Detectors for Slow Neutrons

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Neutron Detection

How does one "detect" a neutron?

- It is impossible to detect slow neutrons (neutrons relevant to materials science, that is) directly —they carry too little energy and have no charge
- Need to produce some sort of measurable quantitative (countable) electrical signal

Nuclear reactions convert neutrons into energetic charged particles.

Neutron Detection

Then one can use some of the many types of charged particle detectors

- Gas proportional counters and ionization chambers
- Scintillation detectors
- Semiconductor detectors

Nuclear Reactions for Neutron Detection

Light charged particle reactions and Q-values

$n + {}^{3}He \rightarrow {}^{3}H + {}^{1}H + 0.764$ MeV

$n + {}^{6}Li \rightarrow {}^{4}He + {}^{3}H + 4.79$ MeV

$n + {}^{10}B \rightarrow {}^{7}Li^{*} + {}^{4}He \rightarrow {}^{7}Li + {}^{4}He + 2.31$ MeV+ gamma (0.48 MeV) (93%)

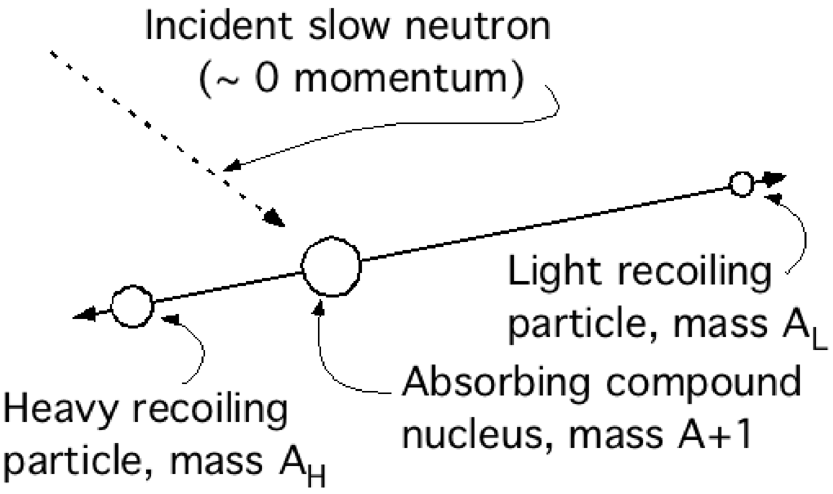
$\rightarrow {}^{7}Li + {}^{4}He + 2.79$ MeV (7%)

$n + {}^{14}N \rightarrow {}^{14}C + {}^{1}H + 0.626$ MeV

The particles share in the total energy inversely according to their masses:

Kinematics of Slow- Neutron Capture Reaction

Ranges of particles



Particles have equal and opposite momenta but share the reaction energy Q inversely according to their masses. The light particle has greater energy and greater range than the heavy particle.

$$E_H = \frac{A_L}{A_H + A_L} Q, \quad E_L = \frac{A_H}{A_H + A_L} Q$$

^{3}He Gas-filled Detectors

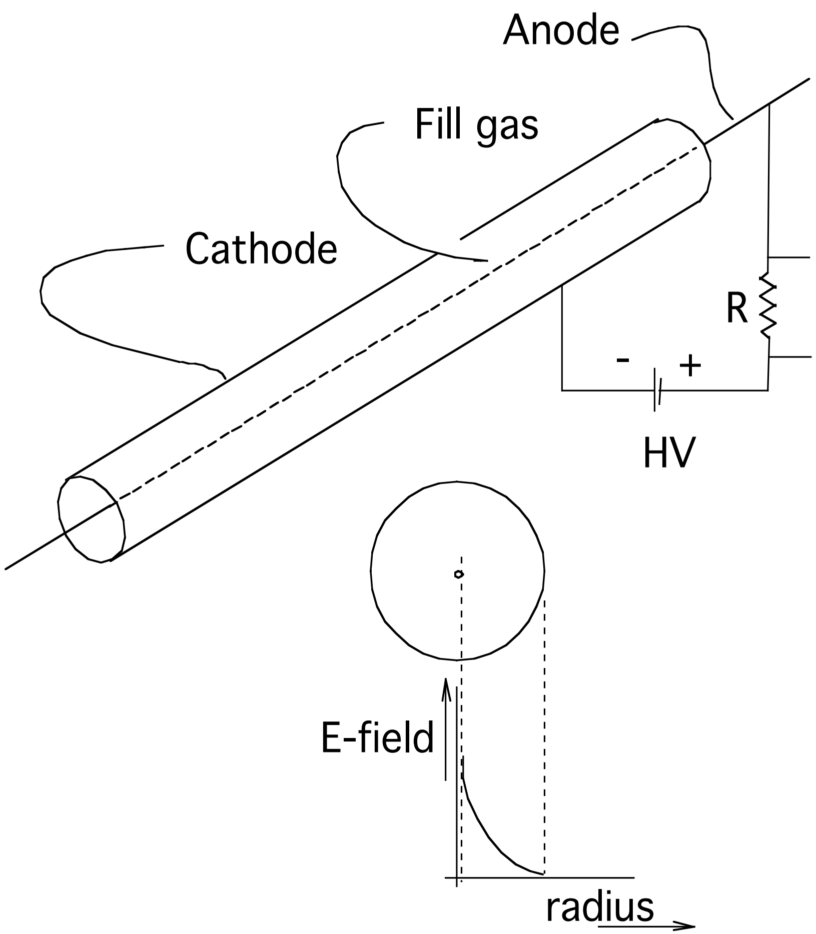
^{3}He is the converter material most used today. Before ~1960 when ^{3}He became widely available, $^{10}BF_3$ was commonly used. But because $^{10}BF_3$ is poisonous, corrosive and otherwise dangerous, it was replaced in most applications by ^{3}He, which is benign.

