Detectors and experimental techniques

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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

Objectives & Disclaimer

Nuclear data: the path from the detector to the reactor calculation

=> Topic: "**Detectors and experimental techniques**"

=> Time: 45 minutes

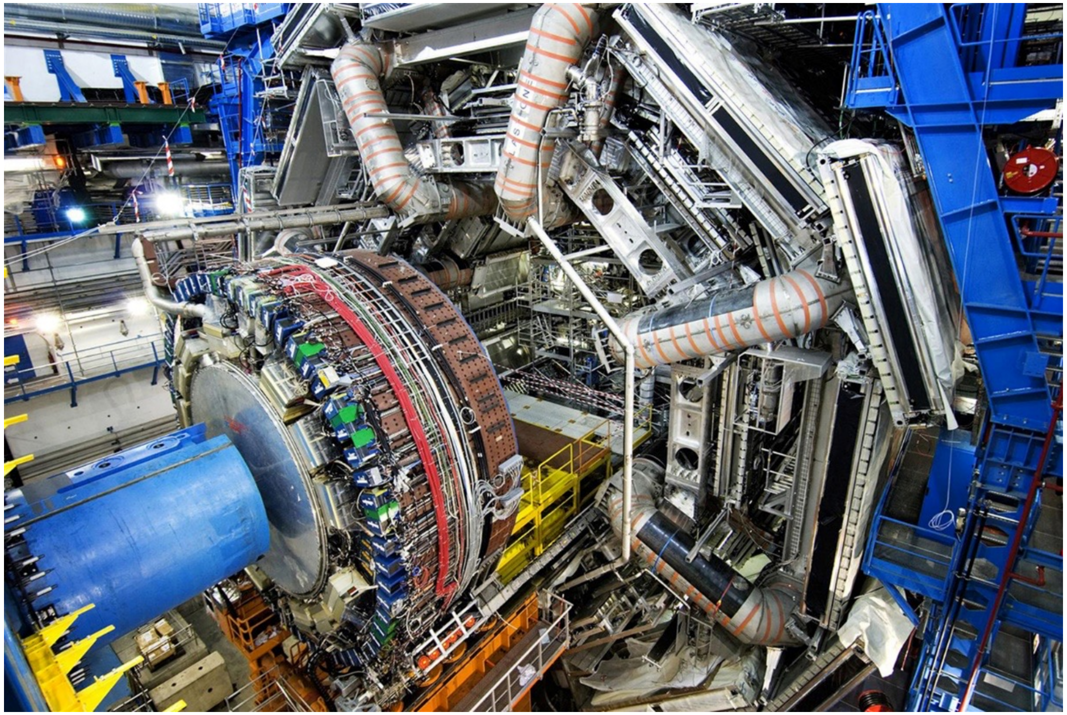
Disclaimer:

- Limited to neutron induced reaction [*some illustrative emphasis on (n,g)*]
- Most, except fission, addressed for the case of time-of-flight
- Necessarily:
  - Many detector types and examples left out
  - Analysis techniques poorly covered
  - Many recent developments left out
  - References not listed
  - NO TIME TO GO INTO MUCH DETAILS

Last, but not least:

This is a school => Please interrupt me and ask!

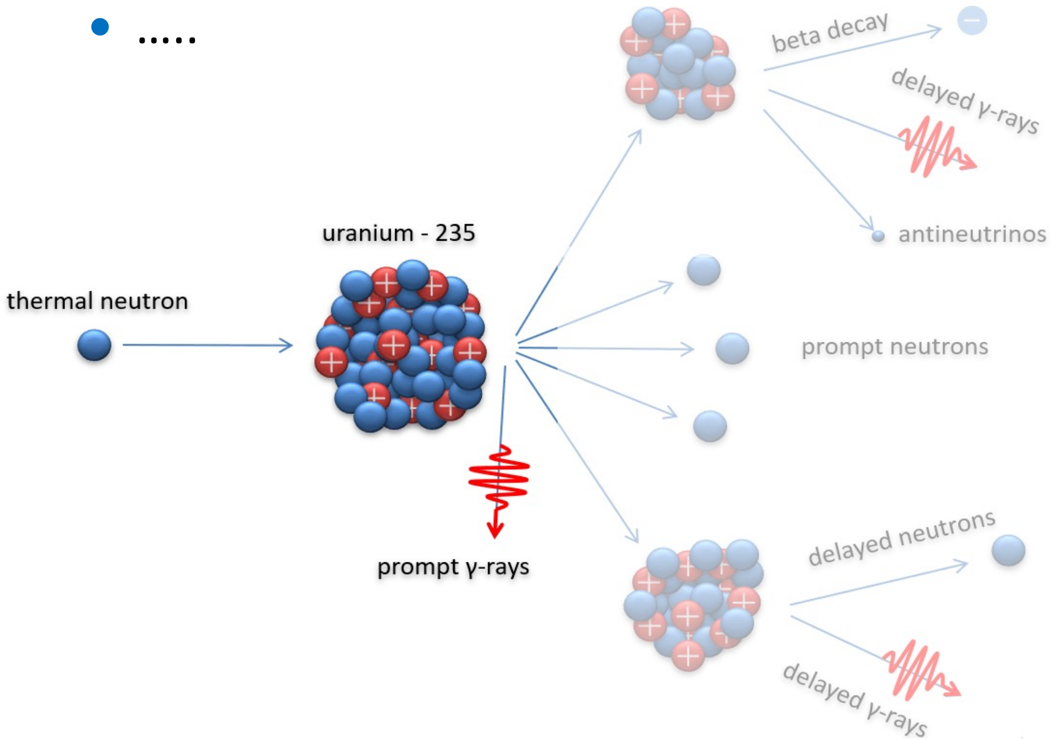
Briefing on particle detectors



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.

Types of detectors: scintillators (I)

A scintillator is a material that exhibits scintillation — the property of luminescence, when excited by ionizing radiation.

→ **BUT photons and neutrons are not "directly" ionizing particles**

Photons (no charge)

Inorganic crystal (e.g.NaI)

2 MeV photon

Compton scattering
(e^- + γ with E_{tot}=2 MeV)

Photoelectric
(e^- with ~2 MeV)

Pair creation
(e^-/e+ with
E_e=(2-1,022)/2 MeV
+ two 511keV photons)

Neutrons (no charge)

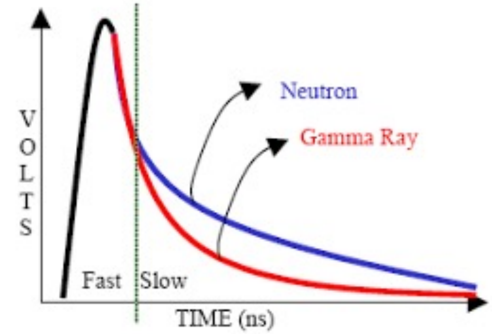
. C_6H_6)

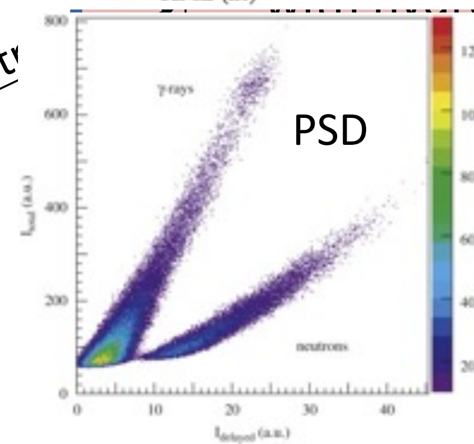
2 MeV neut

ering

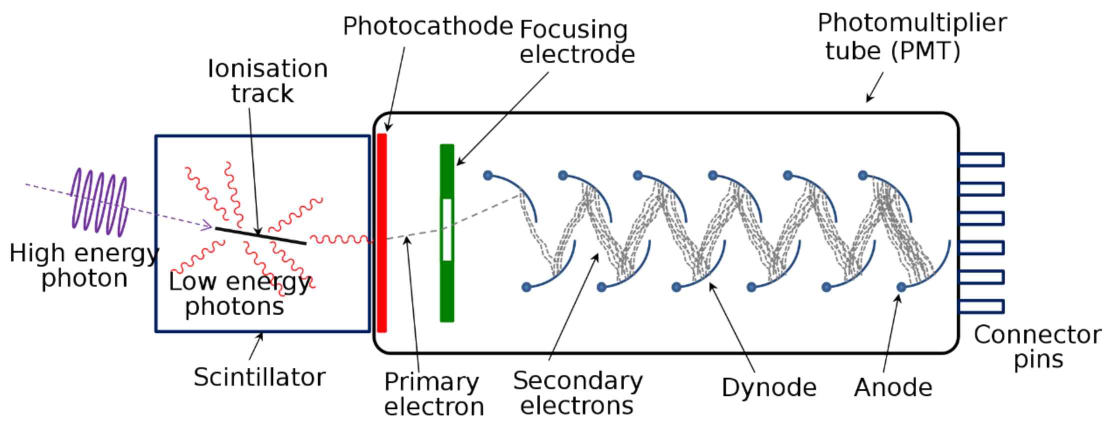
gen

$\leq E_n$)

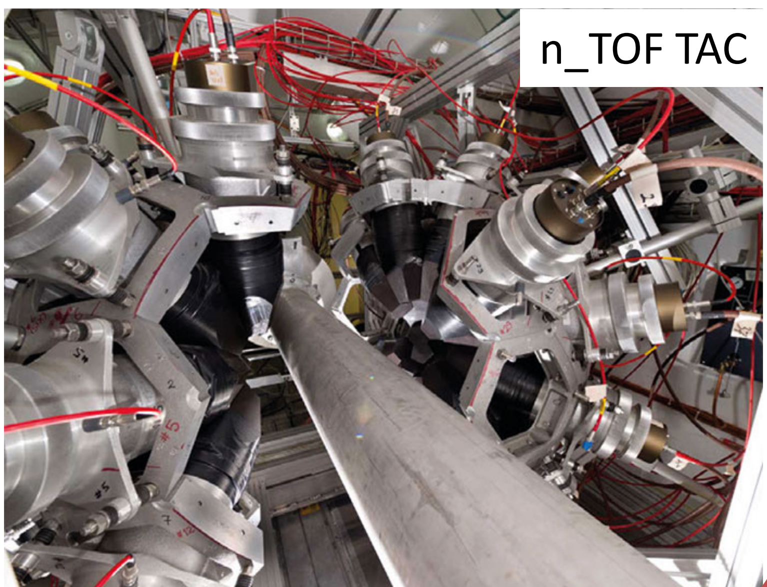




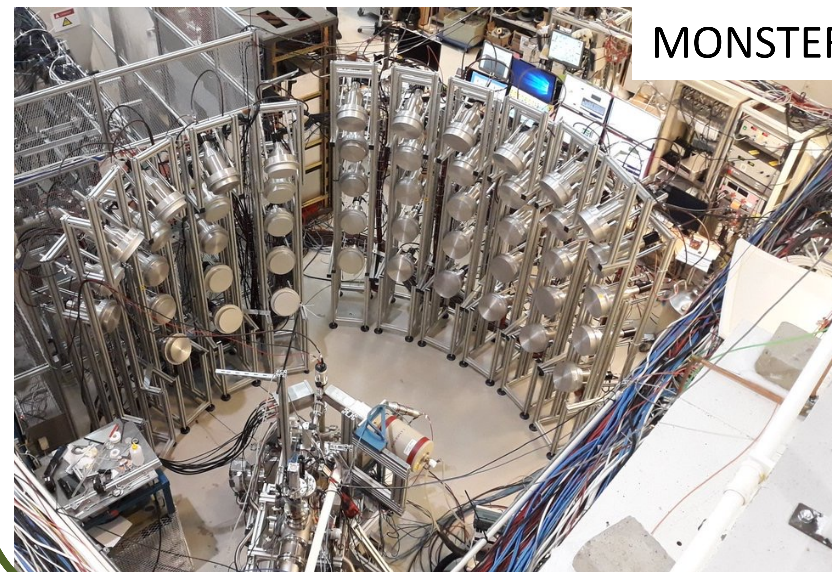
Types of detectors: scintillators (II)



g-rays

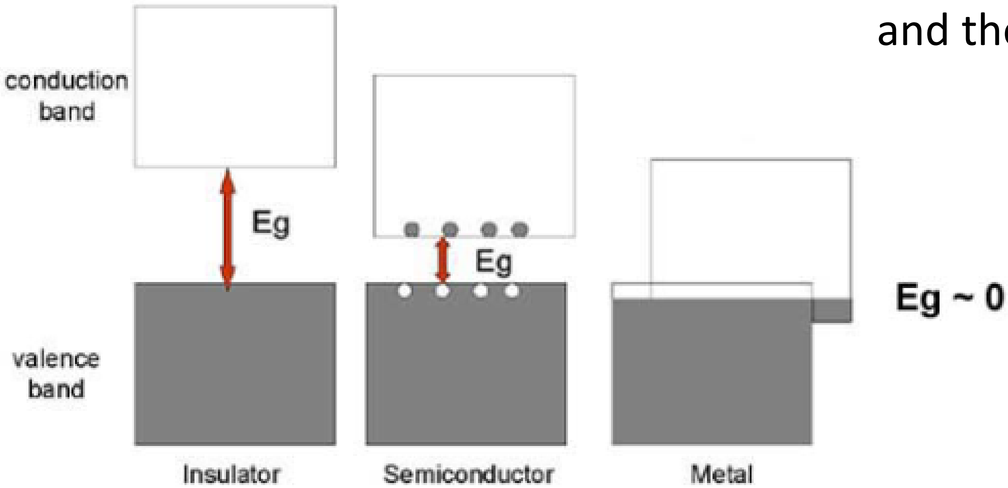


neutrons



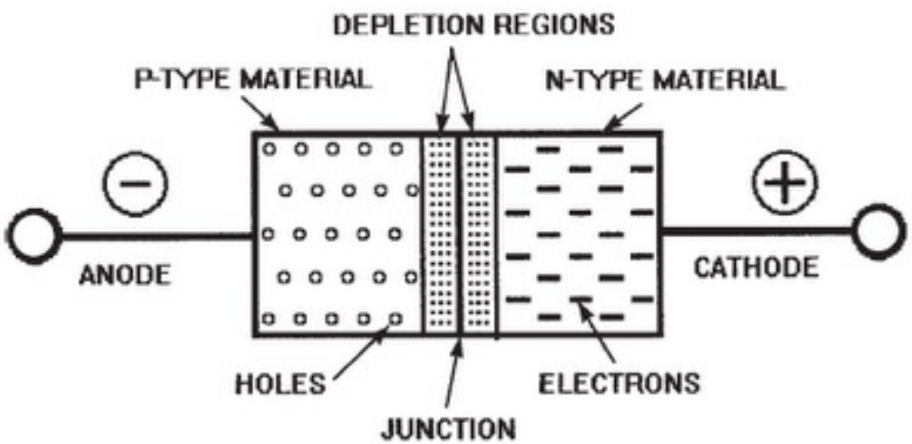
Types of detectors: semiconductors (I)

Both Ge and Si have 4 e^- in their last shell
=> electrons promoted to the conduction band, and the corresponding holes, can move.

