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Manuel Morgano - Paul Scherrer Institut

Detectors for neutron imaging

30.8.2017

Outline

- The challenge of detecting a neutron
- Common materials used for neutron detection
- Standard detectors for neutron imaging
  - Analog methods
  - Digital methods
    - Scintillator + camera (the workhorse)
      - CCD vs. sCMOS
    - Flat panel detectors
- Advanced detectors: ToF
- Fast neutron detection for neutron imaging

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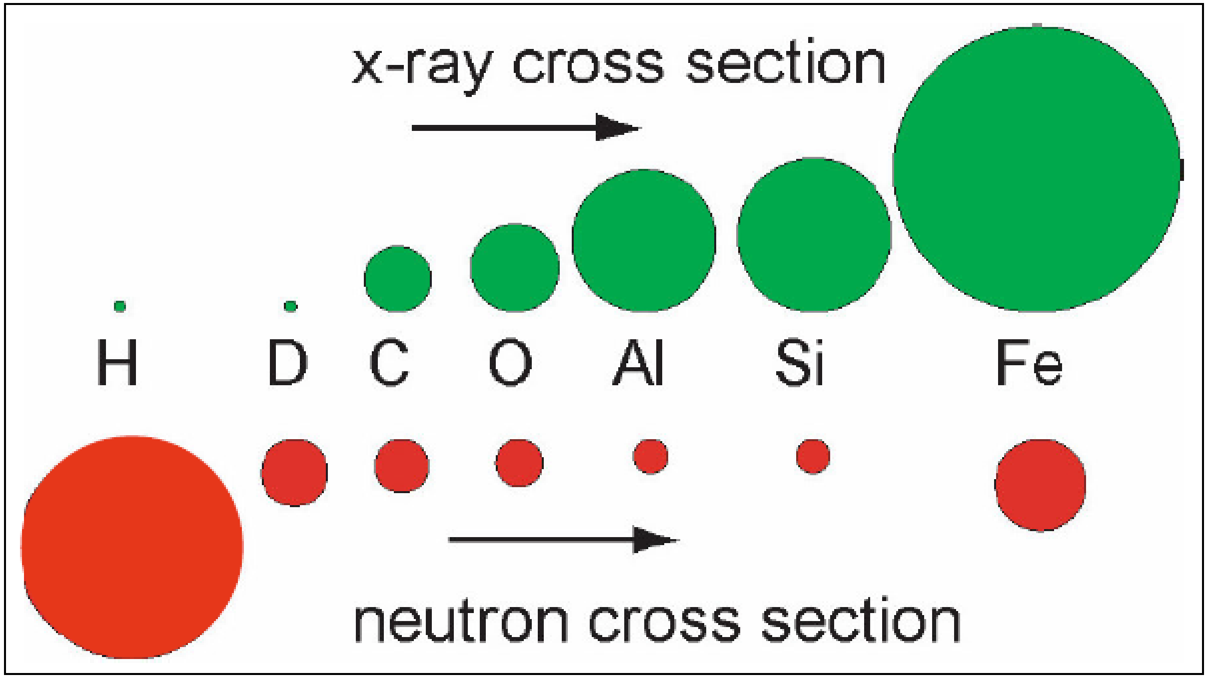
The challenge of detecting a neutron

- You might be familiar with this picture:



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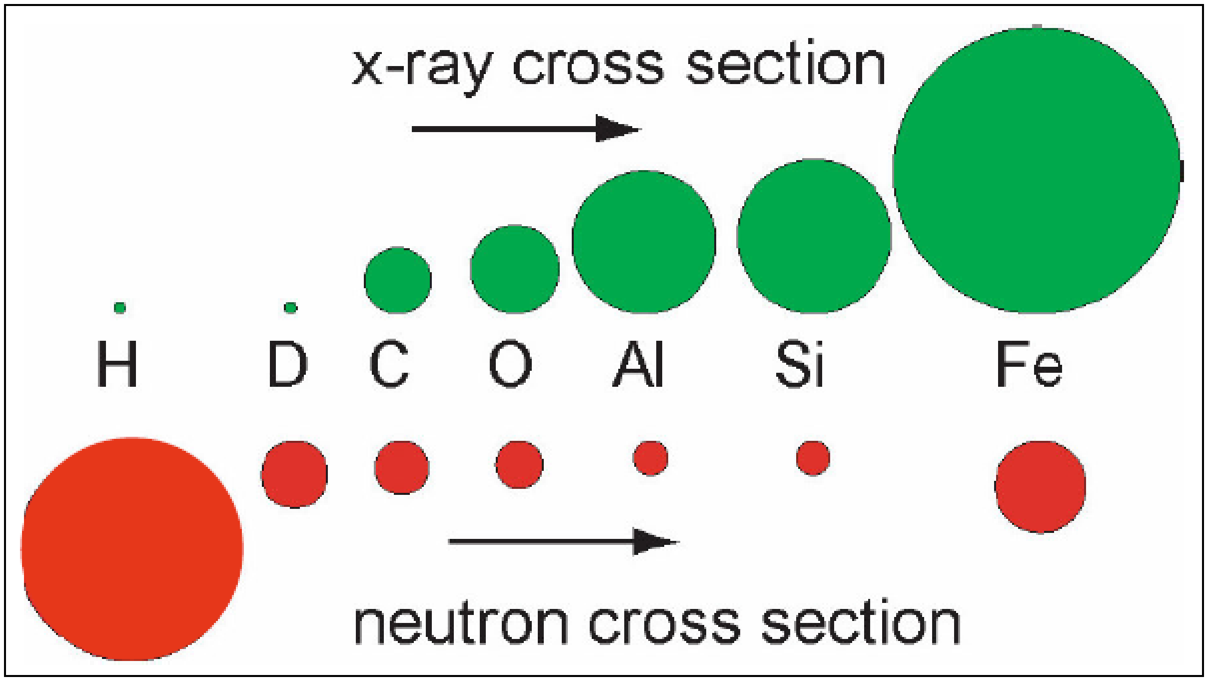

- Plot twist: the size of the x-ray bubbles are reduced by a factor ~1.5

The challenge of detecting a neutron

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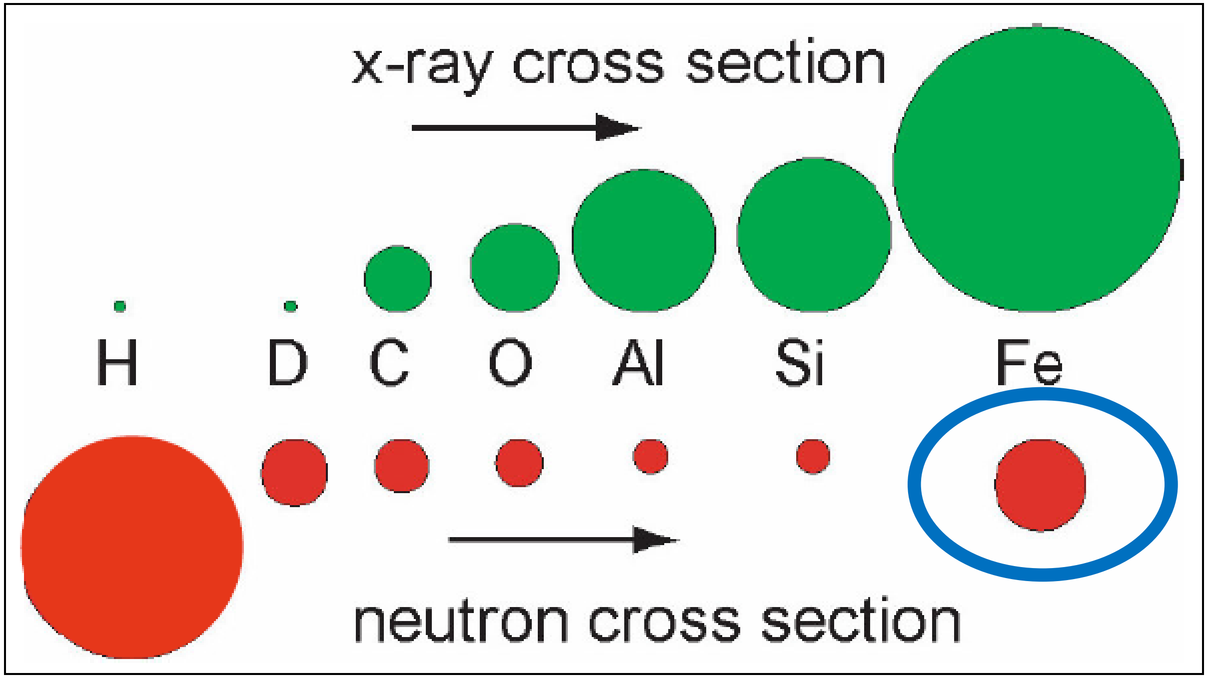

- Plot twist: the size of the x-ray bubbles are reduced by a factor ~1.5

- Please notice the size of the Fe bubble for neutrons, it will come handy later

Common materials for neutron detection

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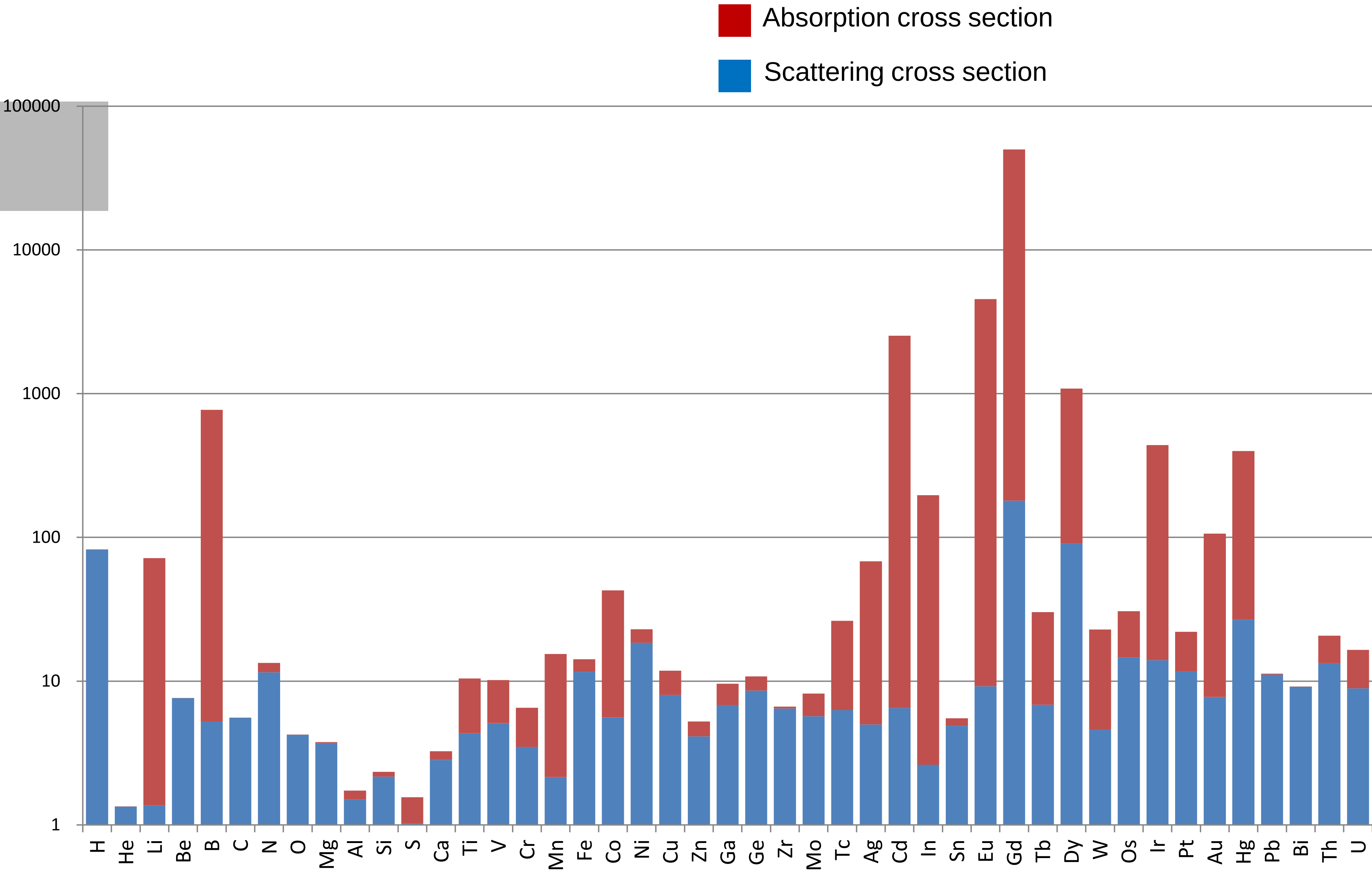
Neutron conversion to light



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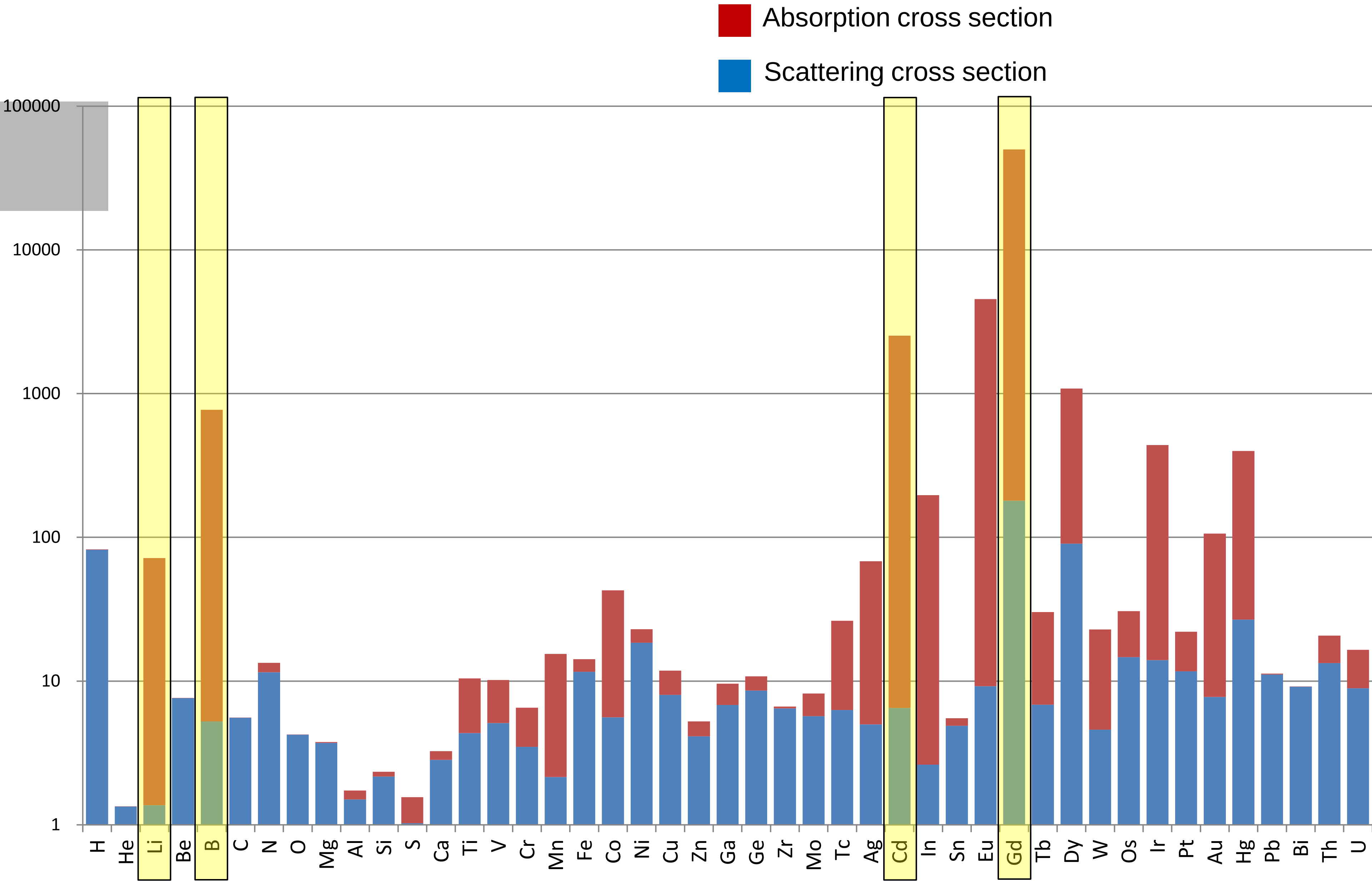

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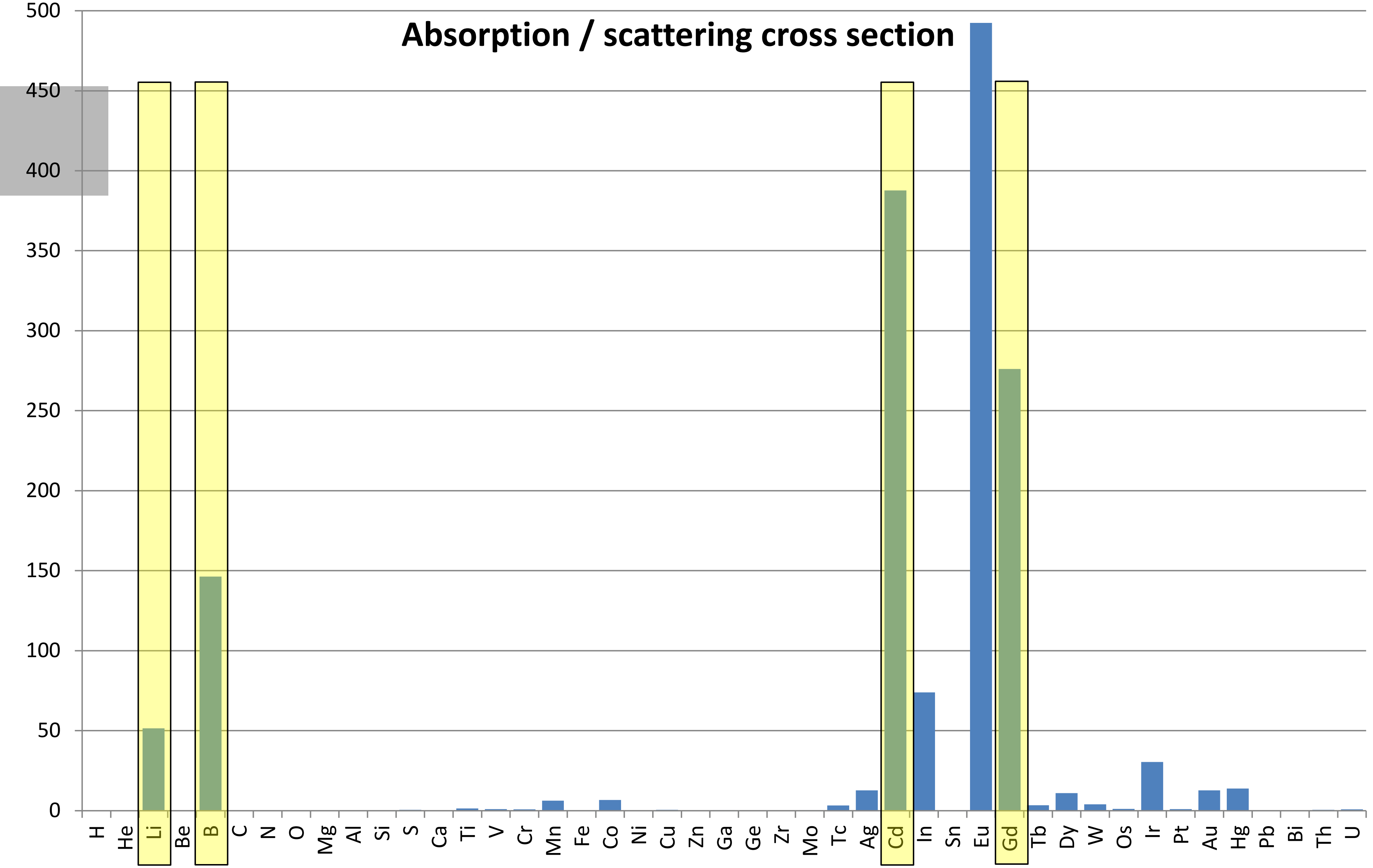