But ^{3}He is now in seriously short supply. Perhaps $^{10}BF_3$ will rise again, or other ^{10}B- or ^{6}LI-based detectors will be developed which replace ^{3}He in some applications.

Students: these developments may lie in your future.

^{3}He Gas Detectors

Gas Proportional Counter



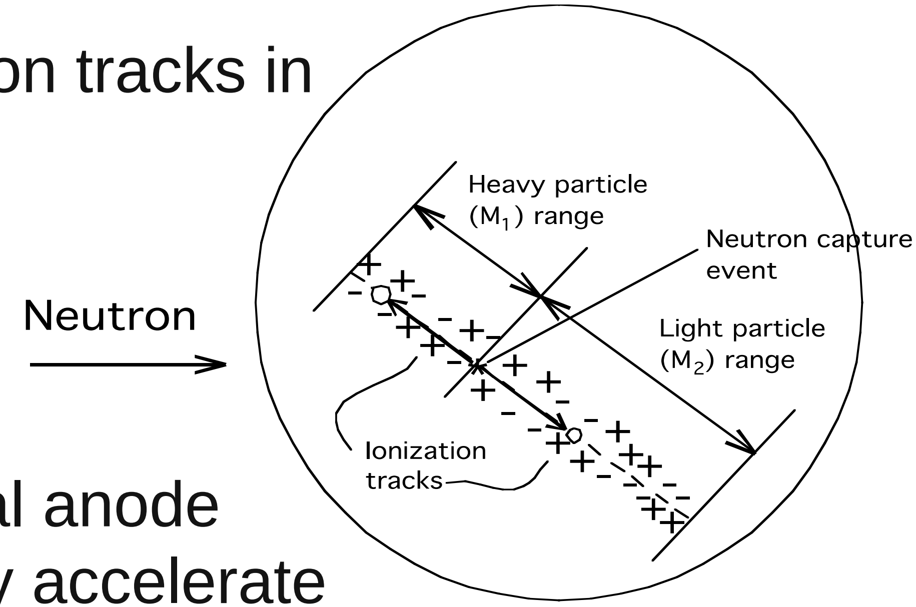
$$n + {}^3He \rightarrow {}^3H + {}^1H + 0.76\ MeV$$

$$s = 5333 \frac{l}{18} \quad barns$$

These particles recoil from the point of capture, which produce ~25,000 ions and electrons (~ 4x10^{-15} coulomb) per neutron captured.

