Detectors for 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
The challenge of detecting a neutron

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The challenge of detecting a neutron

- You might be familiar with this picture:
The challenge of detecting a neutron

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![Diagram showing x-ray and neutron cross sections with elements H, D, C, O, Al, Si, Fe]

- Plot twist: the size of the x-ray bubbles are reduced by a factor $\sim 1.5$
The challenge of detecting a neutron

- You might be familiar with this picture:

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

- 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

\[ n + ^6\text{Li} \rightarrow ^3\text{H} (2.73 \text{ MeV}) + \alpha (2.05 \text{ MeV}) \]

\[ n + ^{157}\text{Gd} \rightarrow 259 \text{ kb} + e^- (29-130 \text{ keV}) \]

\[ n + ^{10}\text{B} \rightarrow 3840 \text{ b} + ^7\text{Li} (94\%: 840 \text{ keV}) \quad (6\%: 1.02 \text{ keV}) + \alpha (94\%: 1.47 \text{ MeV}) \quad (6\%: 1.78 \text{ MeV}) \]
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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-

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- **Base:** Structural support

- High resolution (<10 μm) and big FoV (easily ~ 500 cm²)
- 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
Digital methods

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The scintillator
The scintillator

- A scintillator takes an ionizing radiation and produces the light along the path the radiation takes
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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)
The scintillator

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- Made up of 4 parts:
  1. The substrate: physically supports the scintillator, blocks unwanted light. Should be made of a neutron transparent material (Al or Si)
  2. The absorber: converts neutrons to ionizing particles that can be detected
• A scintillator takes an ionizing radiation and produces the light along the path the radiation takes
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  3. The fluorescent crystal: upon excitation from ionizing radiation produces light

![Diagram of scintillator](image-url)
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  4. A binder: binds everything together and makes the scintillator easy to handle. It should be optically transparent and contain little hydrogen
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How do you choose which absorber?
How do you choose which absorber?

- $^6\text{Li}$, 940 b, $^3\text{H}$ (2.73 MeV)
- $^7\text{Li}$ (94%: 840 keV) (6%: 1.02 keV)
- $^1\text{H}$ (2.05 MeV)
- $^7\text{Li}$ (94%: 840 keV) (6%: 1.02 keV)
- $^6\text{Li}$, 259 kb, $^\text{e}^-$ (29-130 keV)
- $^7\text{Li}$ (94%: 840 keV) (6%: 1.02 keV)
- $^{157}\text{Gd}$, 3840 b, $^\alpha$ (2.05 MeV)
- $^{157}\text{Gd}$, 440 kb, $^\alpha$ (2.05 MeV)
- $^{10}\text{B}$, 940 b, $^\alpha$ (2.05 MeV)
How do you choose which absorber?

- $^6\text{Li}$: $^3\text{H}$ (2.73 MeV)
- $^6\text{Li}$: $\alpha$ (2.05 MeV)
- $^7\text{Li}$: (94%: 840 keV) (6%: 1.02 keV)
- $^7\text{Li}$: $\alpha$ (94%: 1.47 MeV) (6%: 1.78 MeV)
- $^{157}\text{Gd}$: $e^-$ (29-130 keV)
- $^{157}\text{Gd}$: $\beta^-$ (259 kb)
- $^{10}\text{B}$: $\alpha$ (94%: 1.47 MeV) (6%: 1.78 MeV)
How do you choose which absorber?

Absorption at 1.8 Å

Absorption at 3 Å

[Graphs showing absorption vs. thickness for different materials]
The absorber

How do you choose the thickness?

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

How do you choose the thickness?

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50um-LiF+ZnS → 20um-Gadox → 10um-Gadox

1mm
How do you choose the thickness?

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

50um-LiF+ZnS  20um-Gadox  10um-Gadox

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

- $^6\text{Li}$:
  - $n + ^6\text{Li} \rightarrow \alpha + ^3\text{H}$ (940 b, 3H (2.73 MeV), α (2.05 MeV))

- $^{157}\text{Gd}$:
  - $n + ^{157}\text{Gd} \rightarrow \alpha + ^{157}\text{Gd}$ (259 kb, e⁻ (29-130 keV))

- $^{10}\text{B}$:
  - $n + ^{10}\text{B} \rightarrow 7\text{Li}$ (3840 b, 7Li (94%: 840 keV), 6%: 1.02 keV)
The absorber

