Practical session on neutron detection

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Grupo de ESPECTROSCOPÍA GAMMA Y DE NEUTRONES

Detection of ionizing radiation

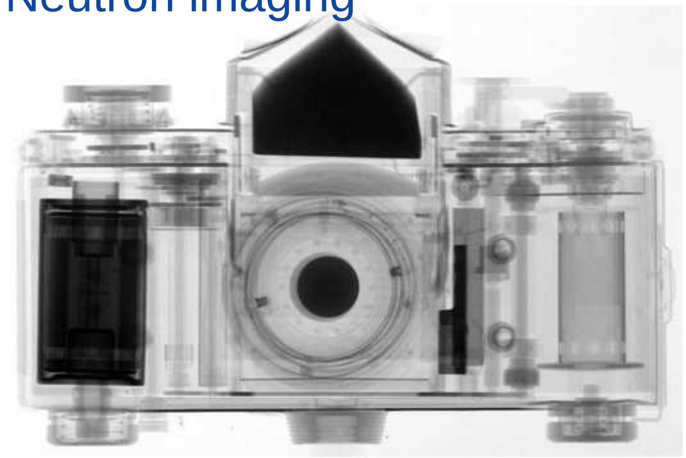
- **Interaction of radiation detector (sensible material)**
  → Radiation transfer energy to the media.

- **Charged particles (p, 4He, etc): direct detection**
  - Coulombian interaction with electrons in the media.
  - Ionization or excitation, nuclear reactions.

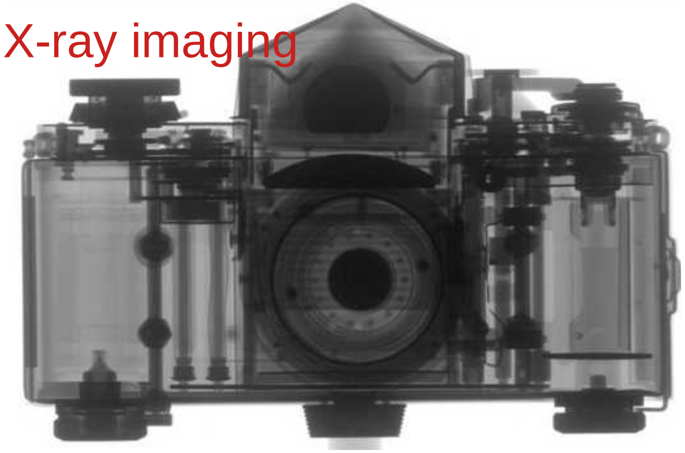
- **Non-charged or neutral particles (photons, neutrons): indirect detection**
  - Photons: they interact “easily” with matter (photoelectric effect, Compton scattering, Pair production). Interaction probability depends on charge number (Z) and photon energy (E).

  - Neutrons: interaction depends on the nuclear force, thus the interaction probability is strongly dependent on the charge number (Z), mass number and neutron energy (En). Therefore, detection of neutrons require the use of special materials.

Neutron imaging



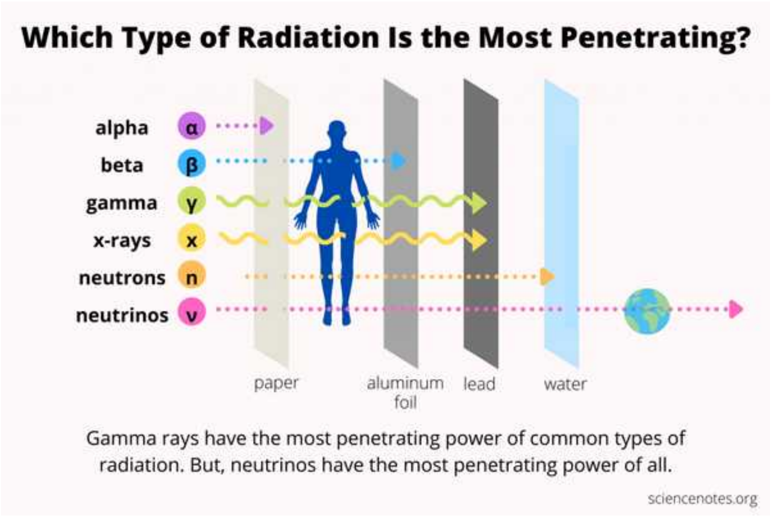
X-ray imaging



Radiograph of an analog camera: by neutrons (top) by X-rays (bottom). While X-rays are attenuated more effectively by heavier materials like metals, neutrons make it possible to image some light materials such as hydrogenous substances with high contrast: in the X-ray image, the metal parts of the photo apparatus are seen clearly, while the neutron radiograph shows details of the plastic parts. Source: www.psi.ch

The challenge with neutrons

- **Neutrons don't interact by Coulombian forces**
  - They don't produce electric charge directly
  - Neutron detection rely on secondary processes!
- **Neutron are a highly penetrating type of radiation**
  - They can travel several centimeters without any interaction!



What can be done to detect neutrons?

- **Nuclear reactions:** reaction products are charged particles. These particles are detected.

$$A+n \rightarrow B+C$$

- **Activation:** a target nucleus is activated by neutron capture. The decay products, typically gammas or beta-particles, are detected.

$$A+n \rightarrow B^* \rightarrow C+\gamma$$

- **Scattering**: neutrons transfer energy to light particles (protons) by elastic collisions. The ionization produced by the recoiling particle is detected.

Neutron detection and shielding

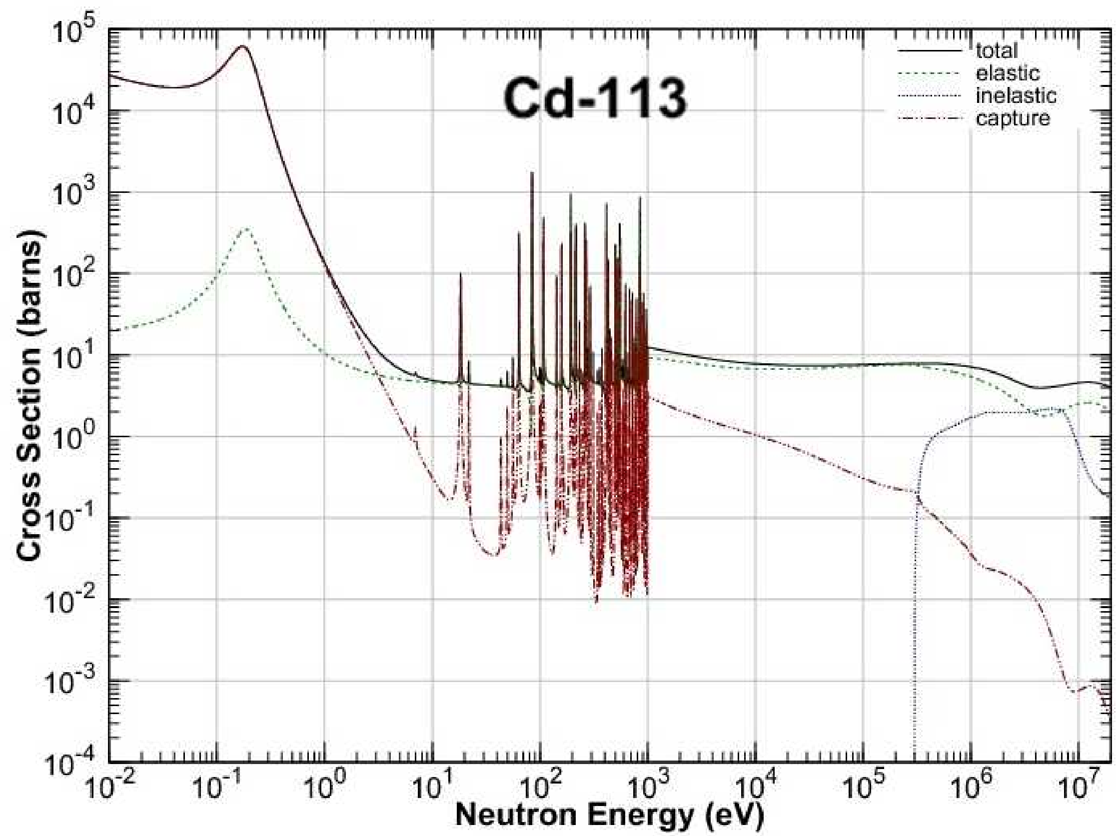
In the nuclei chart →

The probability of interaction (cross section) depends on the neutron energy:

- Thermal neutrons: E=0.025 eV
- Epithermal neutrons: E < 0.5 eV
- Fast neutrons: E> 0.5 eV

At E~0.5 eV → Cadmium cutoff energy, ~ 1000x increase of capture cross section around this energy.

Other materials like Boron or Lithium can be also used for neutron shielding



Some characteristics of neutron detectors

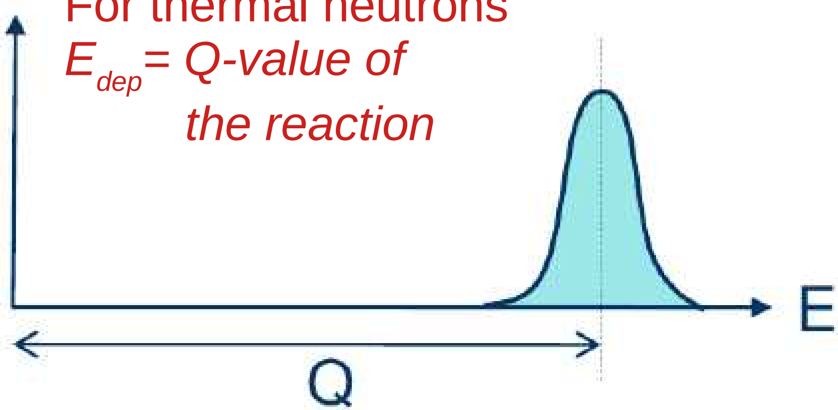
- **The intrinsic detection efficiency depends on:**
  - Reaction cross section
  - Isotopic abundance of the target
  - Size of the active volume

- **Flux distortion**
  - The use of neutron absorbers o moderating materials may modify the radiation field around the detector.

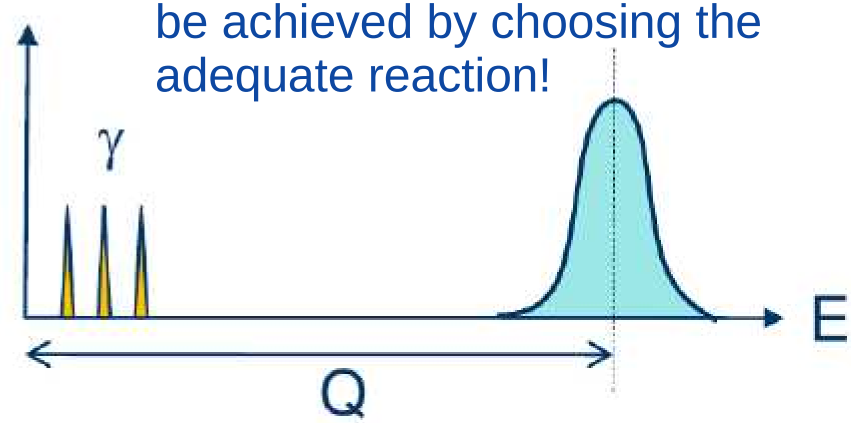
- **Influence of the reaction heat Q**
  - Let's assume a nuclear reaction ($X+n \rightarrow Y+b$), target X at rest, full energy of the reaction products is transfer to the detector ($E_{dep} = E_Y + E_b$).

$$Q = E_b + E_Y - (E_n + 0) \Rightarrow Q = E_{dep} - E_n$$

For thermal neutrons
E_{dep}= *Q-value of the reaction*



Discrimination gamma/n can be achieved by choosing the adequate reaction!



Fluence

Point scalar quantities: mathematical definition

$$\frac{d\Phi(\vec{r},t)}{dt}=\int v(E)\cdot n(\vec{r},E,t)\,dE$$

Fluence rate or Flux density

Particles/cm^2/s

$$\phi(\vec{r})=\int \frac{d\Phi(\vec{r},t)}{dt}\,dt$$

Simply known as Fluence

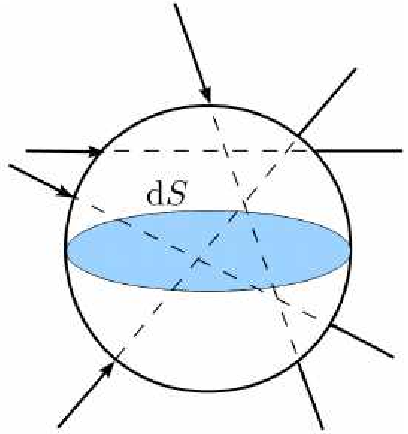
Particles/cm^2

Alternative definition

In ICRU report 85a an alternative definition of fluence is given:

If $\mathrm{d}N$ is the number of particles crossing an infinitesimal sphere centered at point $\vec{\mathbf{r}}$ and with cross sectional area $\mathrm{d}S$ then the fluence at that point is

$$\Phi(\vec{\mathbf{r}}) = \frac{\mathrm{d}N}{\mathrm{d}S}$$



In dosimetric calculations, fluence is frequently expressed in terms of the lengths of the particle trajectories. It can be shown (Papiez and Battista, 1994; and references therein) that the fluence, Φ, is given by

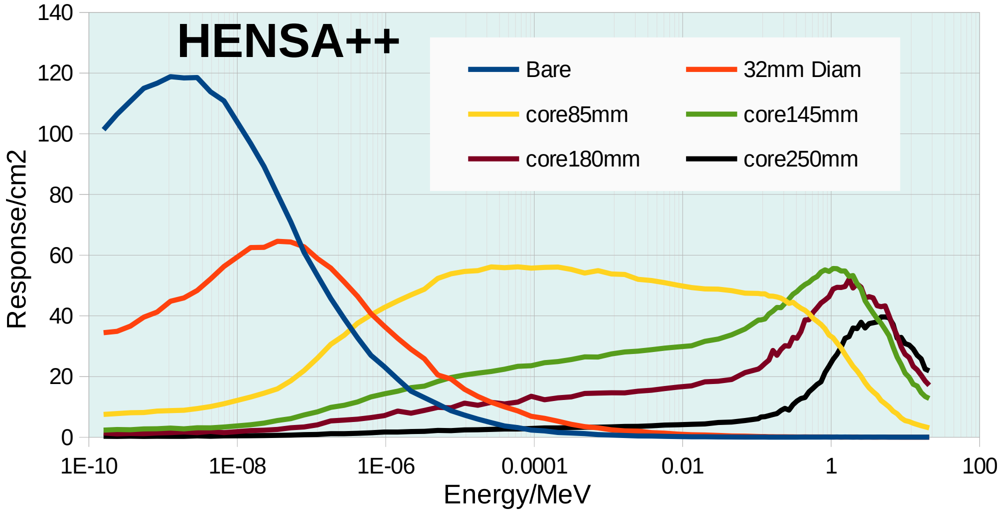
$$\Phi = \frac{\mathrm{d}l}{\mathrm{d}V}, \qquad (3.1.6)$$

where $\mathrm{d}l$ is the sum of the lengths of particle trajectories in the volume $\mathrm{d}V$.