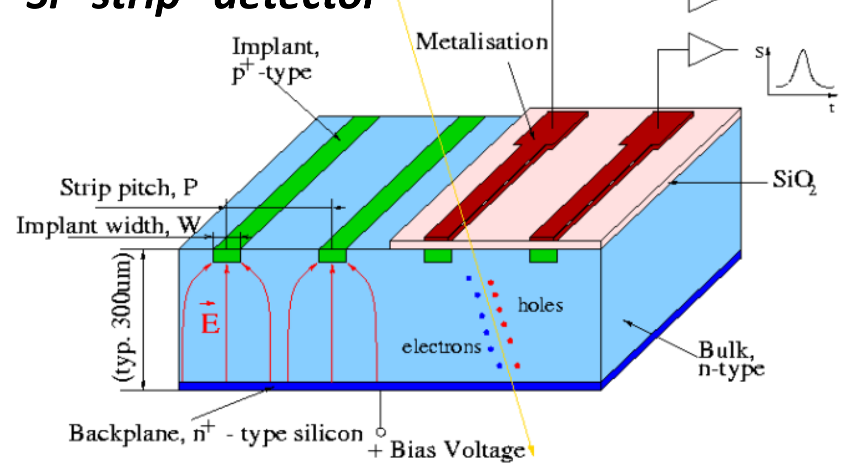


Ge: E_{gap}= 0.66 eV
Si: E_{gap}= 1.11 eV

Very good E resolution
Z(Ge) >> Z(Si) => higher ε for γ

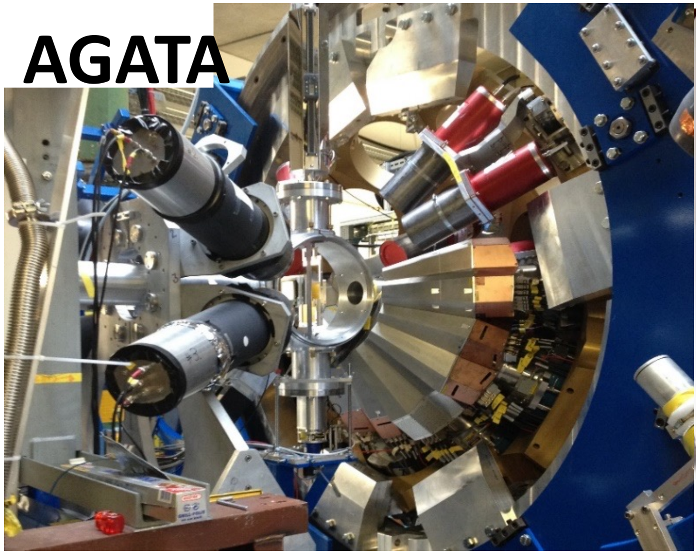


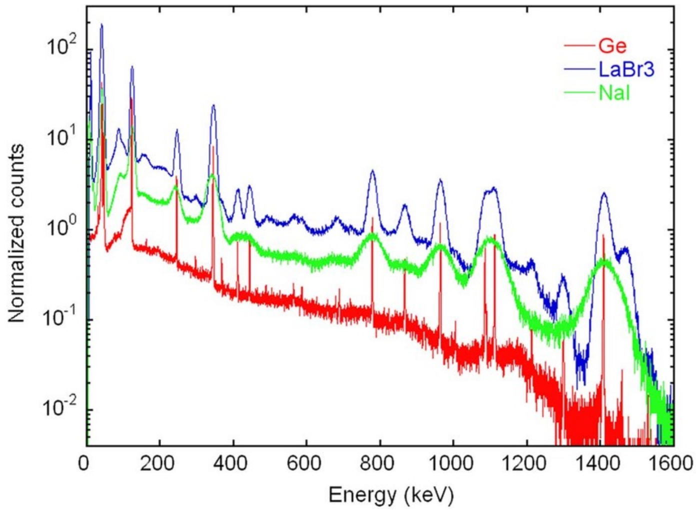
Si "strip" detector



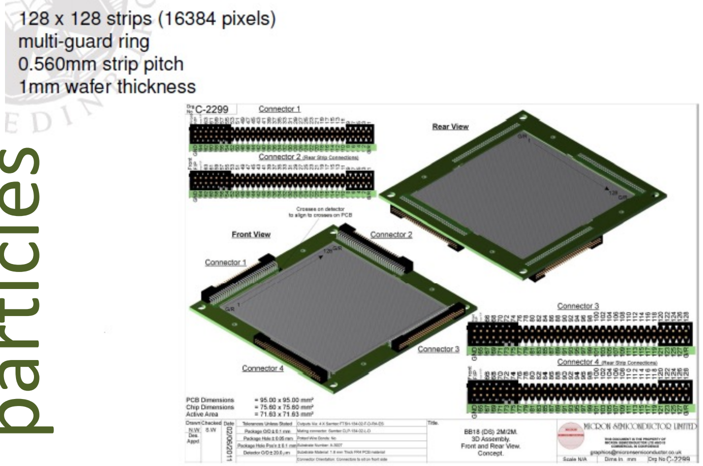
Types of detectors: semiconductors (II)

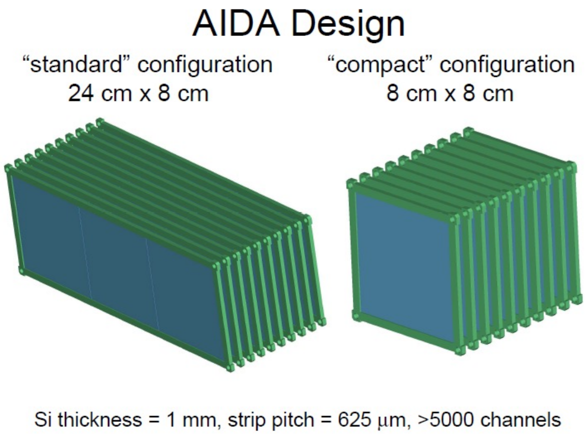
g-rays





Charged particles

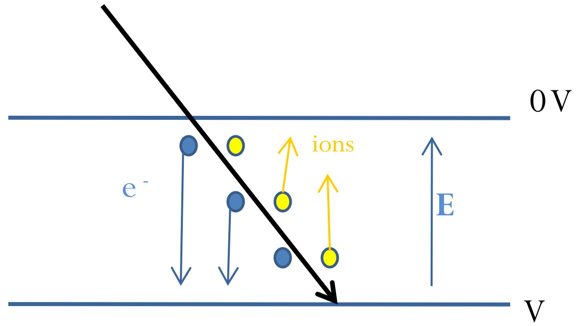




Types of detectors: gas detectors (I)

Basic process:

- moving charged particles ionizes the gas
- e^-/ions drift to opposite sides (E field)
- an electric current is produced, the signal



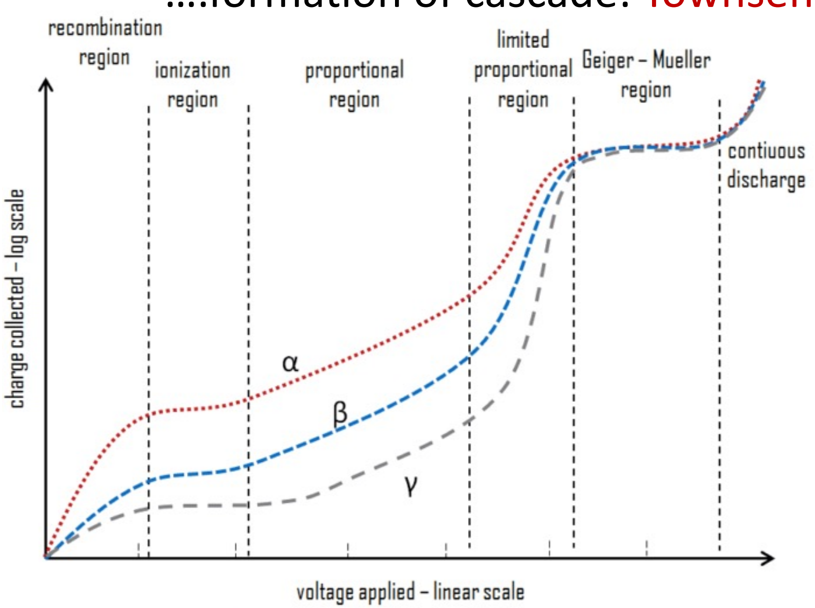
Avalanche Process: Multiplication of charged carriers

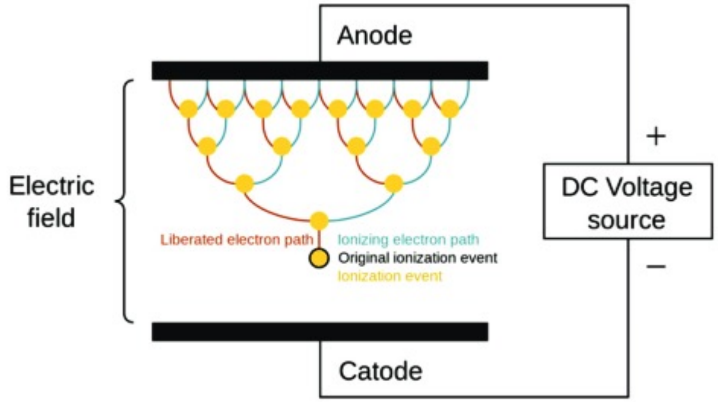
$E<E_{th}$ migration of the primary ions and electrons to the electrodes

$E>E_{th}$ e_1^- induces ionization…

e_2^- induces further ionization…

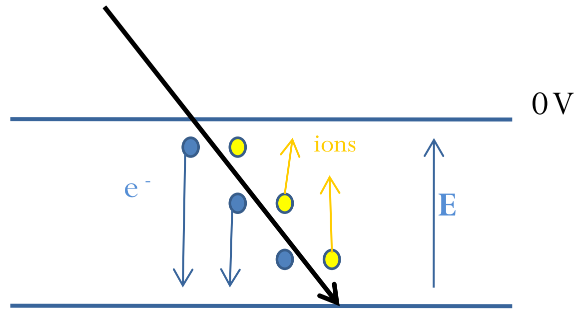
….formation of cascade: Townsend avalanche



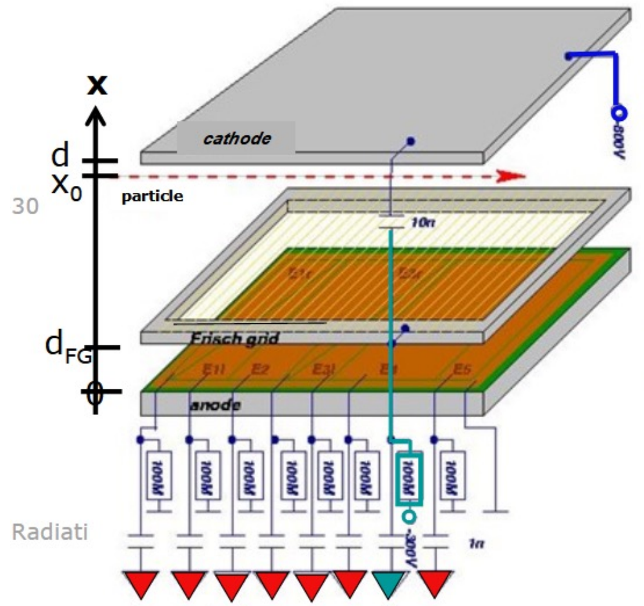


Types of detectors: gas detectors (II)

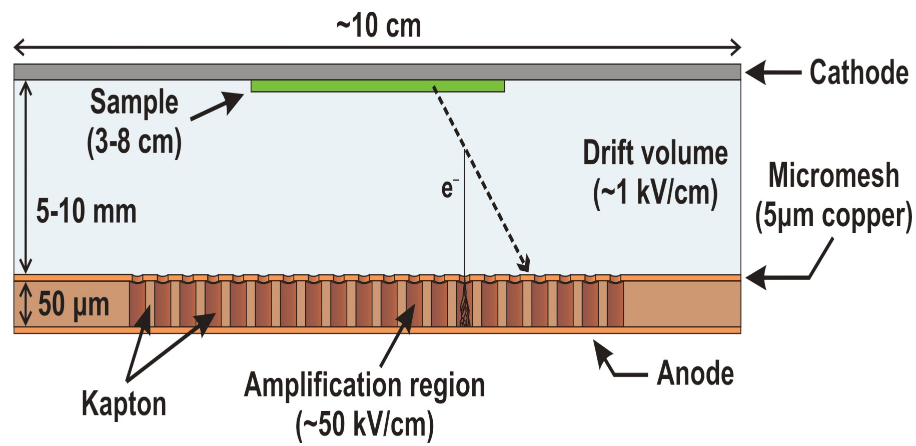
- Ionization chambers



Frisch Grid Ioniz. Chambers

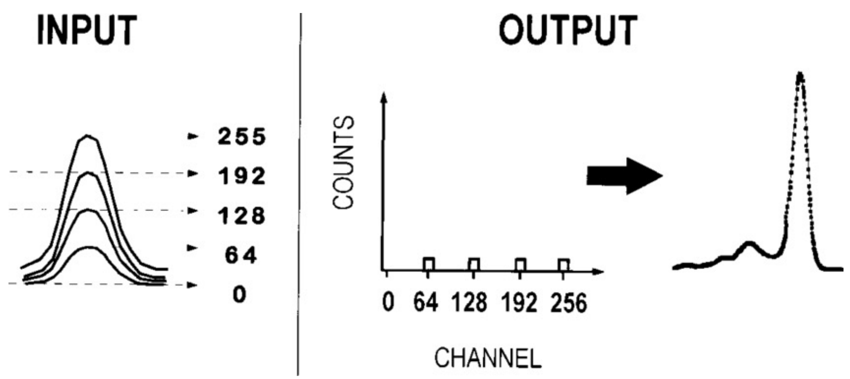


MicroMegas



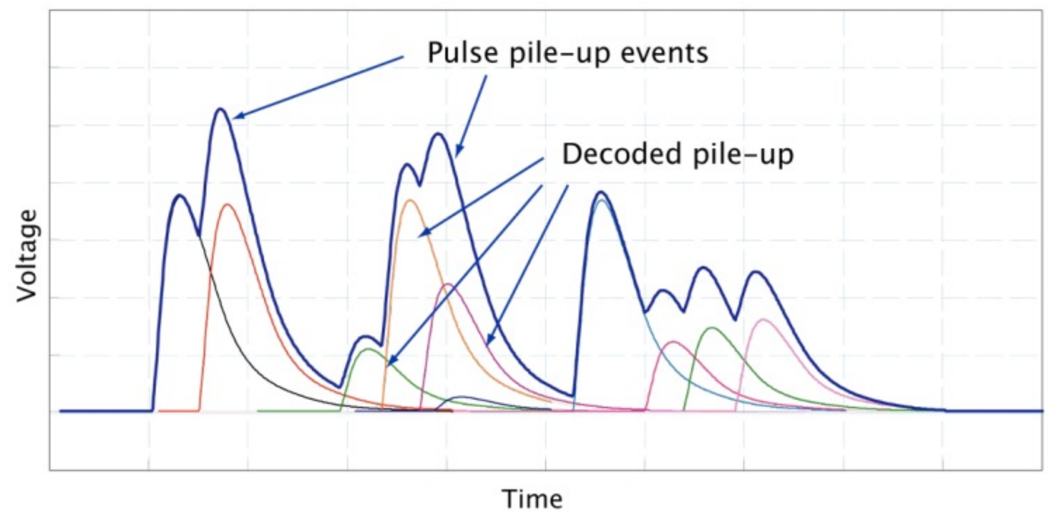
Signal shapes and DAQs

- Multi-Channel Analyzer (MCA)