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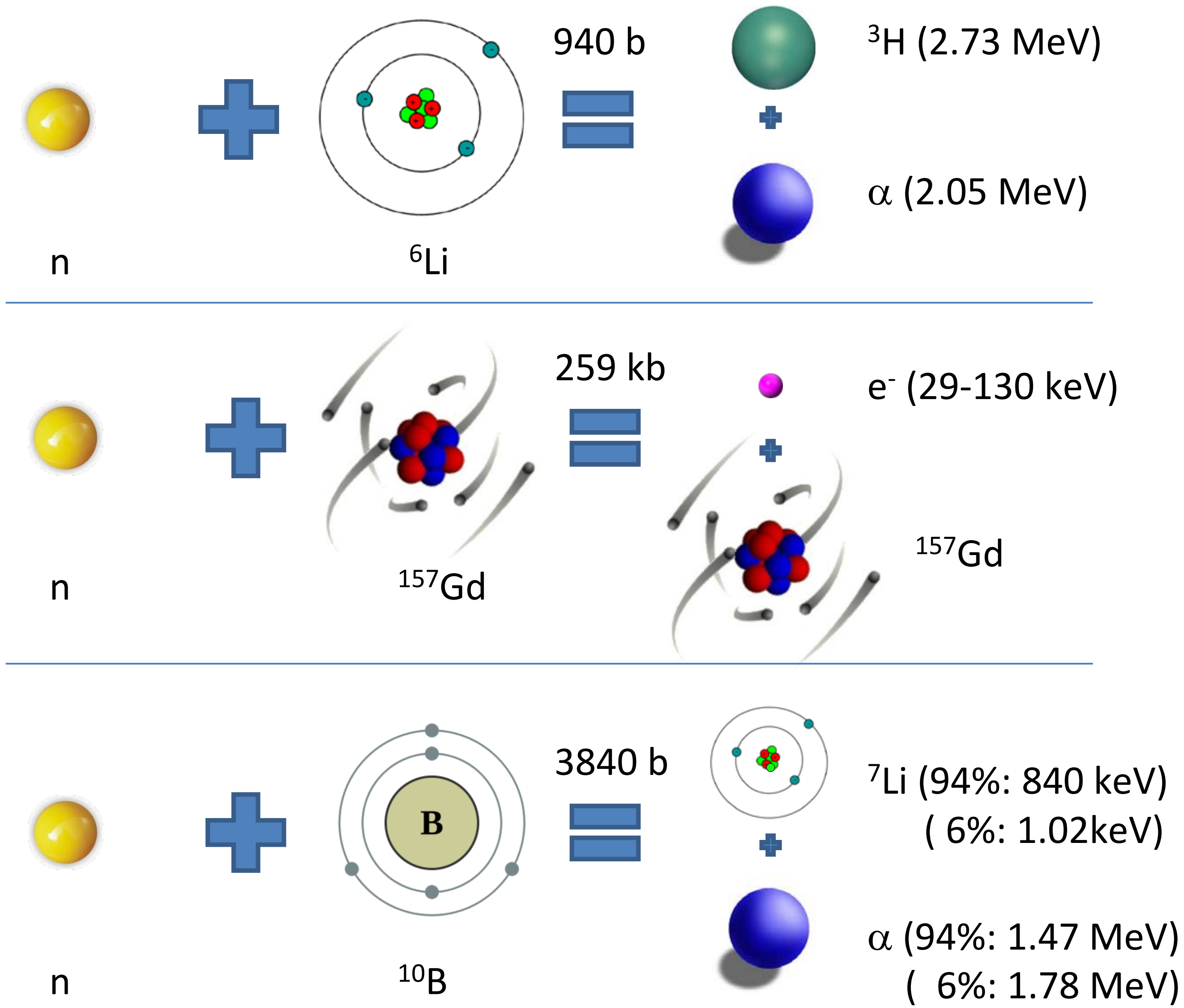

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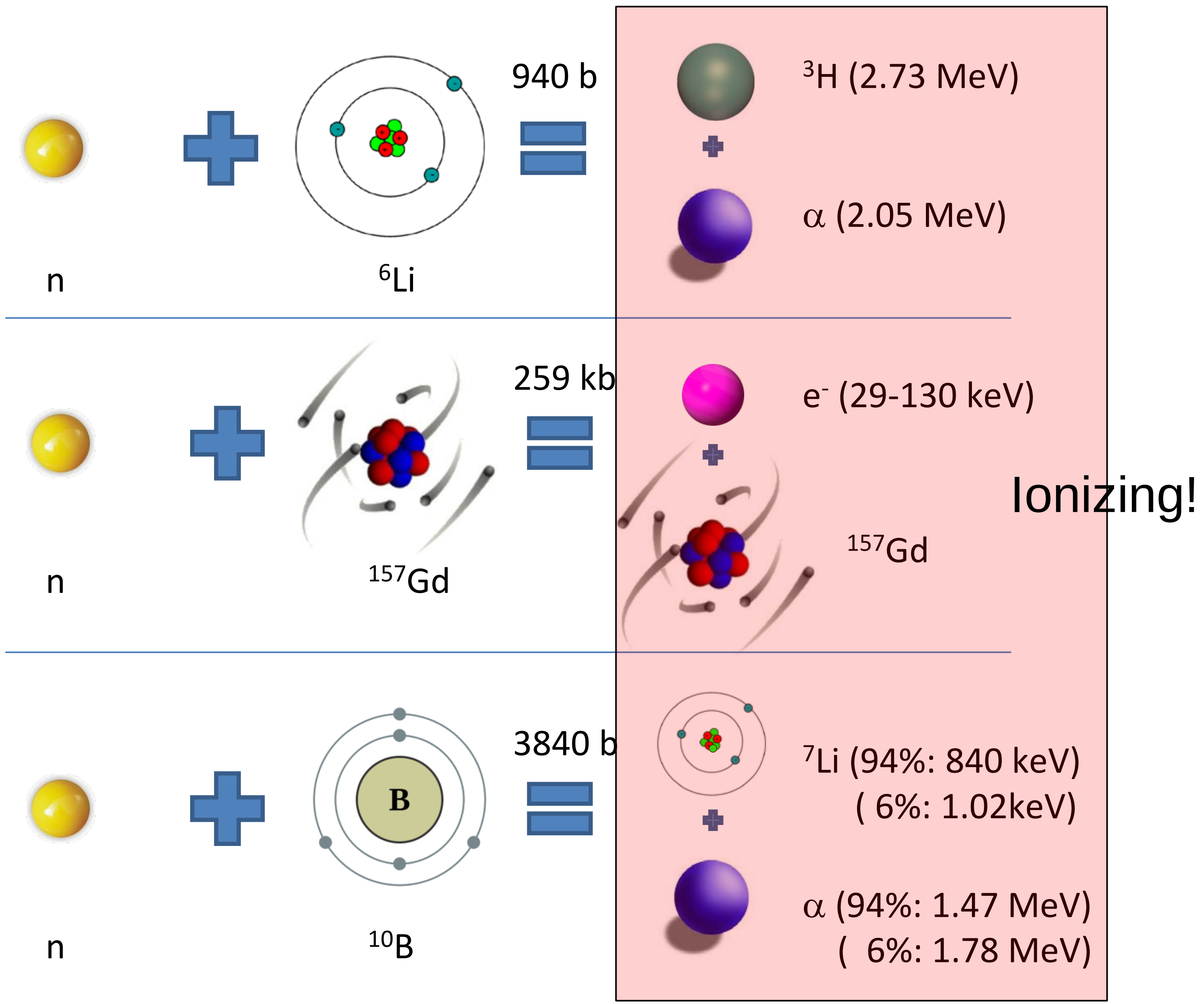

Analog methods

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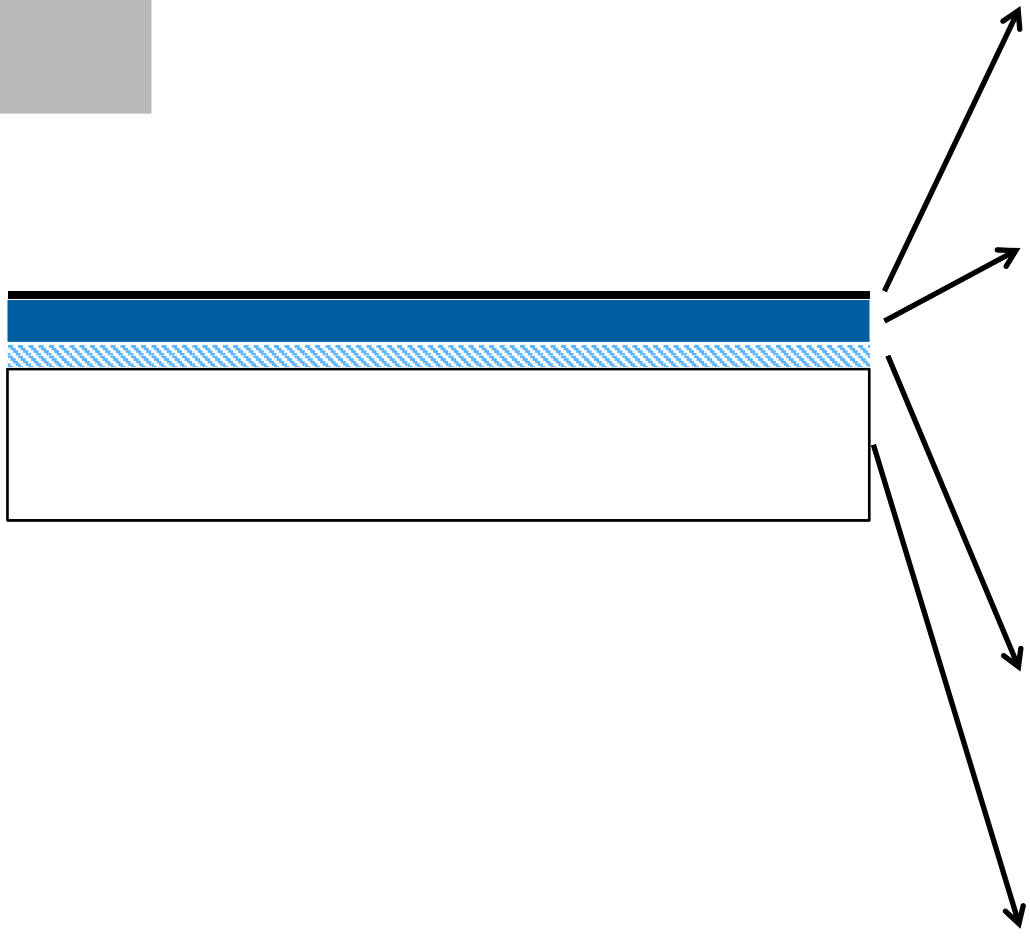
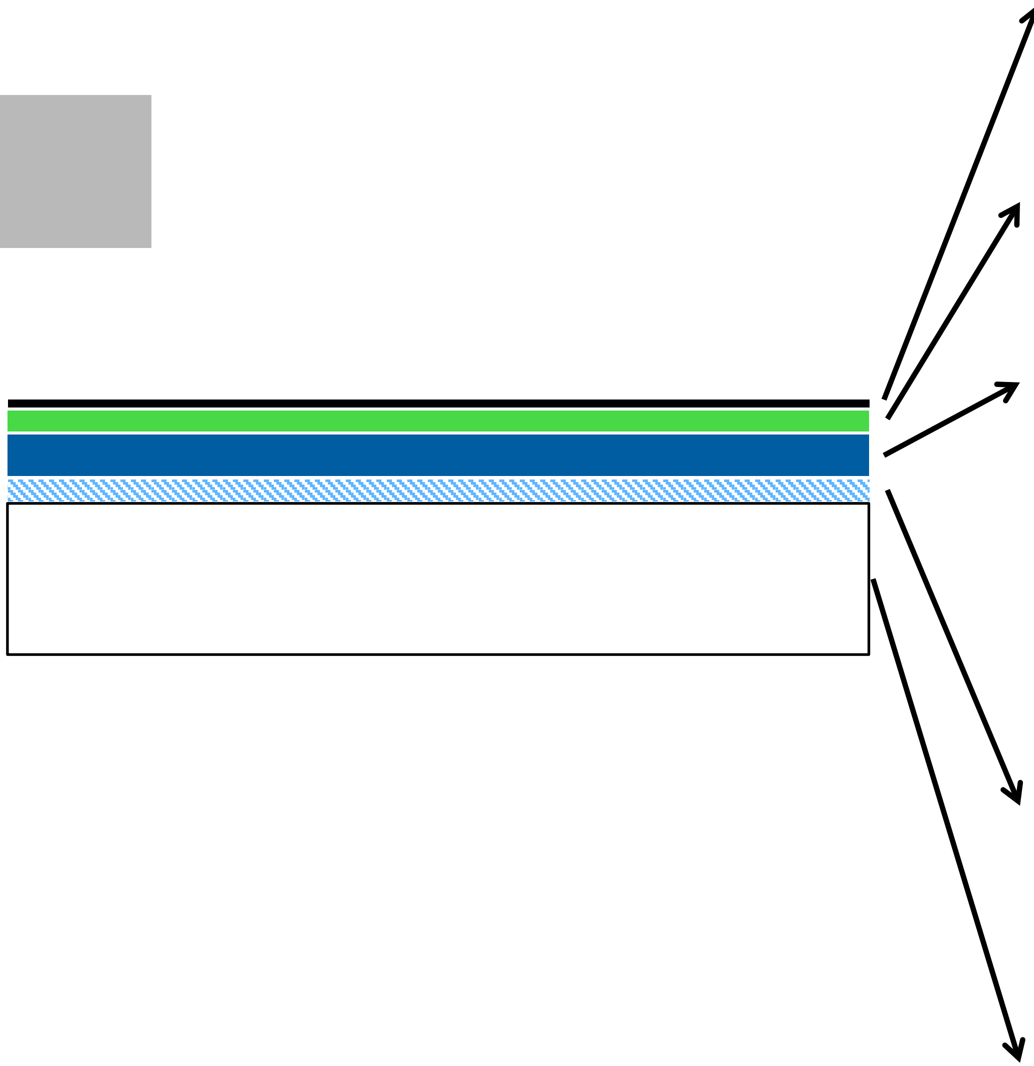
X-ray film



- Cassette-protective layer: Protection against scratches and light
- Emulsion-gelatine of silver halide crystal (AgBr, AgCl, AgI…): When hit by x-ray, it becomes more sensitive to reduction and leaves a silver trace when developed, forming the image
- Adhesive: Keeps the emulsion tight and flat against the base
- Base: Structural support

X-ray film + converter plate



- Cassette-protective layer: Protection against scratches and light
- Converter plate (Gd): Absorbs neutrons and produces e-
- Emulsion-gelatine of silver halide crystal (AgBr, AgCl, AgI…): When hit by e-, it becomes more sensitive to reduction and leaves a silver trace when developed, forming the image
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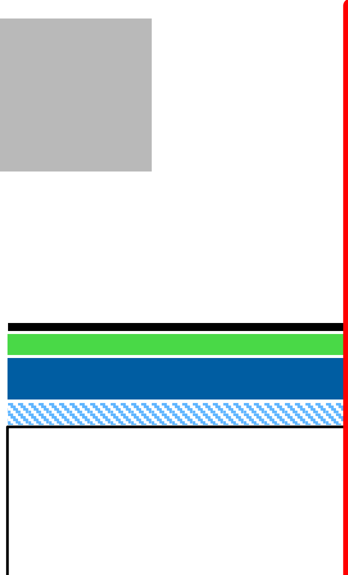
X-ray film + converter plate

- Cassette-protective layer: Protection against scratches and light



- High resolution (<10 um) and big FoV (easily ~ 500 cm^2)
- Analog method, must be digitalized for computed processing with loss of resolution
- “one shot only”, if overexposed one has to repeat the experiment
- Almost no time resolution
- Very time consuming and “messy” procedure to see the image

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Digital methods

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The scintillator

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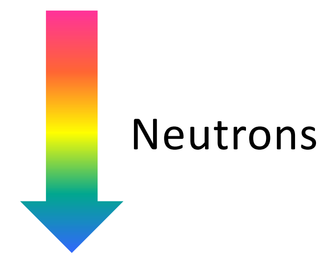

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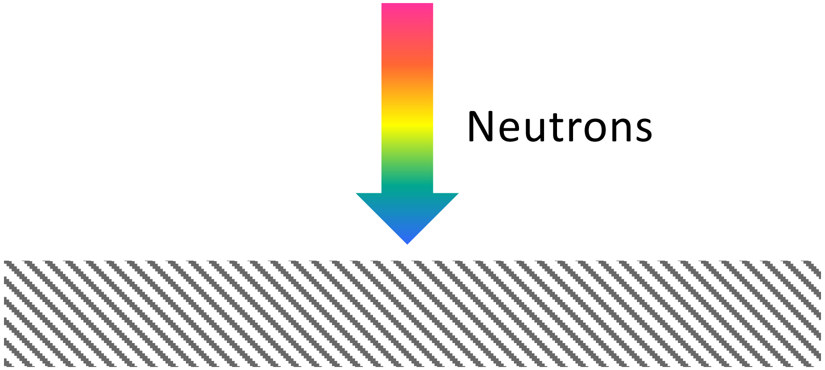
1. The substrate: physically supports the scintillator, blocks unwanted light. Should be made of a neutron transparent material (Al or Si)



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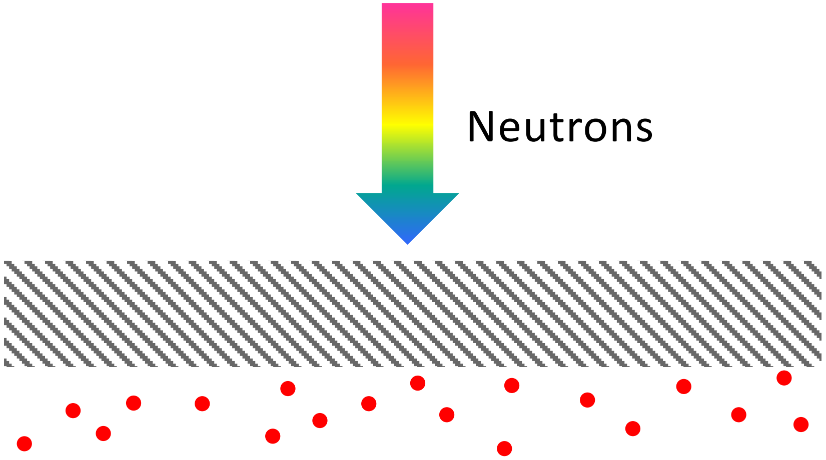

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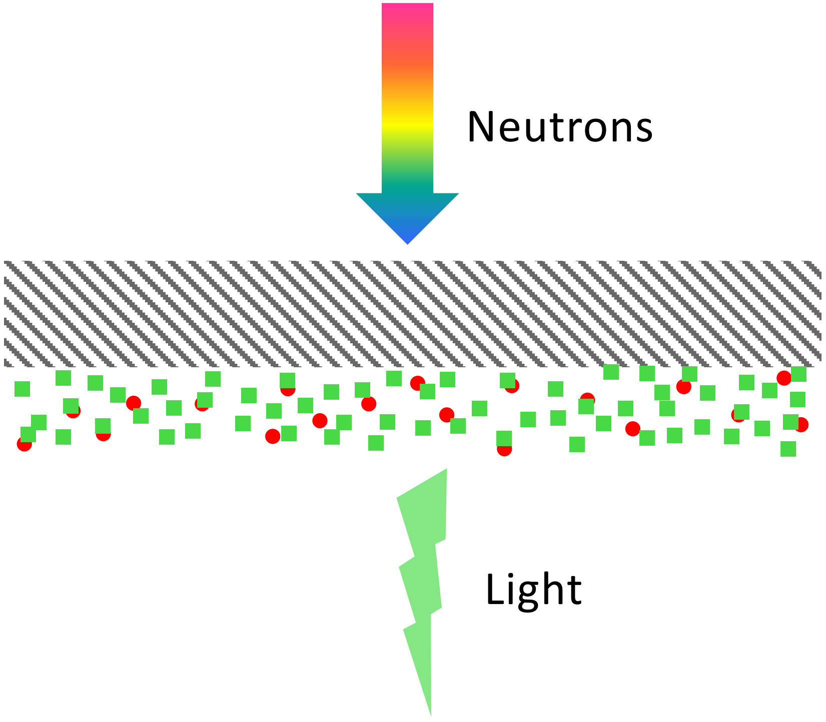

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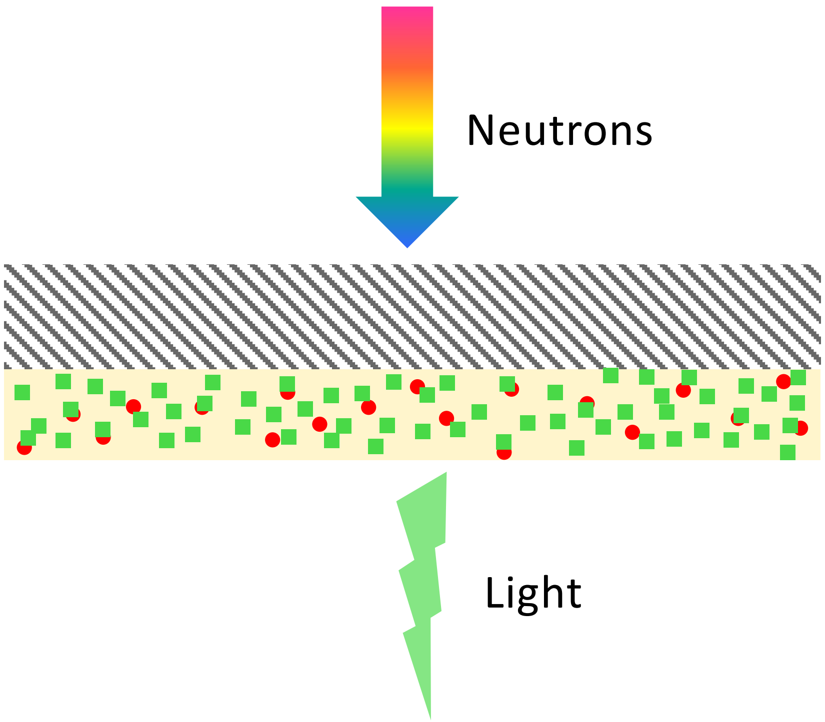

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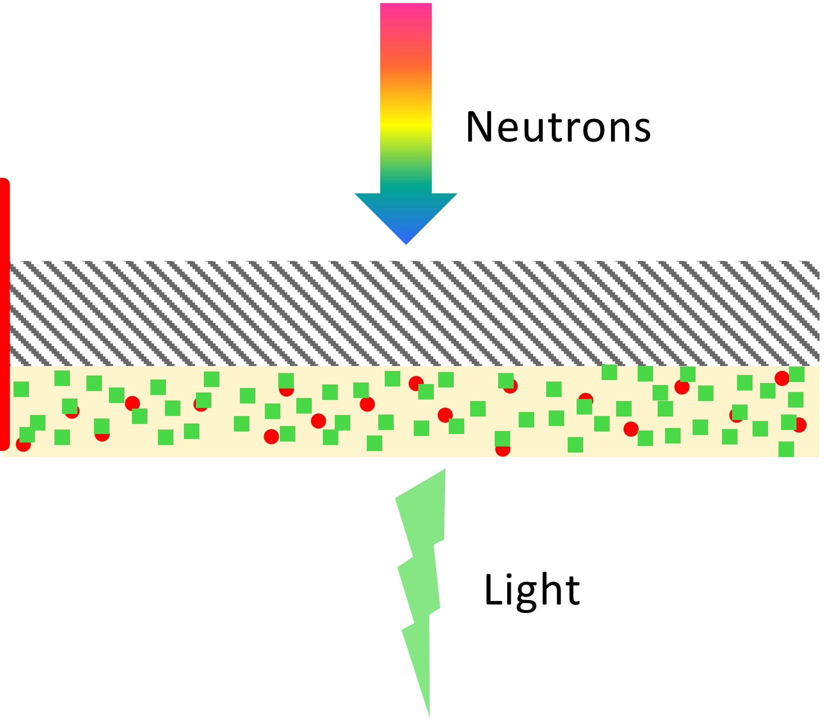

The absorber

How do you choose which absorber?

