Bureau International des Poids et Mesures

Webinar on neutron spectrometry for radiation protection

CCRI

Neutron spectrometry in radiation protection

Roberto Bedogni[1], David Thomas[2]

[1] INFN-LNF Frascati (RM) Italy
[2] NPL National Physical Laboratory, Teddington (UK)

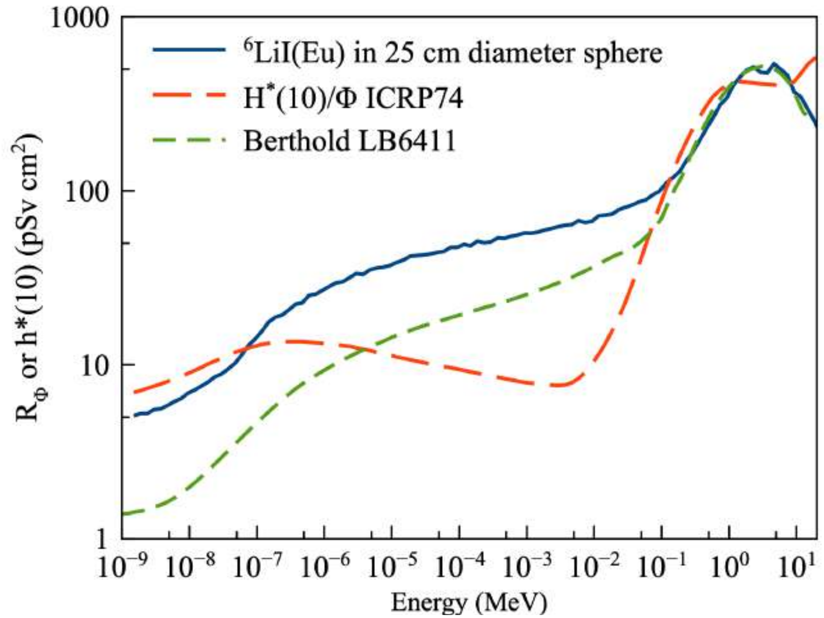
NPL National Physical Laboratory

INFN LNF Istituto Nazionale di Fisica Nucleare

Measuring neutrons

- Neutrons are neutral particles and are indirectly detected through the charged particles they liberate in elastic scattering or a nuclear reactions.
- **Spectrometry requires to measure the energy of these particles**
- Neutron spectra tend to span over various orders of magnitude in energy:
  - from tens of keV to 10-12 MeV for radionuclide neutron sources
  - From thermal neutrons to tens / hundred MeV in workplaces
- No single sensitive element exists which can respond over these intervals

When determining dose equivalent quantities, the fluence of every energy component must be weighted according to the complex energy dependence of the pertinent fluence to dose equivalent conversion coefficient



Quantities needed in neutron spectrometry

Radiometry quantities = quantities defining the radiation field

Fluence

$$\Phi = \frac{dN}{da}$$

quotient between the number of particle dN incident on the elemental sphere having cross sectional area da, and the cross sectional area da; unit m^{-2}, cm^{-2}.

- All particles are equally weighted, independently on their direction.
- An instrument with isotropic response is ideally needed
- Monte Carlo codes derive the fluence in a cell of volume V as

$$\Phi = \frac{\sum \ell_i}{V}$$

where li are the track lengths in the volume V

Fluence rate

$m^{-2}\,s^{-1}$, more frequently $cm^{-2}\,s^{-1}$

$$\dot{\Phi} = \frac{d\Phi}{dt}$$

The distribution of the fluence with respect to energy (spectrum)

$$\Phi_E(E) = \frac{d\Phi}{dE}$$

$m^{-2}\ J^{-1}$, $cm^{-2}\ MeV^{-1}$

- Plotting dΦ/dE vs. E is often a misleading representation, as E varies over many orders of magnitude and is difficult to note the main features of the spectrum
- A convenient concept is the **unit spectrum**, i.e. normalised to the total fluence. The unit spectrum has unit integral and only contains the "shape" of the spectrum.

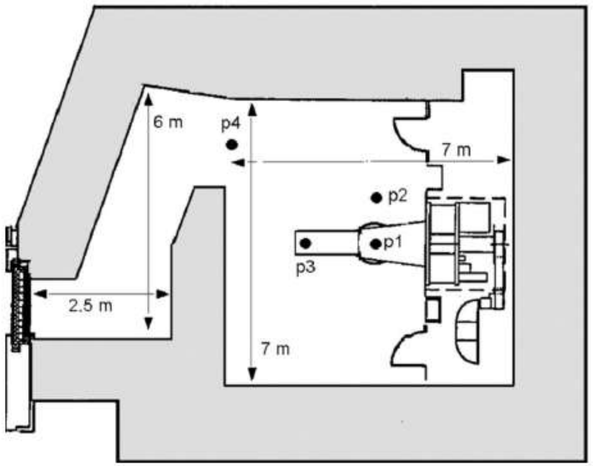
$$\varphi_E = \frac{1}{\Phi} \cdot \frac{d\Phi}{dE} \qquad \int dE \cdot \varphi_E = 1$$

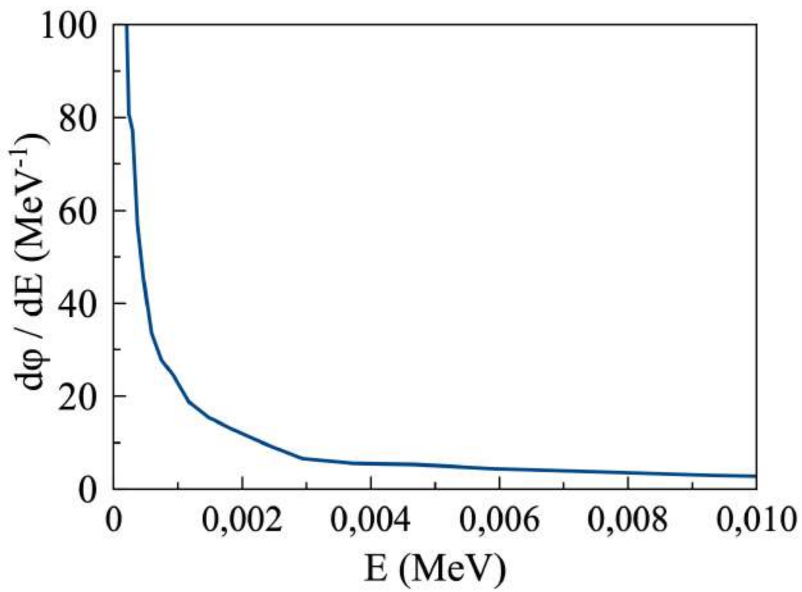
- The unit spectrum is used to derive spectrum averaged quantities

$$h = \frac{H}{\phi} = \frac{\int dE \frac{d\phi}{dE} h(E)}{\int dE \frac{d\phi}{dE}} = \frac{\phi \int dE \frac{d\varphi}{dE} h(E)}{\phi \int dE \frac{d\varphi}{dE}} = \int dE \frac{d\varphi}{dE} h(E)$$

Representation of the neutron spectra

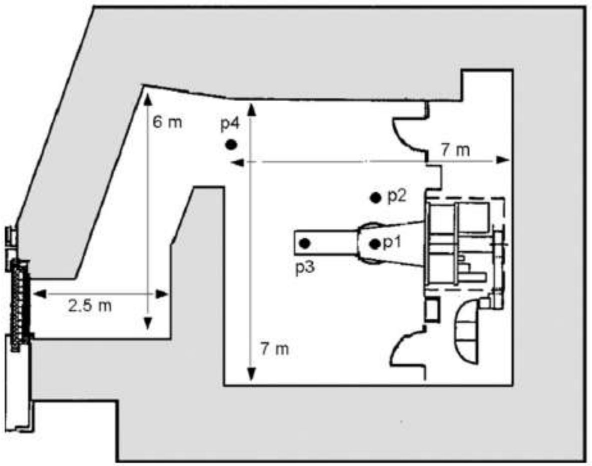
- Plotting dΦ/dE vs. E is often a misleading representation, as E varies over many orders of magnitude and is difficult to note the main features of the spectrum
- Example: unit spectrum @ 1 m from the isocentre of a 15 MV medical linac

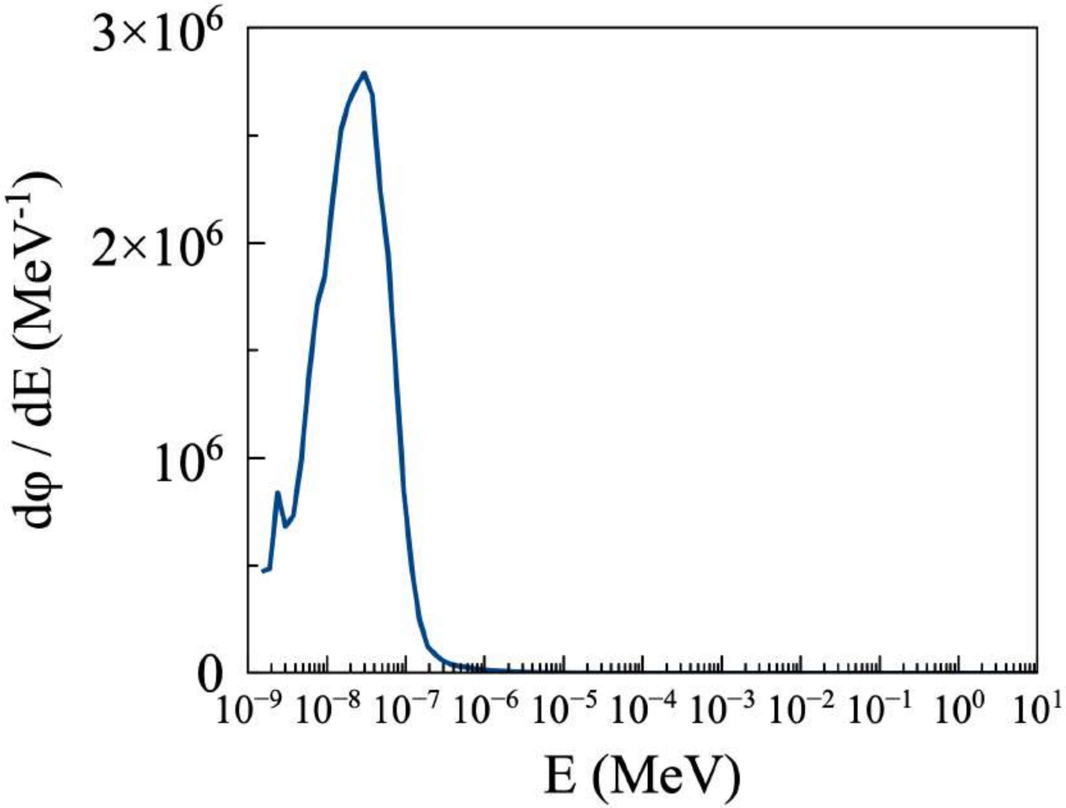




- This representation can be of help to focus on a limited part of the spectrum

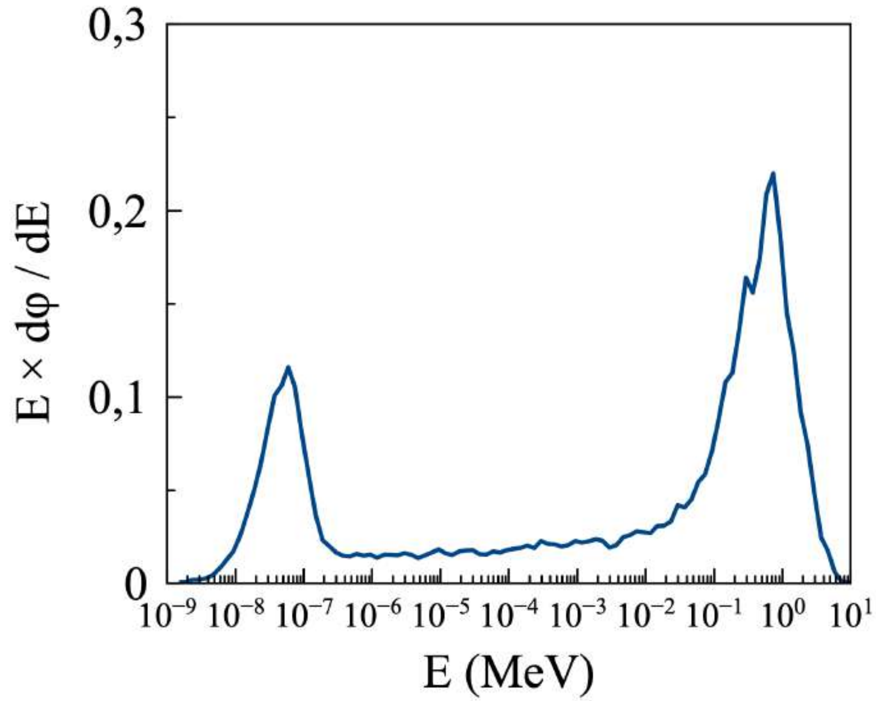
- Plotting dΦ/dE vs. log(E) is of more help but it does not preserve the proportions
  - We ideally desire that equal areas correspond equal neutron fluence values





- The proportions are preserved if the lethargy distribution of the fluence dφ/du is plotted vs. log(E)

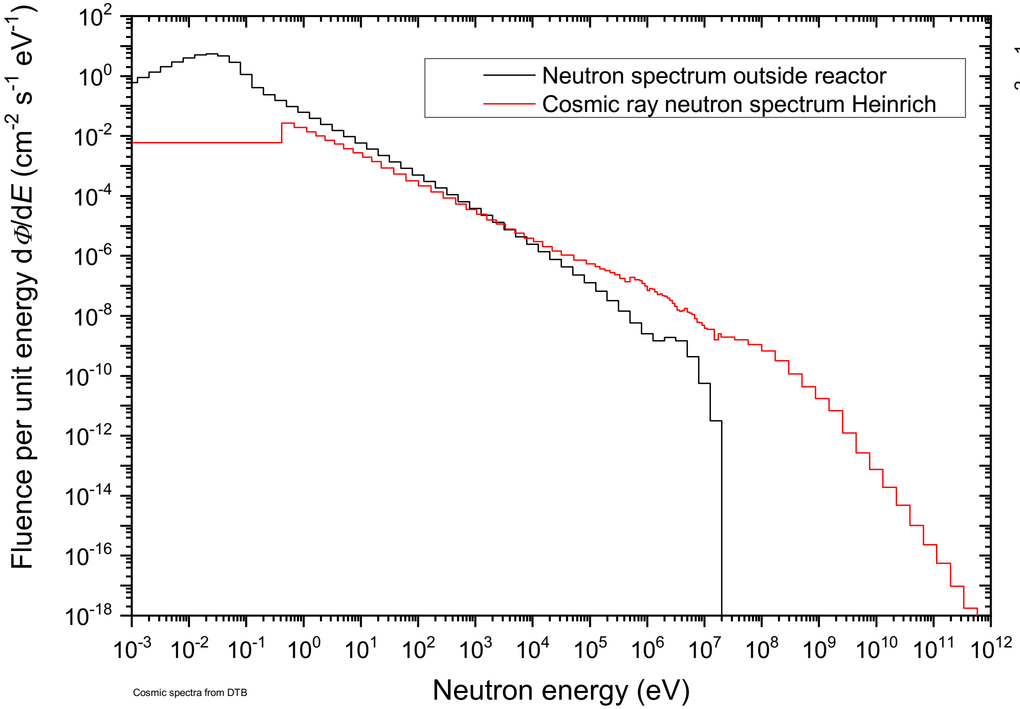
  u = lnE
  du = dE/E
  dφ/du = E dφ/dE

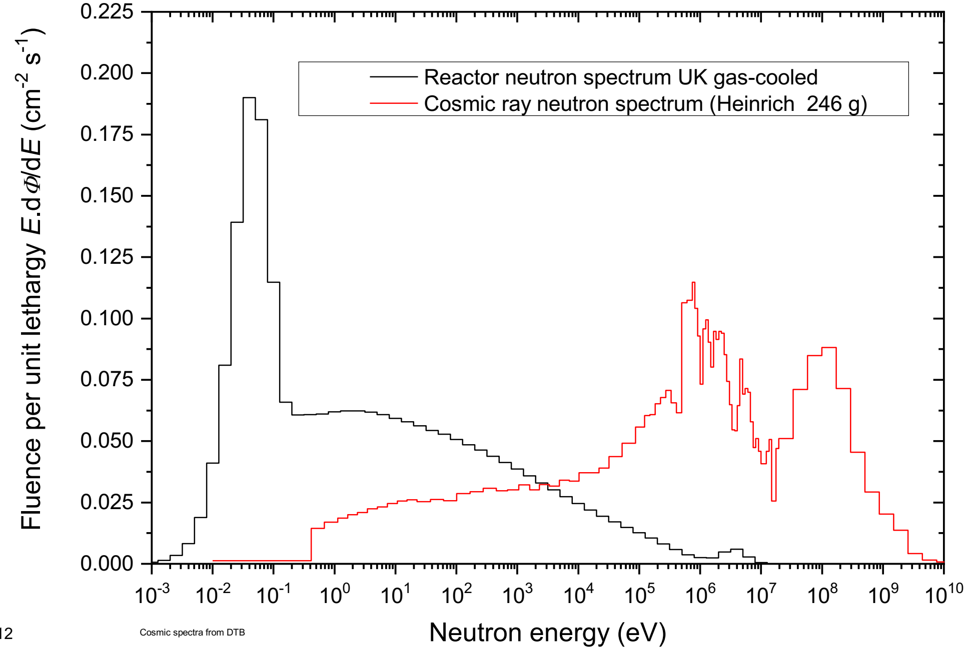


- Why are the proportions preserved?
  - Imagine to calculate the graphical integral

$$\int d(\ln(E))\, E\,\frac{d\Phi}{dE} = \int \frac{dE}{E}\, E\,\frac{d\Phi}{dE} = \Phi$$

Comparing ‘workplace’ neutron spectra





Lethargic representation helps identifying the structures in a spectrum and comparing different spectra

