Detectors for high energy neutrons

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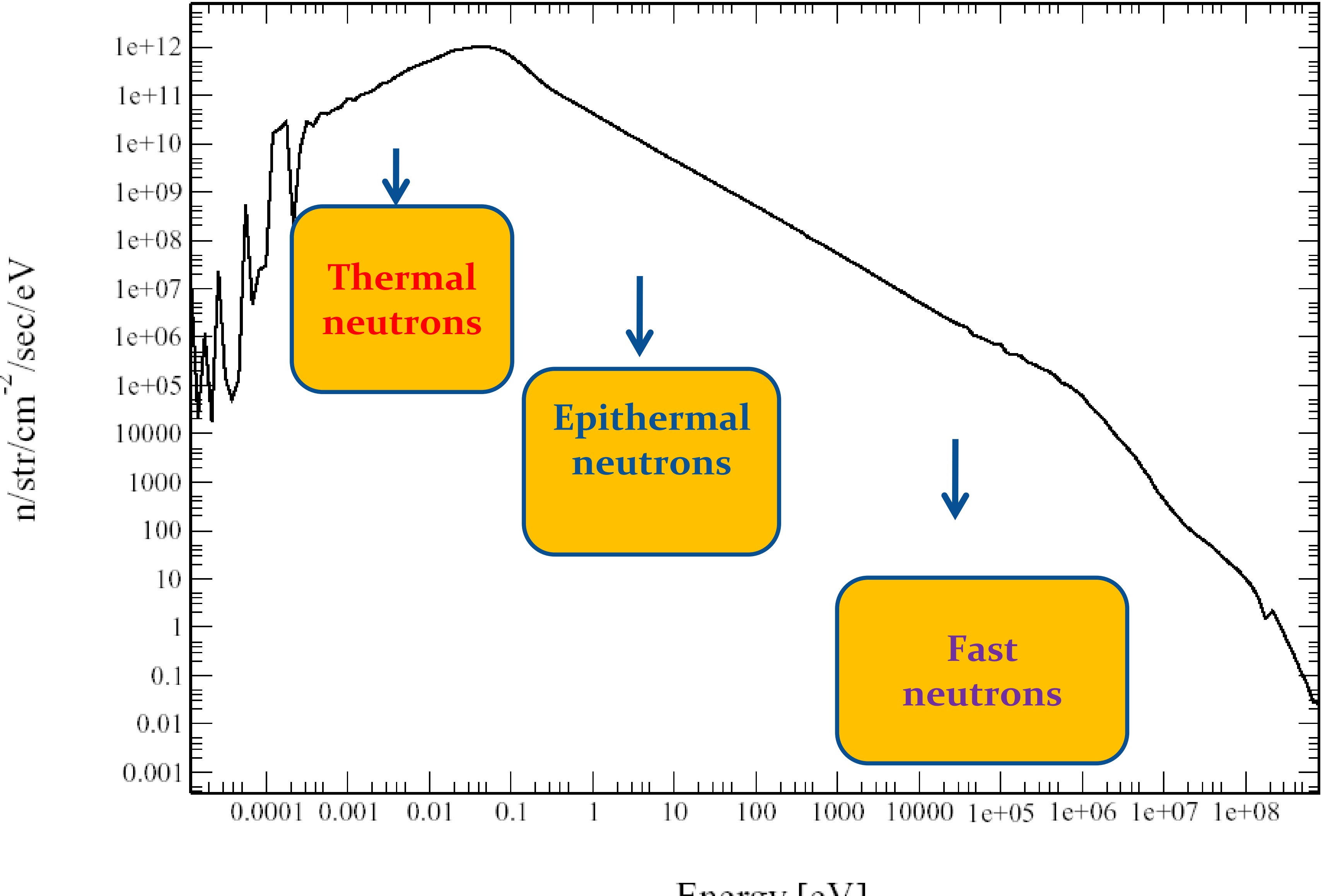
Topics

- **High Energy neutron spectrum from pulsed sources**
- **Scintillation Detectors**
- **Capture-gamma Detectors**
- **Detectors up to 200 MeV**
  - **Reactions**
  - **Principles**
  - **Characteristics**

Neutron spectrum from a water moderator



Thermal neutrons

Epithermal neutrons

Fast neutrons

Detection of Neutrons

It is not possible to detect slow neutrons.

Detection of Neutrons

Directly, that is—their energy is too low to register by electronic methods.

Always, the process requires a converter, a nuclear reaction induced by the neutron which gives off one or two energetic charged particles which produce ionization that does register electronically. And the neutron vanishes.

Neutron-nuclear charged particle reactions

Reactions commonly used as converters in slow neutron detectors:

^{3}He + n —> p + T + 765 keV

^{6}Li + n —> α + T + 4.78 MeV

^{10}B + n —> α + ^{7}Li + 2.79 MeV (6 %) and

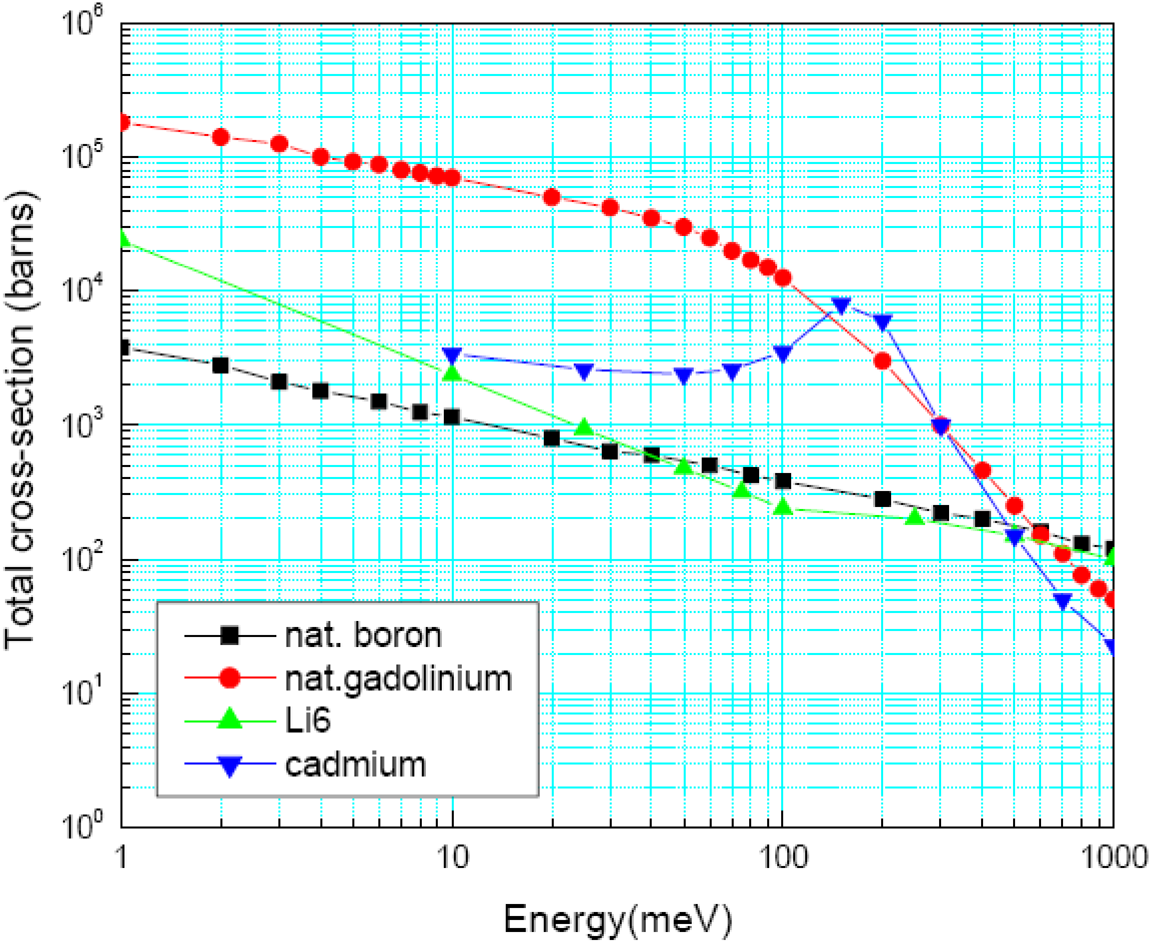
—> α + ^{7}Li* + 2.31 MeV + γ(478 keV)(94%)

$^{155\text{ and}157}$ Gd + n —> $^{156\text{ or}158}$Gd + e^- (70 keV)

^{235}U + n —> A + B + 160 MeV (+ e^-, g, v, &c.)

Sharp resonance capture lines, Ta^{181} (4.28 eV), U^{238} (6.67 eV) …

Detector efficiency depends on cross section



Converter materials

^{3}He is inevitably in the gaseous state, usually at several atmospheres pressure

^{6}Li is usually in chemically combined form, e.g., LiF, Li_2O, $Li_6Gd(BO_3)_3$, or in chemical compounds combined heterogeneously or homogeneously with intrinsic scintillators

B is usually in chemically combined form, e.g., BF_3 (gas) or H_3BO_3 in solution, sometimes as a thin coating in elemental form

Gd as a converter is usually as the oxide or silicate

U is usually thinly coated in oxide form, Ta in thin foil

Time Resolution

The time resolution, that is the uncertainty in the time of arriva of a neutron compared to the time that it passes its mean distance is

$$\sigma_t^2 = [<t^2> - <t>^2] = [<x^2> - <x>^2]/[v\Sigma(v)] = \sigma_x^2 /[v\Sigma(v)].$$

Because in most converter materials the absorption cross section is inversely proportional to the neutron speed v,

$$v\Sigma(v) = \text{constant} = v_o\Sigma(v_o),$$

which is the inverse lifetime of neutrons in the infinite medium

is independent of the neutron speed.