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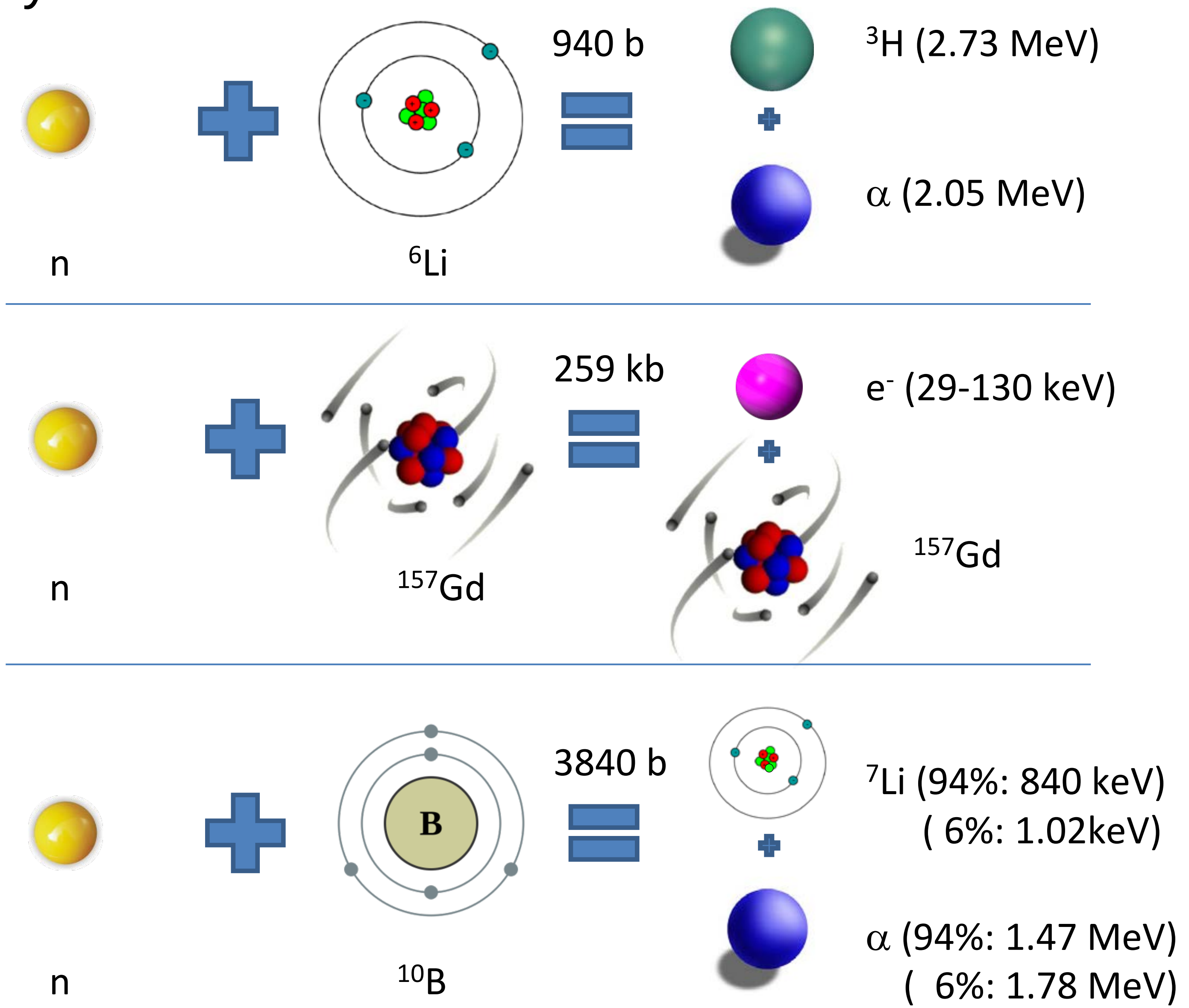

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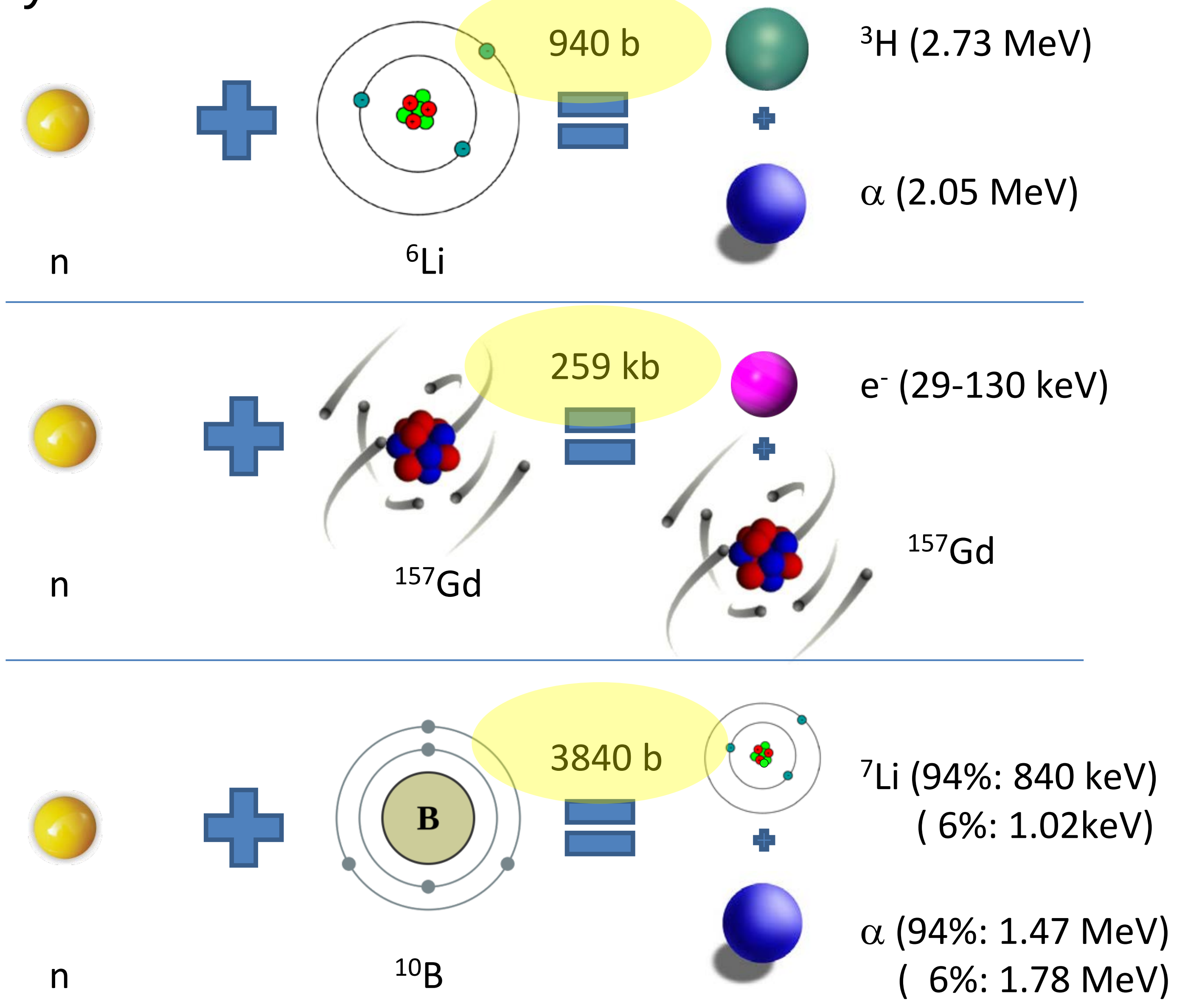

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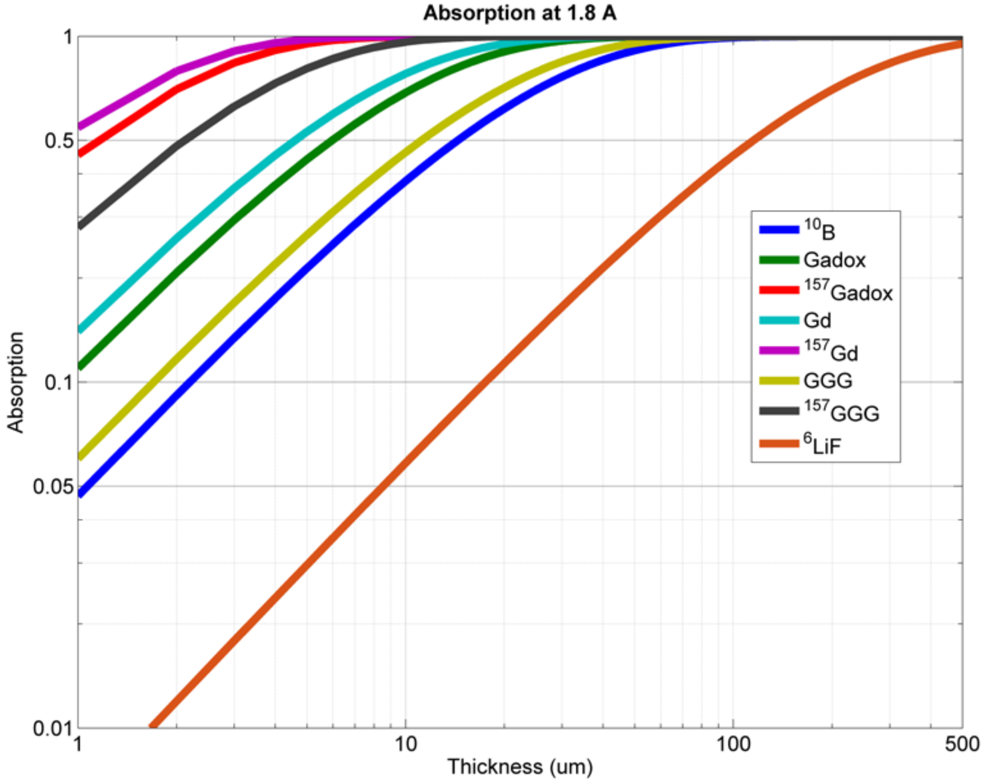

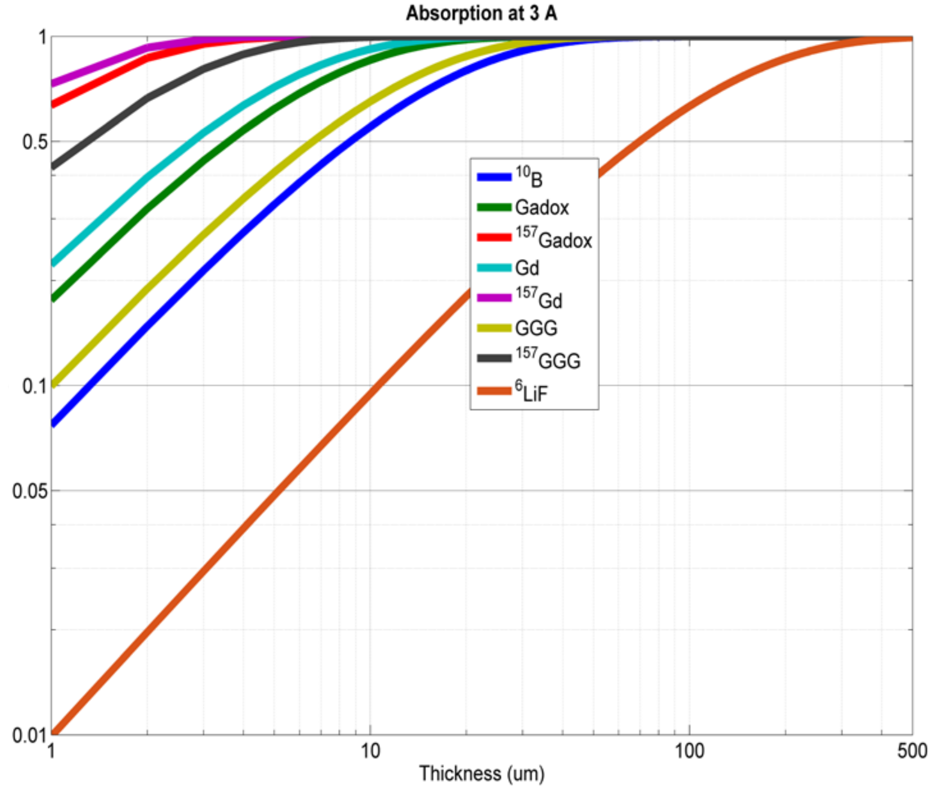

The absorber

How do you choose the thickness?

Rule-of-thumb: thickness = spatial resolution (valid because these scintillators are powder)

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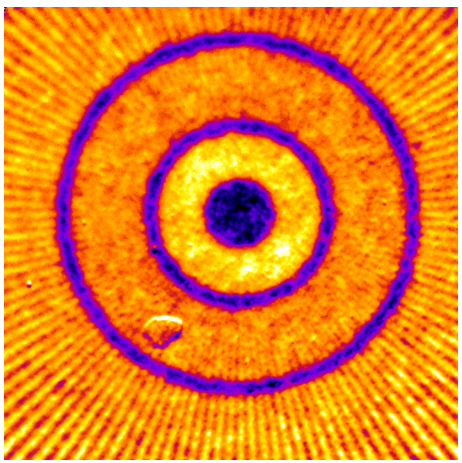
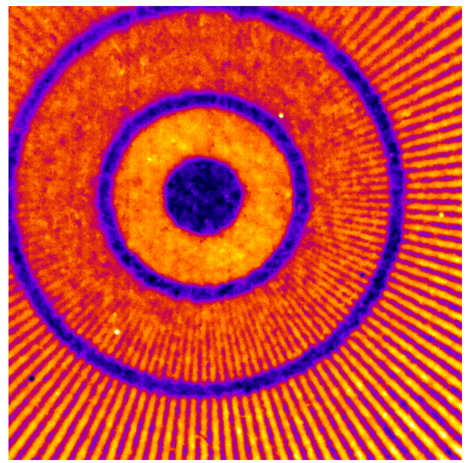
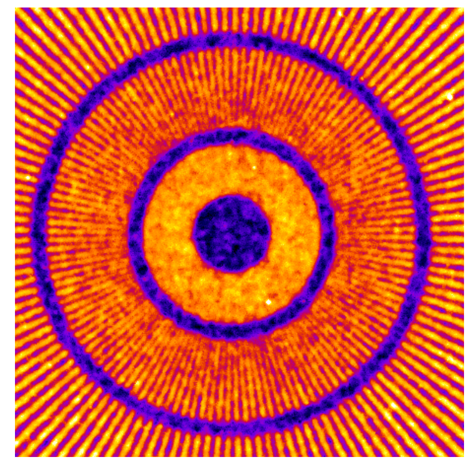
50um-LiF+ZnS



20um-Gadox



10um-Gadox



1mm

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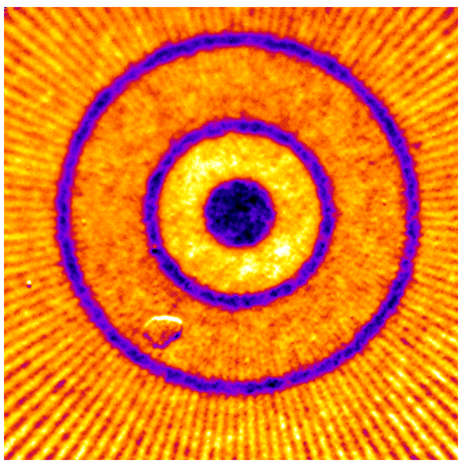

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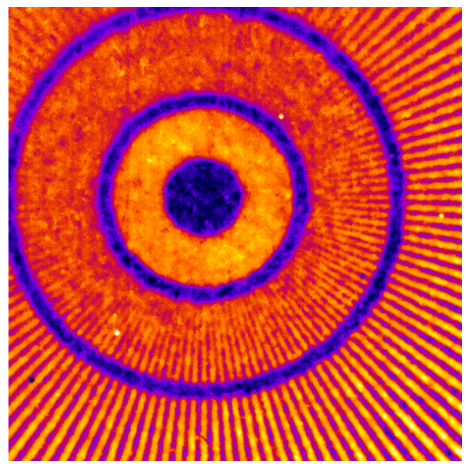

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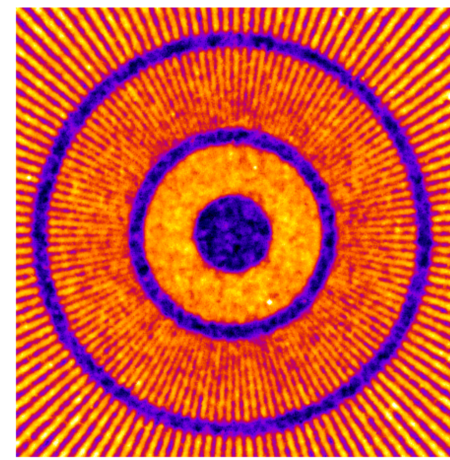
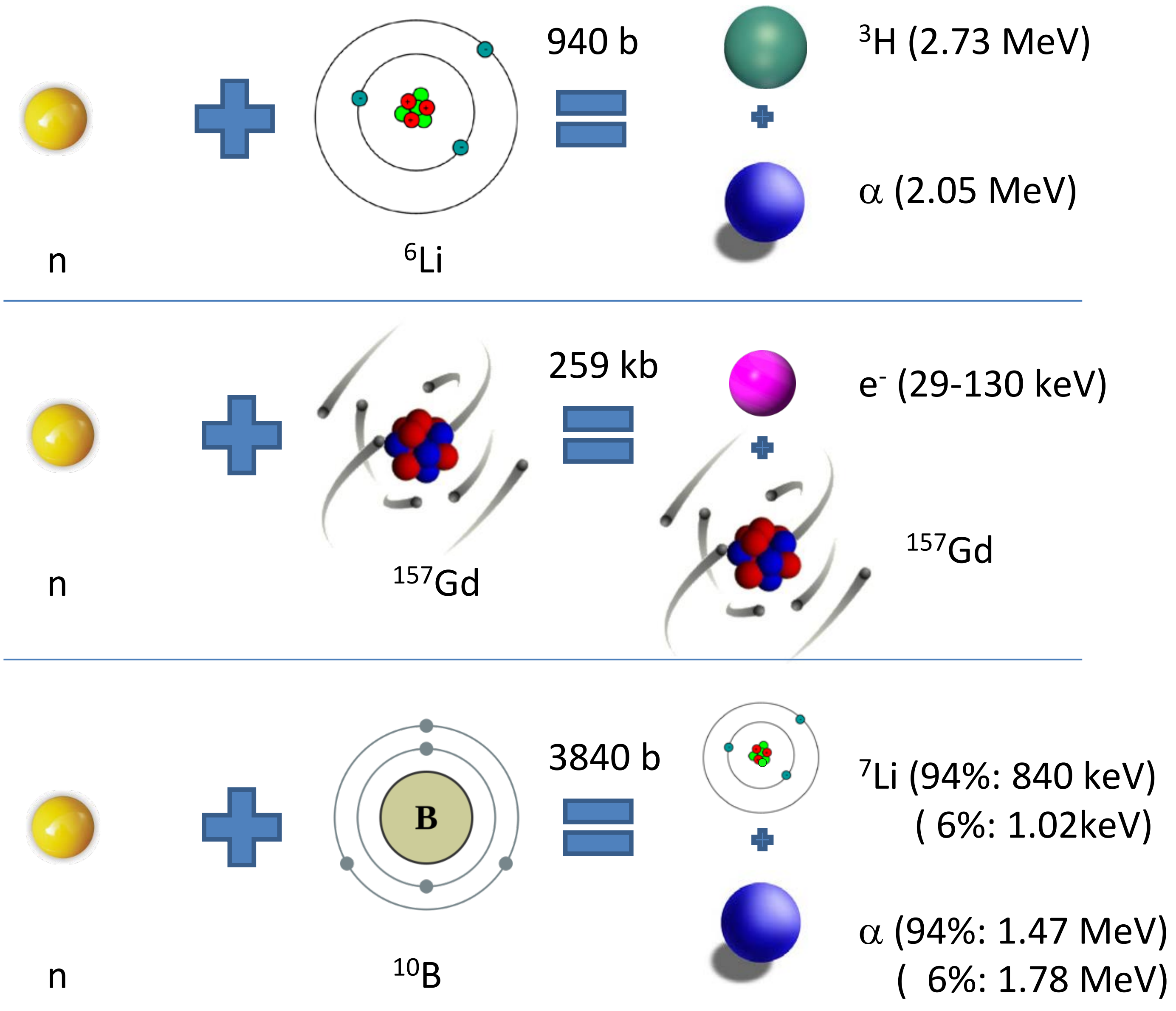