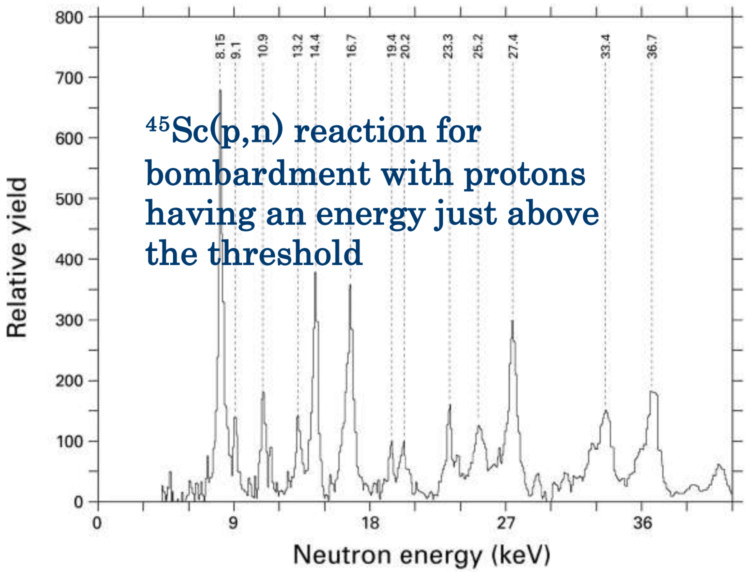
Methods for neutron spectrometry

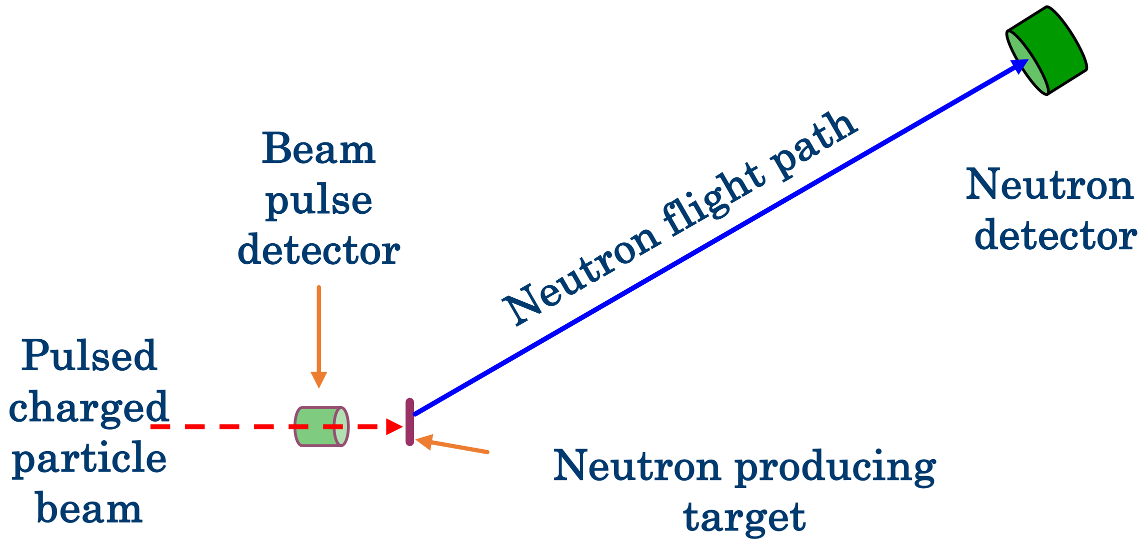
- Time of flight (TOF)
- Nuclear recoil spectrometers
  - Gas-based recoil proportional counters
  - Scintillators
  - Recoil proton telescopes
- Exothermic reaction $^{3}He(n,p)^{3}H$
- Activation spectrometry
- Extended energy-range spectrometers based on moderation
  - (Slow neutron detectors)
  - Bonner spheres
  - Single moderator spectrometers
- Spectrometry in neutron calibration

Time of flight

Time of flight (TOF)

- The energy distribution of neutrons can be determined from a measurement of the flight time t required to travel a distance (flight path)



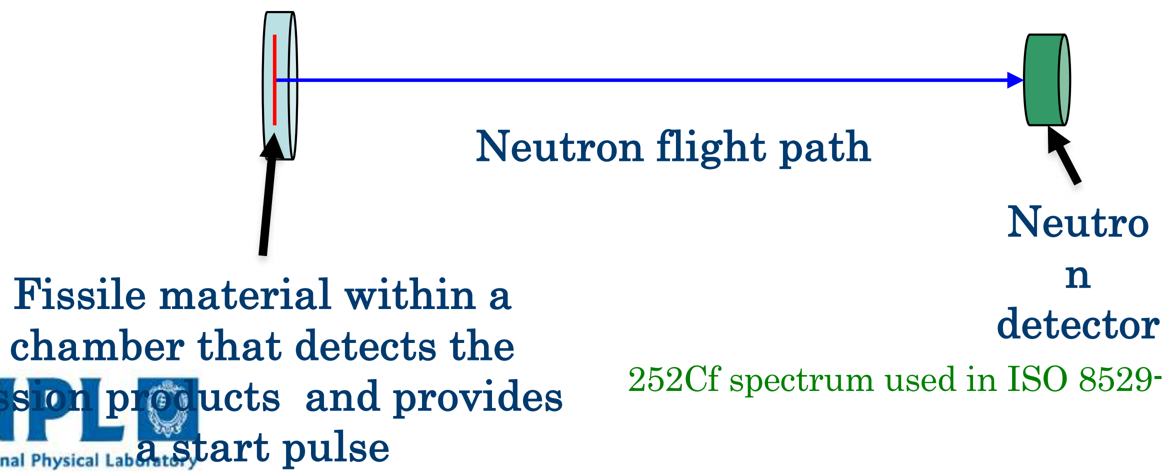


- Starting time = signal from the accelerator diagnostics or any particle or gamma associated with the neutron production, for example fission products in the case of spontaneous fission (^{252}Cf source)

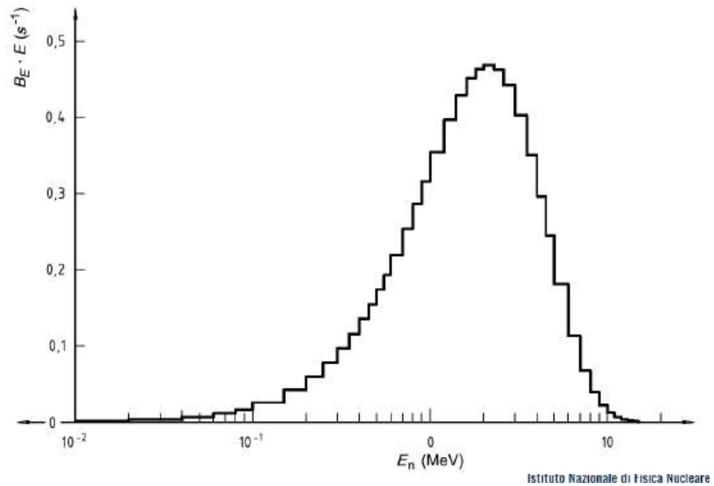
- Arrival time = signal from a detector at a distance “large enough” (few - tens of m) to obtain “long enough” flight time (> hundreds ns)

Numbers and examples

Flight Path Length (m)	Neutron Energy (MeV)	TOF-γ (ns)	TOF n (ns)	ΔE (keV)
10	1	33	722	3
	2		511	8
	10		230	87
	20		164	244
	100		78	2569
	500		44	22739



252Cf spectrum used in ISO 8529-1



Time of flight (TOF)

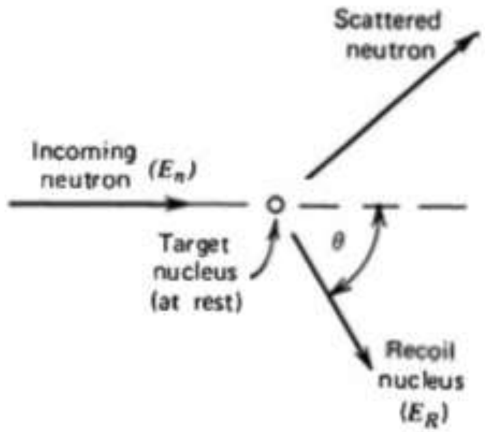
- Desirable:
  - Short neutron pulses (ns)
  - Thin neutron producing targets
  - Neutron detectors with time resolution ≈ neutron pulse duration
  - Detector should be thin compared to flight path

- Keep-in-mind features:
  - Timing electronics can be quite complex.
  - The quality of the spectrum depends on: the pulse width, the detector thickness and area, and the length of the flight path.
  - May have to compromise energy resolution for efficiency.
  - The time-of-flight neutron detector response function needs to be known. Often rely on calculation.

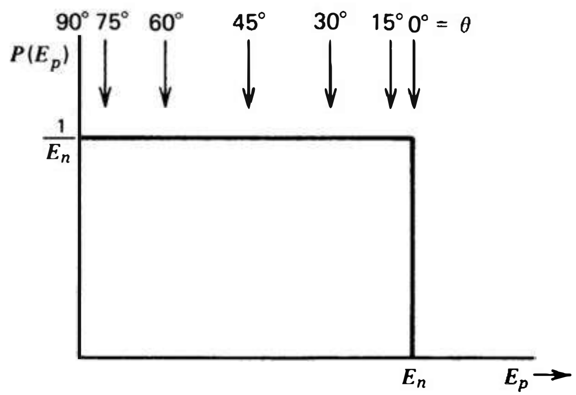
Spectrometers based on recoil nuclei from elastic scattering

•Elastic scattering from light nuclei is convenient because the maximum recoil energy (obtained at θ=0°) decreases as A increases

$$E_R = \frac{4A}{(1+A)^2}(\cos^2\theta)E_n$$



•In case of	Hydrogen	$E_{R\,max} = E_n$
	4-Helium	$E_{R\,max} = 0.64\ E_n$
	Carbon	$E_{R\,max} = 0.28\ E_n$



- Very important simplification: isotropic scattering in CM (ok for H < 5 MeV). The expected proton recoil energy distribution is a rectangle.
- Rectangular shape in real is distorted by a number of effects.
- Efficiency is e = 1-exp(-Σ x)

$$\sigma_s(E_n) = \frac{4.83}{\sqrt{E_n}} - 0.578\ \text{barns}$$

For Hydrogen

Gas-based recoil proportional counter (tens of keV to MeV)

Radiation Protection Dosimetry 107 (2003) 73–93

1. Filling gas can be
   - H_2 (mostly) and CH_4, where recoil nuclei are protons
   - ^4He, where recoil nuclei are alphas
2. Shape of the response functions nearly rectangular (scattering is isotropic in CM for H < 5 MeV) - No multiple scattering - Wall effects always important
3. Need to unfold the spectrum. The response matrix must be known.

1. Low Efficiency
2. Excellent linearity
3. PSD useful to separate 2ry electrons from neutrons (recoil tracks are shorter than electron tracks)
4. Detector shapes are
   - ✧ spherical (isotropic but non uniform electric field)
   - ✧ cylindrical (anisotropic but excellent electric field)

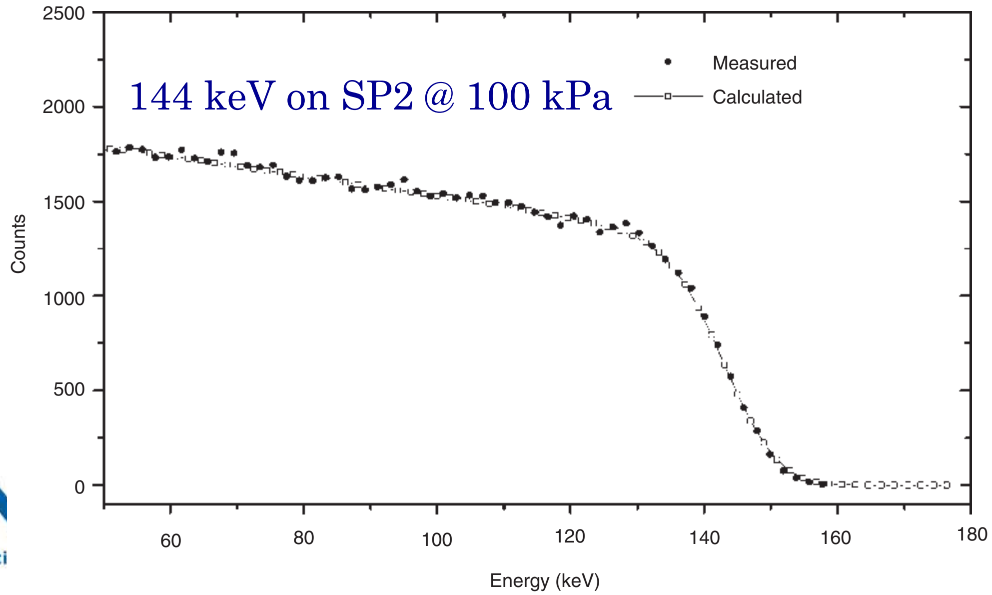
Hydrogen proportional counters
~ tens keV up to 1.5 MeV

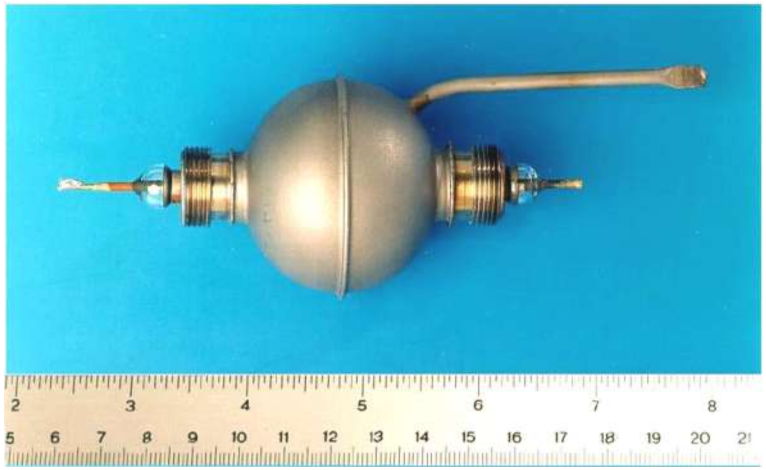
energy region where fluence to dose equivalent conversion coefficients change rapidly

- •Xs well known and reasonably high
- •Scattering is isotropic in CM up to 5 MeV
- •the mean energy loss of secondary protons is constant (36 eV per ion pair)
- •Energy calibration is difficult (internal source or traces ^{3}He)

SP2 (R= 2 cm, various pressures)

✓high energy resolution (d*E*/*E* few %)
✓isotropic response well known and experimented
✓Covers 50–1500 keV energy range

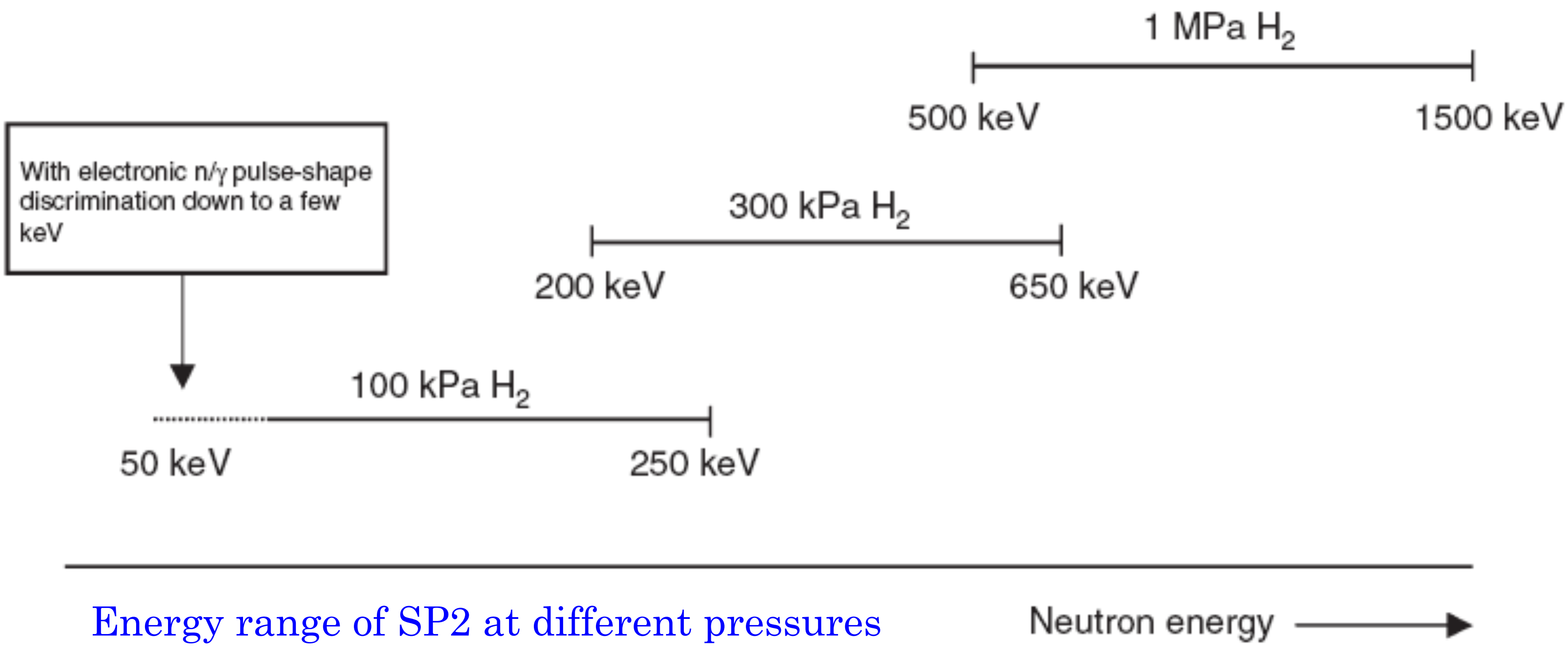




Limited proportionality / distortion

- wall effect
- gas amplification not constant in volume
- electric field drops at ends of anode wire

SP2 Proportional counters



Energy range of SP2 at different pressures

Spectrometry with proportional counters can be extended to neutron energies higher than 1.5 MeV by using:

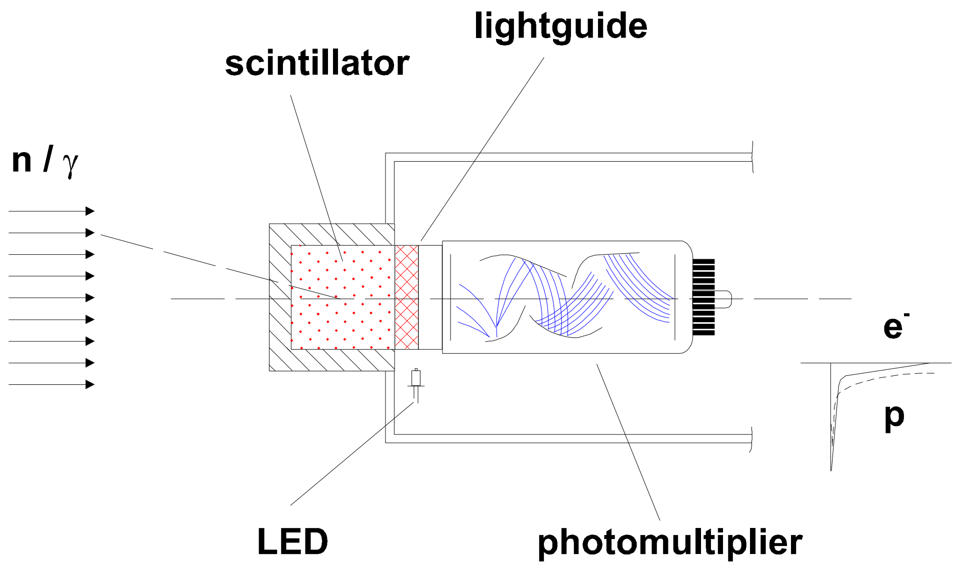
- ✓ large spherical counters filled with hydrogen, methane or propane
- ✓ Ar or Xe to increase stopping power and limit wall effects (up to 5 MeV)
- ✓ ^{4}He filling

Rotating spectrometer (ROSPEC)

Rospec has a number of spherical hydrogen recoil counters. It rotates so the average distance from the source to the measurement point on the axis of rotation is the same for all detectors.