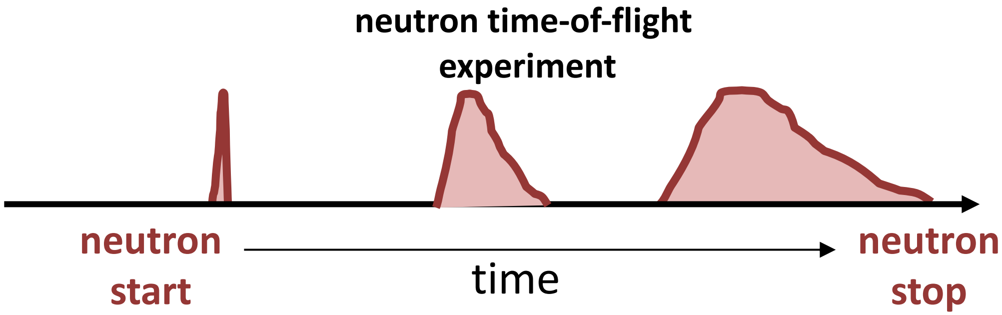


- Need more performant DAQ for:
  - coincidences,
  - pile-up,
  - PSA,
  - PSD,
  - re-análisis,
  - …

Digitizers + off-line PSA

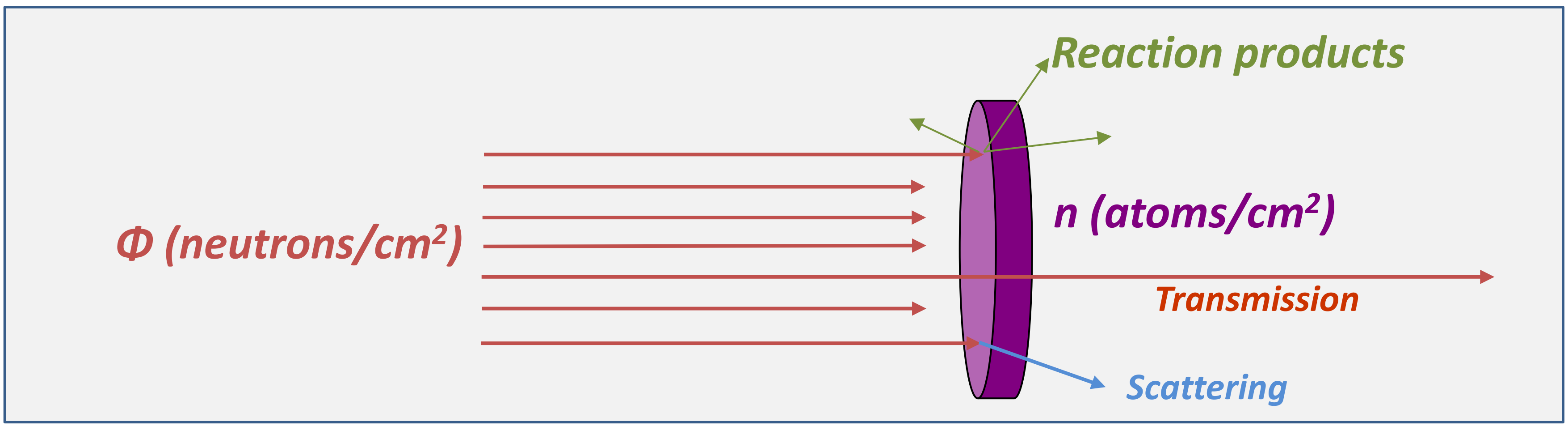


The time-of-flight technique



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

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

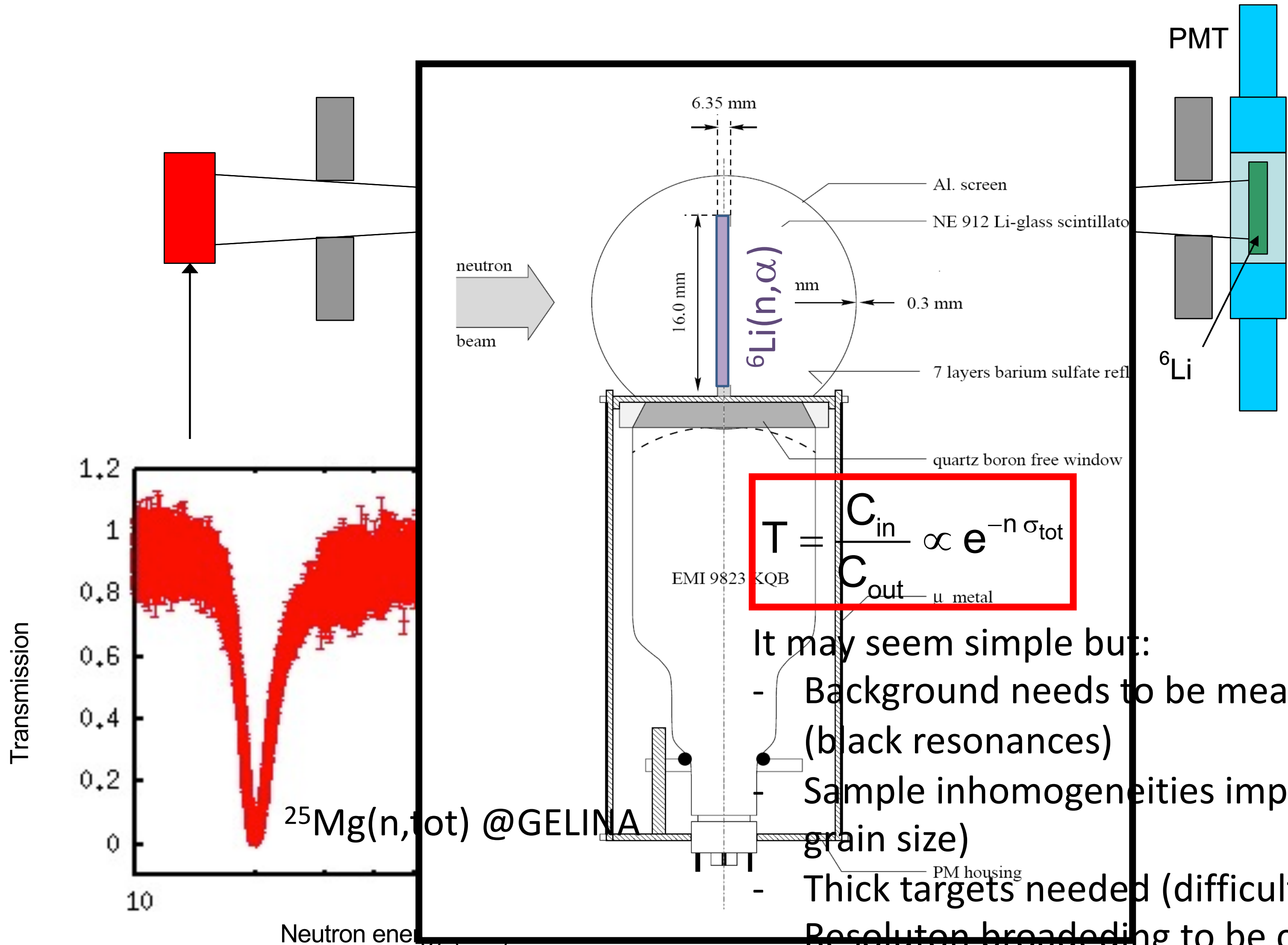


$$Transmission\ probability: \quad T = e^{-n\sigma_{n,tot}}$$

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

Measuring transmission: total cross sections (n,tot)

Transmission measurement

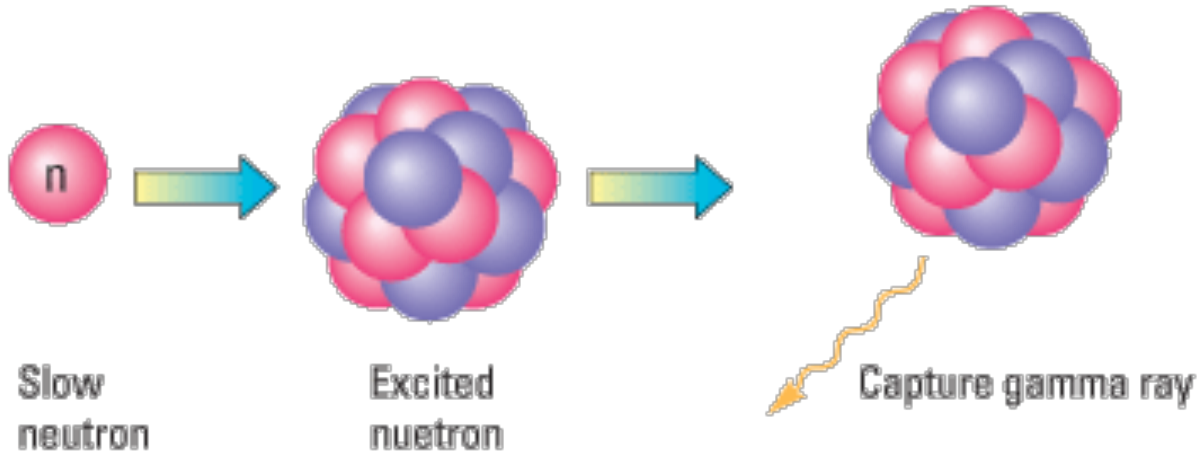


$$T = \frac{C_{in}}{C_{out}} \propto e^{-n\,\sigma_{tot}}$$

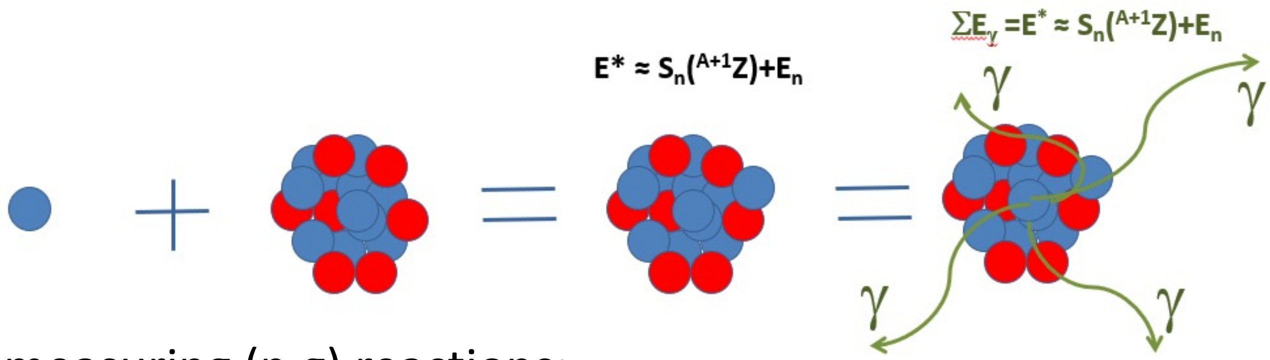
It may seem simple but:

- 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)



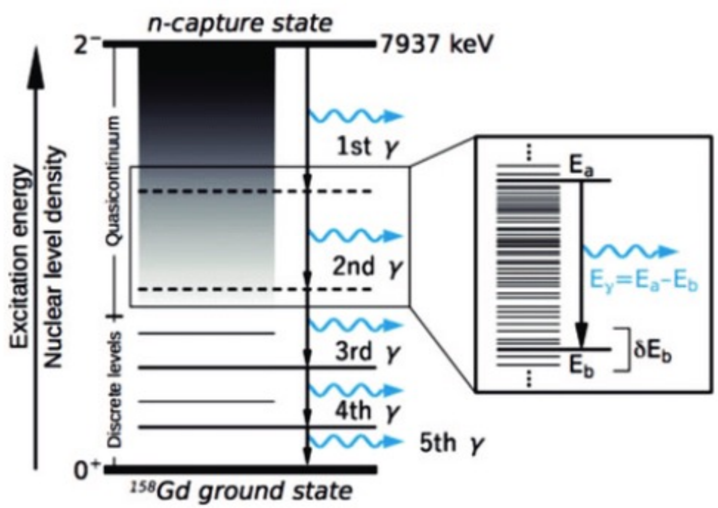
Observables in neutron capture

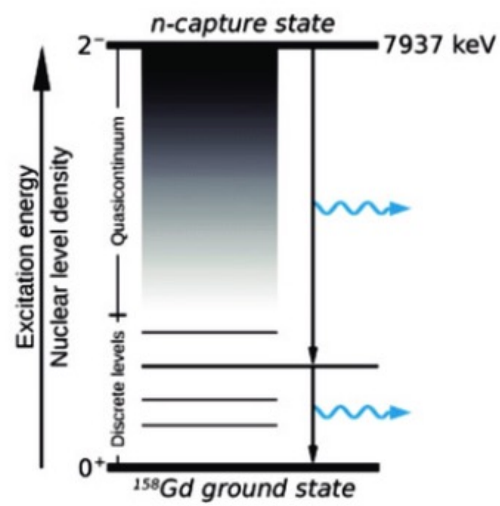


Strategies for measuring (n,g) reactions:

- 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)