That’s not the end of the story (of course)

The absorber



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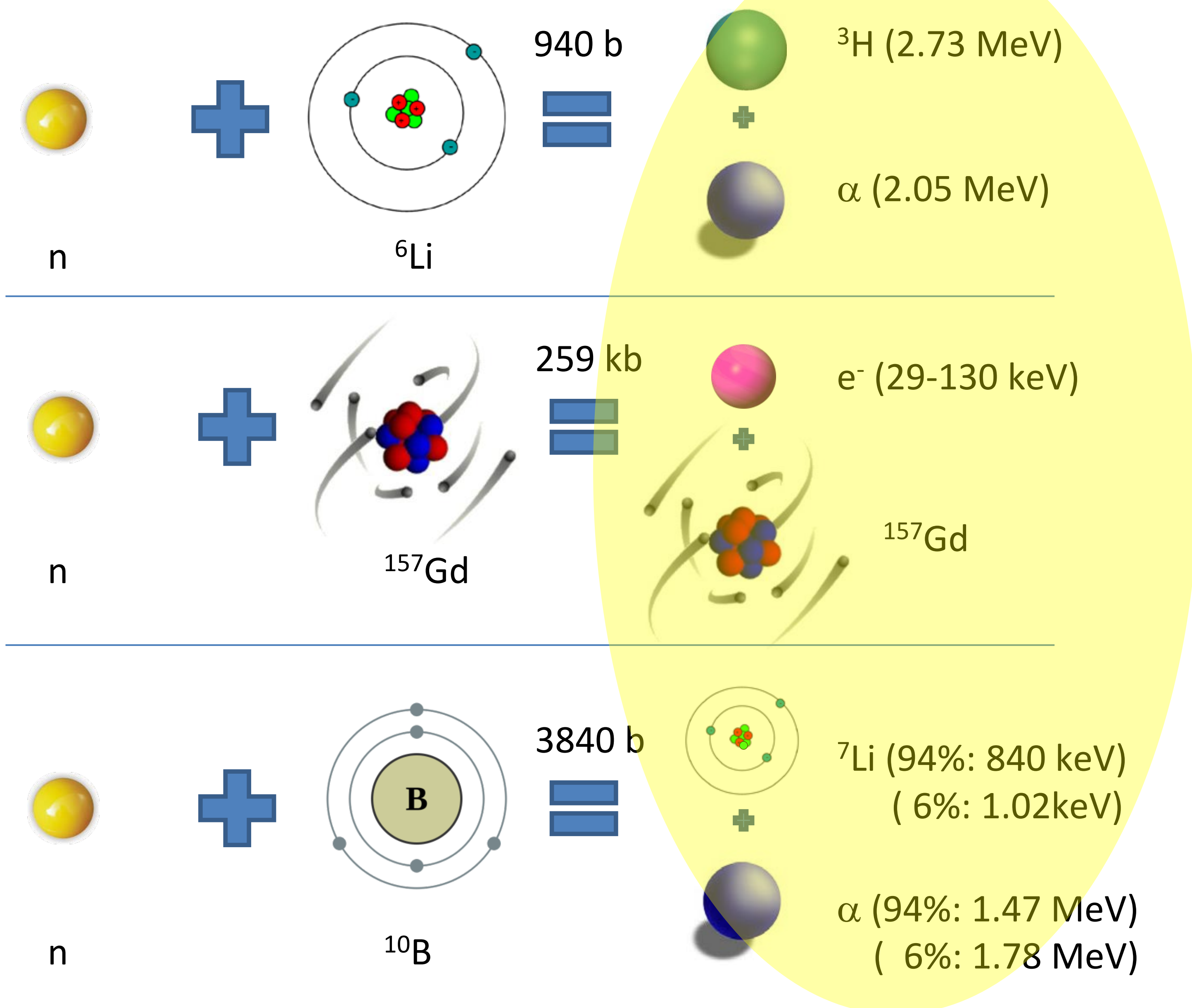

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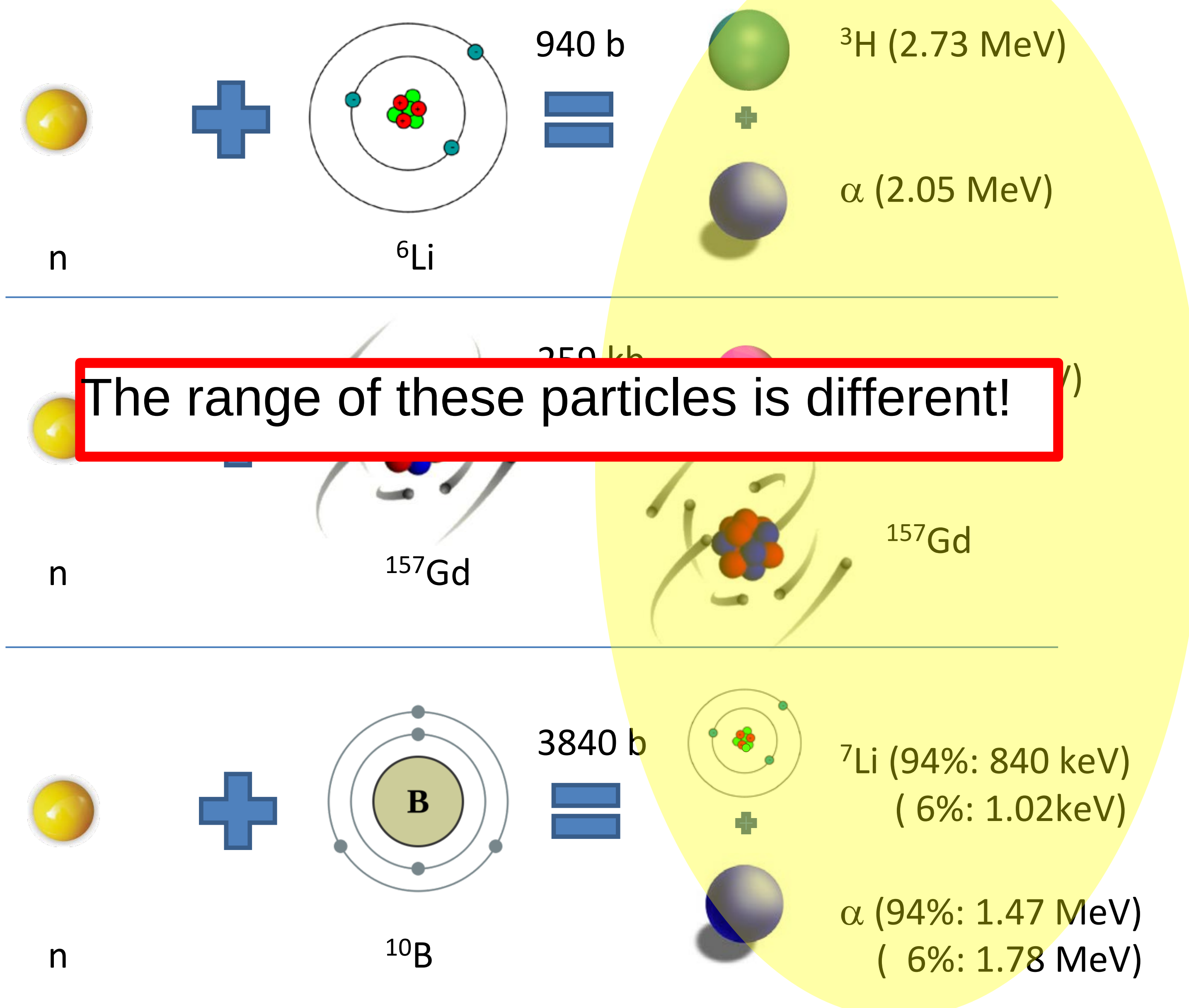
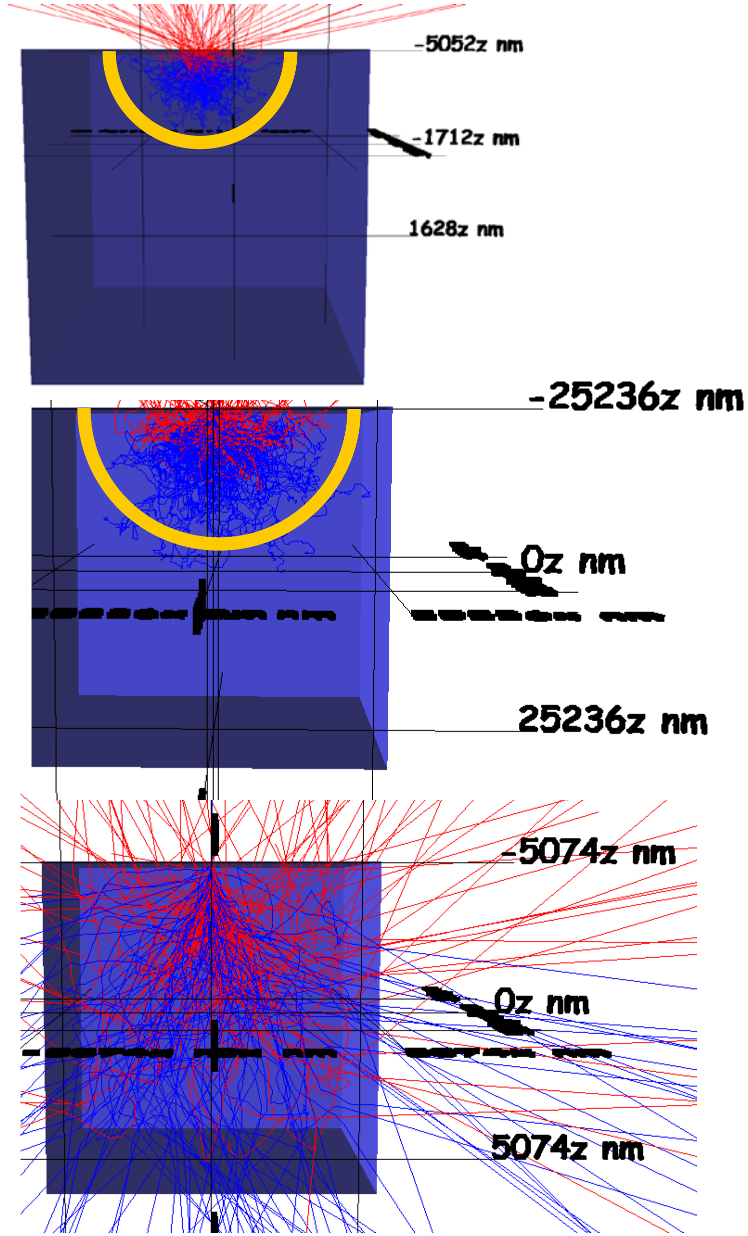


Path of charged particles in scintillators



30 keV electrons in 10 um Gadox

Range: ~4um

Resolution: ~10 um

Almost all the electrons produce light

130 keV electrons in 50 um Gadox

Range: ~40 um

Resolution: ~50um

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130 keV electrons in 10 um Gadox

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Almost all the electron escape

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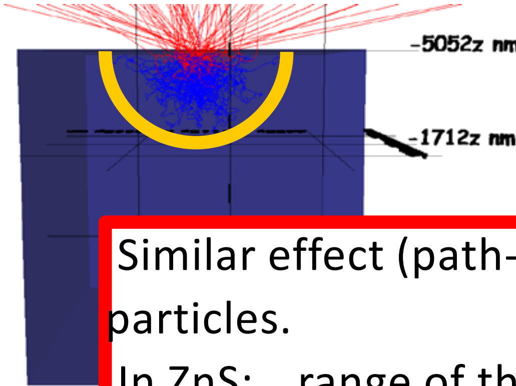

30 keV electrons in 10 um Gadox

Range: ~4um

Similar effect (path-wise) happens with heavy charged particles.

In ZnS: range of the alpha particle from ^{6}Li: **~20um**

range of triton from ^{6}Li: **~100um**

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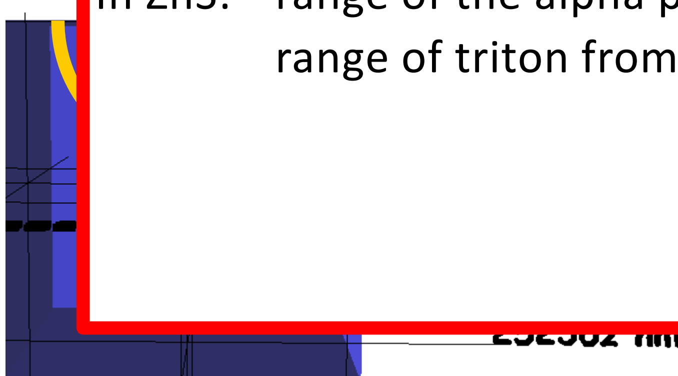

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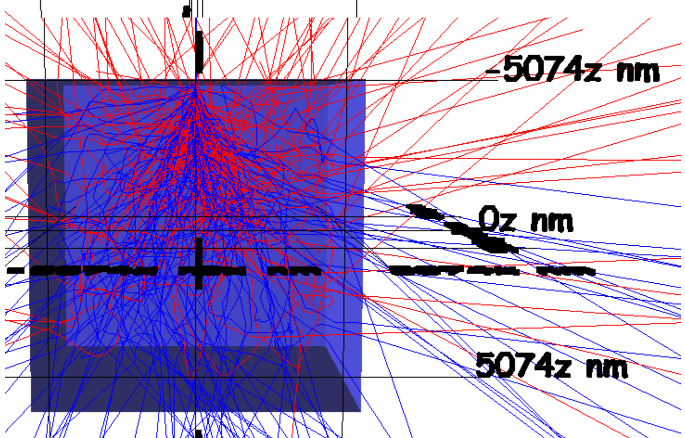


130 keV electrons in 10 um Gadox

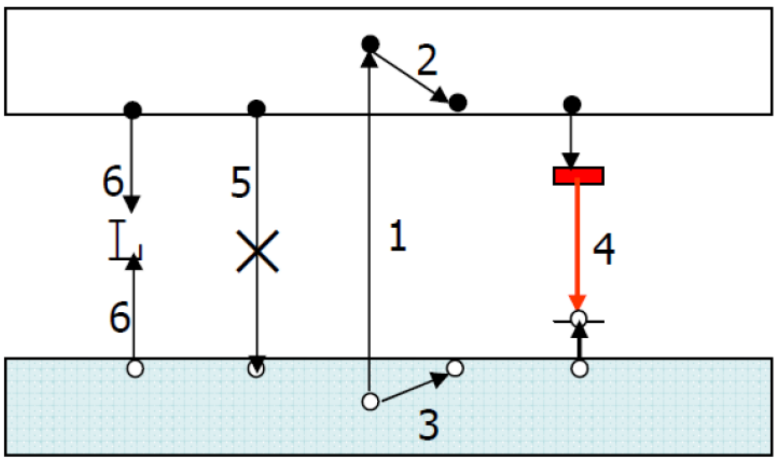
Range: ~40 um

Resolution: ~10um

Almost all the electron escape

Pigment: fluorescence mechanism

- Now we have a charged particle, but how does the light emission work?



1) **Excitation creating a hole in the valence band and an excited electron in the conduction band**
2) **Relaxation of the excited electron to the ground level of the conduction band**
3) **Relaxation of the created hole to the top of the valence band**
4) **Fluorescence emission via an «impurity ion»**
5) **non emittive recombination of the electron and hole**
6) **Like 5) but via an impurity (defect center or impurity ion)**

How many photons are produced?

Light yield:

$$Y_{ph} = \frac{10^6 SQ}{\beta E_g} \text{ photons/MeV}$$

Y_{ph} = number of photons emitted by the scintillator per unit of energy absorbed

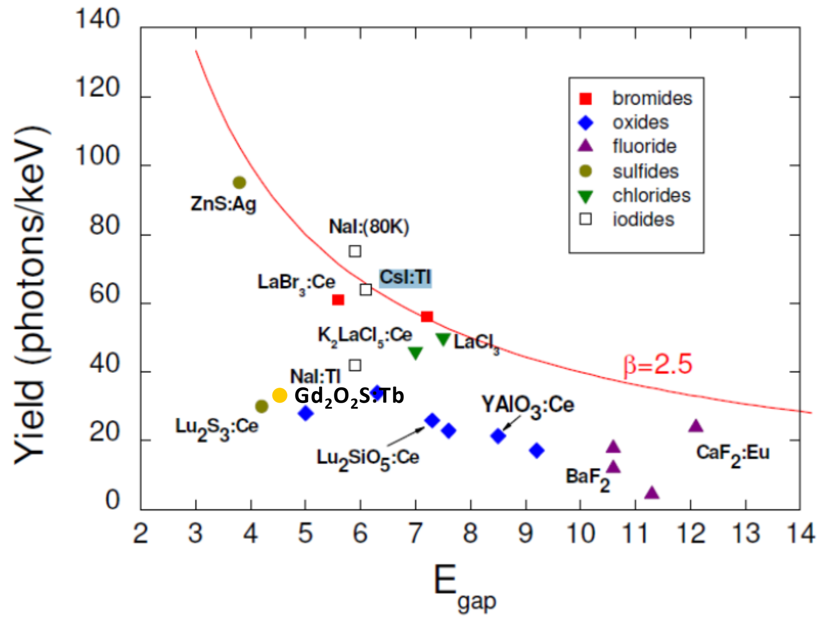
β = constant that appears approximately 2.5

E_g = band gap energy

S = transfer efficiency

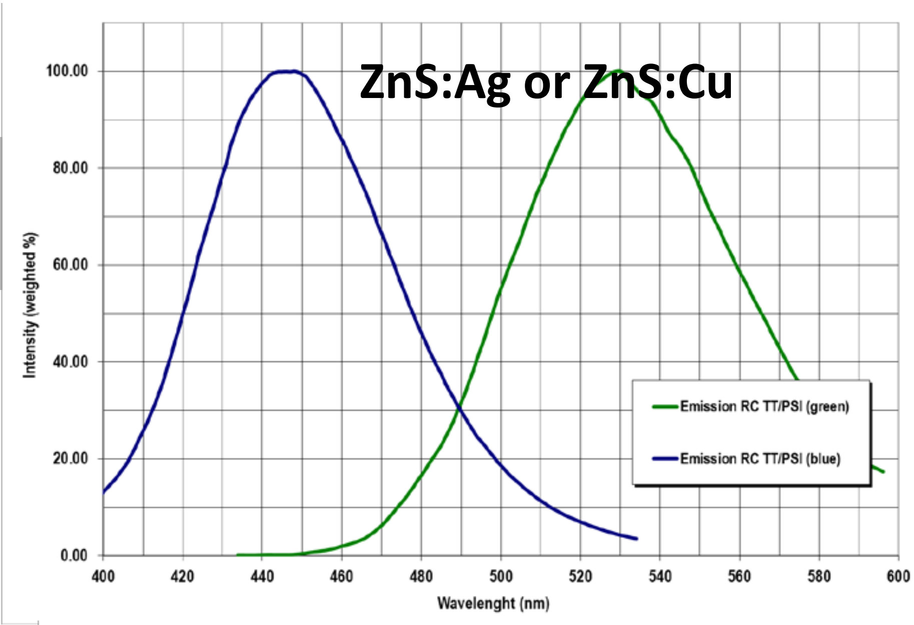
Q = quantum efficiency

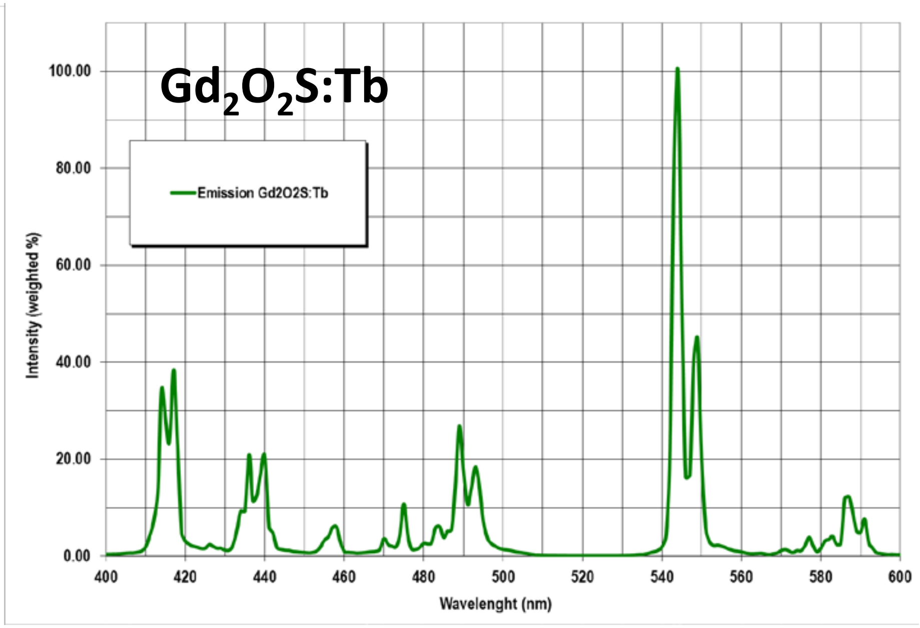
For the ideal situation S and Q are 100%