Scintillators

RPD 107 (2003) 95-109



- Hydrogenated organic scintillators
- Higher efficiency than gas counters
- Proton range << detector size, no wall-effects
- Respond to photons
  Rejection methods based on pulse duration and shape)
- PHD does not differ too much from ideal rectangular shape

Organic crystals

Delicate, Anisotropic, Expensive, high light yield (antracene) and g/n discrimination applicable (stylbene)

Plastic

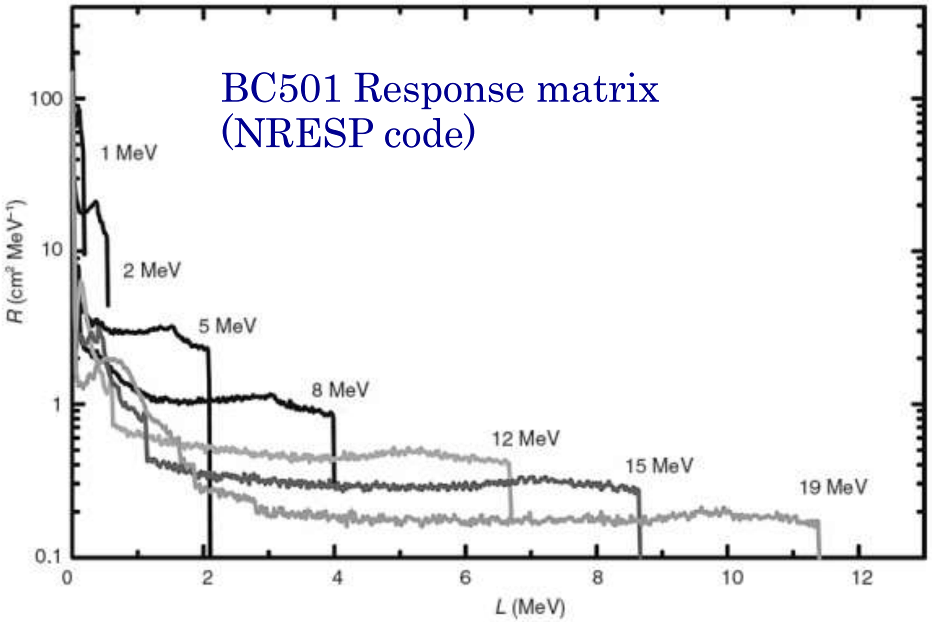
Easy to machine and cheap, transparent, used to have difficult gamma discrimination, but now plastic material with pulse shape discrimination are becoming available

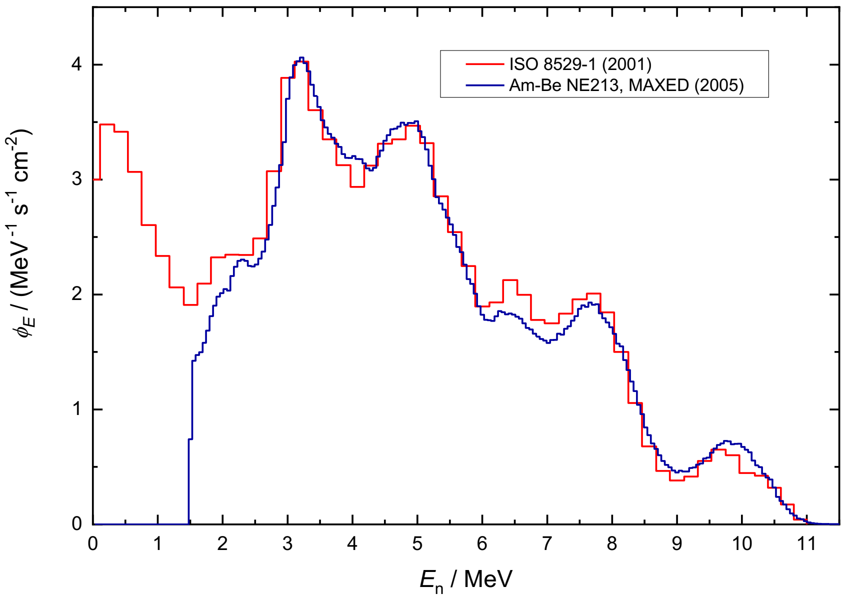
Liquid - NE213 / BC501A

Good g/n discrimination
Light output non linear with proton energy
Difficult calibration (Compton edge)

Measurements with liquid scintillators

Typical energy range 0.5 to > 20 MeV





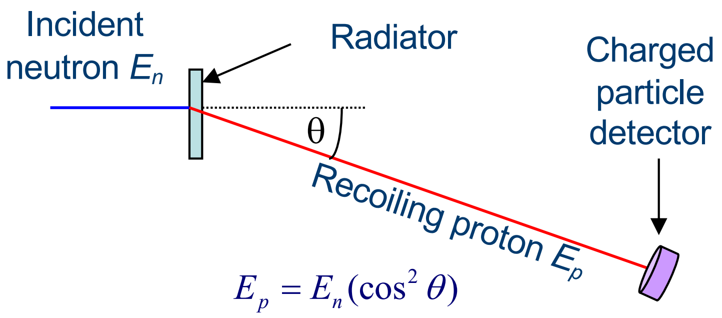
- L(E) not linear but $L(E) \approx E^{3/2}$ thus $E \approx L^{2/3}$
- In case of monoenergetic neutrons the spectrum
  dN/dE = costant (rectangular)
  $dN/dL = dN/dE / (dL/dE)$
  $\approx E^{-1/2} \approx (L^{2/3})^{-1/2}$
  $\approx L^{-1/3}$
- Low-E distortion increased by wall-effect in small volumes

Example of a spectrum measured with an NE213 (BC501, EJ-301) organic liquid scintillator compared to the spectrum in ISO Standard 8529.

By A. Zimbal, PTB

Recoil proton telescopes

Radiat. Meas. 85 (2016) 1-17



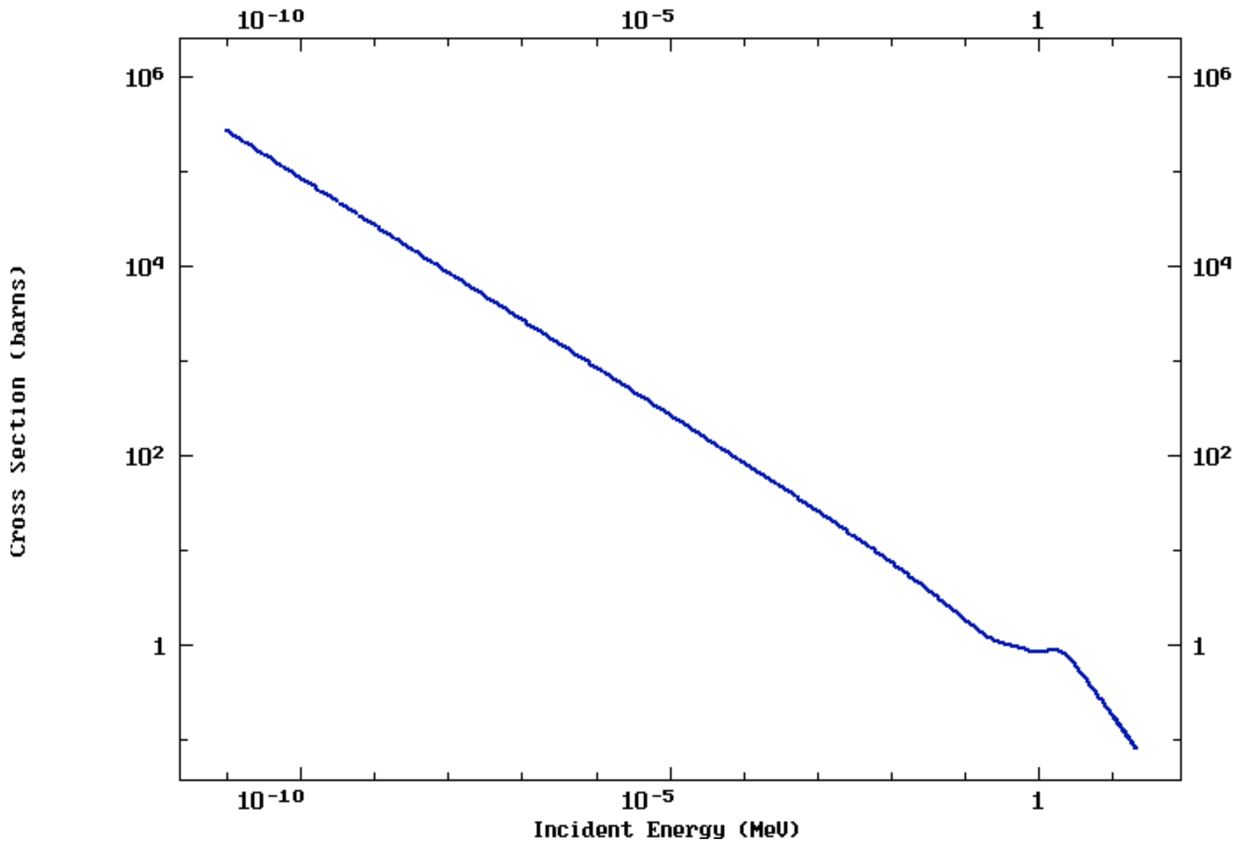
- Typical energy range tens of keV to few MeV
- Incident n direction must be FIXED and well known
- Use a polymer radiator with thickness << lowest range of recoil to be measured
- In vacuum
- Usually $\theta \approx 0$ (not zero to avoid exposing the detector in beam)
- Two detectors in coincidence (usually semiconductors) are used to reduce background (Ep = E1 + E2)
- Very low efficiency (typ. 1E-5):
  - thin PE radiators have 1E-3 / 1E-4 yield;
  -solid angle the detector must be kept low, to favour E resolution
- No wall effects, No multiple scattering
- Active radiator can increase efficiency

Exothermic reaction $^{3}He(n,p)^{3}H$

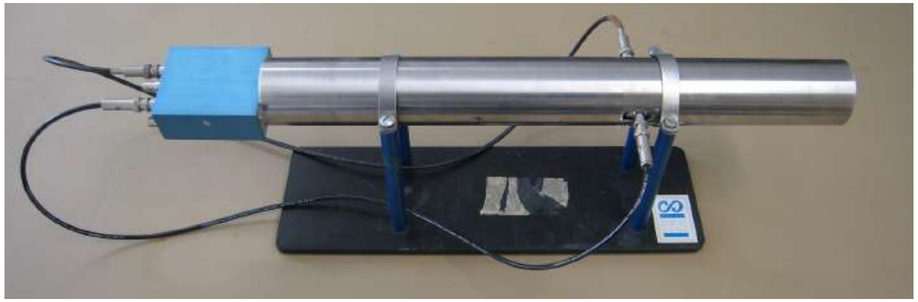
NIM A 510 (2003) 346-356
NIM A 366 (1995) 340-348

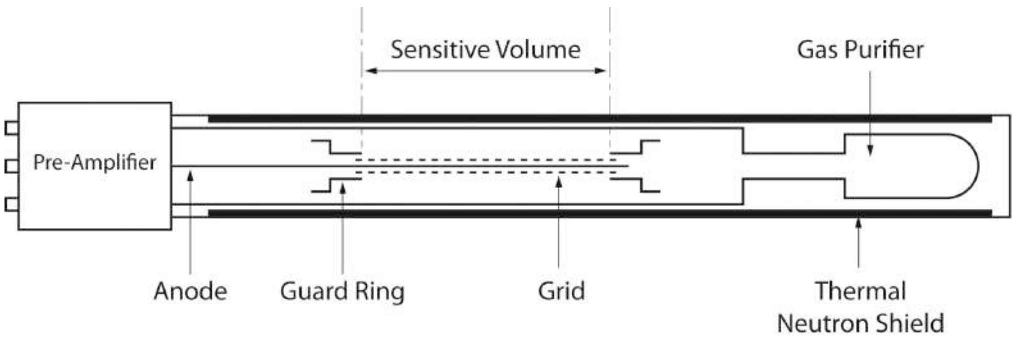
$^{3}He(n,p)^{3}H + Q$ (Q = 764 keV)

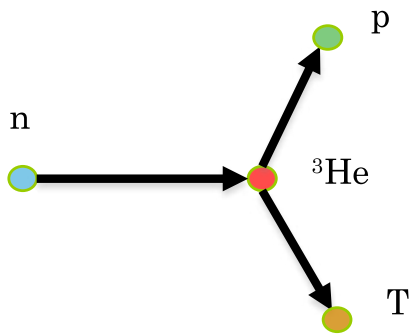
- A neutron of energy E_n produces a pulse of height $E_n + Q$.
- Thermal neutrons appear at 764 keV - Photon discrimination is easy
- Works well up to 1 MeV (where elastic scattering becomes important)



The ^{3}He gridded ion chamber
(only working in very low scatter environment)



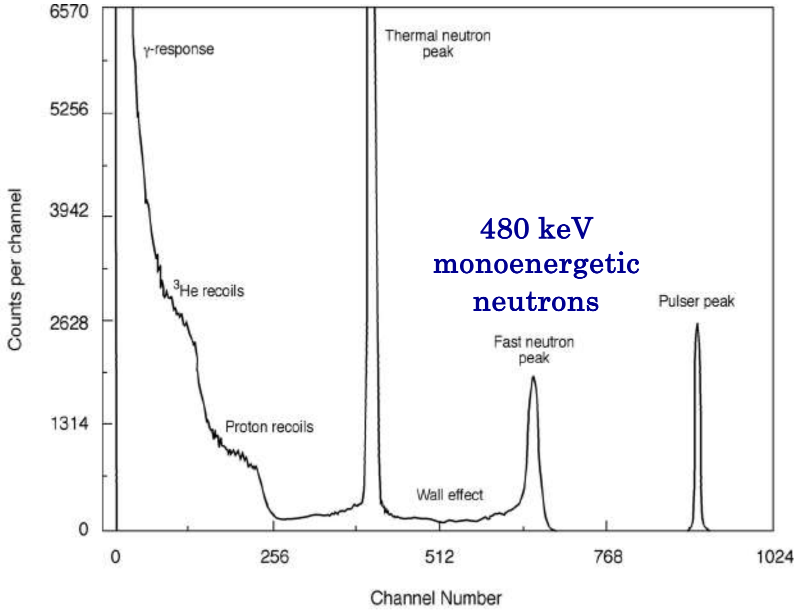


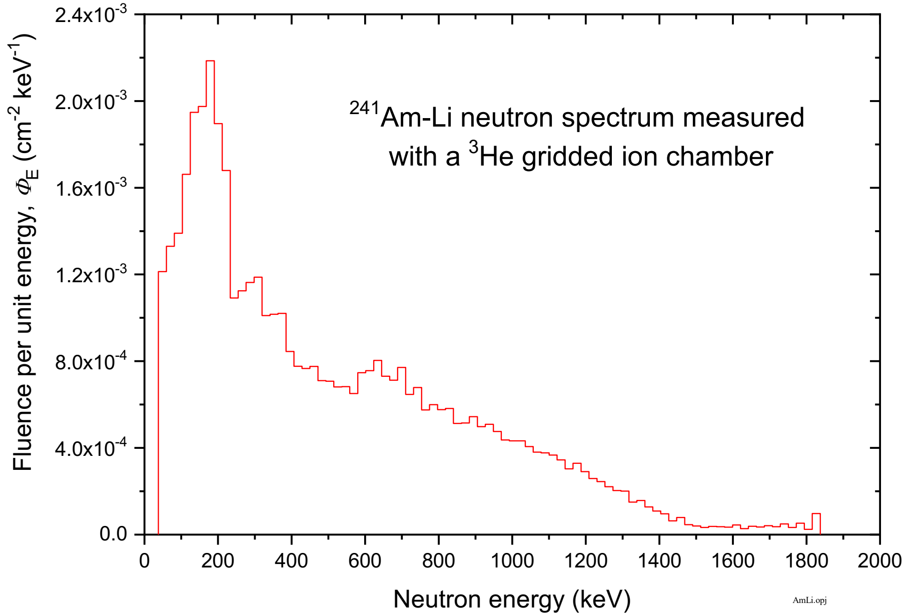


Must measure the full energy of both particles from the ^{3}He(n,p)T reaction to get spectrometric information

The ^{3}He gridded ion chamber

(only working in very low scatter environment)

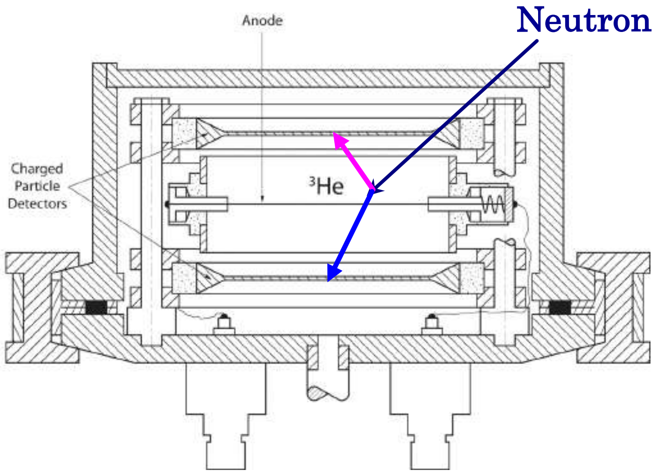


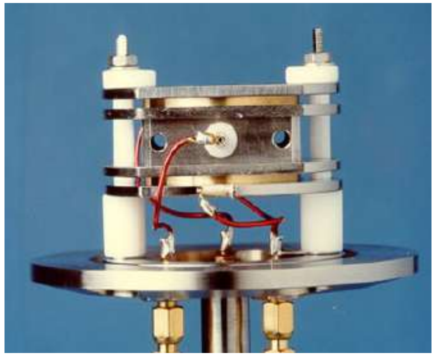


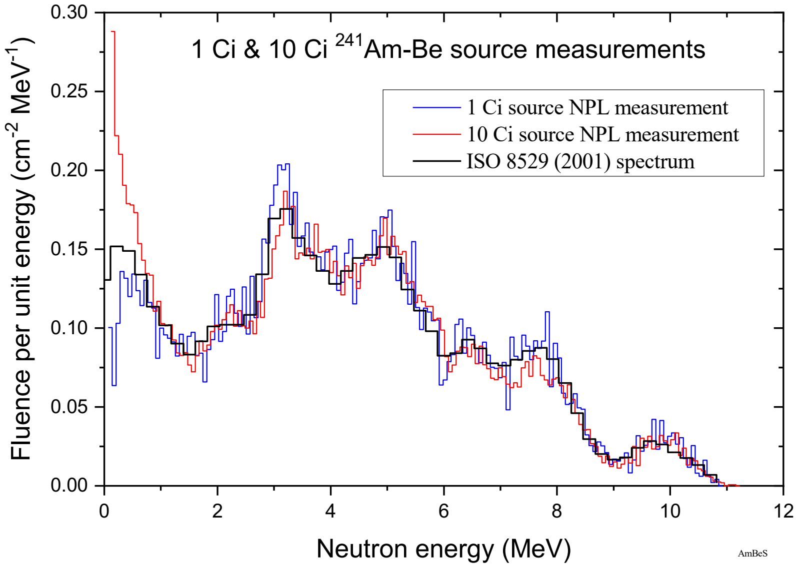
480 keV monoenergetic neutrons measured in a low-scatter environment

The ^{241}Am-Li radionuclide source spectrum measured in the same low scatter area

^{3}He(n,p)T sandwich spectrometer







- ^{3}He gas acts as radiator + proportional gas
- ^{3}He gas is sandwiched between two charged particle detectors
- Proton and the triton go off in opposite directions to preserve momentum
- A triple coincidence between the proportional counter and the two charged particle detectors gives the neutron energy.

