Principles and examples of neutron detection

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Why measuring neutrons?

Neutrons show up in many different fields of science and technological applications:

- Nuclear structure. (Neutron induced) nuclear reactions, delayed neutron emission...
- Nuclear astrophysics.
- Material science. Neutron diffractometers for investigating the structure of materials.

- Fission reactors.
- Fusion research and future fusion reactors.
- Material research for fission and fusion reactions.

- Isotope production.
- Radiobiology.
- Dosimetry in radiotherapy treatments (electrons and protons).
- Dosimetry in aircrafts.
- Dosimetry in space missions.

The characterisation of the neutron fields in these different environments requires a large variety of neutron detectors.

How do we measure neutrons?

Neutrons don’t interact electromagnetically with matter (i.e. don’t produce ionisation) and thus are difficult to measure.

They are mainly detected via **nuclear reactions**. The preferred ones are those that:

- Have a large cross section. The energy dependence of the cross (n,X) reaction will determine the detection **efficiency** of the detector in a **given neutron energy range**.

- Produce **secondaries** which are easily detected, typically **charged particles or γ-rays**:
  - (n,p)
  - (n,t)
  - (n,α)
  - (n,f)
  - (n,γ)

The neutron detection can be prompt (i.e. when the nuclear reaction occurs) or delayed (i.e. counting particles after a long irradiation / activation).

Detection mechanisms

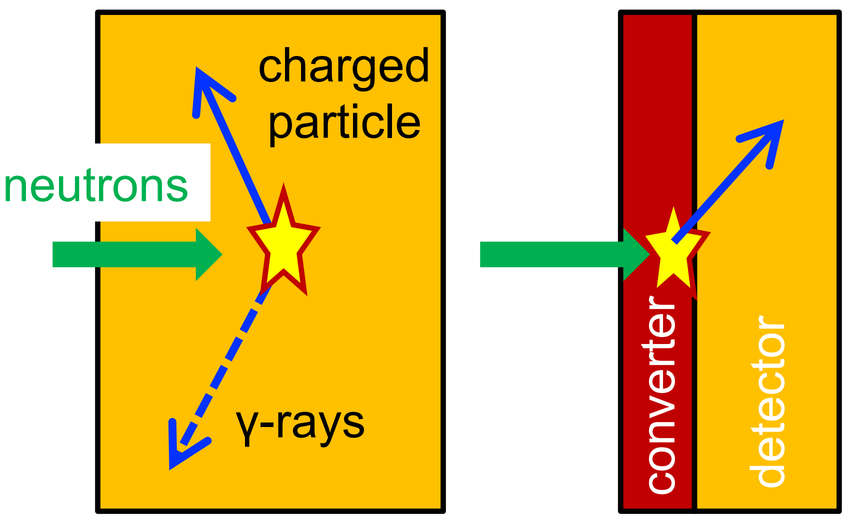
Prompt detection

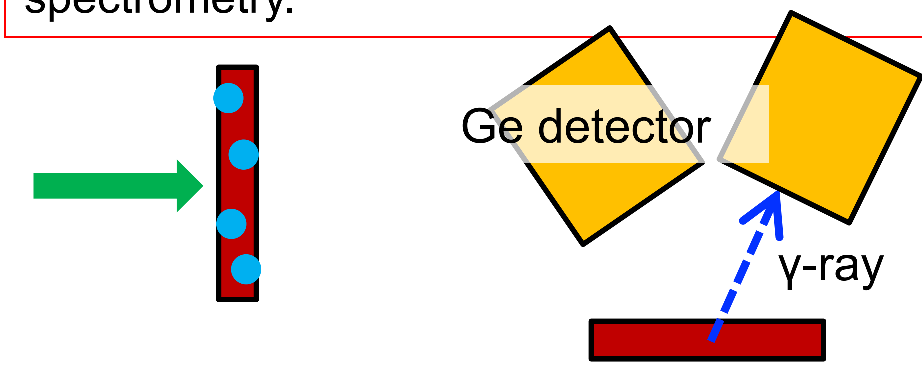
The detector contains an isotope with a large neutron interaction cross section (i.e. dopant, converter…). The secondary particles produced in the neutron reaction (charged particles, γ-rays…) end up in electronic pulses.

Delayed detection

1. A sample is irradiated in a neutron field during a given time.

2. The sample is analysed after the irradiation. Different cross sections/interaction lead to different analyses: tracks in solids, bubbles, γ-ray spectrometry of activation products, mass spectrometry.





Counting holes, counting bubbles, counting atoms produced in (n, γ) reactions.

Common reactions used in neutron detectors

Common reactions used for neutron detection:

Elastic scattering:

n + ^{1}H → n + ^{1}H

n + ^{2}H → n + ^{2}H (abund.=0.015%)

Charged particle:

n + ^{3}He → ^{3}H + ^{1}H + 0.764 MeV (abund.=0.00014%)

n + ^{6}Li → ^{4}He + ^{3}H + 4.79 MeV (abund.=7.5%)

n + ^{10}B → ^{7}Li* + ^{4}He→ ^{7}Li + ^{4}He + 0.48 MeV γ +2.3 MeV (abund.=19.9%, b.r.=93%)

→ ^{7}Li + ^{4}He + 2.8 MeV (b.r.=7%)

Radiative capture:

n + ^{155}Gd → ^{156}Gd* → γ-ray + CE spectrum (abund.=14.8%)

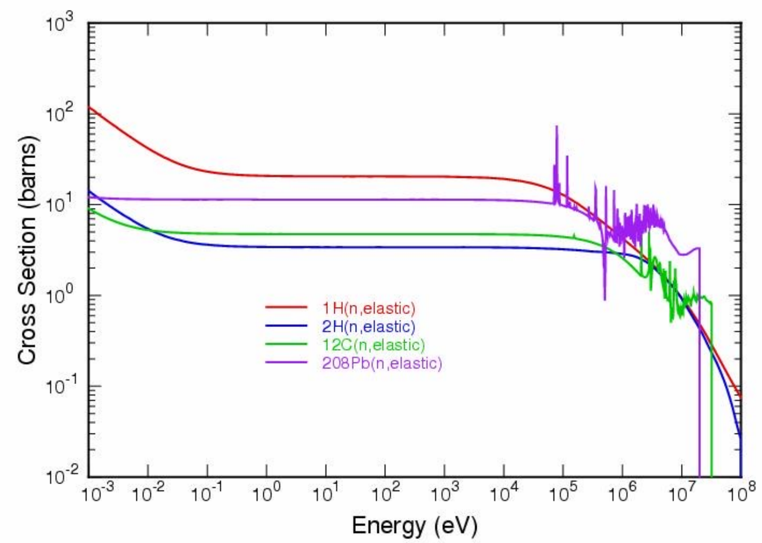
n + ^{157}Gd → ^{158}Gd* → γ-ray + CE spectrum (abund.=15.7%)

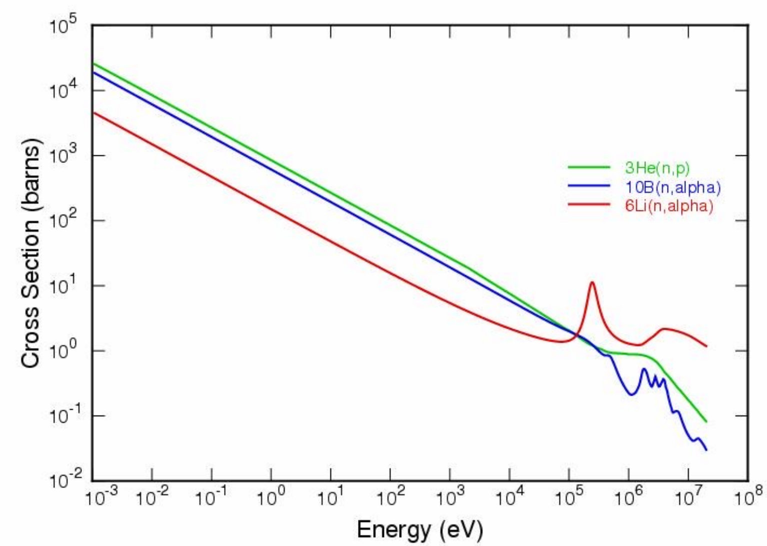
Fission:

n + ^{235}U → fission fragments + ~160 MeV

n + ^{239}Pu → fission fragments + ~160 MeV

n + ^{238}U → fission fragments + ~160 MeV





Neutron Cross section standards

Most of the cross section measurements are relative to a “standard cross section”.
Standard = uncertainty < 1%

Reaction	Energy range
^{1}H(n,n)	1 keV to 20 MeV
^{3}He(n,p)	0.0253 eV to 50 keV
^{6}Li(n, ^{3}H)	0.0253 eV to 1 MeV
^{10}B(n,α)	0.0253 eV to 1 MeV
^{10}B(n,$\alpha_1\gamma$)	0.0253 eV to 1 MeV
C(n,n)	up to 1.8 MeV
^{197}Au(n,γ)	0.0253 eV, and 0.2 to 2.5 MeV
^{235}U(n,f)	0.0253 eV, and 0.15 to 200 MeV
^{238}U(n,f)	2 to 200 MeV

https://www-nds.iaea.org/standards/

Common neutron detectors

Gaseous

- Ionisation chambers
- Proportional counters
- PPACs
- Micromegas

$^{10}B(n,\alpha)$, $^{1}H(n,el)$, $^{235}U(n,f)$, $^{238}U(n,f)$, $^{239}Pu(n,f)$, $^{6}Li(n,t)$

Can stand high radiation doses.
Operated in pulse or current mode.
Low sensitivity to γ-rays.
For the same reaction, lower efficiencies than solids.

Solid or liquid

Prompt:
- Organic scintillators
- Inorganic scintillators
- Semiconductor
- Self Powered

$^{1}H(n,el)$, $^{2}H(n,el)$, $^{6}Li(n,^{3}H)$, $^{10}B(n,\alpha)$, $Gd(n,\gamma)$, other (n,γ)

Can be plastic, liquid or crystalline. Liquids and crystals can have n/γ pulse shape discrimination.
H+Gd allows combined fast and thermal neutron detection.
Issues: toxicity and flammability.

Delayed:
- Track edge detectors
- Gels
- Activation foils

(n,el), $(n,ch.p.)$, (n,f), (n,γ)

Require an irradiation and a later analysis:
- Physical scanning
- Spectrometry

Gaseous detectors

^{3}He neutron detectors

^{3}He is a very rare isotope. Natural abundance 0.000137%. It is a by-product of radioactive decay of tritium, mainly produced via the nuclear weapons program and, at a smaller rate, in nuclear power plants (LWR and CANDU reactors).

^{3}H ($T_{1/2}$ = 12.3 y) $\rightarrow$ $^{3}He + e + \nu_e$

U.S. mass production of tritium ceased in the mid 1990's (weapons reduction) but the demand increased after September 11th (portal monitors, homeland security). Prices increased dramatically are are still high.

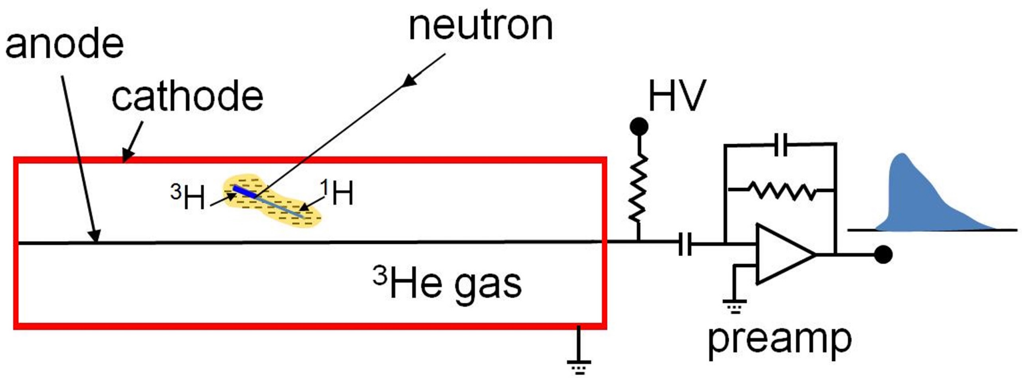
The nuclear reaction of interest is:

$n + {}^{3}He \rightarrow {}^{3}H + p + 764$ keV

Due to momentum conservation: trajectories antiparallel
Due to energy conservation, **proton** kinetic energy = **573 keV** and triton kinetic energy = **191 keV** (3:1) at very low neutron incident energies.

High efficiency for thermal neutrons and low sensitivity to γ-rays.

^{3}He neutron detectors



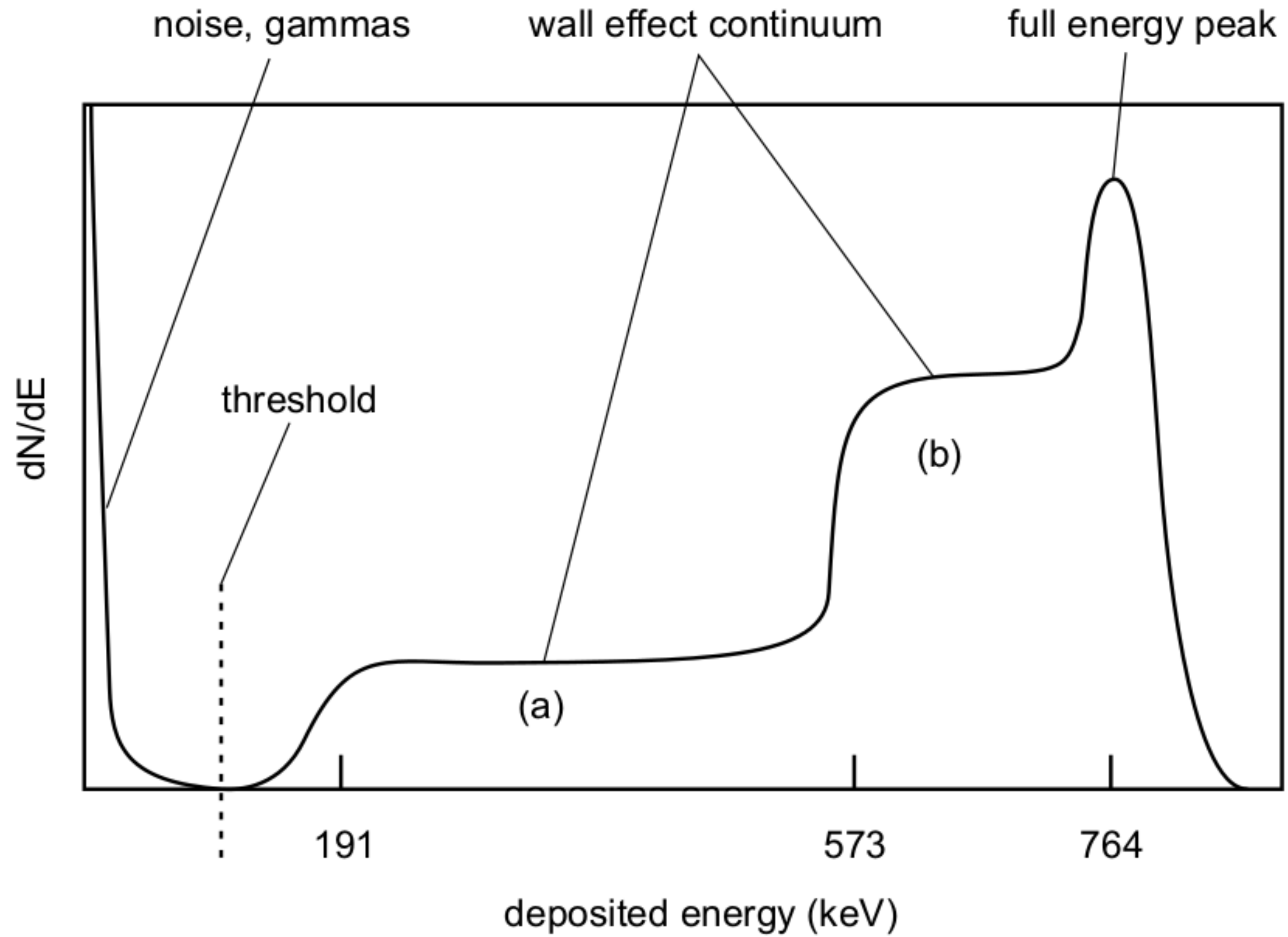
Positive HV on wire, E field falls off as 1/r (strong near wire)

The electrons drift in toward wire (anode), ions drift out toward grounded tube wall (cathode), but at velocities ~ 1000 times slower.

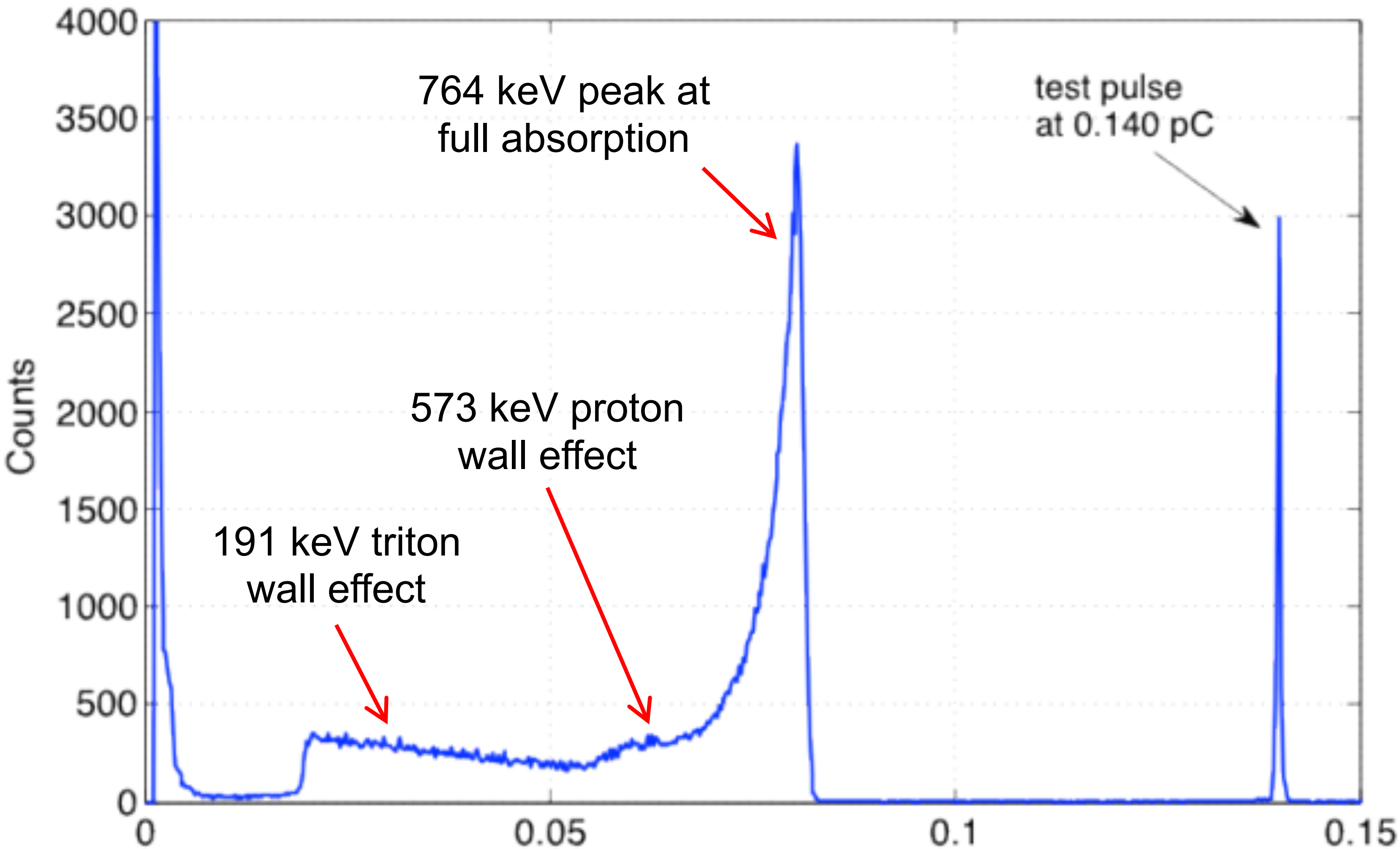
The current pulse measured is proportional to the charge collected on the wire.

^{3}He is typically mixed with CO_2, Ar or other gases for enhancing the avalanche process.

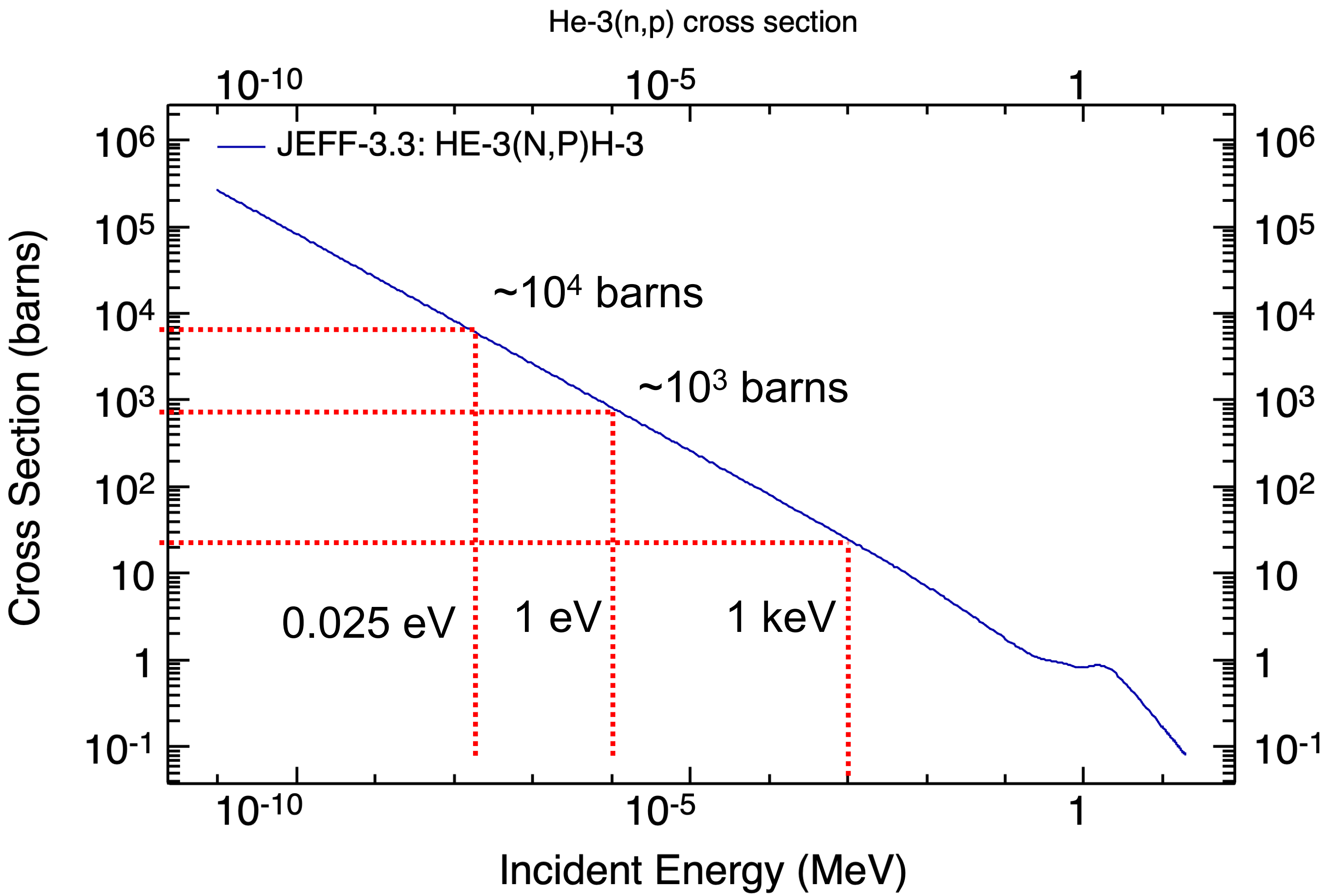
^3He response function



^{3}He response function



The ^{3}He(n,p) cross section



Detection efficiency estimation

^{3}He density $\rho = 1.78 \cdot 10^{-4}$ g/cm^3
$\sigma_{thermal} \sim 10000$ barn
$\sigma_{1\ eV} \sim 1000$ barn

Macroscopic c.s.
$\Sigma_{th} = (\rho \cdot 6.022 \cdot 10^{23}/A) \cdot \sigma_{thermal}$ cm^{-1} = $3.57 \cdot 10^{-1}$ cm^{-1}
$\lambda_{th} = 1/\ \Sigma_{th} = 2.8$ cm

$\Sigma_{1\ eV} = 3.57 \cdot 10^{-2}$ cm^{-1}
$\lambda_{1\ eV} = 1/\ \Sigma_{1\ eV} = 28$ cm