Red solid line represents the maximum light yield

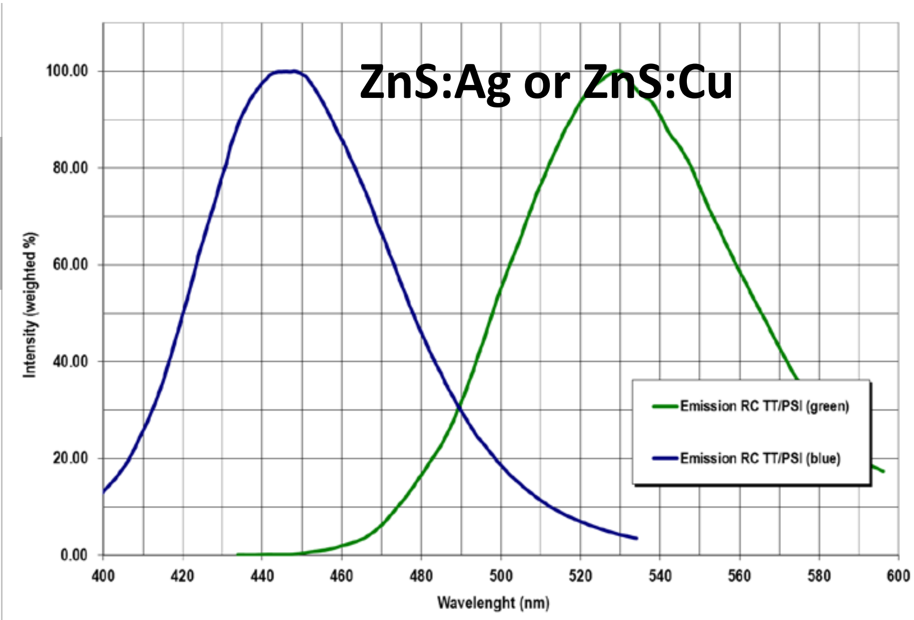
Spectral matching

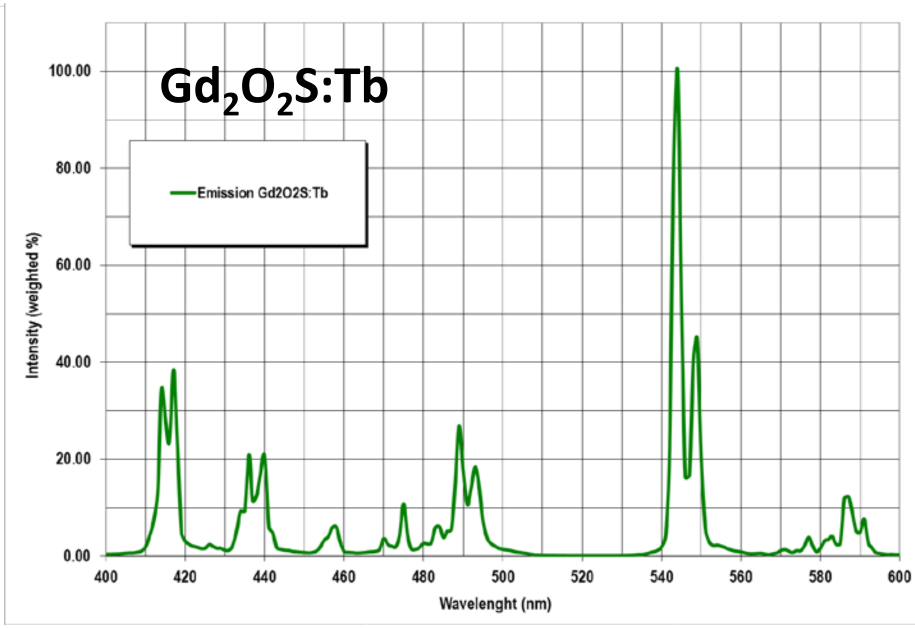


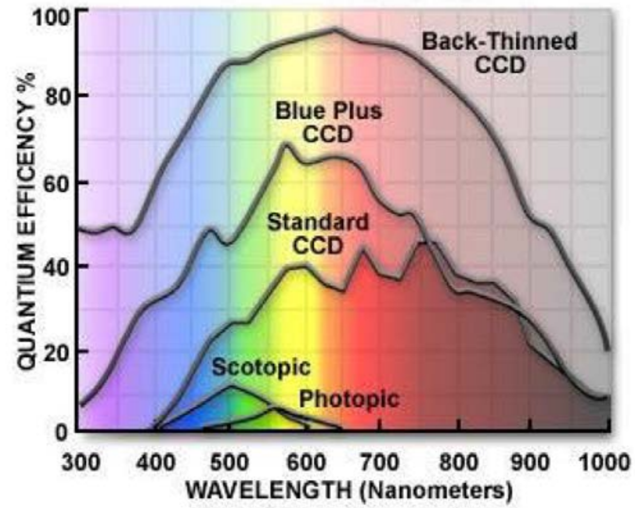


Slide from B. Walfort, WCNR-10, Grindelwald (CH) (2014)

How many photons are produced?







Photosensitivity of CCD

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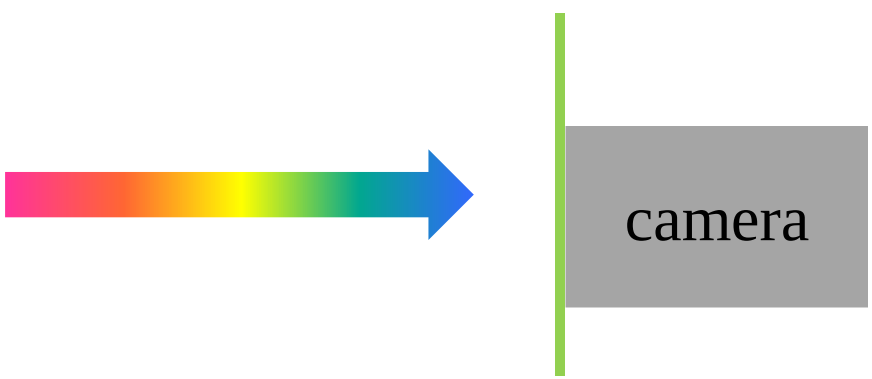
Cameras

Cameras have the duty to convert photons into a charge signal that is presented as a digital image



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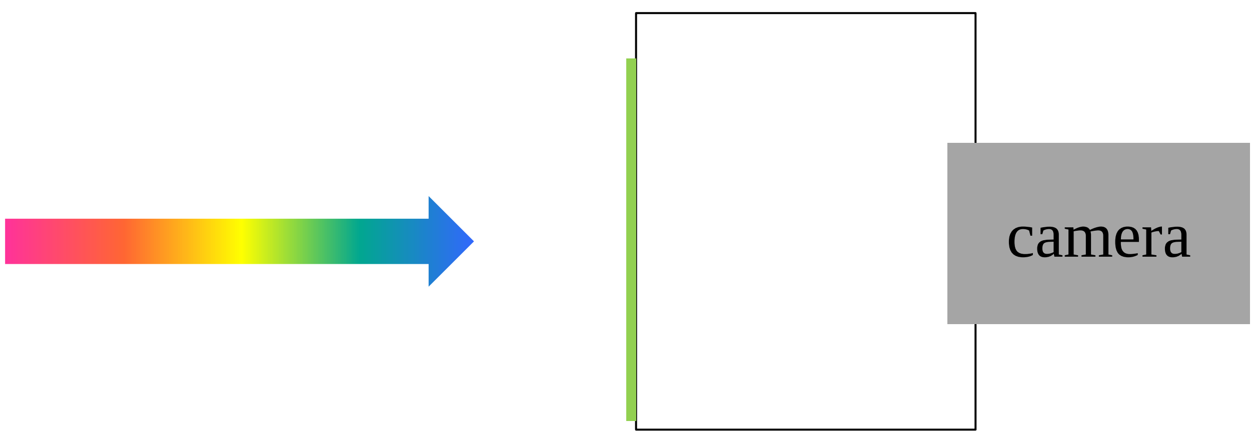
- They sit in a light tight box



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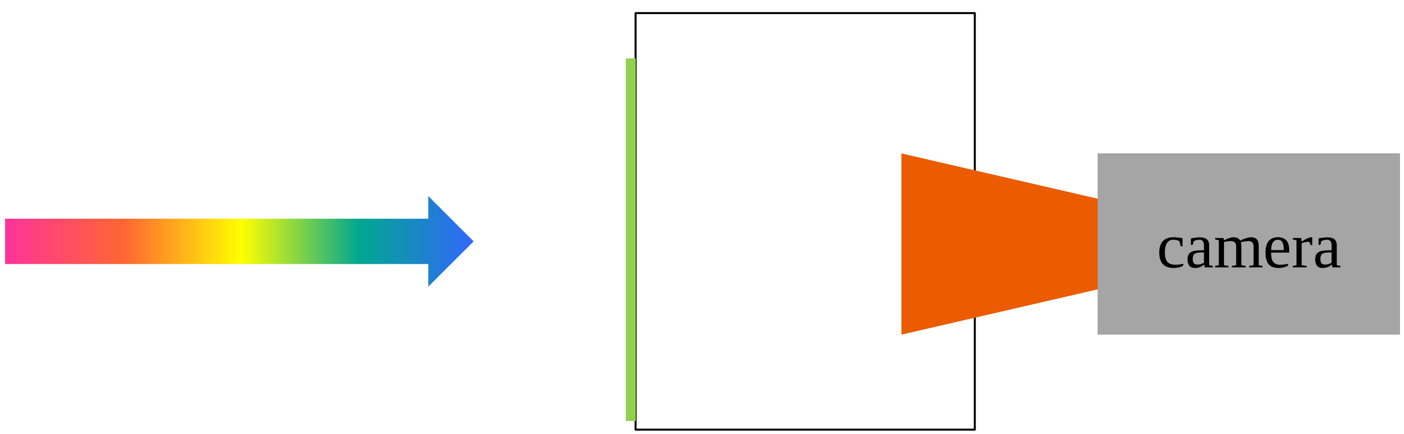
- Attached to an objective



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- They sit in a light tight box
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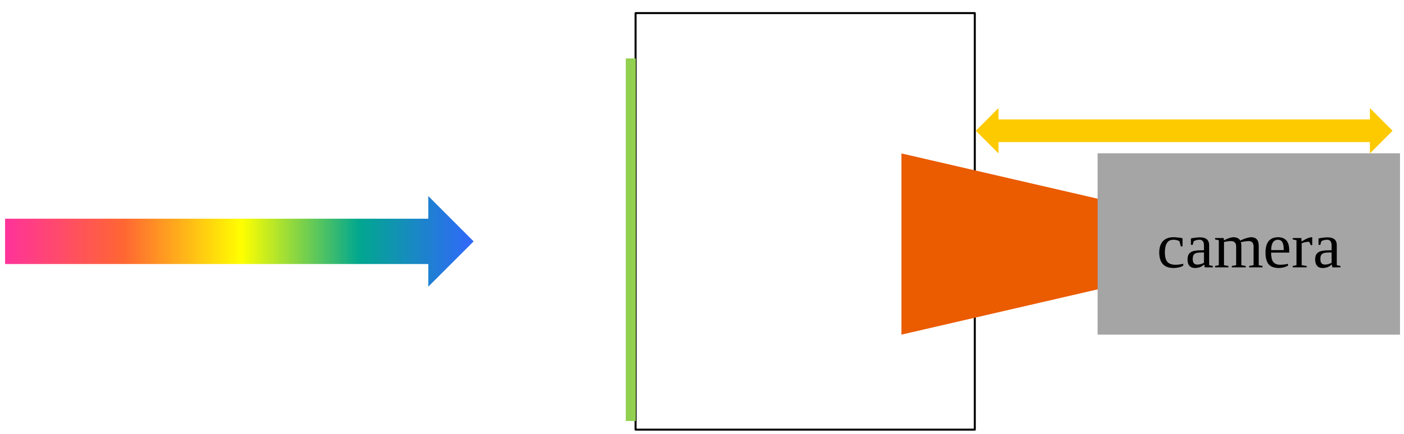
- Movable for focusing



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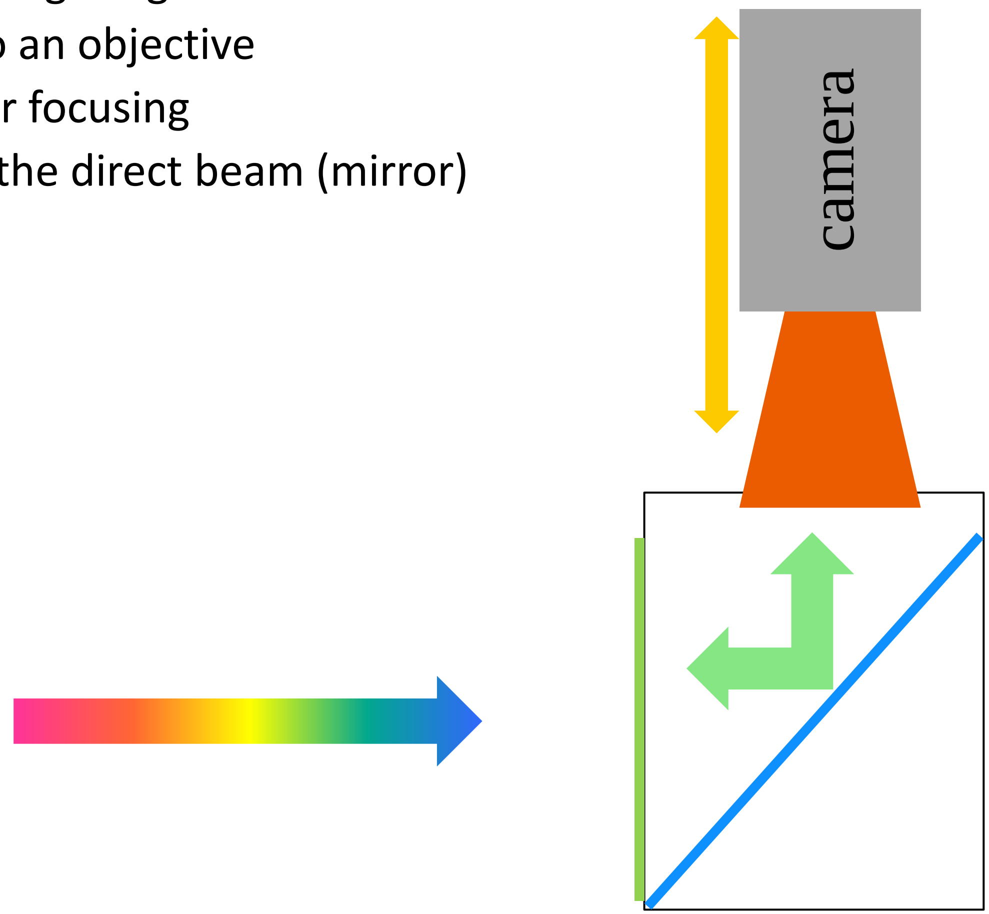
- Outside of the direct beam (mirror)



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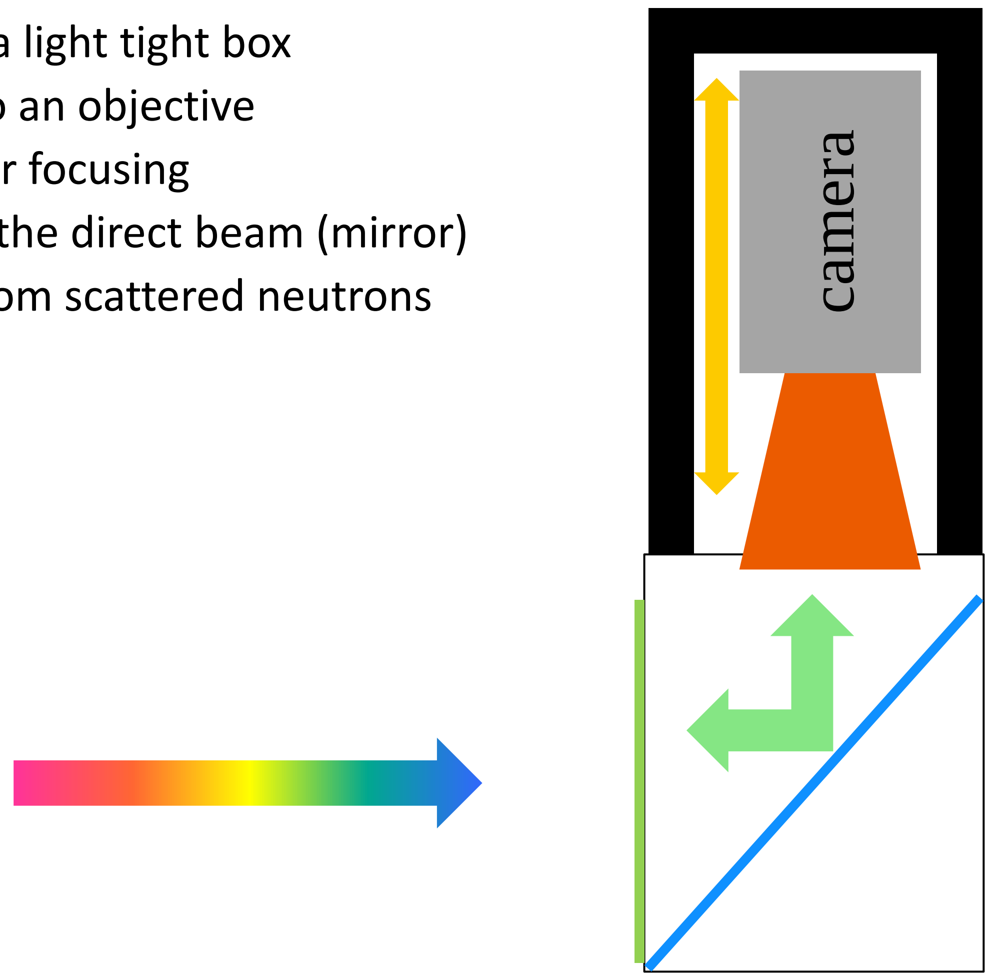