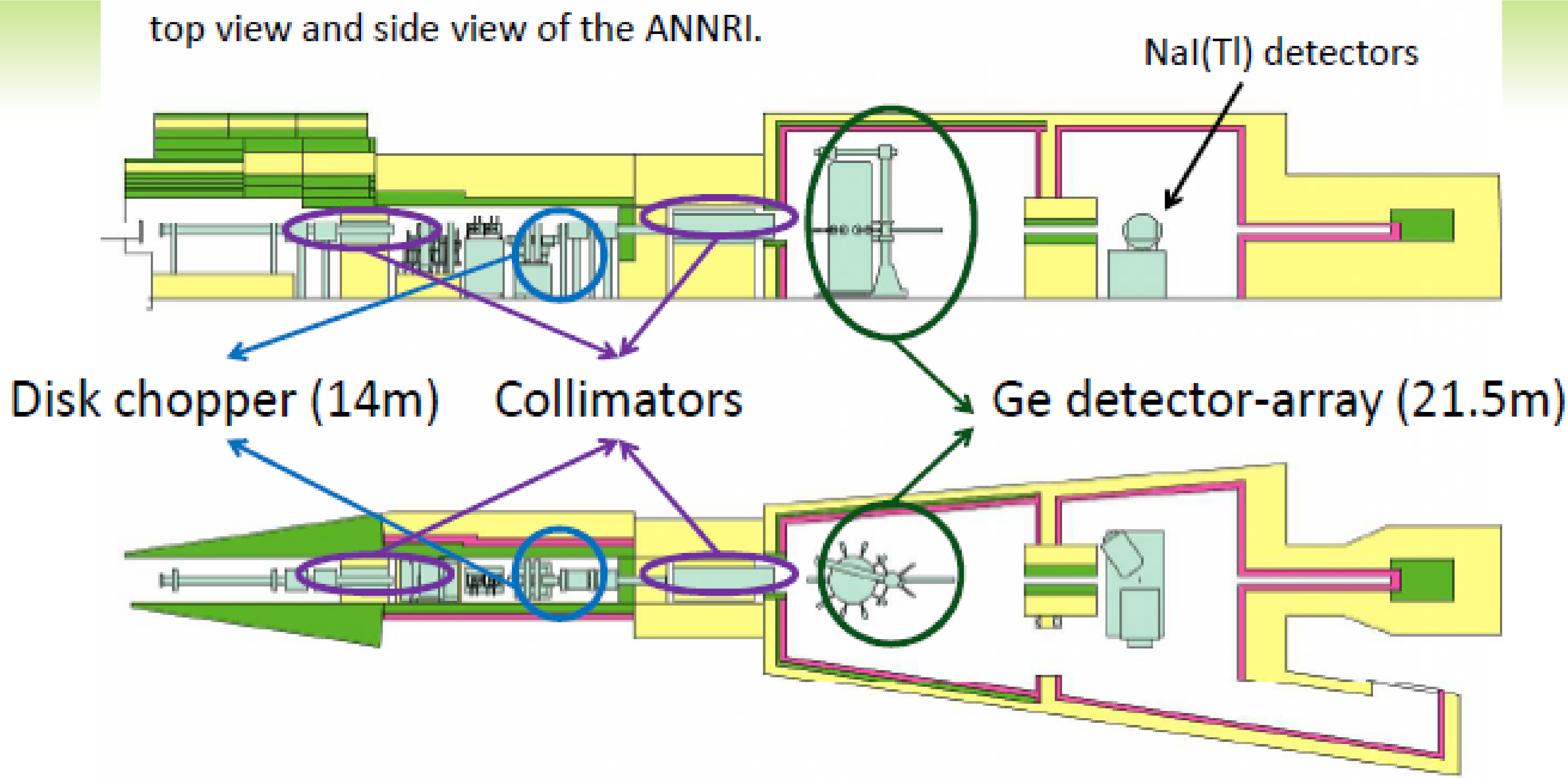
Main challenge:





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

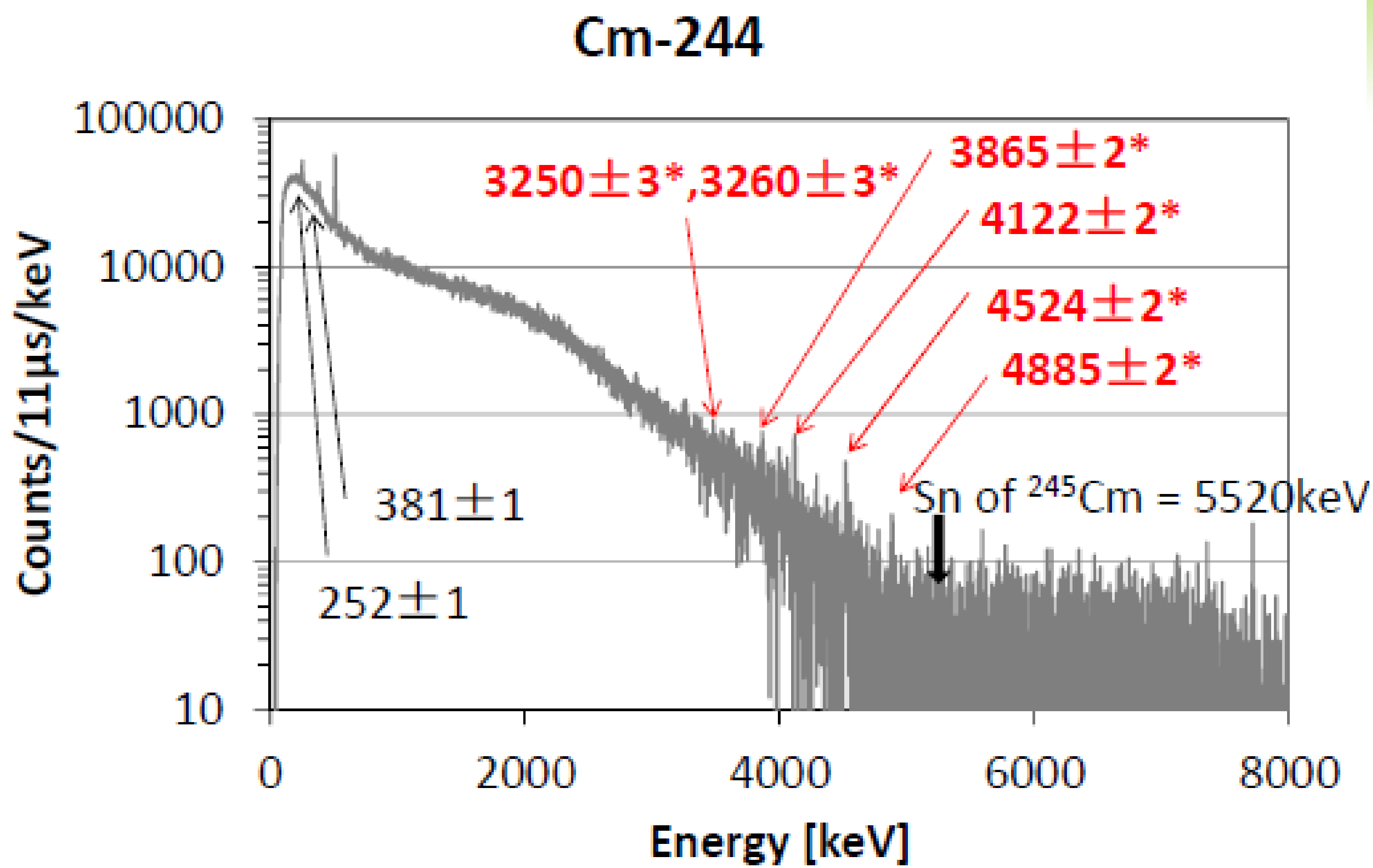
- ANNRI @ J-PARC (Japan)



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?

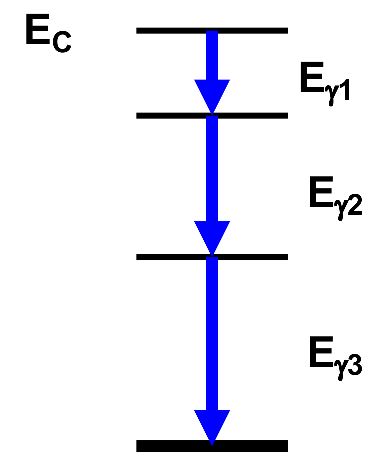
Every decay cascades is different,

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 : $\varepsilon_c = 1 - \Pi(1 - \varepsilon_{\gamma i})$

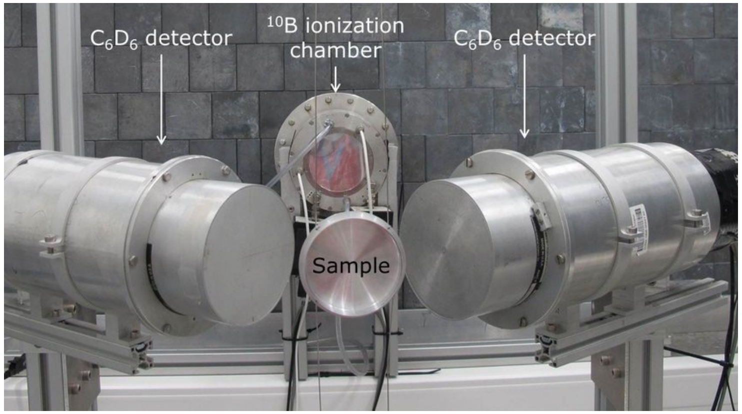


But if $(\varepsilon_{\gamma i} << 1)$ then $\varepsilon_c = \Sigma\varepsilon_{\gamma i}$

Total Energy Detector (TED)

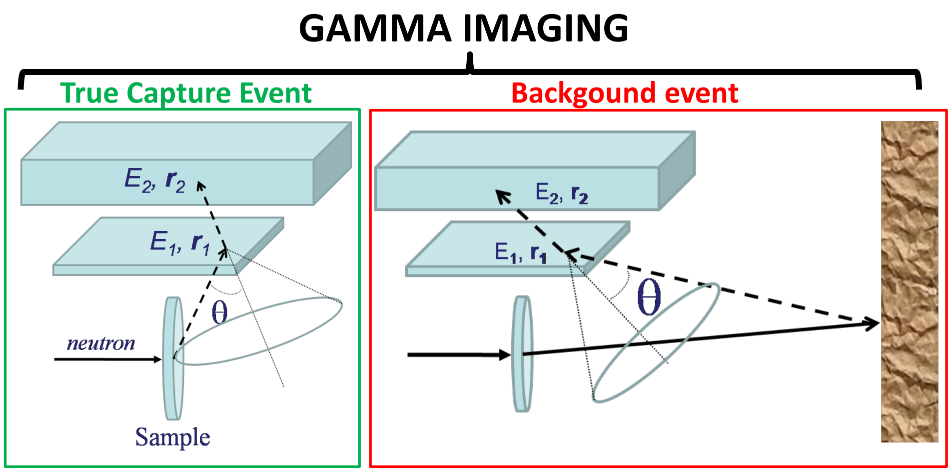
Now, if we had a detector for which $\varepsilon_{\gamma i} = kE_{\gamma i}$

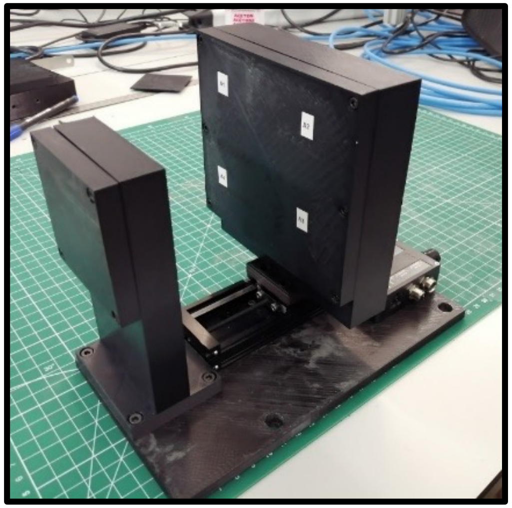
then $\varepsilon_c = \Sigma\varepsilon_{\gamma i} = \Sigma kE_{\gamma i} = k\Sigma E_{\gamma i} = kE_c$

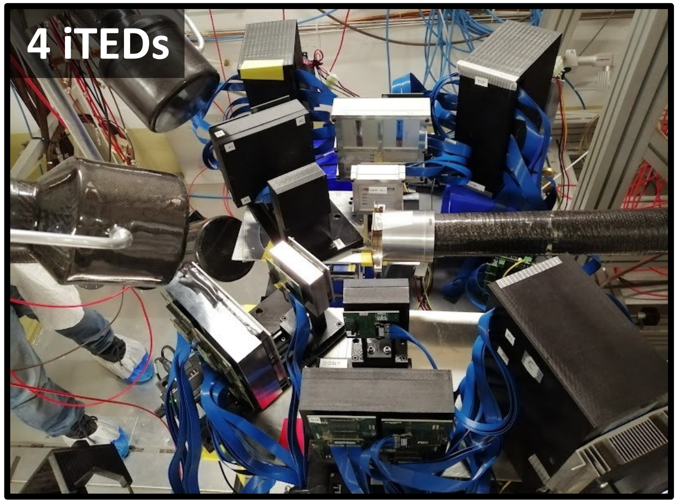


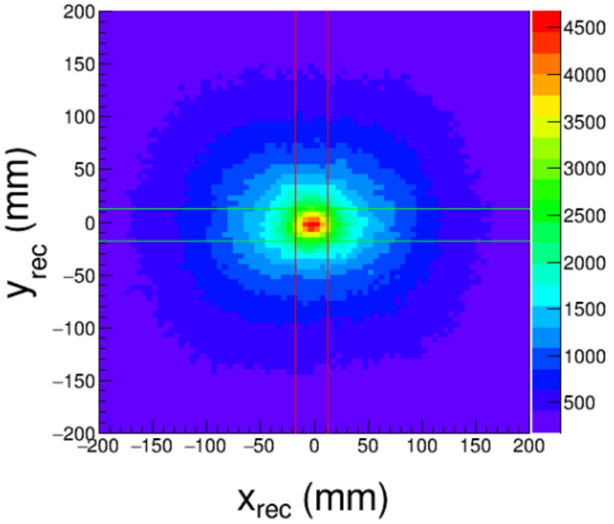
This type of detector can be constructed (Moxon-Rae detectors), but the proportionality is only approximate => <u>MC used instead</u>

