragment separator

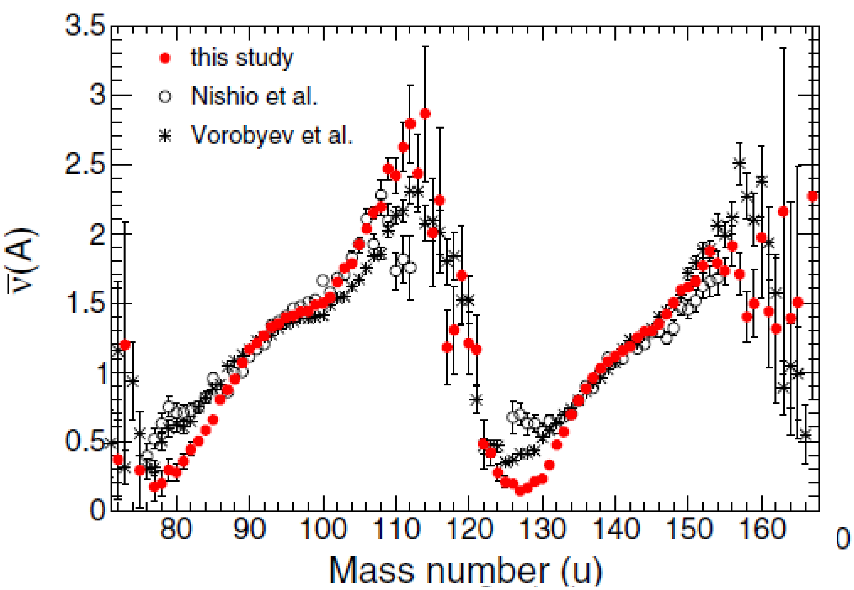




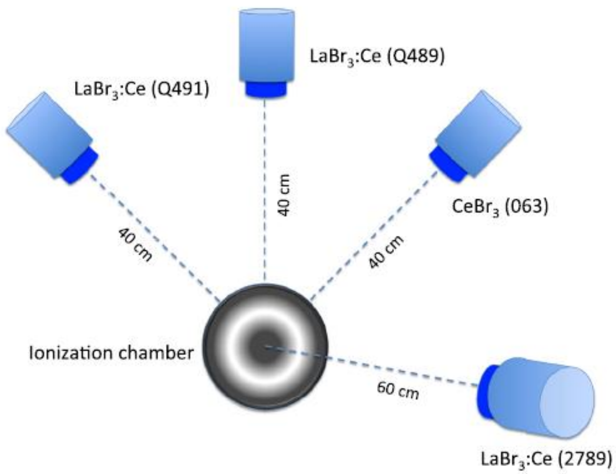
Prompt fission neutrons (PFN) & gammas (PFG)