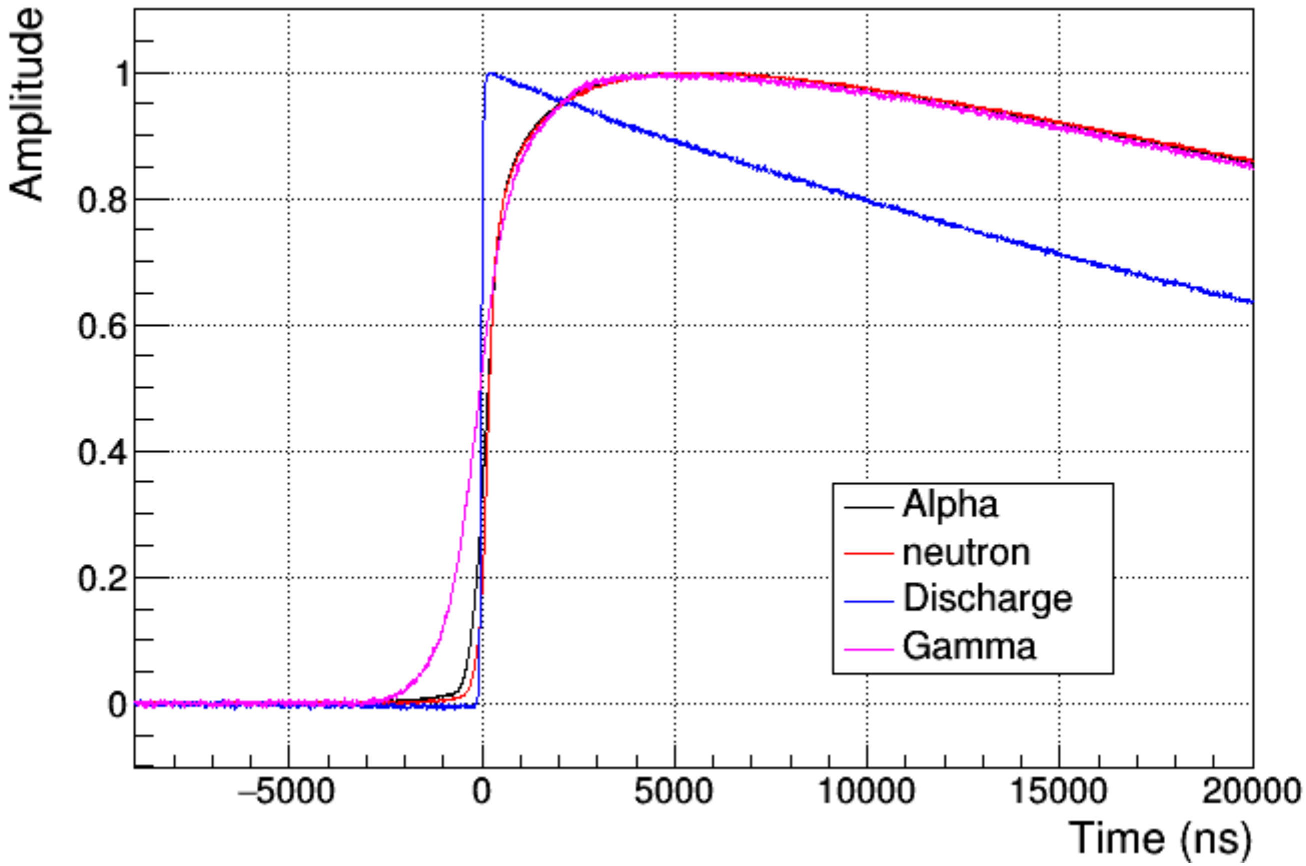
Probability of no interaction in a distance x = $\exp(-\Sigma \cdot x)$
Probability of interaction in a distance x = $1 - \exp(-\Sigma \cdot x)$

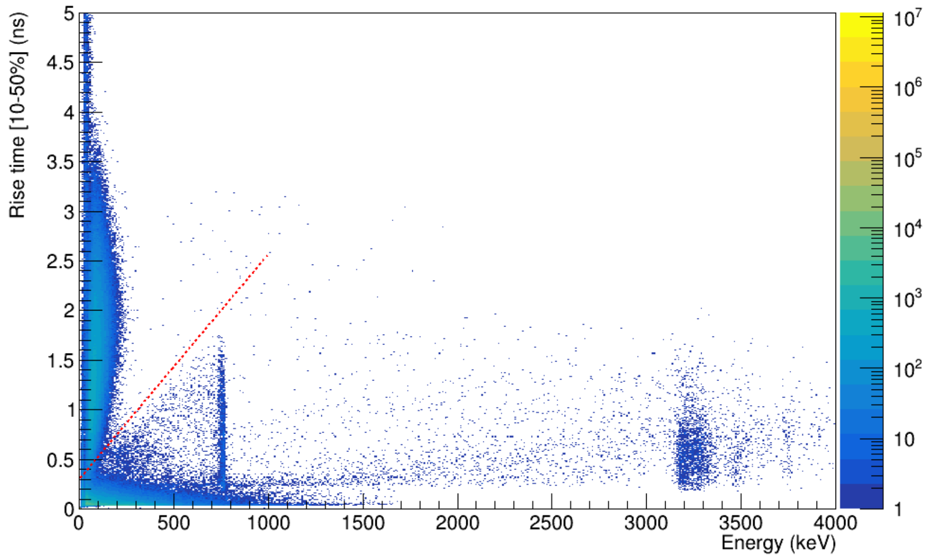
For a 2.8 cm thick detector:

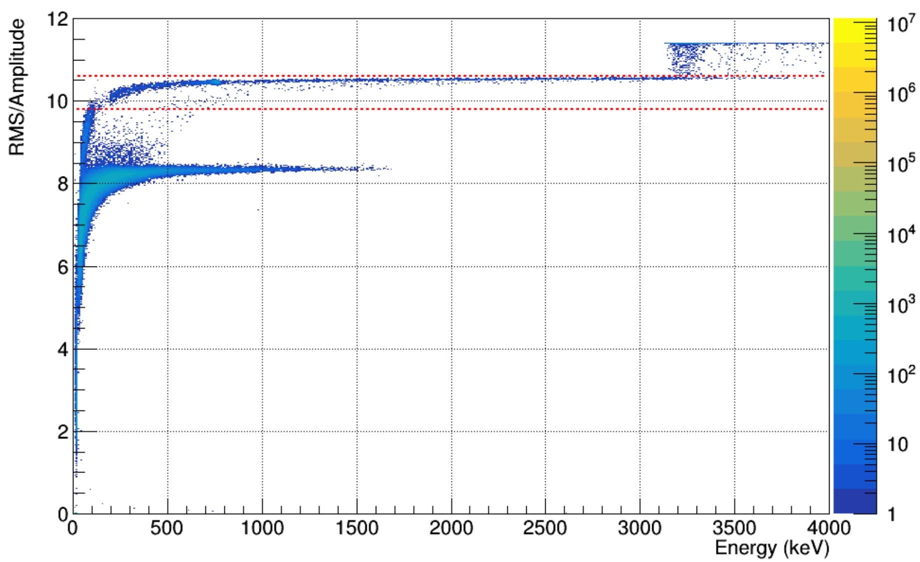
intrinsic efficiency @ 0.025 eV ~ 63 %
intrinsic efficiency @ 1 eV ~ 10 %
intrinsic efficiency @ 1 keV ~ 0.2 %

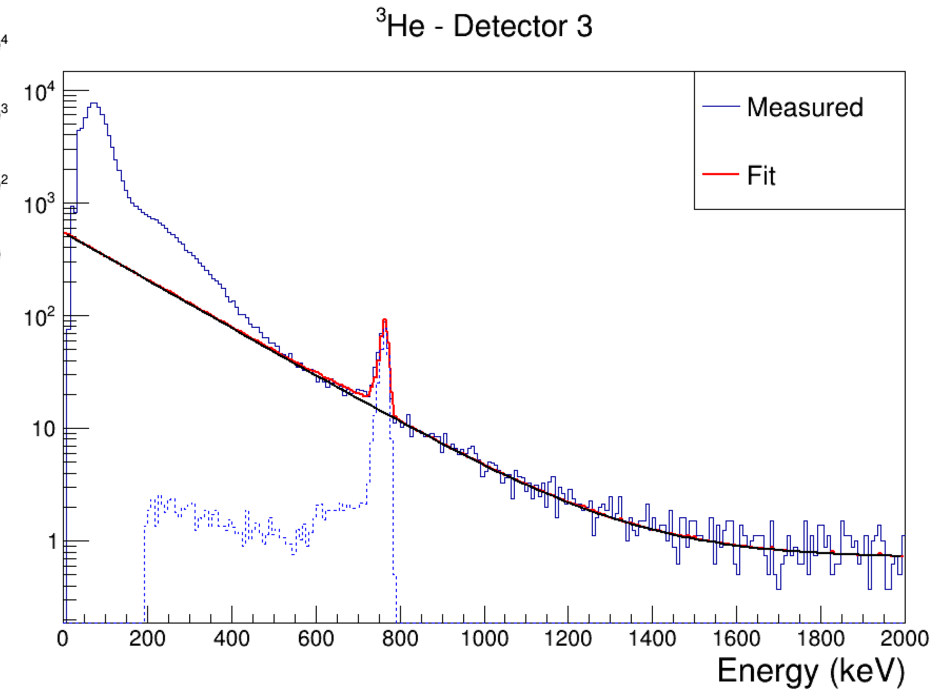
^{3}He pulse shape analysis

Implementation of a pulse shape analysis routine that uses the ^{3}He signal rise time for discriminating neutrons from α, β/e$^-$ and discharges. At present time, very low efficiency for discriminating α from neutrons.




Rise time [10-50%] (ns)
Energy (keV)

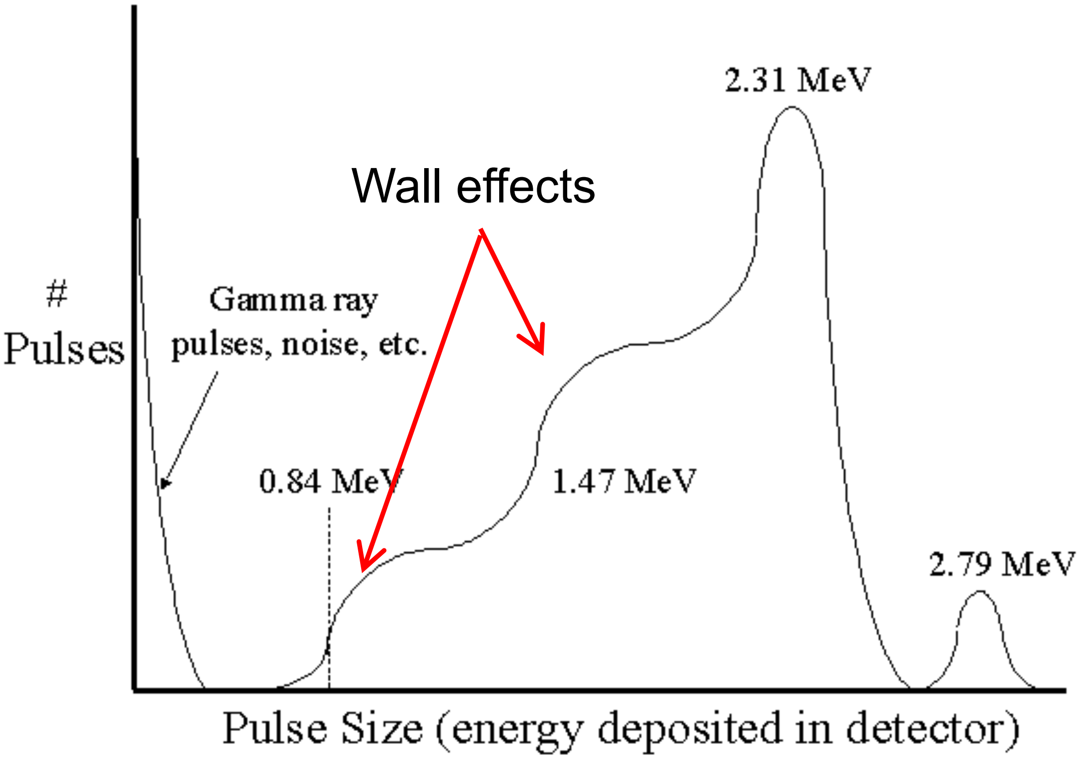

RMS/Amplitude
Energy (keV)


^{3}He - Detector 3
Measured
Fit
Energy (keV)

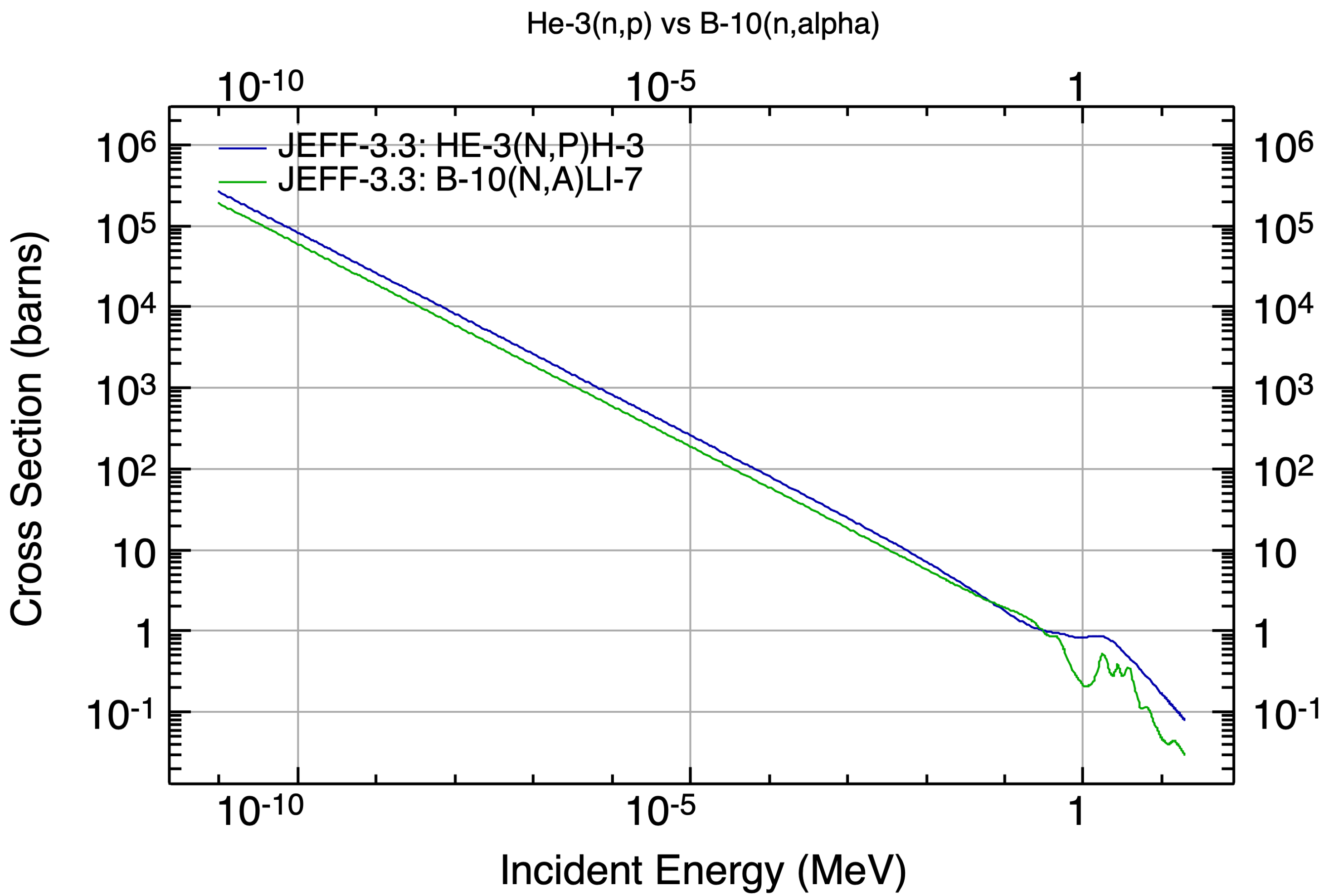
BF_3 detectors

^{10}B (abund.=19.9%) is more abundant than ^{3}He. Due to its large neutron absorption cross section, it was commonly used as neutron BF_3 gas detector prior to the widespread availability of ^{3}He. However, BF_3 is a toxic and corrosive gas (^{3}He is inert) and more sensitive to γ-rays than ^{3}He. Nevertheless, some facilities have recently revisited BF_3 due to the ^{3}He shortage.

$$n + {}^{10}B \rightarrow {}^{7}Li^{*} + {}^{4}He \rightarrow {}^{7}Li + {}^{4}He + 0.48\ \text{MeV}\ \gamma + 2.3\ \text{MeV}\ (\text{b.r.}=93\%)$$
$$\rightarrow {}^{7}Li + {}^{4}He + 2.8\ \text{MeV}\ (\text{b.r.}=7\%)$$

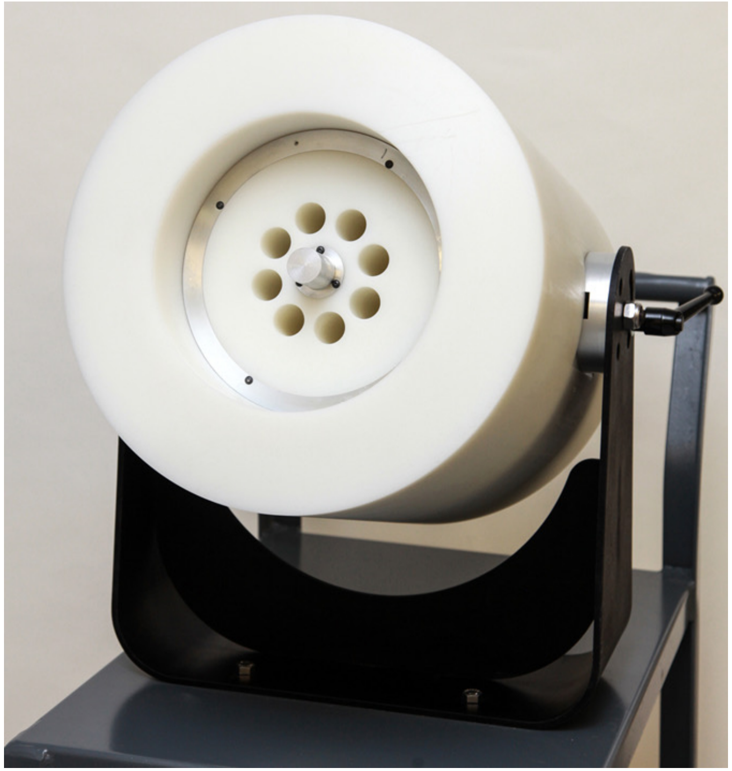


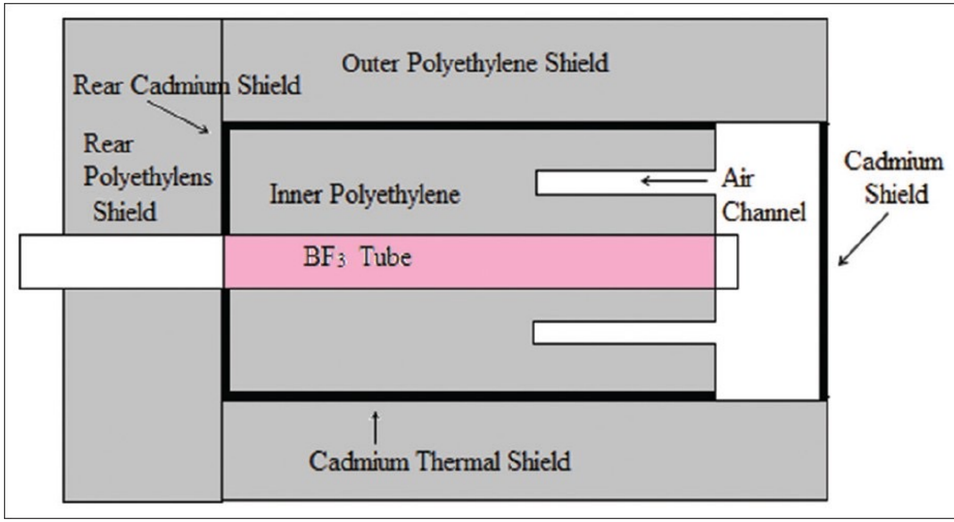
The $^{10}B(n,\alpha)$ cross section

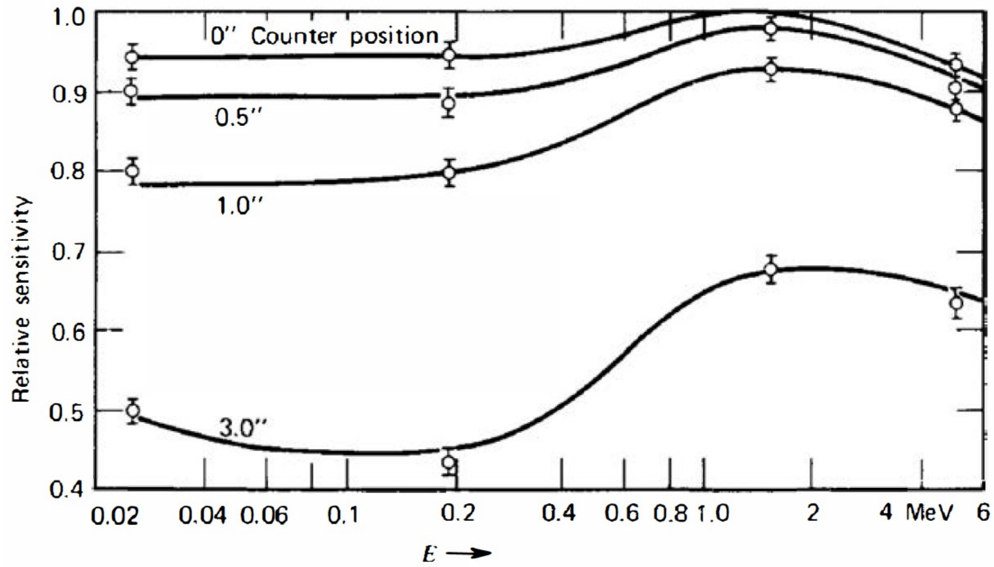


Long counters

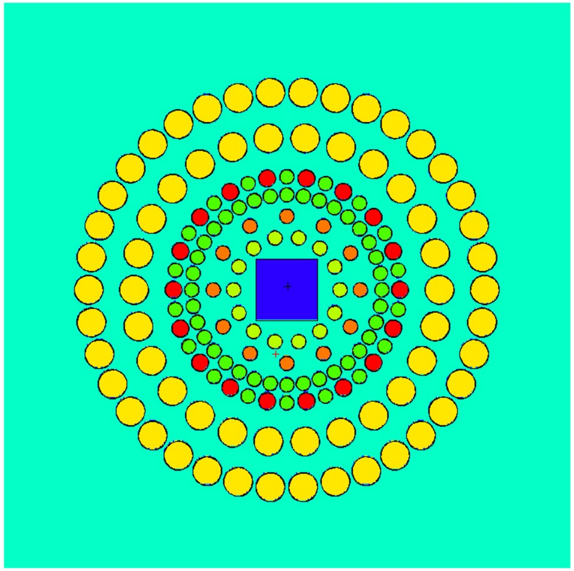
BF_3 detectors have been used for a long period as long counters: neutron detectors that have a constant efficiency over a broad energy range. The tube is surrounded by a moderator for increasing the sensitivity to fast neutrons.



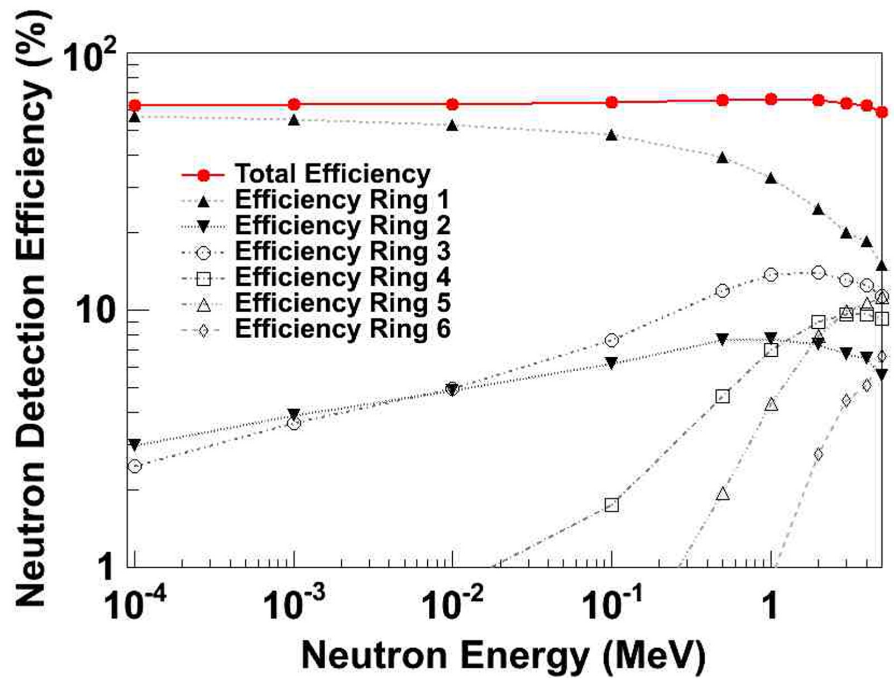




The BRIKEN ^{3}He long counter



Worlds largest ^{3}He long counter 6 rings and 174 ^{3}He counters. Very high and constant efficiency up to several MeV.



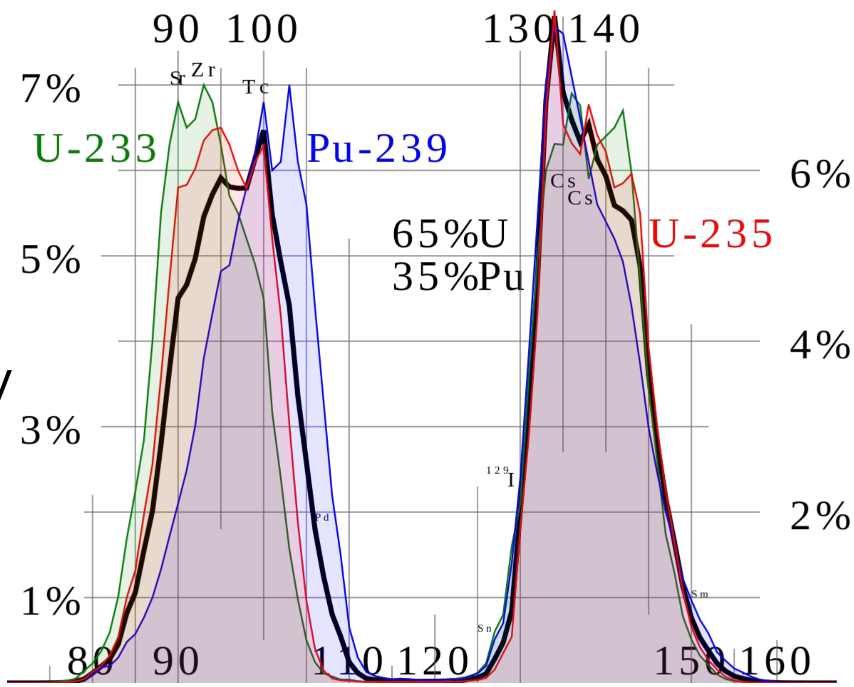
Number of ^{3}He tubes	Pressure (atm)	Diameter (inch)	Institute
42	8	1	UPC
10	10	1	GSI
16	12	2	ORNL
56	10	2	ORNL
24	5.13	1	RIKEN
20	5	1.18	JINR

A. Tarifeño-Saldivia et al., Journal of Instrumentation 12 (04), P04006
A. Tolosa-Delgado et al., NIM A 925, 133 (2019)

Ionisation chambers

Use charge particles produced in neutron reactions for detecting/monitoring neutrons. Use thin targets/coatings of materials with large neutron cross sections.