Gas-filled Detectors

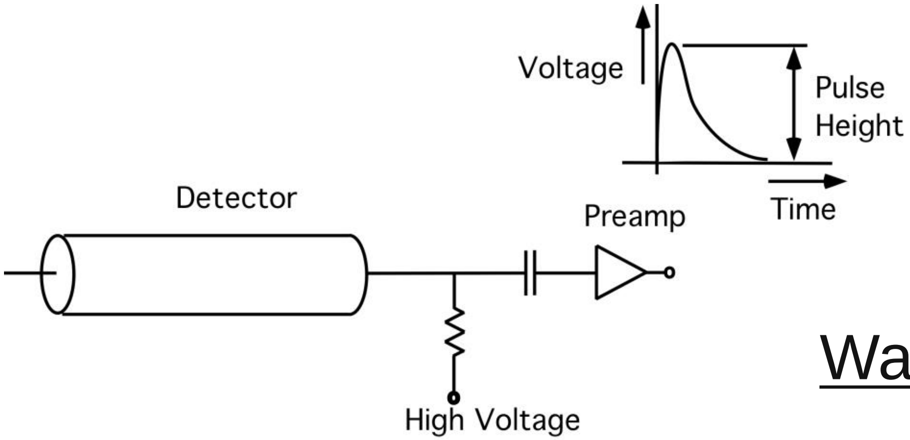
Ionization tracks in fill gas

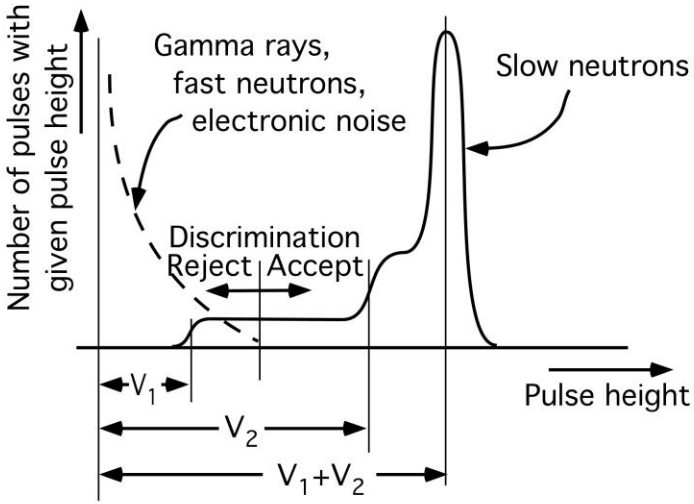


Electrons drift toward the central anode wire. When they get close, they accelerate sufficiently between collisions with gas atoms to ionize the next atom.

A *Townsend avalanche* occurs, in which the number of electrons (and ions) increases many-fold, about x10^3. Separation of these charges puts a charge on the detector, which is a low-capacitance capacitor, causing a voltage pulse that can be amplified and registered electronically.

Pulse Height Discrimination





Wall effect

When capture occurs near the detector wall, the energy of one particle is all or partially lost. At V_1, light particle lost; at V_2, heavy particle lost; main peak; total energy deposited.

Gas-filled Detectors

2-D position-sensitive detector MWPC (Multi-Wire Proportional Counter)

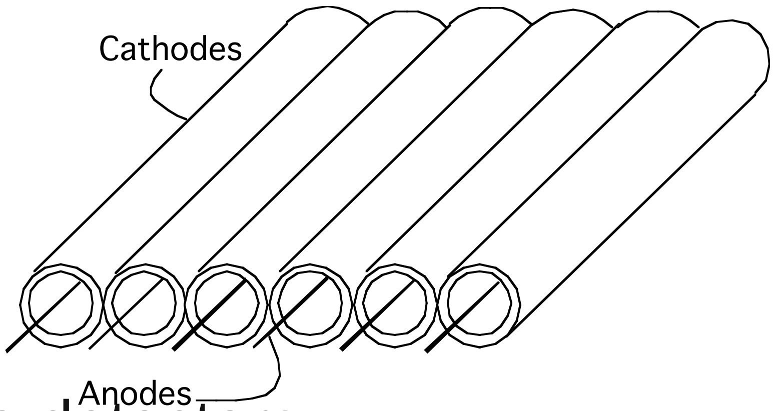
- Many parallel resistive wires extend across a large thick area of fill gas. Each wire operates either as in an LPSD

or

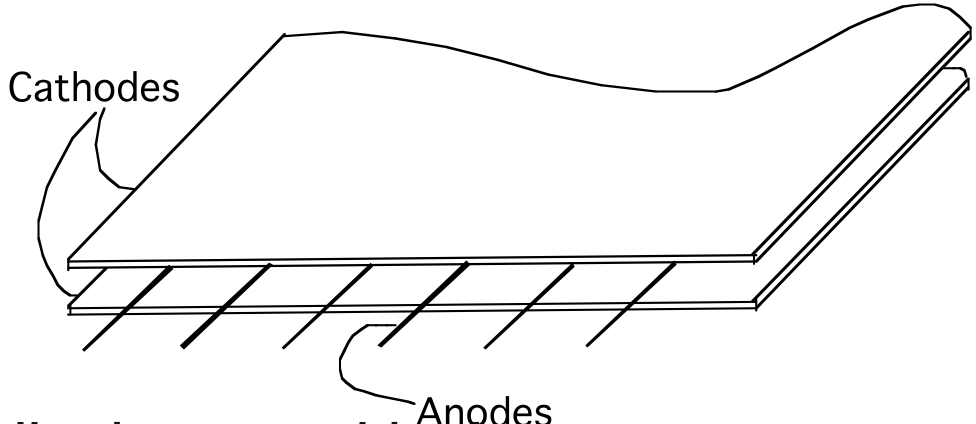
- without position information as in a simple PC: Two mutually perpendicular arrays of anode wires. Each is read separately as an LPSD to give two coordinates for the neutron capture event.