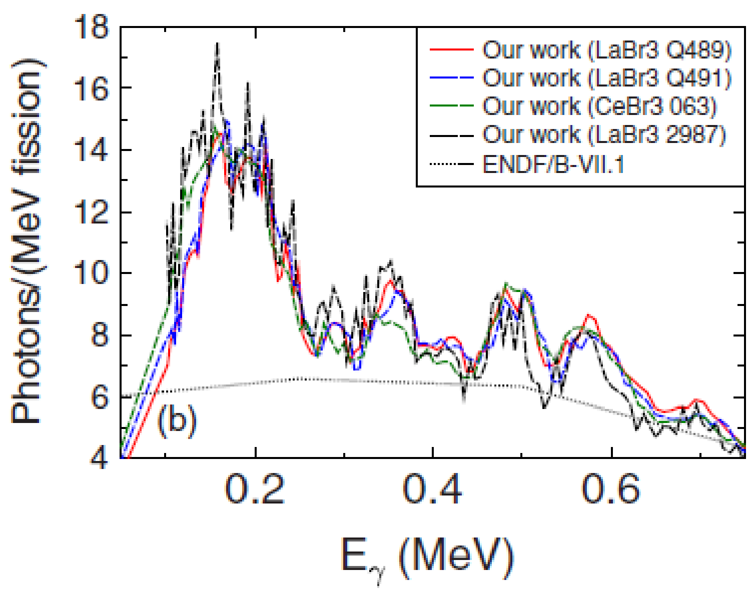
SCINTIA @GELINA





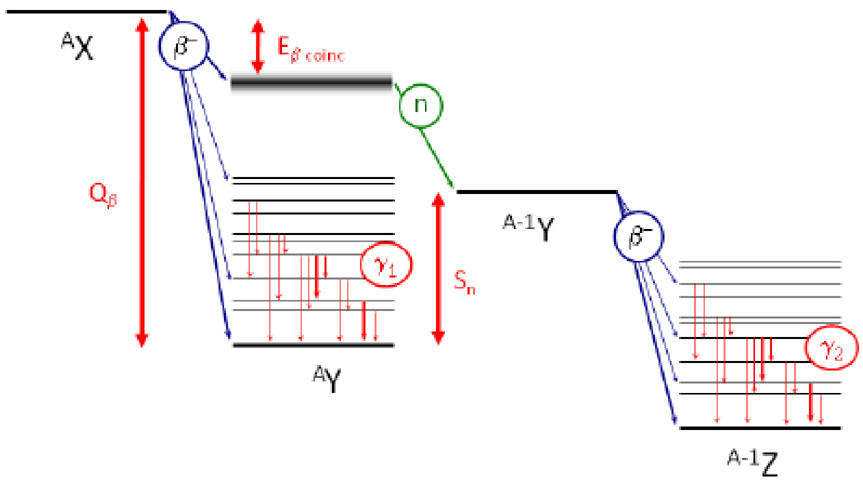
Twin FGIC@BRR



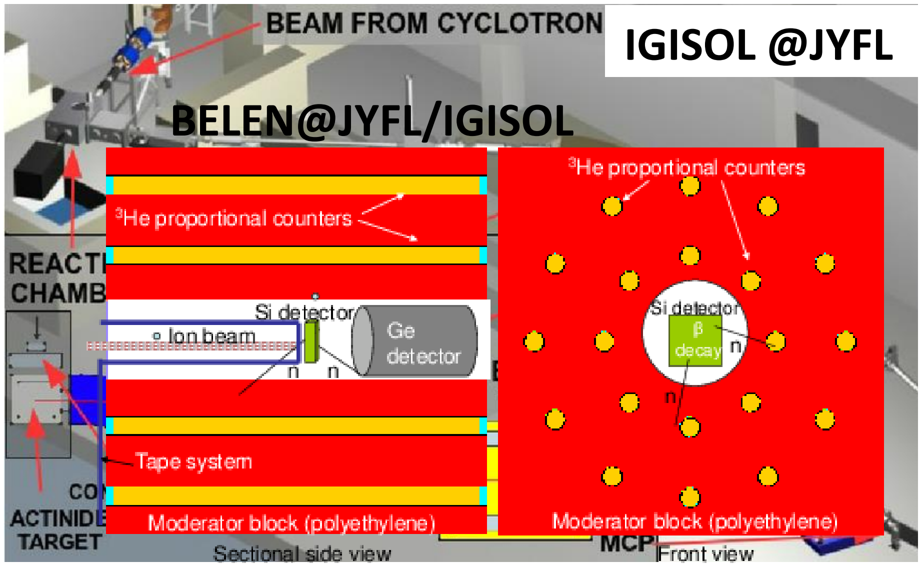


Beta delayed neutron emission

Exotic nuclei at IGISOL (JYFL) => detection beta delayed neutrons