The latest: TED + Imaging







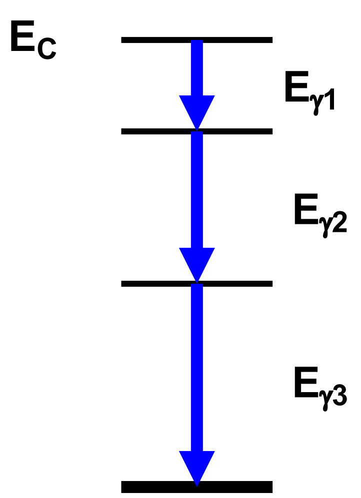


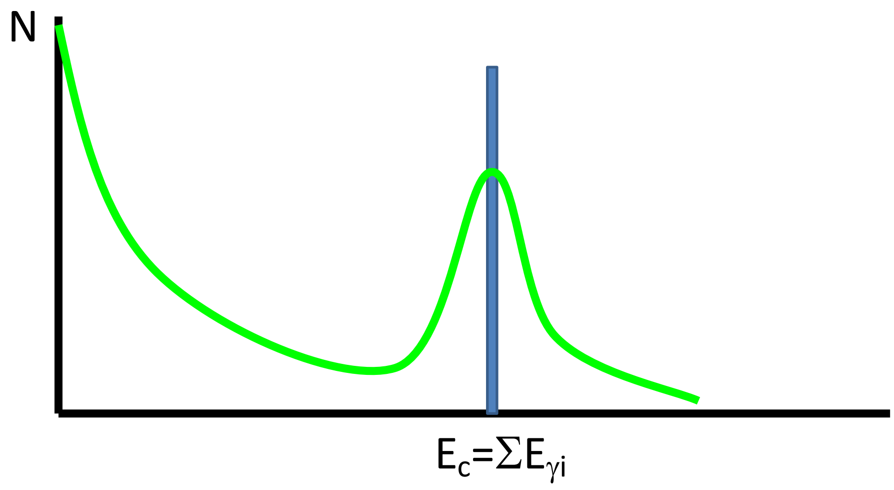
Total Absorption technique

If intrinsic and solid angle efficiencies are large:

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

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

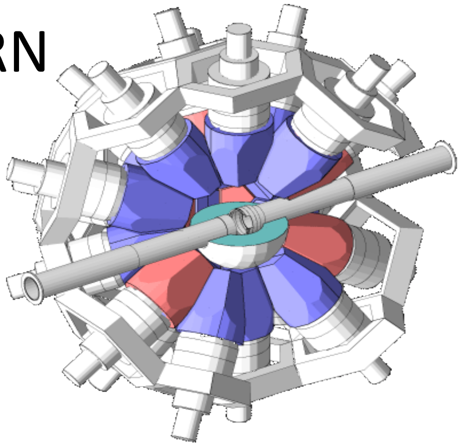




(n,g) calorimeters worldwide

n_TOF Total Absorption Calorimeter (TAC) at CERN

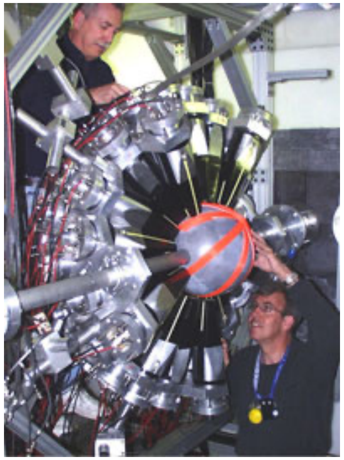
40 BaF_2 crystals covering 4π
(based on the original at FZK)



Similar one at the Back-n at CSNS

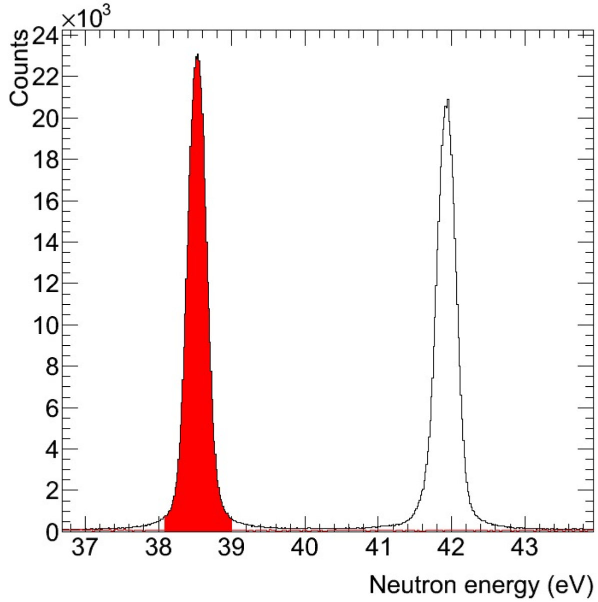
DANCE (Detector for Advance Neutron Capture Experiments) at Los Alamos (USA)

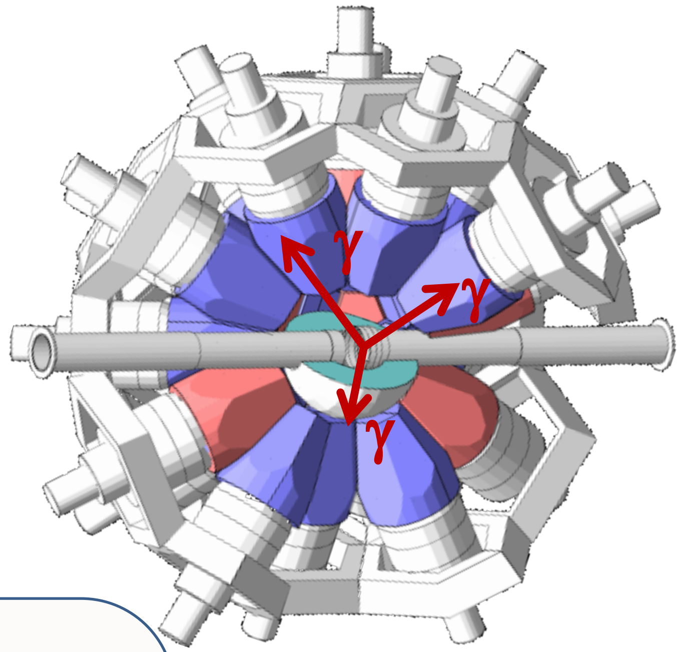
162 BaF_2 crystals covering 4π



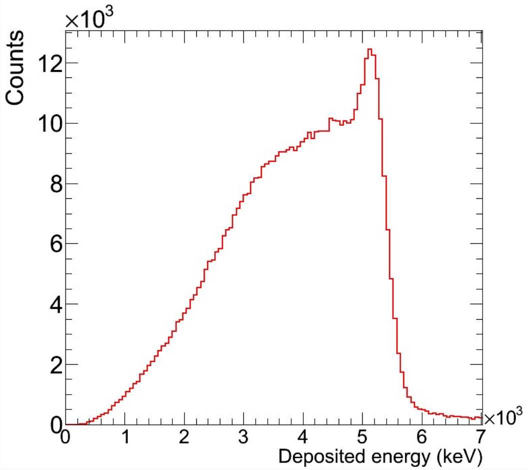
Future: a TAC made of high resolution ($LaBr_3$, etc.) crystals?