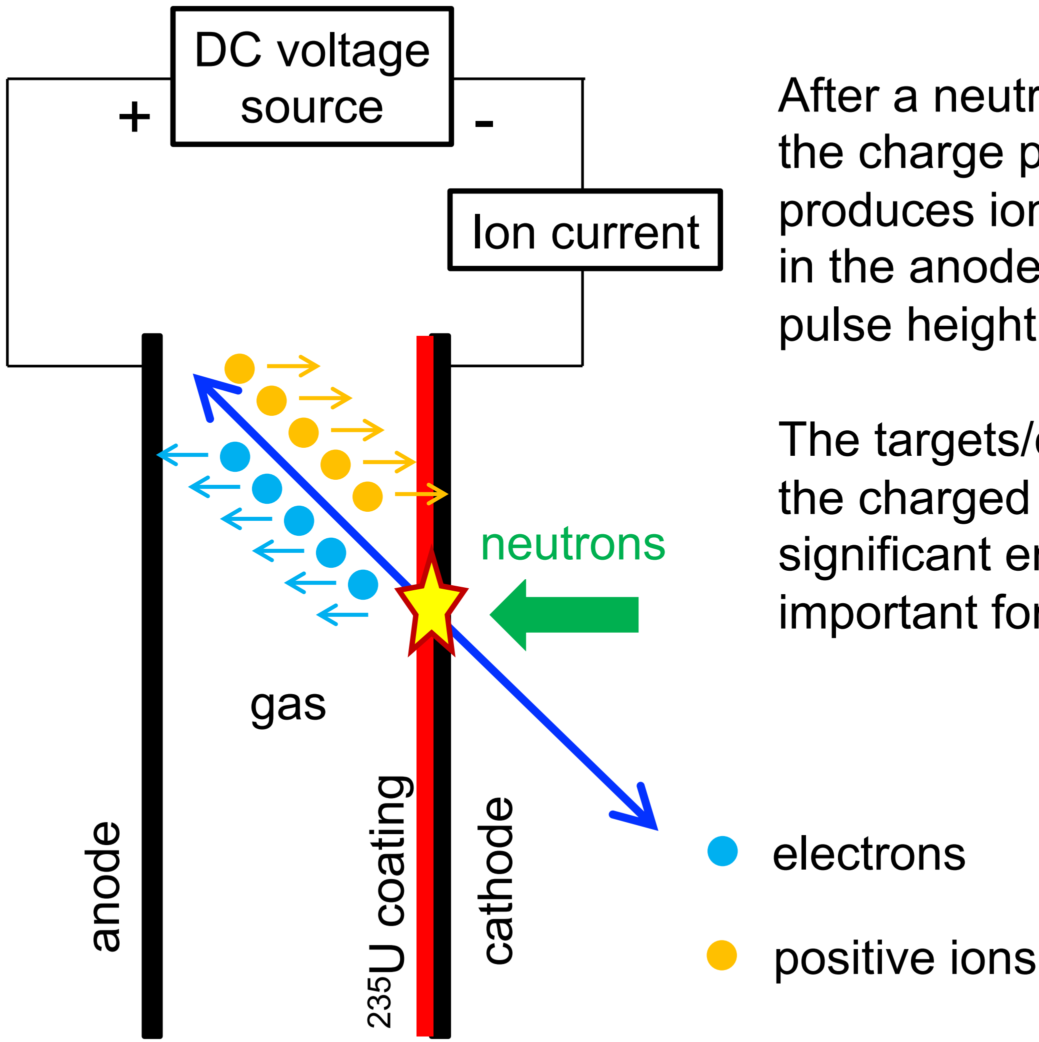
- Have typically low efficiencies.
- Can stand high flux neutron fields (reactor cores, spallation sources).
- Can be operated in pulsed or current modes.
- 1 – 10 ns time resolution.



Typical reactions:

n + ^{235}U → fission fragments + ~160 MeV
n + ^{239}Pu → fission fragments + ~160 MeV
n + ^{238}U → fission fragments + ~160 MeV

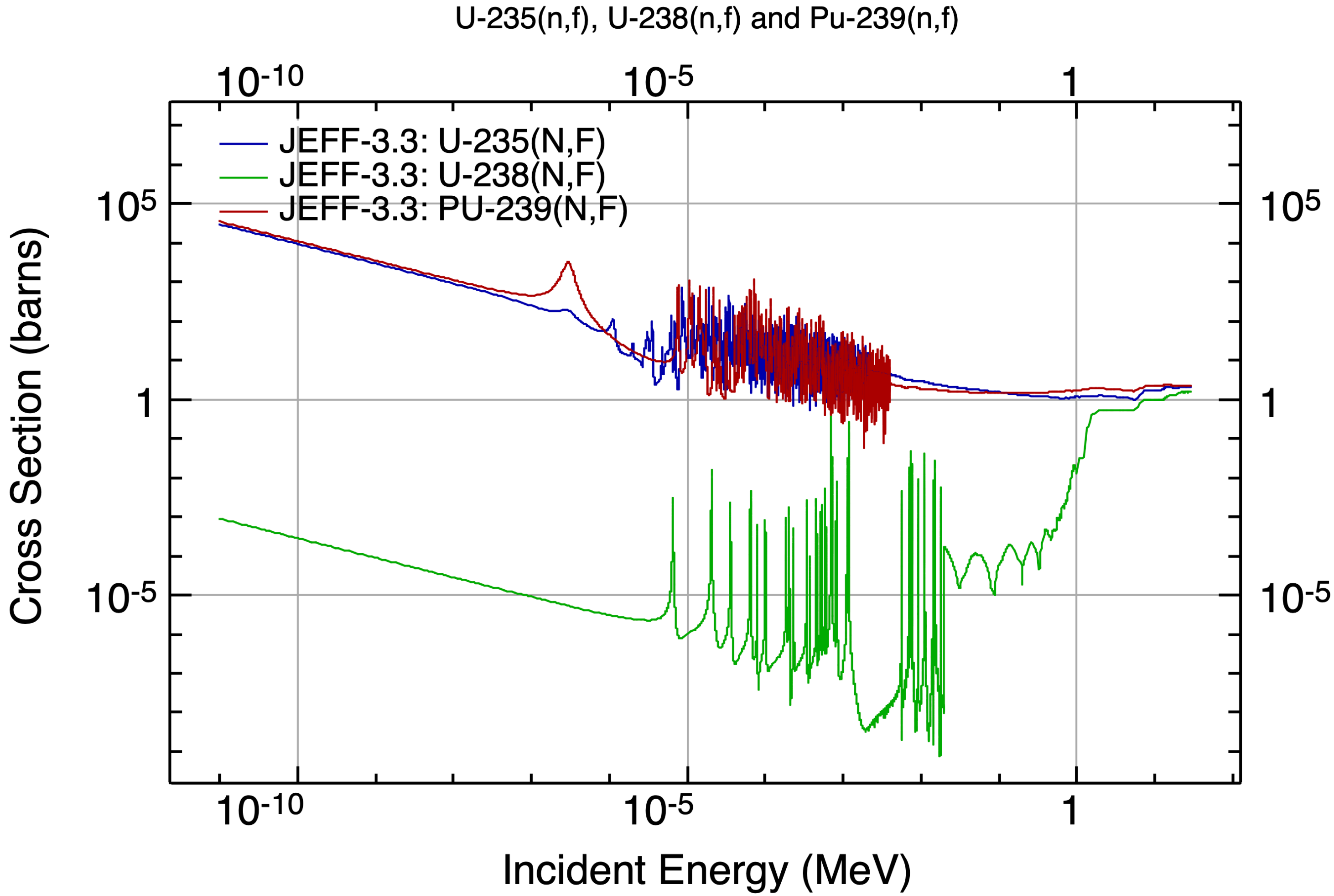
Ionisation chambers



After a neutron reaction in the target/coating, the charge particle enters into the gas and produces ionisation. The charge is collected in the anodes and cathodes and the resulting pulse height is proportional to it.

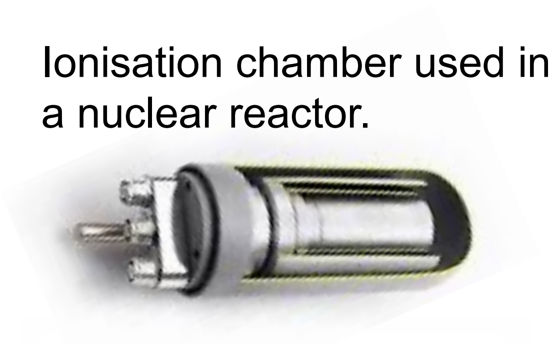
The targets/coatings need to be thin to allow the charged particles escaping without a significant energy loss. This is particularly important for fission chambers.

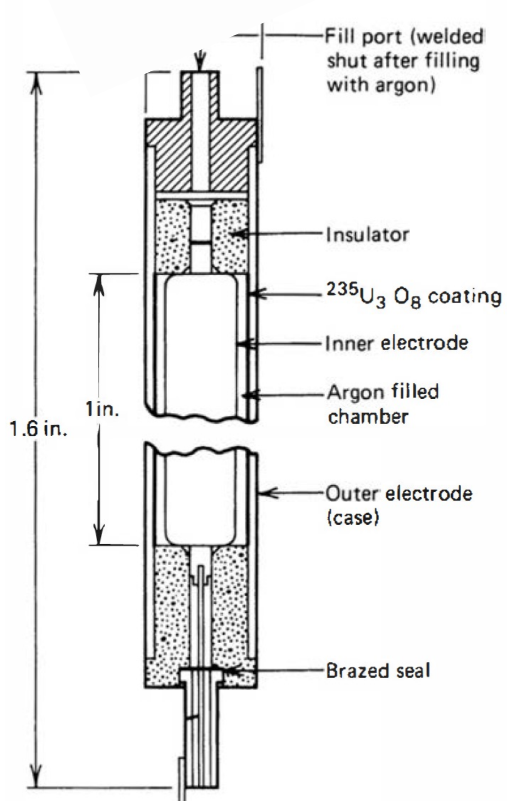
$^{235,238}U$ and ^{239}Pu (n,f) cross sections



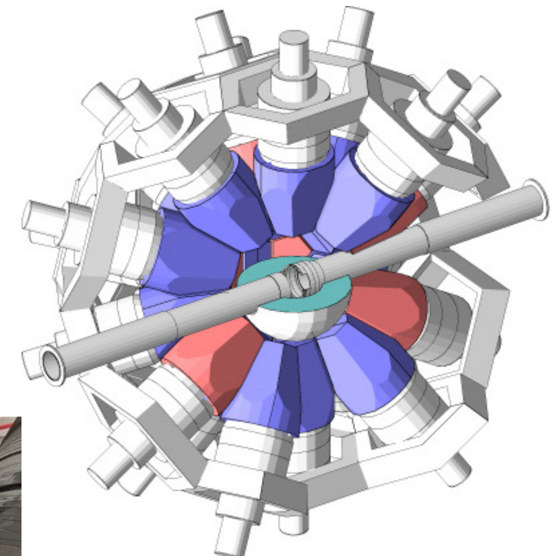
Examples of ionization chambers

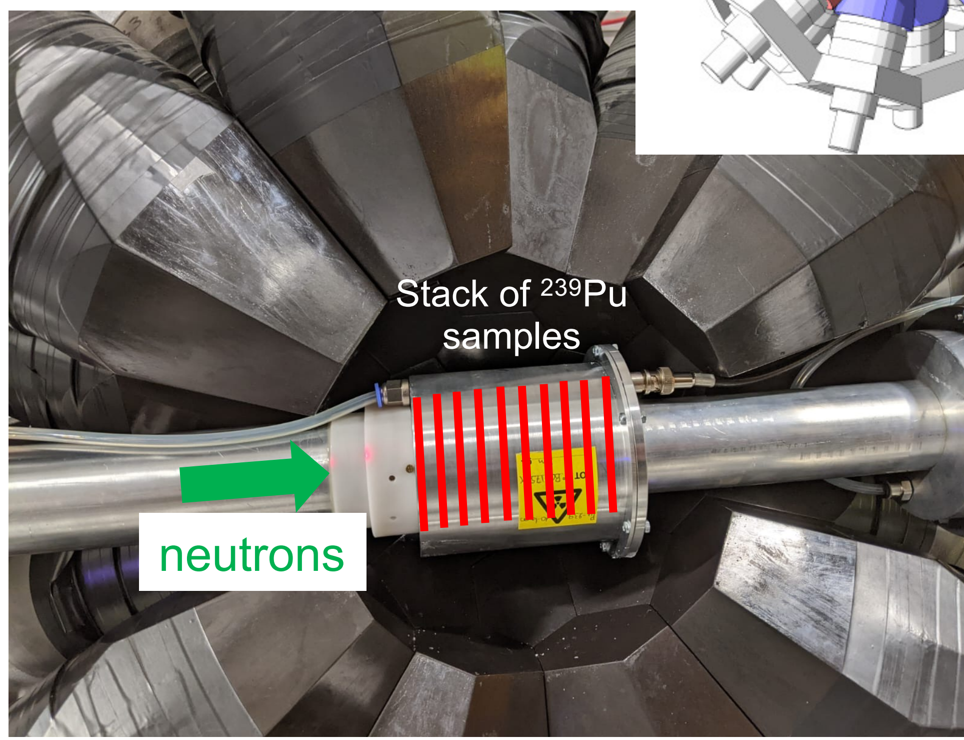
Ionisation chamber used inside a nuclear reactor.





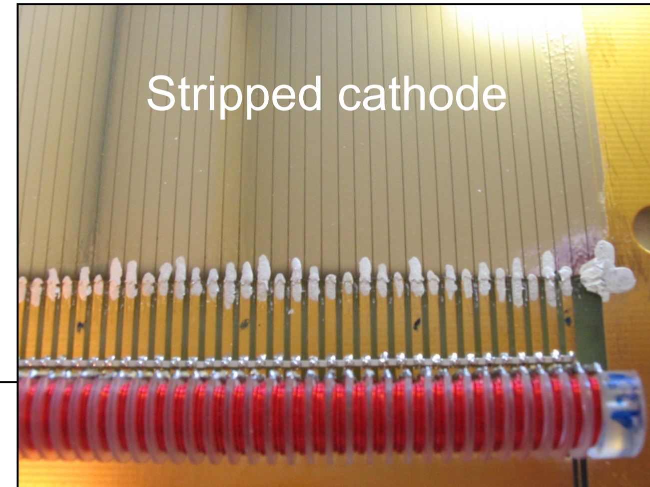
Ionisation chamber with a stack of 10 ^{239}Pu samples used right now at n_TOF. Very compact detector embedded inside a γ-ray calorimeter.

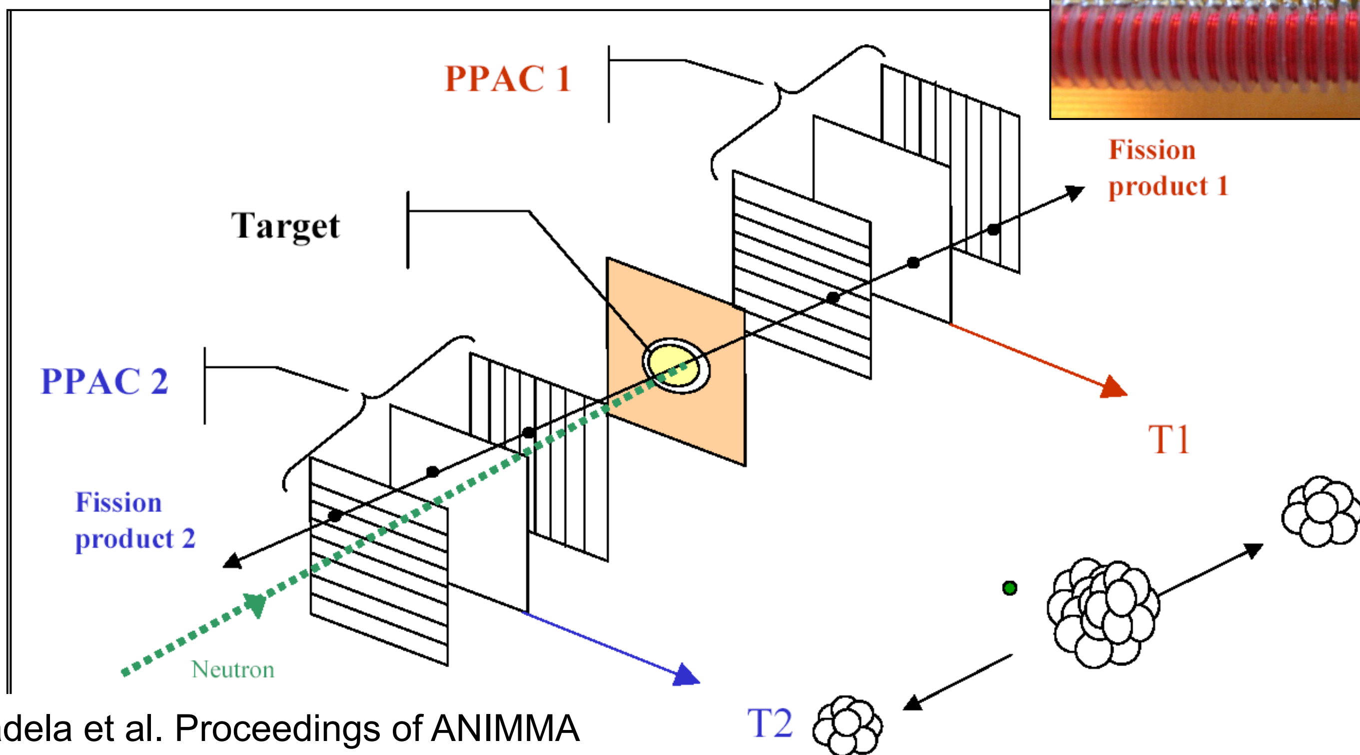




Other gaseous detectors: PPACs

Position sensitive parallel plate avalanche chambers (PPACs) for the measurement of fission cross sections (@n_TOF).

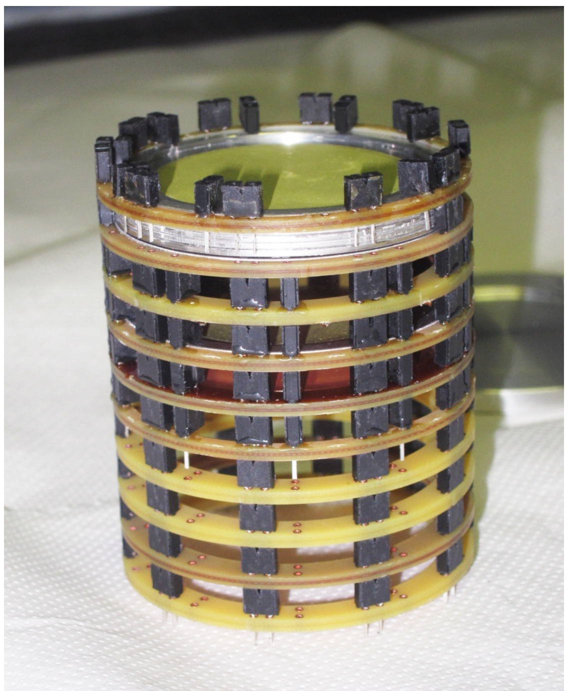


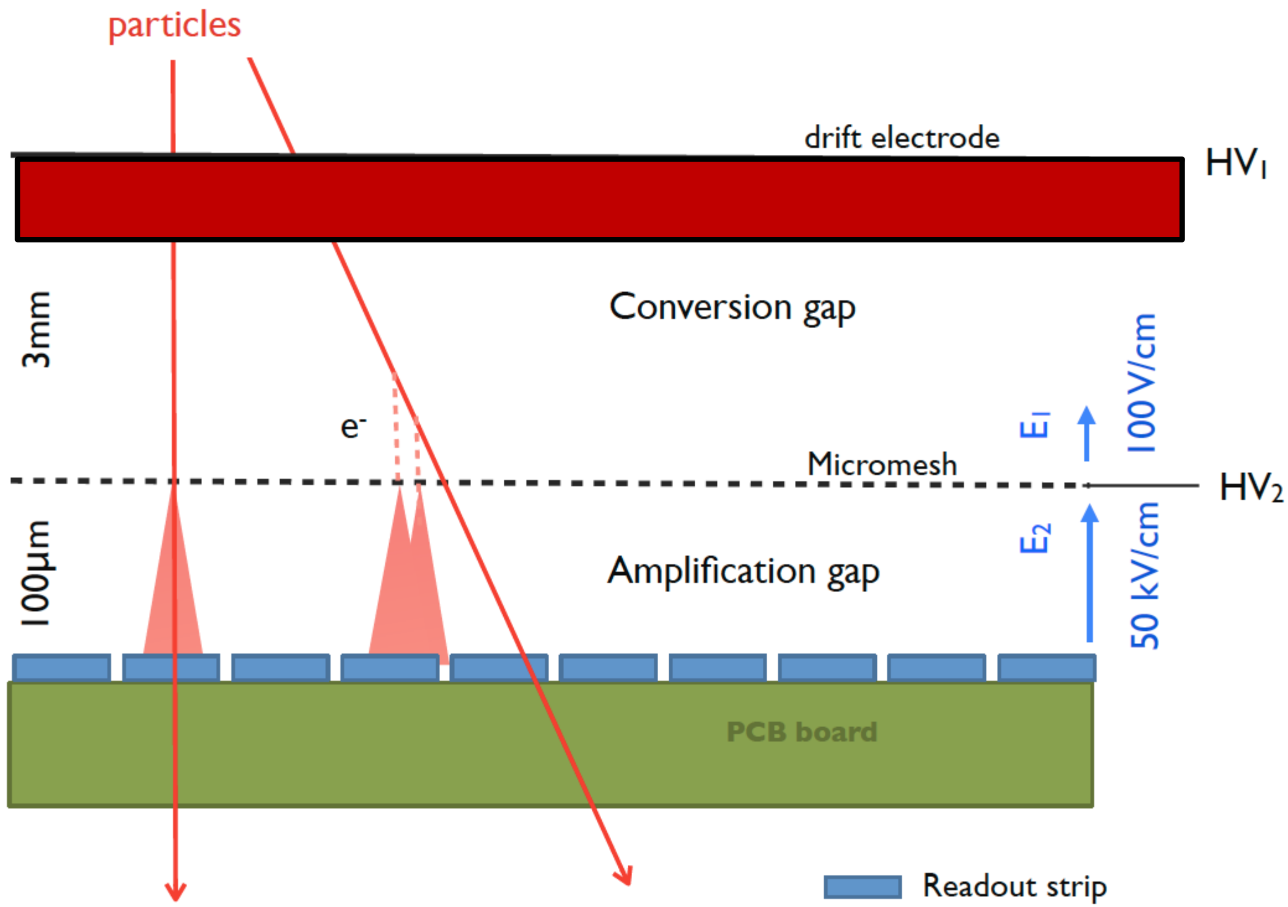


C. Paradela et al. Proceedings of ANIMMA
[10.1109/ANIMMA.2011.6172860](https://doi.org/10.1109/ANIMMA.2011.6172860)

Other gaseous detectors: micromegas

Working principle: **ionisation** (conversion gap) and **avalanche** (amplification). The readout is done with different strips.



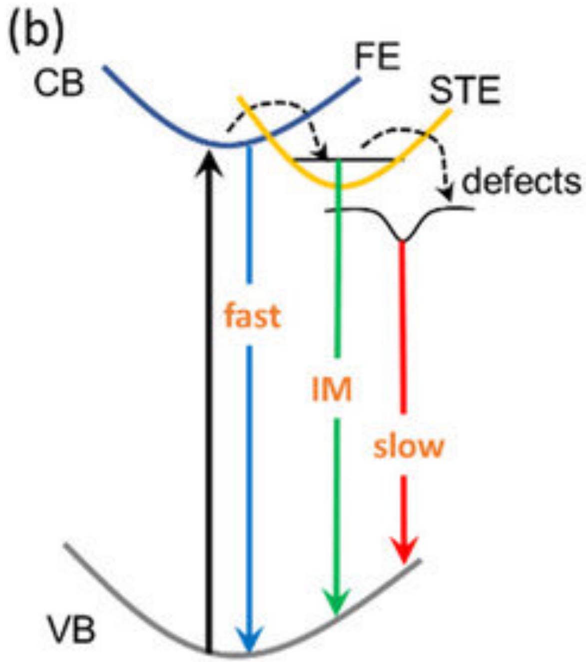


Scintillators

The scintillation

Scintillation: light of a characteristic spectrum is emitted following the absorption of radiation. The emitted radiation is usually less energetic than that absorbed.