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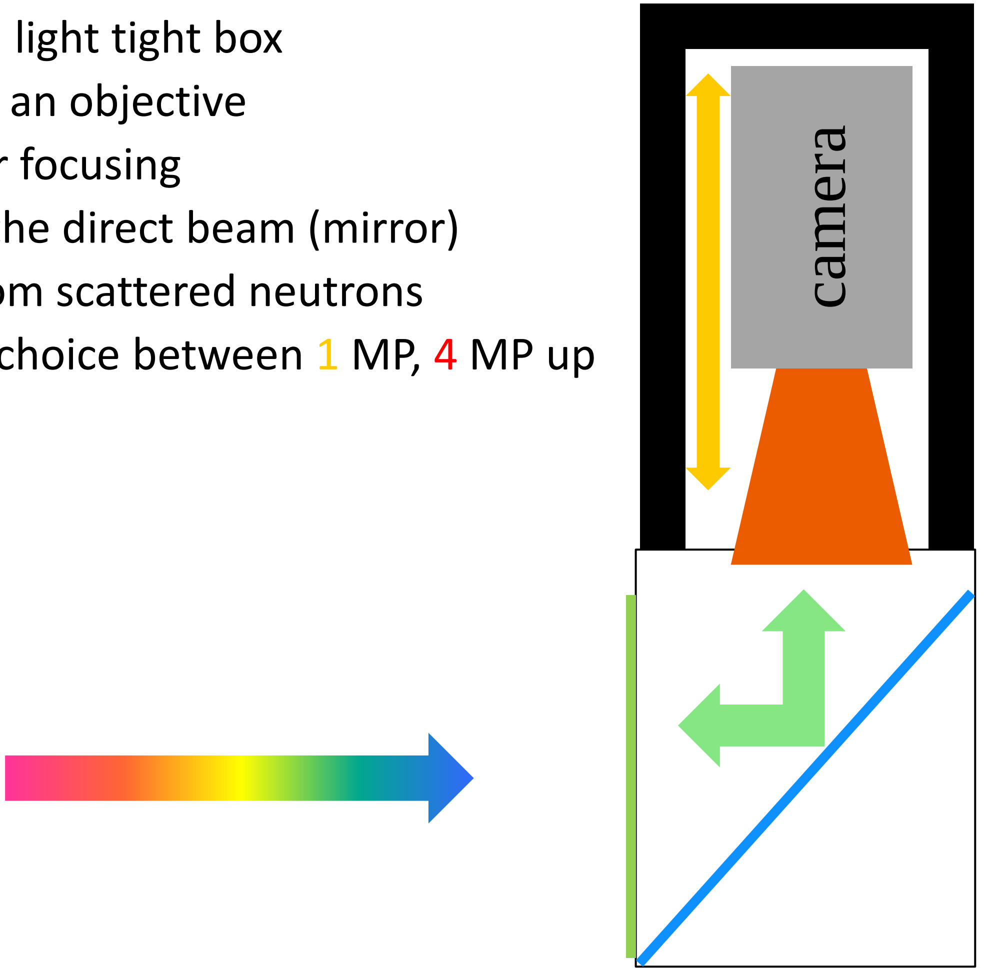

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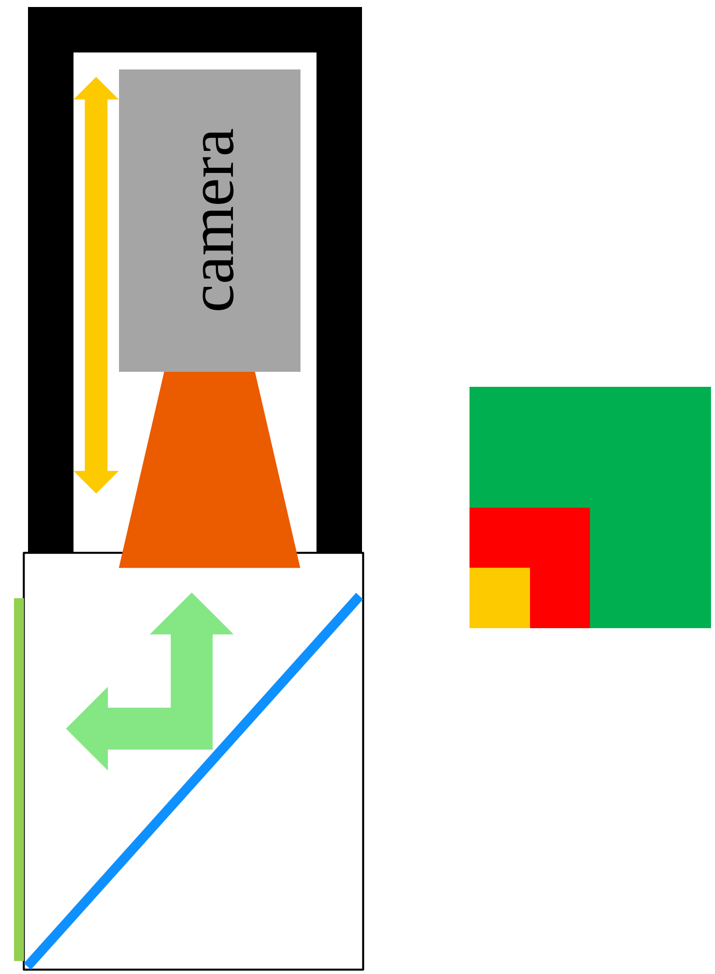
- Pixel size down to ~6 um



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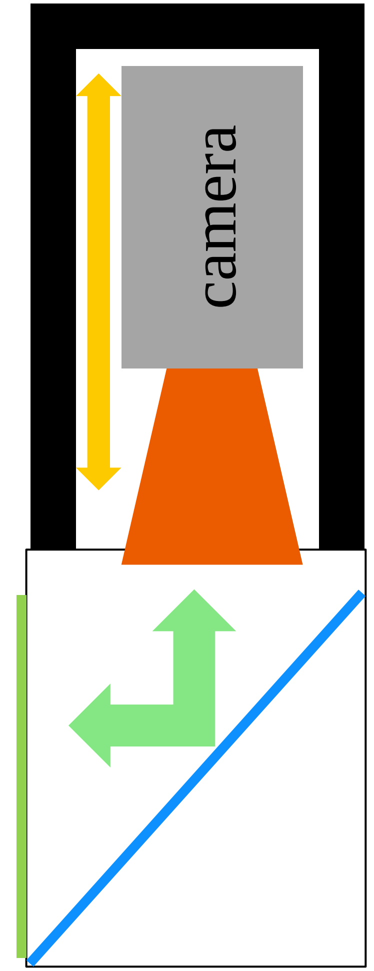
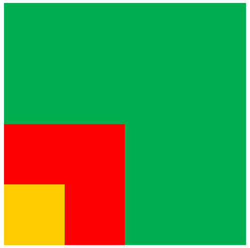
- Nowadays, choice between 1 MP, 4 MP up to 16 MP
- Pixel size down to ~6 um
- Two main technologies: CCD and sCMOS





CCD vs. sCMOS

- The challenge of detecting a neutron
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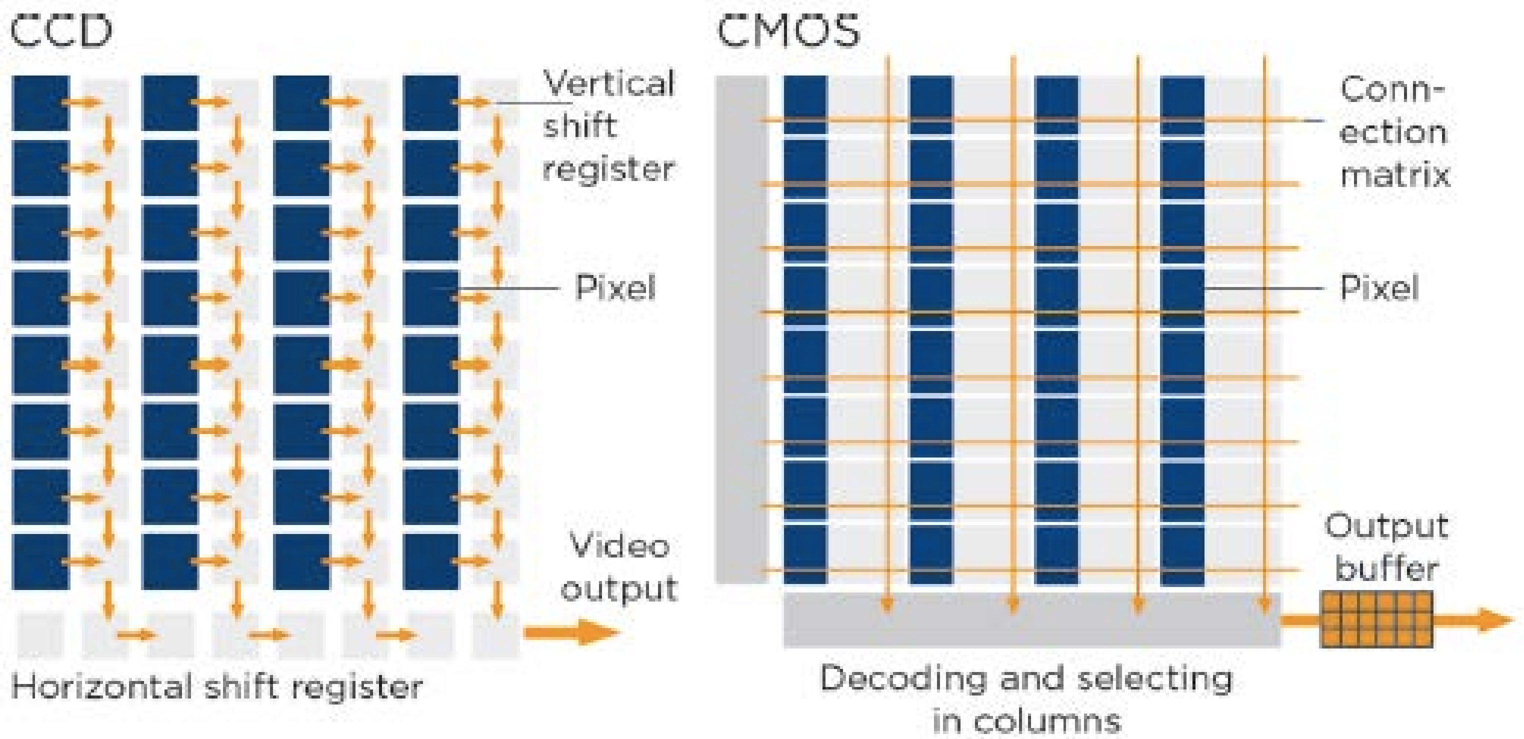
CCDs vs sCMOS



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CCDs vs sCMOS

CCD

- Charge Coupled Device

sCMOS

- (scientific) Complementary Metal Oxide Semiconductor

CCDs vs sCMOS

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- Most commonly used

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- More and more widespread

CCDs vs sCMOS

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- Most commonly used
- More expensive than sCMOS

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CCDs vs sCMOS

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- More pixel area is photosensitive (better low light performances)

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Flat panel detectors

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Flat panel detectors

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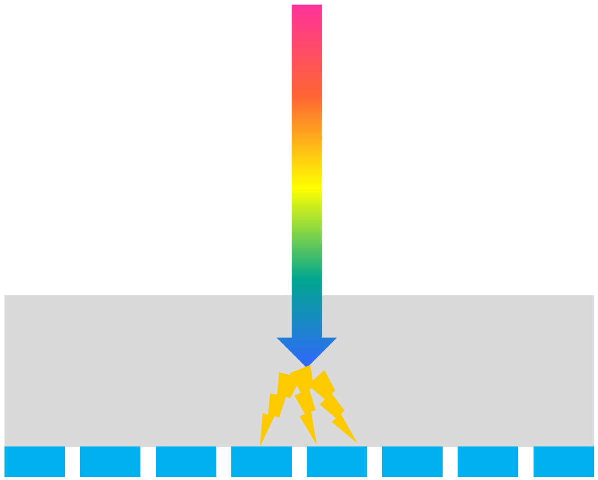

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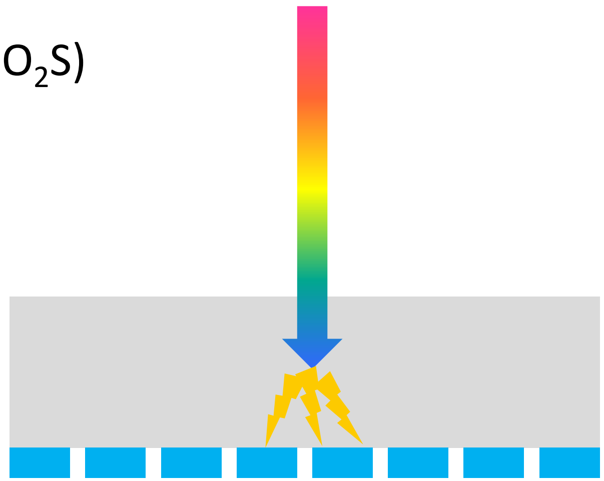
- Borrowed from x-ray
- Pixelated light detector covered with scintillator (Gd_2O_2S)



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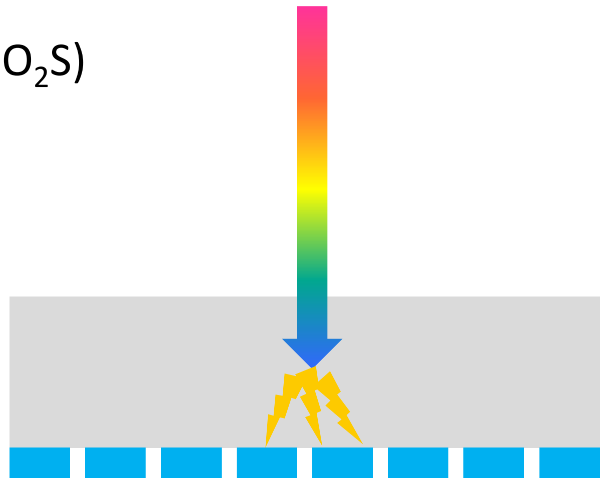

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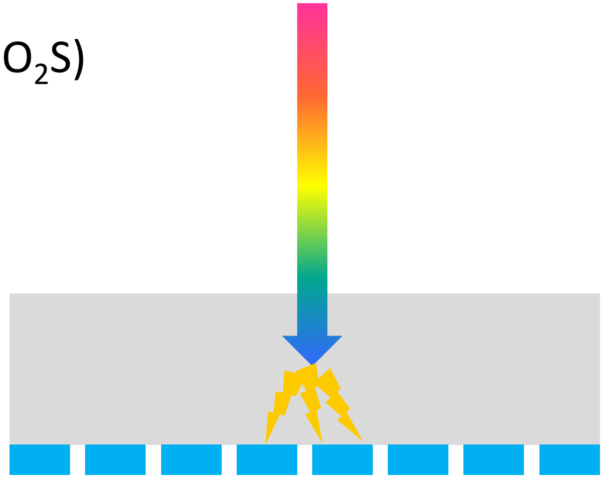

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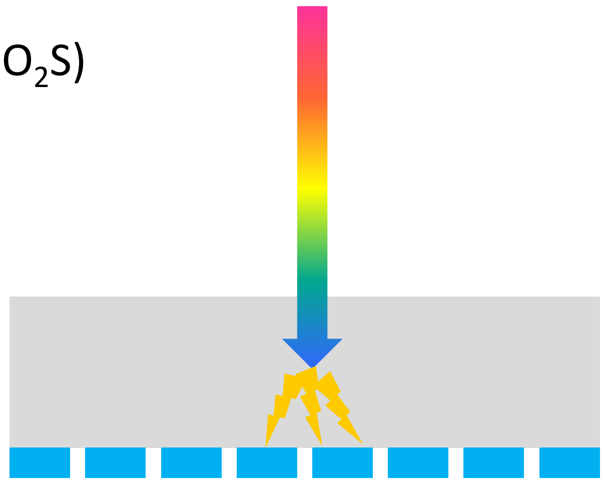

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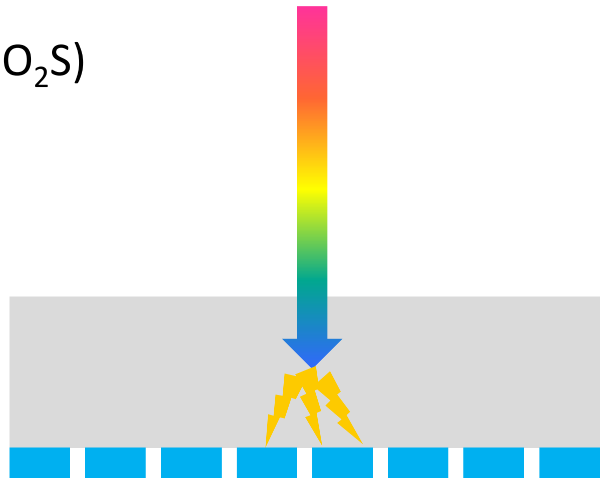

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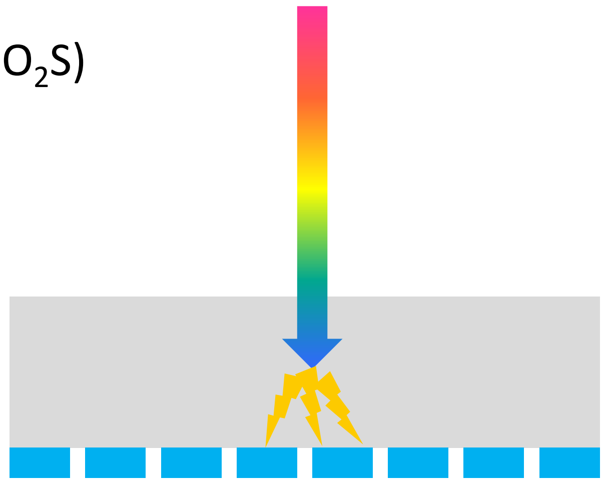

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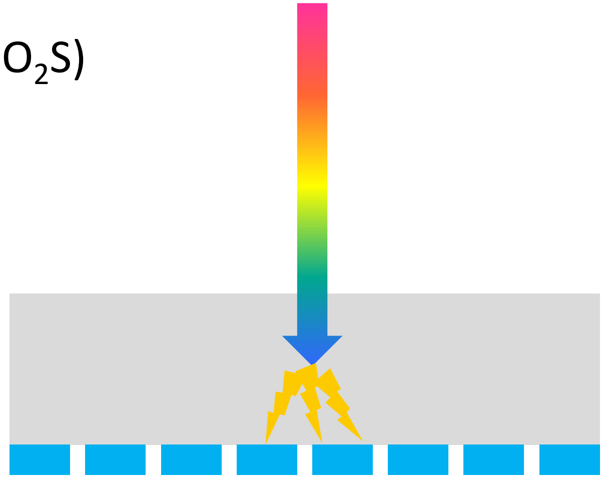

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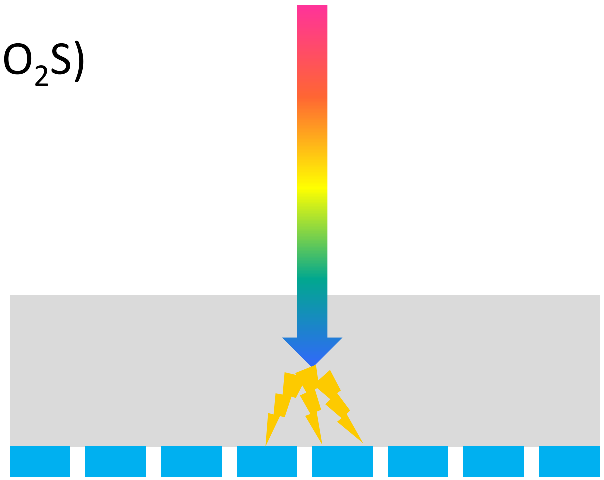

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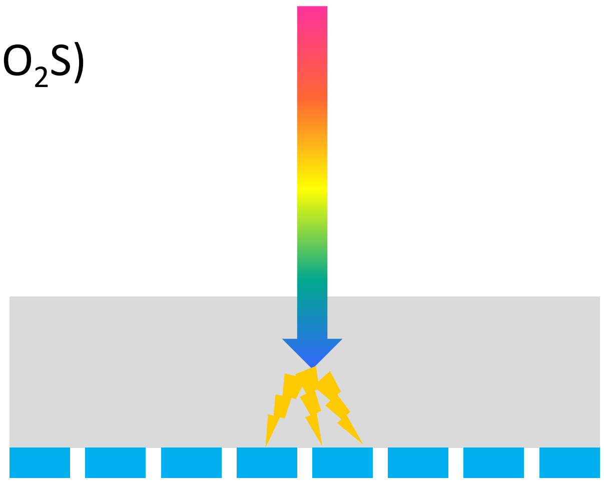
- Still not very commonly used



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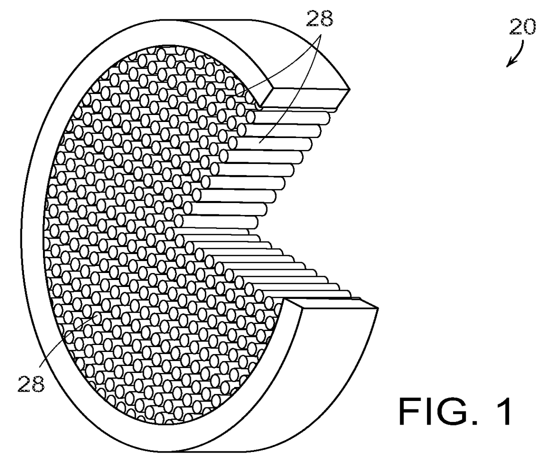
Other useful equations:

$$E[meV] = \frac{81.82}{(\lambda[\text{Å}])^2} \qquad \lambda[\text{Å}] = \frac{9.045}{\sqrt{E[meV]}} \qquad v[m/s] = \frac{3956}{\lambda[\text{Å}]} = 437 \cdot \sqrt{E[meV]}$$

Example: MCP based detector (Berkeley)