- MWPCs usually have a planar configuration.

Multi-Wire Proportional Counter

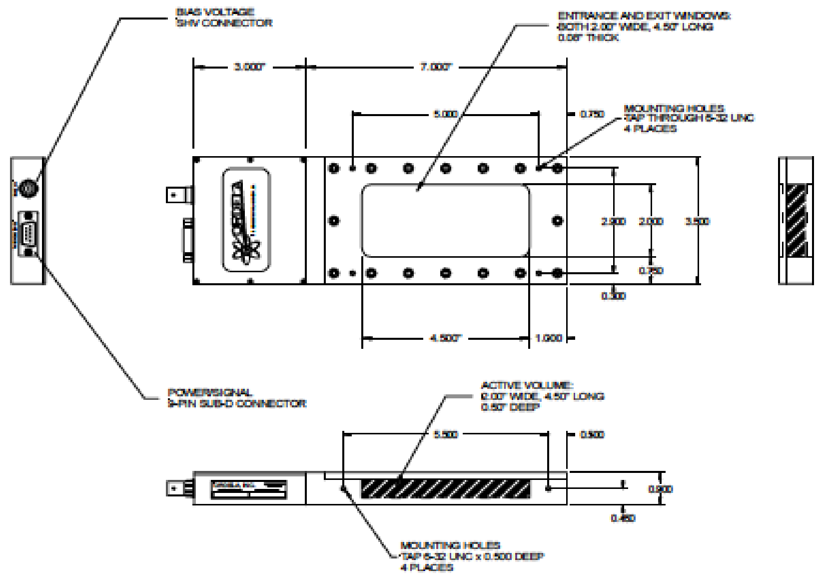


Array of discrete detectors.



Without walls, have multi-wire counter.

Beam Monitor Detectors (Pancake Detectors)



The Ordela model 4511N beam monitor detector has a rectangular active area to cover a 5.1- x 11.4-cm beam. The fill gas is a mixture of ^3He, ^4He, and CF_4 (a stopping gas) with a variable fraction of ^3He, 12.7 cm thick and 760 mm absolute pressure. Windows are 0.2-cm-thick aluminum. With 500-v anode potential, operates as a low-gain proportional counter.

Beam Monitor Detectors (Pancake Detectors)

Round, flat detectors are also in common use. Usually, these are about 1-in. thick. Anode configurations may be round or polygonal loops, harps, meshes, or plates. Sometimes these detectors operate in the ionization regime with no gas gain.

Common fill gases contain ^3He or $BF_{3,}$ sometimes in P-10 (90% argon + 10% CH_4) gas, or ^3He or nitrogen and CF_4,. Some detectors employ converter surface coatings of boron or ^{235}U.

Efficiency of Detectors

Detectors rarely register all the incident neutrons. The ratio of the number registered to the number incident is the efficiency,

$$\eta(\lambda) = 1 - \exp\left(-N\Sigma(\lambda)d\right) \approx N\Sigma(\lambda)d$$

Here:

$\Sigma(\lambda)$ = absorption cross-section (function of wavelength)