Detector response/efficiency

- **Correspond to the detection probability. It is calculated as the number of detected events or detection event rate normalized to:**
  - Radiation fluence
  - Production yield in the source
  - When using the detection event rate, it is also normalize by the counting time

$$s = \frac{\text{real rate of net counts}}{\text{neutron flux}} = \frac{r}{\phi} \quad \left[\frac{\text{cps}}{\text{n}/\text{m}^2 s} \right]$$



- **How to determine the detector response as a function of energy?**
  - This is a very challenging task for neutron detectors. Requires well characterized radiation fields, mono-energetic neutron sources.
  - In practice, this task is achieved by Monte Carlo (MC) simulations. The simulations are then validated with experimental measurements for a few set of available neutron energies or neutron spectra.
  - MC tools for simulation of neutron detectors (not an exhaustive list):

https://mcnp.lanl.gov/ https://fluka.cern/ https://phits.jaea.go.jp/ https://geant4.web.cern.ch/

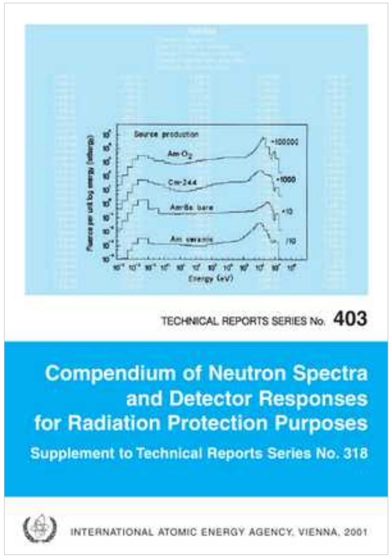
www.particlecounter.net

Detector response/efficiency: recommendations for *“important”* detectors

- Neutron dosimeters are neutron detectors which require traceable and reproducible response calibrations. These detectors are used for radiation protection. Their use is incorporated in legal frameworks.

- **The ISO-8529 standard:**
  - **Part I**: characteristics and methods of production of the reference neutron radiations to be used for calibrations.
  - **Part II**: fundamentals related to the physical quantities characterising the radiation field and calibration procedures in general terms.
  - **Part III**: dosimeters for area and individual monitoring, describing the respective procedures for calibrating and determining the response in terms of the ICRU operational quantities.

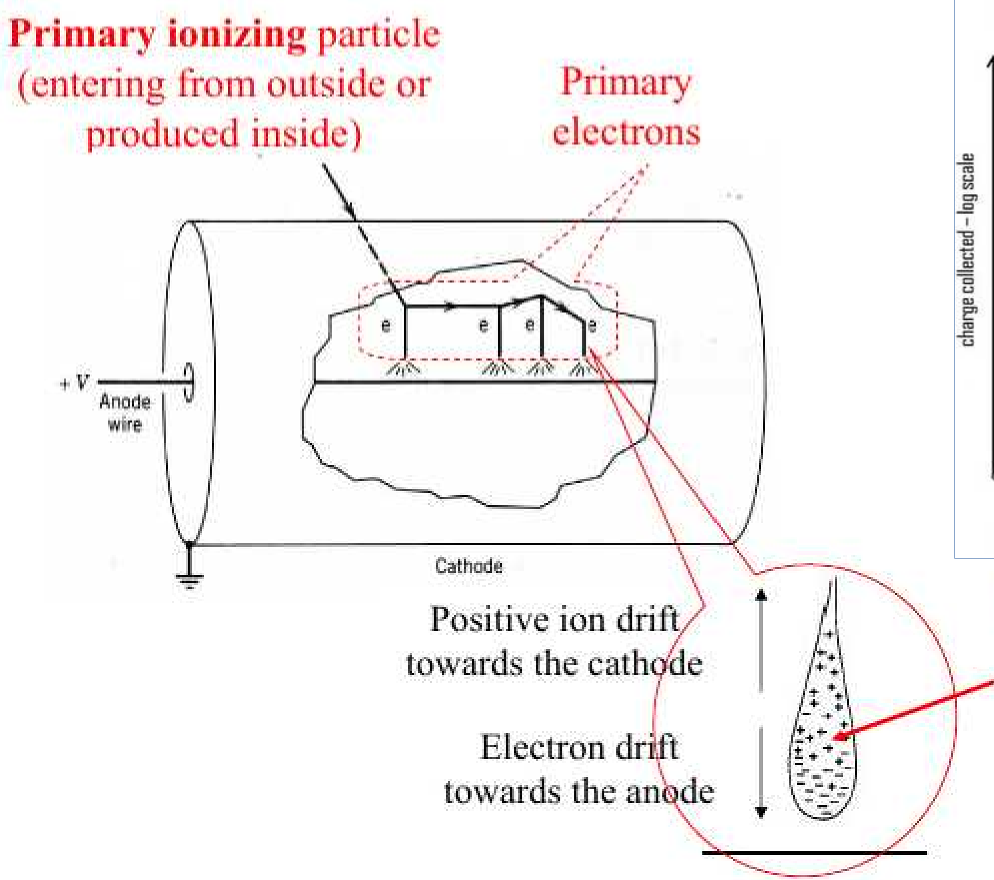
- **IAEA TRS-403: Compendium of Neutron Spectra and Detector Responses for Radiation Protection Purposes**
  - Provides a large compilation data, including responses of different neutron detectors, calibration and reference neutron spectra, operational spectra (facilities) and an easy-to-use database for “simple” calculations using a spreadsheet.

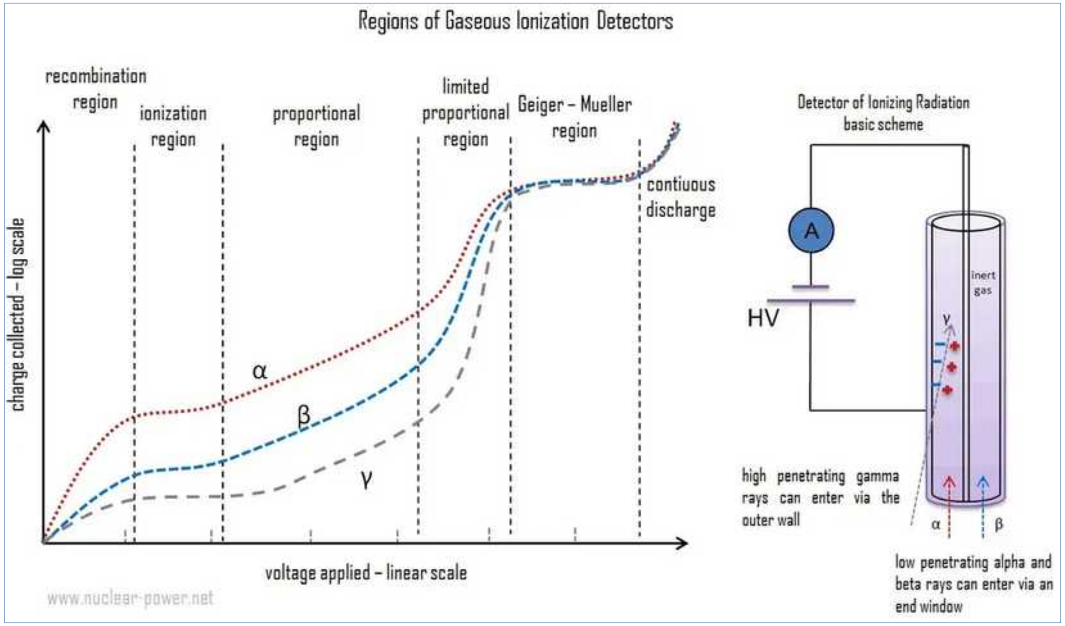


Neutron detection: some nuclear reactions of interest

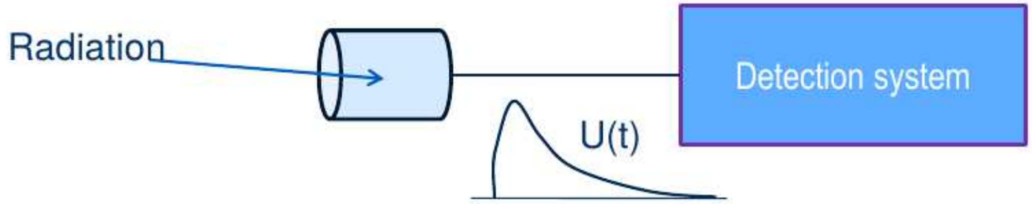
Reaction	σ/barn (for thermal n)	Detector
$n + {}^{3}He \rightarrow {}^{3}H + p + 0.765\ MeV$	5400	^{3}He gas detector
$n + {}^{10}B \rightarrow {}^{7}Li^{*} + \alpha + 2.3\ MeV$ $\rightarrow {}^{7}Li + \alpha + 2.8\ MeV$	3840	BF_3 gas detector
$n + {}^{235}U \rightarrow$ fission fragments + 195 MeV	580	Fission (gas) chamber
$n + {}^{6}Li \rightarrow {}^{3}H + \alpha + 4.79\ MeV$	940	Scintillator detector
$n + {}^{157}Gd \rightarrow {}^{158}Gd^{*} \rightarrow {}^{158}Gd + \gamma, e$	255000	^{157}Gd doped plastic and liquid scintillators

Principles of operation of gas-filled detectors





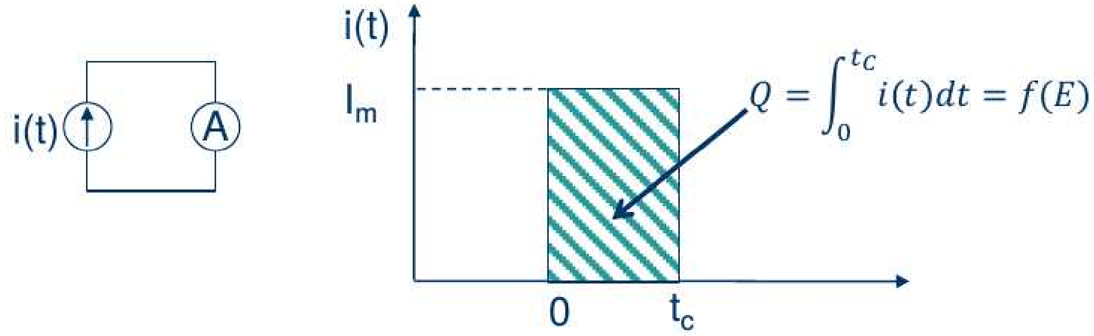
Avalanche: secondary ionizations produced by a primary electron that gain enough energy from the electric field between collisions.



- The detector produce an electric pulse
- Detector is part of an electric circuit

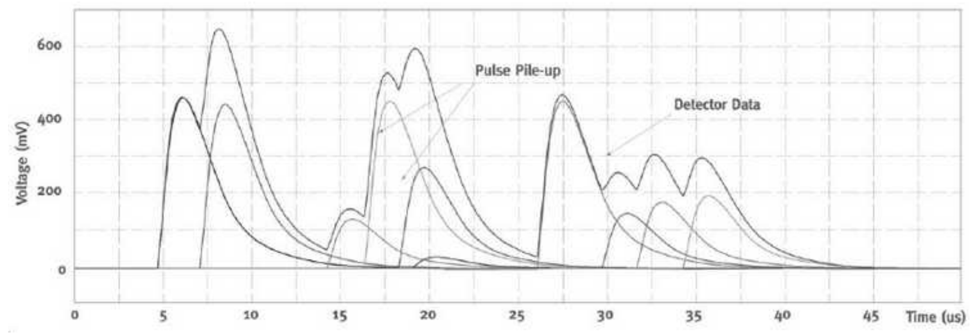
Principles of operation of gas-filled detectors

- Collection of charge produces a pulse of current (electric signal) at the electric output of the detector. This signal has to be processed by an amplifier and then by analog or digital electronics in order to count events.



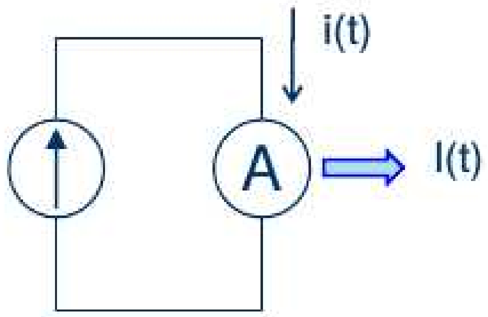
t_c Time collection of charge carriers

- When two or more event detection happens close in time, the output of the detector shows pulse pile-up. This may lead to loss of detected events or misidentification of amplitudes.