The time resolution depends entirely on the geometric part

σ_x^2, but because σ_x^2 depends on $\Sigma(v)$ in a more-or-less

complicated way, σ_t^2 also depends on the speed.

Scintillators

In scintillation detectors the neutron capture event produces ions, but the energy excites short-lived light-emitting electronic states in the medium.

Emitted photons (isotropic) travel out of the detector medium into a light-sensing device (typically a photomultiplier).

There, photons eject photoelectrons, which accelerate in an internal electric field, then encounter another surface that emits secondary electrons, perhaps ten times over, multiplying the number of electrons each time, in the end, by ~ x 10^6.

The field directs the electron charge to an anode collector, connected to electronics that registers the event.

Scintillator Materials

Intrinsic scintillators contain small concentrations of ions ("wave shifters") that shift the wavelength of the originally emitted light to the longer wavelength region easily sensed by photomultipliers.

ZnS(Ag) is the brightest scintillator known, an intrinsic scintillator that is mixed heterogeneously with converter material, usually Li^6F in the "Stedman" recipe, to form scintillating composites. These are only semitransparent. But it is somewhat slow, decaying with ~ 10 μsec halftime.

GS-20 (glass,Ce^{3+}), is mixed with a high concentration of Li_2O in the melt to form a material transparent to light

$Li_6Gd(BO_3)_3$ (Ce^{3+}), and LiF(Eu) are intrinsic scintillators that contain high proportions of converter material and are typically transparent

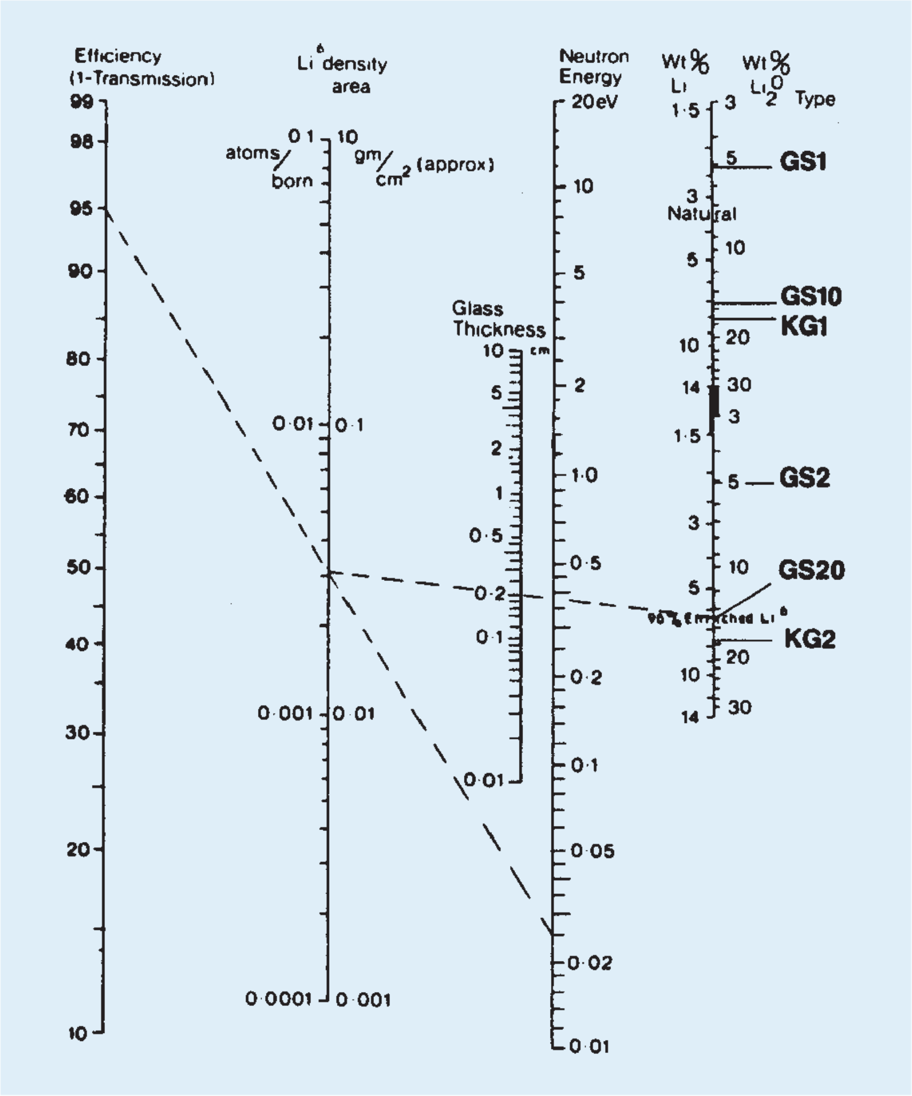
Scintillation Detectors

Single-Detector, Single Photosensor

This is the obvious simple combination. Size is limited by the method of fabricating the phosphor and the size of available photomultipliers. (25 - 150 mm are common.)

If E above 5 eV?

- **Compensate for 1/v efficiency decrease**
- **Neutron velocities above 30000 m/s**
- **Time of flight ranges below 500 μs**
- **Need of FAST detectors with response below 0.5 μs**



Nomogram: detection efficiencies of glass scintillators for slow neutrons.

If E above 5 eV?

Neutron Scattering above 5 eV: Resonance Capture Gamma Ray Detectors

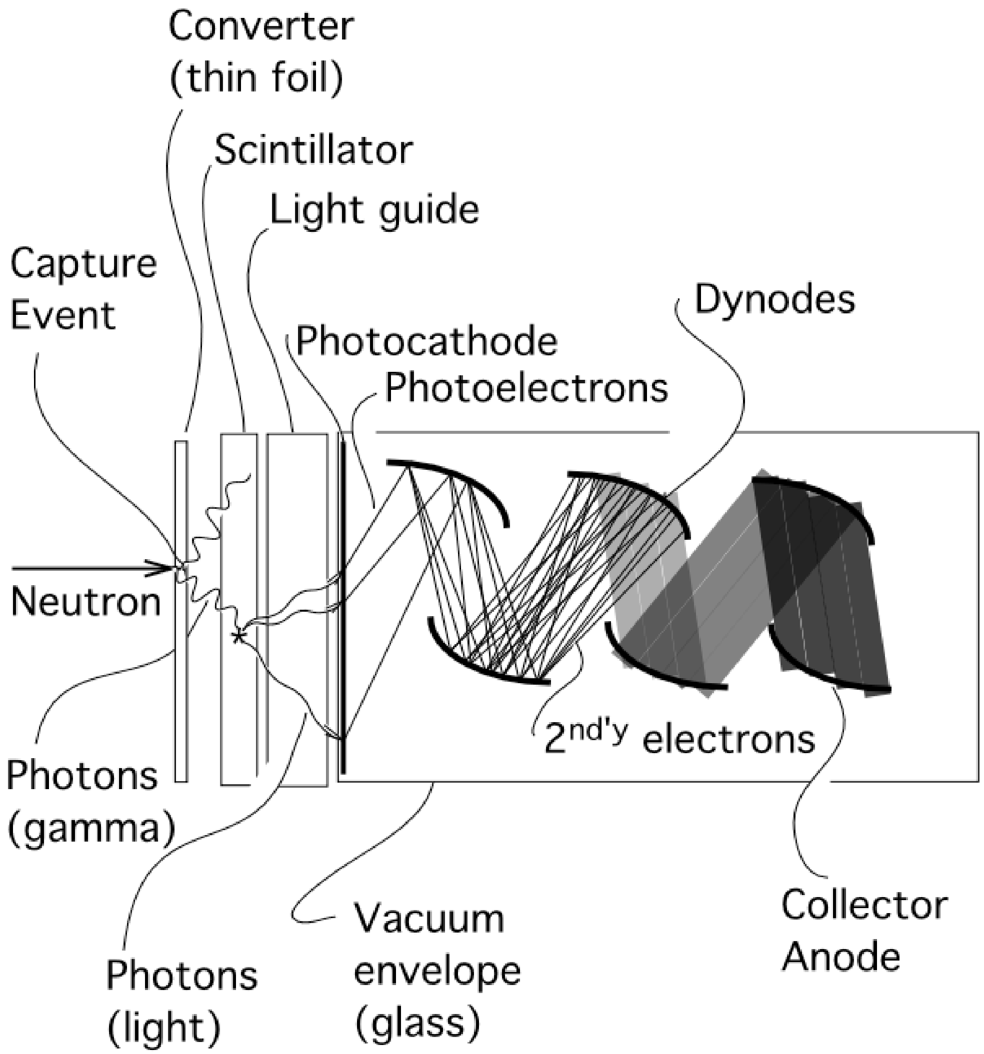
Some spectrometers use detectors that register prompt capture gamma rays given off when an absorber (converter) captures a neutron in a sharply defined resonance (which defines the neutron energy).