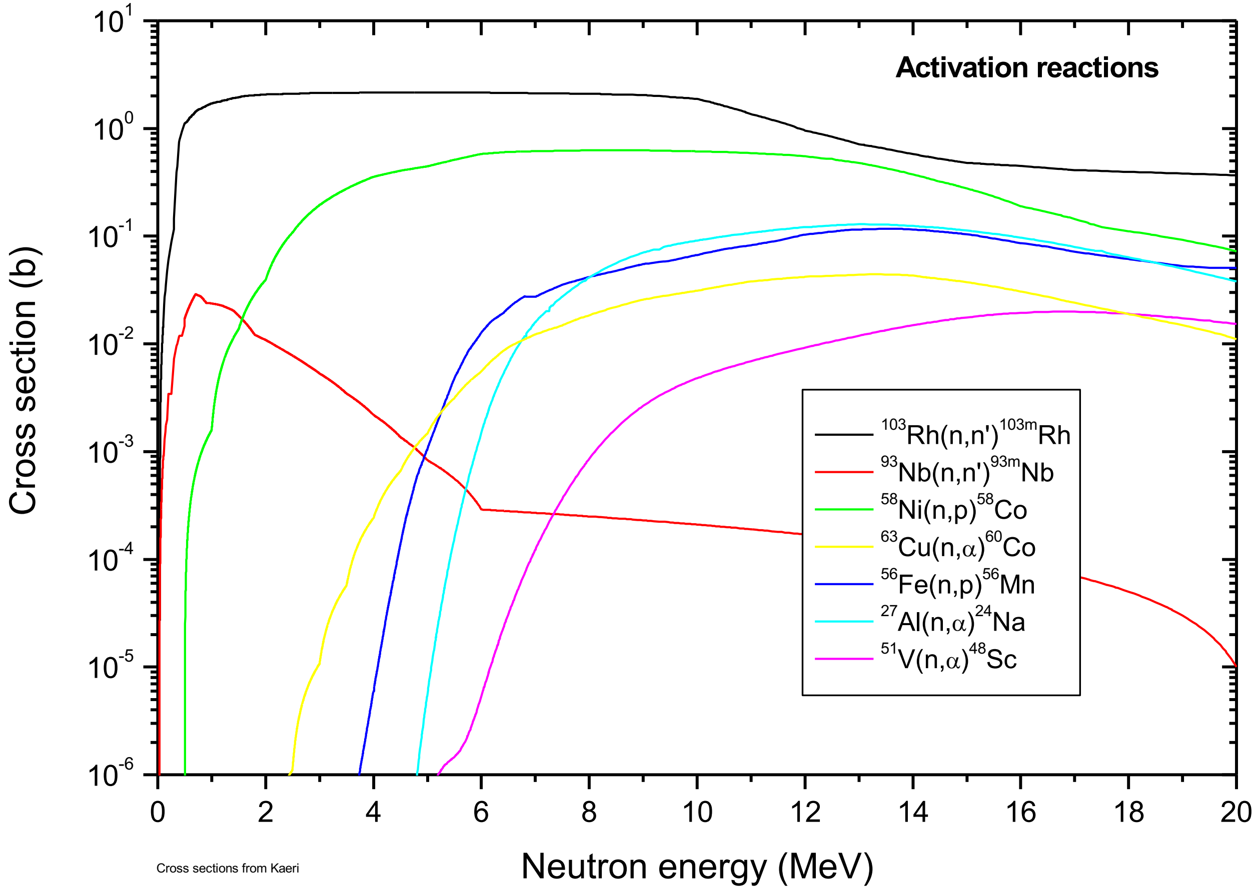
Activation spectrometers

- Used for intense fields, such as e.g. for reactor dosimetry measurements to derive information about pressure vessel integrity, or at fusion facilities to derive information about the plasma and neutron production.
- Foils of different materials (usually metals) have cross sections with different thresholds / resonances / shapes that are unfolded by inverting the integral equation

$$M_k = \sum_{i=1}^{n} \sigma_{ki} \phi_i$$

Uncertainty, and often covariance data, are available for the cross sections and codes have been written to use this information, e.g. STAYSL, which also uses uncertainties in the Φ_i values.

Cross sections for some activation materials



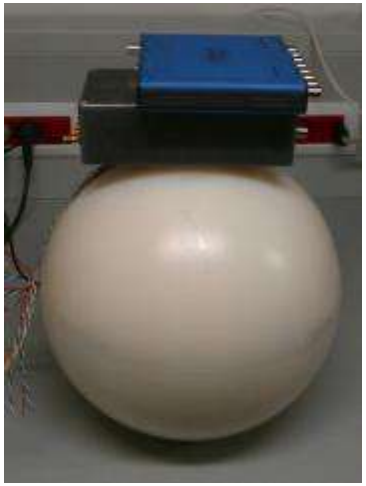
Activation cross section shapes have threshold features.

Example:

^{51}V(n,α)^{48}Sc: 6 MeV treshold
^{63}Cu(n,α)^{60}Co: 3 MeV treshold

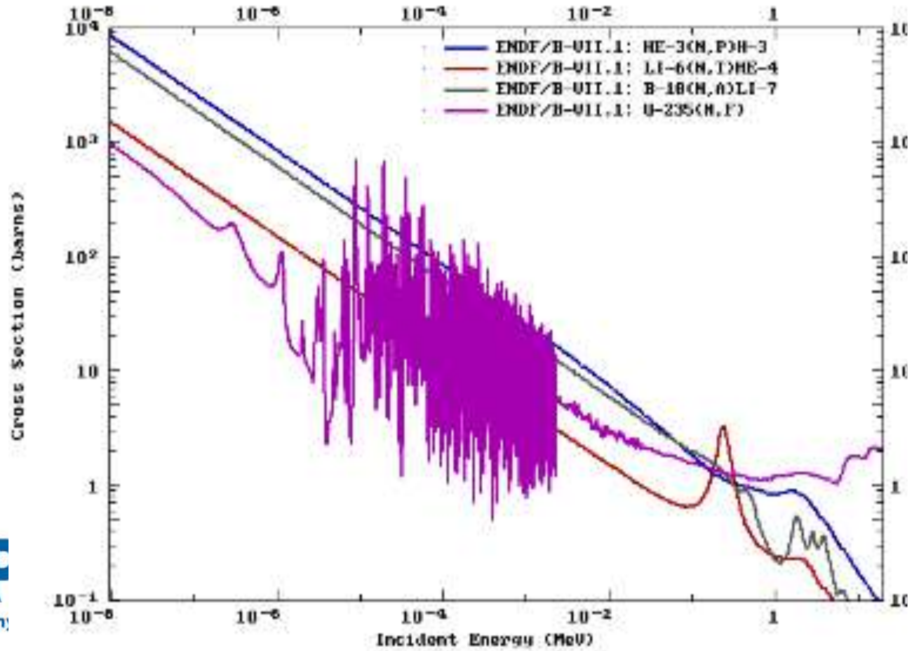
Thus the difference between the activation of these isotope gives information about the neutrons between 3 and 6 MeV.

Extended energy-range spectrometers based on moderation



Slow neutron detectors

1. High cross section
2. High abundance, or low-cost enrichment
3. Gamma insensitive process – high Q value
4. Easy-to-detect-secondary particles (charged better)
   - Recoil nuclei
   - Protons
   - Alphas
   - Fission fragments
5. Secondary particles possibly stopped in the detector (minimize wall effect)



$^{10}B(n,\alpha_0)^7Li$:	$Q_0 = 2.792$ MeV
$^{10}B(n,\alpha_1\gamma)^7Li$:	$Q_1 = 2.310$ MeV
$^6Li(n,t)^4He$:	$Q = 4.78$ MeV
$^3He(n,p)^3H$:	$Q = 0.764$ MeV
$^{235}U(n,fiss)$:	$Q \approx 200$ MeV

Boron-10

$^{10}B(n,\alpha)^{7}Li$ 3840 barn at 25 meV
19.8% abundance in nat-B

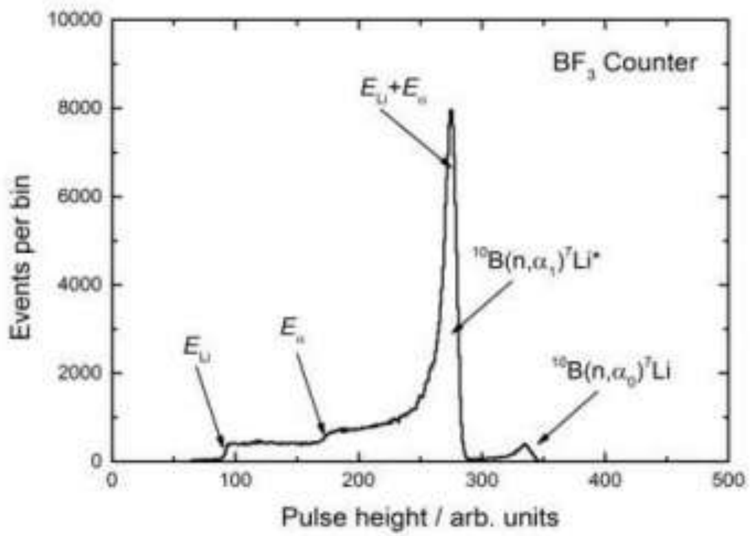
$$^{10}_{5}B + ^{1}_{0}n \rightarrow \begin{cases} ^{7}_{3}Li + ^{4}_{2}\alpha & 2.792\ \text{MeV (ground state)} \\ ^{7}_{3}Li^{*} + ^{4}_{2}\alpha & 2.310\ \text{MeV (excited state)} \end{cases}$$

(Q-value)

- 94% goes to excited state, 478 keV gamma decay
- Thermal neutron energy negligible compared to Q
- α and ^{7}Li move in opposite directions and share Q as the inverse mass ratio

$$E_{Li} = 0.84\ \text{MeV} \quad \text{and} \quad E_{\alpha} = 1.47\ \text{MeV}$$

- BF_3 proportional counters up to 1 atm, 1 m
- Large size, limited cost (dangerous material)
- The PHD is characterised by the wall effect



Other slow neutron detectors
based on Boron coating/enrichment:

- B_4C lined proportional counters (wall effect)
- Scintillators
- Semiconductors (1-2 μm coating)
- Multi Wire Proportional Chambers
- GEM

Helium-3

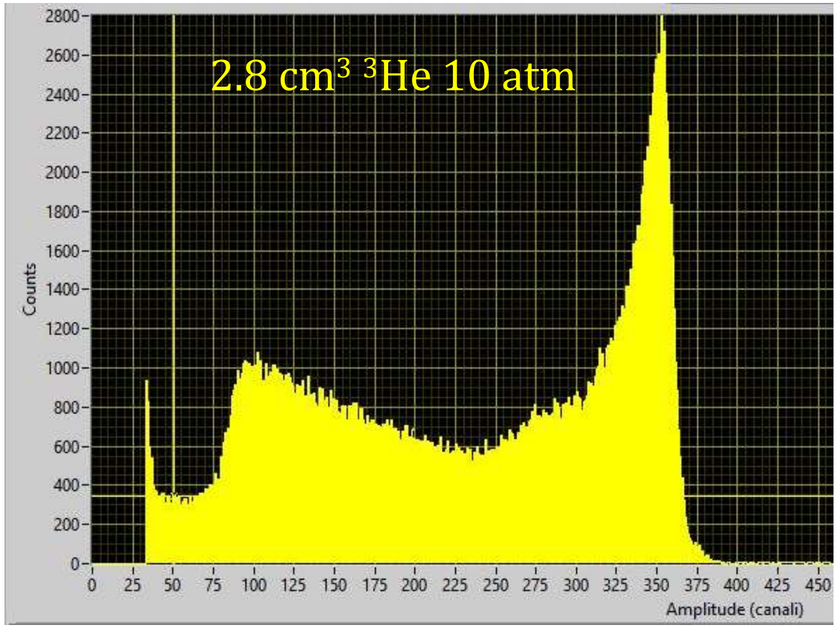
$^{3}He(n,p)^{3}H$

5330 barn at 25 meV

Acts as radiator and proportional gas

Q value 764 keV

E_p=573 keV and E_{3H}=191 keV



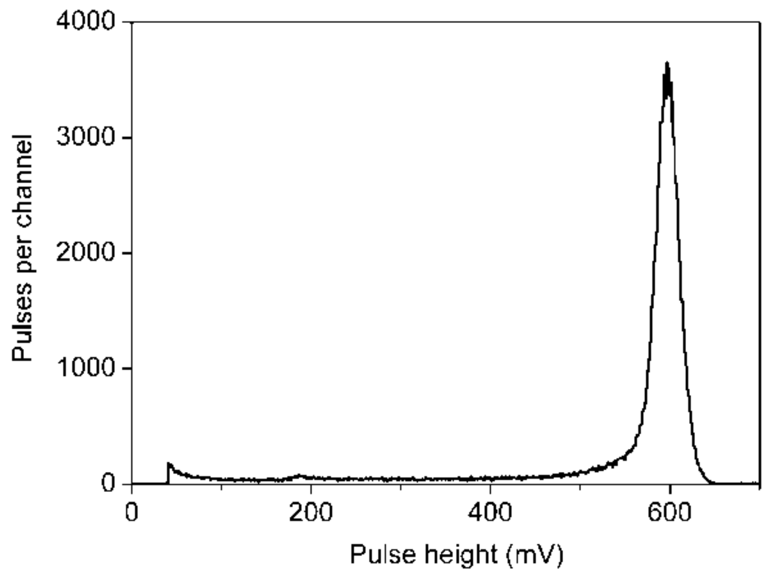
- Noble gas = no solid compounds = only gaseous detectors
- up to 10 bar
- Low-Z and gaseous: path of reaction products is long, thus wall effect is an issue, more than in BF_3
- Small fraction of heavier gases are added to increase the stopping power

Lithium-6

^{6}Li(n,t)α 940 barn at 25 meV
6Li is 7.40% of nat-Li

$$ {}^{6}_{3}\mathrm{Li} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{3}_{1}\mathrm{H} + {}^{4}_{2}\alpha \qquad \frac{Q\text{-value}}{4.78\,\mathrm{MeV}} $$

$$ E_{^{3}\mathrm{H}} = 2.73\,\mathrm{MeV} \quad \text{and} \quad E_{\alpha} = 2.05\,\mathrm{MeV} $$



^{6}LiI(Eu) scintillator with 11 mm diam. x 3 mm thickness NIM A 897 (2018) 18–21

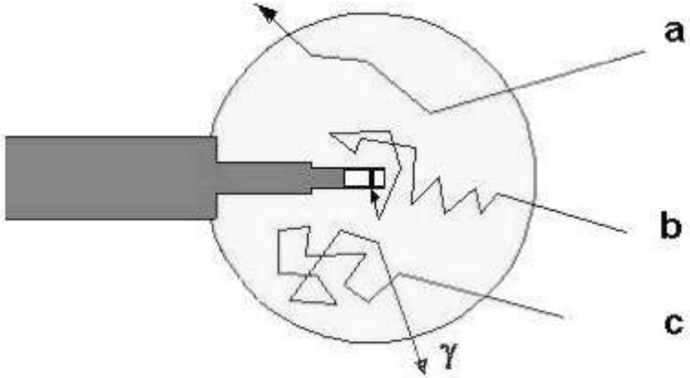
- Only one reaction channel
- Larger Q-value is an advantage over ^{3}He and ^{10}B, resulting in greater energy given to the reaction products.
- Solid form causes larger gamma sensitivity than gaseous media

- Alternatives to the ^{6}LiI(Eu) scintillator are

  ^{6}LiF powder + ZnS(Ag) for large area coating
  6Li glasses

Bonner spheres

- Bramblett et al., "A new type of neutron spectrometer" NIM A 9 (1960) 1-12.
- HDPE spheres of multiple diameters (5-30 cm), sequentially exposed with the same thermal neutron detector in their centre.



The tracks in figure correspond to:
B- neutron with "optimal energy" being thermalized and producing a pulse
A- higher energy neutron escaping from the assembly,
C- lower energy neutron absorbed in the polyethylene.