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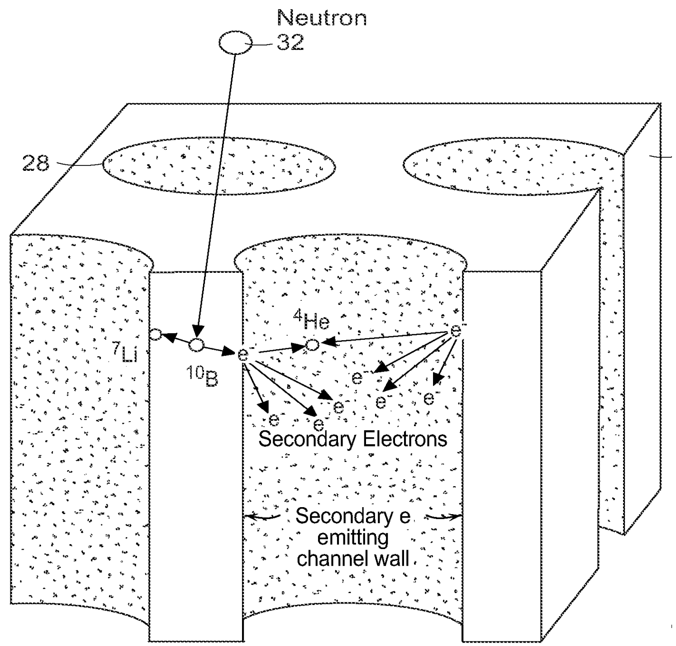
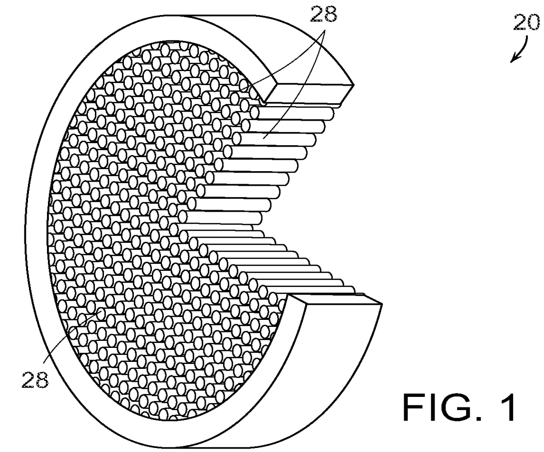


Example: MCP based detector (Berkeley)

- ^{10}B-loaded glass Micro Channel Plate (MCP)



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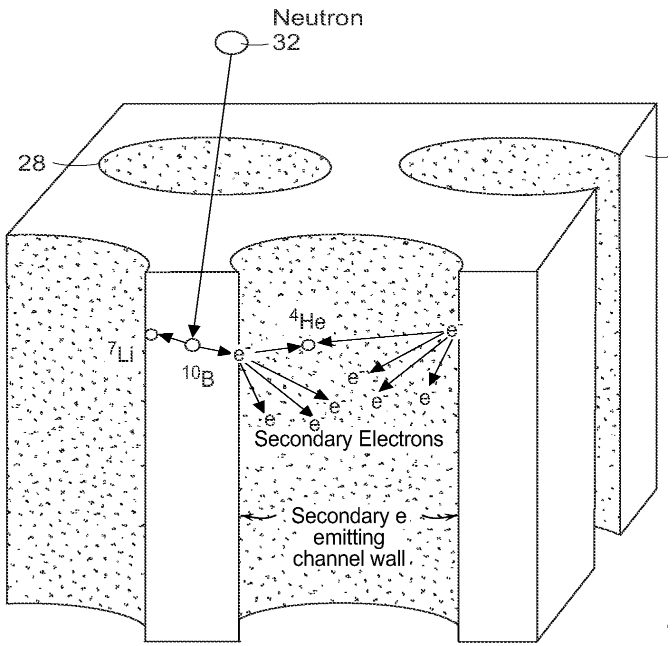

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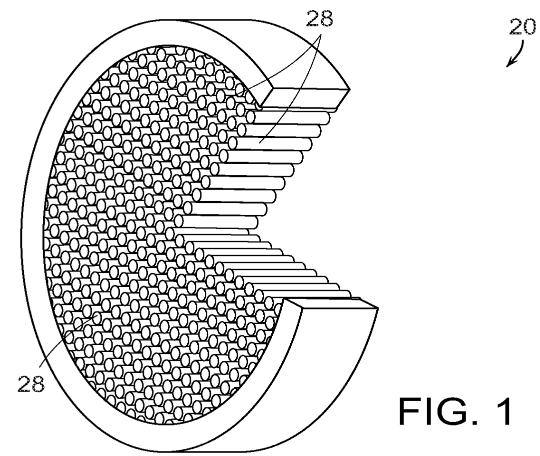

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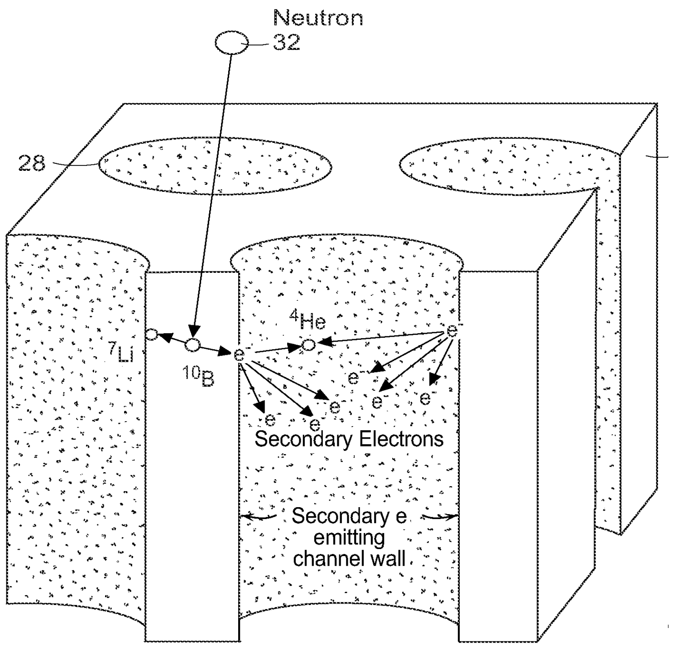

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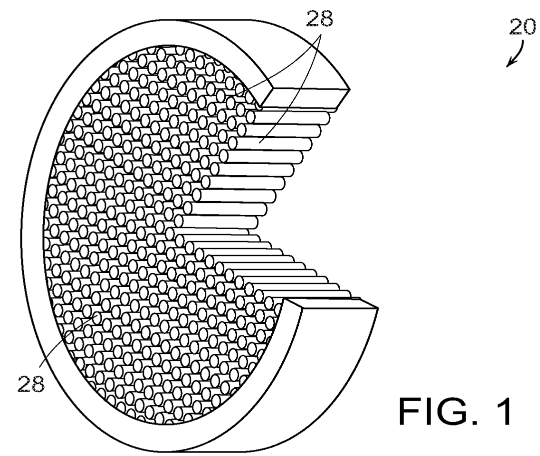

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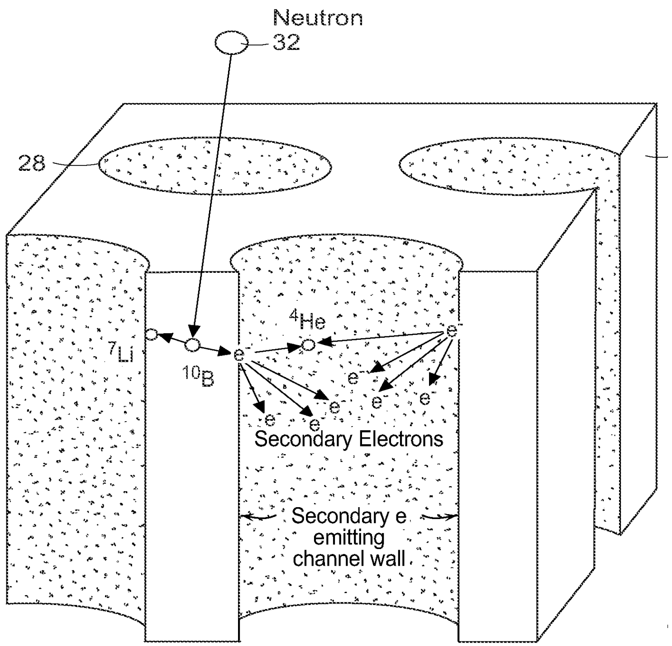

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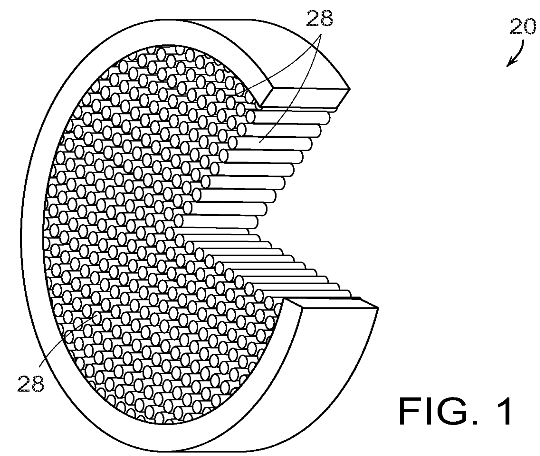

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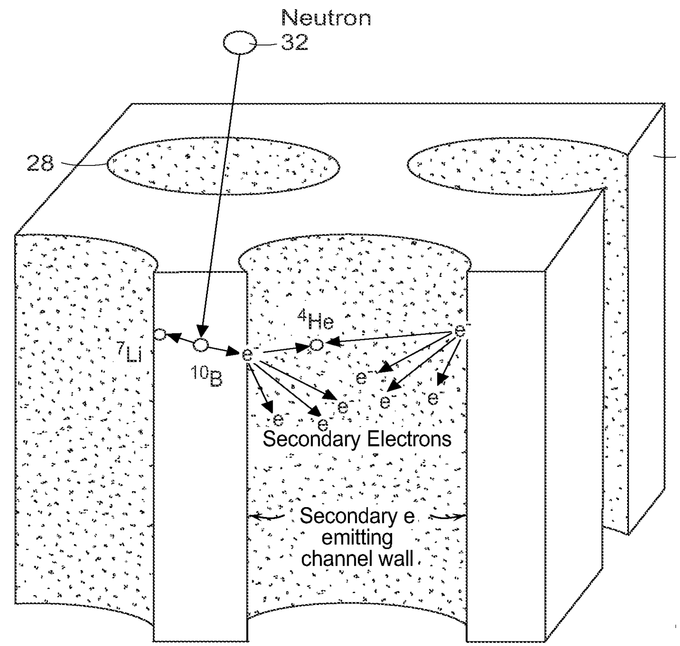

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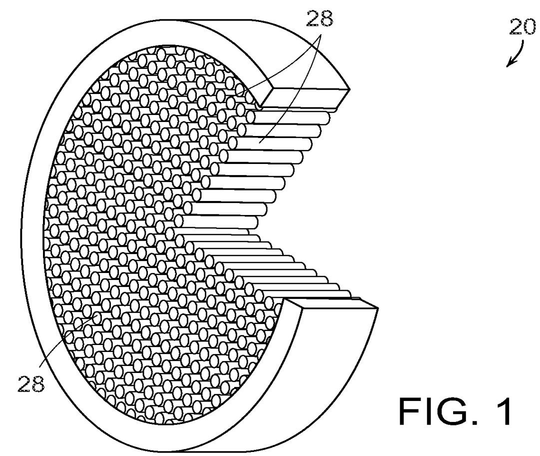

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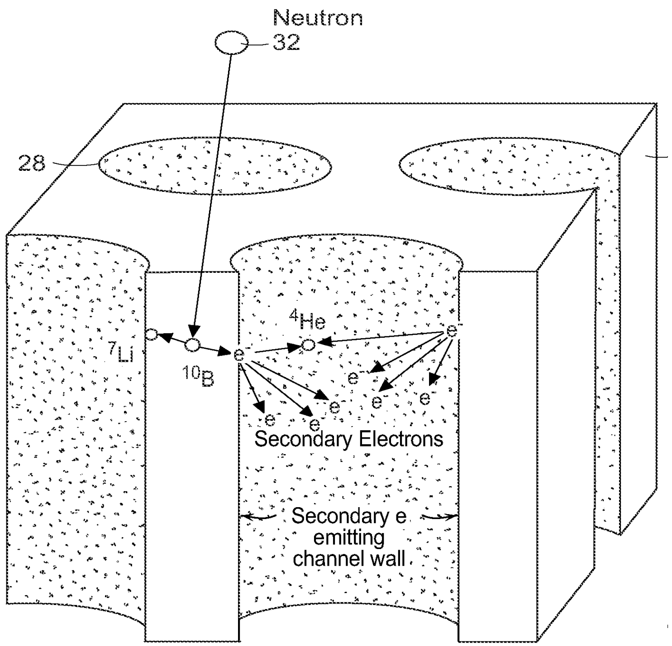

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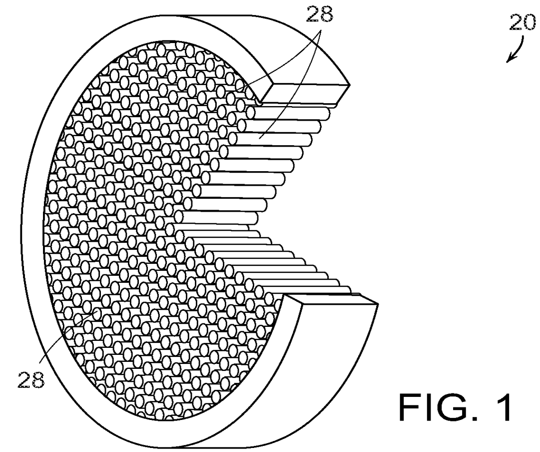

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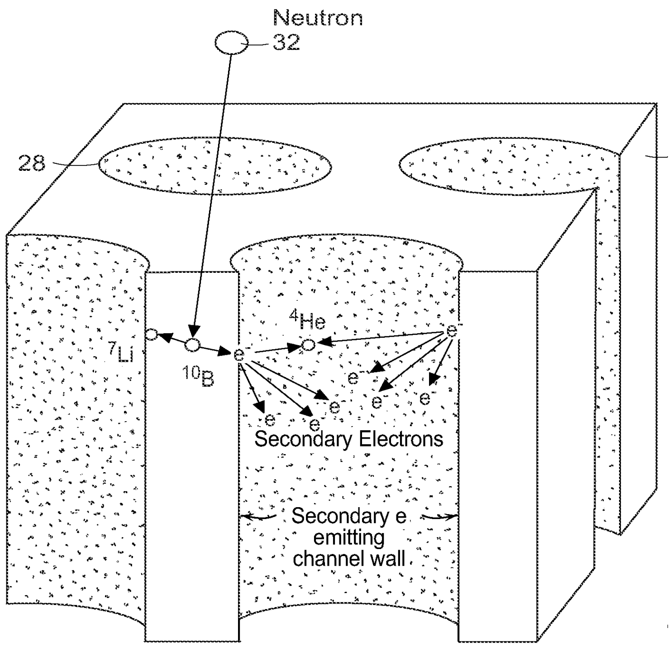

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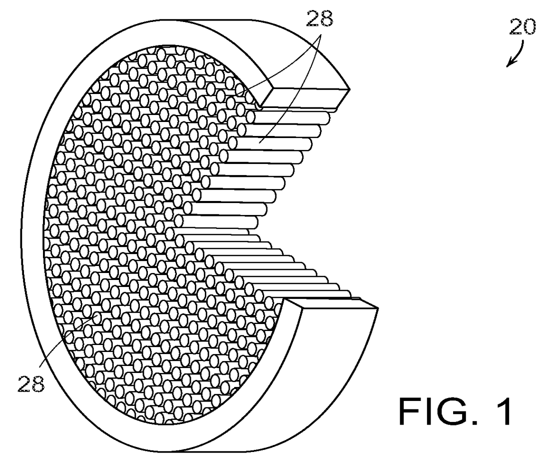

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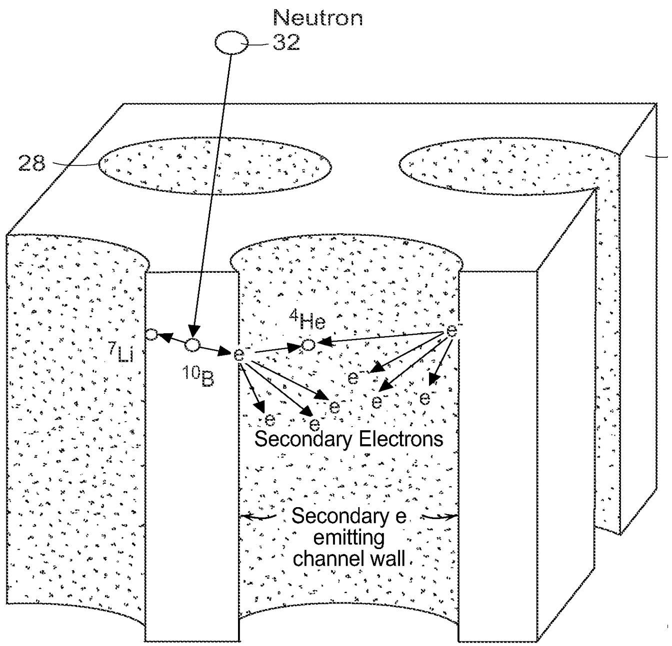

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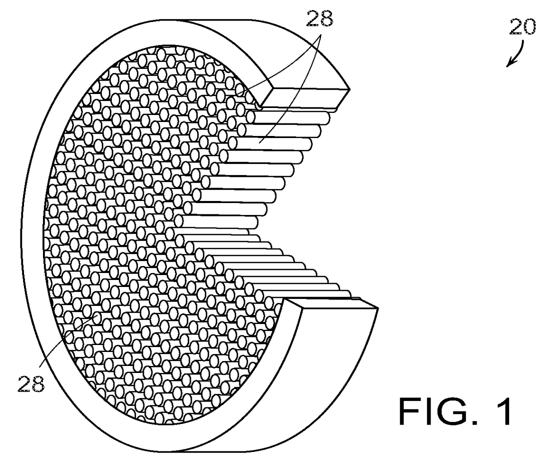

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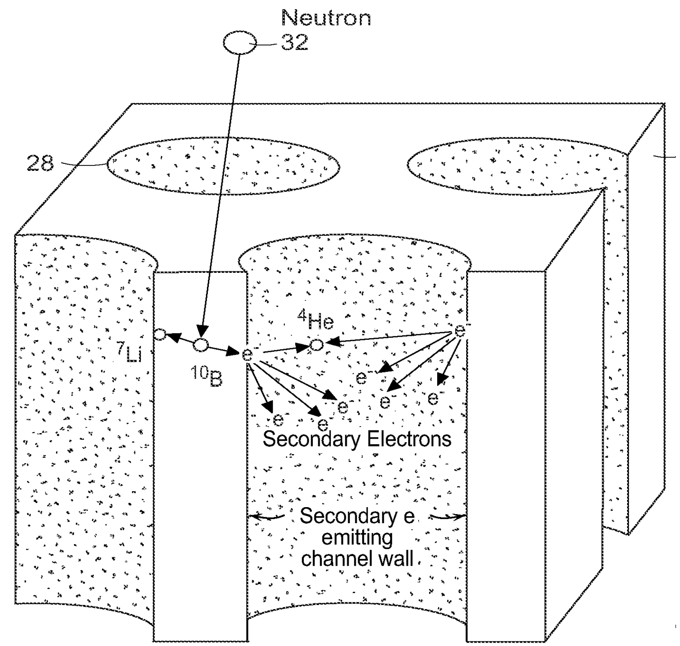

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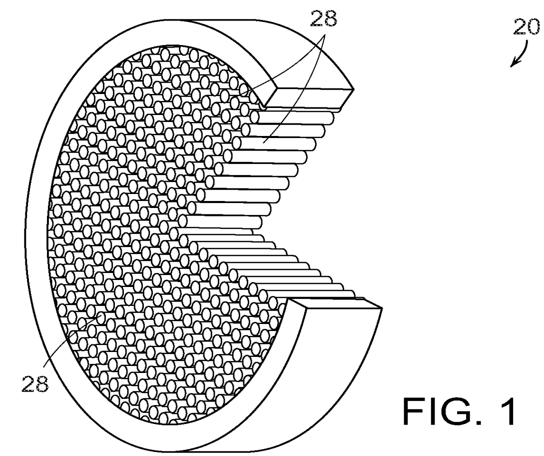

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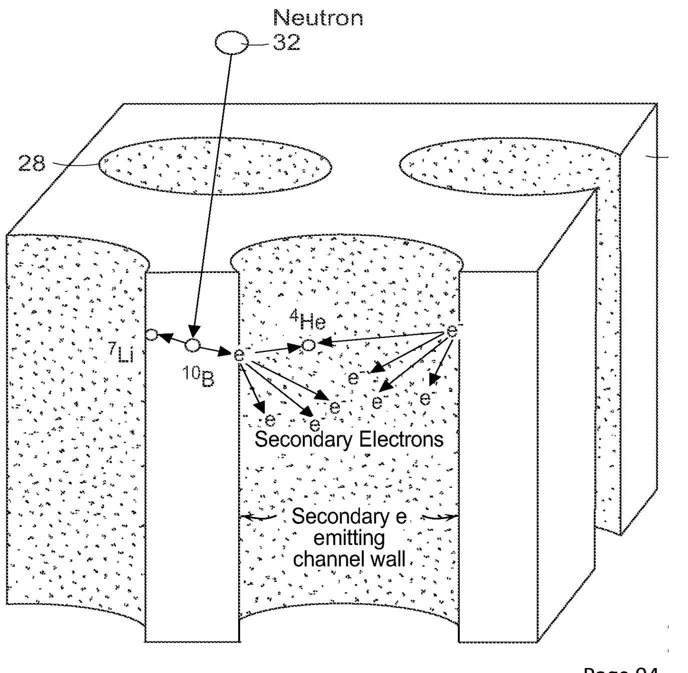