A closely located scintillator responds to incident γs and a coupled photomultiplier registers the pulse.

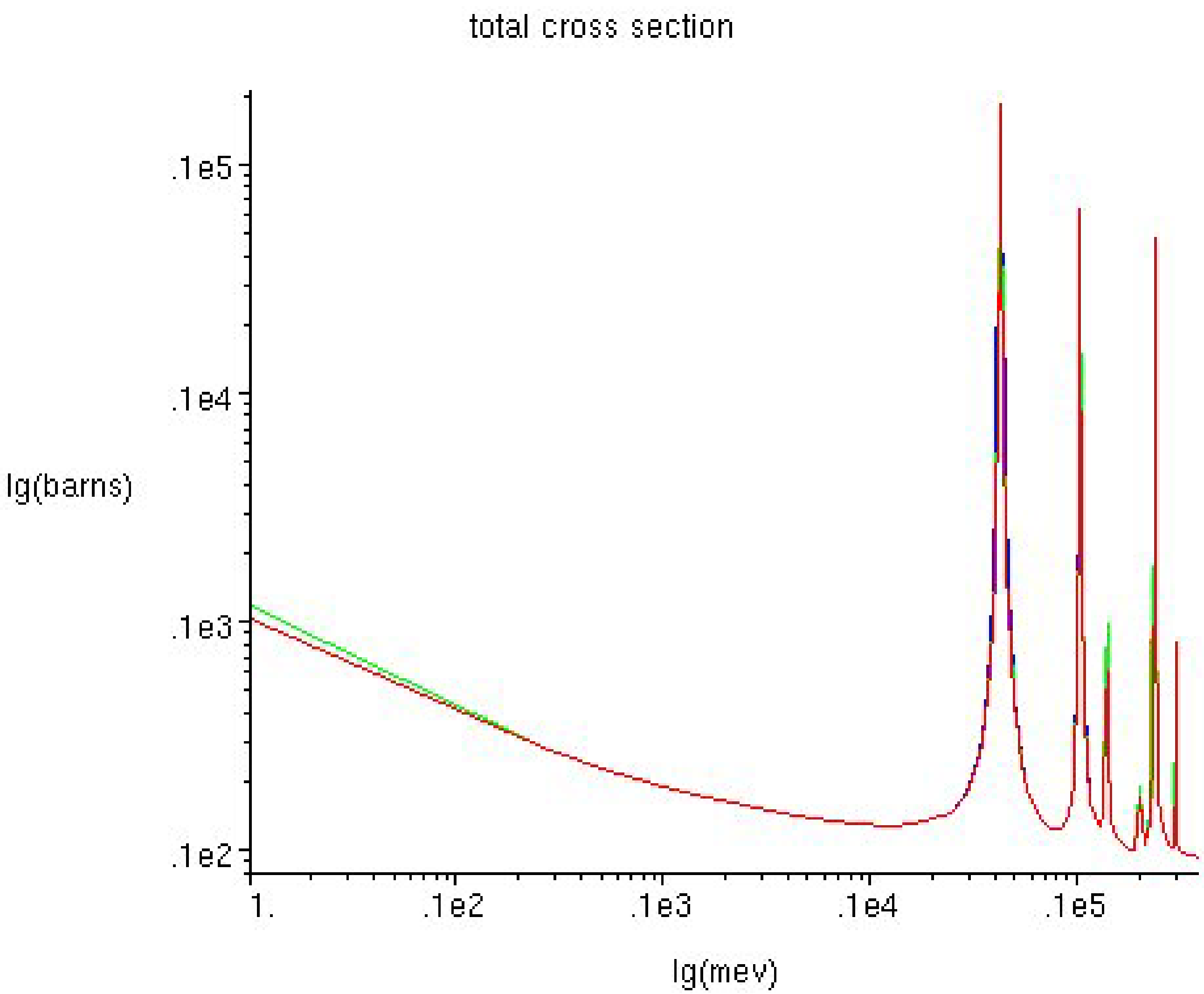
The gamma-ray spectrum is specific to the compound nucleus formed in the capture and the electronics sometimes selects specific prominent lines of the spectrum.

An RD is really more than a detector. It is a monochromating device (almost—it responds to several specific energies, which can be sorted out in time-of-flight applications.)