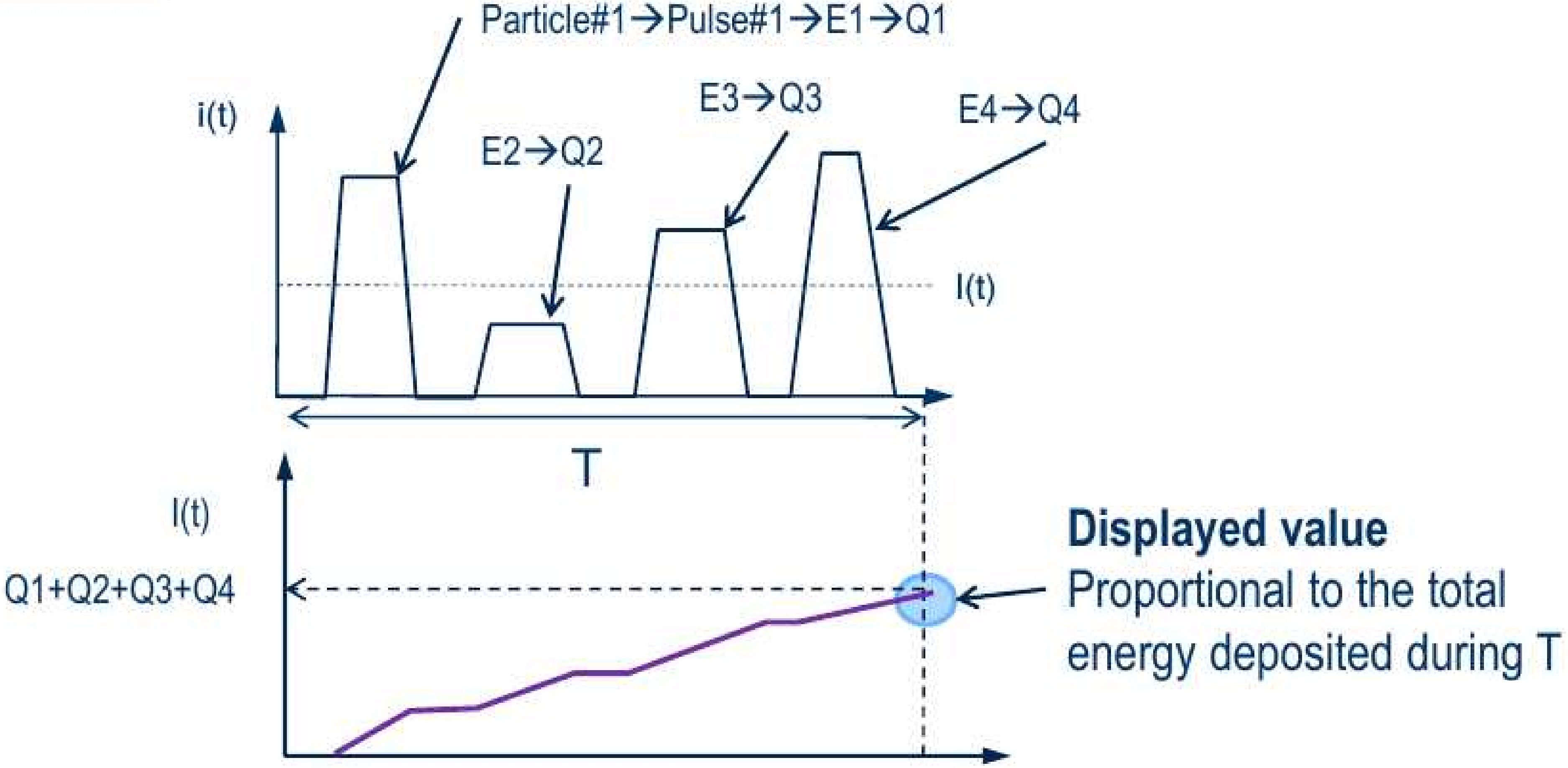


- **Detector operation modes:**
  - Current mode
  - Pulse mode
  - Charge integration mode

Current mode

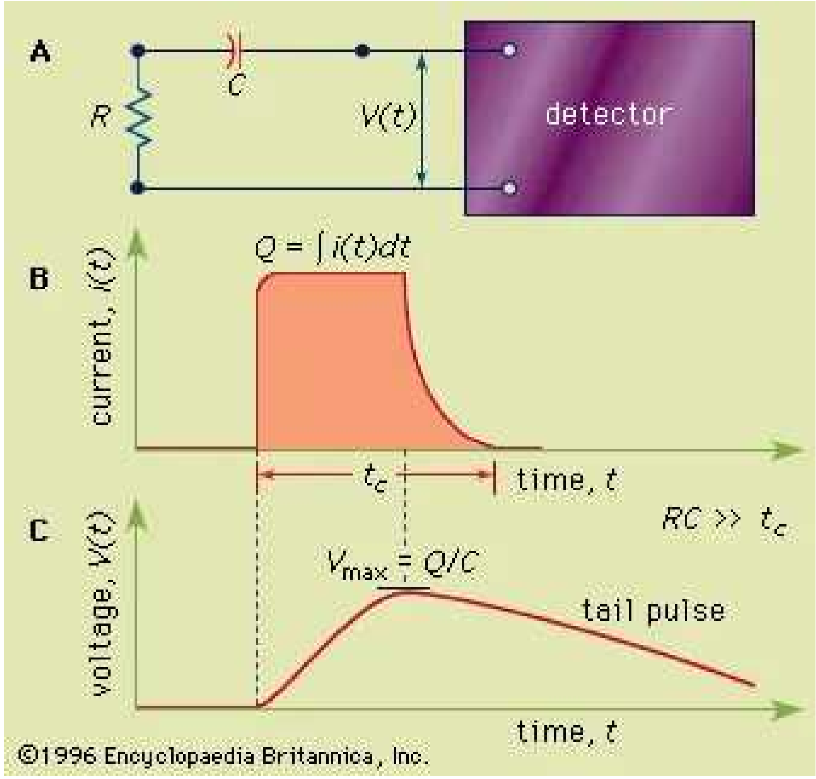


$$I(t)=\frac{1}{T}\int_{t-T}^{T} i(t')dt'$$



Pulse mode

Each pulse is processed individually
Each pulse corresponds to one particle.



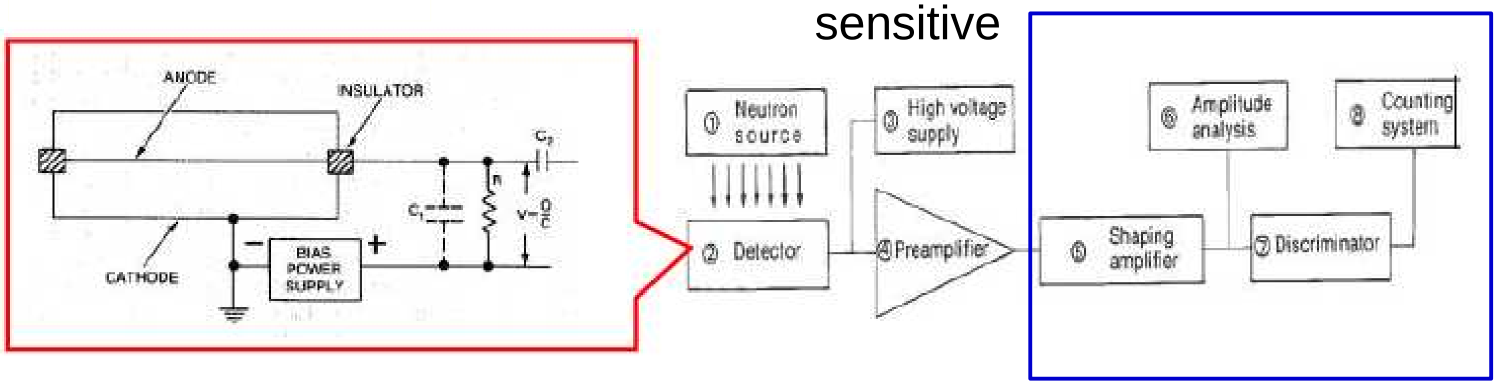
Information available:

- Pulse Amplitude → Particle energy
- Time between pulses → Rate of events
- Number of pulses .→ Number of events

Typical configurations.

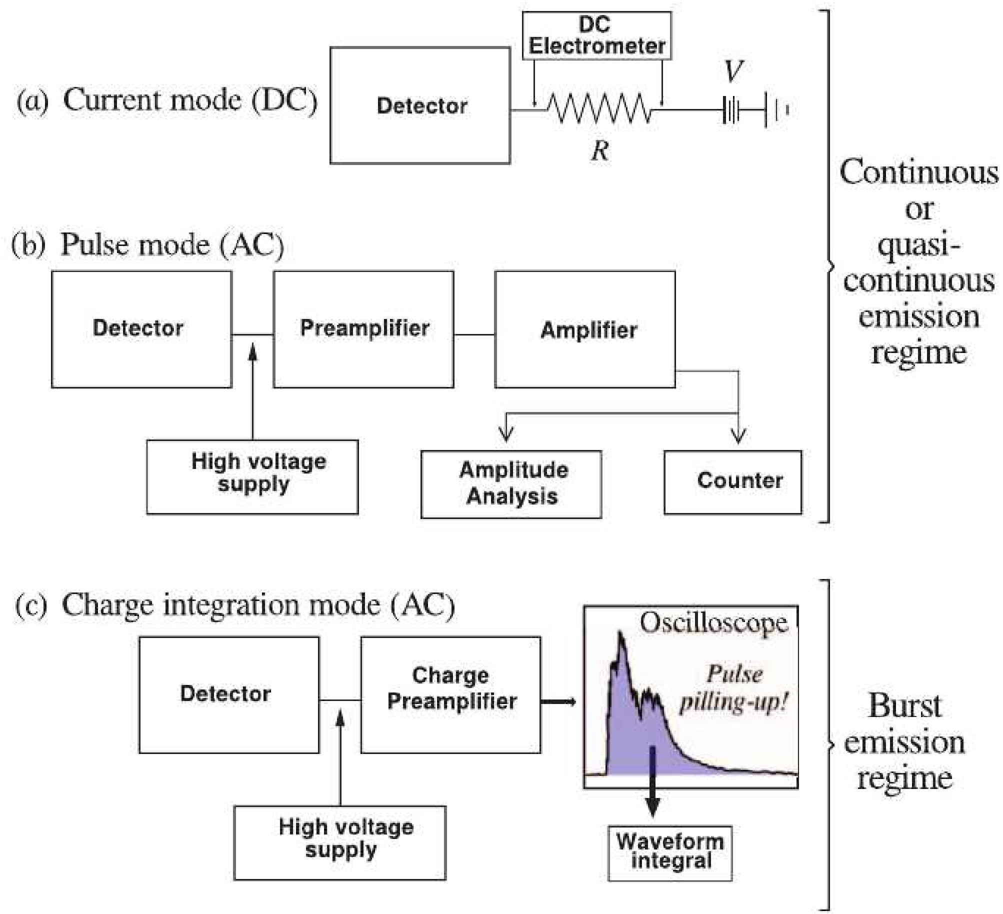
- Pulse counting → Number of particles detected
- Spectrometry → Number of particles detected sorted by its energy, presented in an energy histogram called energy spectrum

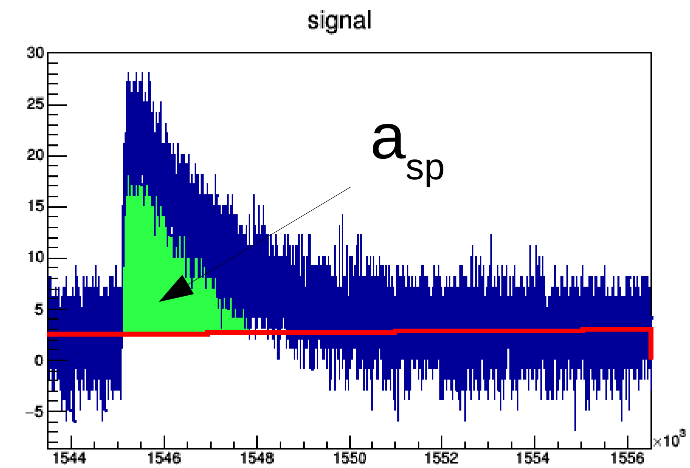
Charge sensitive

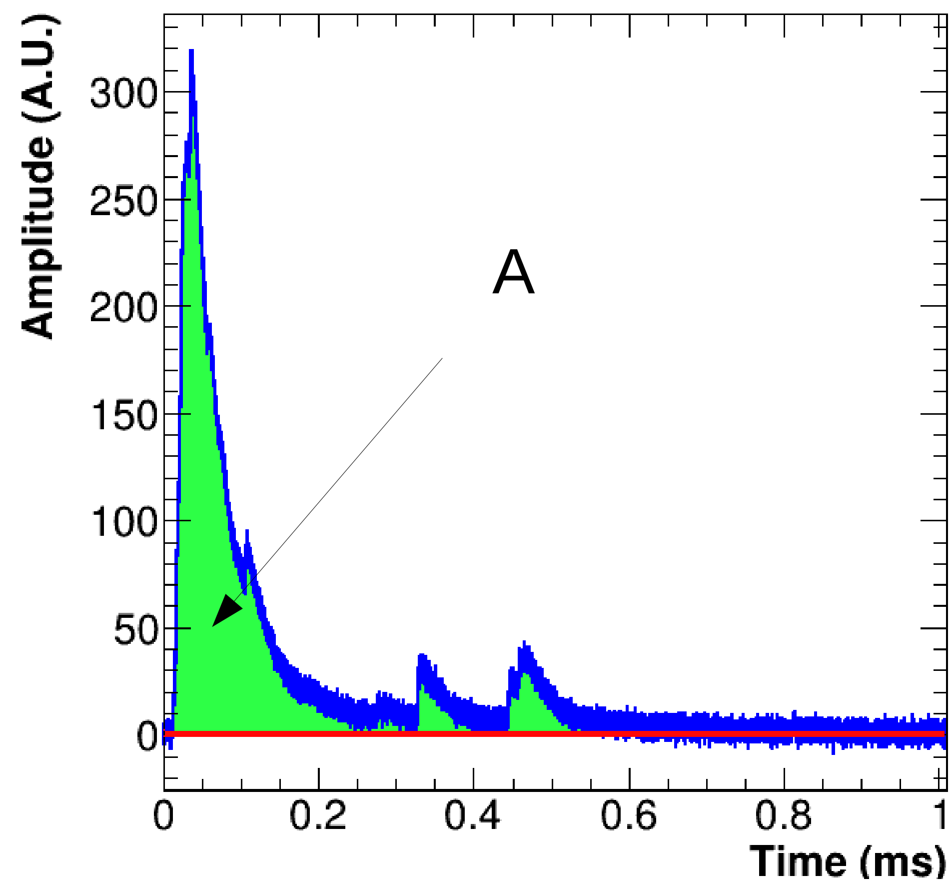


Analog
Or
Digital
electronics

Charge integration mode ("hybrid" mode)







When using a charge sensitive preamplifier:
$Q_{total} \sim V_{signal}$

Number of detected events ≈ A /<a_{sp}>

^{3}He counters for **neutrons**

$$^3_2He + ^1_0n \rightarrow ^3_1H + ^1_1p \qquad Q=0.765\text{MeV}$$

Q>> thermal neutron energy $\Rightarrow$ energy of reaction products ~Q

→p and ^{3}H are emitted in opposite directions

→ E_p=0.574 MeV and E_H=0.191 MeV

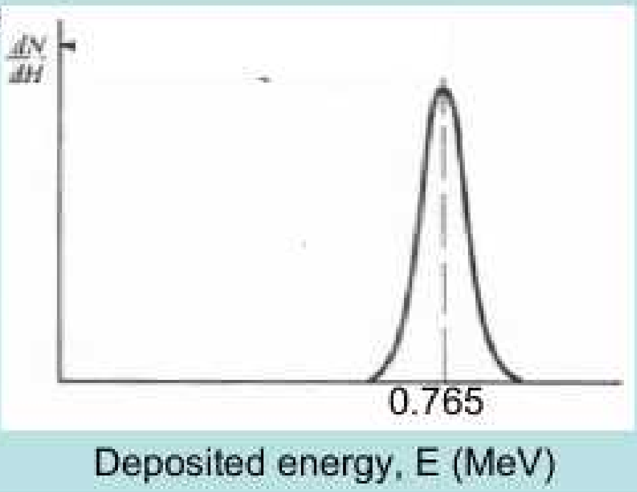
^{3}He is the target material for conversion of the neutrons and the media for detecting the proton and the tritium produced in the conversion process