N = number density of absorber

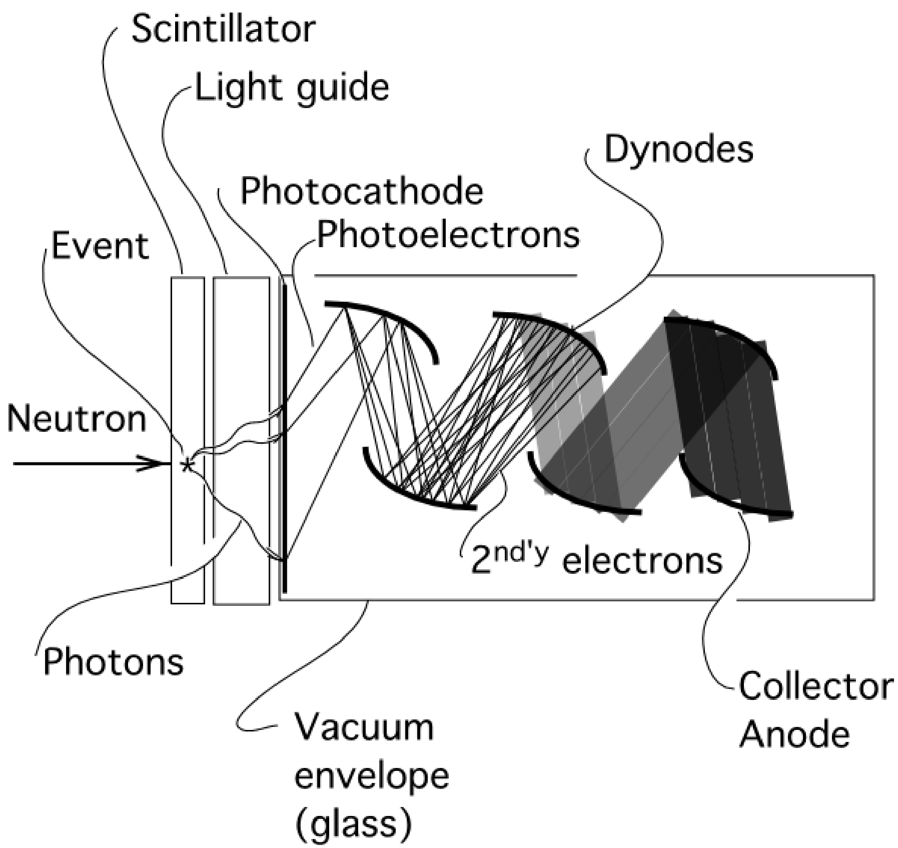
d = thickness

$N = 2.7 \times 10^{19}\ \text{cm}^{-3}$ per atm for a gas at 300 K.

For 1-cm thick ^{3}He at 1 atm and 1.8-Å neutrons, $\eta(1.8\,\text{Å}) = 0.13$

Expressions for cylindrical detector efficiencies are more complex.

Scintillation Detectors, Photomultiplier



$$n + {}^{6}Li \rightarrow {}^{4}He + {}^{3}H + 4.79\ MeV$$

$$s = 940 \frac{/}{1.8} \text{ barns}$$

Silicon Photomultiplier

A recent development is the Silicon Photomultiplier SiPM. These are thin-film solid-state devices based on p-n junctions reverse-biased at a voltage V_{bias} higher than the breakdown voltage V_B. One or more photons insert charge carriers into the depletion layer of the semiconductor, triggering a charge avalanche.

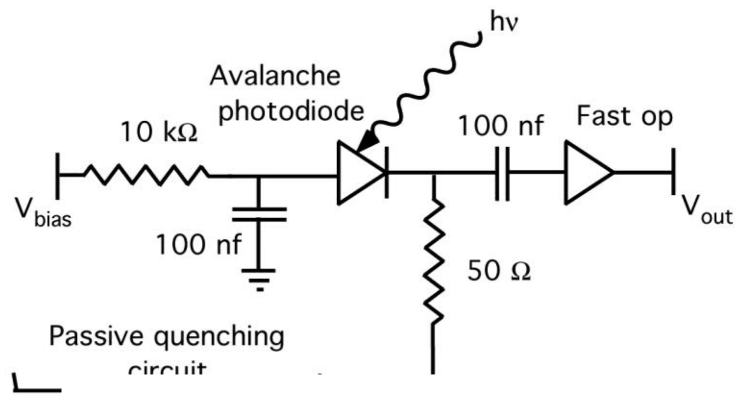
Significant advantages over standard dynode photomultipliers are low voltage operation (~100v), low power dissipation, compact size (>~ 20 μm), and are very fast, signaling photon arrival in tens of picoseconds. SiPMs are immune to the influence of magnetic fields. They can be assembled into large arrays, several mm in size. The charge gain can be as high as 10^6, similar to a PMT, perhaps joined together in cascade to produce higher gains.

Thermally generated carriers can stimulate the avalanche process. This dark current limits SiPM applications, but cooling to modest temperature (~ -40 C) reduces the dark current. Active developments continue to improve SiPMs.

Silicon Photomultiplier

The current rises until the ballast load in the quenching circuit lowers the bias voltage lowers the bias field at the diode down to or below V_B, so that the electric field can no longer accelerate carriers to impact-ionize lattice atoms. The device therefore acts in the Geiger mode, producing a standard voltage pulse V_{out} at the output. The device is dead while the quenching circuit recovers (millisec).

Geiger Silicon Photomulitplier (G-SiPM)