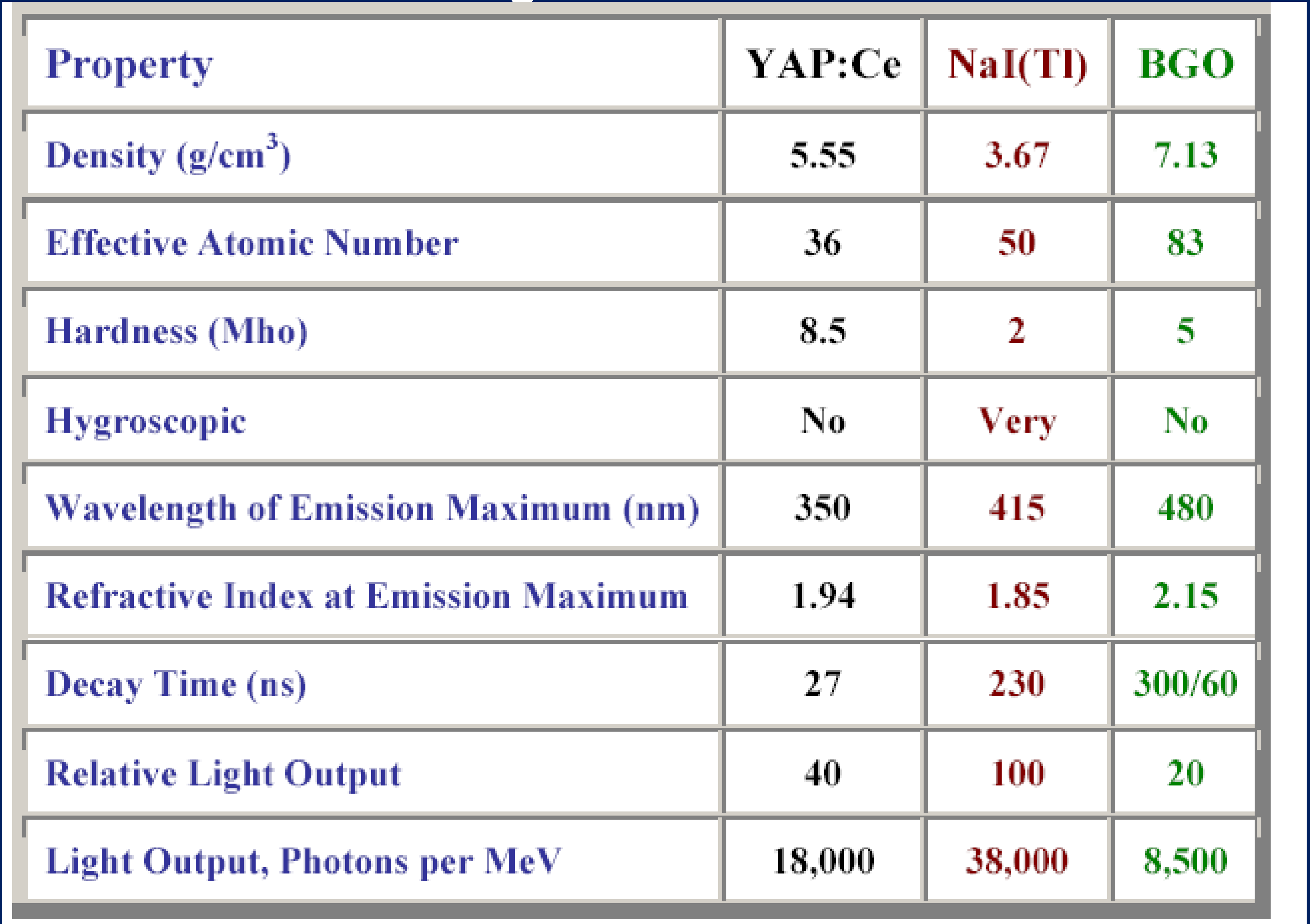
Capture Gamma-ray Detector



Total cross section of Tantalum

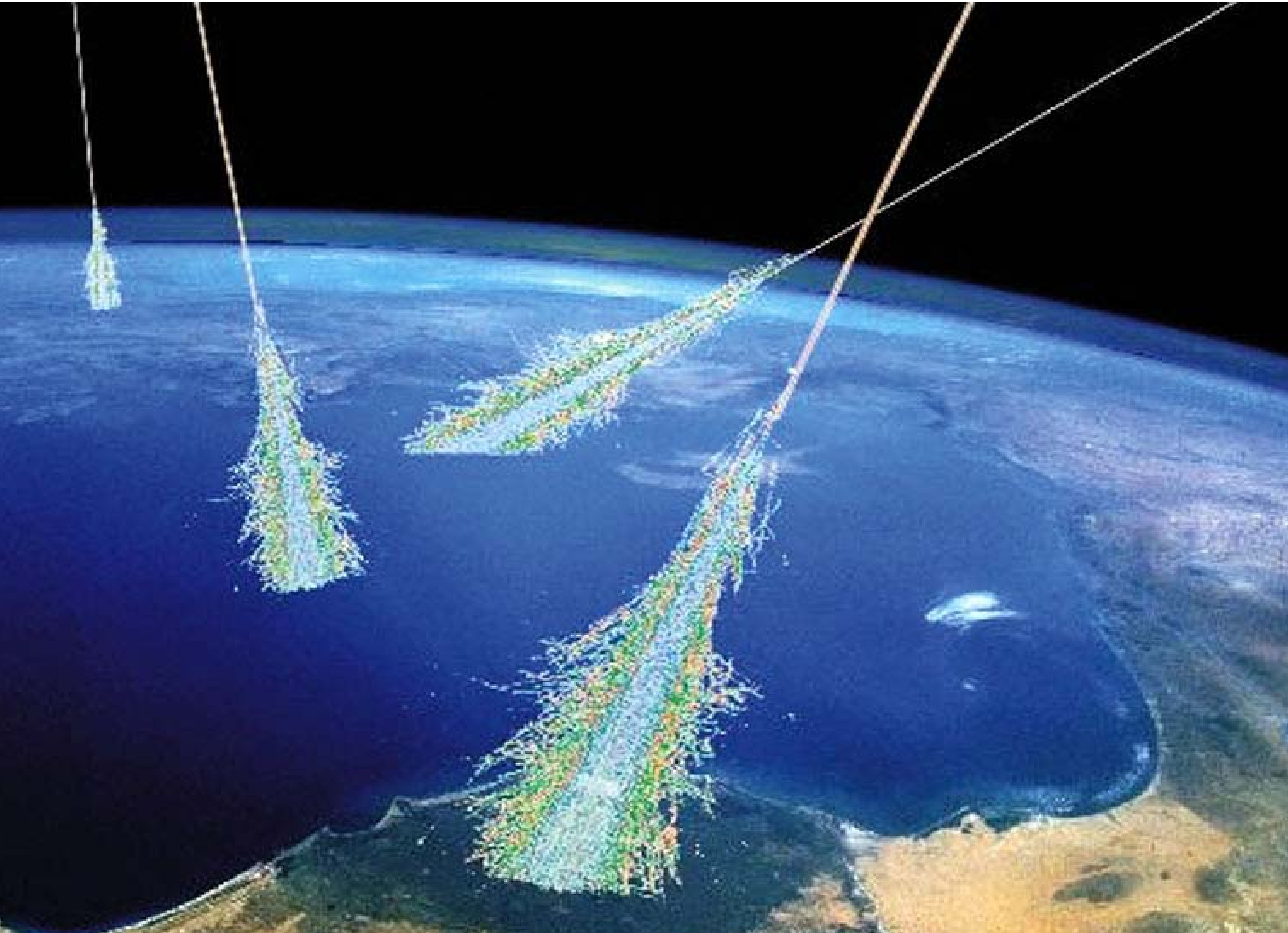


Properties of YAP crystal compared to other types of inorganic scintillators

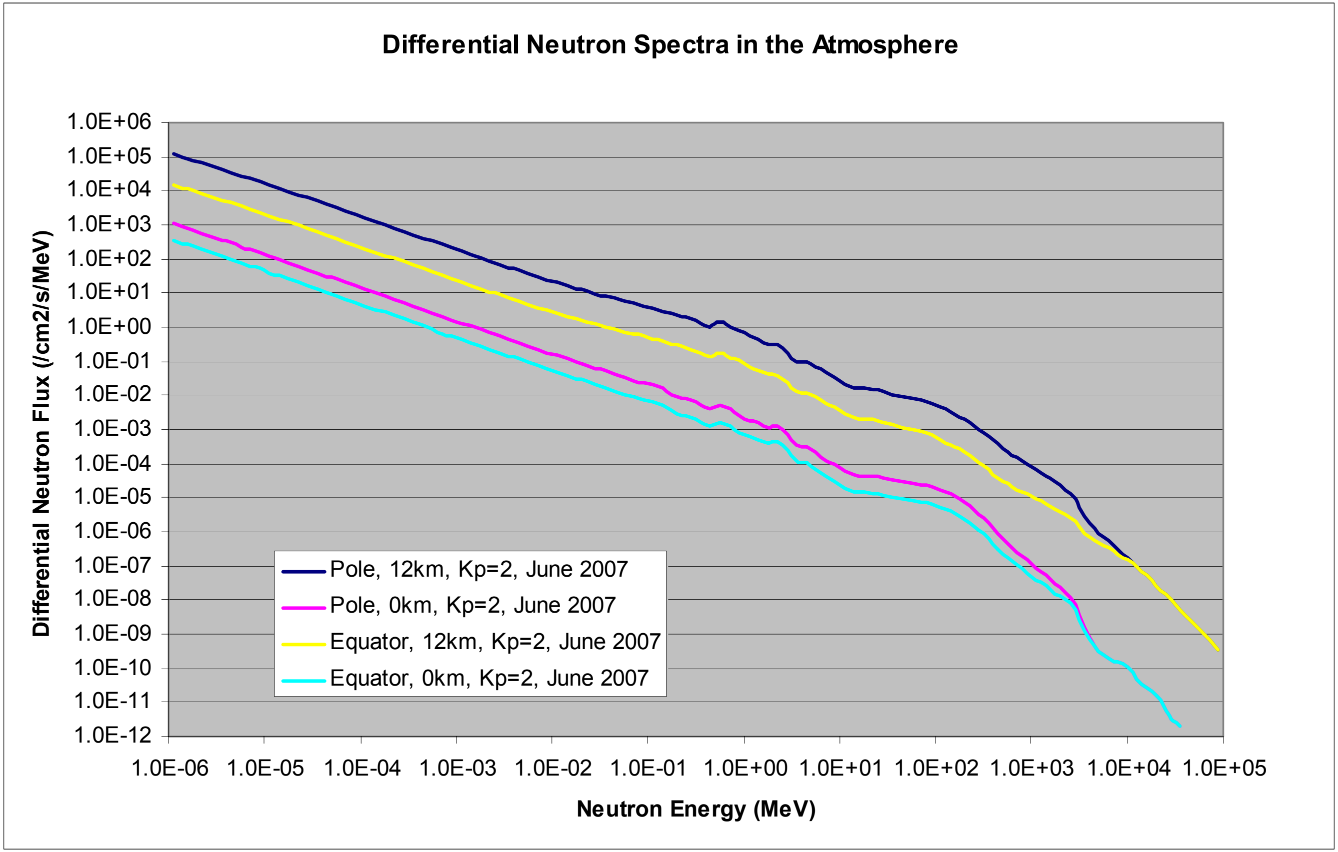


Property	YAP:Ce	NaI(Tl)	BGO
Density (g/cm^3)	5.55	3.67	7.13
Effective Atomic Number	36	50	83
Hardness (Mho)	8.5	2	5
Hygroscopic	No	Very	No
Wavelength of Emission Maximum (nm)	350	415	480
Refractive Index at Emission Maximum	1.94	1.85	2.15
Decay Time (ns)	27	230	300/60
Relative Light Output	40	100	20
Light Output, Photons per MeV	18,000	38,000	8,500