- The probability for a neutron to be moderated and giving a "count" in the detector is uniquely related to its energy and to the sphere diameter
- The energy that maximizes such probability is uniquely related to the sphere diameter. This reflects into a peak of the response (counts per unit fluence) at that energy
- The neutron spectrum is derived from:

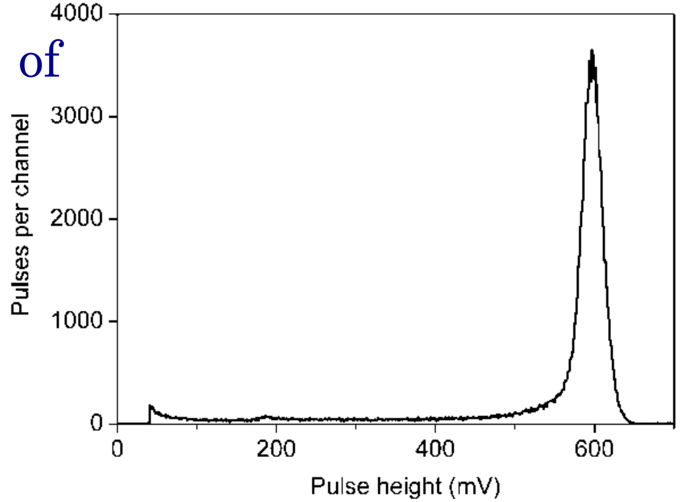
- the count rates as a function of the sphere size (w. their uncertainties)
- the response function of every sphere (w. its uncertainties)
- Some unavoidable pre-information to partially compensate the "lack of information"

Choice of the central detector

Choice of the central detector

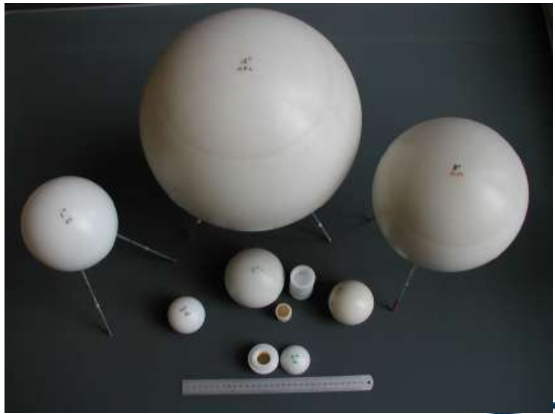
- Intensity / time structure of the field;
- Intensity and energy distribution of photons

^{6}LiI(Eu) 11x3
NIM A 897 (2018) 18–21



Active counters

Central detector model	Sensitive volume and shape	R (1 MeV, 200 mm) cm^2
05NH1	8 kPa, ^{3}He Cylindrical, 10 mm × 9 mm	0.4
SP9	200 kPa, ^{3}He Spherical, 32 mm diameter	2.5
^{6}LiI(Eu)	Scintillator Cylindrical, 4 mm × 4 mm	0.2
^{6}LiI(Eu)	Scintillator Cylindrical, 11 mm × 3 mm	0.6



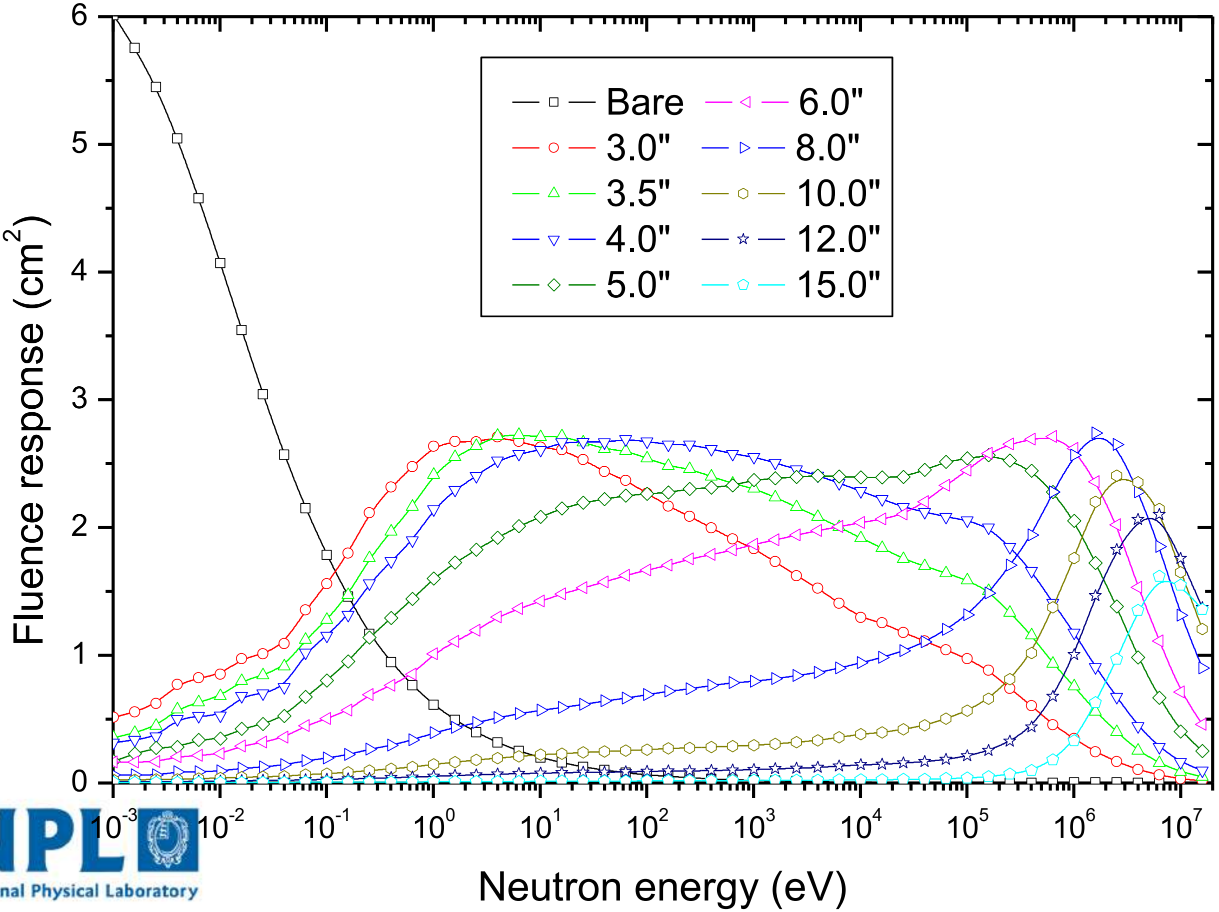
Passive detectors

TLD pairs
Activation foils (gold, Indium, Dysprosium)
ETD

The response function

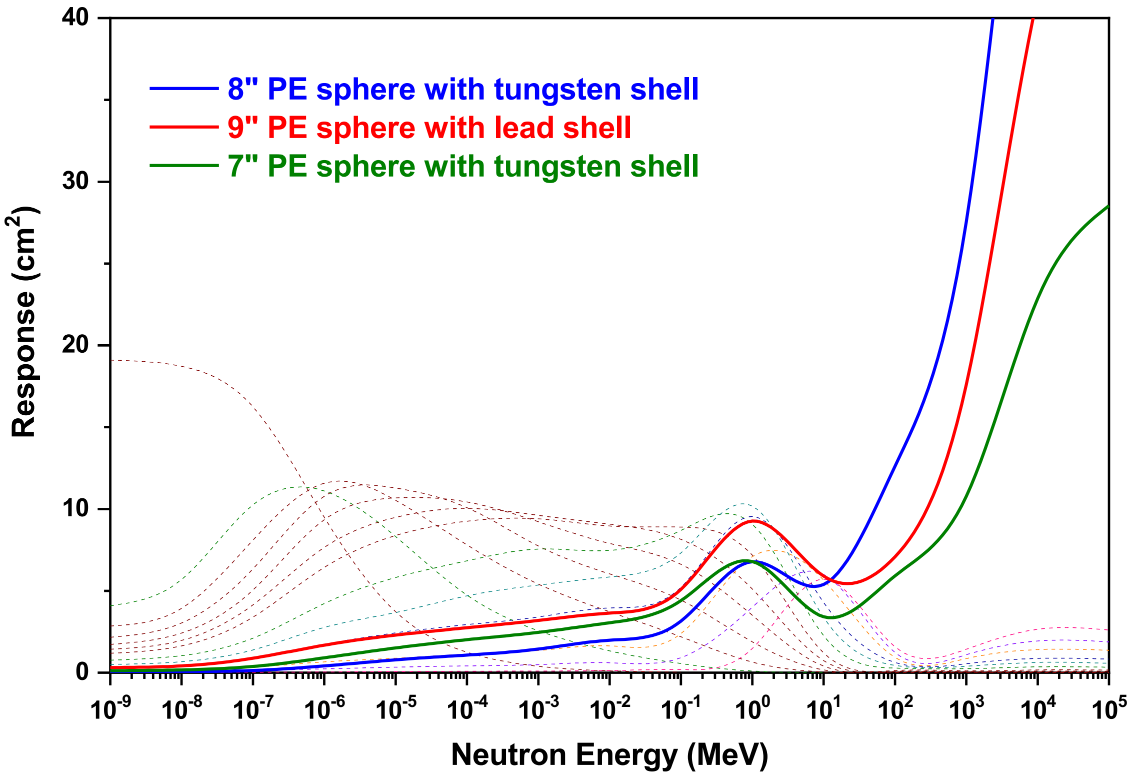
Response matrix = counts per unit fluence as a function of the energy and the sphere size under uniform irradiation condition.

Uniform irradiation does nor mean "parallel beam", but only that the energy and direction distribution of the fluence is constant over the space occupied by the sphere. **Indeed** the sphere isotropically respond so it is insensitive to the direction distribution.



- All spheres are sensitive to neutrons between thermal and high energies.
- The maximum of the response is shifted to higher energies with increasing sphere diameter.

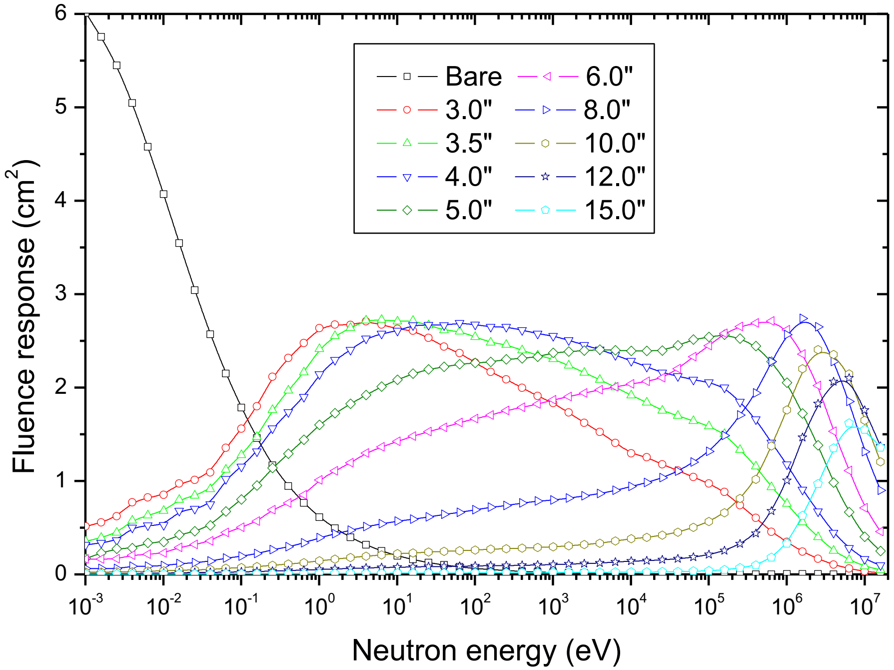
Extending the energy interval above 20 MeV

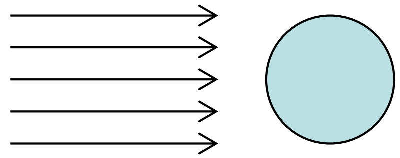


Developments have tried to address problem areas for example the lack of response above about 20 MeV

Use of heavy metal shells to extend range above 20 MeV through *n,nx* reactions

Calculating the response function





- The number of mono-chromatic energies must be consistent with the complexity of the response function.
- Fine structures such as resonances (Au foils) need special consideration
- Usually 50 to 100 simulations per sphere are needed to satisfactorily describe the response

Φ total neutron fluence in cm^{-2};

φ(E) unit spectrum;

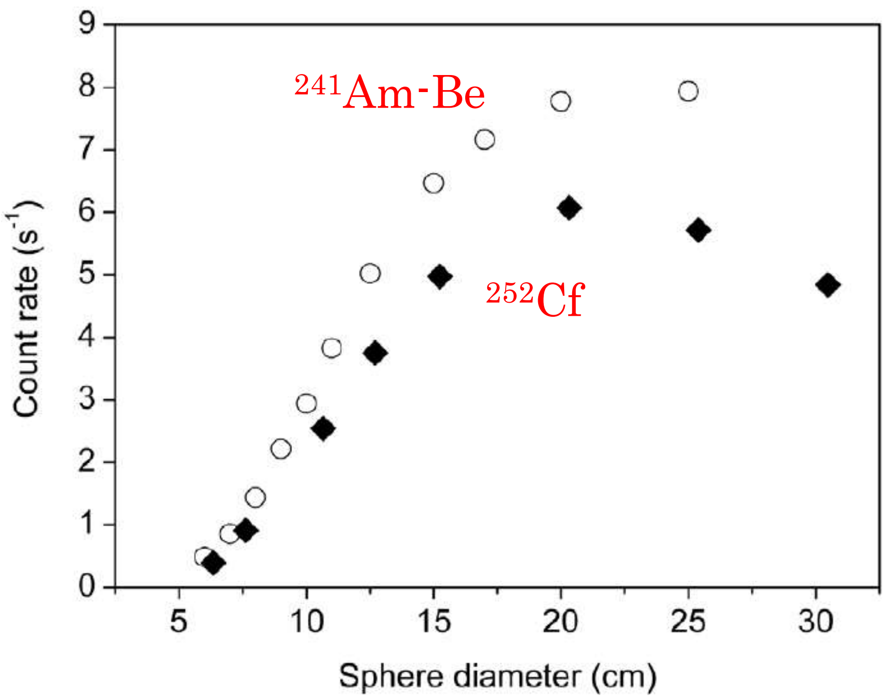
R_i(E) response function of the sphere (in cm^2).

C_i counts in the i-th spheres

$$C_i = \Phi \int_{E_{min}}^{E_{max}} R_i(E)\varphi(E)\,dE$$

The counts of different spheres exposed to the same fluence of a given spectrum form a plot as a function of the diameter (count profile).

As response functions are smooth curves, this plot is a smooth curve too.



The profile contains the totality of the BS-"available" spectrometric information.
Not all spectrometric info is available to BS, due to the shape of the response functions (limited energy resolution). That is why some amount of pre-information is always needed

The profile curve is completely described by placing few (5-6) "well chosen" points on the plot, thus this is the minimum number of number of spheres needed to obtain the totality of the BS-"available" spectrometric info

From a mathematical point of view, the "minimum" number of spheres is obtained by investigating the rank (number of non-vanishing eigenvalues) of the structure matrix $^{T}R \times R$

The unfolding problem

$$C_i = \Phi \int_{E_{min}}^{E_{max}} R_i(E)\varphi(E)\,dE$$

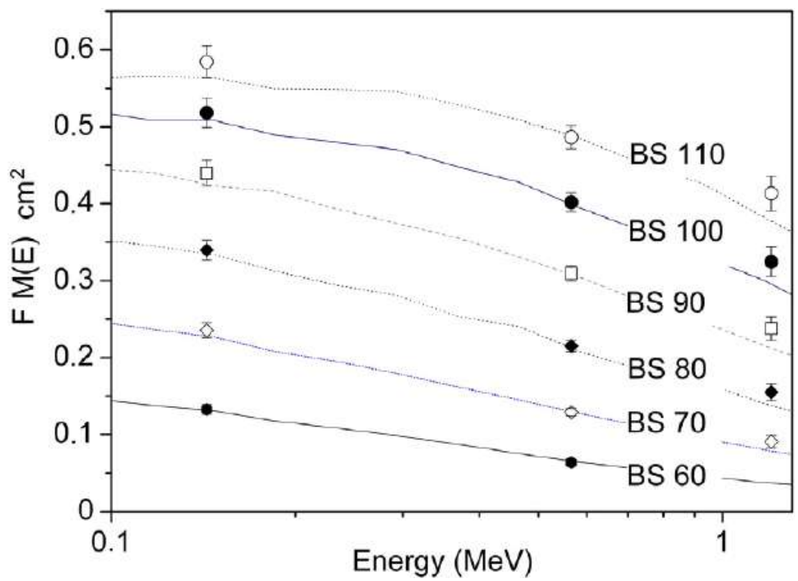
- "Unfolding" means inverting the integral to find **φ(E)** and **Φ**
- Infinite φ(E) exist which mathematically satisfy the equation. From our point of view, the solution is a function which:

➢ respects the physics behind the radiation environment

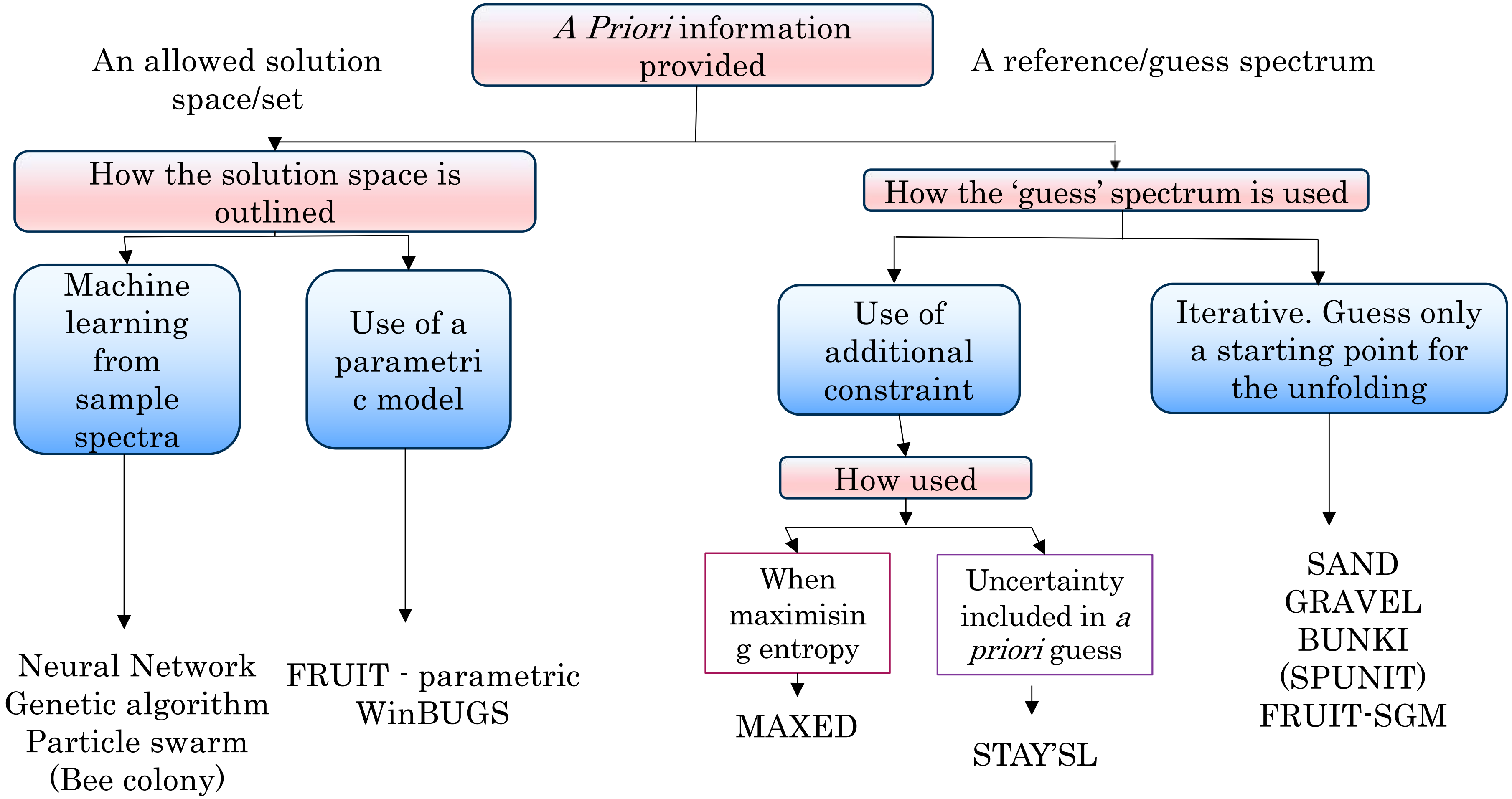
  ➢ when convoluted to $R_i(E)$ reproduces the counts within their uncertainties

  Note: also $R_i(E)$ has uncertainties which are usually determined with irradiations in neutron reference fields, including monoenergetic ones. Typical overall unc. from thermal to 20 MeV: 3-4%