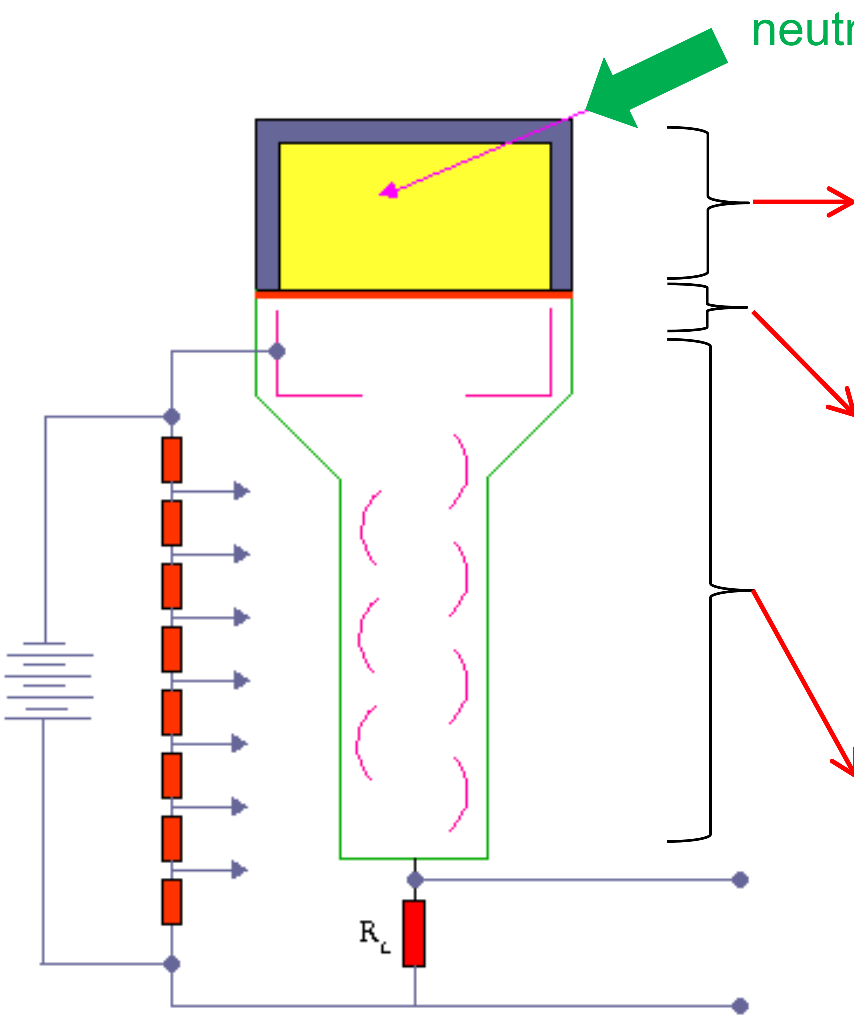
Scintillation is an inherent molecular property in conjugated and aromatic organic molecules and arises from their electronic structures. It also occurs in many inorganic materials, including salts, gases, and liquids.



Main characteristics of scintillation detectors:

- **Solid** (crystals or plastics) or **liquid**. Easy to handle.
- **High density** (solid or liquid, also gaseous) which leads to potential **high efficiency**.
- **Fast time response**. Many materials have sub-nanosecond time resolutions. Various time components are present.
- **Pulse shape discrimination** capabilities. The interaction of electrons (from g-rays) and charged particles (from neutron interactions) leads to different pulse shapes.

Scintillators



Scintillator material (solid, liquid or even gas) surrounded by a reflector material for maximising the light collection.

Optical coupling between the scintillator and the photosensor: direct coupling, window + grease or glue, complex light guides…

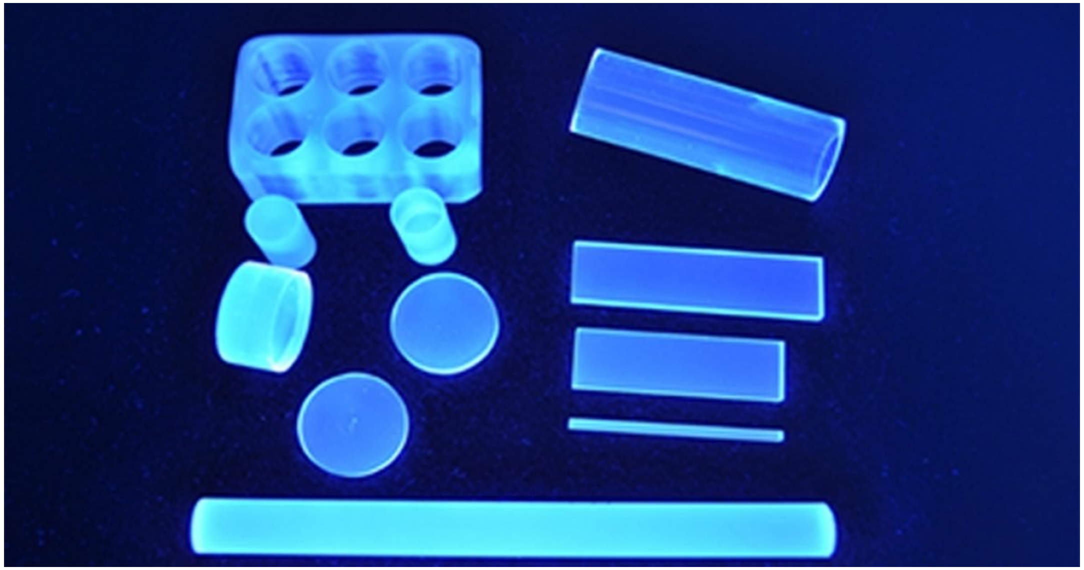
Photosensor that transforms the collected light into electric pulses. Has to be adapted to the scintillation spectrum (UV, visible, IR…)

Photomutiplier tubes (PMTs), avalanche photodiodes (APDs), silicon photomultipliers (SiPMs).

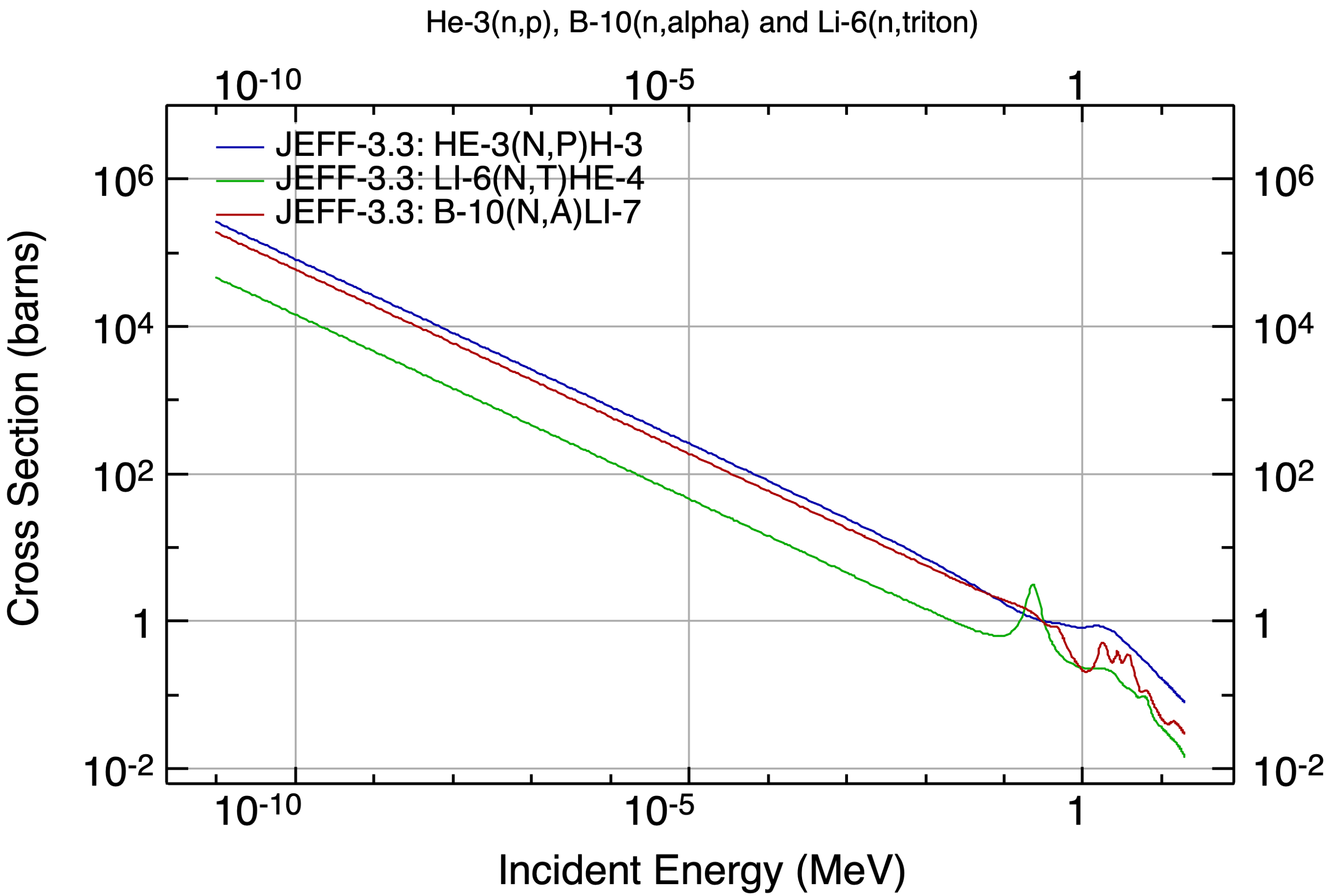
^{6}Li doped glass detectors

Lithium glass scintillators are made from ^{6}Li-enriched substrate. The cross section of ^{6}Li is lower than that of ^{3}He but larger detection efficiency can be achieved thanks to the larger content of ^{6}Li nuclei in the solid scintillators vs. gas filled proportional counters.

Time resolution ~ 1 ns.
Density ~2 g/cm^3.
Can be shaped in different sizes and forms.
Very common in solid state experiments.



The $^6Li(n,^3H)$ cross section



Organic scintillators

Liquid and plastic scintillators are mainly obtained from two companies: St. Gobain Crystals (BC) and Eljen Technologies (EJ).

PLASTIC SCINTILLATORS	LIQUID SCINTILLATORS
BC-400, 404, 408, 412, 416	BC-501A, BC-519
BC-418, 420, 422, 422Q	BC-505
BC-428	BC-517 Series
BC-430	BC-521, BC-525
BC-440, BC-448	BC-523, BC-523A
BC-444	BC-533
BC-452	

Similar products from **Eljen** and additional ones:

EJ309, with and without ^{10}B. Less toxic and higher flash point

EJ299 – 33 with a (not really fantastic) neutron/ γ-ray discrimination

Fast neutron detection with organic scintillators

Organic scintillators (liquid and plastics) are excellent fast neutron detectors.

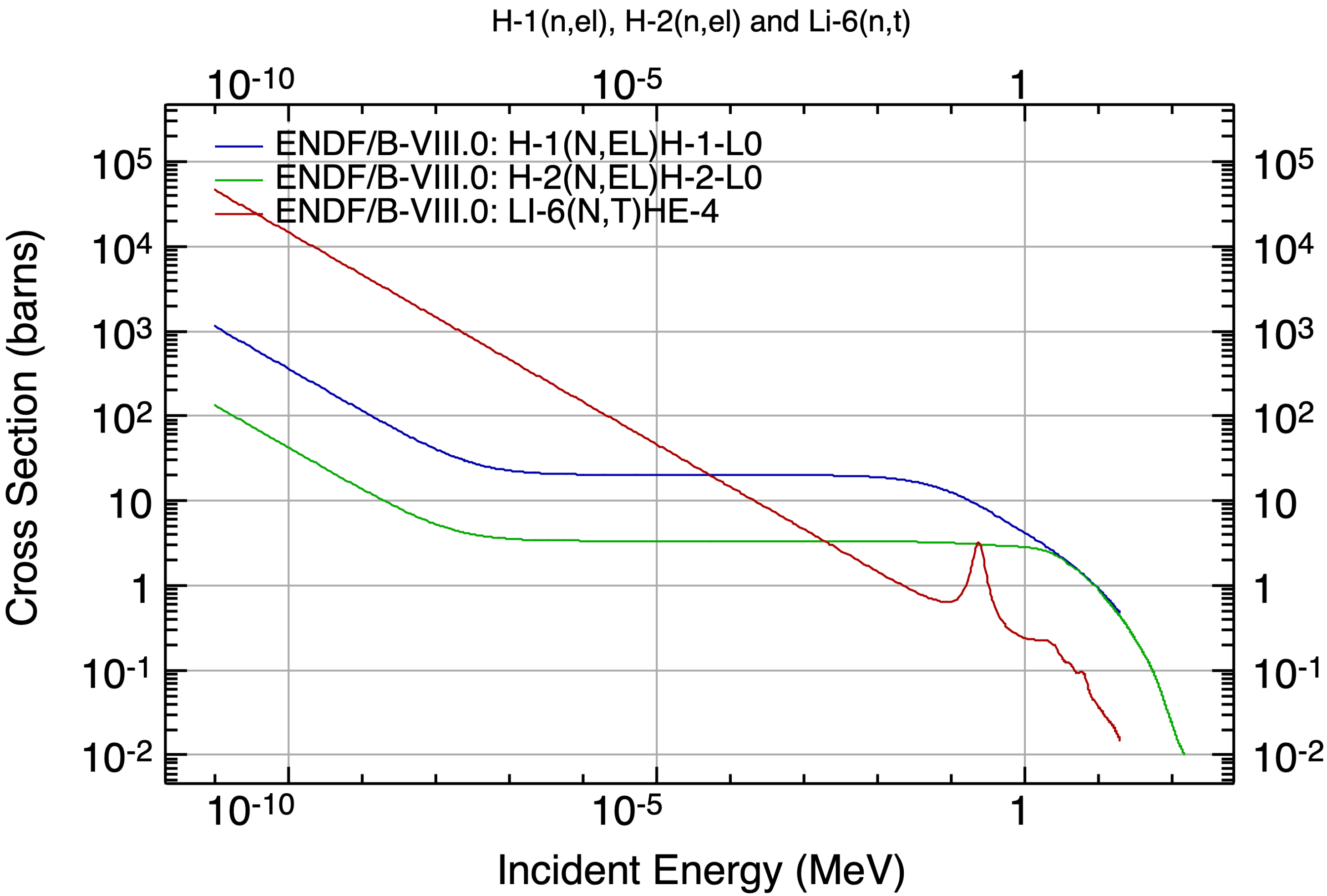
Detection principle: (n,p) reactions in the Hydrogen rich material

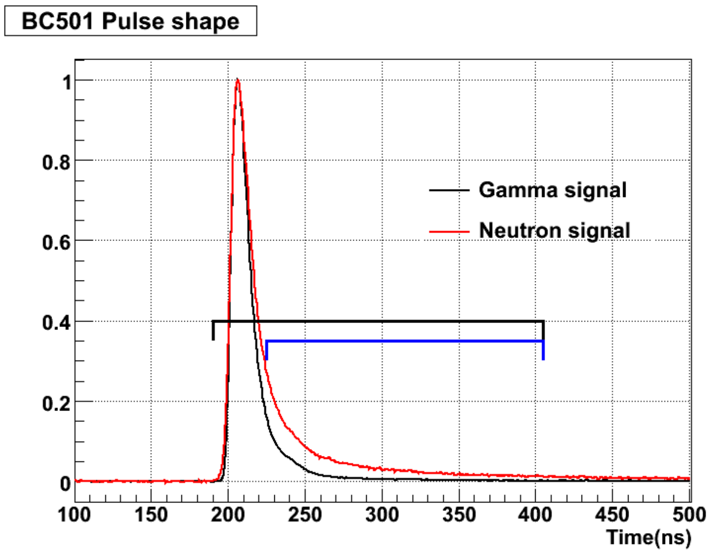
- High intrinsic efficiency (50% to 20% in the 1 MeV – 10 MeV range for 3"x3" detectors) due to the large (n,p) cross section and reasonable density (~1 g/cm^3). Sensitive to neutrons at all energies above the detection threshold (100 keVee).
- Time resolution < 1 ns.
- Low sensitivity to high energy γ-rays (large compared to gaseous).
- Some liquids offer excellent neutron/γ pulse shape discrimination capabilities.

Drawbacks:

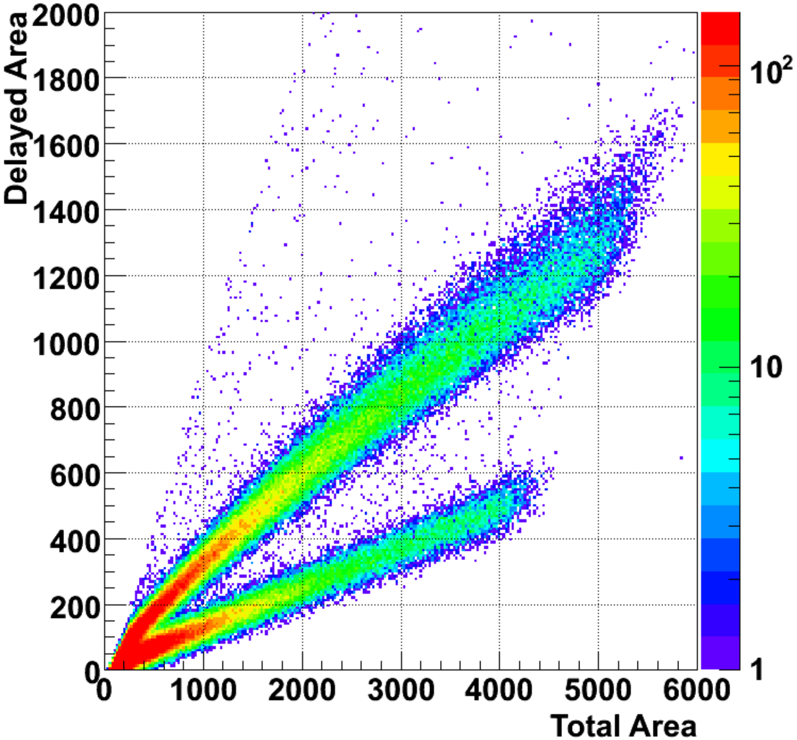
-poor energy resolution (~25% at 1 MeV)
-particle dependent and non-linear light output (e^-, protons, D, T, a, ^{12}C...).
-high intrinsic threshold E_n>100 keV due to the light output.
-the information of the incident neutron energy is not easily recovered from the spectral analysis. TOF or unfolding techniques are necessary for extracting the information on the incident neutron energy.

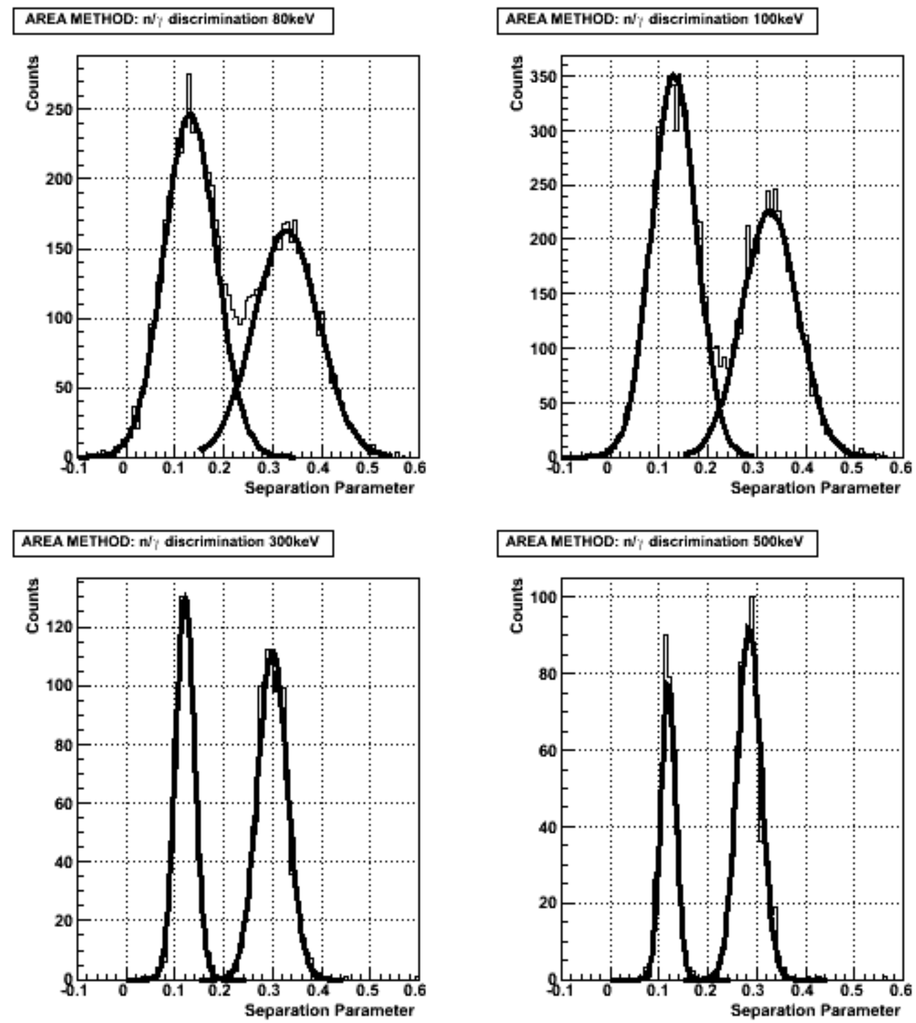
$^{1}H(n,el)$, $^{2}H(n,el)$ and $^{6}He(n,^{3}H)$ cross sections



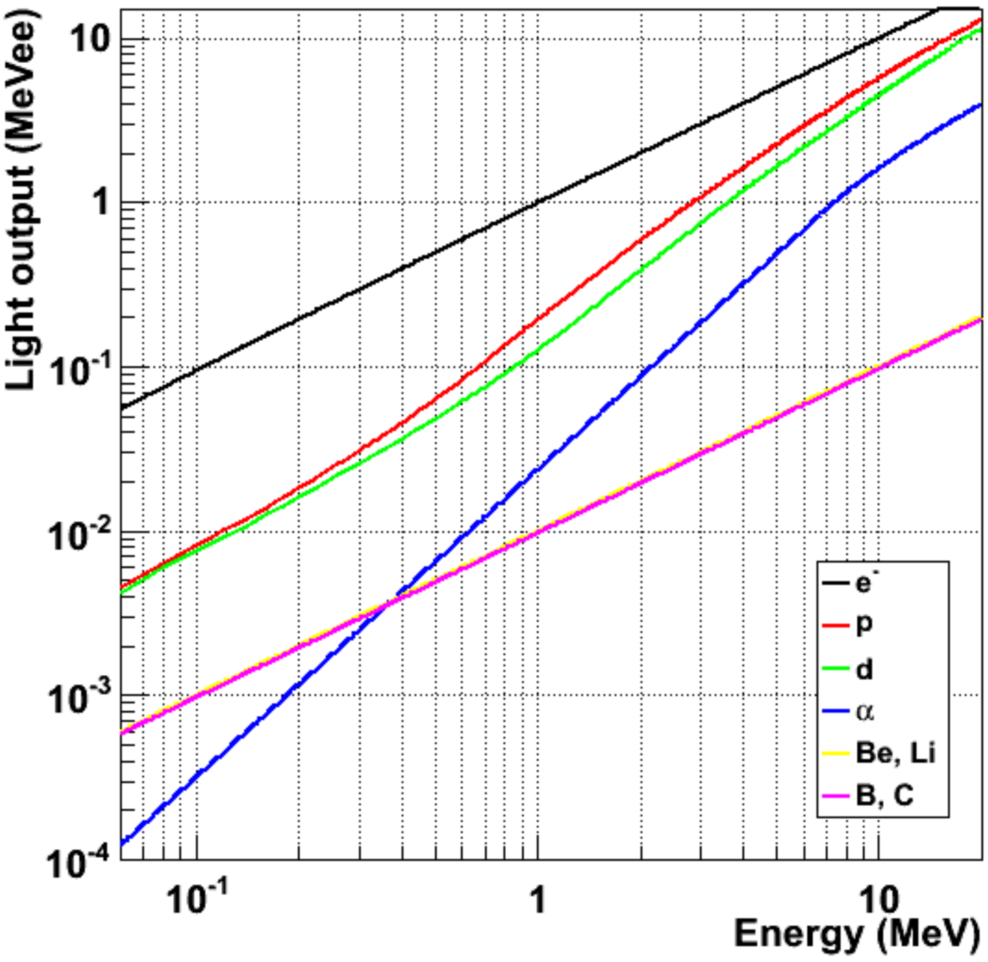


The BC501A scintillator offers good overall n/γ pulse shape discrimination capabilities. At $E_n > 1$ MeV the separation is really excellent.