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

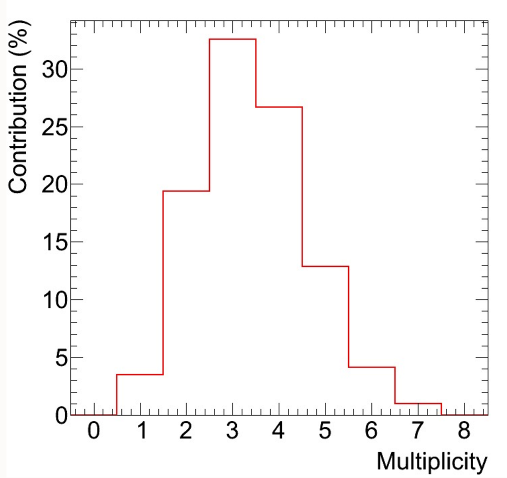




Deposited energy

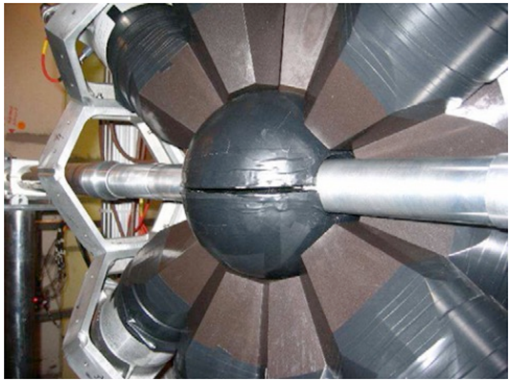


Multiplicity

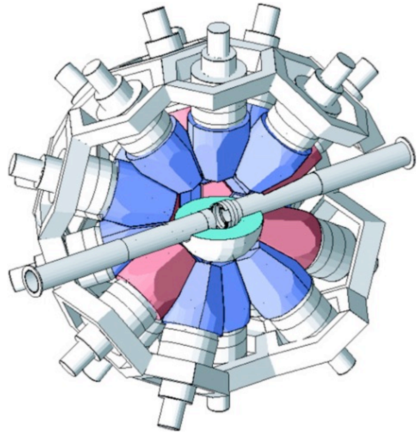


The role of Monte Carlo simulations

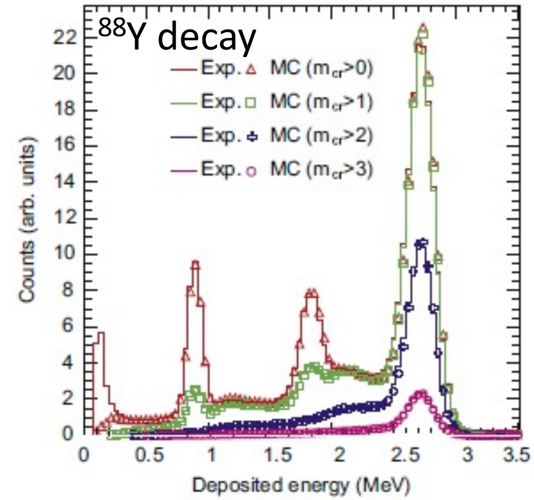
Reality



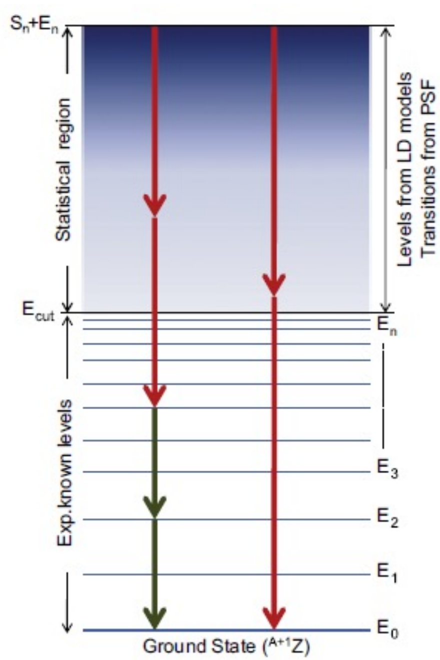
Geant4 simulation

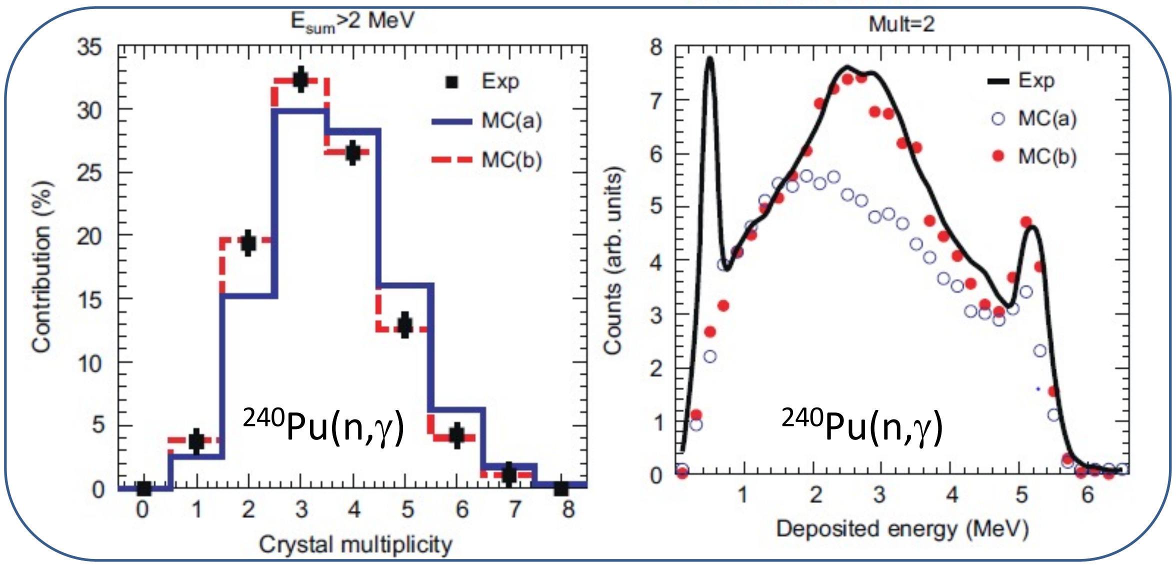


Validation



Simulation of (n,g) EM cascades

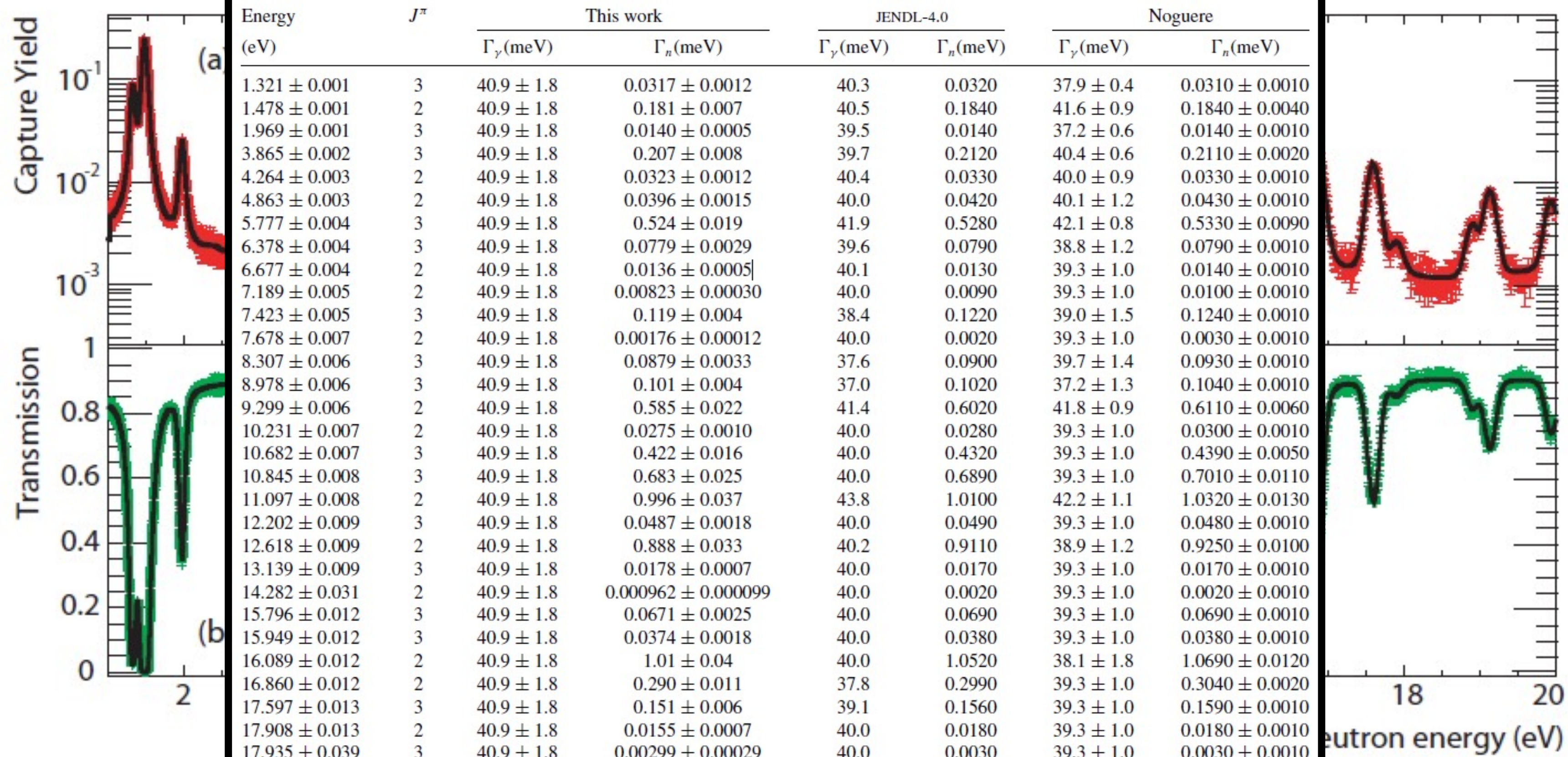




Only now can I calculate accurately $\varepsilon_{n,g}$

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

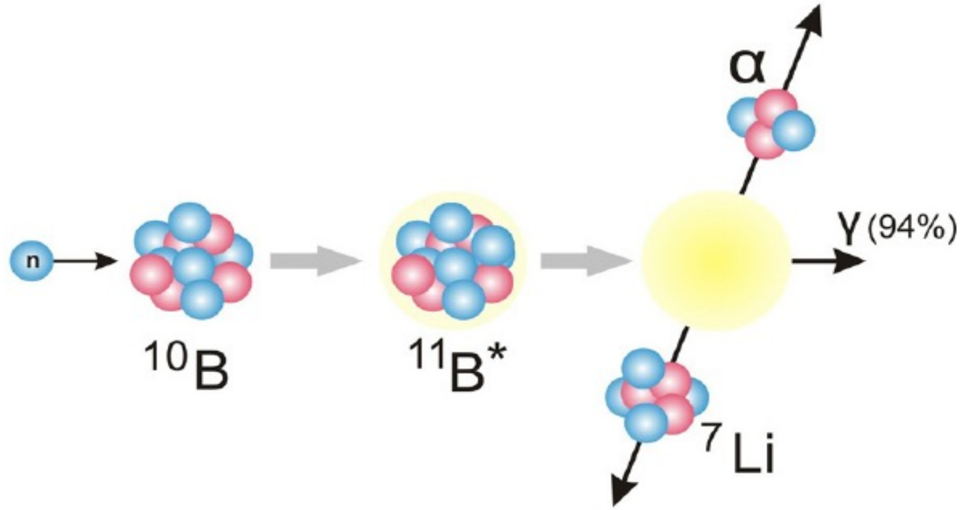
$$Transmission:\ T = \frac{C_{in}}{C_{out}} \propto e^{-n\ \sigma_{tot}} \qquad Capture\ yield:\ Y = \frac{C - B}{\varepsilon\ \Phi} = (1 - e^{-n\ \sigma_{tot}})\frac{\sigma_{n,g}}{\sigma_{tot}}$$



Resonance parameters from RSA with SAMMY

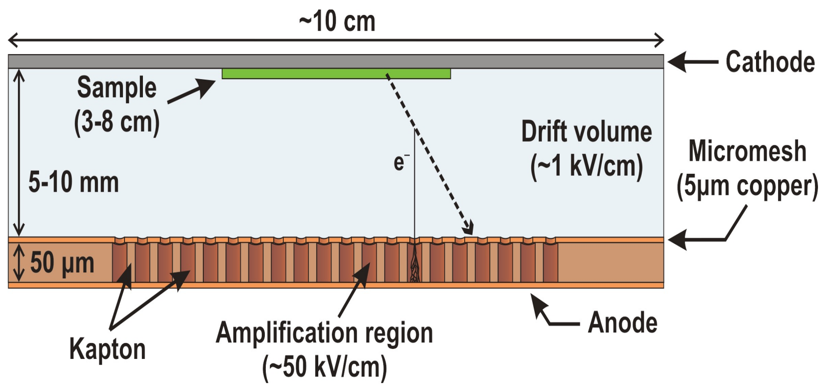
Energy	J^π	This work		JENDL-4.0		Noguere	
(eV)		Γ_γ(meV)	Γ_n(meV)	Γ_γ(meV)	Γ_n(meV)	Γ_γ(meV)	Γ_n(meV)
1.321 ± 0.001	3	40.9 ± 1.8	0.0317 ± 0.0012	40.3	0.0320	37.9 ± 0.4	0.0310 ± 0.0010
1.478 ± 0.001	2	40.9 ± 1.8	0.181 ± 0.007	40.5	0.1840	41.6 ± 0.9	0.1840 ± 0.0040
1.969 ± 0.001	3	40.9 ± 1.8	0.0140 ± 0.0005	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

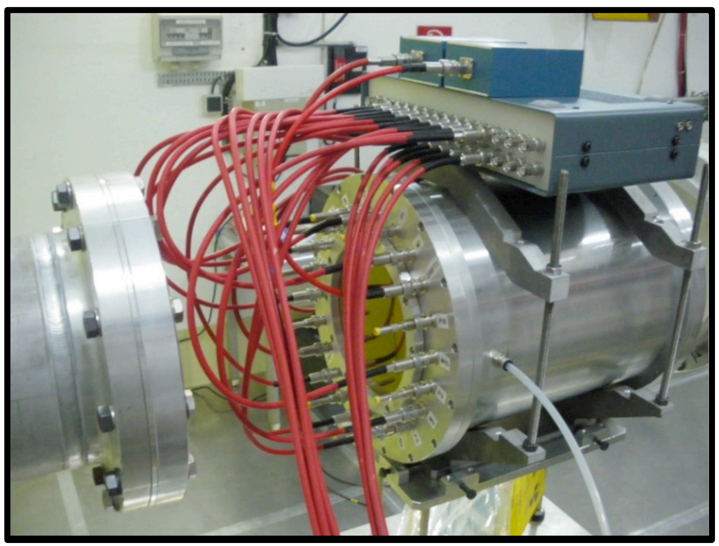
Measuring light charged particle production (n,chp)



Gaseous detectors for measuring (n,lcp)

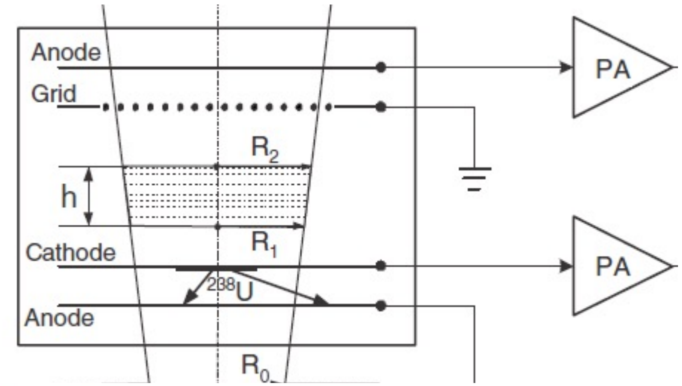
MicroMegas

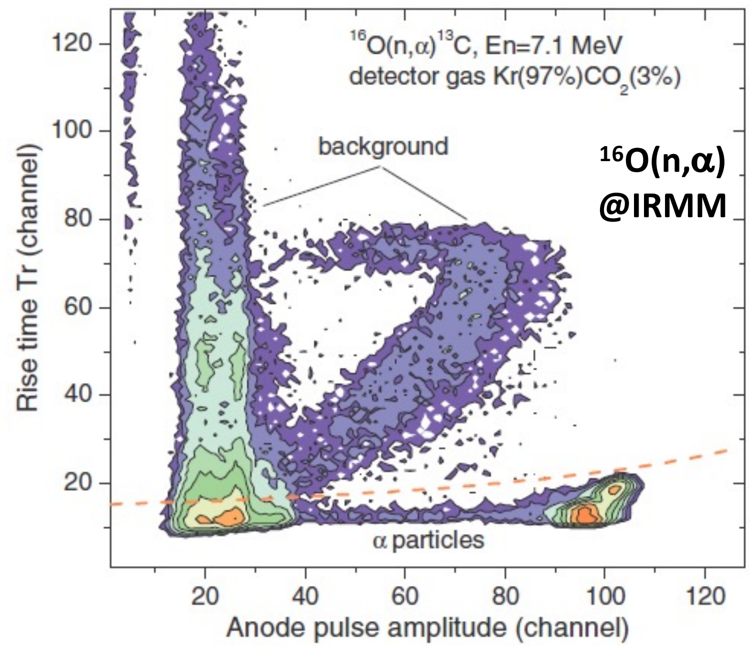




Beam monitoring & σ(n,α) measurements at n_TOF

Frisch Grid Ionization Chambers

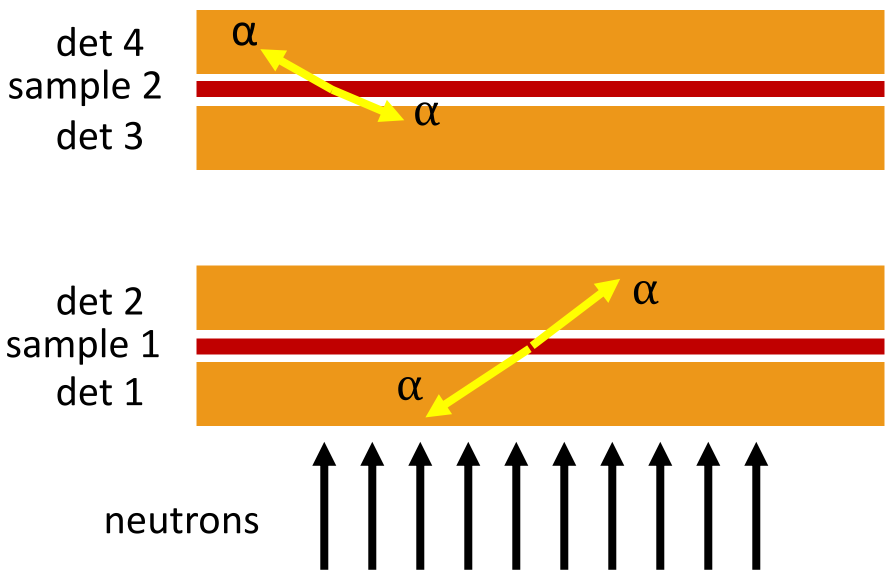




(n,α/p) with high radioactive (GBq) targets

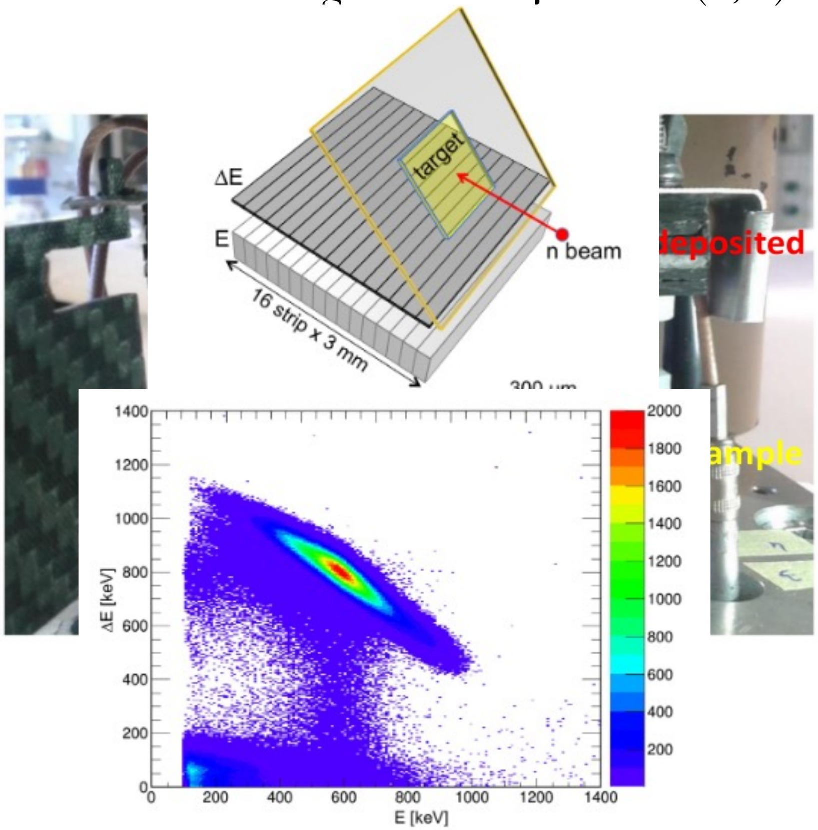
7Be(n,a)/(n,p) at CERN n_TOF => Unambiguous identification!