In a **ideally large detector** where:

- all the neutron interactions took place in the central part of the detector
- the p and ^{3}H stopped entirely in the gas volume

→ each thermal neutron would deposit 0.765 MeV in the detector (≡ Q)

→ flat and large plateau for counting purposes



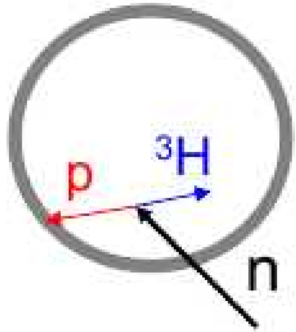
REALITY: the energy deposited is not always equal to Q because of the wall effect

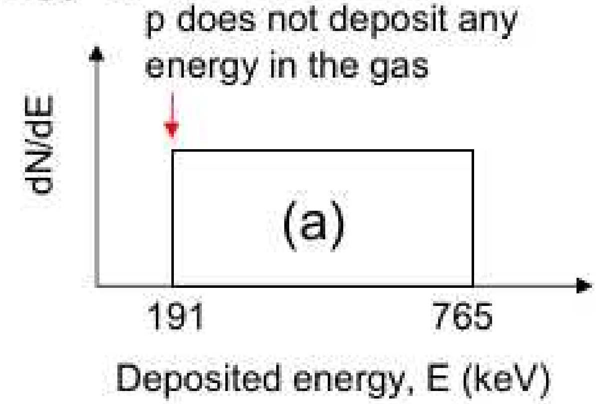
Wall effect:

^{3}H or p (or both) can deposite only part of their energy in the detector

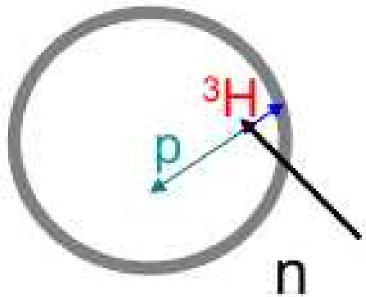
Different events can deposit a different amount of energy in the detector:

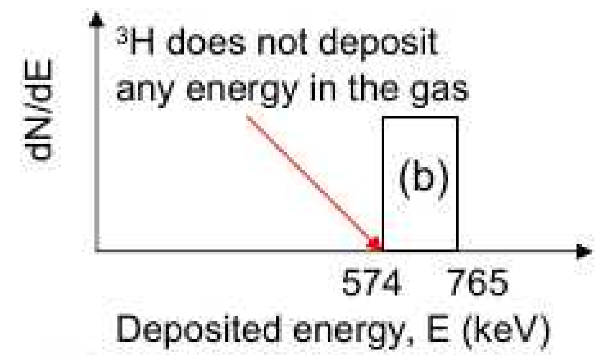
(a) ^{3}H energy is fully deposited in the detector but the proton deposited a fraction of its energy only;



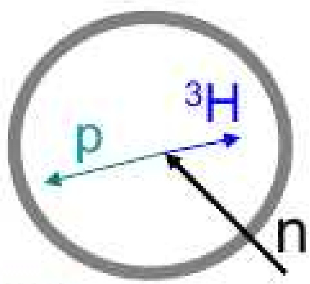


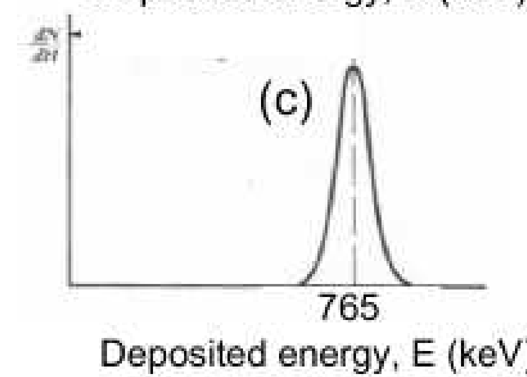
(b): Proton energy is fully deposited , but the ^{3}He deposits a fraction of its energy only;





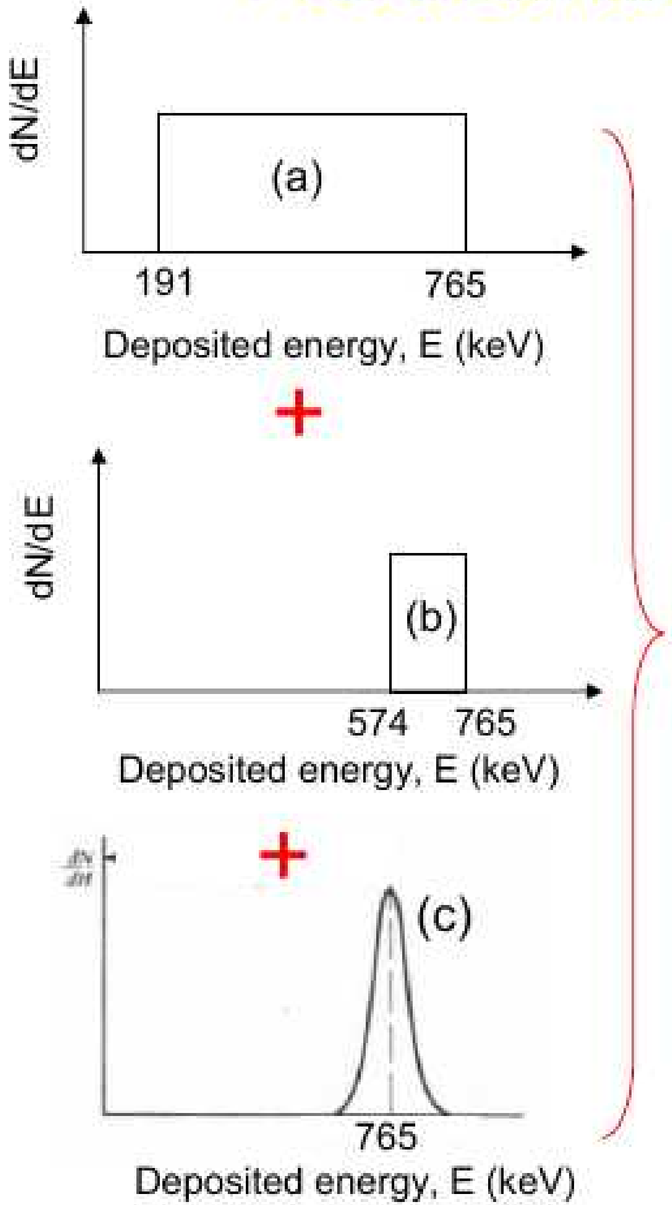
(c): ^{3}H and the proton are both fully stopped in the gas.

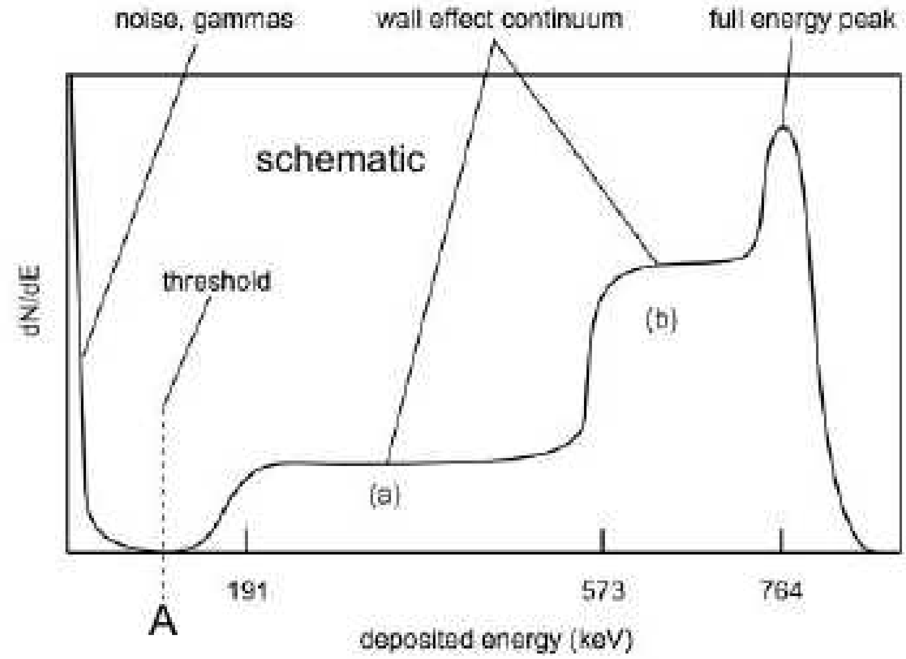




Range of *p* in ^{3}He at 5 atm is ~ 1mm;
It is decreased by adding a heavy gas as CF_4

^{3}He counters: n/γ discrimination

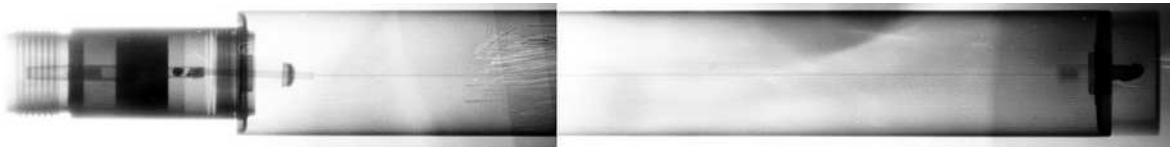


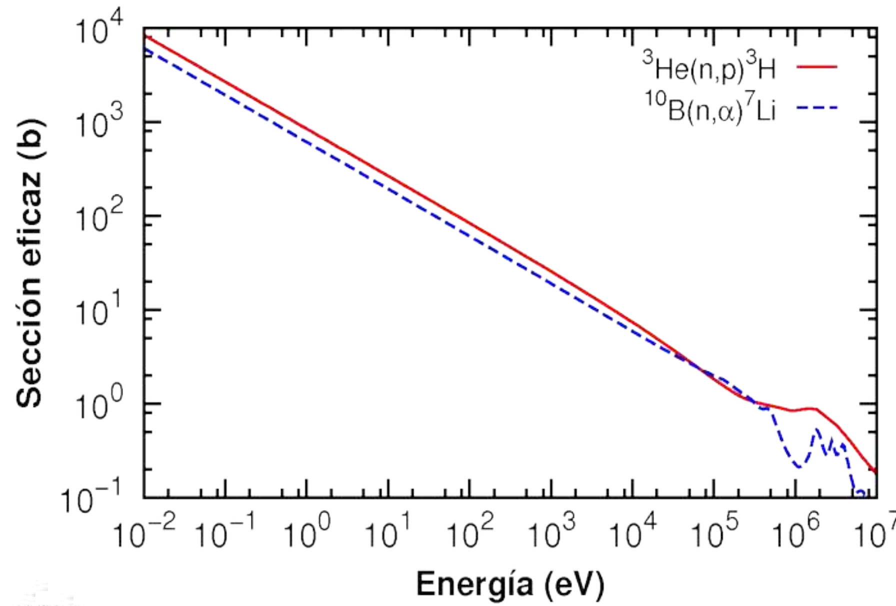


- Spectrum depends on size and geometry detector
- γ interactions produce small amplitude pulses that can be eliminated by amplitude discrimination
- For counting purposes, the threshold should be set around A

Isabel Lopes

^{3}He-filled proportional neutron counters: remarks





Detection reaction:

$$^3He + n \rightarrow {}^3H + p \qquad Q = 0.764\ MeV$$

High Thermal cross section: **5330 barns!!!**

Table 13-1. Neutron and gamma-ray interaction probabilities in typical gas proportional counters and scintillators

	Interaction Probability	
Thermal Detectors	Thermal Neutron	1-MeV Gamma Ray
^{3}He (2.5 cm diam, 4 atm)	0.77	0.0001
Ar (2.5 cm diam, 2 atm)	0.0	0.0005
BF_3 (5.0 cm diam, 0.66 atm)	0.29	0.0006
Al tube wall (0.8 mm)	0.0	0.014
	Interaction Probability	
Fast Detectors	1-MeV Neutron	1-MeV Gamma Ray
^{4}He (5.0 cm diam, 18 atm)	0.01	0.001
Al tube wall (0.8 mm)	0.0	0.014
Scintillator (5.0 cm thick)	0.78	0.26

*Extracted from Neutron Detectors, T. W. Crane and M. P. Baker

- These neutron counters are gaseous ionization detectors that use 3He as converting gas.
- Due to the high thermal capture cross section, 3He filled counters have a high neutron sensitivity.
- For non-thermal neutrons, the high efficiency can be exploited by using moderators.
- In addition, the low gamma-ray sensitivity makes these detectors very attractive for **neutron spectroscopy (Bonner spheres)**.

Example of thermal neutron counter

Founded 1964

LND, INC.