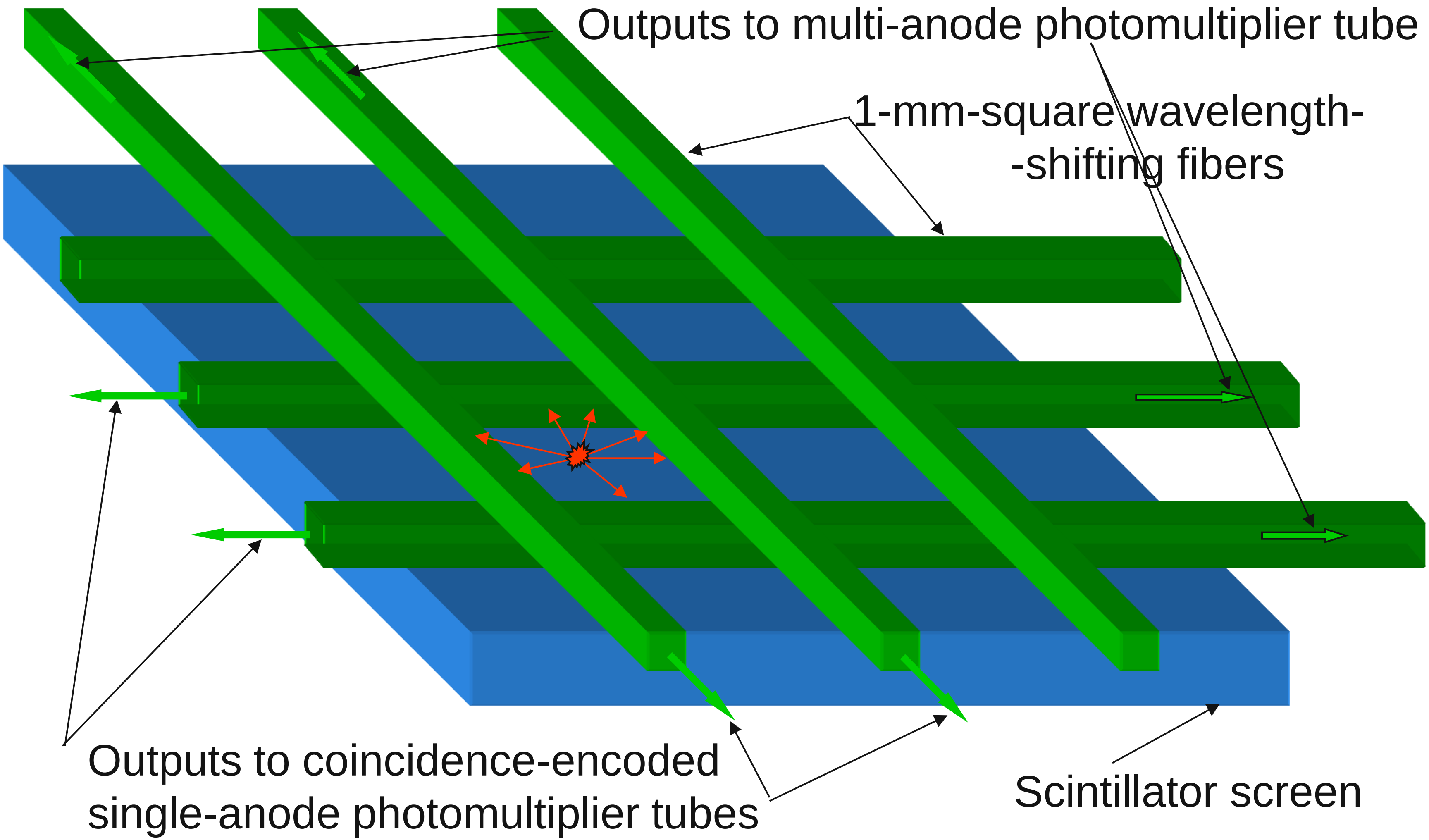
www.ketek.net/products/sipm

A 4x4-pixel array of 3-mm SiPM sensors by sensL.

Some Common Scintillators for Neutron Detectors

Material	Density of ^{6}Li atoms (cm^{-3})	Scintillation efficiency	Photon wavelength (nm)	Photons per neutron
Li glass (Ce), GS-20	1.75×10^{22}	0.45 %	395 nm	~7,000
LiI (Eu)	1.83×10^{22}	2.8 %	470	~51,000
ZnS (Ag)-^{6}LiF	1.18×10^{22}	9.2 %	450	~160,000
$Li_6Gd(BO_3)_3$ (Ce),	3.3×10^{22}	2.4%	~ 400	~40,000
YAP	NA		350	~18,000 per MeV gamma

Principle of Crossed-Fiber Position-Sensitive Scintillation Detector



Coincidence Encoding

Several optical fibers attached to each scintillator tile lead to a group of photosensors. Each sensor is attached to several distinct scintillation tiles. The pattern of attachments uniquely relates pairs or higher multiples of light sensors to each individual tile.