- $^6\text{Li}$ to $^3\text{H} (2.73 \text{ MeV})$ and $^6\text{He} (2.05 \text{ MeV})$
- $^1\text{H}$ to $^7\text{Li} (94\%: 840 \text{ keV}, 6\%: 1.02 \text{ keV})$ and $^7\text{Li} (94\%: 1.47 \text{ MeV}, 6\%: 1.78 \text{ MeV})$
- $^1\text{H}$ to $^4\text{He} (29-130 \text{ keV})$ and $^1\text{H}$ to $^7\text{Li} (94\%: 840 \text{ keV}, 6\%: 1.02 \text{ keV})$
- $^1\text{H}$ to $^7\text{Li} (94\%: 1.47 \text{ MeV}, 6\%: 1.78 \text{ MeV})$
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The absorber

- $^6$Li
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  - $\alpha$ (94%: 1.47 MeV)

- $^{157}$Gd
  - $\alpha$ (29-130 keV)
  - $^7$Li (94%: 840 keV)
  - $\alpha$ (94%: 1.47 MeV)

- $^{10}$B
  - $^7$Li (94%: 840 keV)
  - $\alpha$ (94%: 1.47 MeV)

The range of these particles is different!
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
Almost all the electrons produce light

130 keV electrons in 10 um Gadox
Range: ~40 um
Resolution: ~10um
Almost all the electron escape
Path of charged particles in scintillators

- 30 keV electrons in 10 um Gadox
  - Range: ~4 um
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  - Range: ~40 um
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  - Almost all electrons produce light

- 130 keV electrons in 10 um Gadox
  - Range: ~40 um
  - Resolution: ~10 um
  - Almost all electrons escape

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

- In ZnS:
  - Range of the alpha particle from $^6$Li: ~20 um
  - Range of triton from $^6$Li: ~100 um
• 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 emissive 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:**

\[ Y_{ph} = \frac{10^6 S Q}{\beta E_g} \text{ photons/MeV} \]

- \( Y_{ph} \) = number of photons emitted by the scintillator per unit of energy absorbed
- \( \beta \) = 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

ZnS:Ag or ZnS:Cu

Gd$_2$O$_2$S:Tb

Slide from B. Walfort, WCNR-10, Grindelwald (CH) (2014)
How many photons are produced?

ZnS:Ag or ZnS:Cu

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Photosensitivity of CCD

Slide from B. Walfort, WCNR-10, Grindelwald (CH) (2014)
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- Two main technologies: CCD and sCMOS
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CCDs vs sCMOS

CCDs:
- Charge Coupled Device
- Most commonly used
- More expensive than sCMOS
- Can be cooled more than sCMOS
- Has lower noise levels
- Has an exposure time-dependent DC
- Can be exposed for longer time (typically higher full well capacity)
- Long readout time
- More pixel area is photosensitive (better low light performances)

sCMOS:
- (scientific) Complementary Metal Oxide Semiconductor
- More and more widespread
- Cheaper than CCD
- Cooled to a lower temperature
- Higher noise level
- DC is constant
- Limited exposure time
- Fast readout (up to >100 full frames per second)
- Lower low light performances
CCDs vs sCMOS

CCD
• Charge Coupled Device

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CCDs vs sCMOS

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## CCDs vs sCMOS

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- Higher noise level
- DC is constant
- Limited exposure time
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Flat panel detectors

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- Pixelated light detector covered with scintillator (Gd$_2$O$_2$S)
Flat panel detectors

- Borrowed from x-ray
- Pixelated light detector covered with scintillator (Gd$_2$O$_2$S)
- Medium frame rate $\sim$fps
Flat panel detectors

- Borrowed from x-ray
- Pixelated light detector covered with scintillator (Gd$_2$O$_2$S)
- Medium frame rate ~fps
- Large area
Flat panel detectors

- Borrowed from x-ray
- Pixelated light detector covered with scintillator (Gd$_2$O$_2$S)
- Medium frame rate ~fps
- Large area
- Fixed pixel size ~150 um
Flat panel detectors

- Borrowed from x-ray
- Pixelated light detector covered with scintillator (Gd₂O₂S)
- Medium frame rate ~fps
- Large area
- Fixed pixel size ~150 um
- Fixed scintillator thickness
Flat panel detectors