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



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)

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



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)

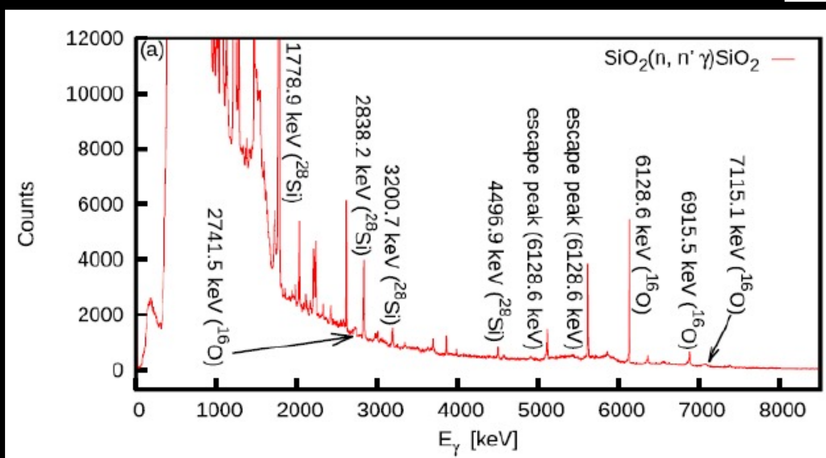
Detectors for inelastic reactions (I)

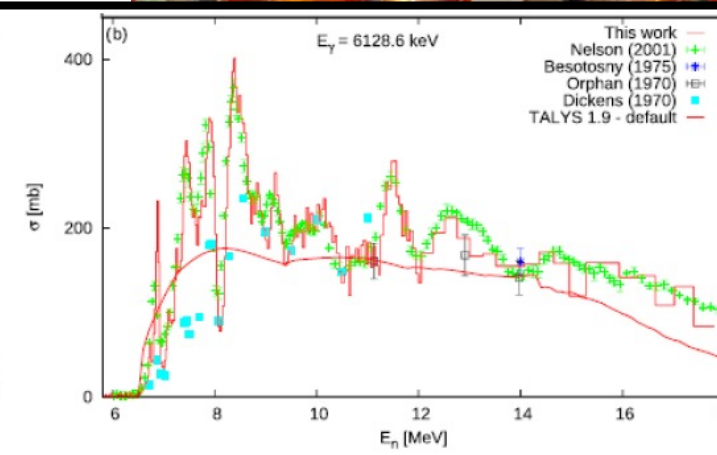
The g-rays from (n,n') reactions are measured by HPGe detectors

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

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

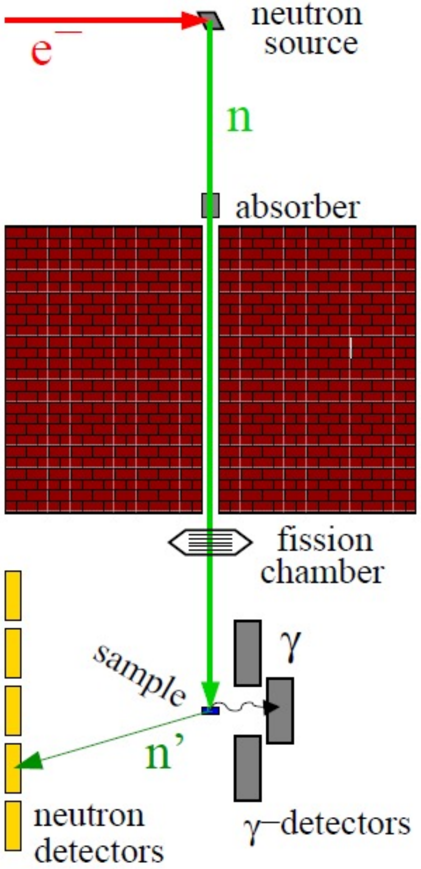
^{16}O(n,n') & ^{28}Si(n,n') @GAINS/GELINA

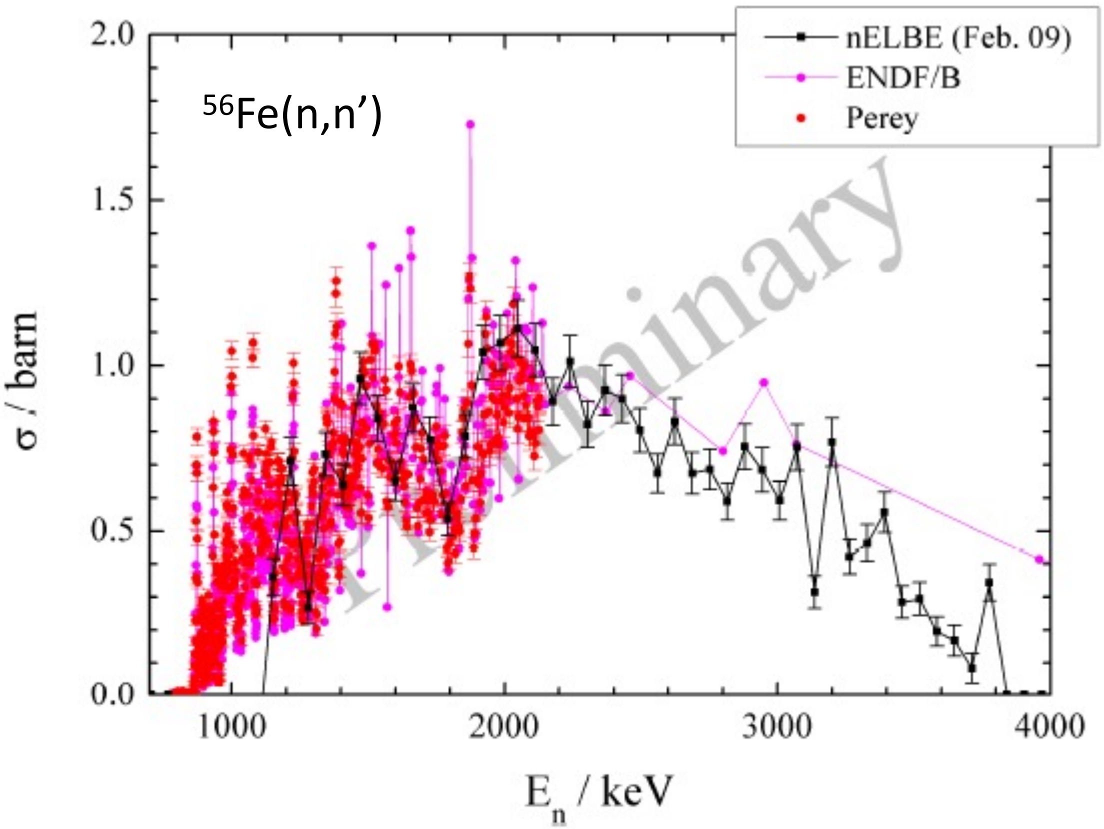




Detectors for inelastic reactions (II)

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.

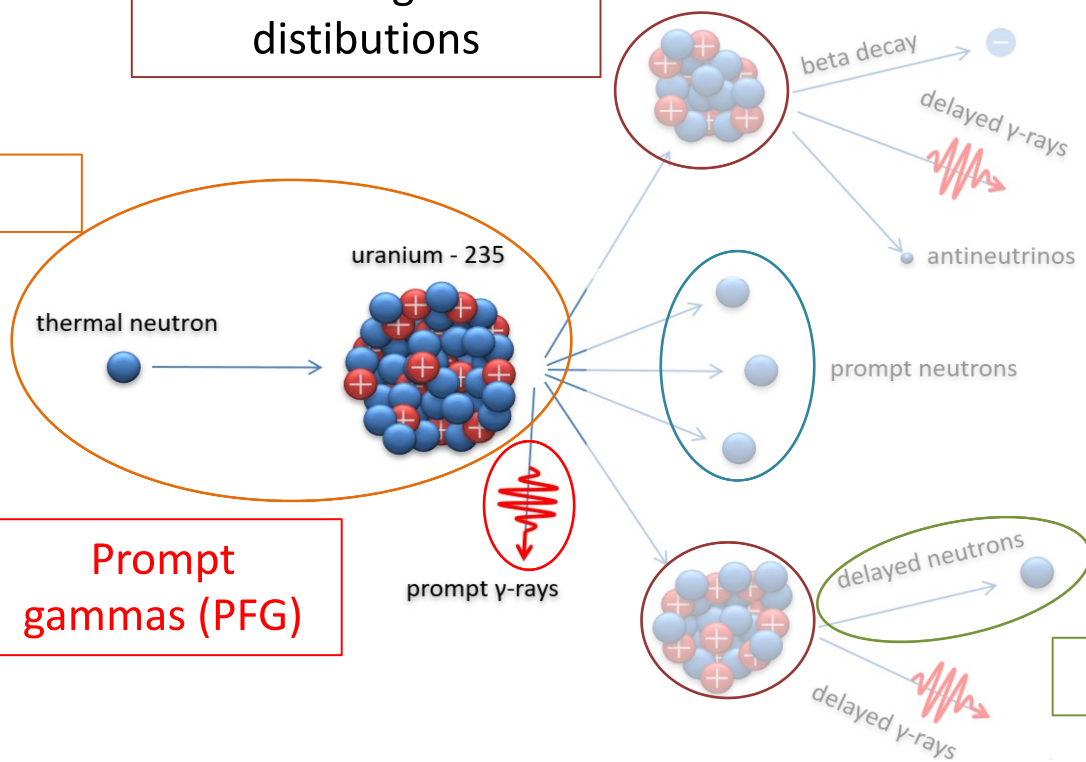




Measuring fission

Fission fragments distibutions

Fission



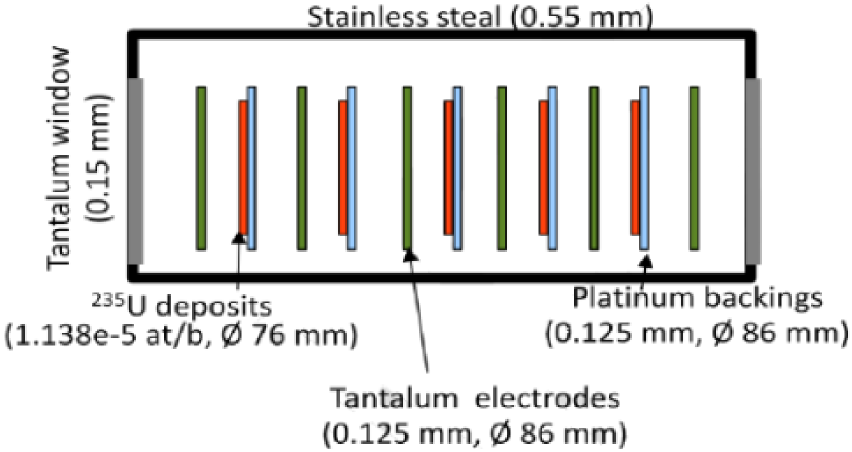
Neutron multiplicities

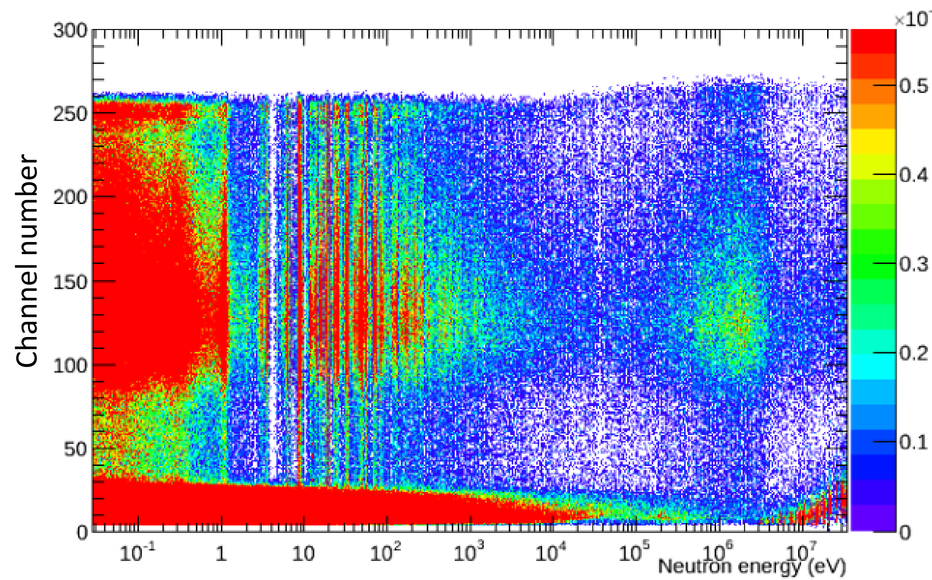
Prompt gammas (PFG)

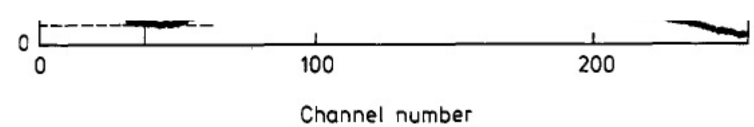
β delayed neutrons

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.



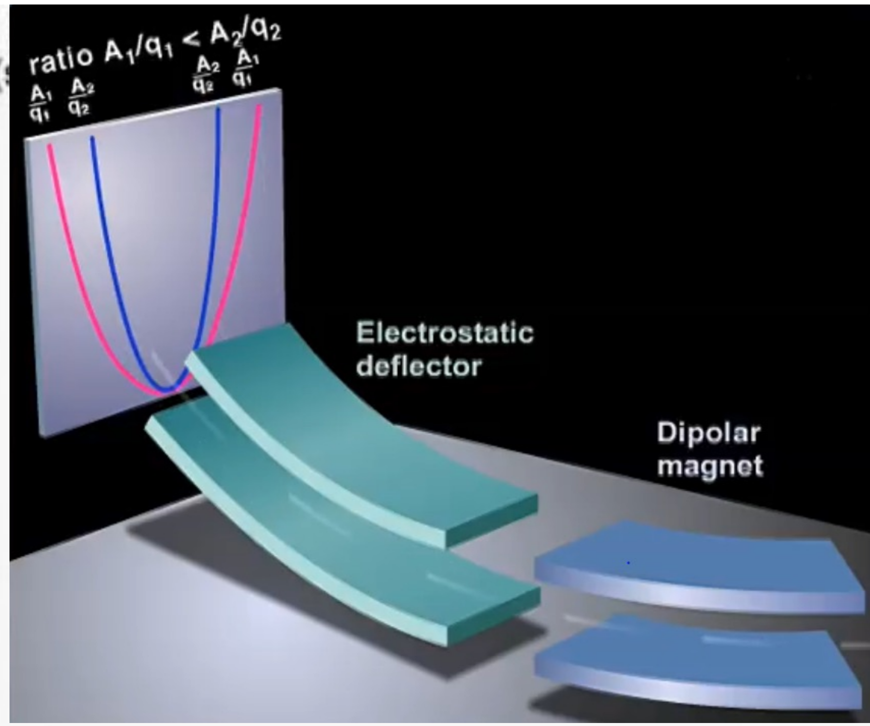


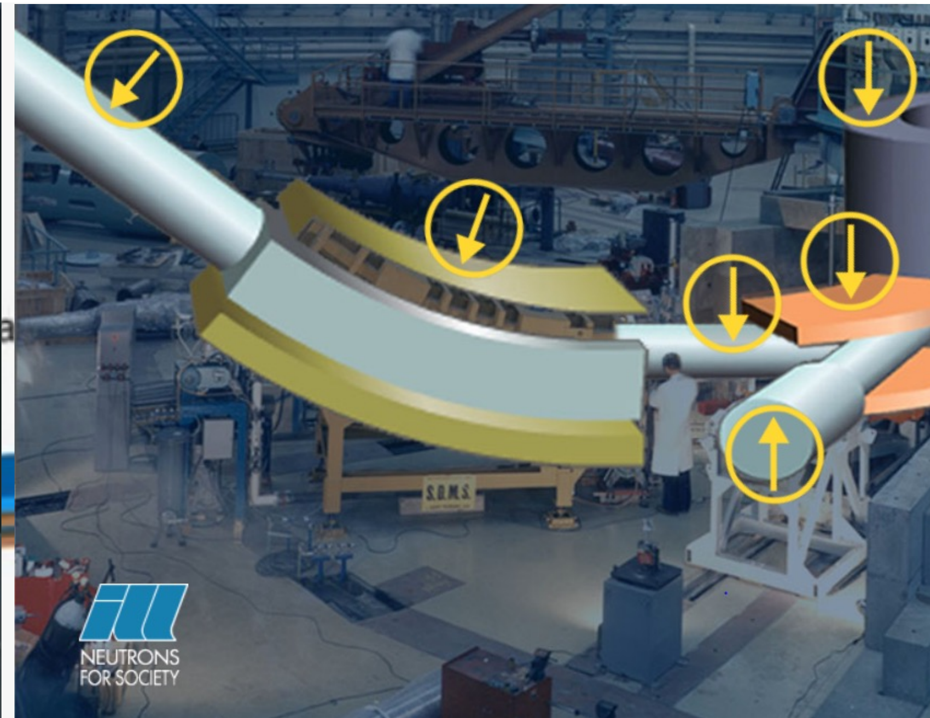


The key:

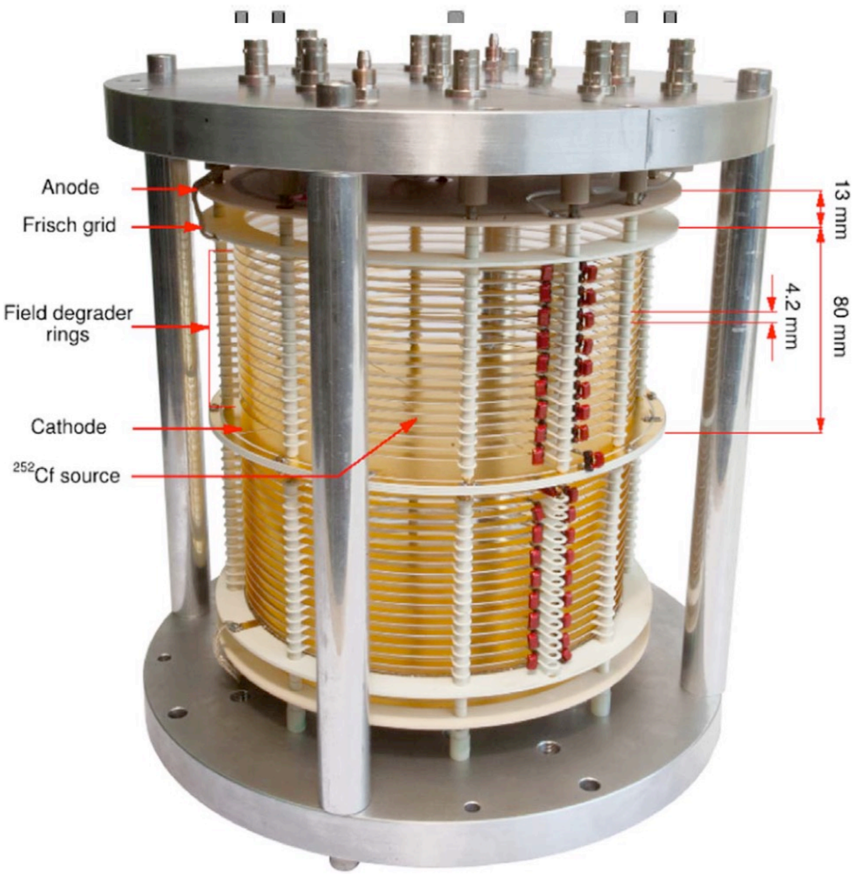
- Samples very well charecterized
- Efficiency very well characterized: 98% for E>0,45P

Fission fragments with a fragment separator



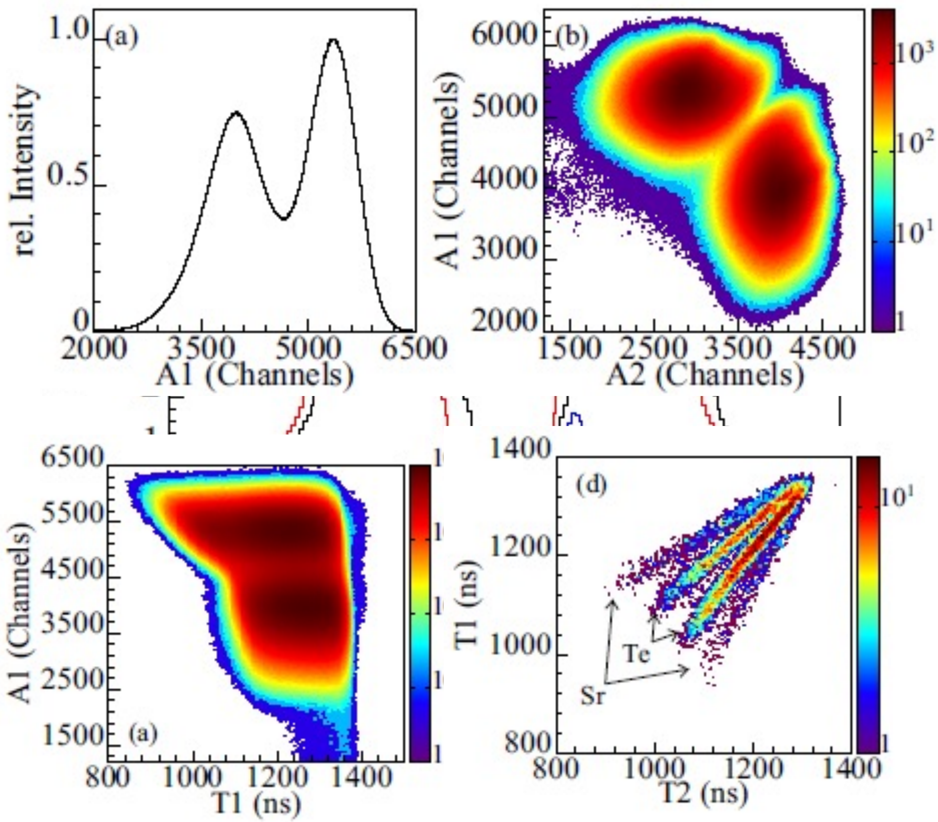


Fission fragments with ionization chambers



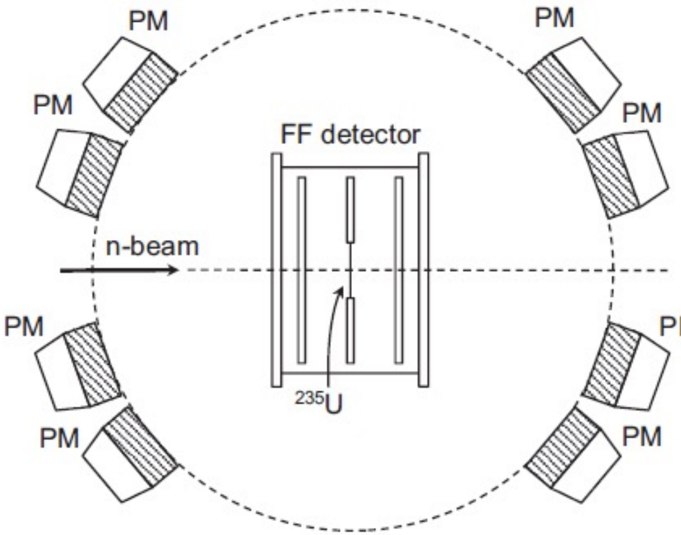
$$M_1 = M\frac{E_2}{E_1+E_2}\,,\qquad M_2 = M - M_1\,,$$

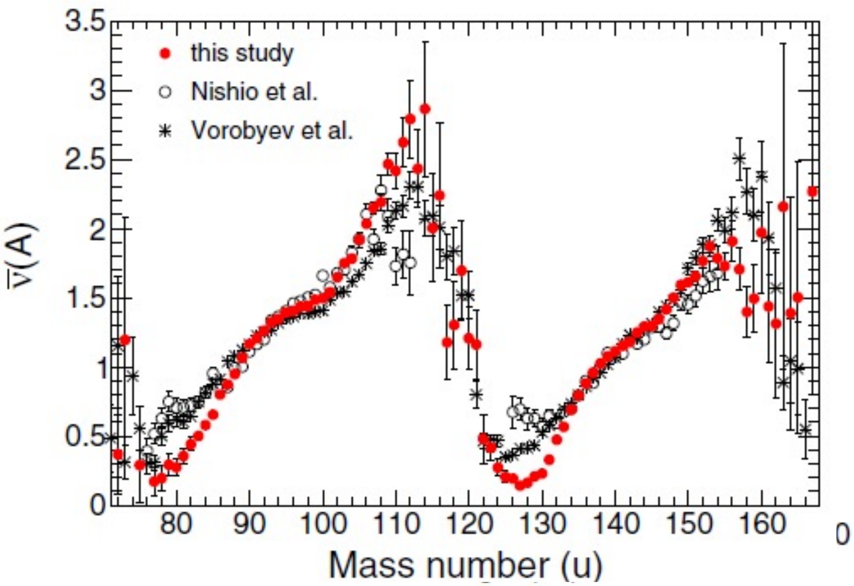
$$E_{1,2} = E_{1,2}^{post}\left(1+\frac{v_{1,2}^{post}}{M_{1,2}}\right),$$



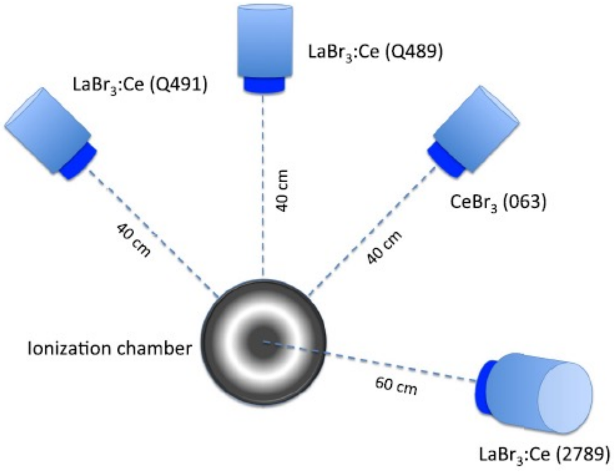
Prompt fission neutrons (PFN) & gammas (PFG)

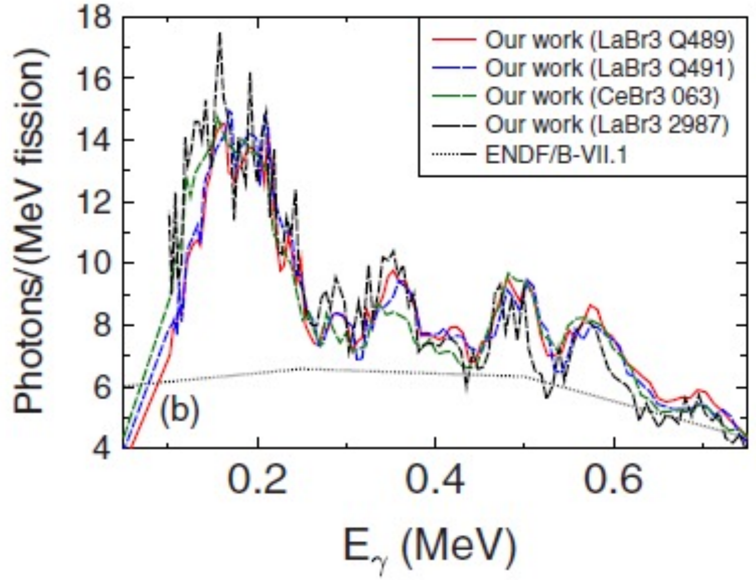
SCINTIA @GELINA





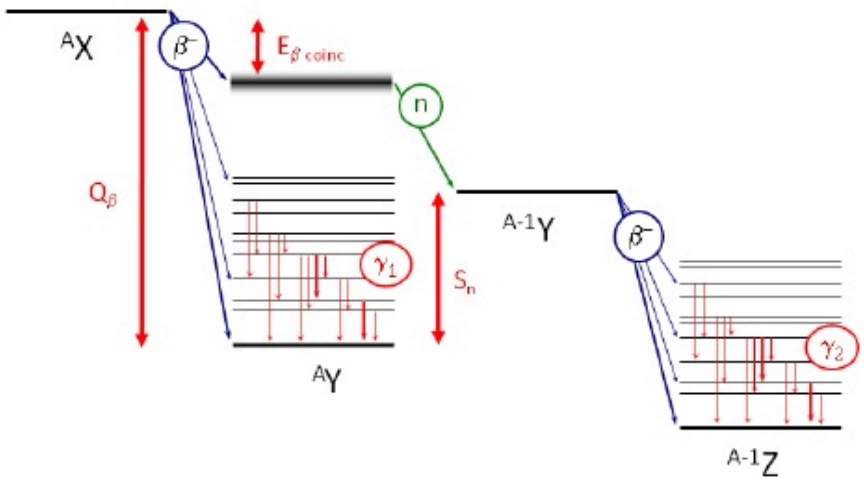
Twin FGIC@BRR



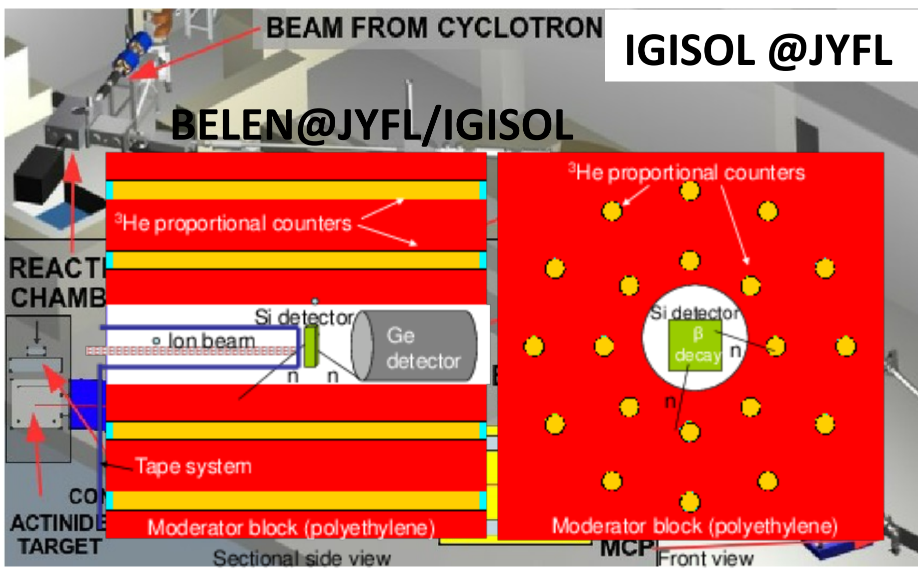


Beta delayed neutron emission

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



MONSTER@JYFL/IGISOL



Summary

- Many neutron induced reactions of interest
- Many observables from each reaction

=> Large variety of detection systems and techniques