Designers & Manufacturers of Nuclear Radiation Detectors

3230 LAWSON BLVD., OCEANSIDE, NEW YORK 11572

E-mail: info@lndinc.com Web Site: http://www.lndinc.com

1-516-678-6141 Fax: 1-516-678-6704

2527 Cylindrical He3 Neutron Detector

LND252541 (SHV connector)

GENERAL SPECIFICATIONS

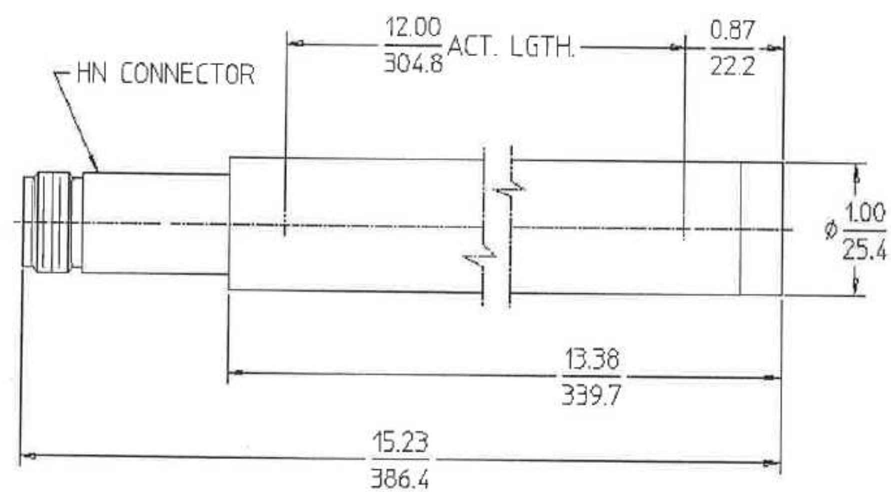
Gas pressure (torr)	15200
Cathode material	Stainless Steel
Maximum length (inch/mm)	15.23/386.84
Effective length (inch/mm)	12.0/304.8
Maximum diameter (inch/mm)	1.0/25.4
Effective diameter (inch/mm)	0.96/24.38
Connector	HN
Effective volume (cm³)	142.26
Operating temperature range °C	-50 to +100

ELECTRICAL SPECIFICATIONS

Recommended operating voltage (volts)	2200
Operating voltage range (volts)	2050-2400
Maximum plateau slope (% / 100 volts)	1
Maximum resolution (% fwhm)	7
Tube capacitance (pf)	8
Weight (grams)	200

THERMAL NEUTRON SENSITIVITY

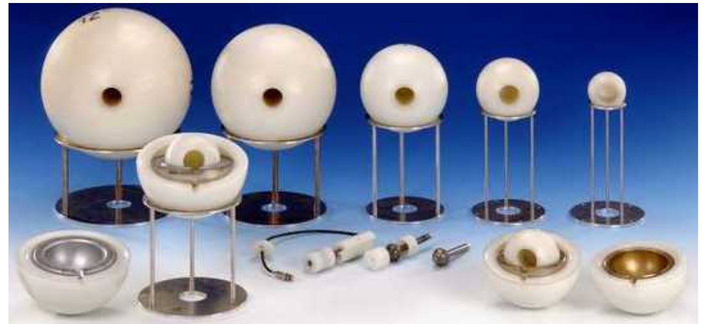
Sensitivity (cps / nv)	174.3



Referential

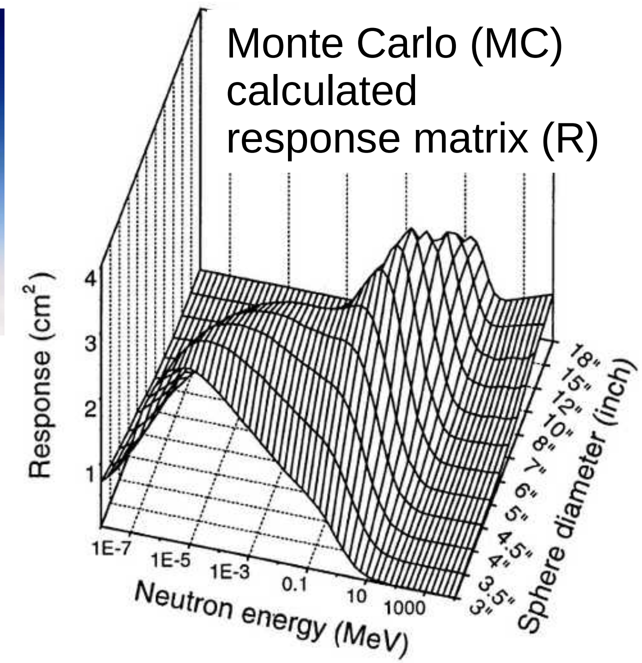
The Bonner's spheres neutron spectrometer

- Bonner's Spheres (BS) spectrometers are among the most known and widespread techniques for neutron spectrometry.
- Moderated proportional neutron counters. Useful from thermal to GeV region.
- Typically 5 up to 14 spheres → ***Ill-posed linear inverse problem*!**
- Extensive MC simulations and unfolding algorithms are required to solve the inverse problem.

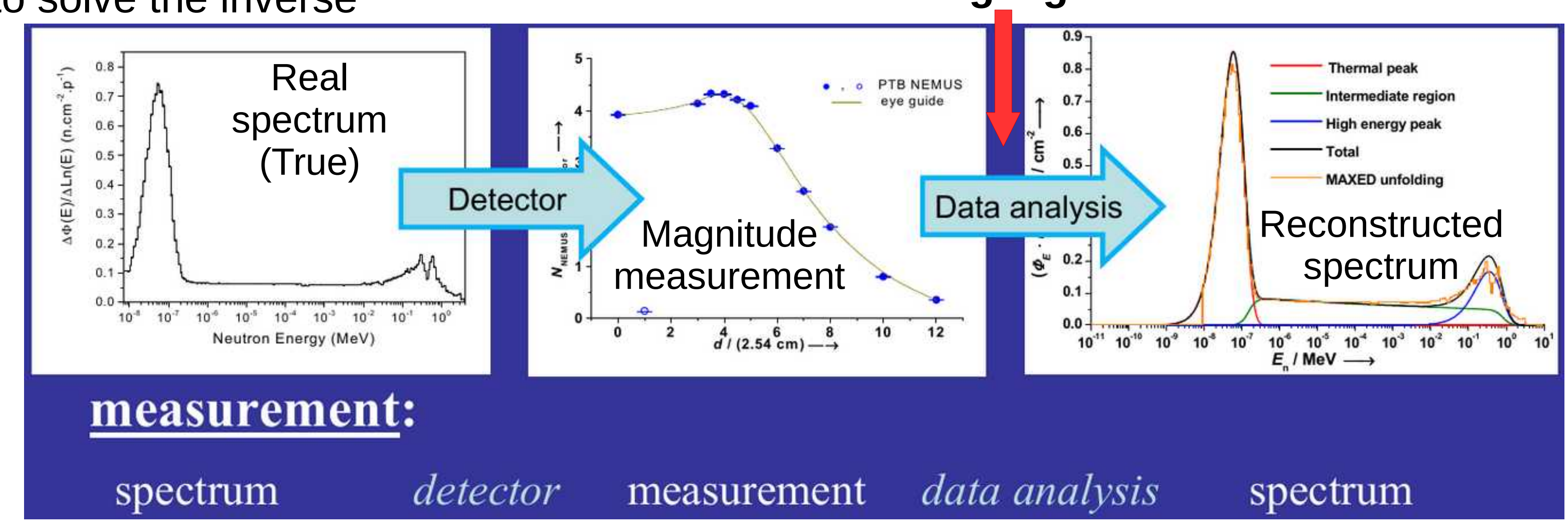


$$M_i = \int R_i(E)\phi(E)\,\mathrm{d}E.$$

$$\rightarrow \quad M_i = \sum_{j=1}^{n} R_{ij}\phi_j$$



Unfolding algorithm



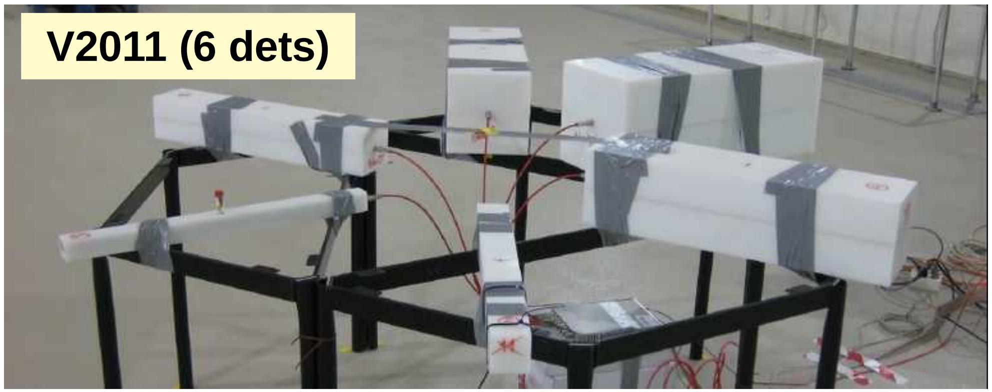
Bonner's spheres spectrometers: advantages and drawbacks*

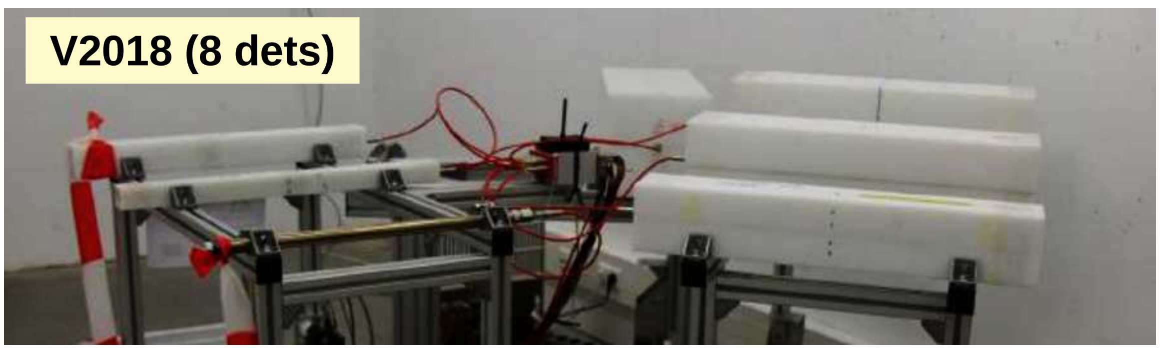
Characteristic	Verdict	Comment
Energy resolution	Poor	Restricted by similarity of response functions available
Energy range	Excellent	The only spectrometer presently available which will cover the energy range from thermal to the GeV region
Sensitivity	Good	High sensitivity by comparison with other neutron spectrometers, and can be varied by changing the thermal sensor
Operation	Simple but lengthy	Making measurements is simple, with no really complex electronics, but it can be time consuming
Angular response	Isotropic	Do not need to know the direction of the neutron field. Ideal for deriving ambient dose equivalent, but provides no angular data for deriving effective dose
Spectrum unfolding	Potential for errors	Complex unfolding code required, and the under-determined problem means that any solution is not unique; significant errors are possible
Photon discrimination	Good	By the choice of an appropriate sensor systems can be made insensitive, even to intense photon fields

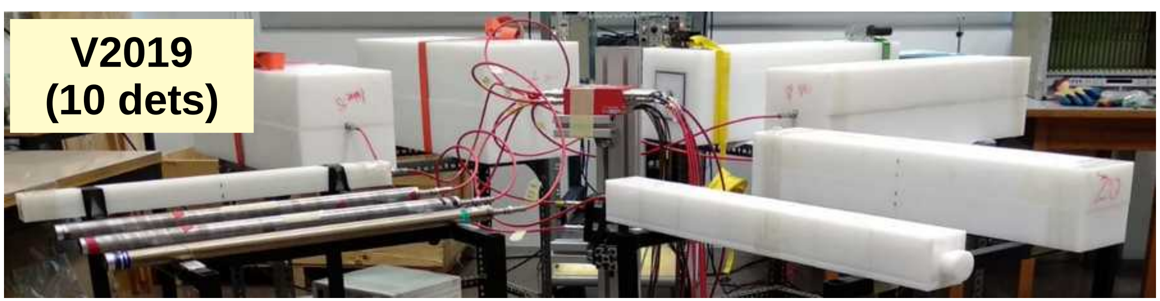
* Extracted from D.J. Thomas, A.V. Alevra / NIMA 476 (2002) 12–20

The High Efficiency Neutron Spectrometry Array (HENSA)

- HENSA is based of the Bonner Spheres Principle. Energy sensitivity from thermal to 10 GeV.
- Research lines: neutron background in underground facilities, cosmic rays neutrons and space weather, environmental radioactivity...





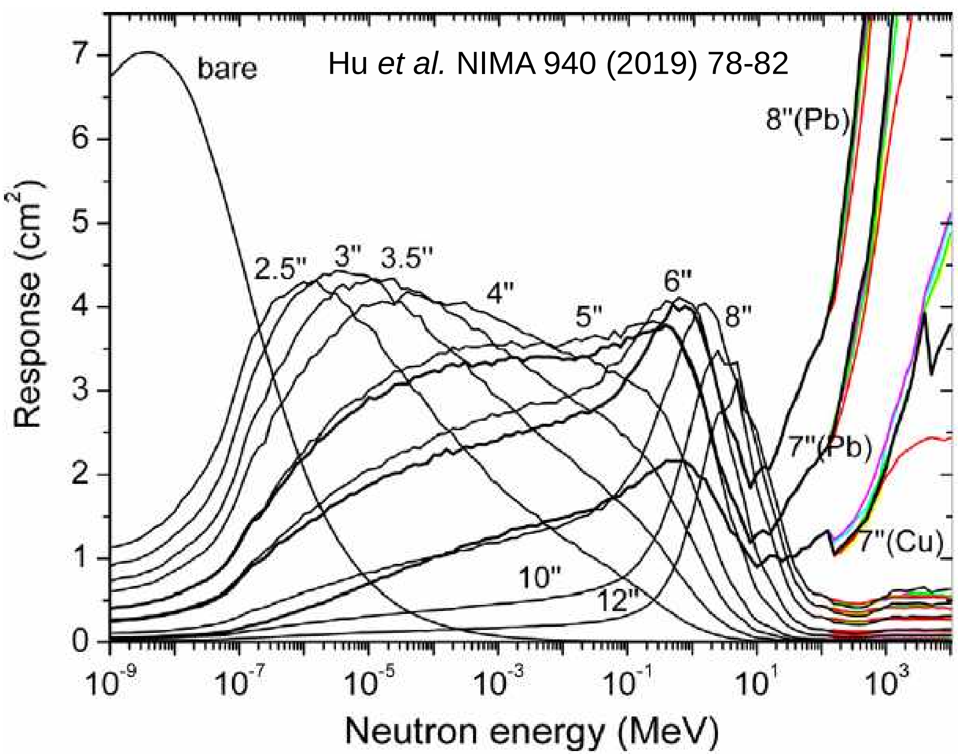


www.hensaproject.org

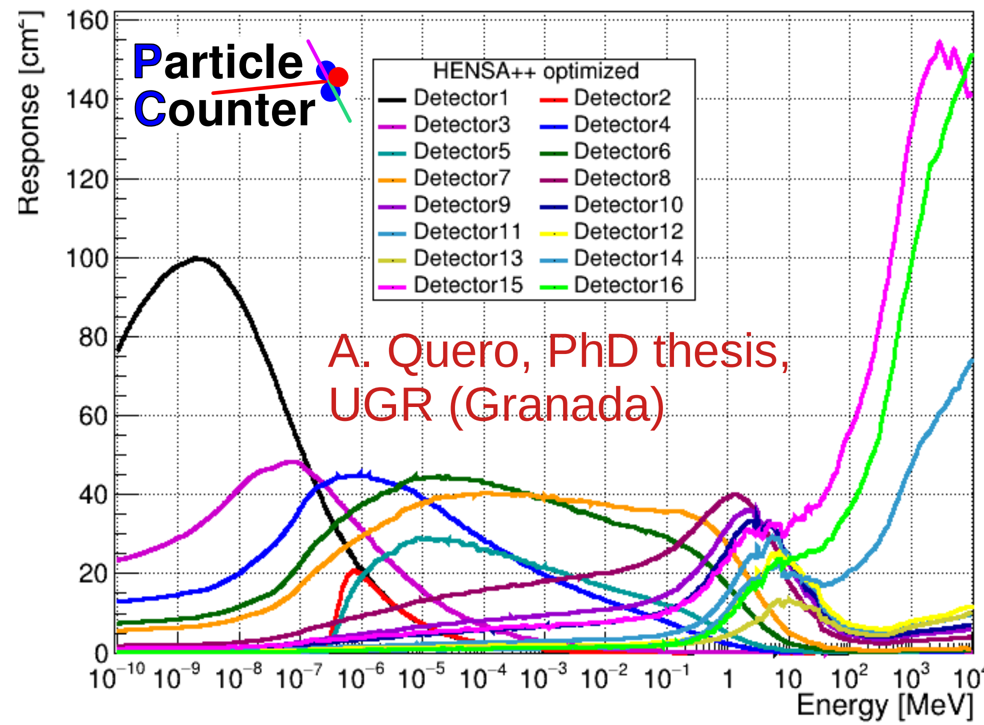
HENSA
High Efficiency Neutron Spectrometry Array