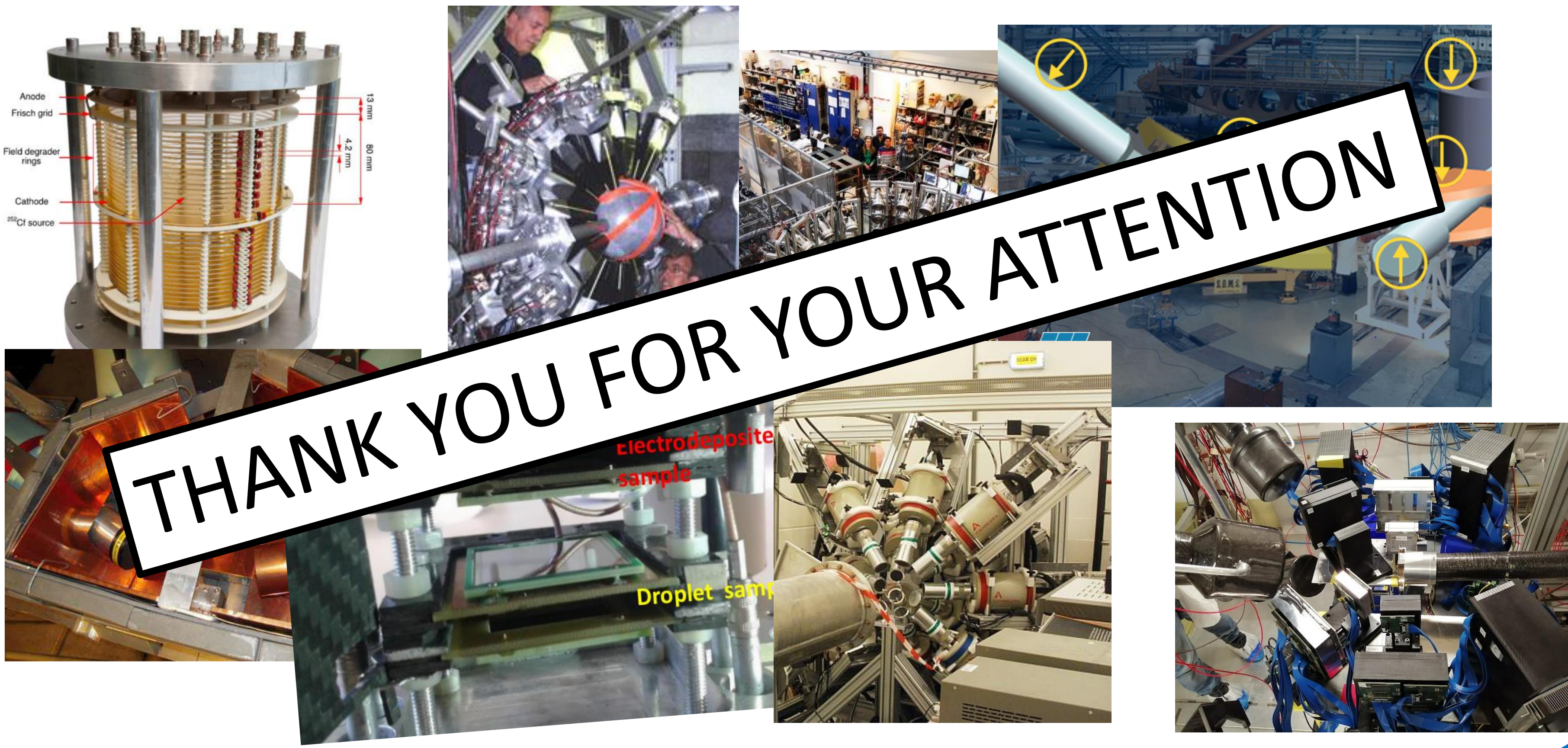
MONSTER@JYFL/IGISOL



Summary

- Many neutron induced reactions of interest for nucl. Tech.
- Many observables from each reaction

=> Large variety of detection systems and techniques



THANK YOU FOR YOUR ATTENTION