Timewise coincidence of light pulses from groups of light sensors identifies the tile where the neutron interacted. For example, N_s sensors encoding in pairs allow distinguishing tile positions numbering N_t tiles,

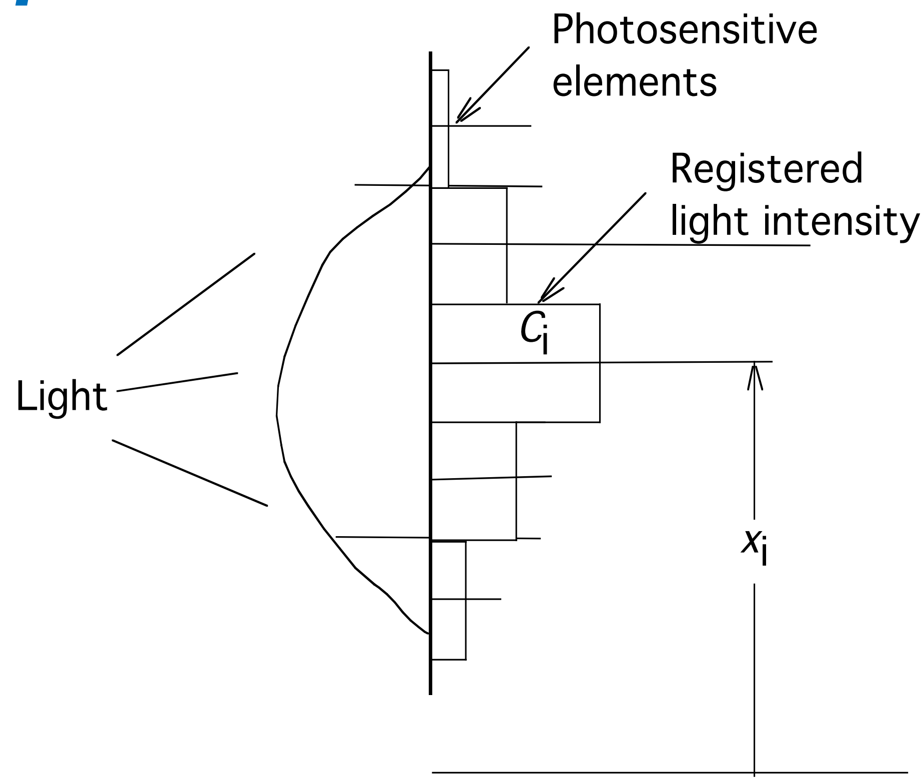
$$N_t = N_s! / [(N_s - 2)!\, 2!].$$

For example, 20 sensors operated in 2-fold coincidence can uniquely encode 190 sources. Count clicks next time you toast at dinner.

Anger Camera Principle

Light incident on the i^{th} photosensitive element located at position x_i registers as intensity C_i. The intensity-weighted intensities provide the average position

$$\langle \ \rangle \quad \frac{\sum_{i}}{\sum_{i}} \ .$$



The result is an electronic signal that is binned more finely than the size of the photosensitive elements, with a precision limited by the number of photons collected as C_i.

The process is actually carried out in two dimensions.

Image Plates

After exposure to neutrons, the plates pass through a "reader" that scans the surface with a laser beam. The laser stimulates emission of de-excitation light from the phosphor material that registers in a photosensor.

The connected readout computer registers the position-dependent light intensity, providing a numerical file.

The computer-accessible format enables contour diagrams of the area density of the neutron capture intensity.

Picture of an Image Plate

Image plates are about 20 x 30 cm in size, and look like a blank piece of paper, about 2 mm thick. They are flexible and cut-able.

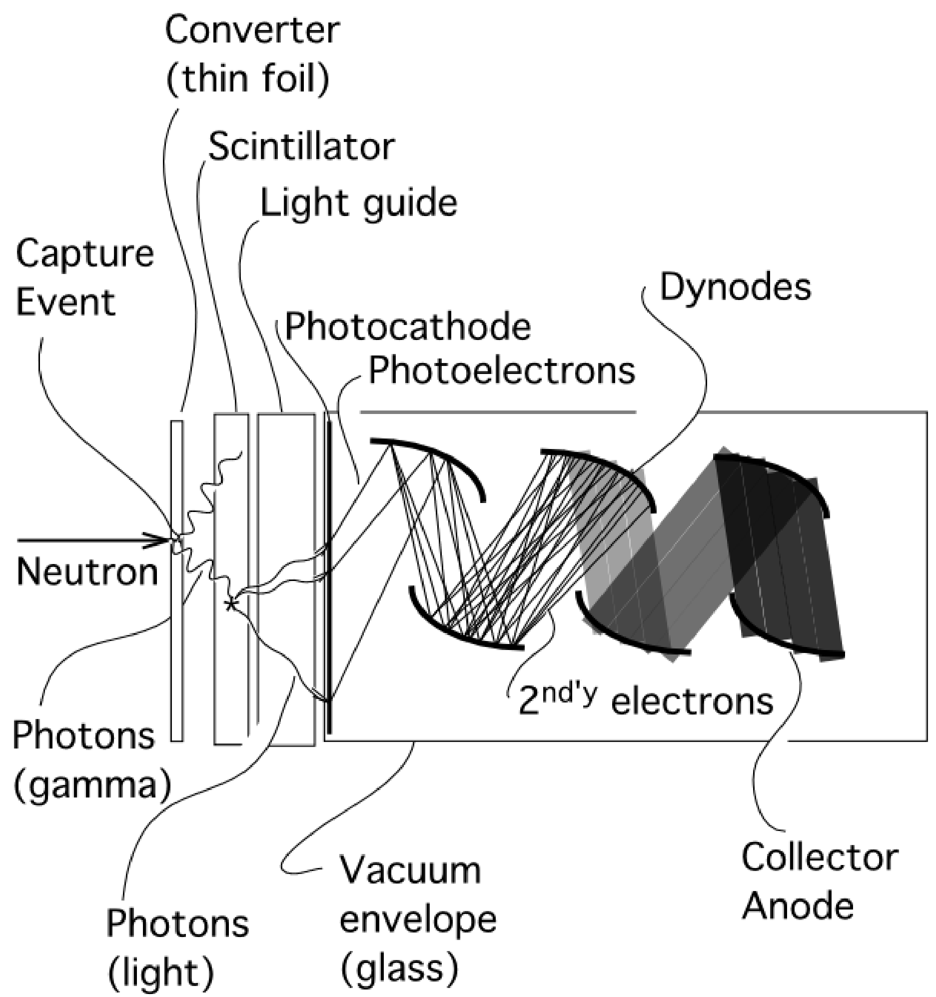
Resonance Capture Gamma-Ray Neutron Detectors