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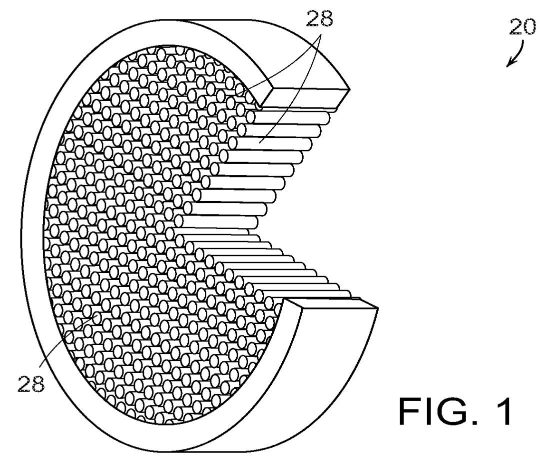

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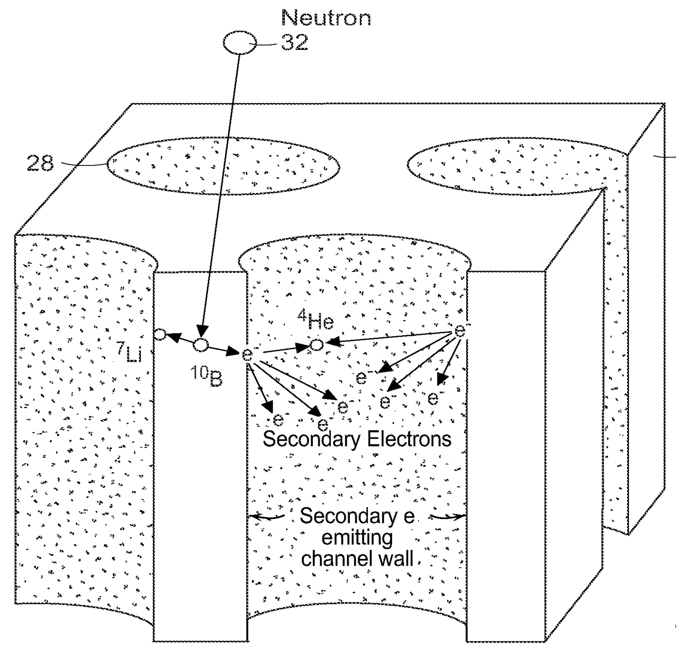

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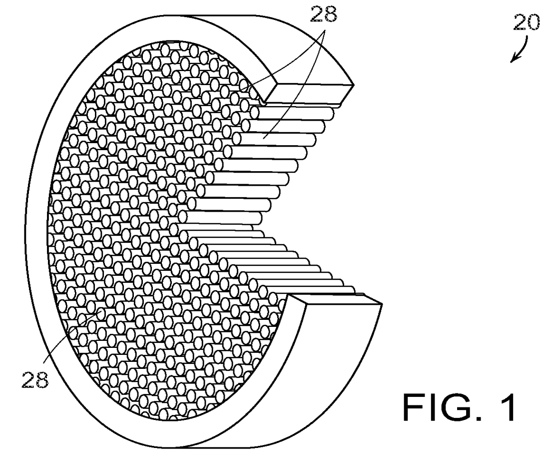

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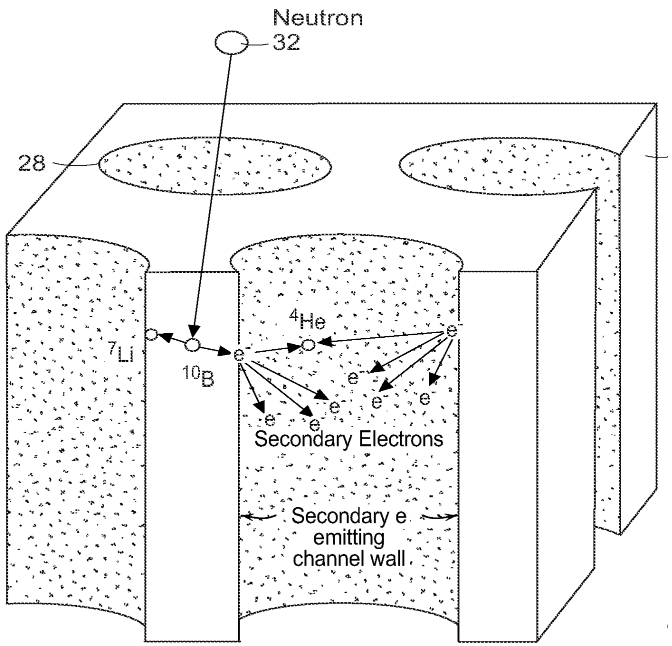

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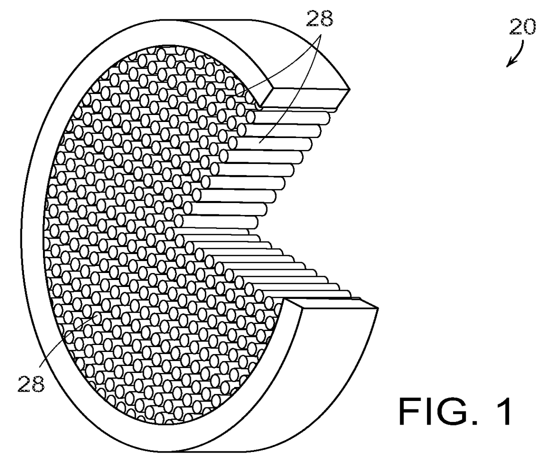

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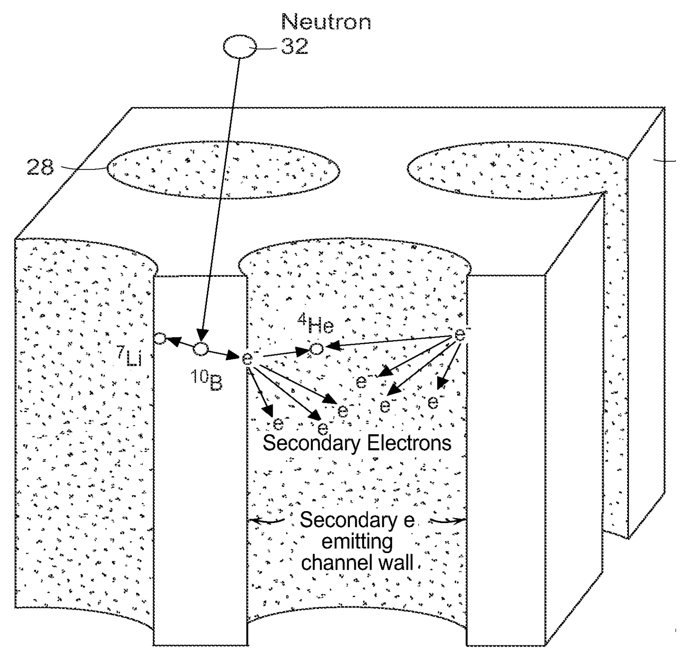

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- 256 x 256 pixels chip, stacked in a 2 x 2 matrix
- Seams between chips
- 28 x 28 cm2
- Single particle counting and arrival time mode
- Able to calculate centroiding
- ns timing capabilities
- Limit on the total flux (10^7n/s/cm^2)
- Readout gaps for buffer reading (older versions)

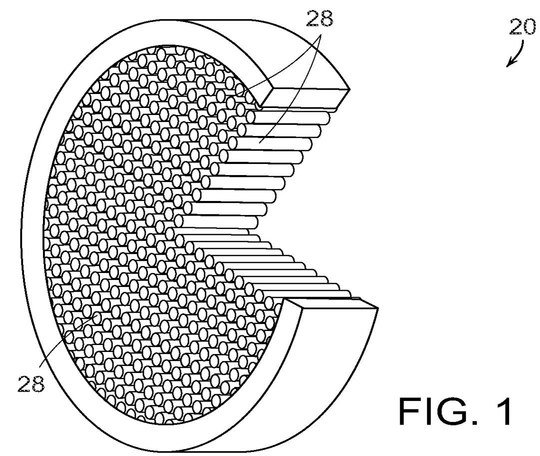
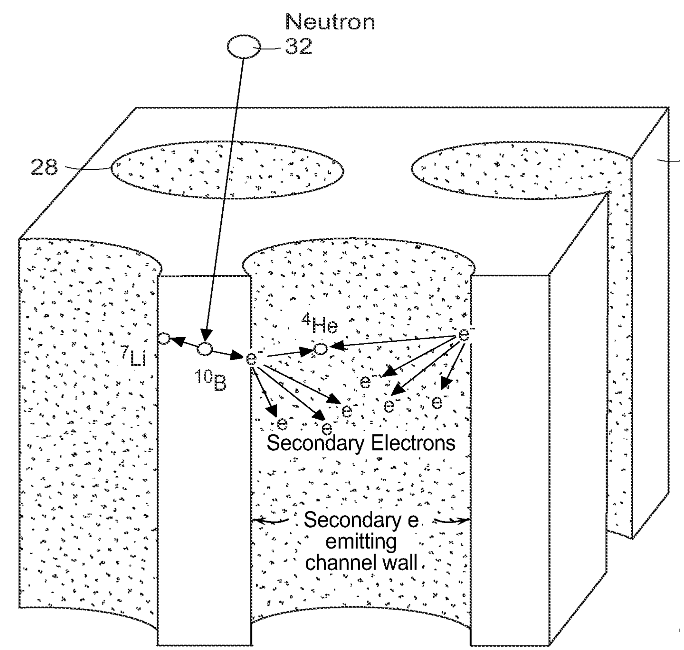


FIG. 1



Example: MCP based detector (Berkeley)

- ^{10}B-loaded glass Micro Channel Plate (MCP)
- Reaction particles create e-
- e- are accelerated and multiplicated by HV in vacuum
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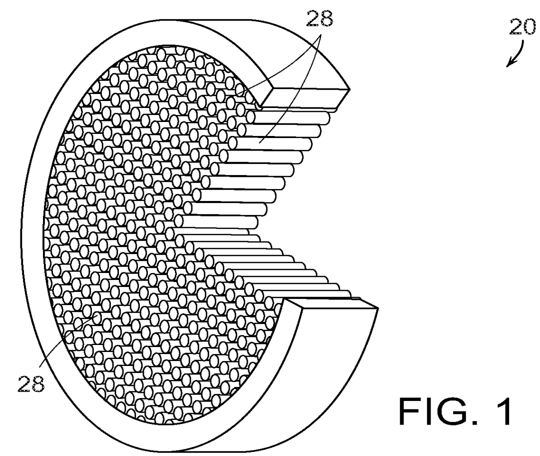

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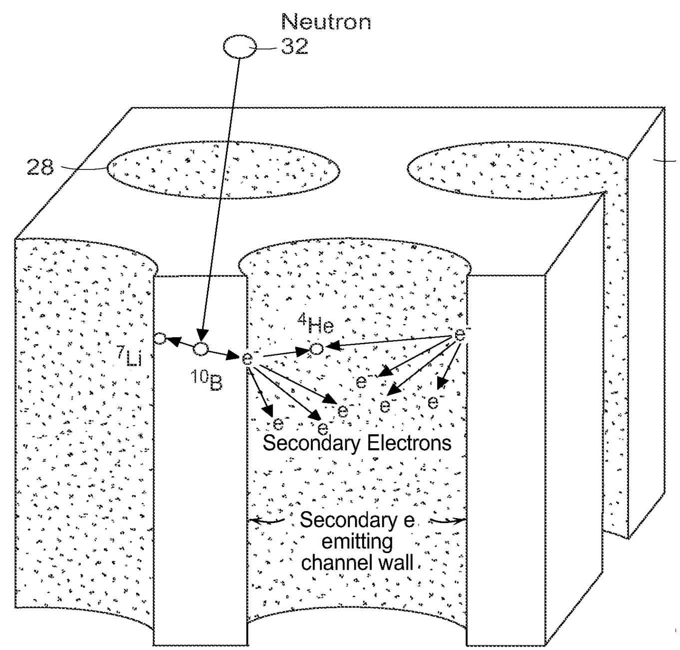

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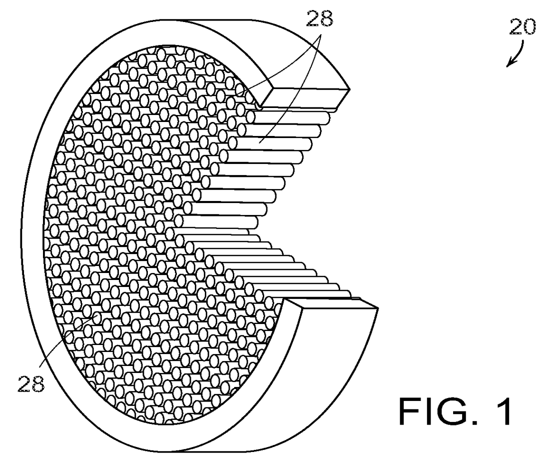
- BONUS! Resonance imaging



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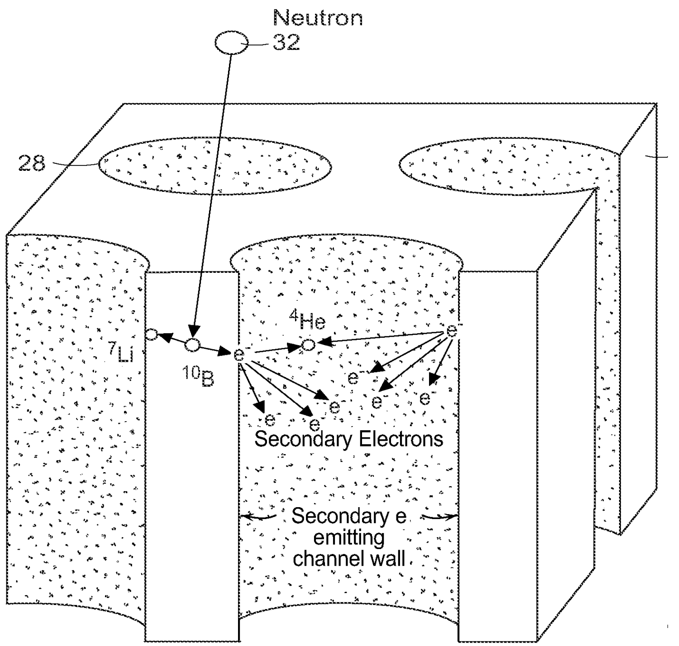

Fast neutron imaging

- The challenge of detecting a neutron
- Common materials used for neutron detection
- Standard detectors for neutron imaging
  - Analog methods
  - Digital methods
    - Scintillator + camera (the workhorse)
      - CCD vs. sCMOS
    - Flat panel detectors
- Advanced detectors: ToF
- Fast neutron detection for neutron imaging

Fast neutron detection

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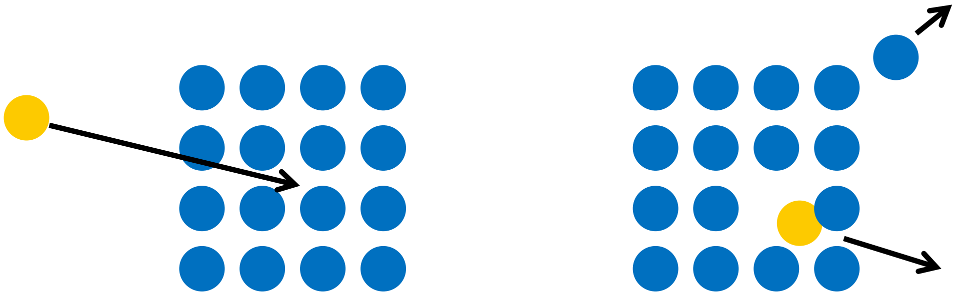

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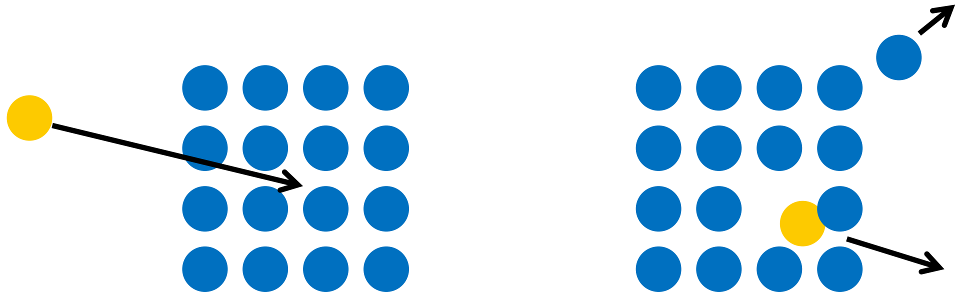

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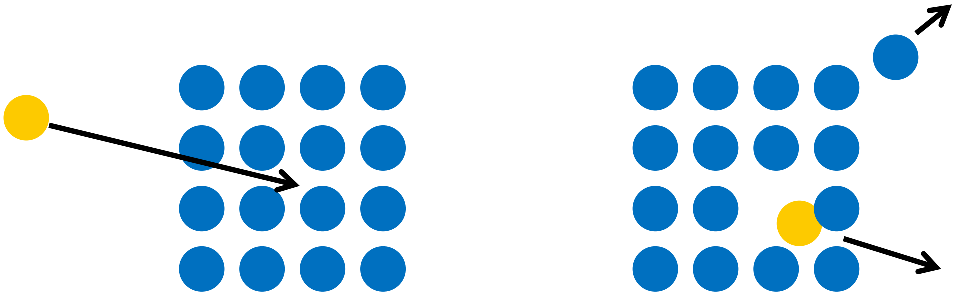

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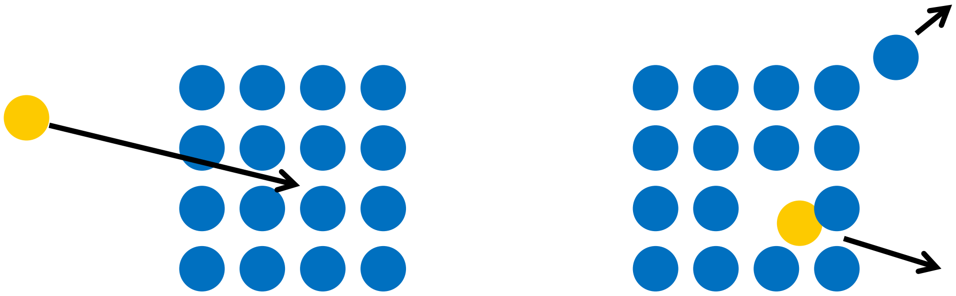
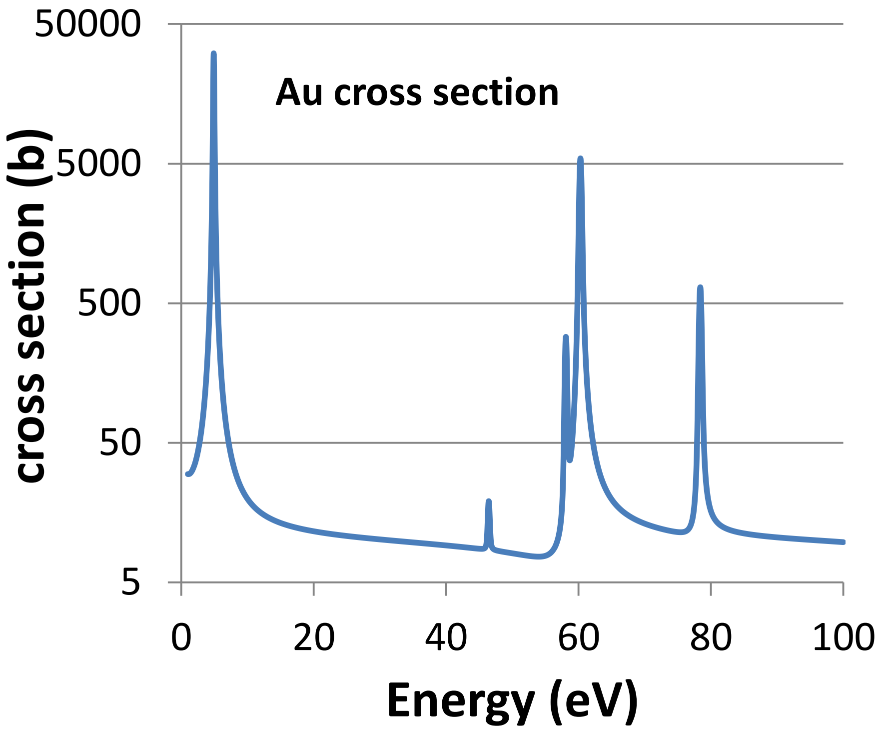
- Very low interaction probability → long counting time
- Normal scintillator + camera / timepix detector
- Isotopic sensitivity with good ToF resolution by using resonance analysis





Thank you for your attention!