- The unfolding problem is under-determined, as with maybe ten partially independent readings (the sphere counts) we aim at determining a function defined on maybe 100 energy bins.
- A given amount of pre-information is always needed
- Unfolding codes differ in the way to provide/formulate the pre-information and in the importance given to the pre-information and on the sphere counts



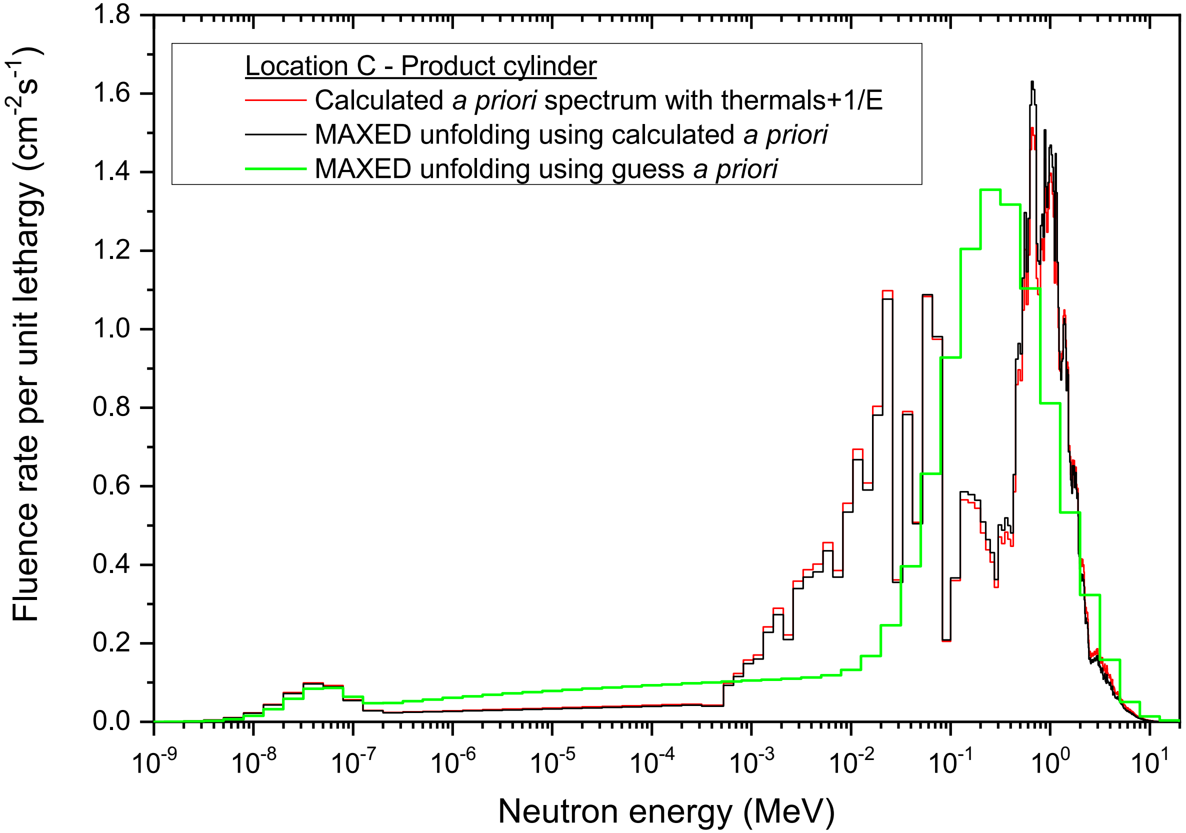
Use of *a priori data* (all codes minimize χ^2 in some way)



Unfolding nowadays

- ✓ Require basic knowledge of the radiation environment
- ✓ Offer multiple possibilities to introduce pre-info
- ✓ treat the uncertainties
- ✓ More training material, training courses and solved exercises are available

Role of the pre-information



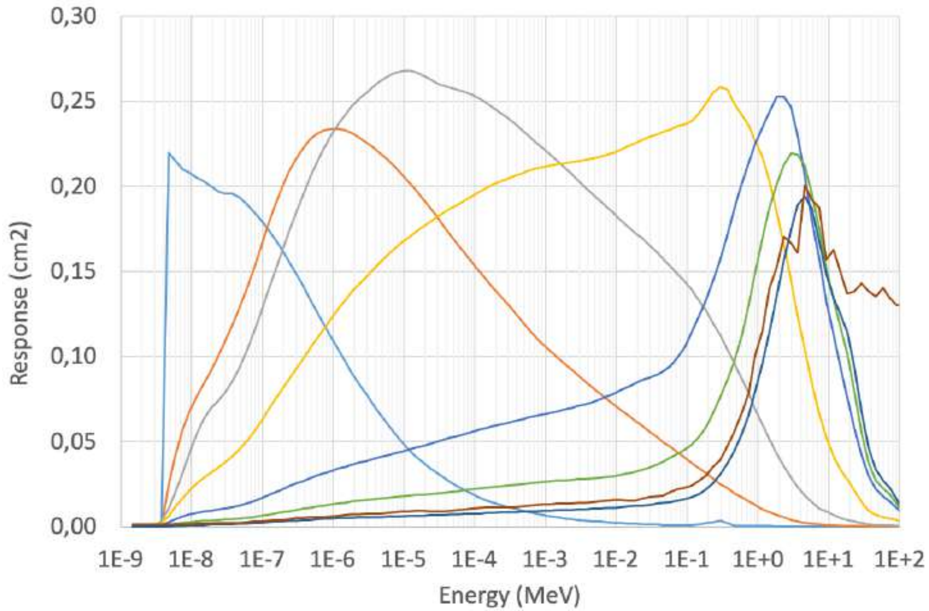
- When the *a priori* information, from calculations in this case, is good, the unfolding code will barely change the spectrum.
- If it is poor BS do not have the resolution in the high energy region to give a good spectrum.

Response matrix and resolution

- The energy resolution is higher in those energy regions where the degree of differentiation of the different response functions is higher

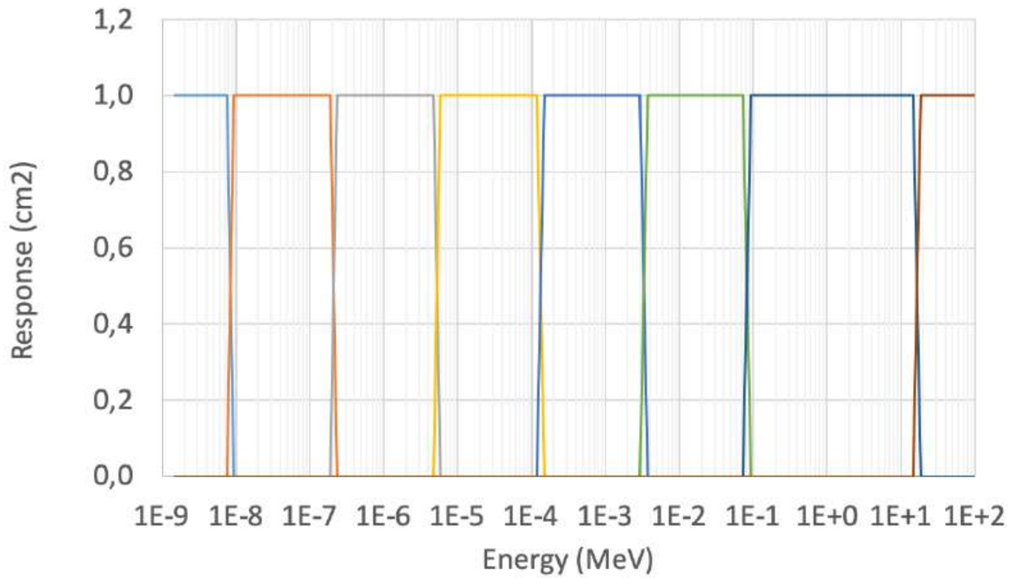
Realistic Matrix:

- More resolved in the 0.01 – few MeV

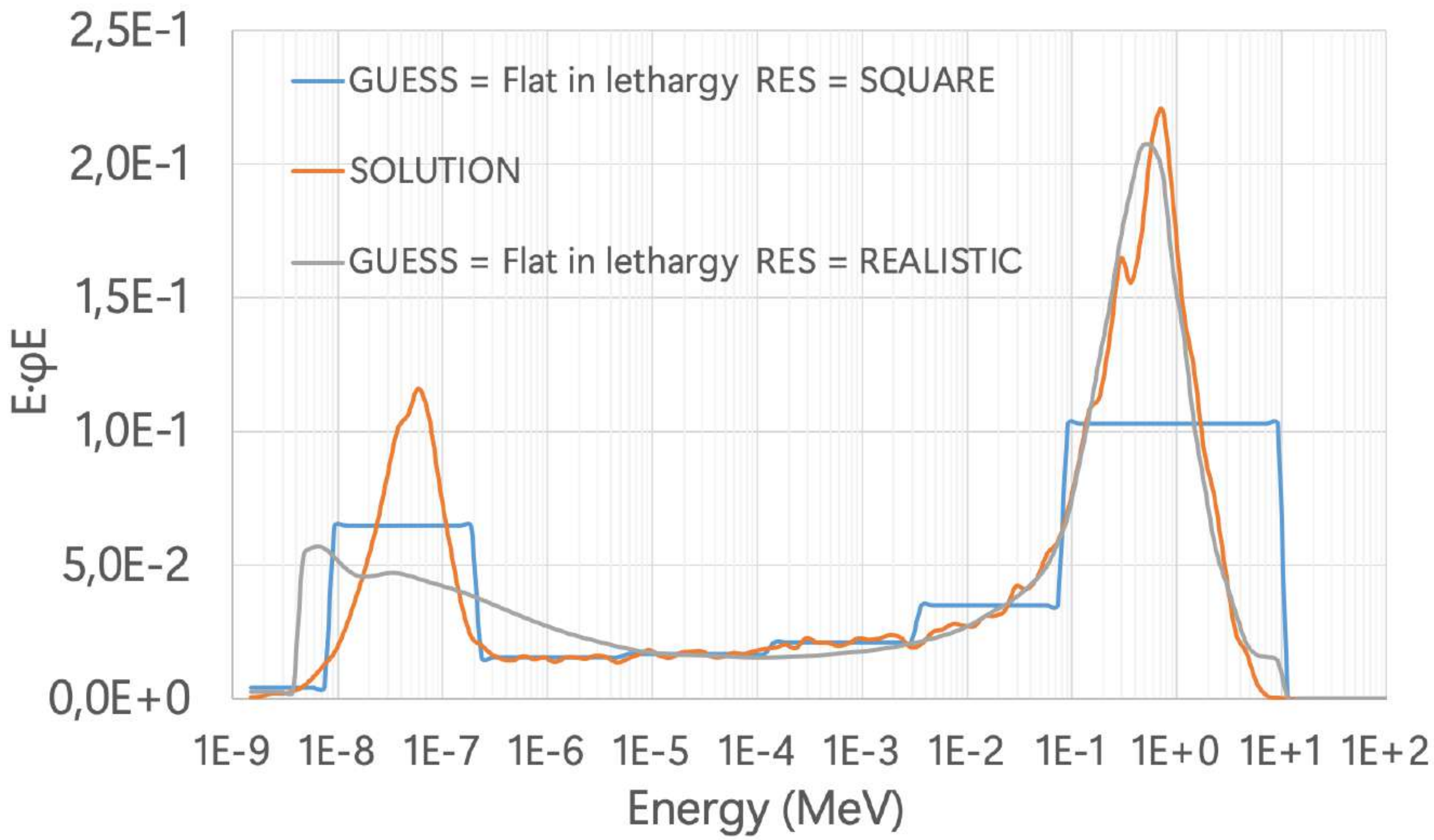


"Artificial" matrix

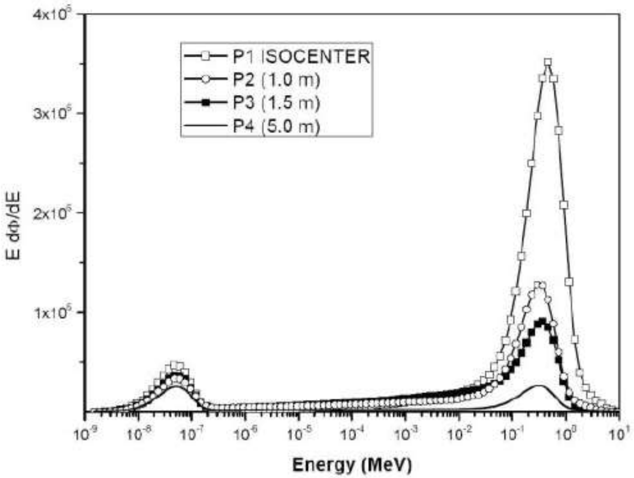
- More resolved below 1-10 keV



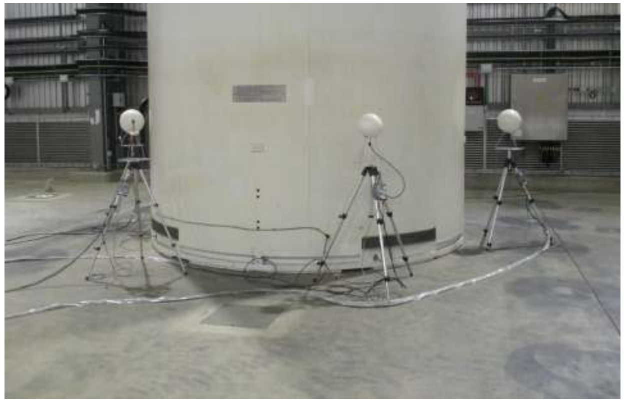
Role of the energy-resolution



BS measurement locations



BS pro et contra

Positive features

- Very wide energy range
- Relatively simple and easy to use
- Isotropic response
- Good n/γ discrimination
- Can have high or low efficiency depending on choice of sensor

Negative features

- Poor energy resolution and responses low above 20 MeV
- Measurements are sequential and lengthy: field must remain stable over the measurement or a monitor is needed - Can not operate in real-time
- Equipment bulky
- Unfolding needs skills

Bonner spheres feature in more published field measurements than all the other devices put together

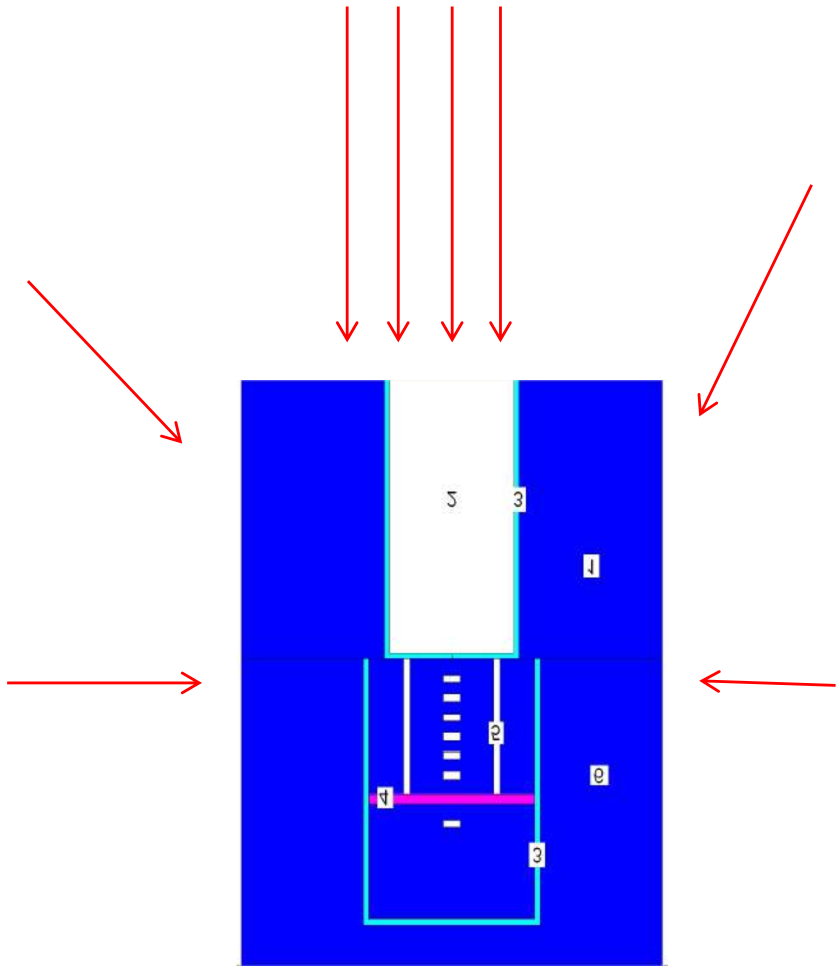
D. J. Thomas. *Neutron spectrometry for radiation protection.* Radiat. Prot. Dosim. (2004), **110** (1-4), 141-149.