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

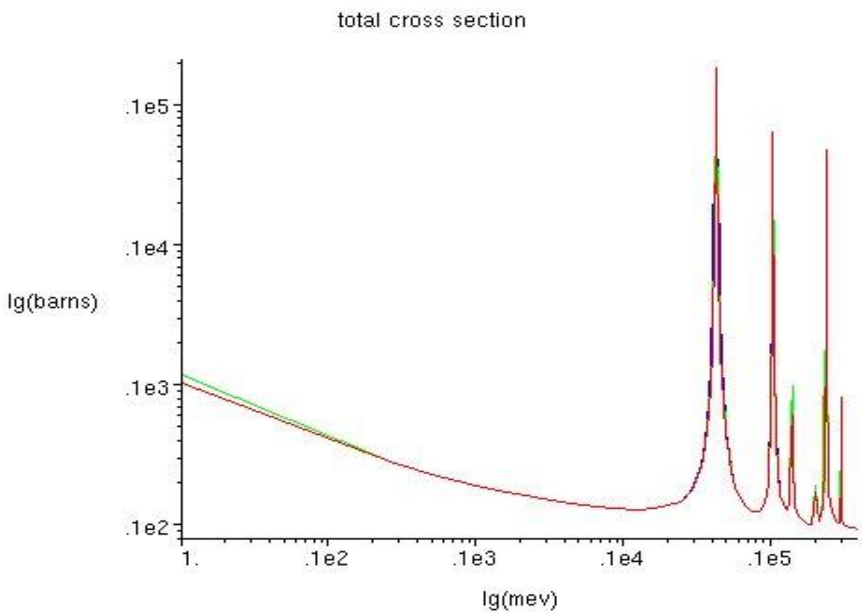
A closely located scintillator responds to incident gamma rays, and a coupled photomultiplier registers the pulse.

A Resonance Detector is 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



Cross section of Tantalum



Narrow isolated resonance
at 4.28 eV

Summary

Detectors as well as sources constrain what can be done in neutron scattering instruments.

There is a continuing need for improvements:

- Efficiency.
- Time response.
    - High counting rates.
    - Sharp time determination.
    - Fast readout.
- Spatial resolution.

Doubling the capability of detectors to double the effectiveness of a neutron scattering instrument at a cost of, say, $10M, is far more effective than doubling the intensity of a neutron source for $1B.

Summary

Active subjects of development in an ongoing, coordinated, world-wide development activities:

- In scintillators
  - Converter composition
  - optics
- In gas detectors
  - Gas electronics
  - Field configurations
- In LPSDs and MWPCs
  - Spatial resolution
  - Time response (intrinsic to converter type)
  - Counting rate (electronic design)
  - Compact multicathode photomultipliers
  - Fast-readout CCDs

Summary

There is a world-wide shortage of ^{3}He. This is because demands for border security systems, heavily based on neutron detection, have required a large portion of available supplies.

Our community also depends heavily on ^{3}He detectors.

We are detector developers. THEREFORE:

We should devote strong efforts to develop non-^{3}He detectors

- better suited to border security applications than ^{3}He
- suited to neutron-scattering applications, to reduce our dependence on ^{3}He.

I have not described Boron-coated detectors, which have limited neutron detection efficiency because the solid coatings must be thin ($<5 \times 10^{-4}$ g/cm^{2}). But developments proceed on replacements for ^{3}He detectors in security applications.

End of Presentation

Thank you!