HENSA spectral sensitivity

Standard extended Bonner Spheres



HENSA++ optimized version 2023

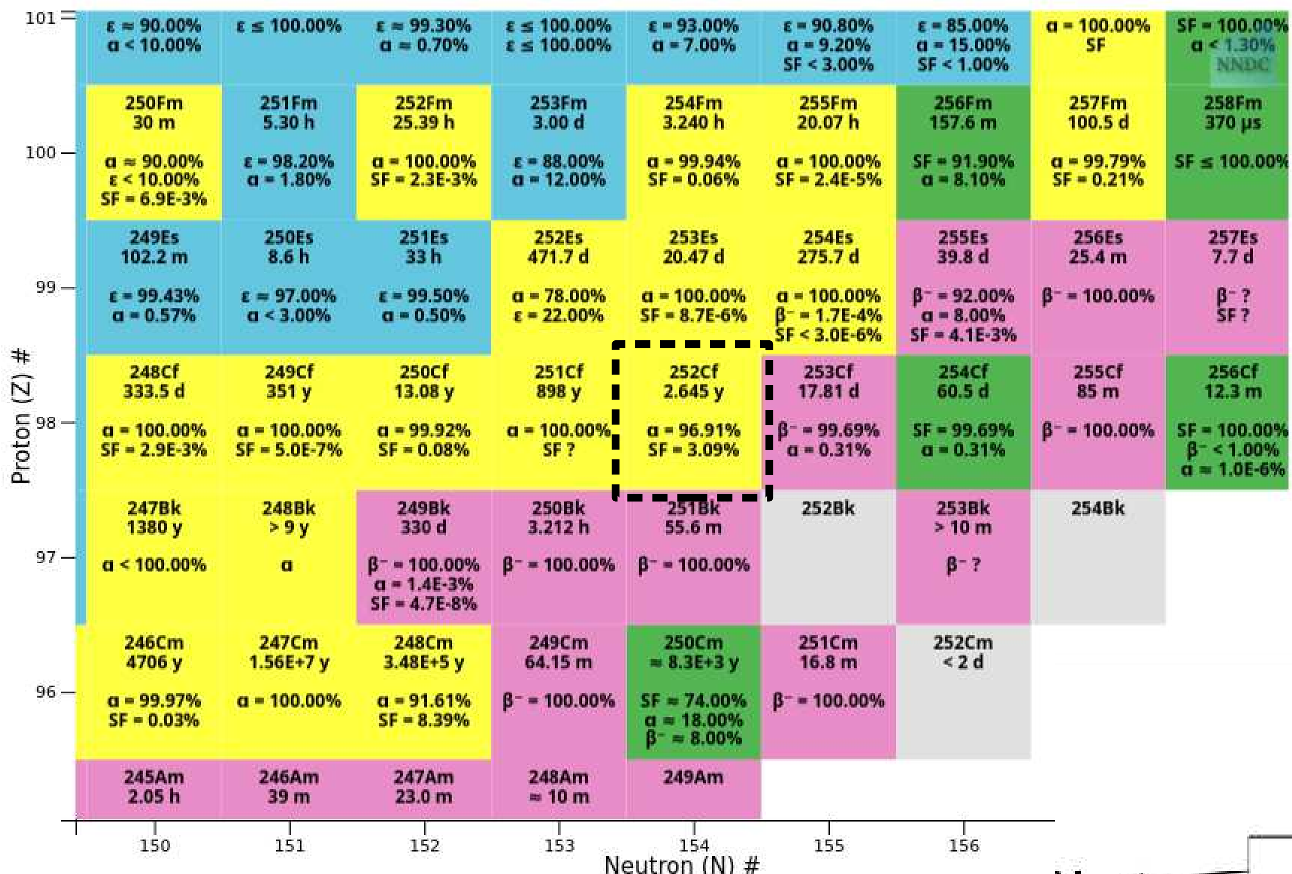


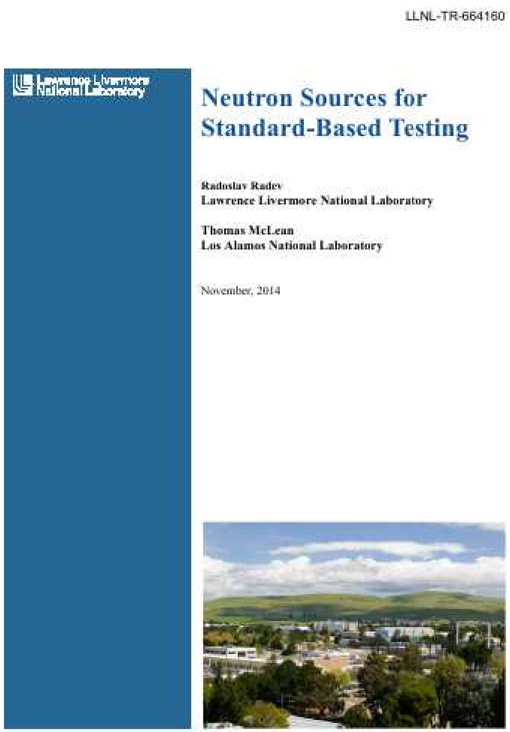
HENSA neutron response is ~ 5-15 times larger than standard Bonner Spheres systems in the energy range from thermal up to 10 GeV.

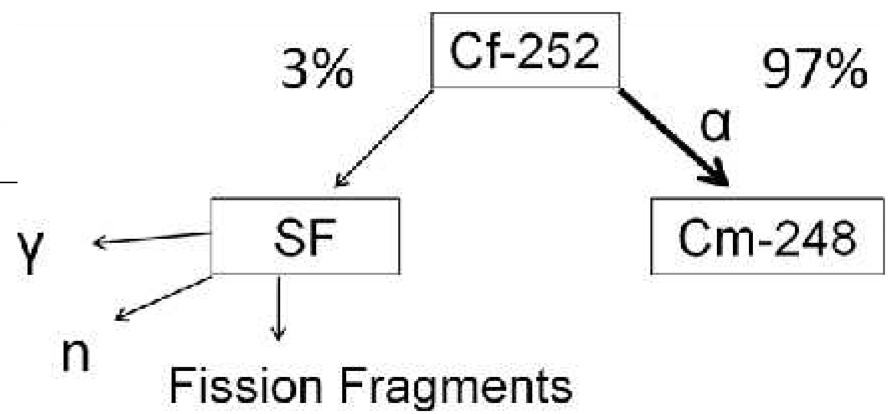
The higher neutron response means:

- Improved precision in low radioactivity or underground facilities.
- Temporal response in the scale of ten of minutes to hours for fluctuations of the neutron background at ground or air based measurements.

Decay of Cf-252







Basic properties of Cf isotopes

Nuclide	Half-Life ($T_{1/2}$)	a-Decay Branching Fraction	Spontaneous Fission (SF) Branching Fraction	Average Neutron Yield per Fission (SF)	Total Neutron Emission Rate [n/(g.s)]
^{249}Cf	351 y	≈ 1.0	$5.2x10^{-9}$	3.4	$2.676x10^{3}$
^{250}Cf	13.20 y	0.99921	0.00079	3.53	$1.117x10^{10}$
^{251}Cf	898 y	≈ 1.0	$9.0x10^{-6}$	3.7	$1.954x10^{6}$
^{252}Cf	2.645 y	0.96904	0.03096	3.768	$2.314x10^{12}$
^{253}Cf	17.81 d	0.0031	Unknown	Unknown	$8.406x10^{4}$
^{254}Cf	60.5 d	0.00299	0.99701	3.93	$1.232x10^{15}$

The energy spectrum of ^{252}Cf can be described by the Watt equation:

$$N(E) = e^{-E/a}\sinh(\sqrt{bE}),$$

where E is the neutron energy in MeV and for ^{252}Cf, a=1.18 MeV and b = 1.03419 MeV^{-1}. The average neutron energy is 2.13 MeV and the most probable energy is 0.70 MeV.

Production and market

Production

Californium properties, production, supply and applications are reviewed in several reports and presentations [1-5]. Californium is produced in two facilities world-wide: at the High Flux Isotope Reactor (HFIR) located at the Oak Ridge National Laboratory (ORNL) in Tennessee, USA and at the Research Institute for Atomic Reactors (RIAR) in Dimitrovgrad, Russia (Figure 1).

Figure 1. Oak Ridge National Laboratory facility in USA and Research Institute for Atomic Reactors in Dimitrovgrad, Russia

2/5 most expensive elements in the world...

Californium – $25 million per gram

Our 252Cf source

Eckert & Ziegler
Isotope Products

24937 Avenue Tibbitts
Valencia, California 91355

Tel 661·309·1010
Fax 661·257·8303

NOMINAL SOURCE CERTIFICATE

Customer: Eckert & Ziegler Isotope Products Gmbh
Purchase Order No.: 38597
Model No.: Not applicable
Catalog No.: CF230360005U
Capsule Type: A3036-2
Active Diameter/Mass: 3.2 mm (0.125 ")
Cover: Stainless steel
Backing: Stainless steel

Certificate Date: 01-Jul-10
Quantity: 1
SS&DR No.: Not applicable
ISO Classification: Not applicable
Special Form No.: Not applicable
Nuclide Half Life: 2.645 ± 0.008 years
Recommended Working Life: 15 years

Nuclide	Source No.	Activity	Radiation Output	Reference Date
Cf-252	H2-164	5 μCi/185 kBq	Not applicable	1-Aug-10

Cf-252 Technical data

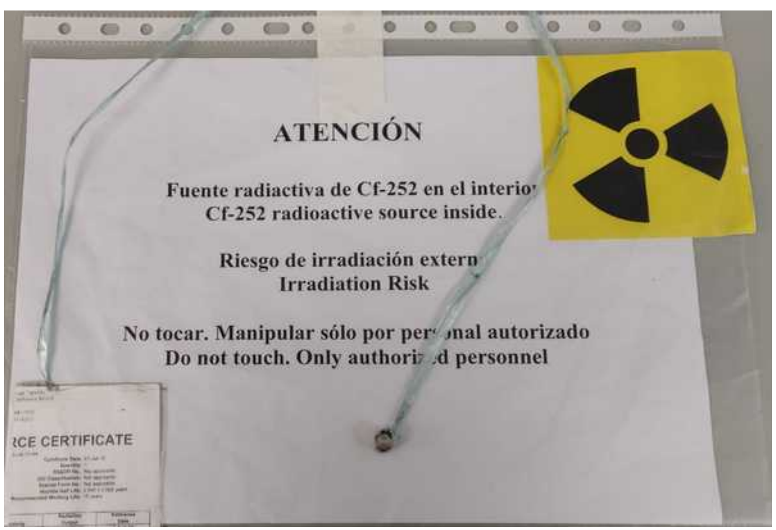
The Cf-252 used to prepare your order was taken from Eckert & Ziegler Isotope Products Laboratories Lot #5128001 and it had the following composition as of 15 Mar 10.

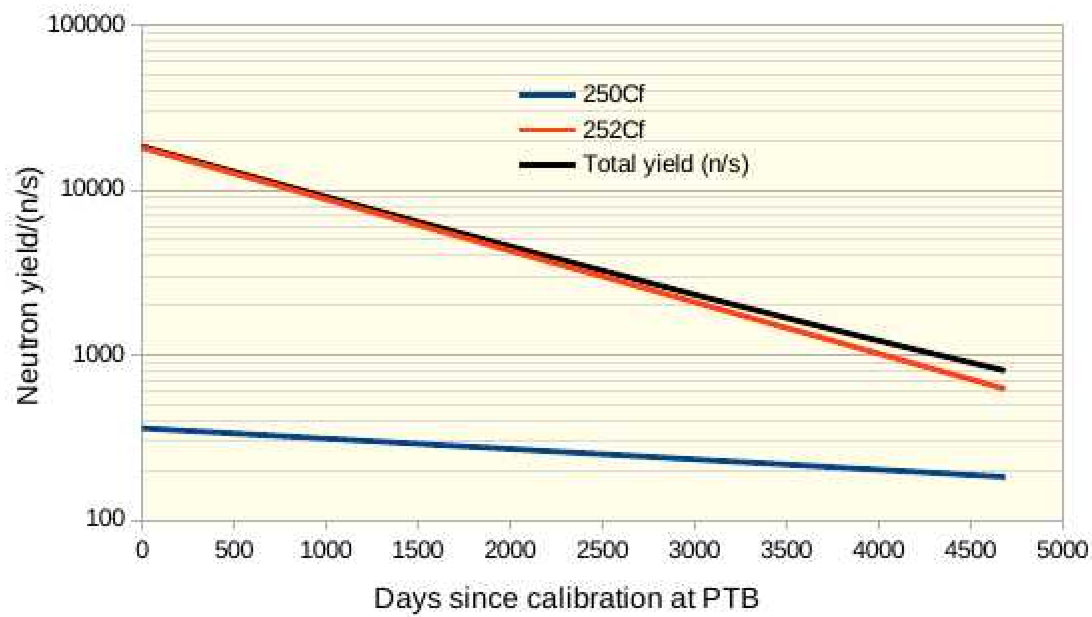
Nuclide	Mass %	Activity %
Cf-249	9.936	0.1495
Cf-250	30.643	12.266
Cf-251	15.053	0.0877
Cf-252	44.368	87.497

The Cm-248 decay product was last separated on 3 Apr 01

Isotopic composition provided by Oak Ridge National Laboratory

If you have any questions, please contact Eckert & Ziegler Isotope Products Technical Service: 661-309-1010