Single moderator spectrometers

- Single Moderator Neutron Spectrometers (SMNS)
- SMNS internal sensors and readout
- The Spherical Spectrometer SP^2 (2013)
- The Cylindrical Spectrometer CYSP (2012)
- NCT-WES (**N**eutron **C**apture **T**herapy **W**ide **E**nergy **S**pectrometer) (2021)
- Tetra-Ball (2024)

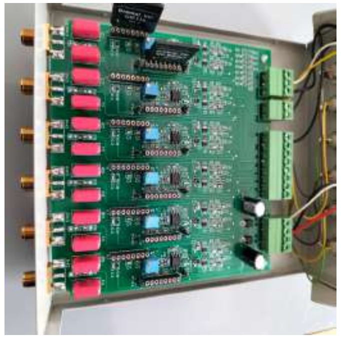
Spherical design

Cylindrical design



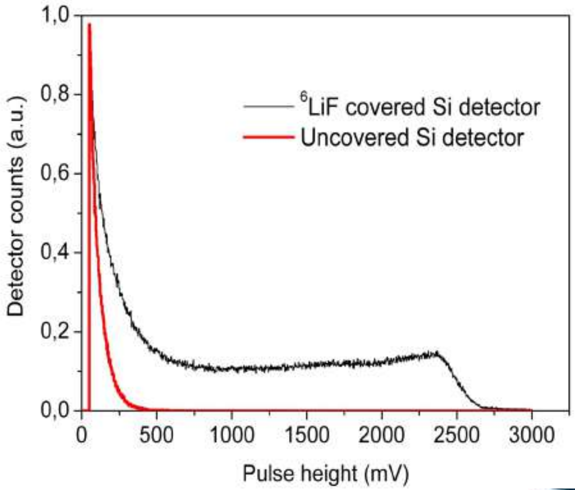

- Thermal neutron sensors are semiconductors coated with 30 μm ^{6}LiF:

  Si diode for calibration-grade fields
  SiC diodes for intense neutron fields



- Custom multi-detector analogue board (charge preamp. + shaper amp.)
- Individually calibrated in thermal neutron field.
- Digital elaboration using commercial digitizer and laptop

NIM A 1018 (2021) 16585
NIM A 780 (2015) 51-54
Radiat. Prot. Dosim. 161 1-4 (2014) 229-232
Eur. Phys. J. Plus 137 (2022) 1358

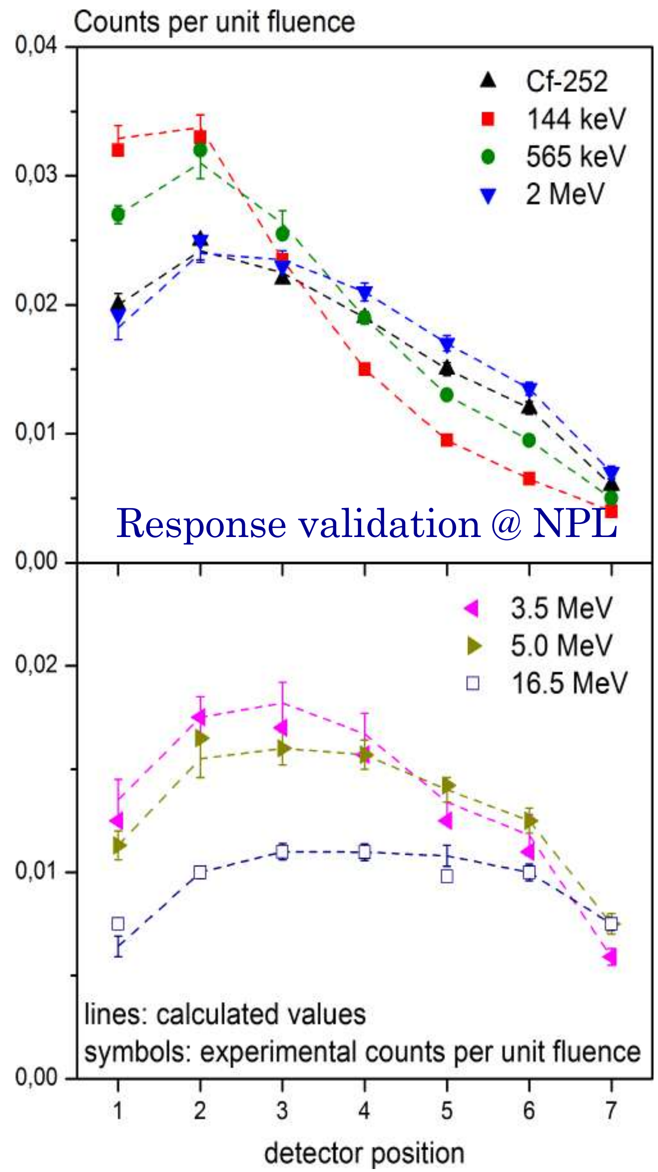


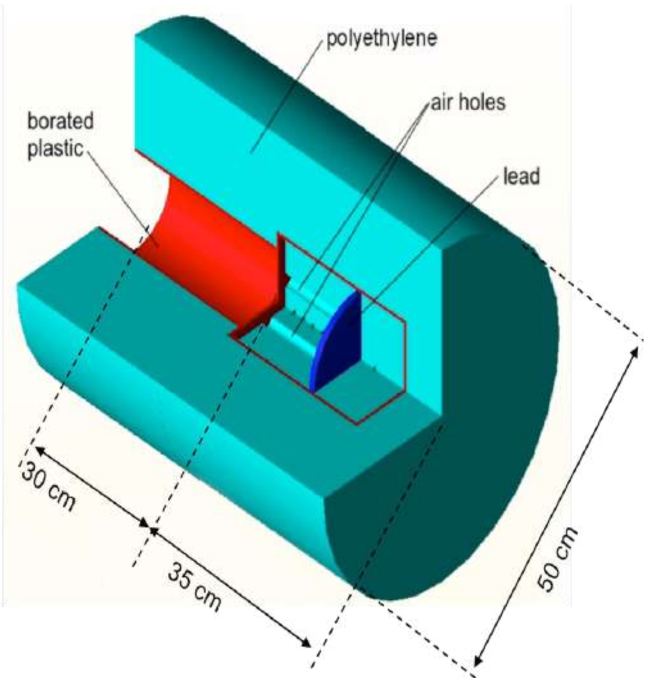
Designed to provide a sharply directional response
- collimating aperture
- sensitive capsule laterally protected by PE + B-rubber

Seven TND at different depths + 1 cm lead

Air holes enhance response of deep detectors

Mimic a 7-sphere BSS

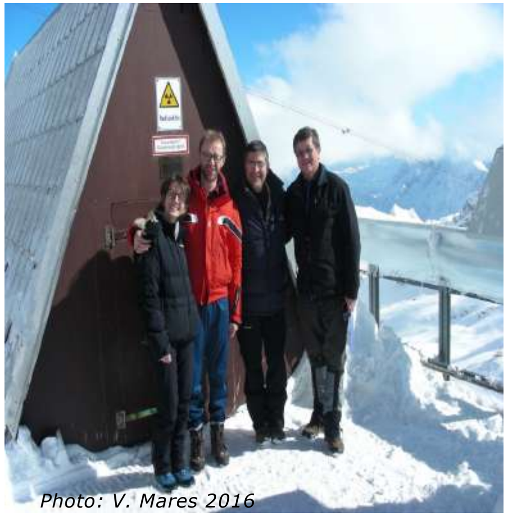


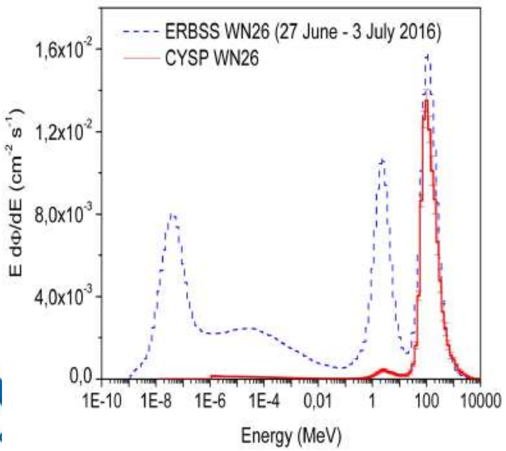


– Radiat. Meas. 82 (2015) 47-51
– NIM A 782 (2015) 35-39
– Eur. Phys. J. Plus (2015) 130: 24
– Radiat. Prot.Dosim.161(2014) 37-40

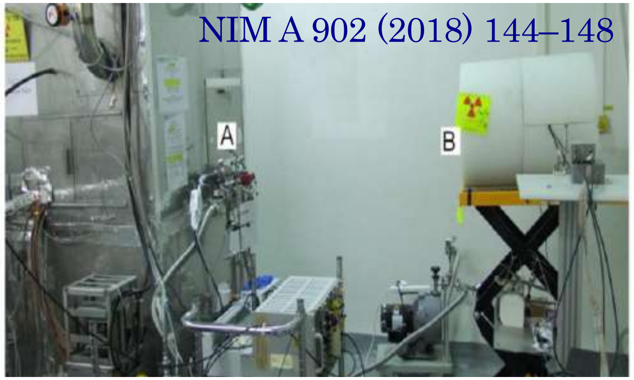
Use of CYSP

Measuring the vertical component of cosmic neutrons

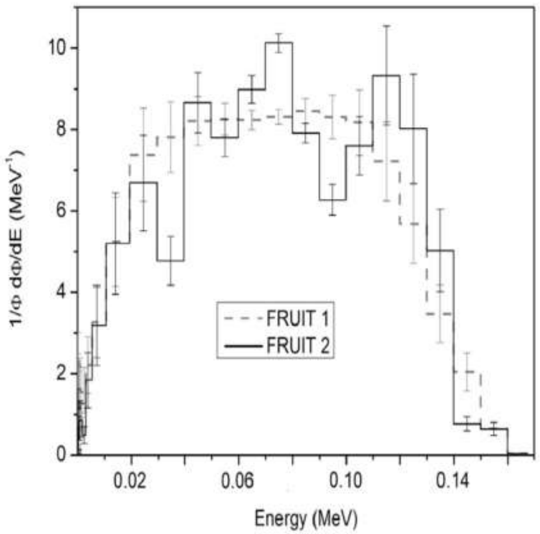




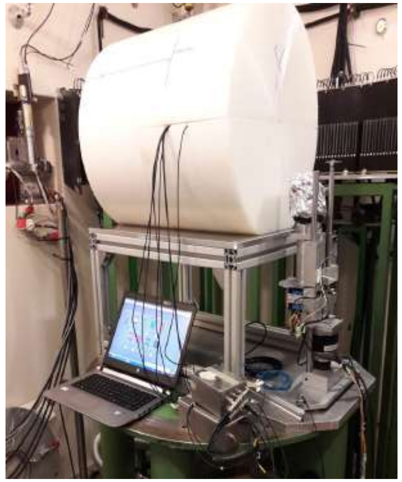
Neutron spectrum from the Liquid Li p,n target @ SOREQ

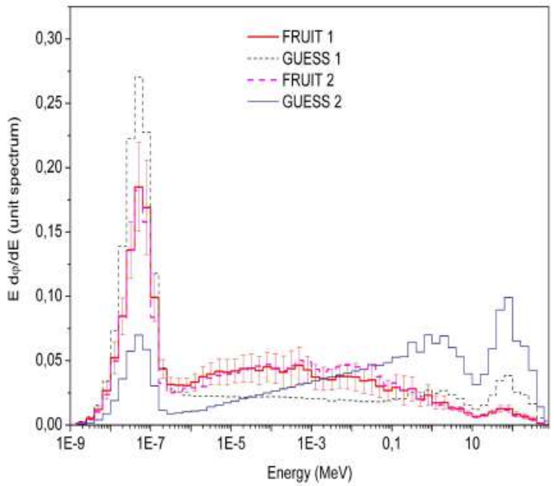


Ep=1.92 MeV, 0.5 mA x 0.1 ms @ 500 Hz



INES neutron beam-line @ ISIS (RAL, UK)





EPL, 127 (2019) 12002
NIMA 927 (2019) 151

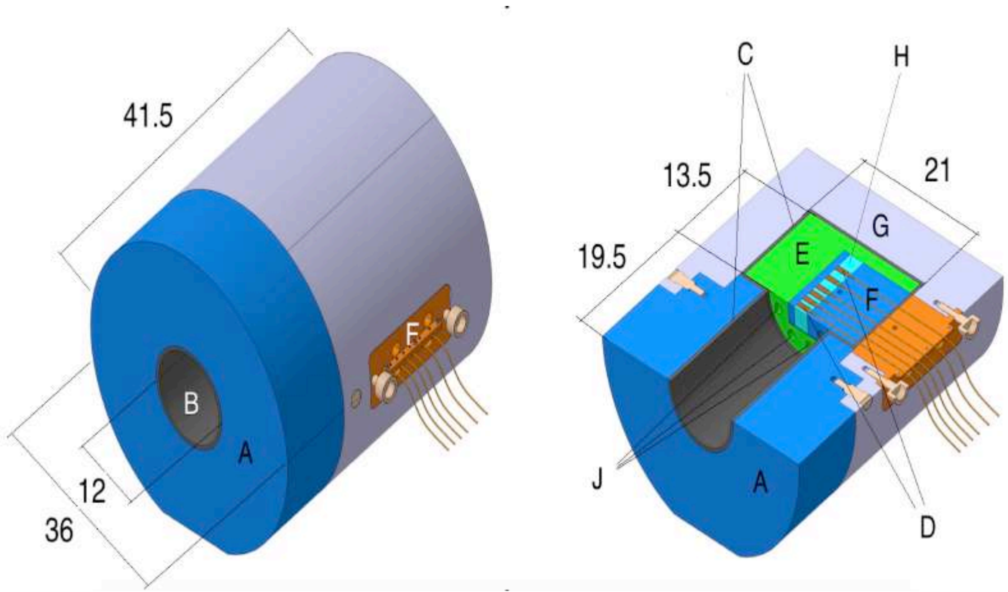
INFN LNF Istituto Nazionale di Fisica Nucleare

The advent of AB-BCNT is requiring real-time spectrometry techniques for the therapeutic beam

INFN project ENTER_BCNT designed NCY-WES, a modified CYSP with design objectives:

- ❑ Directional response to reject room scatter
- ❑ Emphasise resolution in epithermal domain
- ❑ weight and portability
- ❑ E < 20 MeV
- ❑ Implement rad-hard sensors

- Advances in BCNT, 2023 (IAEA book)
- Modern Neutron Detection IAEA-TECDOC-1935 (
- Europhys. Lett. 134, 42001 (2021).

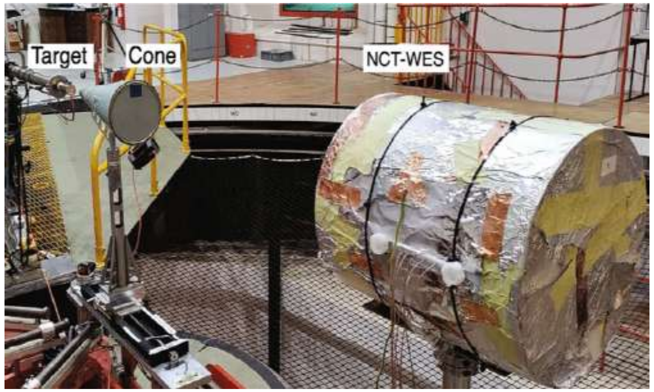


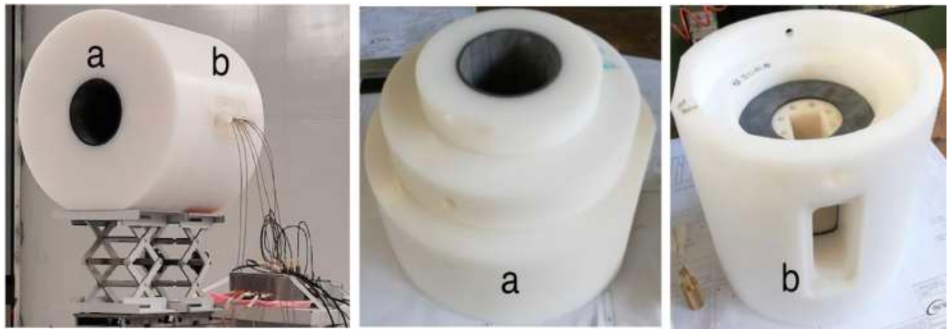
Detector depths within capsule
7.5, 20.5, 33.5, 46.5, 66.5, 86.5 mm

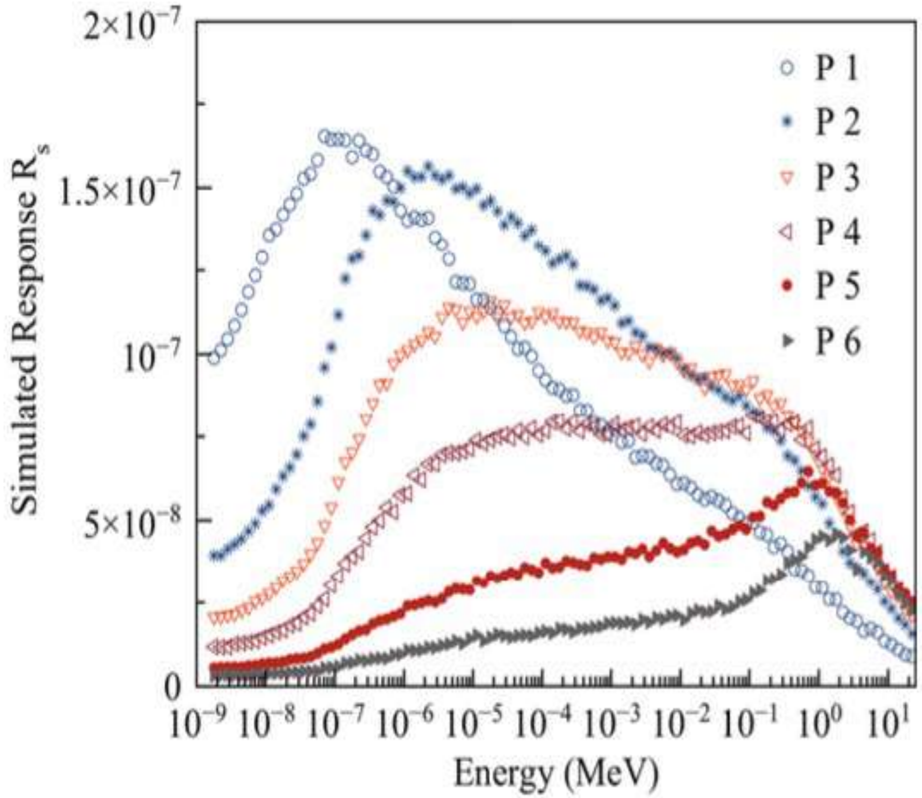
Response verification at NPL

71.5, 144.2, 565.1, 841.9, 1200.4 keV

R_{calc} and R_{meas} agree within 2%





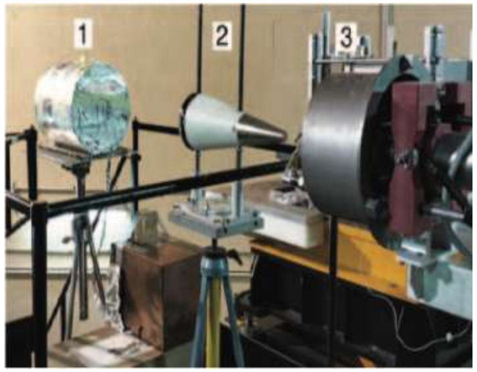


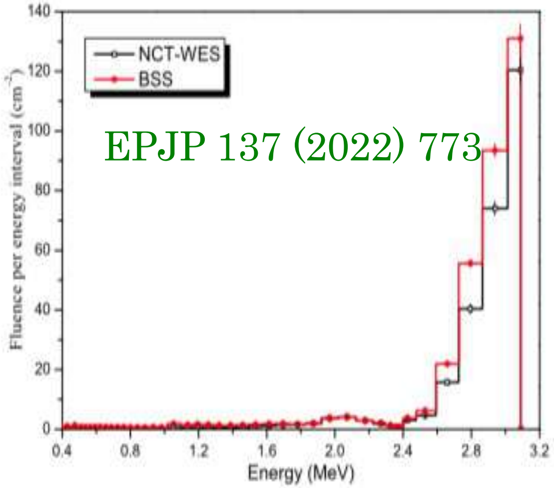
EPJP 137 (2022) 773

Webinar on neutron spectrometry for radiation protection

Applications on NCT-WES

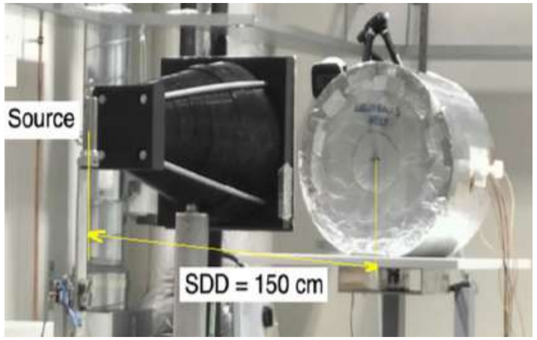
ENEA Fast Neutron Generator in D-D



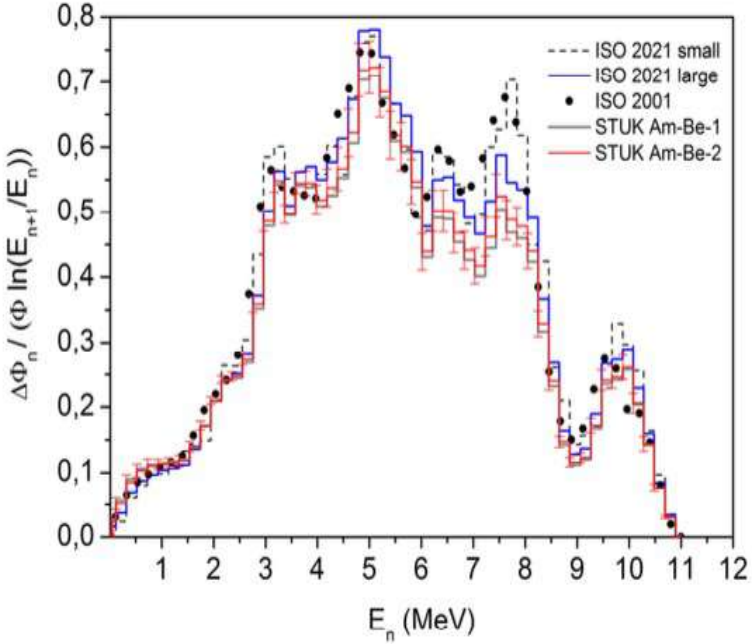


EPJP 137 (2022) 773

Characterizing n sources at Finnish neutron metrology center (STUK)