Light output of BC501A



Virtually for all organic scintillators (I am aware of):

$L(E) \simeq k \cdot E$ for e^-

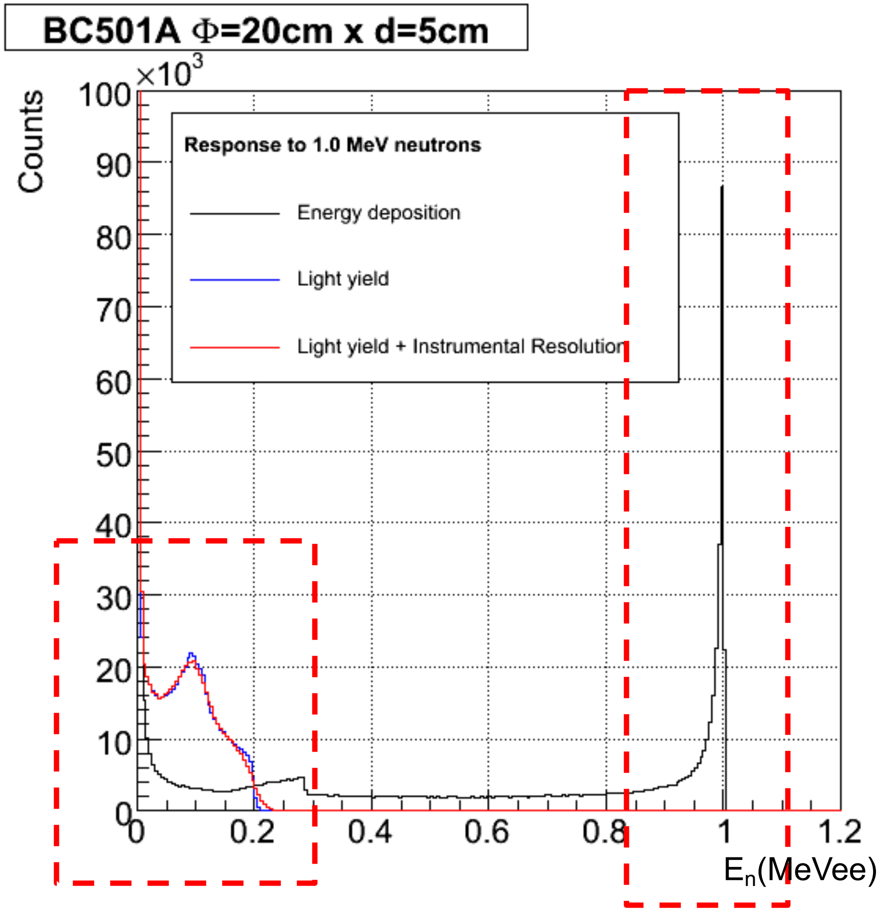
but

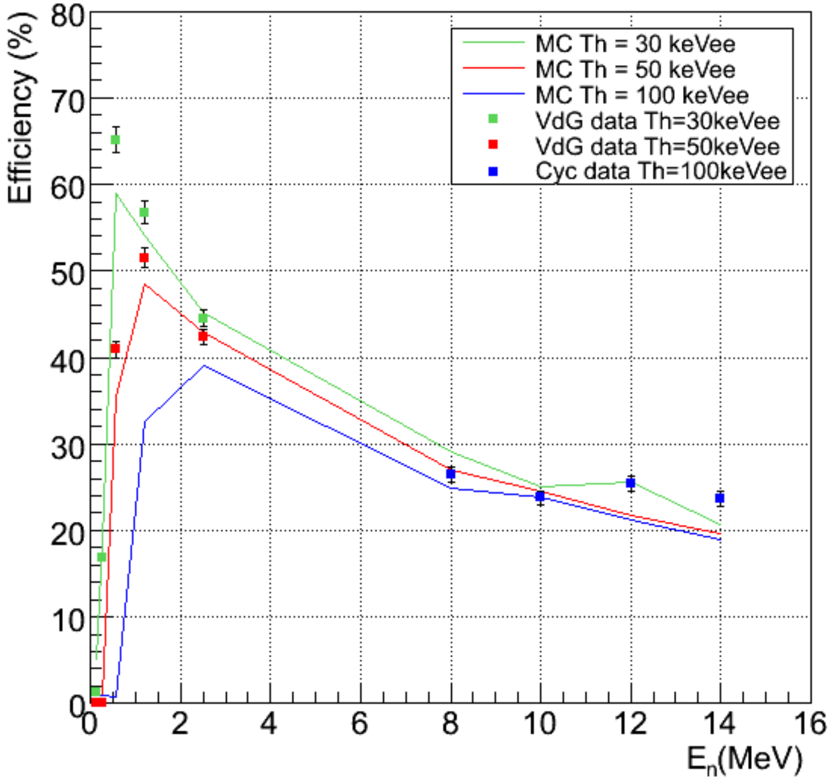
$L(E) \neq k \cdot E$ for protons and heavier charged particles

Important consequences for the energy loss of the proton recoil:

$L(3\text{ MeV}) - L(2\text{ MeV}) \neq$
$L(2\text{ MeV}) - L(1\text{ MeV})$

Response function of BC501A





The shape of the efficiency curve depends largely on the light yield and on the threshold. A good calibration and Monte Carlo modelling are necessary.

Inorganic scintillators: CLYC

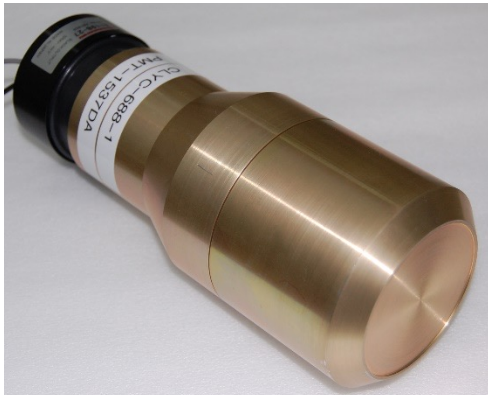
Cs_2LiYCl_6:Ce (CLYC) inorganic scintillator belonging to the "elpasolite" family of crystals:

- Typical gamma resolution ~5% @ 662 KeV.
- Thermal neutron detection via **$^{6}Li(n,^{3}H)$ reaction**.
- Fast neutron detection possible with ^{7}Li and ^{35}Cl.

Growth of different sizes and shapes of crystals.

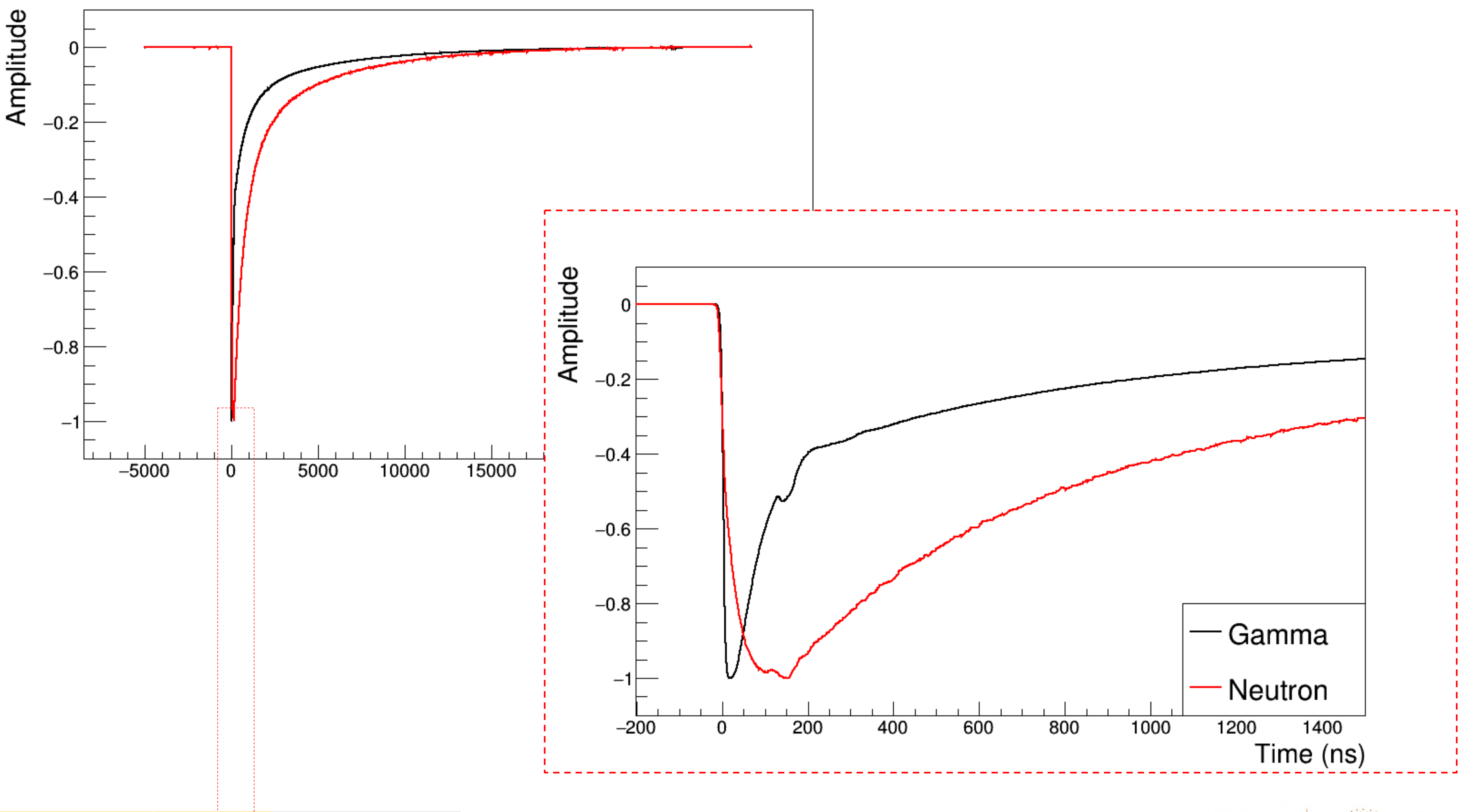
Possible uses as:

- Dual monitor system (neutron, gamma)
- Gamma calorimeter in the presence of high neutron fields (cross section measurements)
- Possible alternative to ^{3}He detectors for some applications



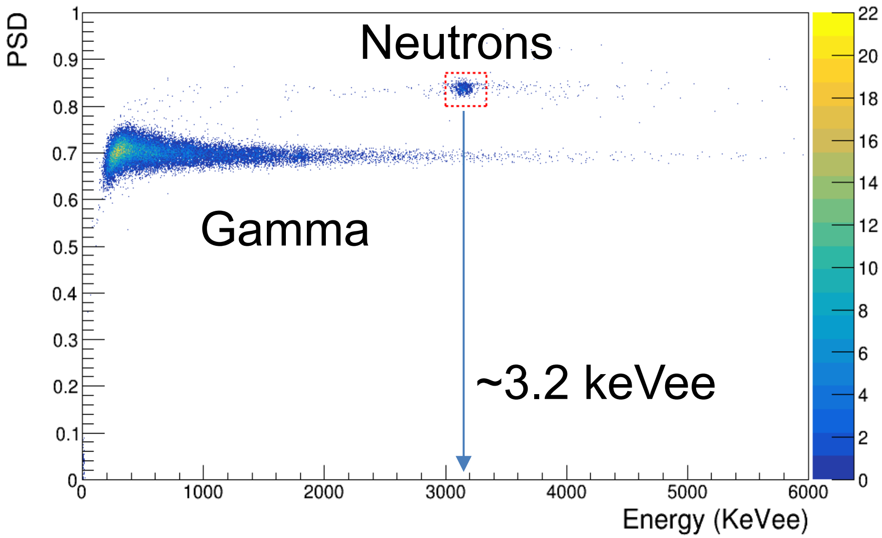
Neutron / γ-ray discrimination

As for the BC501A, the fast component for neutron signals is suppressed with respect to the γ-ray signals.



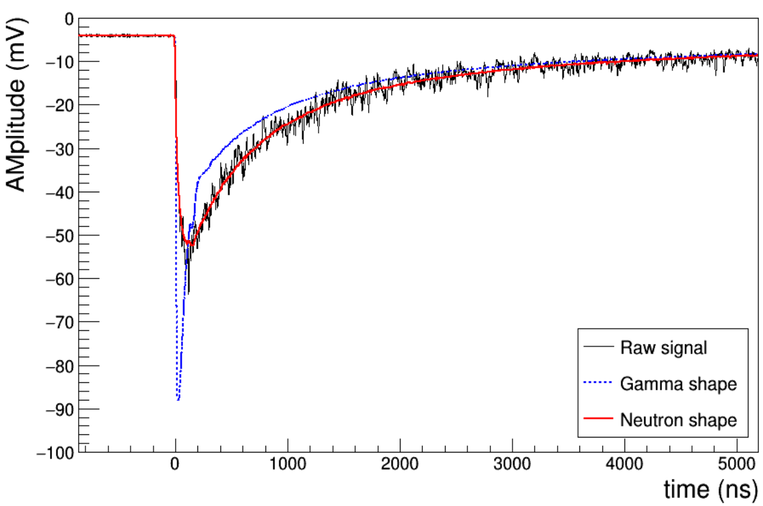
Neutron – gamma discrimination

Area discrimination

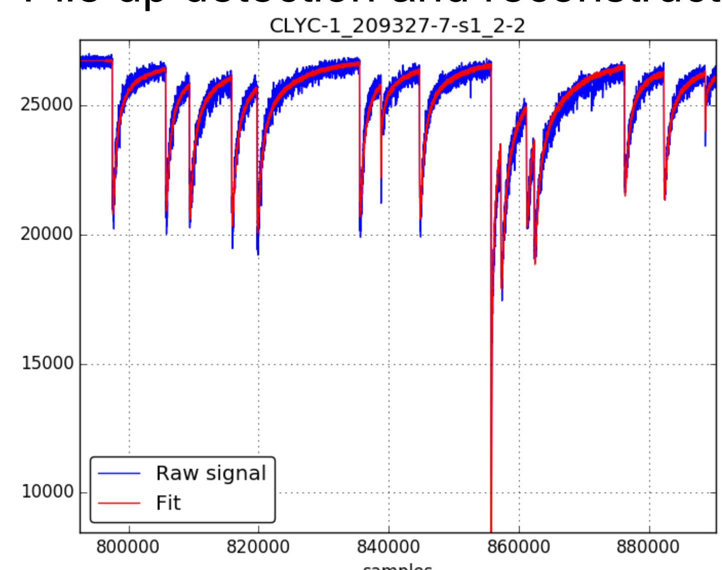


Digitalization of raw signals and development of custom routines allows to make dedicated analysis for each detector type.

Discrimination by fit of average signal



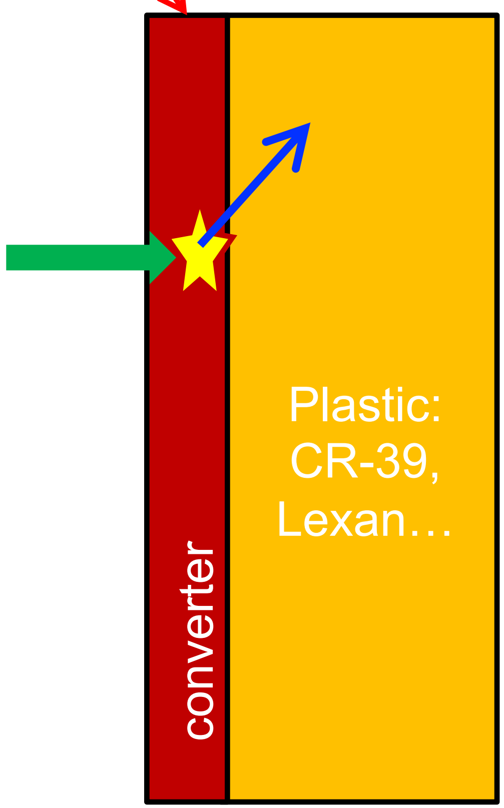
Pile up detection and reconstruction

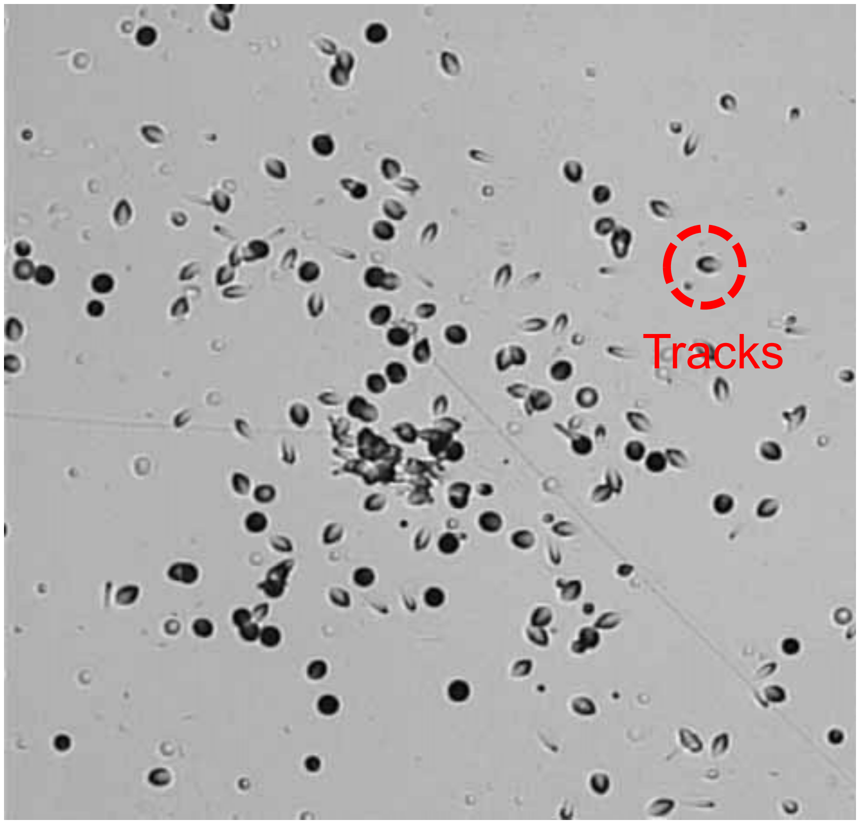


Passive neutron detectors

Converter: thin layer of ^{10}B, ^{6}Li, hydrogen rich plastic (protons), ^{235}U, ^{238}U…

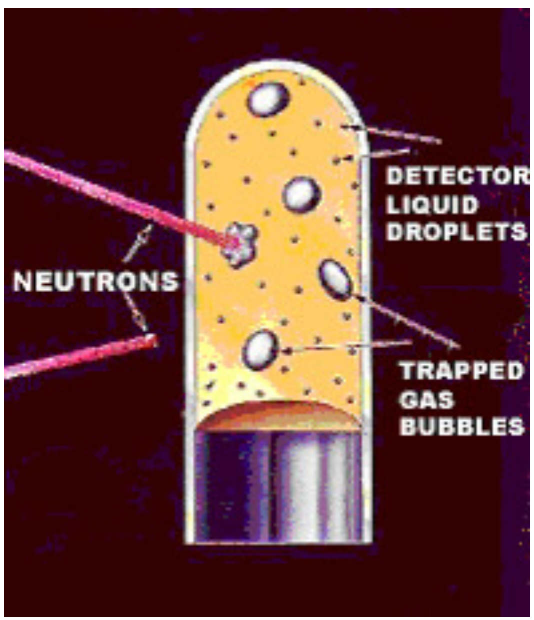
Track edge detectors: charged particles induce microscopic damage in a solid detector. The damages are fixed in a development procedure and then the solid is scanned with a microscope, flatbed scanner...





Bubble detectors consist of an elastic polymer throughout which droplets of a superheated liquid have been dispersed. When these droplets are struck by neutrons, they form small gas bubbles that remain fixed in the polymer to provide a visual record of the dose. Dose is directly proportional to the number of bubbles.

Very simple to use and analyse (= counting bubbles). Commonly used in aircrafts and space missions.



Activation foils use neutron absorption reactions with known cross sections. After the irradiation, decay g-ray spectroscopy allows to infer the number of activation products (i.e. reactions) and subsequently the number of incident neutrons (knowing the mass and the cross sections). Different sets of foils are available for covering different energy ranges.

Fast Neutron Foils Kit

Range: 0.6 MeV - 13.5 MeV
10 Cd cover sets + 2 each of:

Al	Aluminum	0.005″
Cu	Copper	0.005″
Fe	Iron	0.005″
In	Indium	0.005″
Mg	Magnesium	0.005″
Ni	Nickel	0.010″
NaCl	Sodium Chloride	0.075″
S	Sulfur	0.075″
Ti	Titanium	0.010″
V	Vanadium	0.002″
Zn	Zinc	0.010″
Zr	Zirconium	0.005″

Thermal Neutron Foils Kit

Range: 0.025 eV - 5000 eV
10 Cd cover sets + 2 each of:

Au	Gold	0.002″
Co	Cobalt	0.002″
Cu	Copper	0.005″
Fe	Iron	0.005″
In	Indium	0.005″
Lu-Al	5.2% Lu-Al	0.004″
Mn-Cu	87% Mn-Cu	0.002″
Mo	Molybdenum	0.003″
NaCl	Sodium Chloride	0.075″
Sc	Scandium	0.005″
W	Tungsten	0.005″

Broad Spectrum Foils Kit

Range: 0.025 eV - 13.5 MeV
10 Cd cover sets + 4 each of:

Al	Aluminum	0.030″
Au	Gold	0.002″
Cu	Copper	0.005″
Fe	Iron	0.005″
In	Indium	0.005″
Mg	Magnesium	0.005″
Ni	Nickel	0.010″
Sc	Scandium	0.005″
Ti	Titanium	0.010″
V	Vanadium	0.002″
Zr	Zirconium	0.005″

Neutron Spectroscopy

Determination of the intensity and energies of the neutrons. We don't have something similar to the NaI or Ge detectors for neutrons and thus need to use alternative methods:

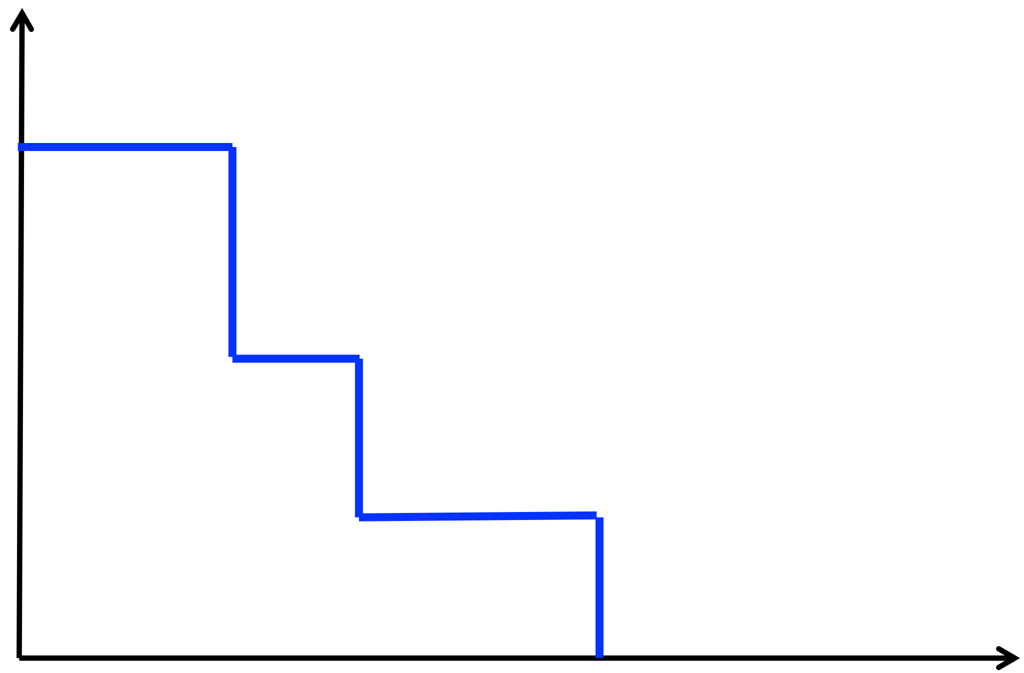
- **Unfolding methods**. Applicable for continuous neutron sources. Typically a low energy resolution is achieved. Can be used with virtually any type of detectors (gaseous, scintillators, track edge, TLDs).

- **Time Of Flight technique** (TOF). Applicable when the neutrons are pulsed. Good energy resolution can be achieved with fast detectors (scintillators or fast semiconductors).

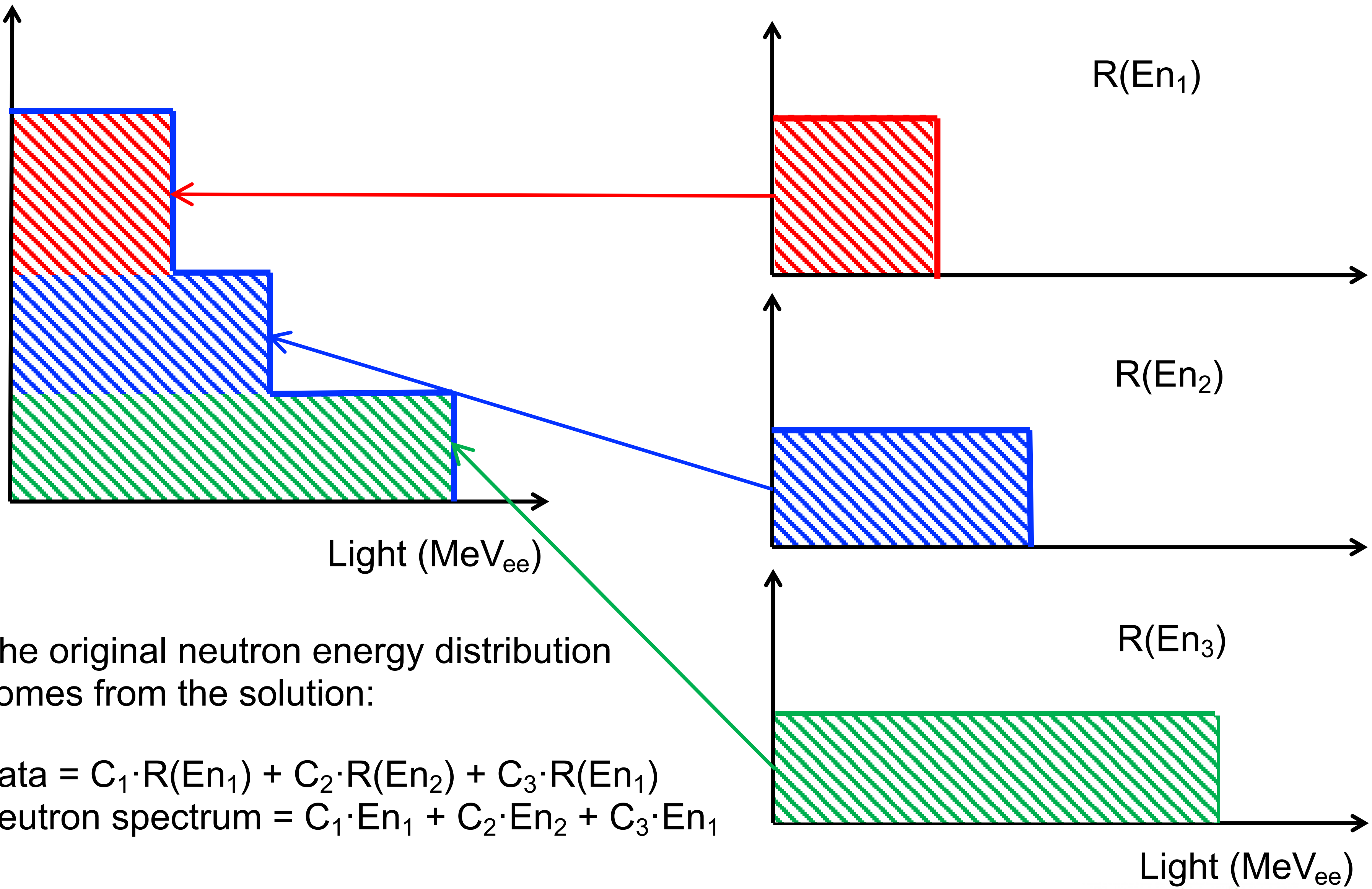
Combination of both…

The idea behind the unfolding: a simple case

Imagine that you measure the following pulse height spectrum with a neutron detector.