Neutron production in the atmosphere

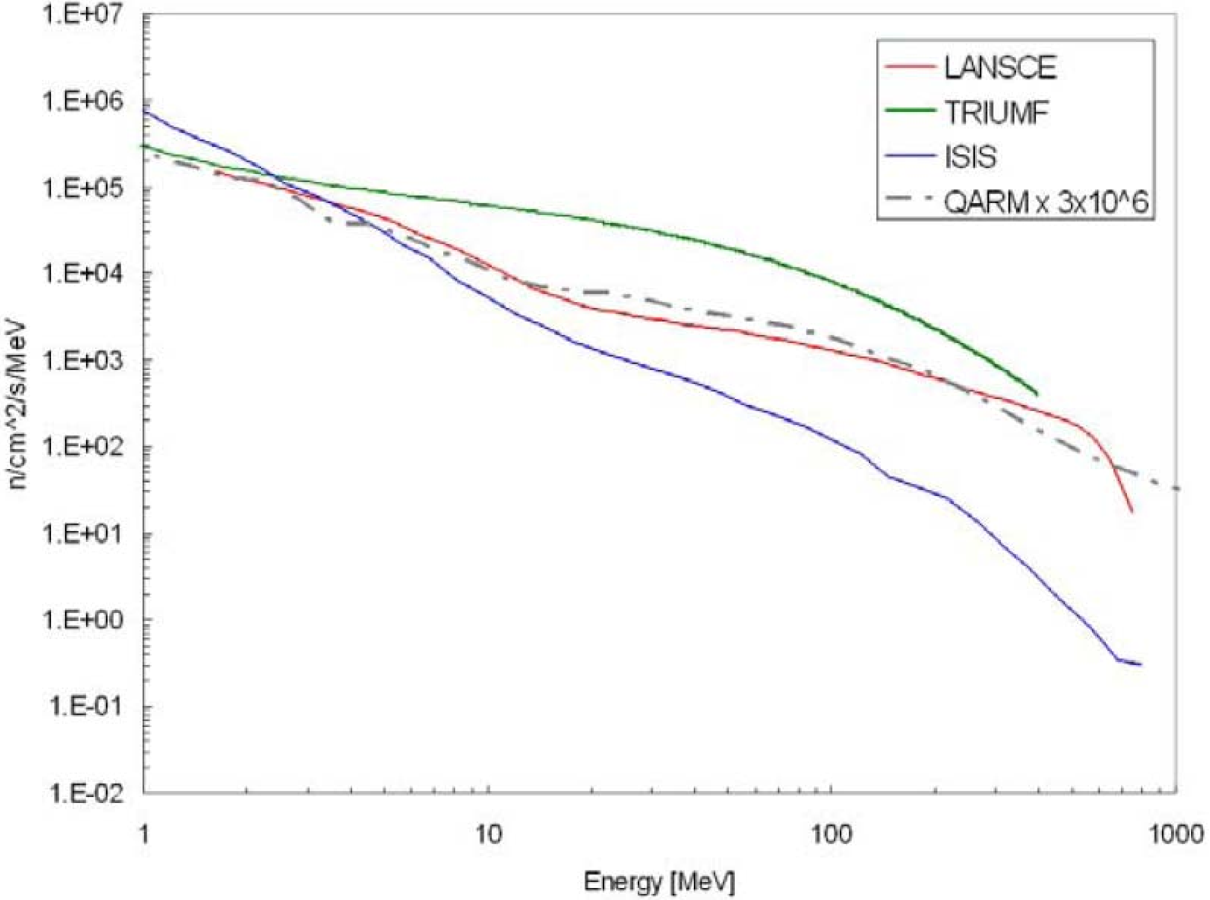


Atmospheric neutrons



http://geoshaft.space.qinetiq.com/qarm/

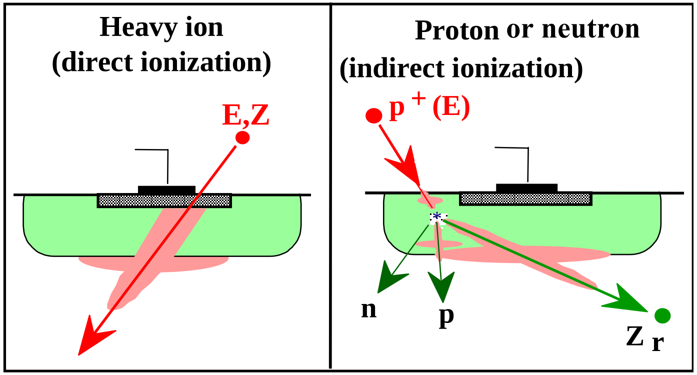
Atmospheric neutrons

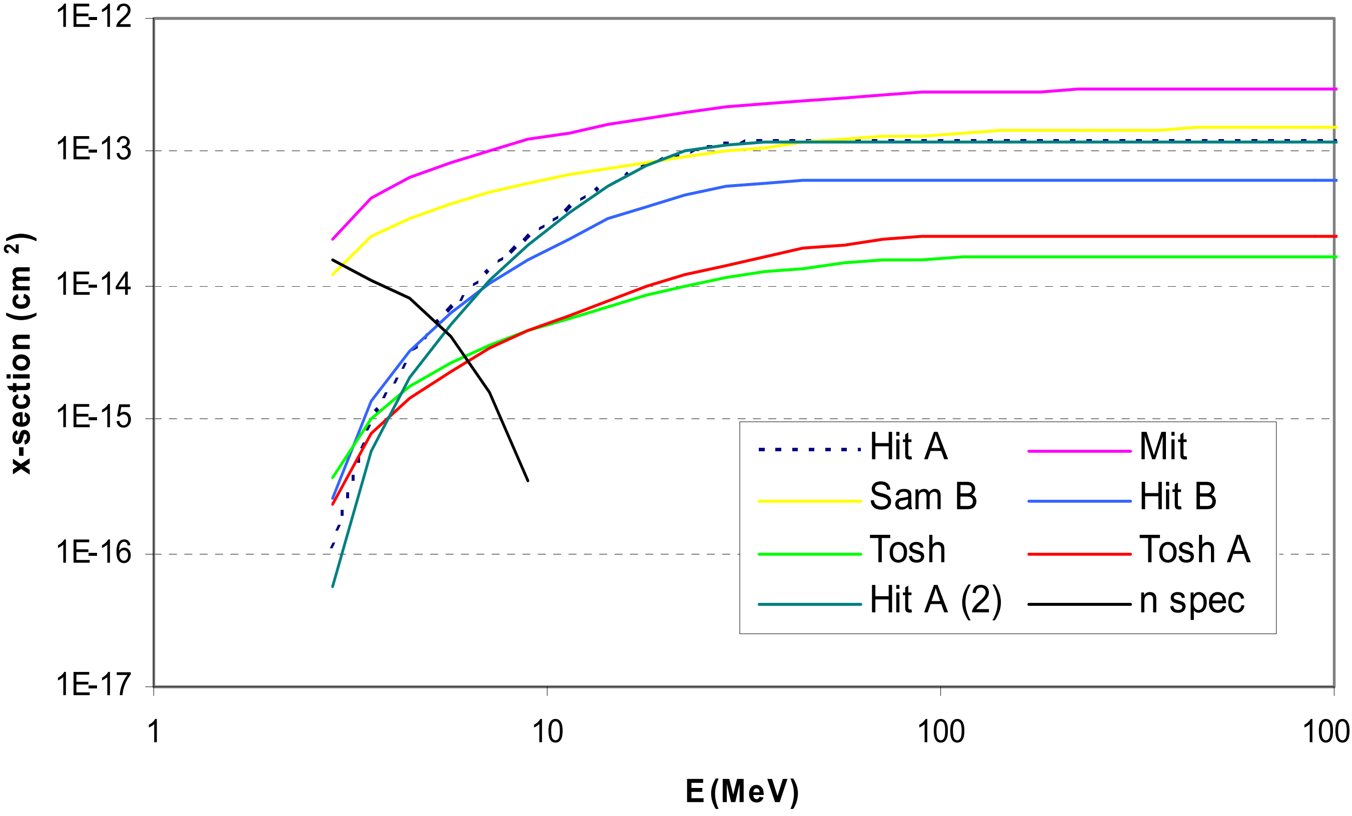


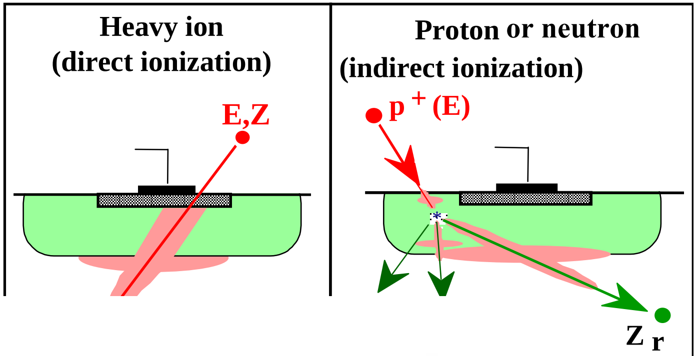
And spallation neutron sources

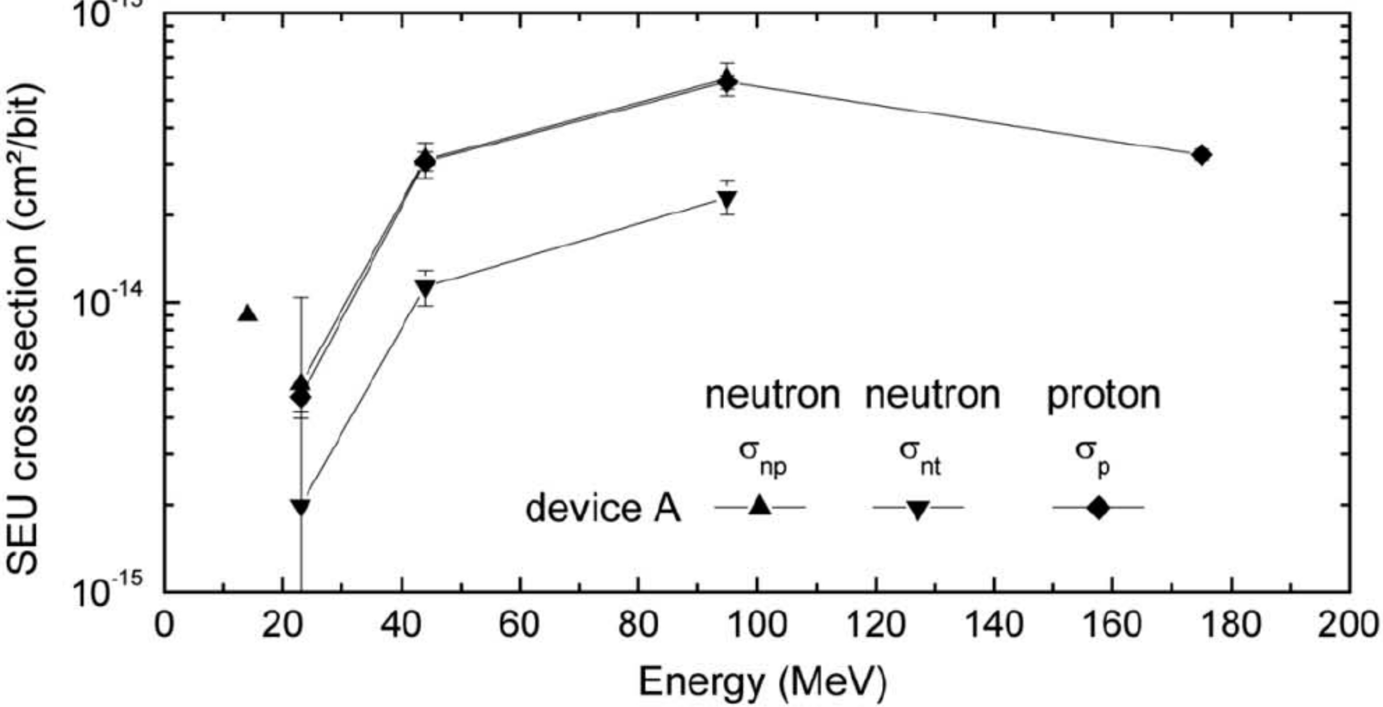
- information and data products to aircraft owners, operators, pilots and engineers to assist in the investigation and mitigation of space weather related problems