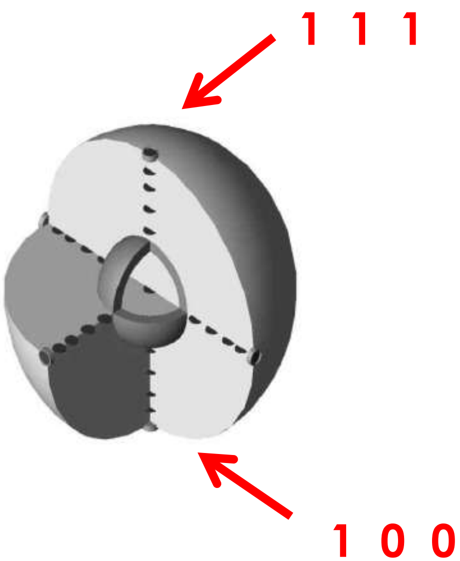
EPJP 139 (2024) 384

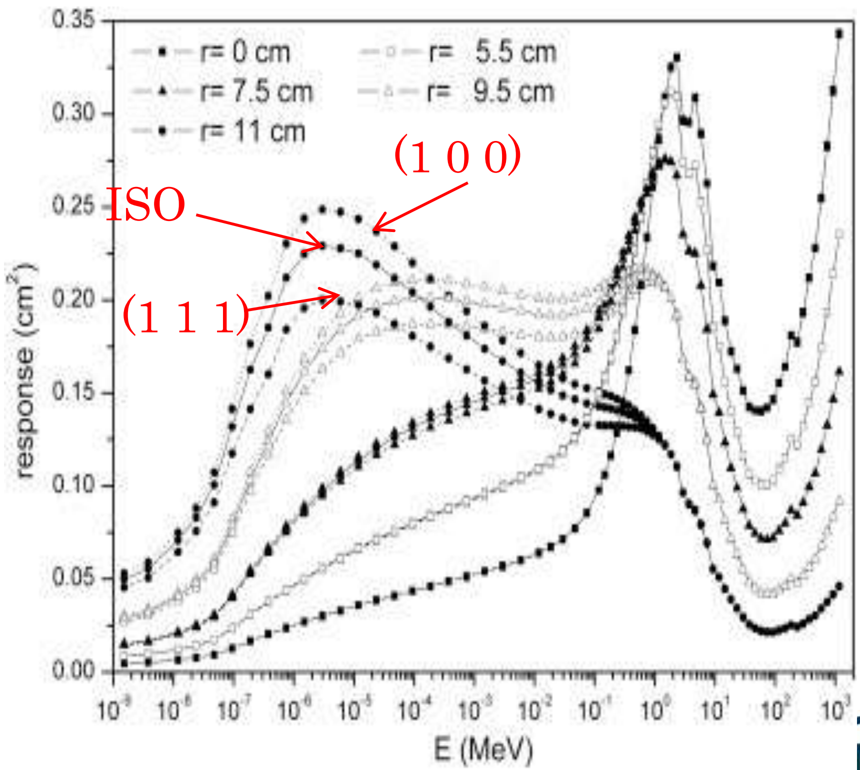


Source	$B_{nominal}$ (s^{-1}) 12/7/2023	$B_{measured}$ (s^{-1}) 12/7/2023
Cf-1	9.12×10^6	$(1.08 \pm 0.03) \times 10^7$
Cf-2	2.82×10^7	$(2.98 \pm 0.08) \times 10^7$
Am-Be-1	2.09×10^6	$(1.98 \pm 0.05) \times 10^6$
Am-Be-2	1.99×10^7	$(1.92 \pm 0.05) \times 10^7$

The (isotropic) Spherical Spectrometer SP^2

- 25 cm diameter sphere including a one cm lead insert
- 31 thermal neutron detectors (customised: usually 1-cm^2 Si-diode + ^{6}LiF)
- Response matrix is in principle direction-dependent
- Studies to evaluate the impact of this “imperfect” isotropy
- Single exposure
- Mimics a 6-sphere BSS





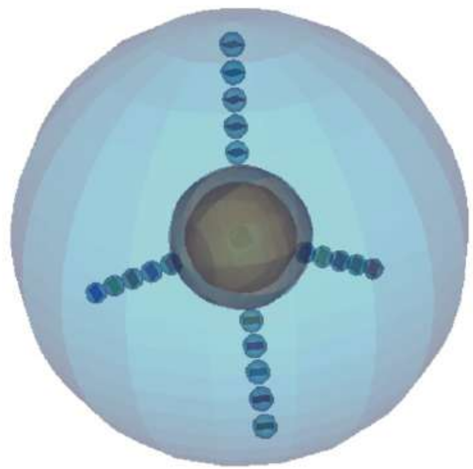
- INFN-LNF papers on SMNS: 398 citations (Google Scholar)
- Prototypes openly inspired by INFN SMNS:
    - Y. Zou, Construction and test of a single sphere neutron spectrometer based on pairs of 6Li-and 7Li-glass scintillators, Radiation Measurements, 127 (2019) 106148.
    - W. Zhang et al., Development of a portable Single Sphere Neutron Spectrometer, Radiation Measurements, 140 (2021) 106509.
    - X. Li et al Design and verification of a multi-layer single-sphere neutron spectrometer with water as the moderator. JINST 16 (2021) T12010
    - S. Paulet al. Neutron spectrometry and dosimetry using a multi-shell Single Sphere Neutron Spectrometer with thermo-luminescent and optically stimulated luminescent detectors. NIM A 1053 (2023) 168395.
- Two private companies replicated SP^2 for commercial purposes

Tetra-Ball
CMS BRIL collaboration

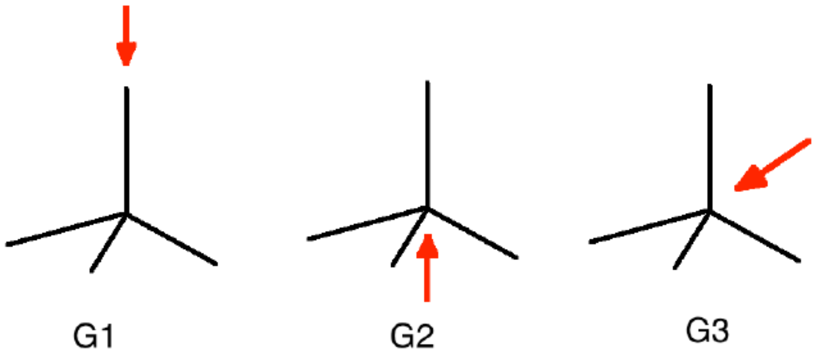
- Measuring the n background in CMS during LHC Phase 2 High-Luminosity
- 4000 fb^{-1} @ 7 TeV per beam (BRIL TDR)
- Accumulated n fluence **up to** 10^{13} cm^{-2}
- Instantaneous fluence rate **up to** 10^{5}-10^{6} cm^{-2} s^{-1}
- Less than ten portable spectrometers
- 21 Rad-hard sensors: pairs of SiC (7.6 mm^2)

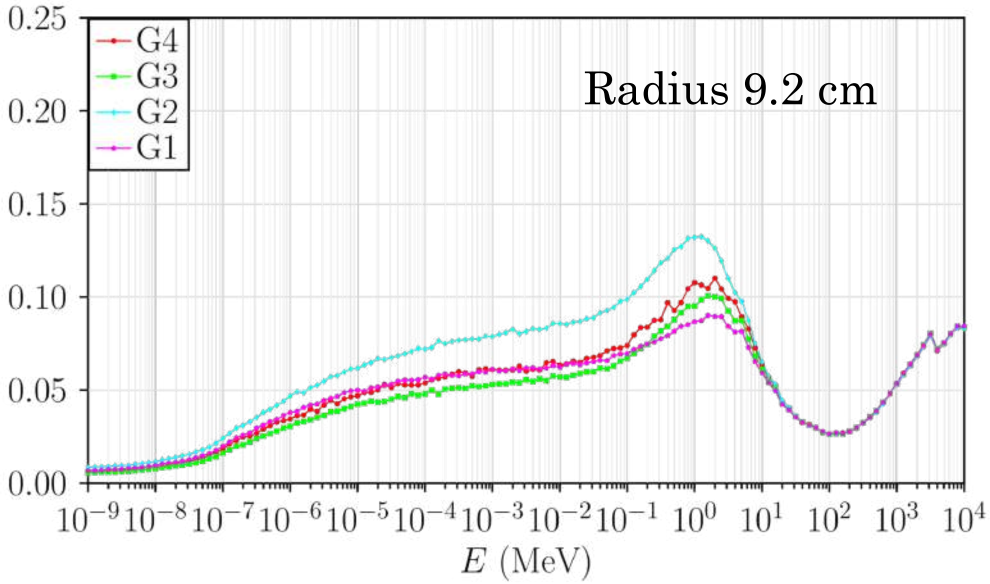
  one bare, one coated with 30 μm ^{6}LiF

- Spherical spectrometer <u>with less detectors than SP^2</u>

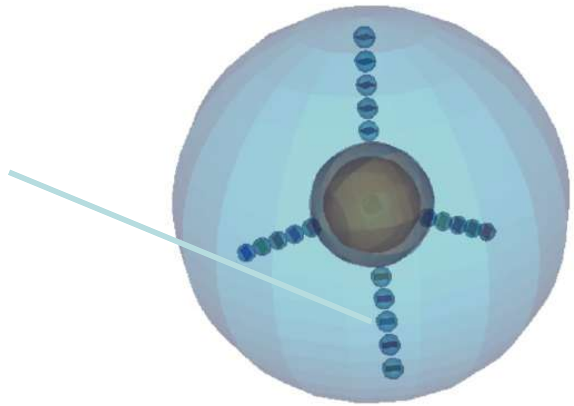


Response and geoemtry

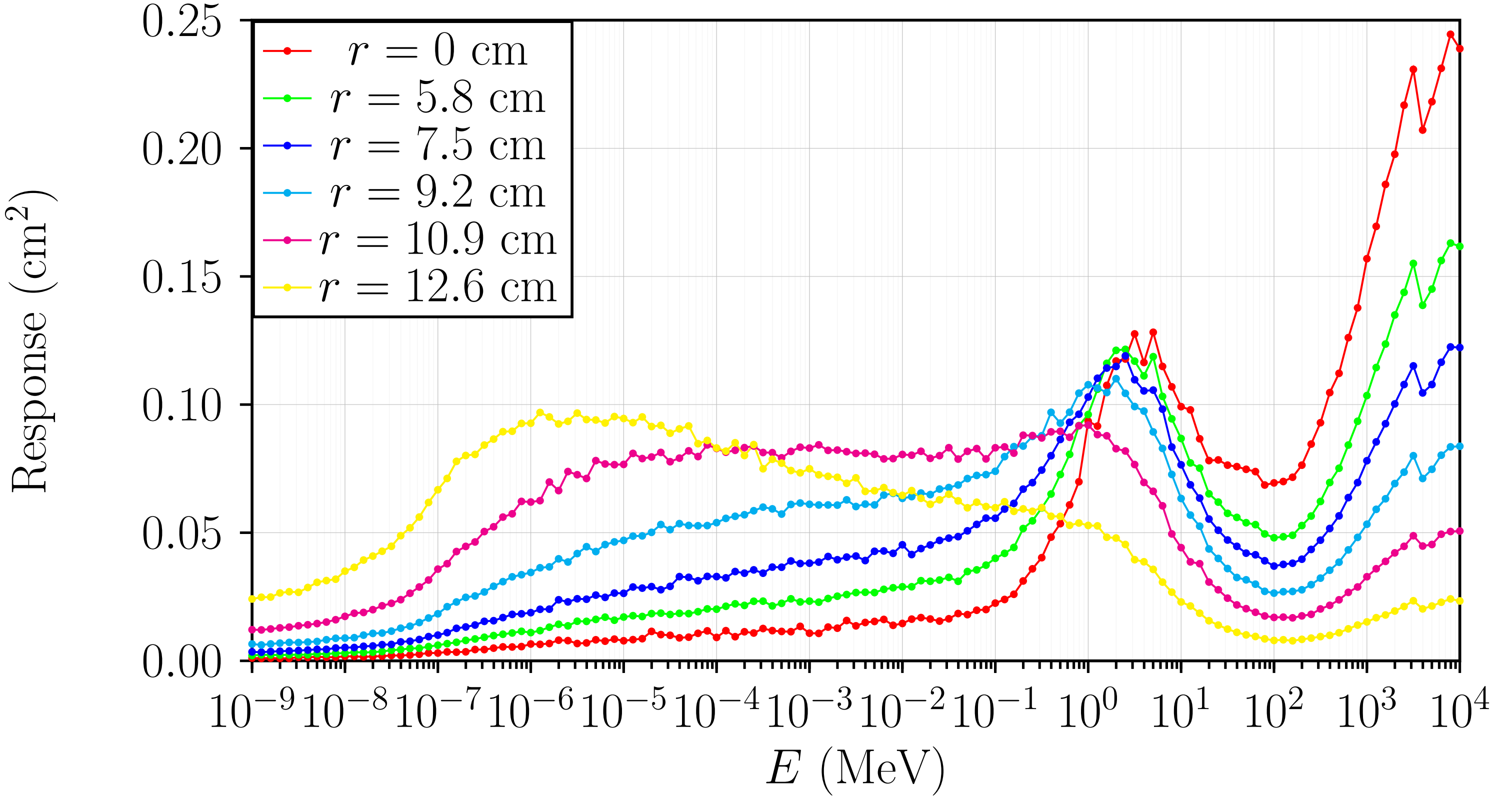




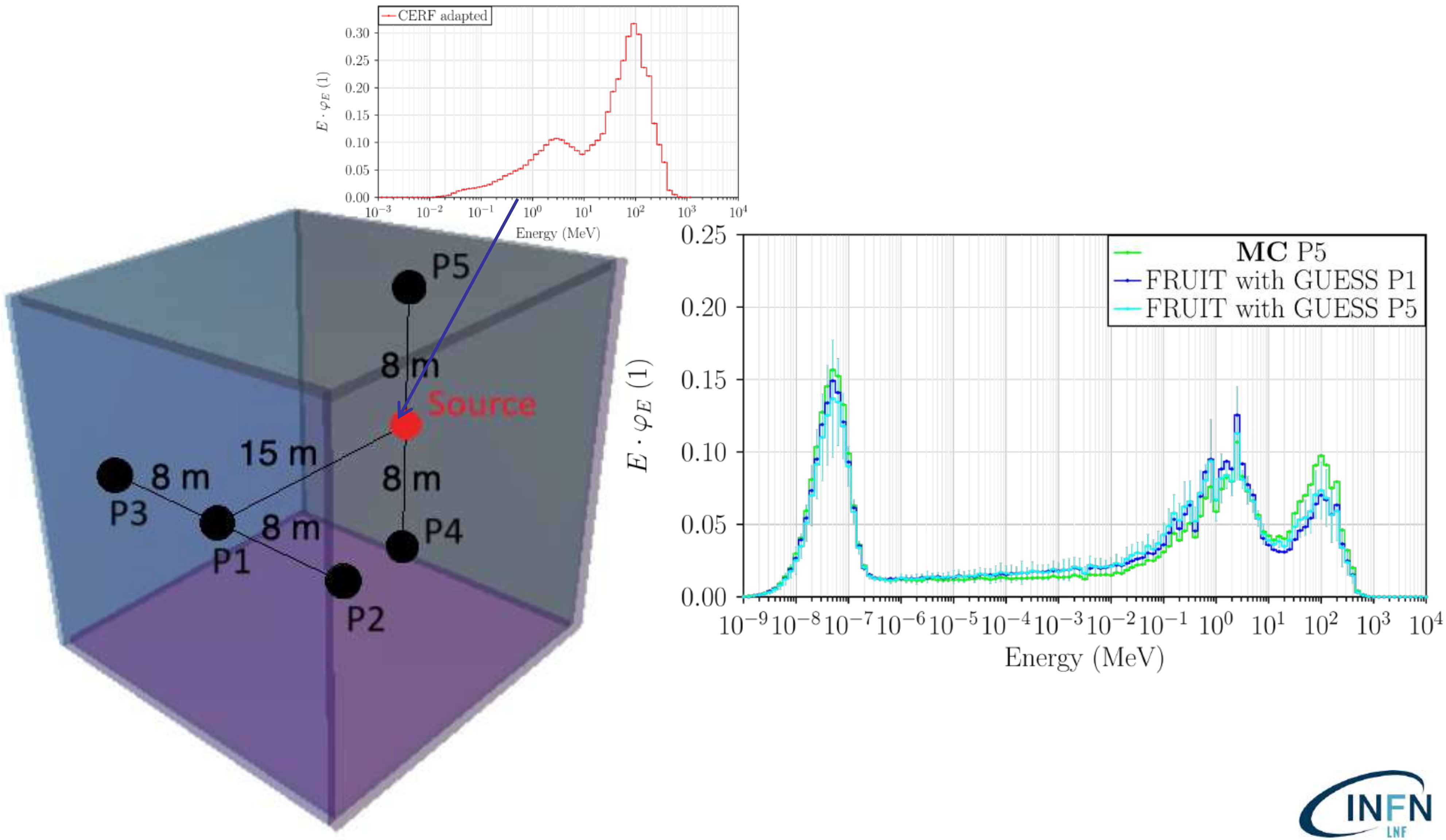
Radius 9.2 cm



Response matrix under isotropic irradiation



Simulated irradiation & unfolding tests assuming G4 response (P5 worst case)



Thank you

ROBERTO.BEDOGNI@LNF.INFN.IT

DAVID.THOMAS@NPL.CO.UK