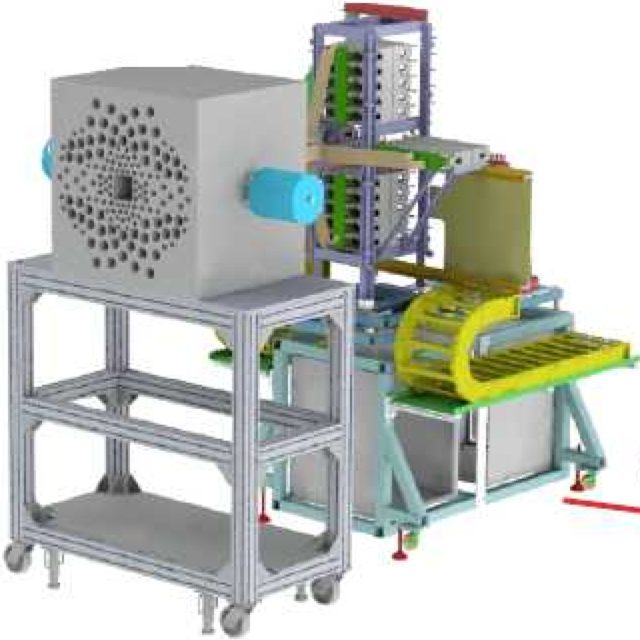




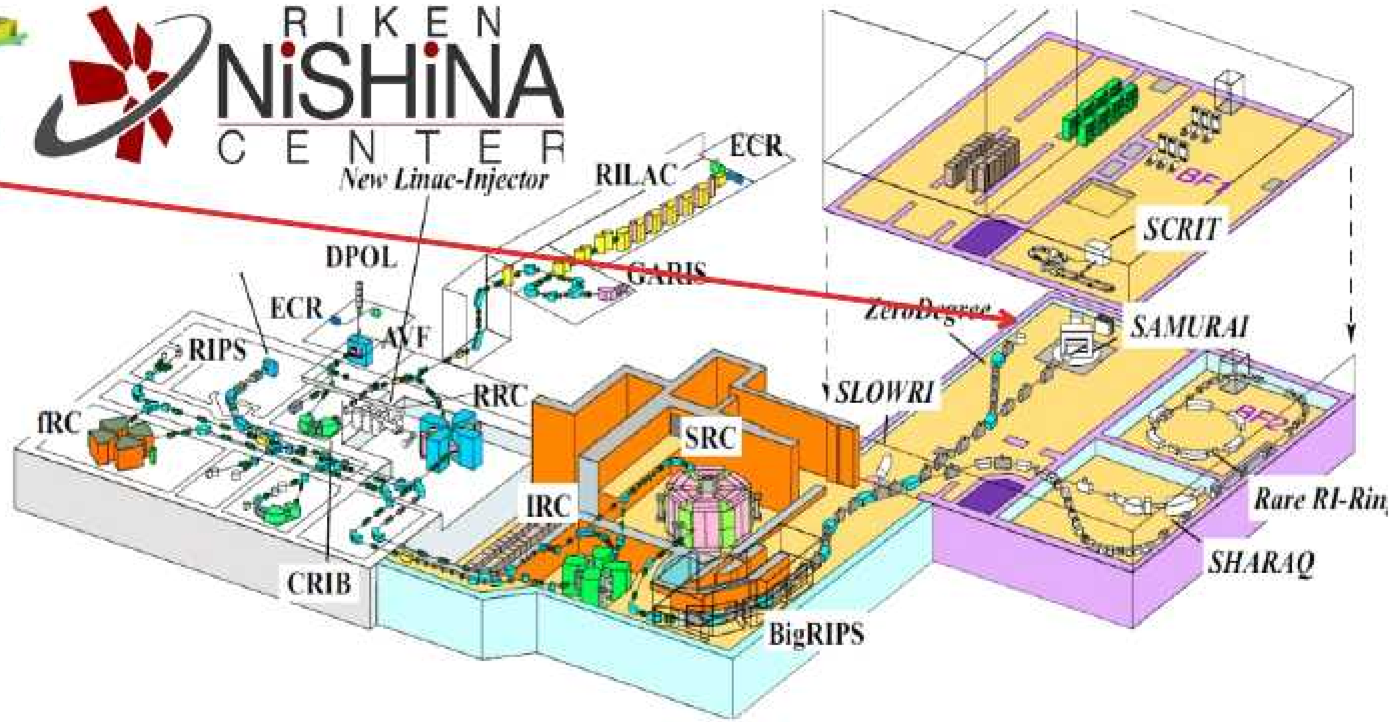
Neutron detectors: some examples

- **BRIKEN project**

β-delayed neutrons at RIKEN

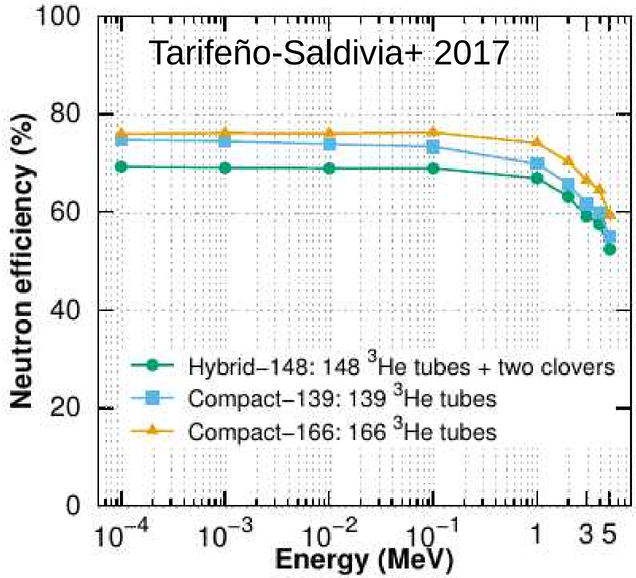


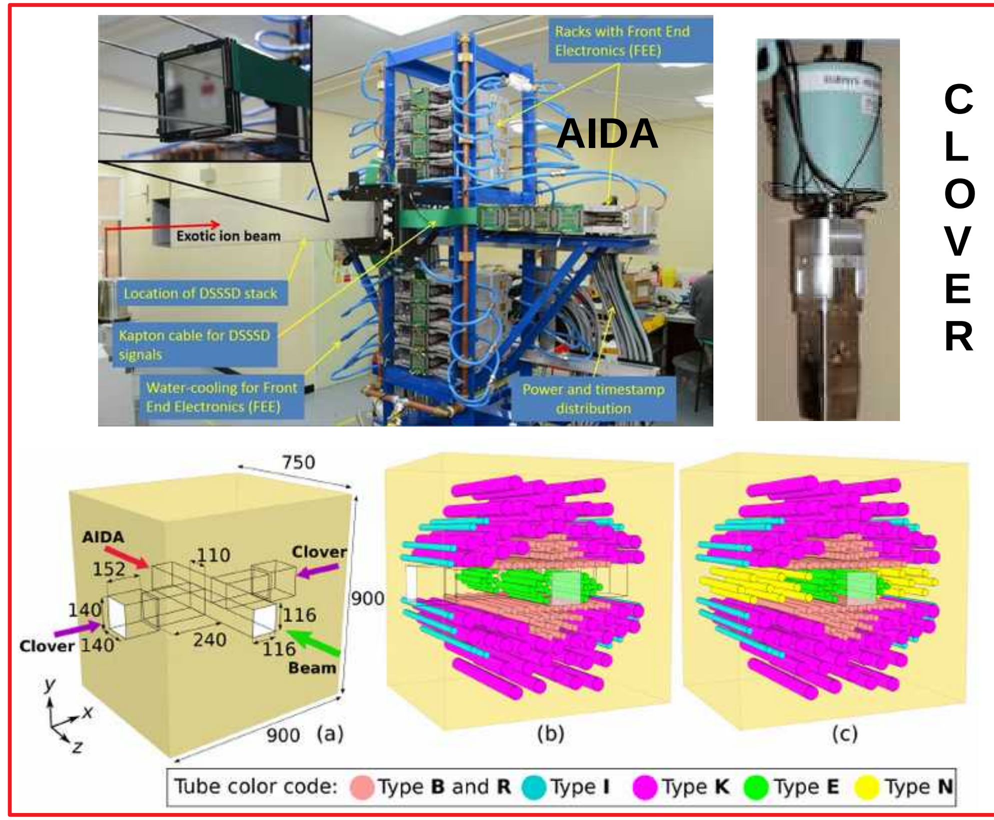
- **The largest ^{3}He moderated neutron counter**
- **The AIDA implant/decay detector**
- **The RIBF high intensity radioactive beams**
- **The BigRIPS+ZeroDegree spectrometer**

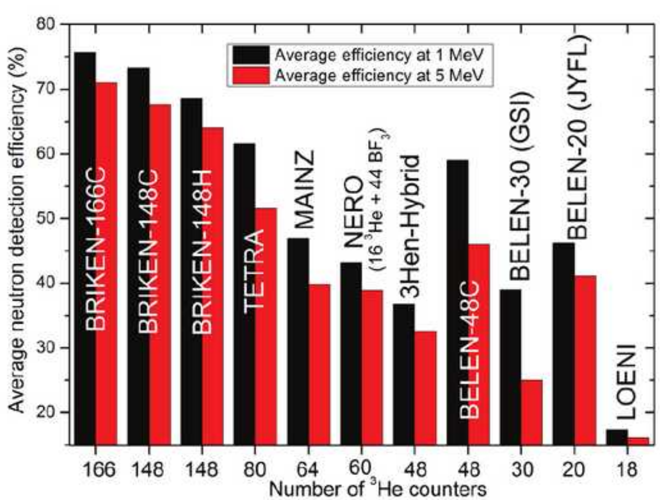


- **20 institutions**
- **50 participants**

- **BRIKEN neutron counter: conceptual design**



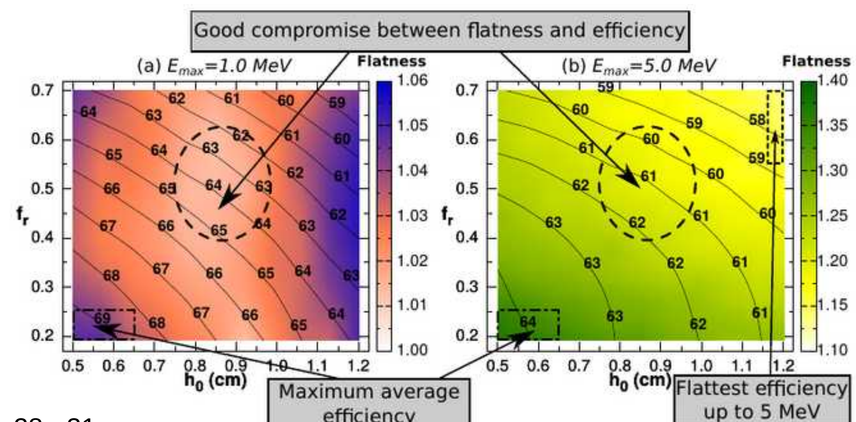




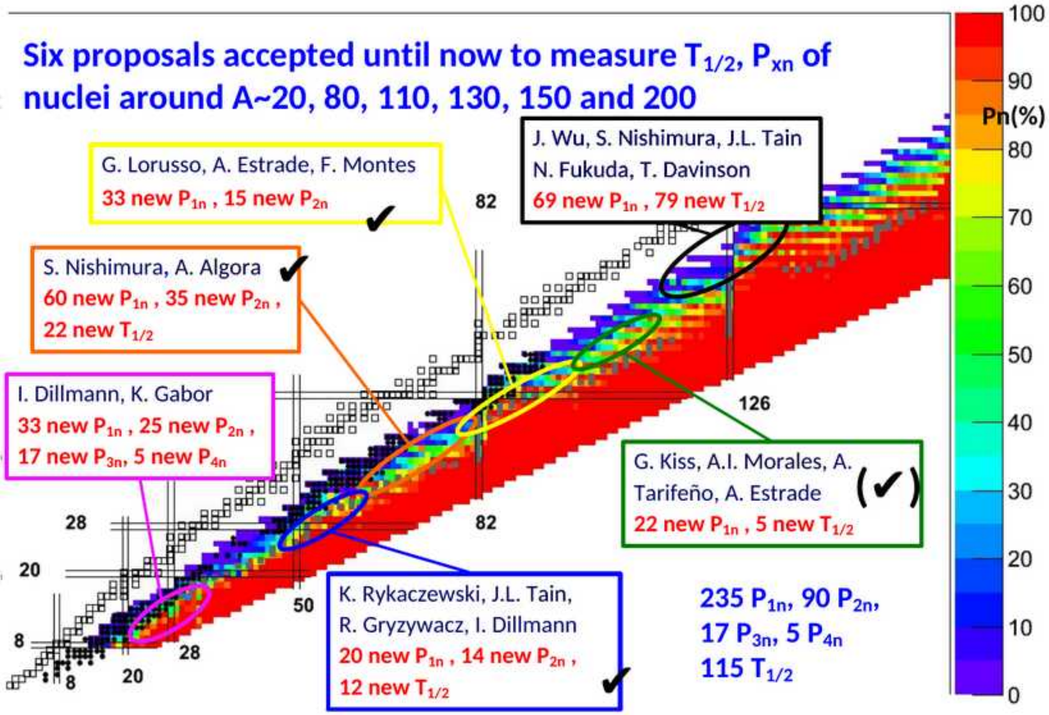
Particle Counter

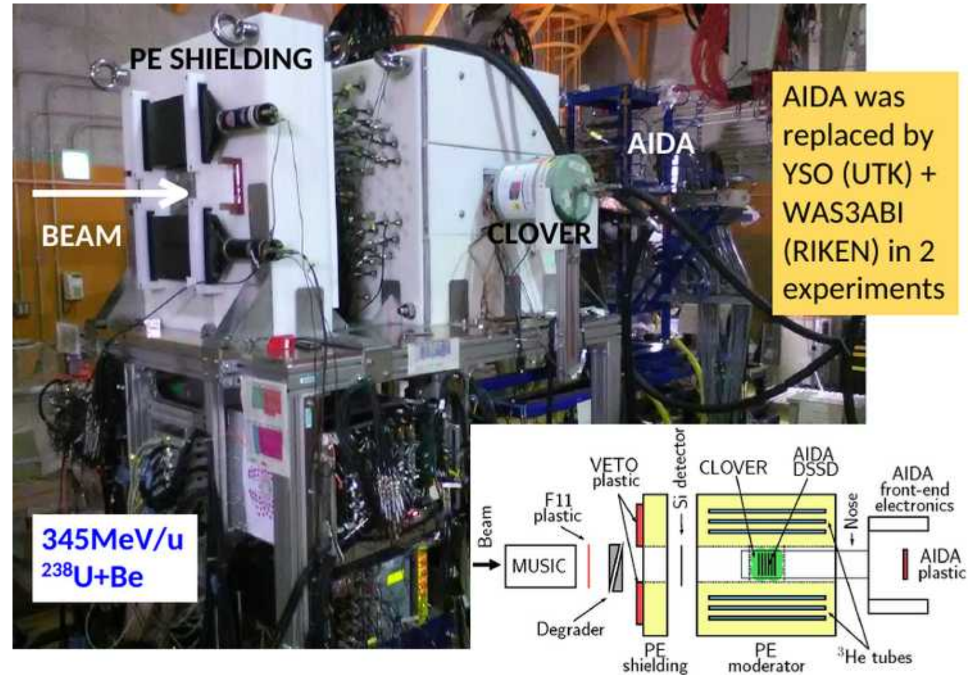
The largest beta-delayed neutron counter!