Device characterization in ***proton & neutron environments*** is via ***cross-section*** as a function of particle energy









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Neutron spectrometry

Two important aspects of neutron spectrometry:

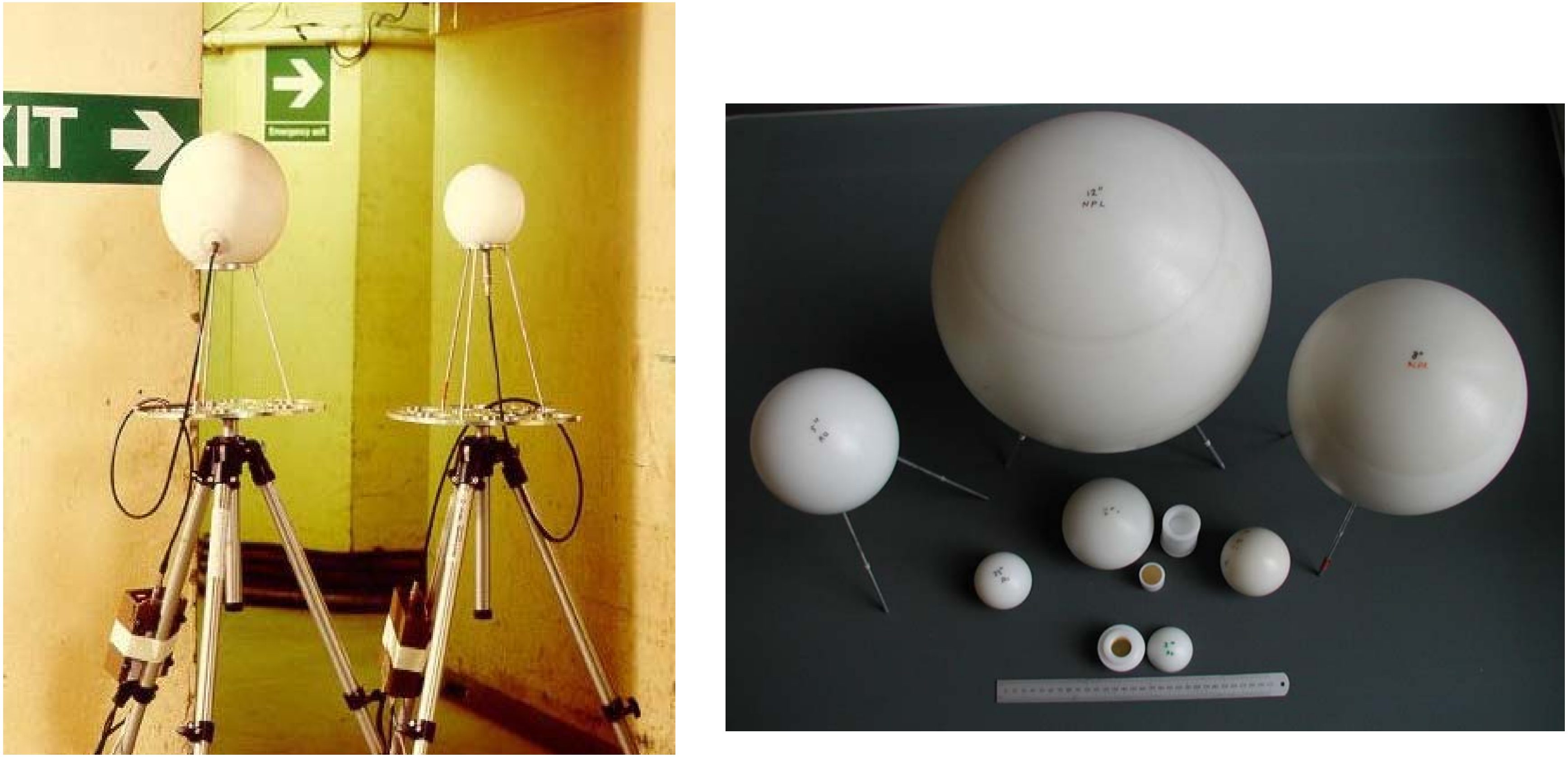
1. Neutron cross sections are known reasonably well below 20 MeV but only very poorly above this energy. Largely for this reason spectrometry can be done reasonably well below 20 MeV, but above this energy is much more difficult
2. The appearance of a neutron spectrum depends on what is plotted!

Neutron spectrometry techniques

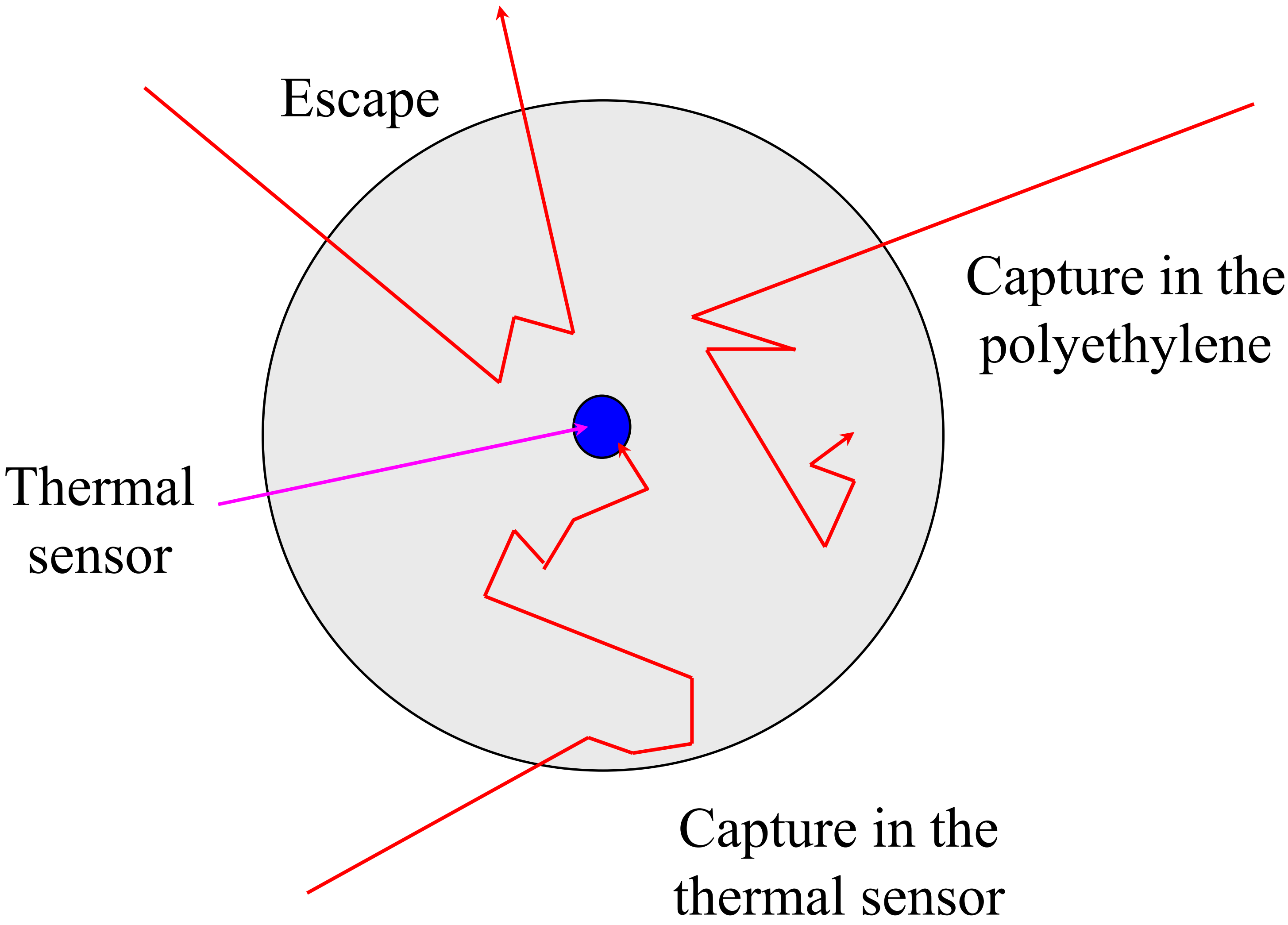
- **Time-of-flight**
- **Nuclear reaction methods, e.g. ^{3}He(n,p)T, or ^{6}Li(n,α)T**
- **Nuclear recoil methods, mainly neutron-proton (n-p) scattering**
- **The use of ‘integral’ detectors, e.g. Bonner spheres**