Unfolding of scintillator pulse heigh spectra

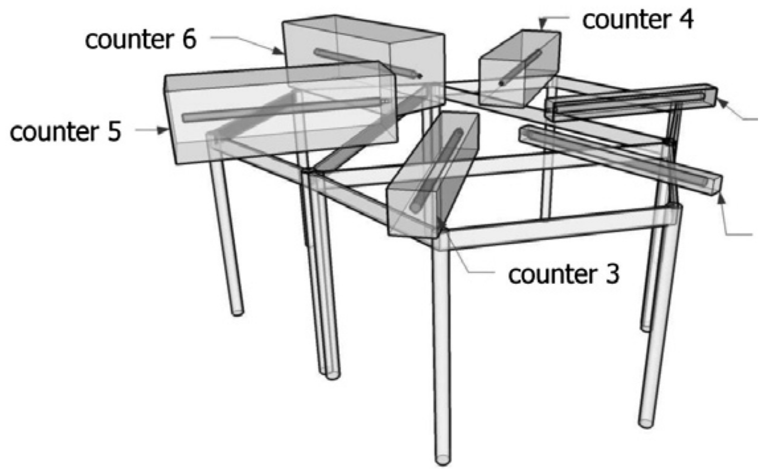


The original neutron energy distribution comes from the solution:

$\text{Data} = C_1 \cdot R(En_1) + C_2 \cdot R(En_2) + C_3 \cdot R(En_1)$

$\text{Neutron spectrum} = C_1 \cdot En_1 + C_2 \cdot En_2 + C_3 \cdot En_1$

Unfolding of ^{3}He data

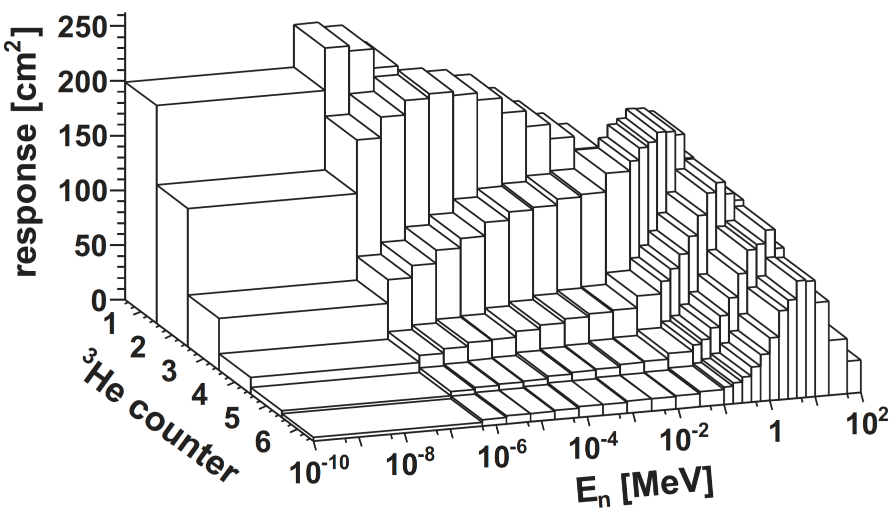


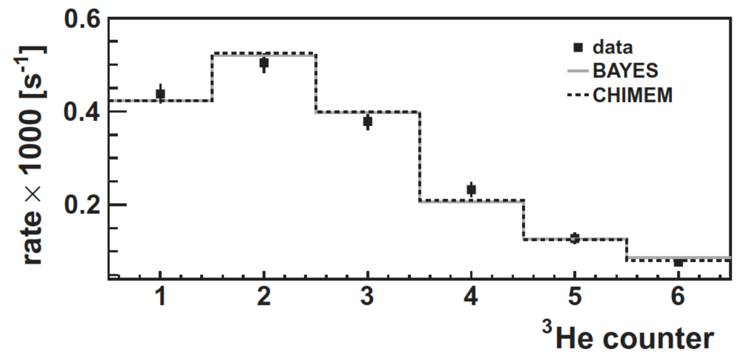
Array of ^{3}He detectors embedded in polyethylene matrices of different thicknesses (i.e. sensitive to different neutron energies).

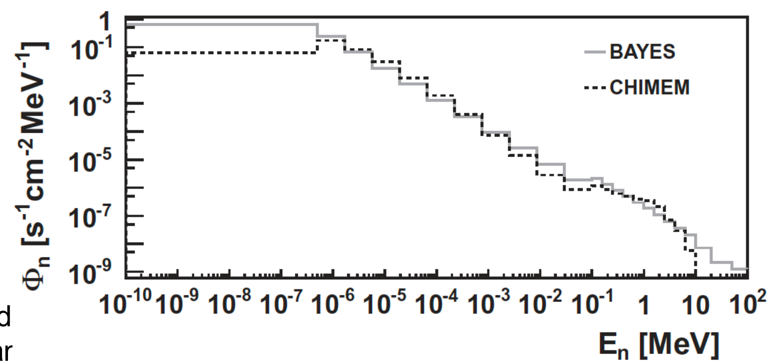
The neutron counts C_i in the different ^{3}He detectors are related to the neutron fluxes in different energy groups via:

$$C_i = \sum_j R_{ij}\phi_j$$

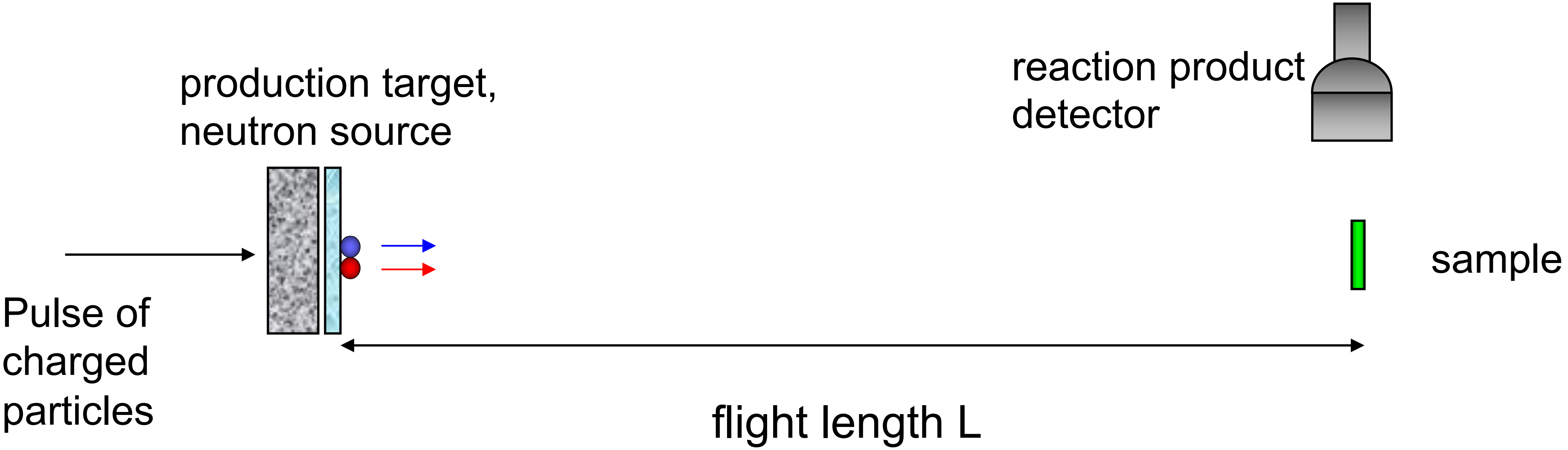
D. Jordan et al. Astroparticle Physics 42 (2013) pp 1-6





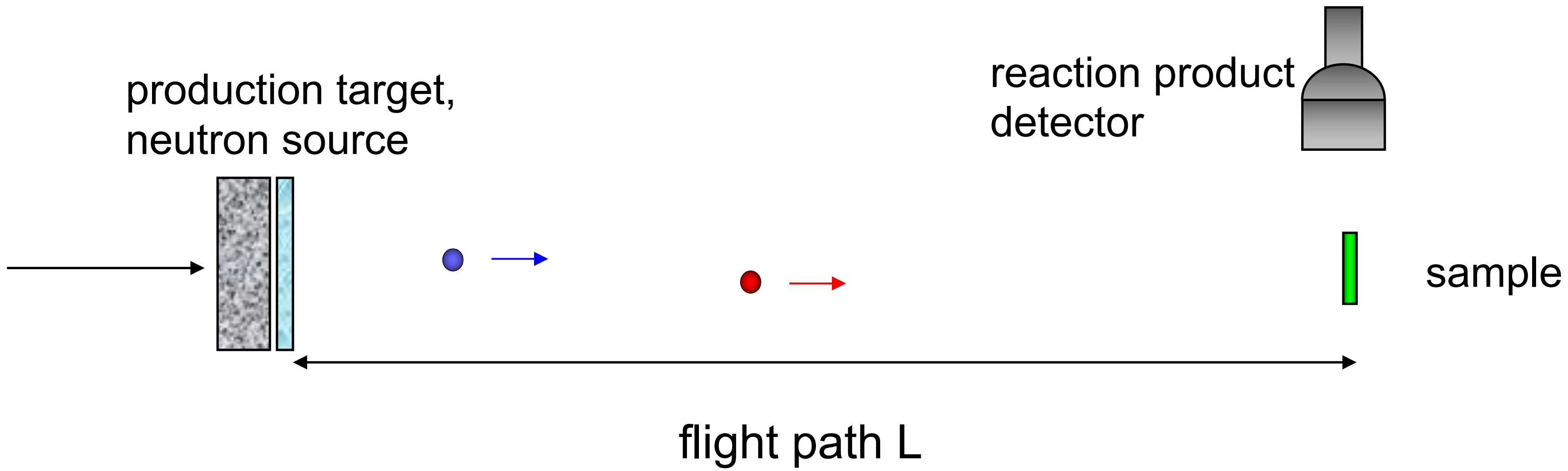


Time – Of – Flight technique

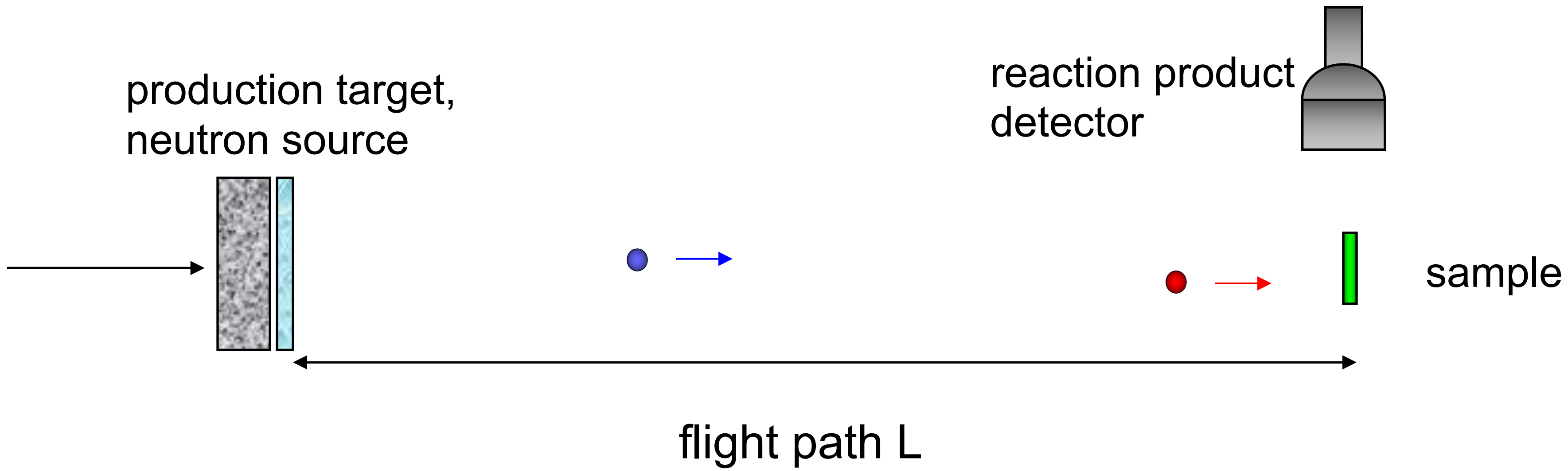


time zero = t_o

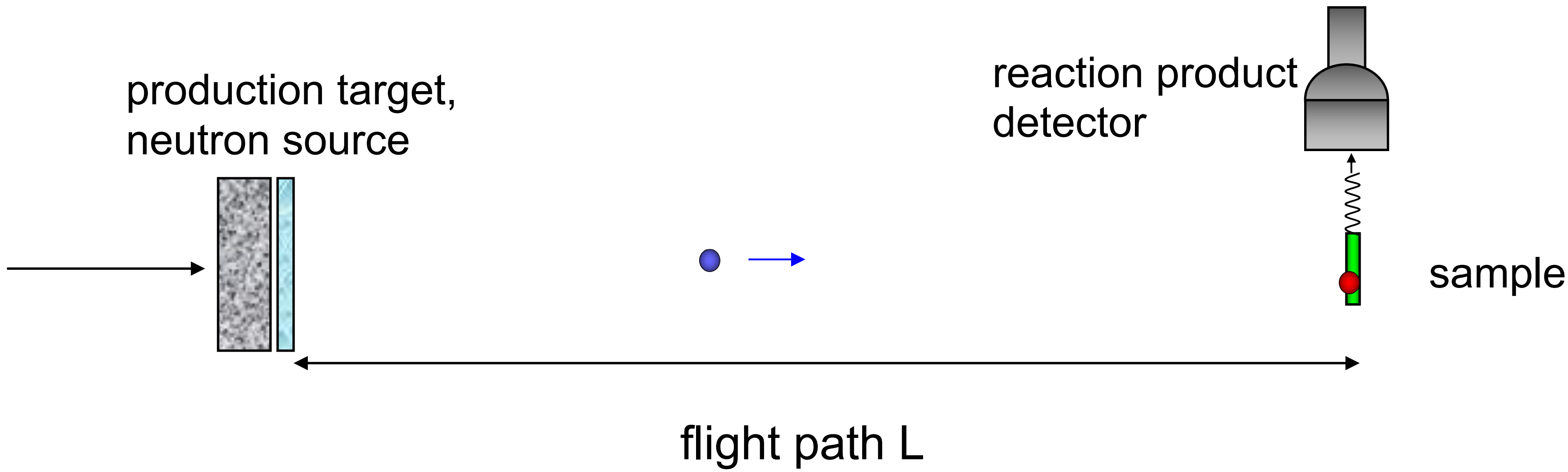
Time – Of – Flight technique



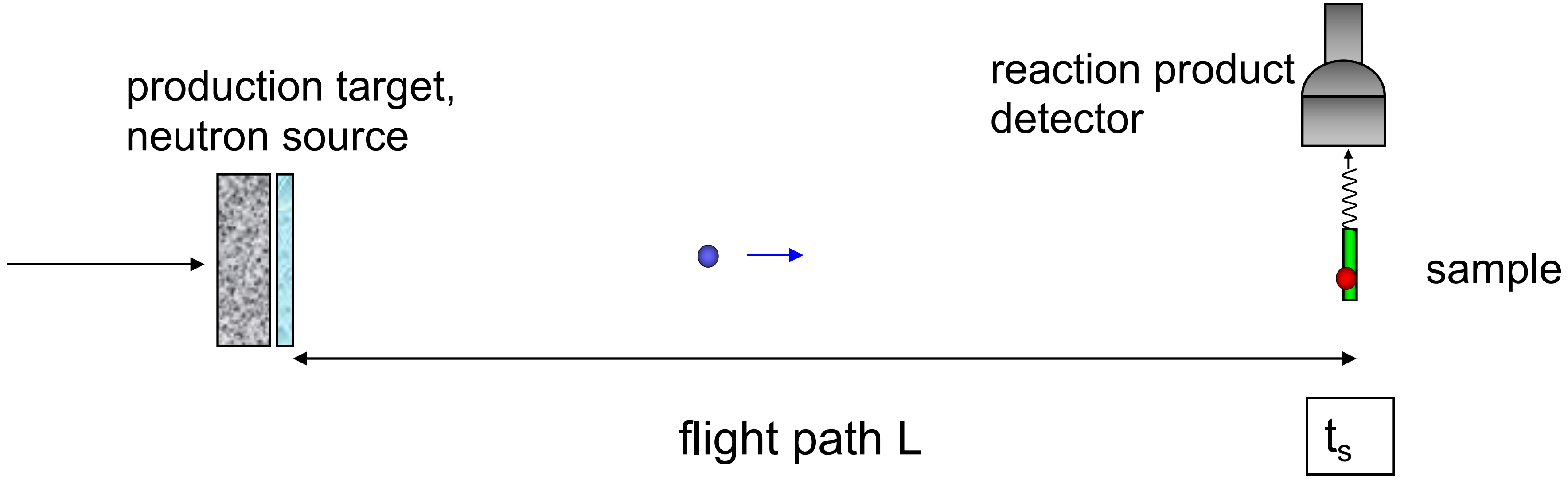
Time – Of – Flight technique



Time – Of – Flight technique

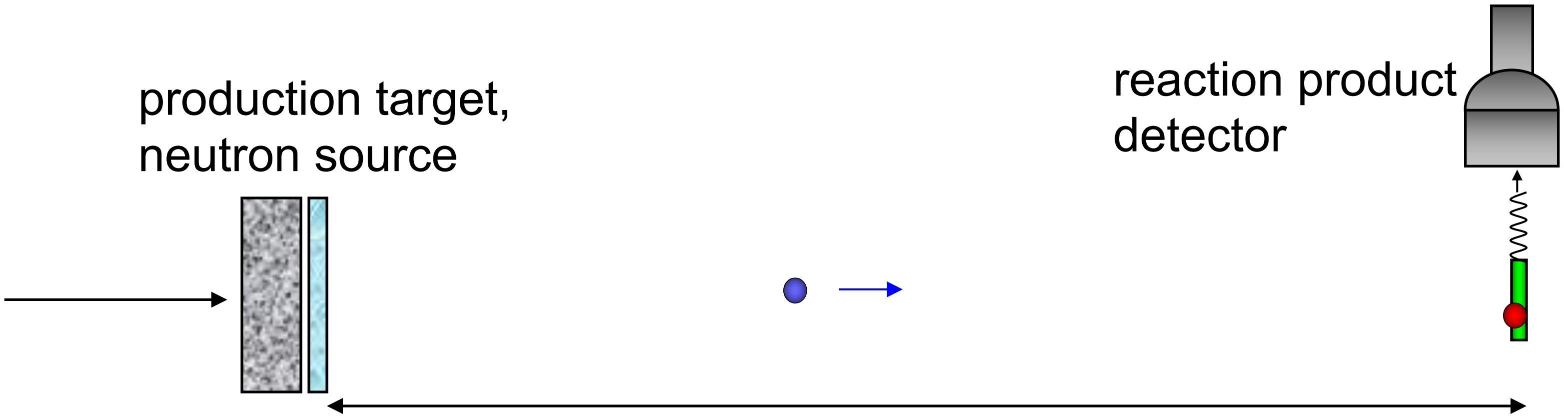


Time – Of – Flight technique



$t_n = t_s - t_o$

Time – Of – Flight technique



$$t_n = t_s - t_o$$

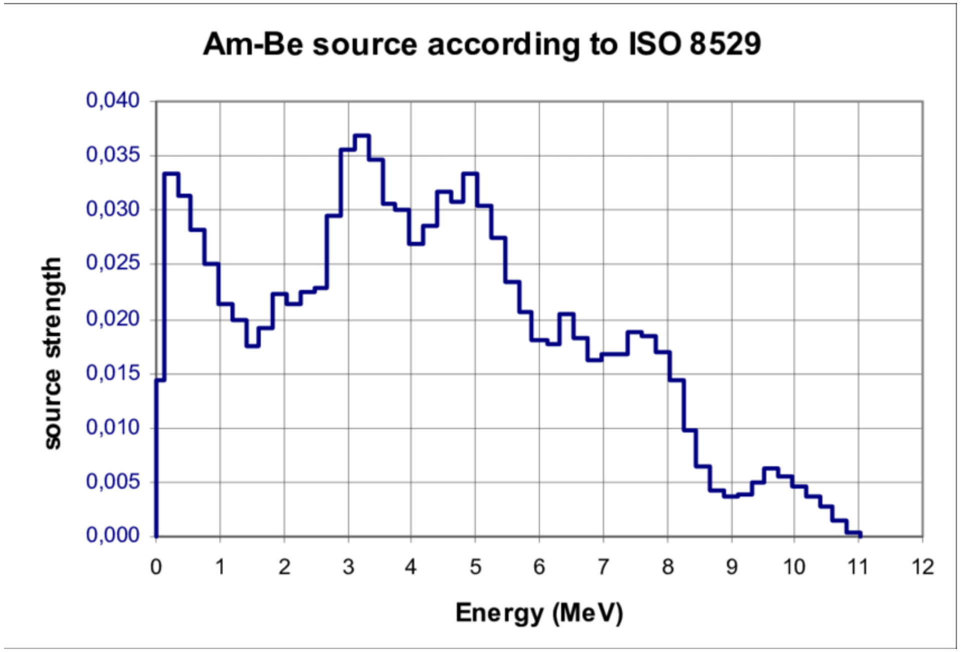
Kinetic energy of the neutron by time-of-flight

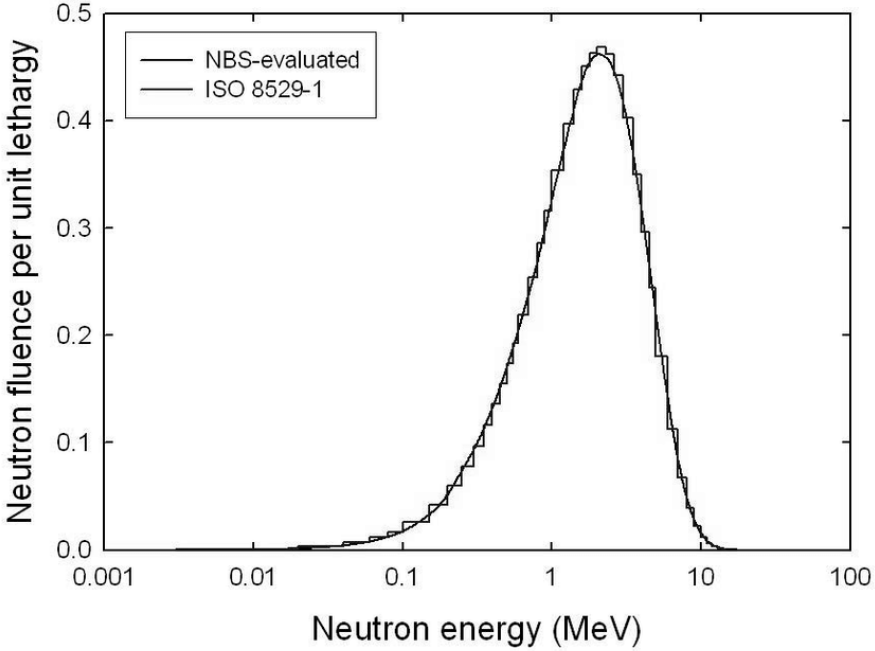
$$E_n = m_n c^2 \left(\frac{1}{\sqrt{1-(v_n/c)^2}} - 1 \right) \qquad v_n = \frac{L}{t_n}$$

Calibration of neutron detectors

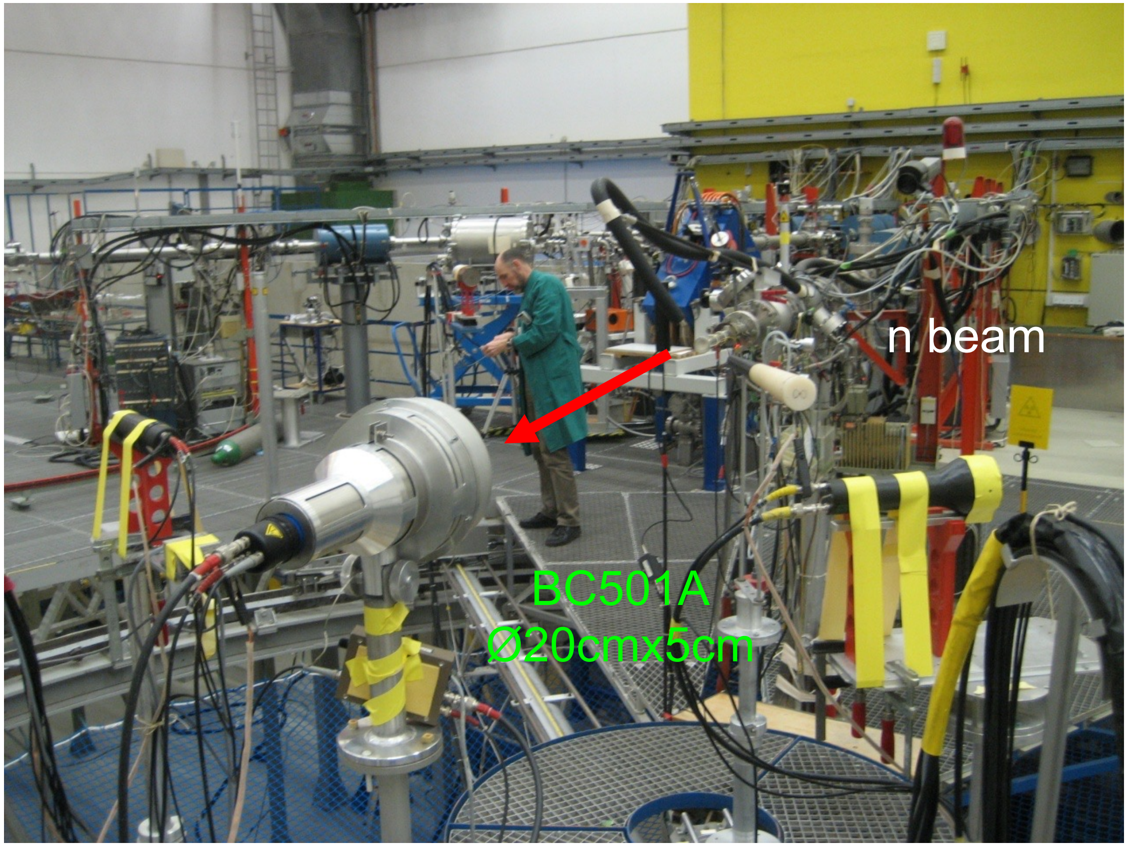
The calibration process is very important for determining the intrinsic properties of each detector. The process needs to have a variety of neutron sources.