- Borrowed from x-ray
- Pixelated light detector covered with scintillator (Gd$_2$O$_2$S)
- Medium frame rate ~fps
- Large area
- Fixed pixel size ~150 um
- Fixed scintillator thickness
- Relatively thin and lightweight (3-4 cm, few kg)
Flat panel detectors

• Borrowed from x-ray
• Pixelated light detector covered with scintillator (Gd₂O₂S)
• Medium frame rate ~fps
• Large area
• Fixed pixel size ~150 um
• Fixed scintillator thickness
• Relatively thin and lightweight (3-4 cm, few kg)
• In the direct beam
Flat panel detectors

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- In the direct beam
- Dead pixels issue
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- Still not very commonly used
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ToF detectors: very brief introduction

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ToF detectors: very brief introduction

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- We have the following equations:

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\[ ToF = \frac{mL\lambda}{h} \] or
In many experiments it is advantageous to know or select a specific neutron wavelength.

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\[ ToF = \frac{mL\lambda}{h} \quad \text{or} \quad \lambda = \frac{h \cdot ToF}{mL} \]
• In many experiments it is advantageous to know or select a specific neutron wavelength
• We have the following equations:

\[ E = \frac{1}{2}mv^2 \quad mv = \frac{h}{\lambda} \quad v = \frac{L}{ToF} \]

\[ ToF = \frac{mL\lambda}{h} \quad \text{or} \quad \lambda = \frac{h \cdot ToF}{mL} \]

• So if we know when the neutron was generated and when it arrived at the detector, and how long was its flight path, we have a direct measure of the wavelength
• In many experiments it is advantageous to know or select a specific neutron wavelength

• We have the following equations:

\[ E = \frac{1}{2}mv^2 \quad \Rightarrow \quad mv = \frac{h}{\lambda} \quad \Rightarrow \quad v = \frac{L}{ToF} \]

\[ ToF = \frac{mL\lambda}{h} \quad \text{or} \quad \lambda = \frac{h \cdot ToF}{mL} \]

• So if we know when the neutron was generated and when it arrived at the detector, and how long was its flight path, we have a direct measure of the wavelength

• We need a pulsed source and a (pixelated) detector with precise timing capabilities!
In many experiments it is advantageous to know or select a specific neutron wavelength.

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So if we know when the neutron was generated and when it arrived at the detector, and how long was its flight path, we have a direct measure of the wavelength.

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Other useful equations:

$$E\,[meV] = \frac{81.82}{(\lambda[\AA])^2} \quad \lambda[\AA] = \frac{9.045}{\sqrt{E\,[meV]}} \quad v[m/s] = \frac{3956}{\lambda[\AA]} = 437 \cdot \sqrt{E\,[meV]}$$
Example: MCP based detector (Berkeley)
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- $^{10}\text{B}$-loaded glass Micro Channel Plate (MCP)
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• 28 x 28 cm²
Example: MCP based detector (Berkeley)

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- Reaction particles create $\text{e}^-$
- $\text{e}^-$ are accelerated and multiplicated by HV in vacuum
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- 55um pixel size (fixed)
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- Seams between chips
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- Single particle counting and arrival time mode
Example: MCP based detector (Berkeley)

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- Reaction particles create $e^{-}$
- $e^{-}$ are accelerated and multiplied by HV in vacuum
- TimePix chip readout
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- 256 x 256 pixels chip, stacked in a 2 x 2 matrix
- Seams between chips
- 28 x 28 cm$^2$
- Single particle counting and arrival time mode
- Able to calculate centroiding
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- $e^-$ are accelerated and multiplied by HV in vacuum
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• BONUS! Resonance imaging
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 neutrons are highly penetrating
Fast neutron detection

- Fast neutrons are highly penetrating
- That is true also for the detector itself!
• Fast neutrons are highly penetrating
• That is true also for the detector itself!
• Still need to convert neutrons to charged particle
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• Still need to convert neutrons to charged particle
• Recoil proton in a H₂ rich matrix (plastic)
• Very low interaction probability → long counting time
• Normal scintillator + camera / timepix detector
• Fast neutrons are highly penetrating
• That is true also for the detector itself!
• Still need to convert neutrons to charged particle
• Recoil proton in a H₂ rich matrix (plastic)
• Very low interaction probability $\rightarrow$ long counting time
• Normal scintillator + camera / timepix detector
• Isotopic sensitivity with good ToF resolution by using resonance analysis
Wir schaffen Wissen – heute für morgen

Thank you for your attention!