Integral spectrometers

Bonner spheres



Principle of operation



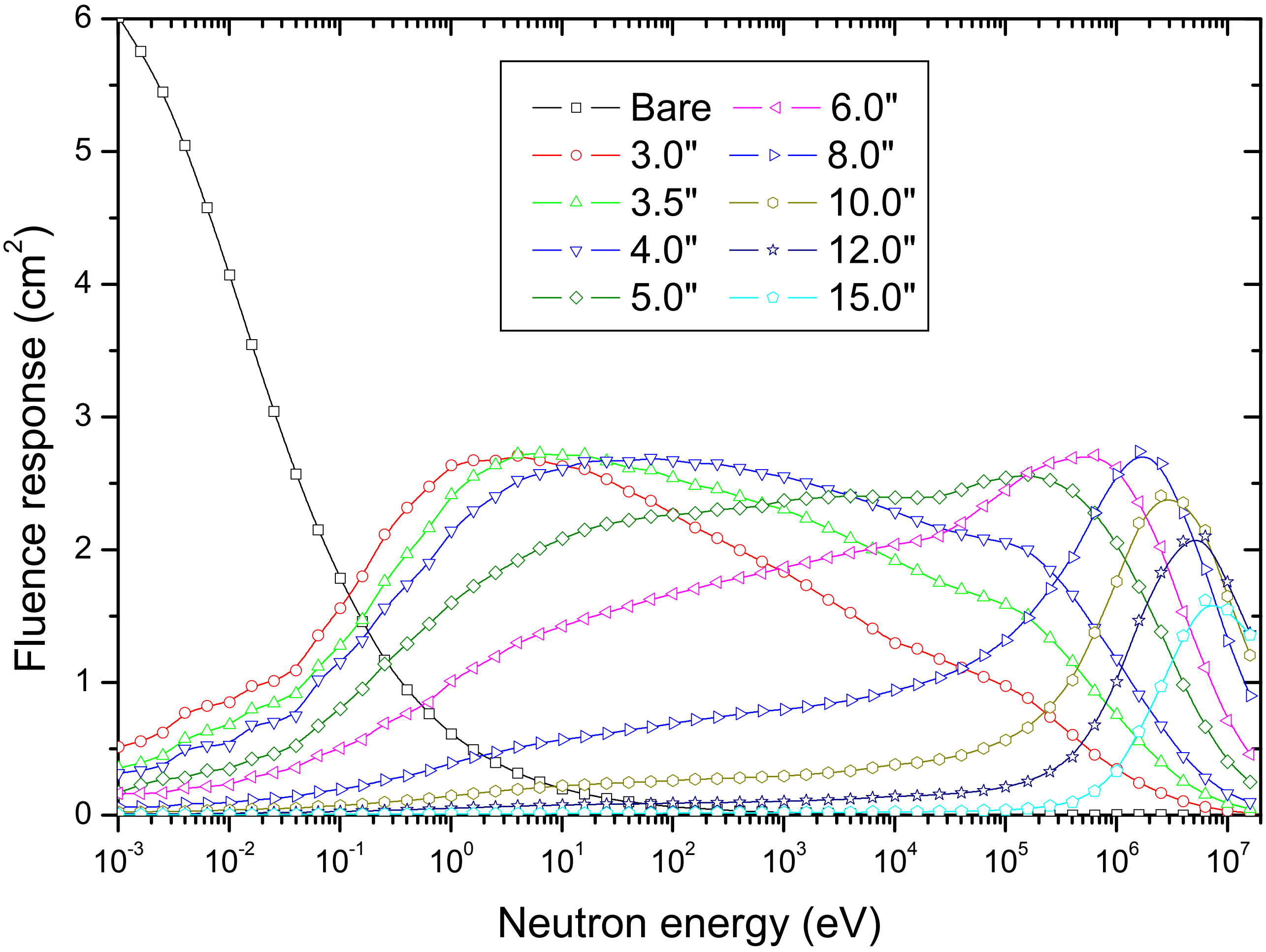
Escape

Capture in the polyethylene

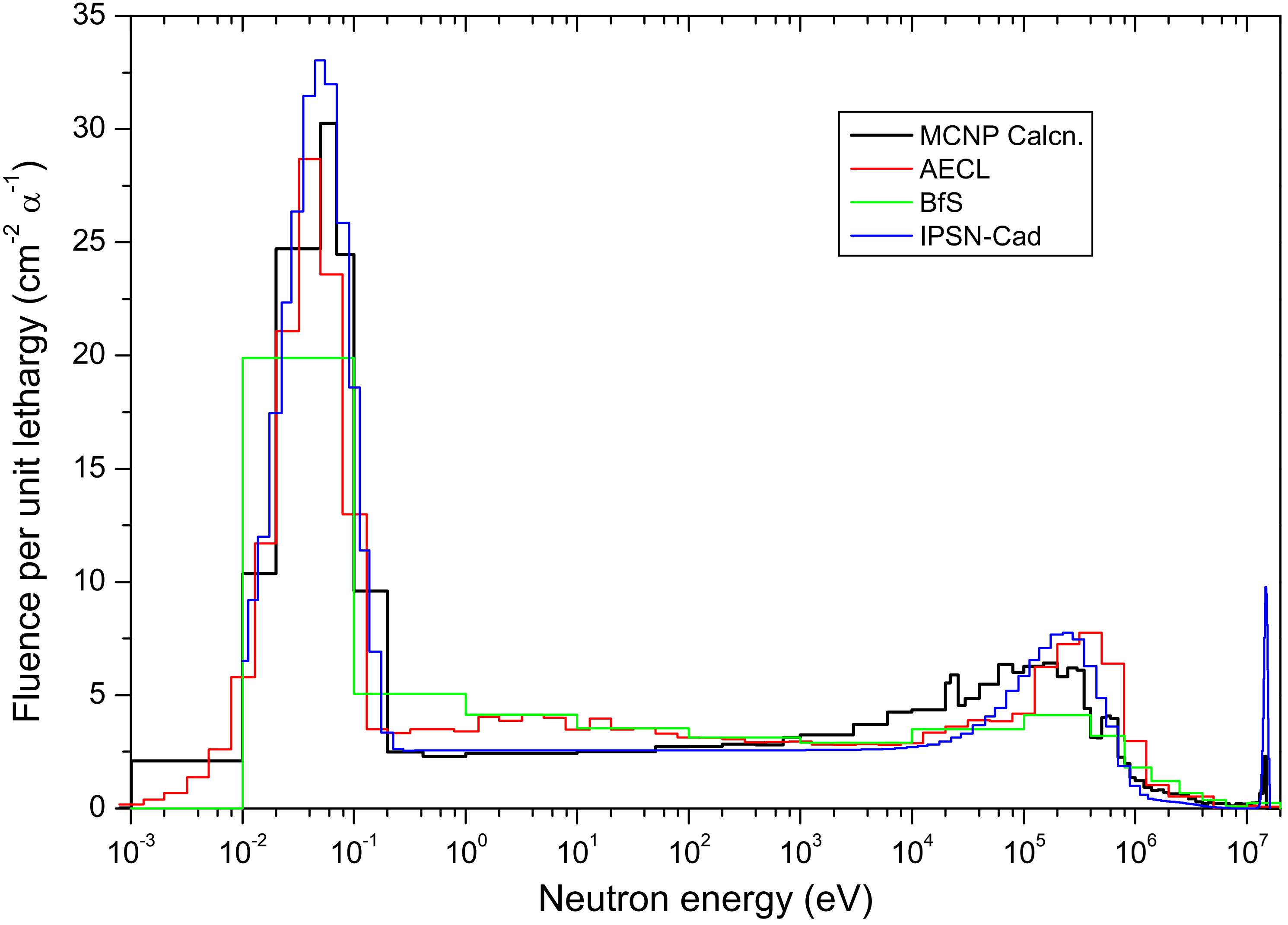
Thermal sensor

Capture in the thermal sensor

Response Functions of Bonner spheres



Bonner sphere spectra from comparison exercise

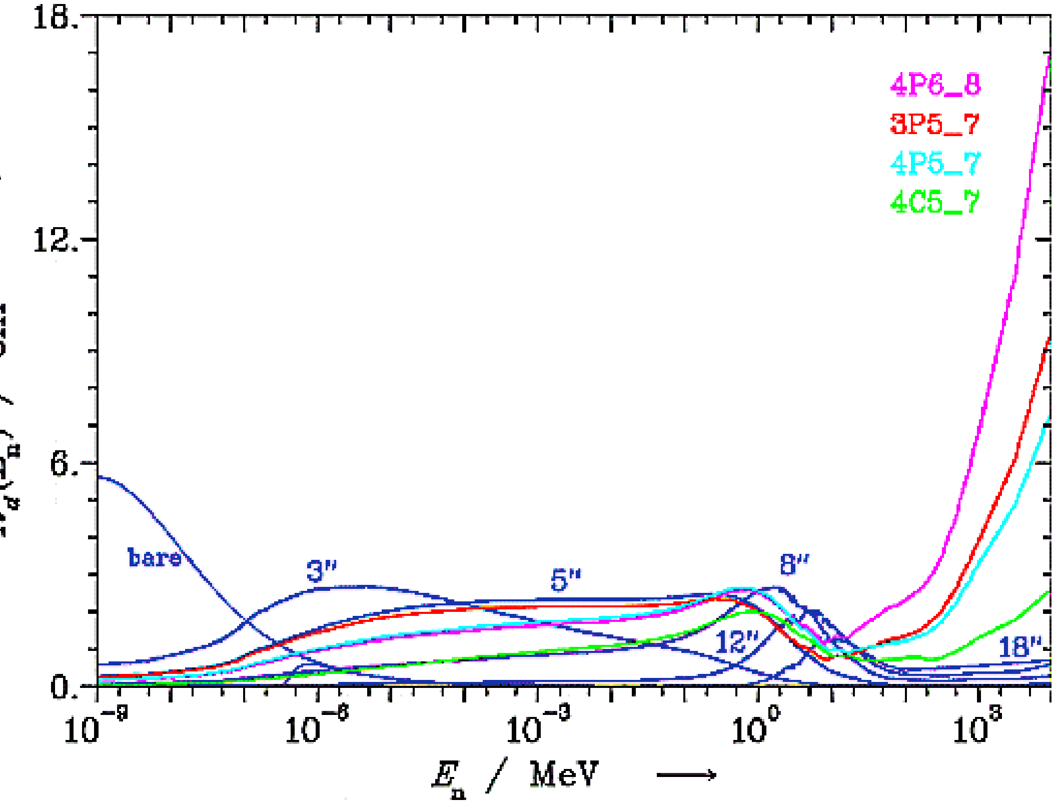


u=ln(E0/E)
du=-dE/E
$\phi(u)=E\phi(E)$

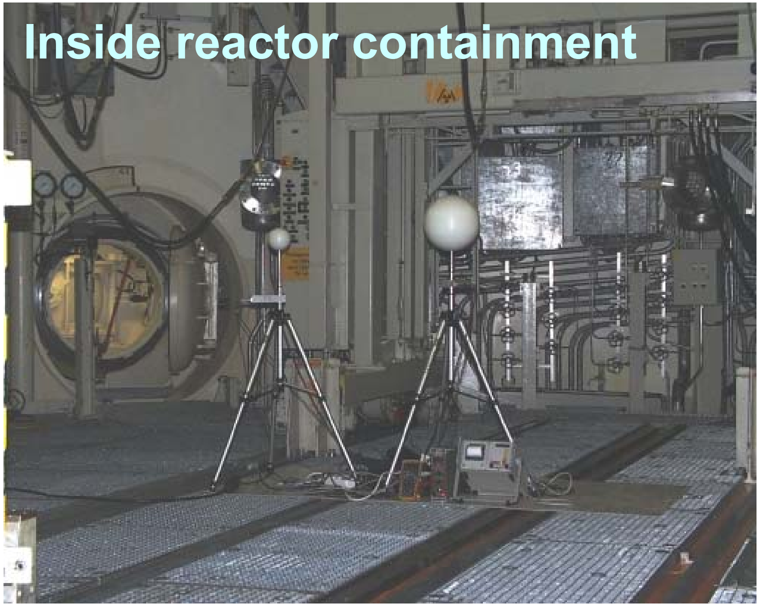
High energy neutron spectrometry with BSs

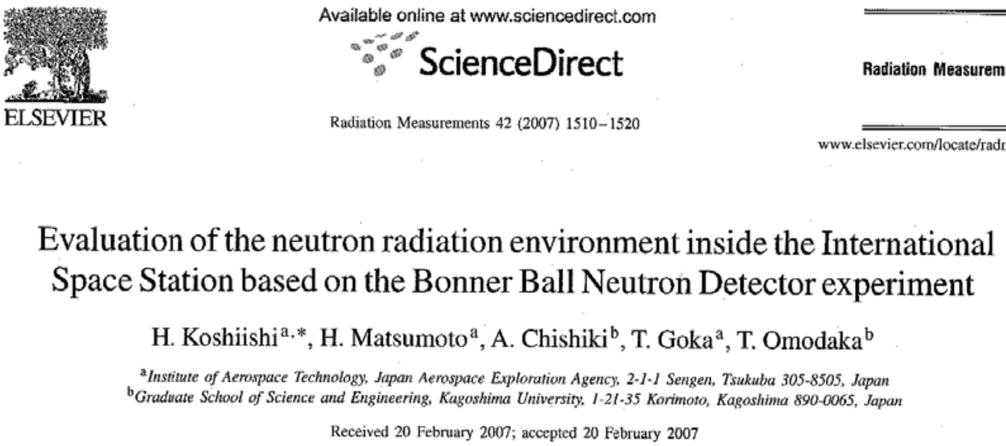
What about going to energies above 20 MeV?

Need to modify the Bonner sphere set by including spheres with metal inserts



eutron spectrometry: outside the lab, all Bonner spheres


Inside reactor containment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Radiation Measurements 42 (2007) 1510–1520

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Evaluation of the neutron radiation environment inside the International Space Station based on the Bonner Ball Neutron Detector experiment