- Radioactive source: (α,n) Am/Be, Pu/Cand spontaneous fission ^{252}Cf.





Facilities with accelerator drive neutron sources



Deuterium-Deuterium and Deuterium-Tritium reactions for E_n>5 MeV

^{7}Li(p,n) reaction, E_n= 0.144, 0.250, 0.565, 1.2, 2.5 MeV

Pulsed beams for TOF background discrimination

TOF measurements at various paths.

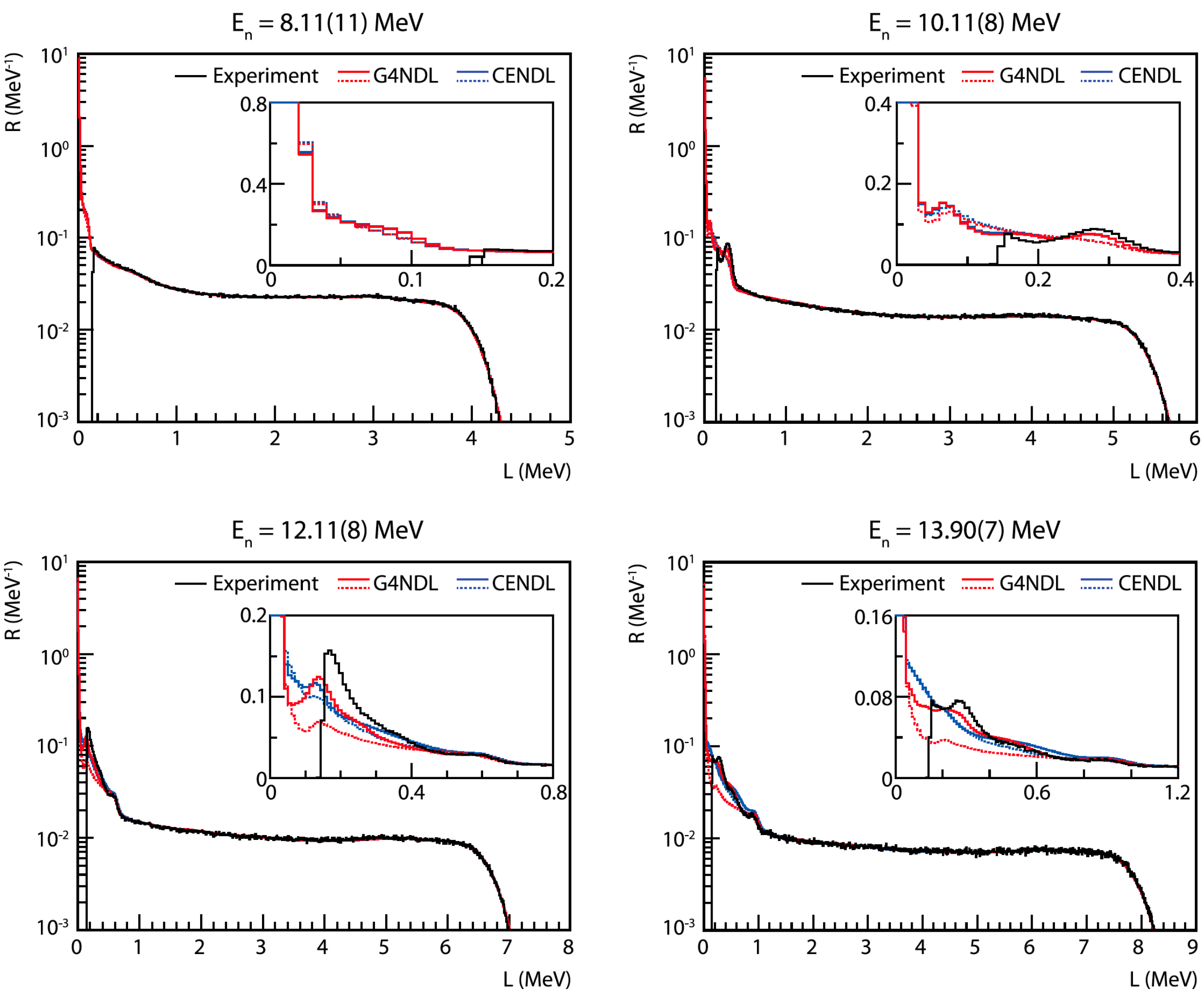
Energy calibration with sources (^{137}Cs, ^{22}Na, ^{207}Bi)

Characterisation at laboratories like **PTB-Braunschweig** (Cyclotron and VdG), **Bruyeres Le Chatelle** (various VdG) or other facilities like **HISPANOS@CNA**.

Monte Carlo simulations

Neutron physics models built in Monte Carlo codes have reached the level of maturity necessary for performing accurate efficiency calibrations (~5%). Very important for complementing the necessary experimental calibrations.

A. R. Garcia *et al.*, Nucl. Instrum. and Methods A, **868**, (2017) 73-81



MCNP: a reference in neutronic calculations. Accurate calculation of detection efficiencies of proportional counters and other types of neutron detectors. Not very usable for complex detector simulations.

GEANT4/G4ParticleHP model: good neutron physics and suitable for complex detectors. Excellent for organic scintillators.

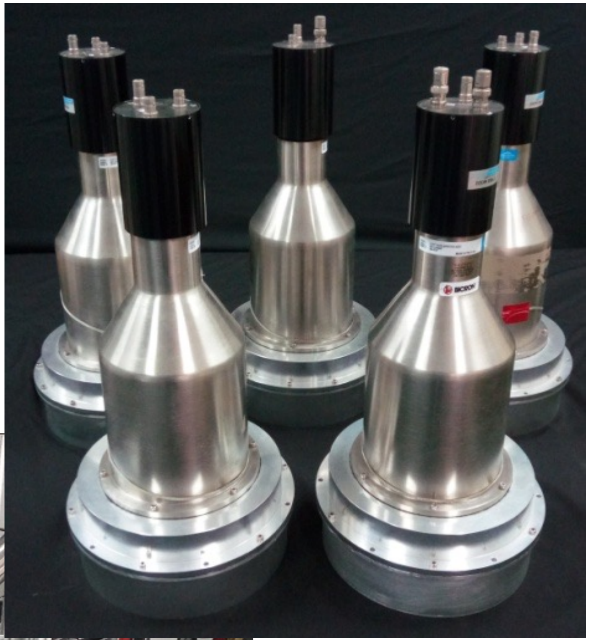
SCINFUL for high energy neutrons.

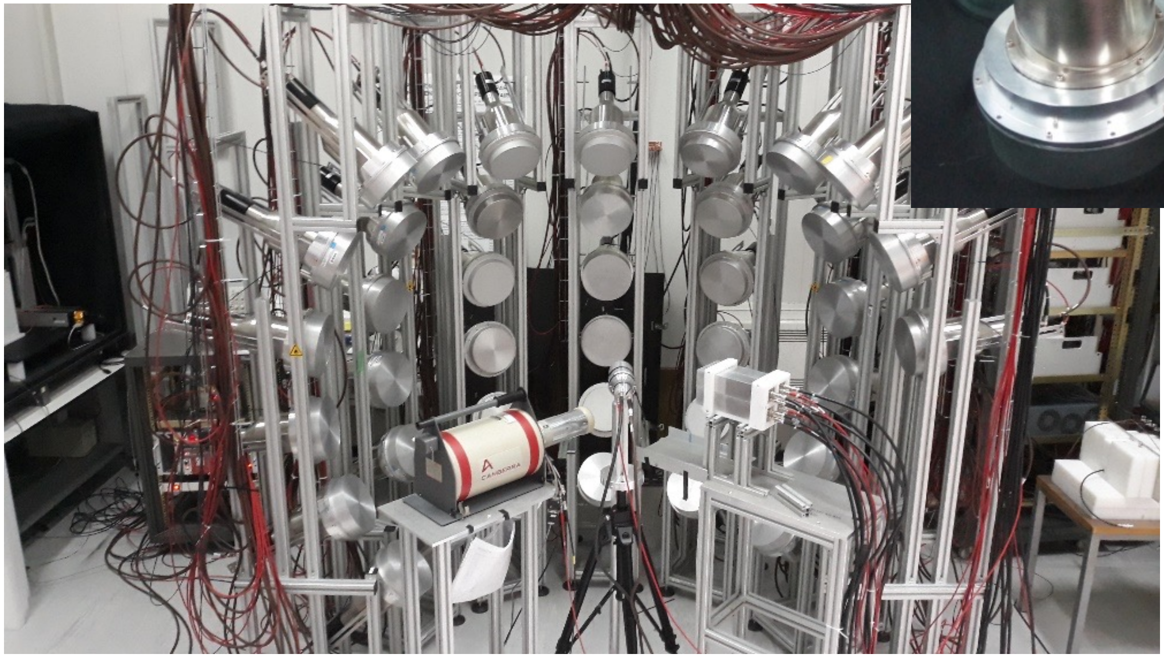
MONSTER

MOdular **N**eutron time of flight **S**pectrome**TER**

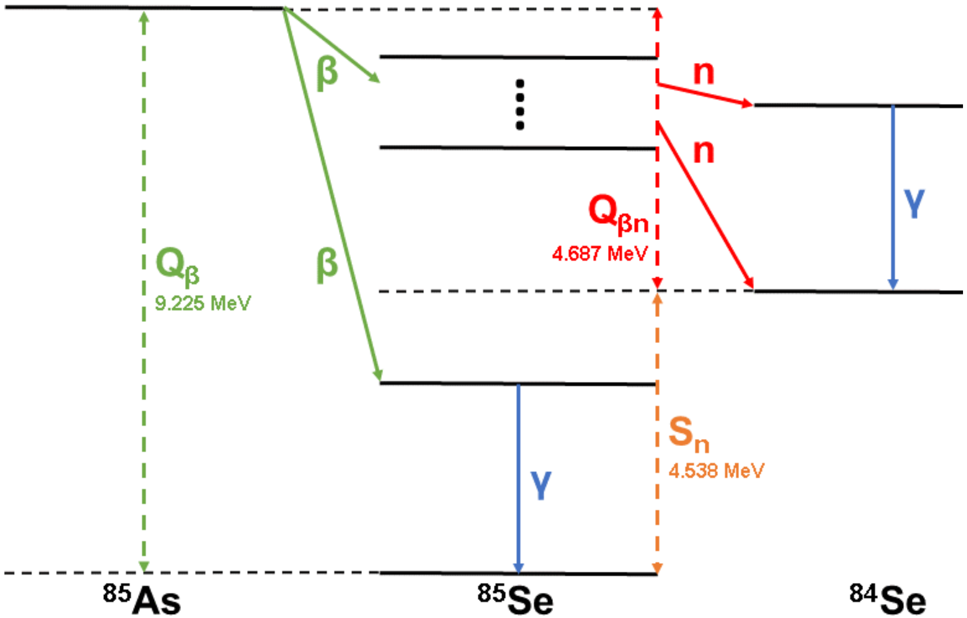
International collaboration between CIEMAT, JYFL, VECC, IFIC, and UPC

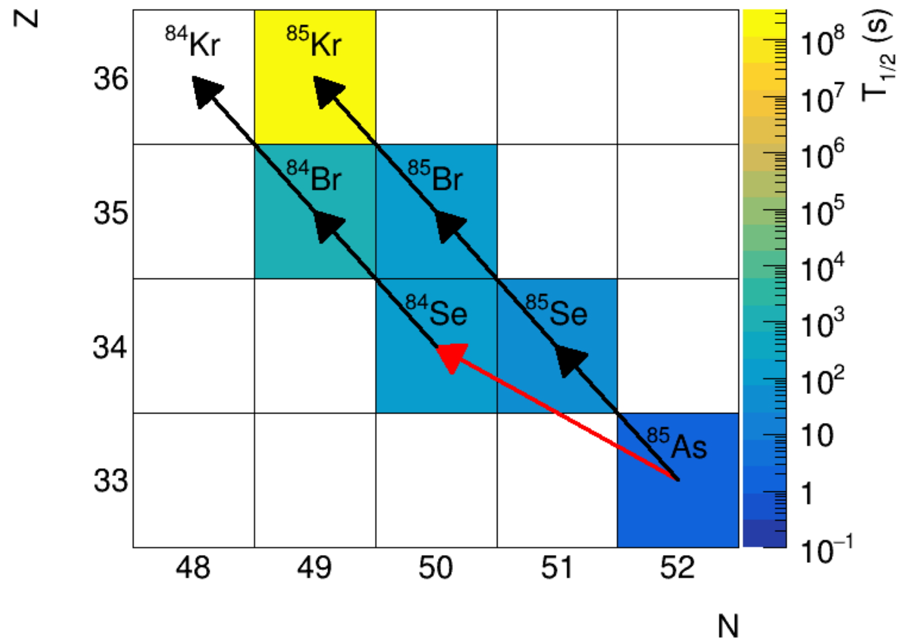
Consists of 65 cells of liquid scintillator (up to 100)





^{85}As β-decay



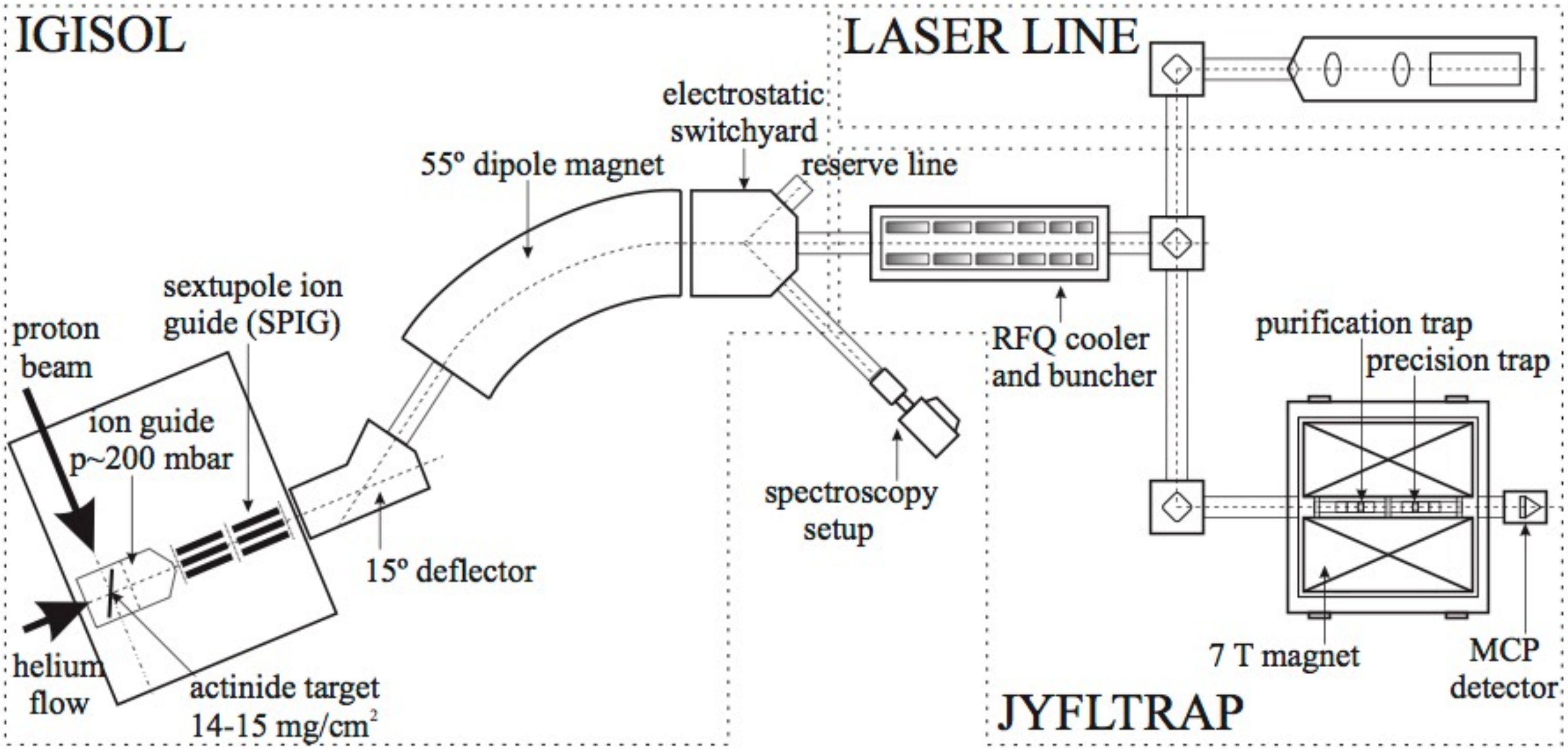


$$P_n = 59.4\ \%$$

PhD thesis of Alberto Pérez de Rada

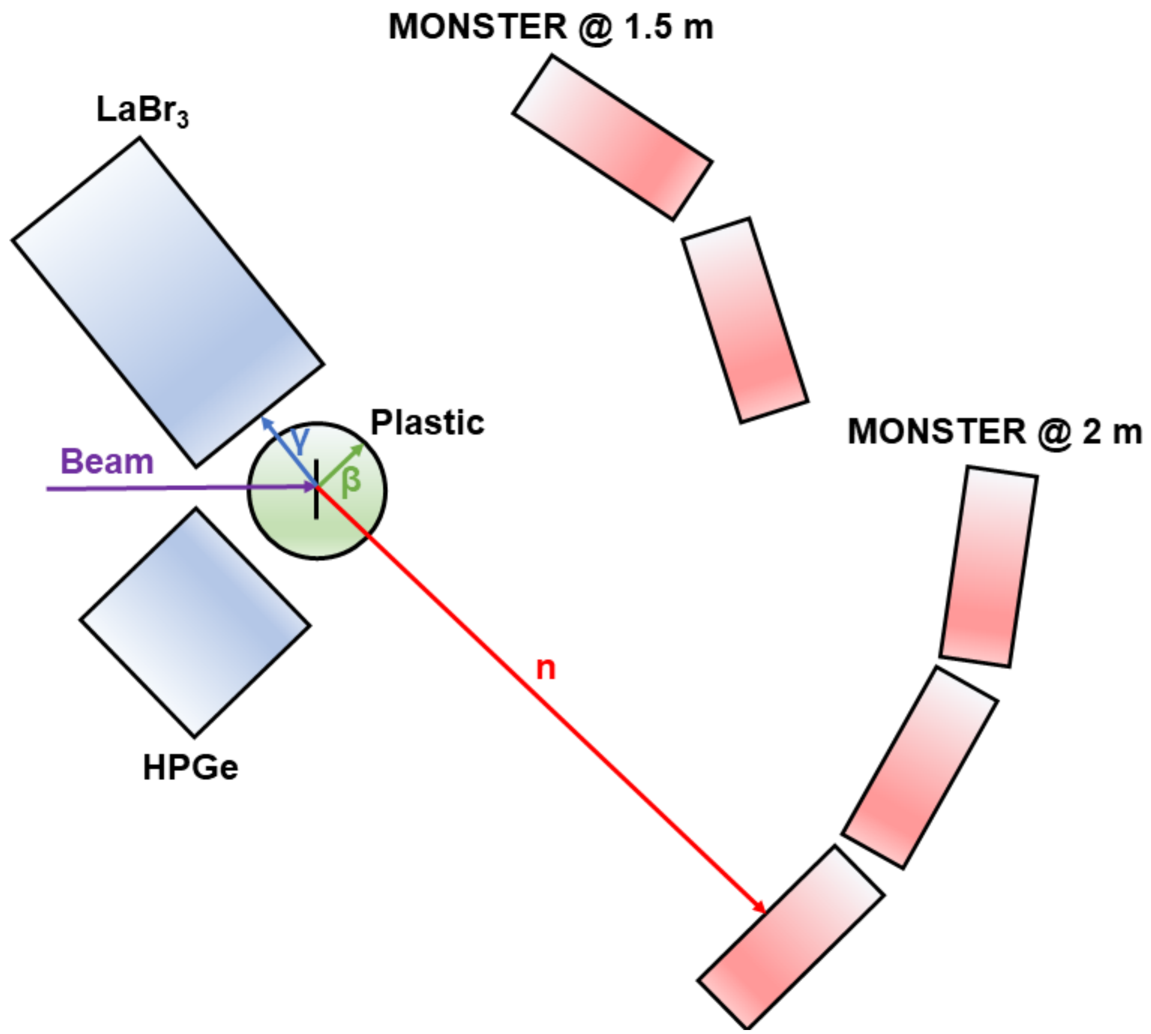
The accelerator laboratory of the University of Jyväskylä (JYFL)