Topological Monte Carlo optimization algorithm



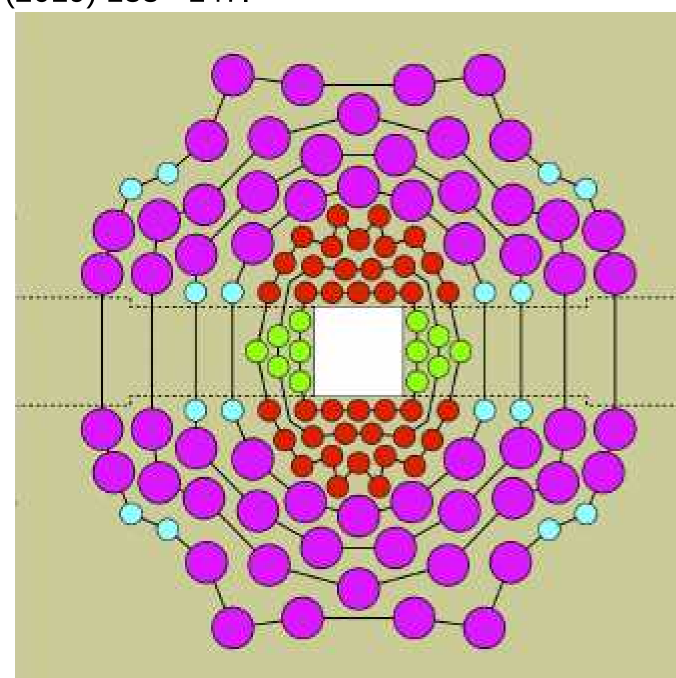
A. Tarifeño-Saldivia et al., Journal of Instrumentation. 12 (2017) P04006
I. Dillmann and **A. Tarifeño-Saldivia**. The "Beta-Delayed Neutrons at RIKEN" Project (BRIKEN): Conquering the Most Exotic Beta-Delayed Neutron-Emitters, *Nuclear Physics News* 28 (2018) pp 28 - 31.





Tolosa-Delgado et el.
NIM A 925 (2019) 133 - 147.

	Identified (Qbxn>0) # of isotopes	Measured (06/2017) # of isotopes	Fraction	Measured mass region
β1n	621	298	48.0%	^{8}He-^{216}Tl
β2n	300	23	7.7%	^{11}Li-^{136}Sb
β3n	138	4	2.9%	^{11}Li-^{31}Na
β4n	58	1	1.7%	^{17}B



Neutron detectors: some examples

- **MANY project**

Two Spanish facilities

Infraestructuras Científicas y Técnicas Singulares

UPC

Universidad de Sevilla

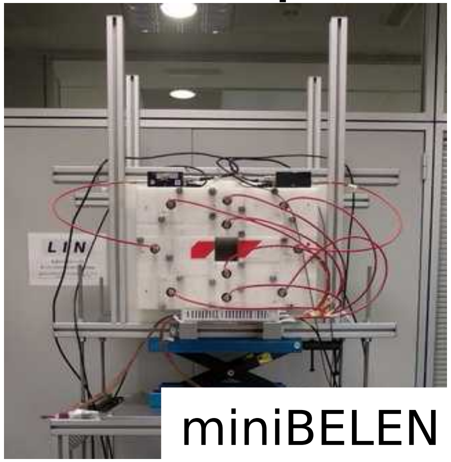
IFIC
INSTITUT DE FÍSICA CORPUSCULAR

Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

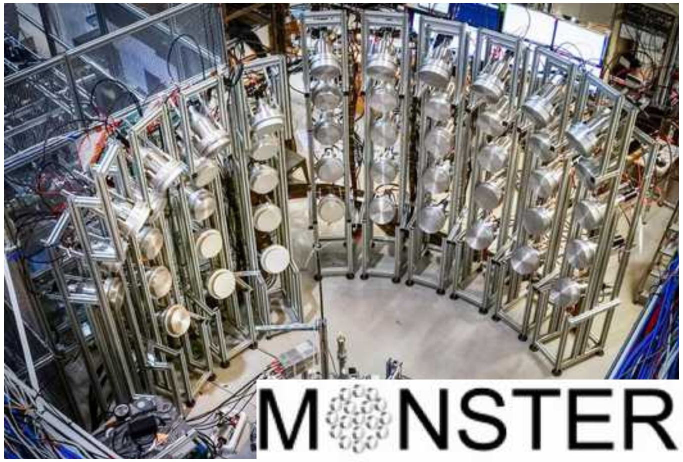
UNIVERSIDAD COMPLUTENSE MADRID

IEM
Instituto de Estructura de la Materia

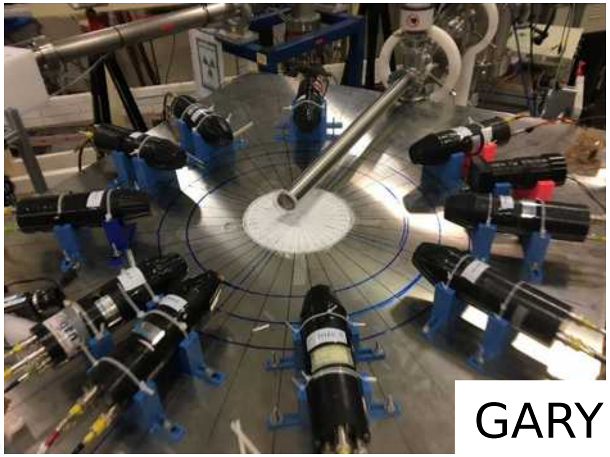
Three Spanish detectors



miniBELEN



MONSTER



GARY

Neutron detectors: some examples

- **MANY project**

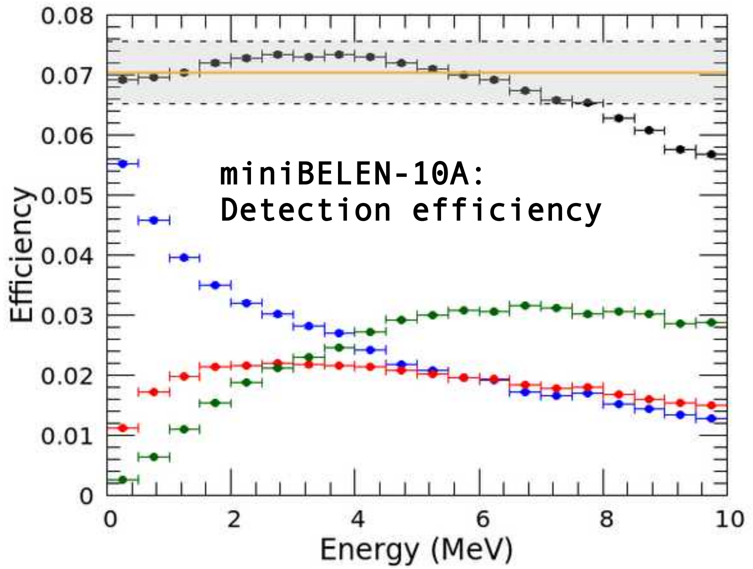
miniBELEN: modular neutron counter for (alpha,n) reactions

Particle Counter

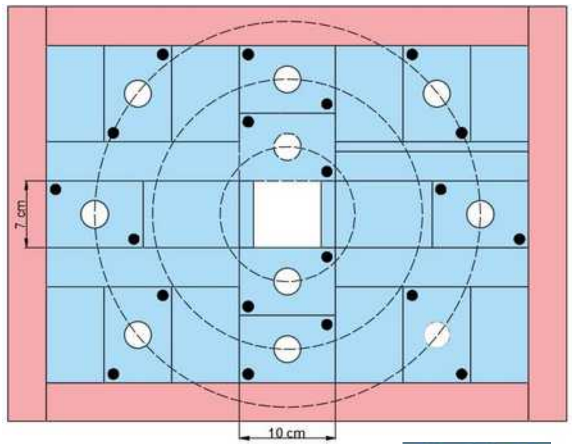
Scientific motivation

(alpha,n) reactions play are important for:

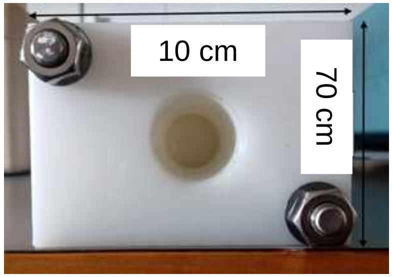
- **Nuclear astrophysics**. Source of neutrons for the s-process, "light" r-process.
- **Rare-event experiments**. Neutron-induced background in underground experiments (dark matter, neutrinos, neutrinoless double beta decay).
- **Nuclear technologies**. Fission and fusion reactors, spent fuel management and nonproliferation. Neutron-induced background in particle accelerators.



Detector cross section



Single moderator Module (HDPE)



miniBELEN-10A:
- A modular neutron detector based on moderated ^{3}He-filled proportional neutron counters (10 tubes, 1" diameter, 60 cm active length).
- Provides a response almost independent of the neutron energy up to 8 MeV.
- Nominal detection efficiency:
7% (up to 8 MeV)
- Detector design: arXiv:2304.07308 (2023)

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Institut de Tècniques Energètiques

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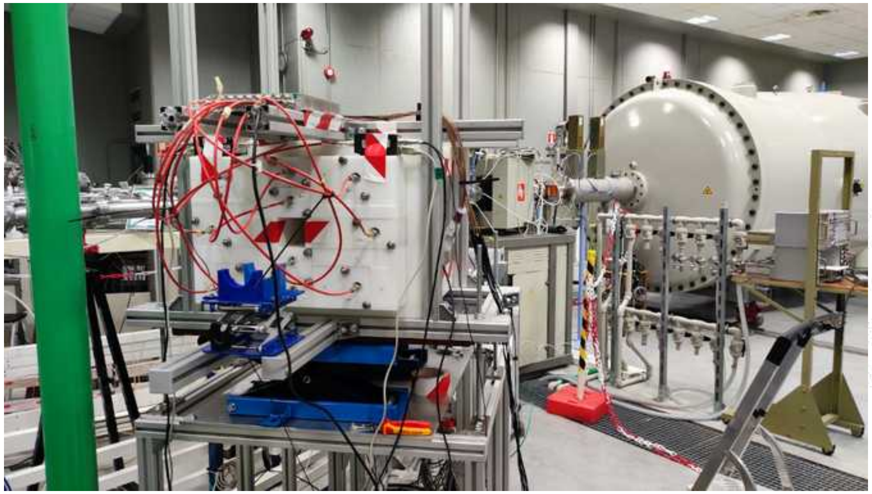
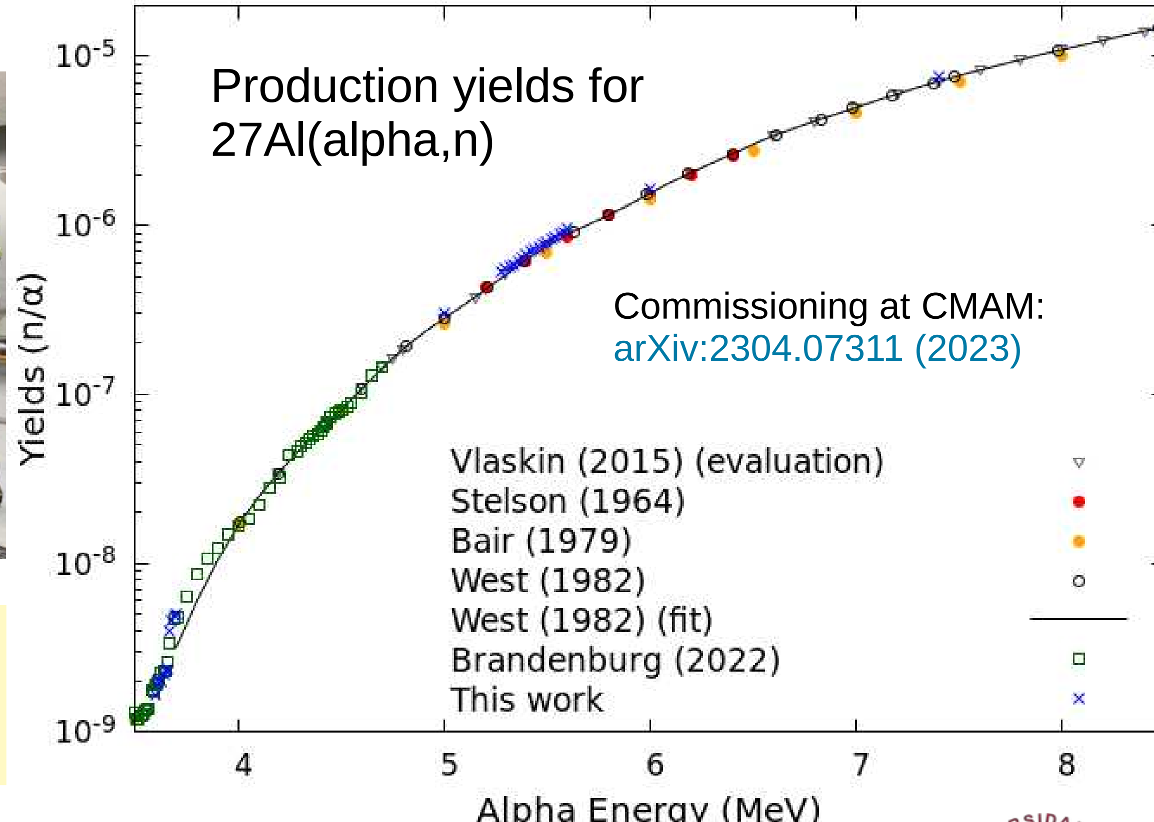
CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

Commissioning 45º beamline @ CMAM (Madrid)





MiniBELEN is part of the **MANY** collaboration: **M**easurement of **A**lpha **N**euntron **Y**ields

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Oportunidades de TFM y tesis doctorales en el contexto del proyecto MANY:
- Propuesta TFM: “Measurements and advanced instrumentation for study of (alpha,n) reactions”
- Posible contrato de tesis doctoral (2do semestre 2024)