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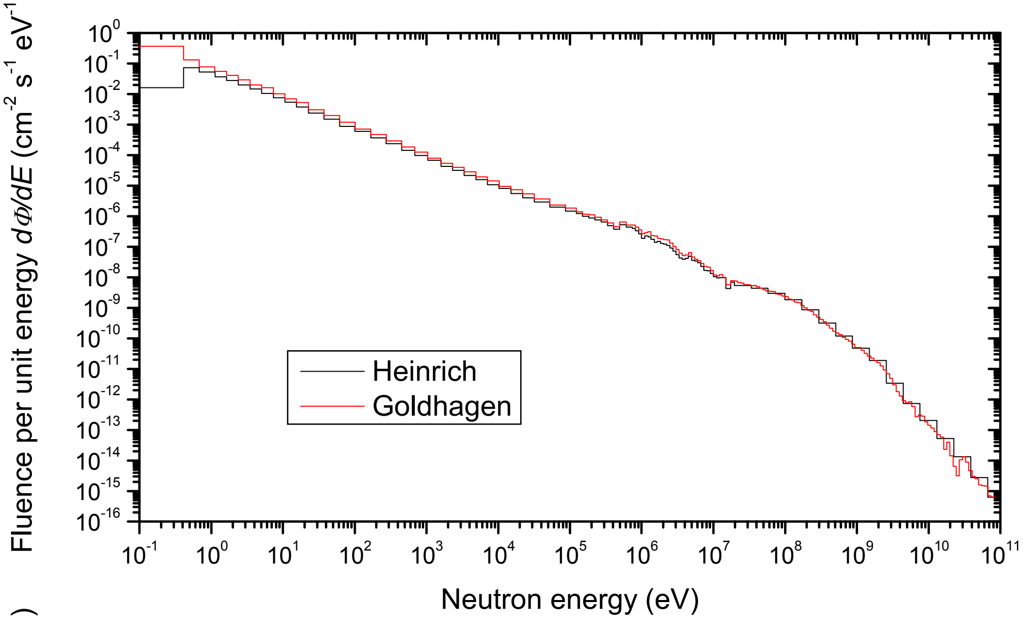
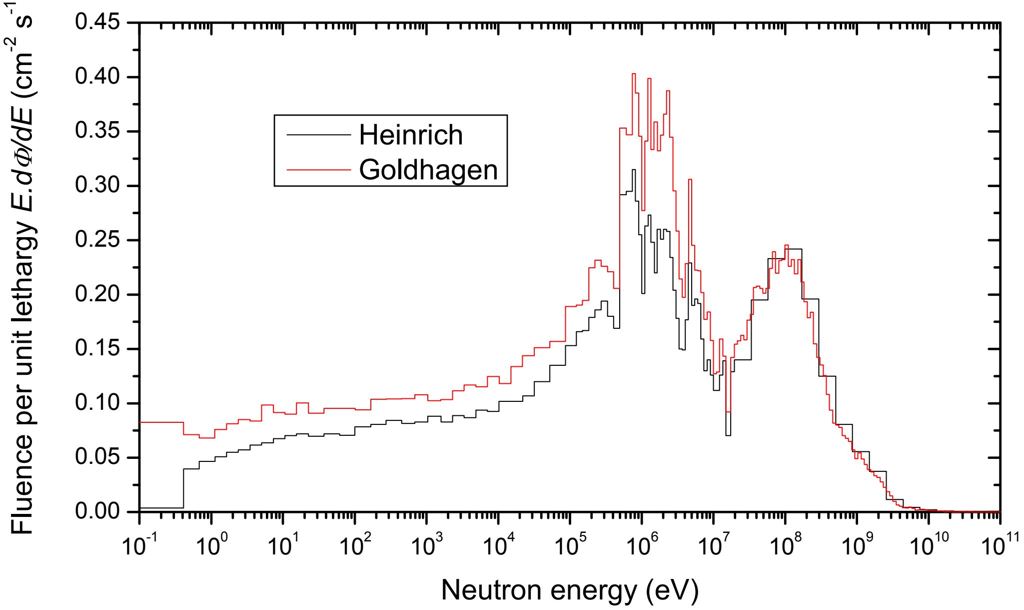
Outside containment UK South Coast


Schneefernerhaus: 2650 m

Neutron spectra





Cosmic ray spectra in the atmosphere as determined by Heinrich and as measured by Goldhagen using Bonner spheres so it can be done using these devices

Characteristics of Bonner spheres

Property	Characteristic
Energy resolution	Poor! But very good for deriving total fluence
Energy range	Thermal to 10 GeV with inserts
Efficiency	High for ^{3}He detector Low for activation
Size & mass	Large
Operation	Simple
Photon discrimination	Good to excellent
Angle response	Isotropic
Unfolding	Complex and subjective
Operation in pulsed beam	Depends on moderation. Always possible with activation material as sensor
Other issues	Need a new response matrix for a pencil beam! May need to correct for other particles (p, μ)