Located in Jyväskyla, Finland
IGISOL → Ion Guide Isotope Separation OnLine

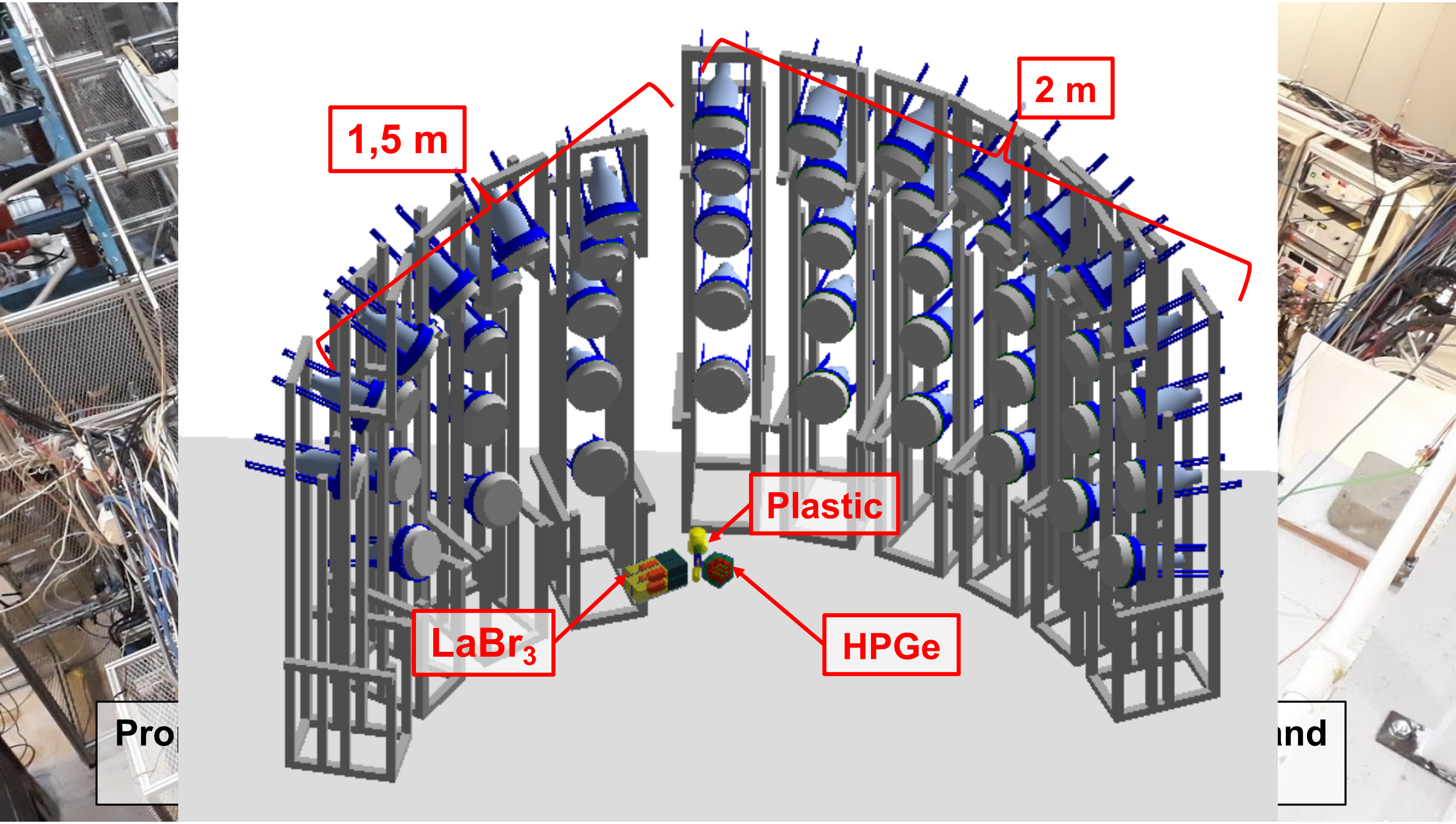


I.D. Moore *et al.*, Nucl. Instrum. and Methods B, **317**, (2013) 208

MONSTER setup @ JYFL

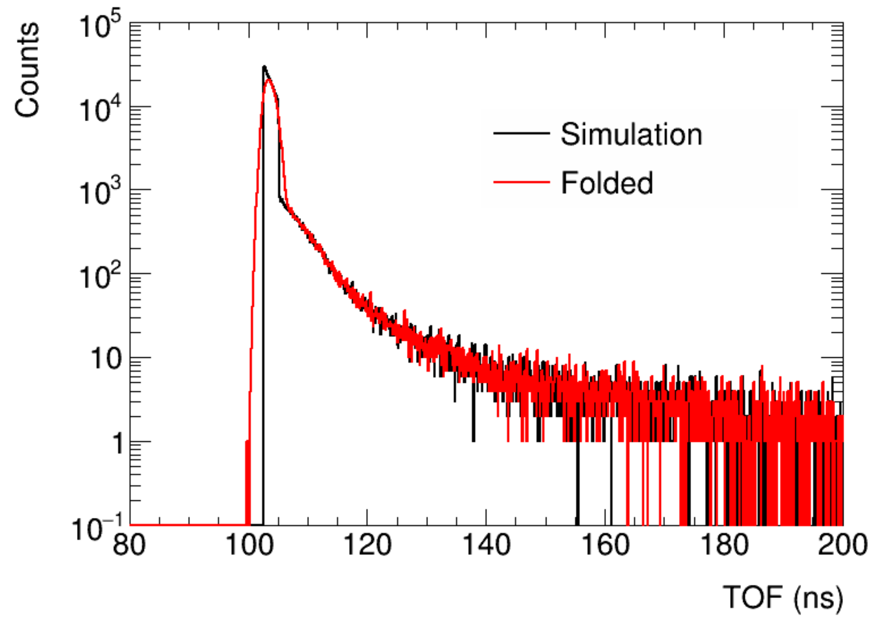


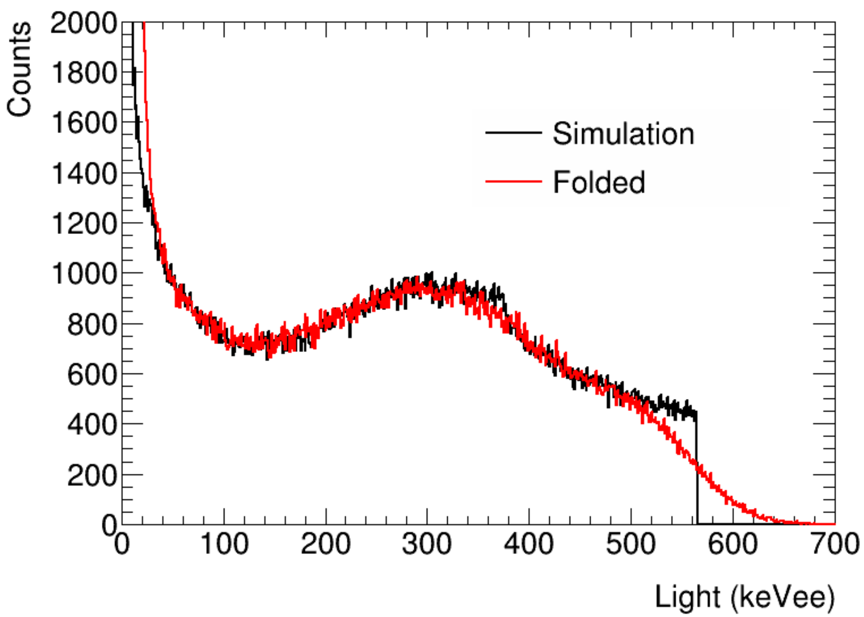
MONSTER setup @ JYFL

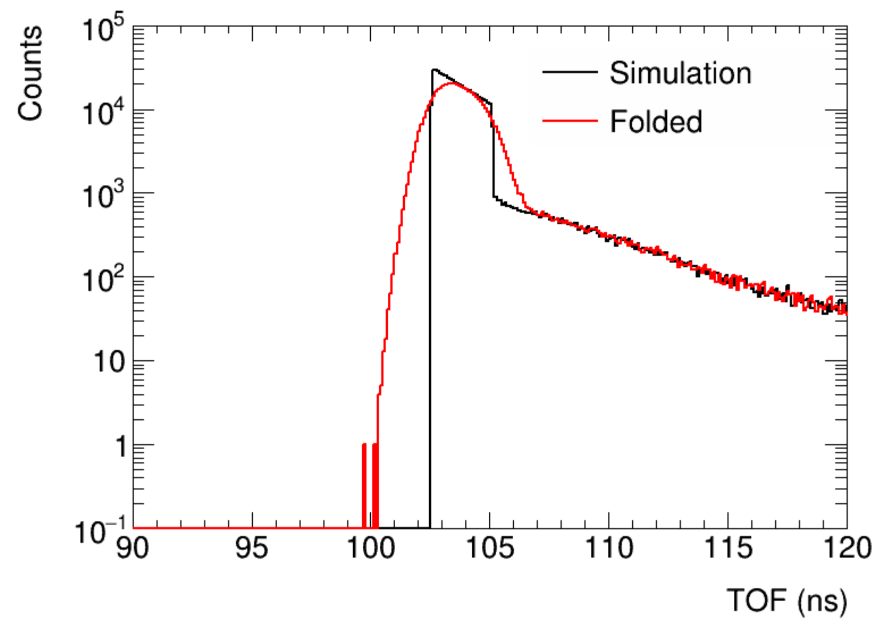


Time and energy response

The conversion of the ionisation into light (light yield) is incorporated in the simulation.
The the spread in the TOF distributions due to the variations in the interaction point (i.e. flight path) is also obtained.
The Light and TOF distributions are folded with energy and time resolutions (light collection, photoconversion, electronics…)

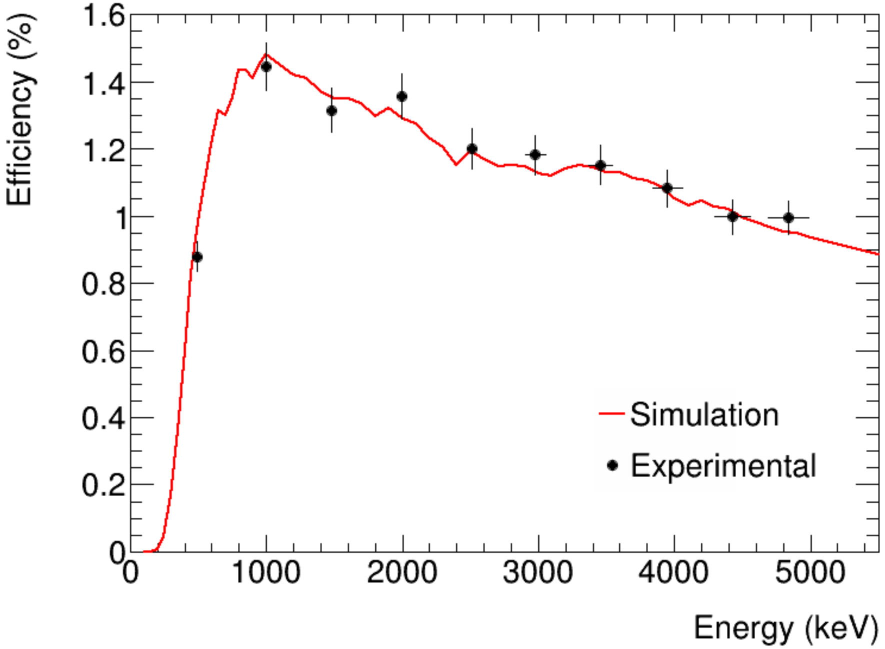




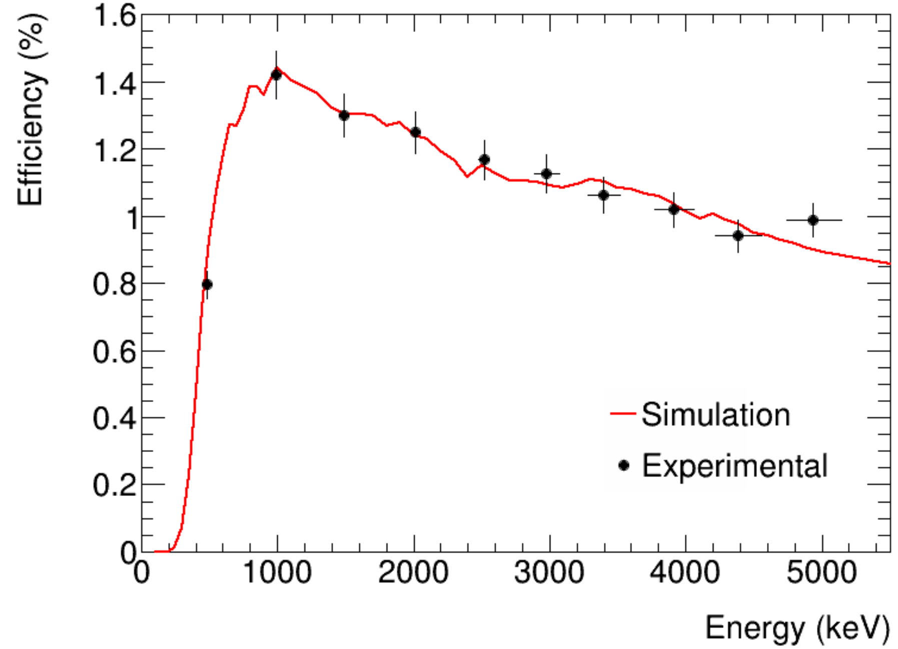


Neutron detection efficiency

2 m flight path



1,5 m flight path

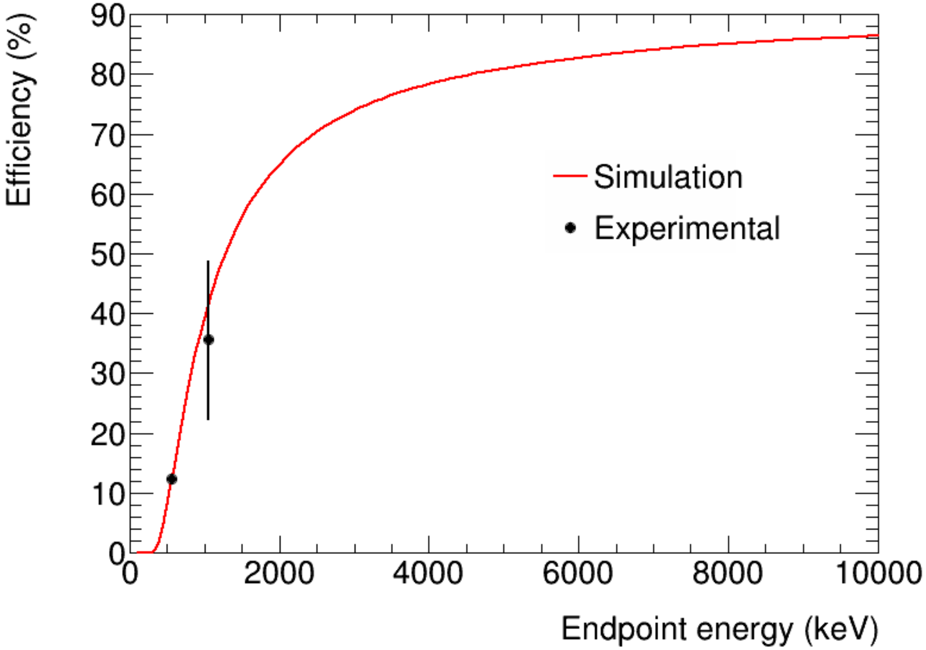


Accurate Monte Carlo simulations calibrated at PTB and in-situ calibration with a ^{252}Cf neutron source.

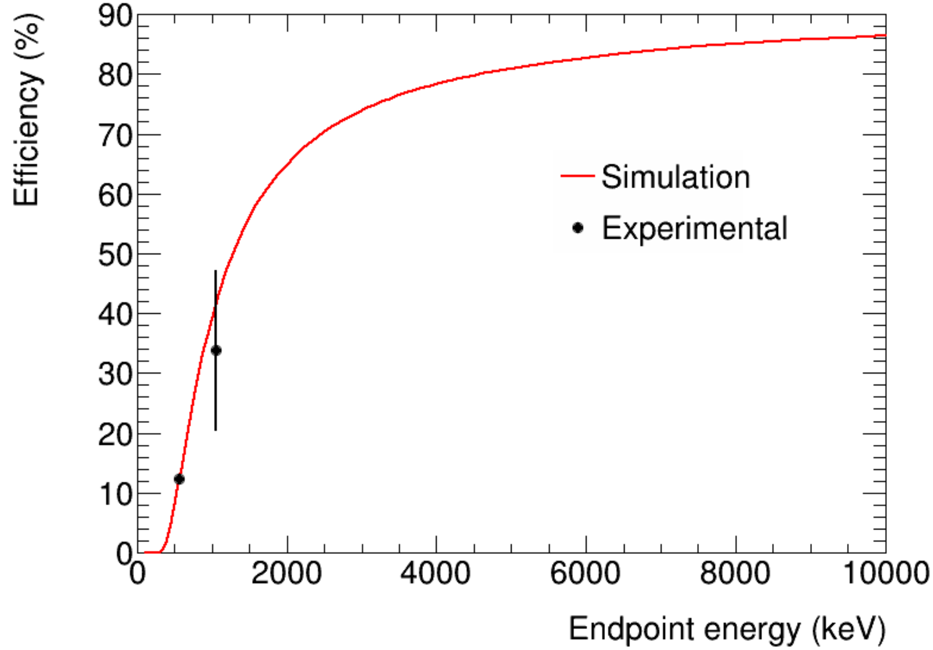
β-detection efficiency

The β-detection efficiency depends on the β-detector threshold and varies up to the Q_{β}.

HPGe



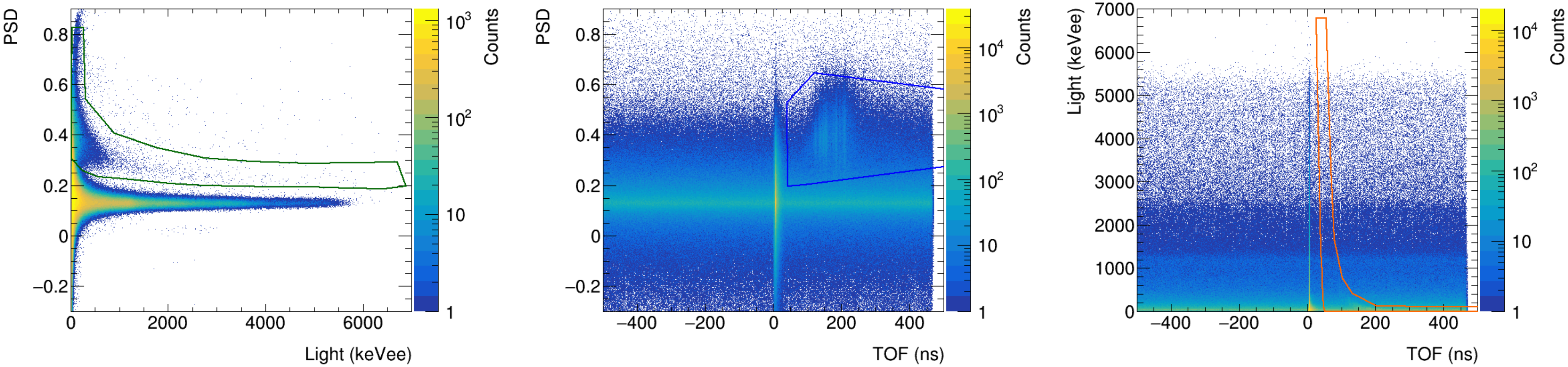
$LaBr_3$

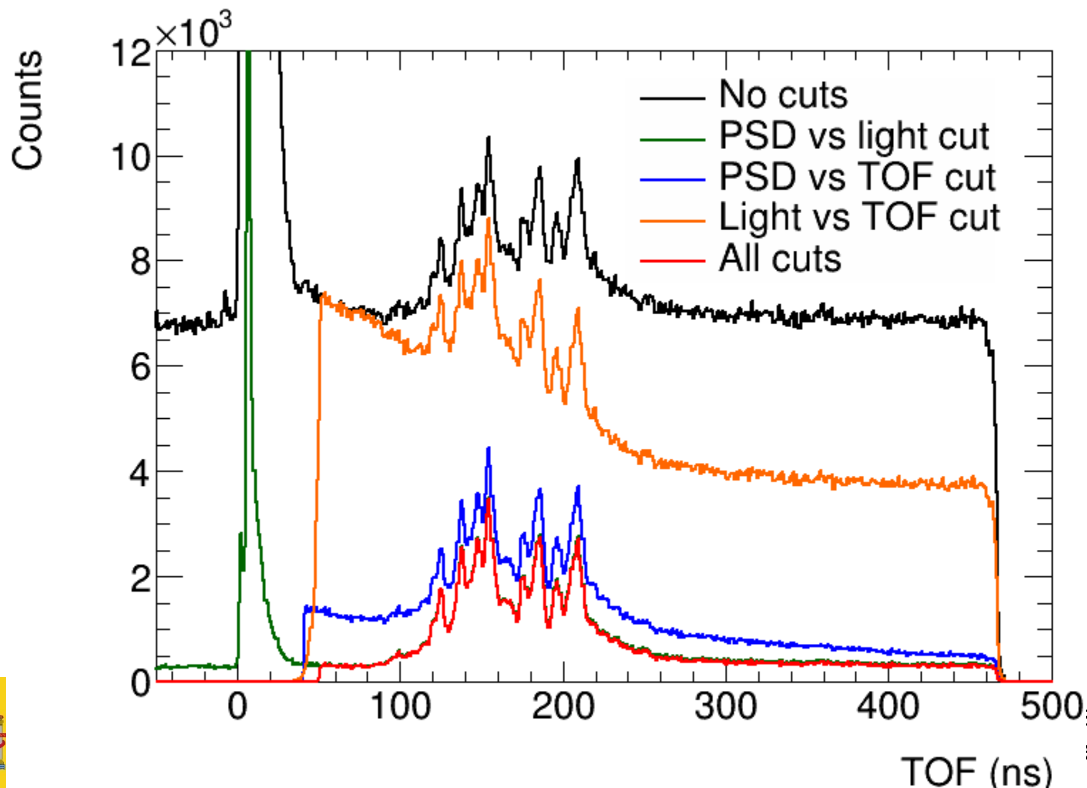


The efficiency for all the decays was obtained by detailed Monte Carlo simulations of the decays and validated with data from ^{92}Sr into ^{92}Y.

Analysis of the ^{85}As neutron TOF data

Different cuts applied to obtain a “clean” neutron TOF spectrum.





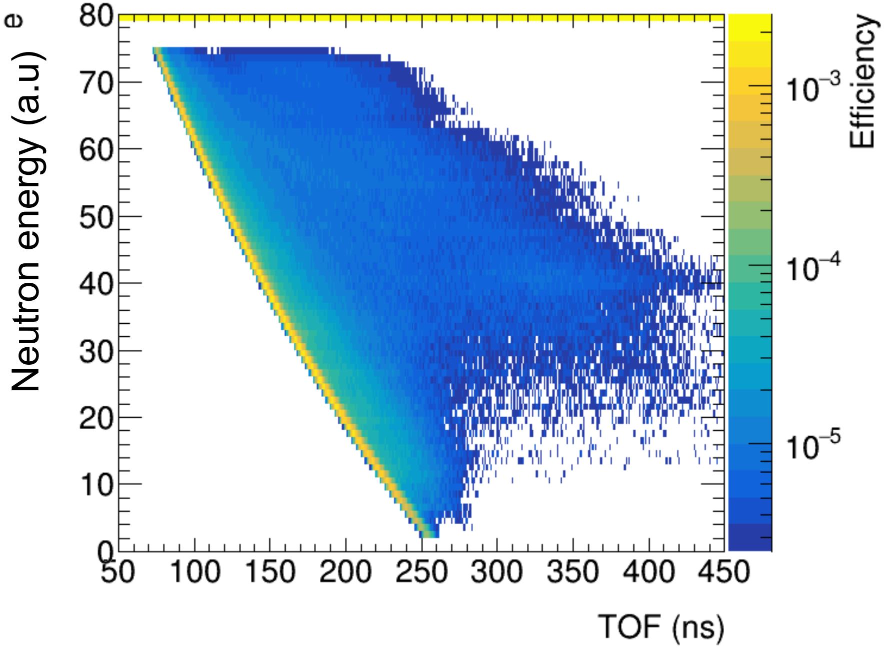
More than one order of magnitude of γ-rays background suppression

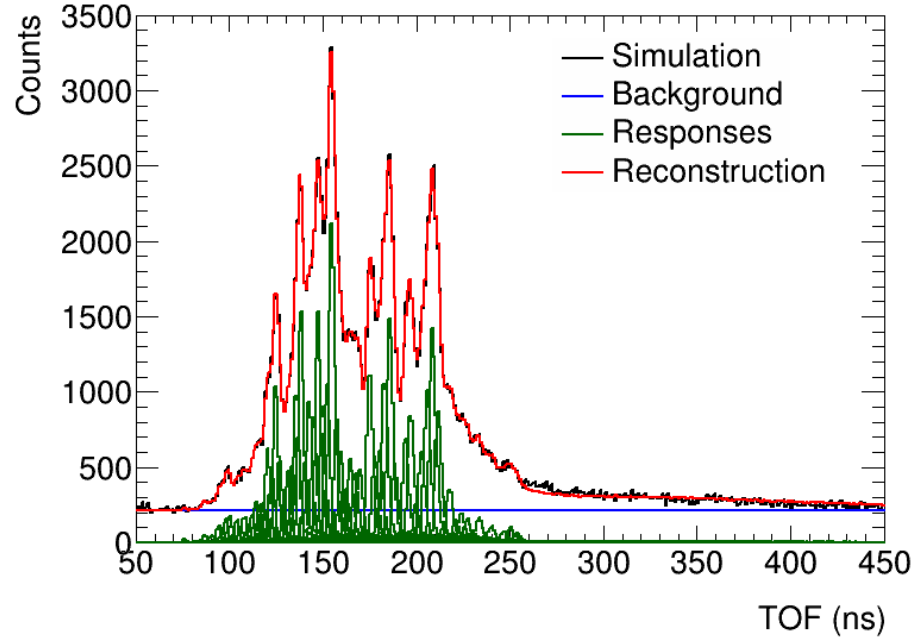
^{85}As neutron TOF data unfolding

Unfolding applying an iterative Bayesian method: neutron energy spectra and P_n value (with number of decays from the β-activity fit.)

Response matrix including the light yield, threshold, and time resolution.

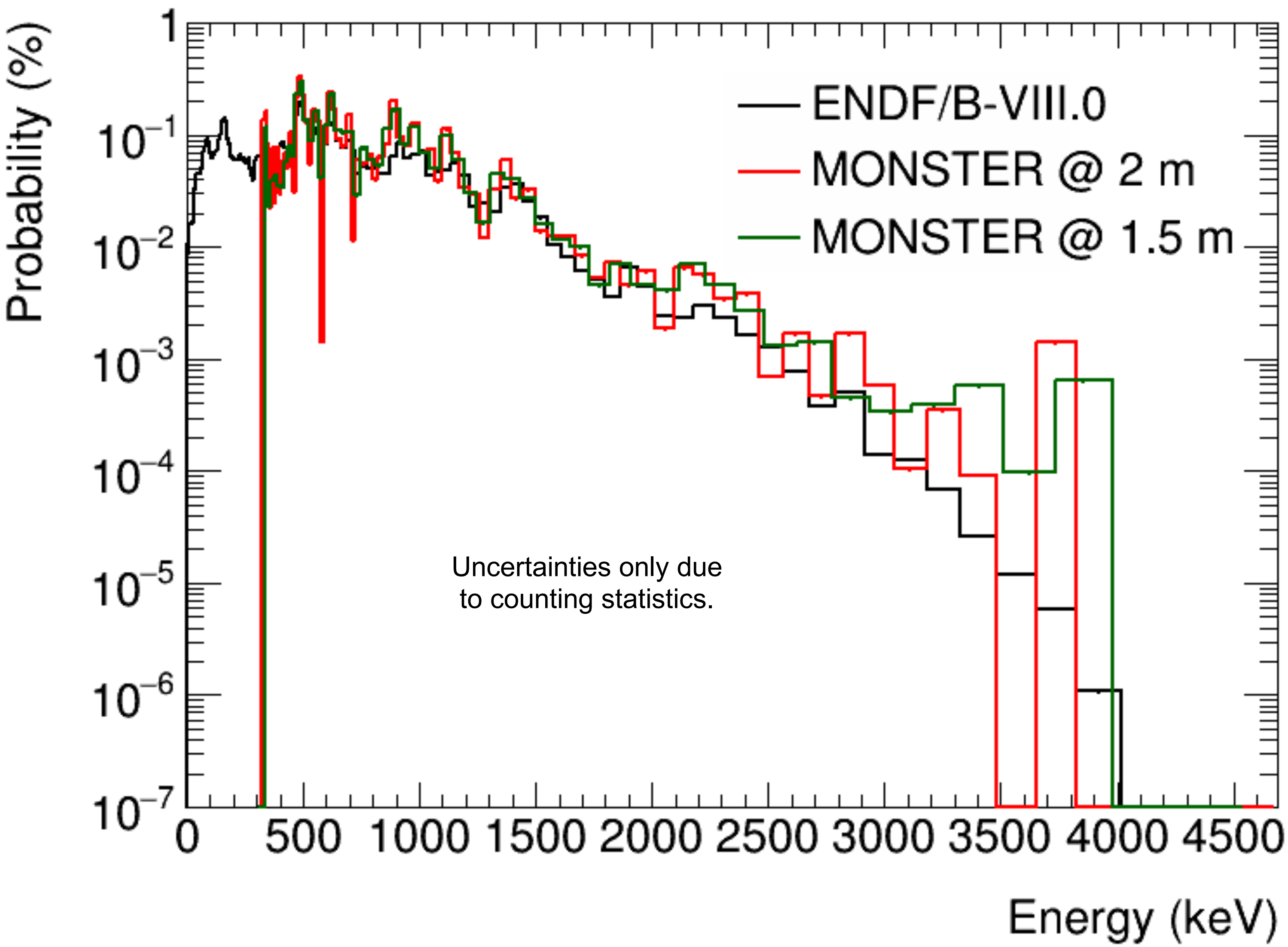
$$\frac{\Delta E}{E} = \gamma(\gamma + 1)\sqrt{\left(\frac{\Delta t}{t}\right)^2 + \left(\frac{\Delta L}{L}\right)^2}$$





$$tof_i = \sum_j R_{ij} \cdot P(E_j) \quad \Longrightarrow \quad P(E_j) = \sum_i R_{ji}^{-1} \cdot tof_i$$

Final results of ^{85}As



The end!

$^{1}H(n,el)$, $^{2}H(n,el)$ and $^{3}He(n,p)$ cross sections