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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

Need to use nuclear reactions to 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%)

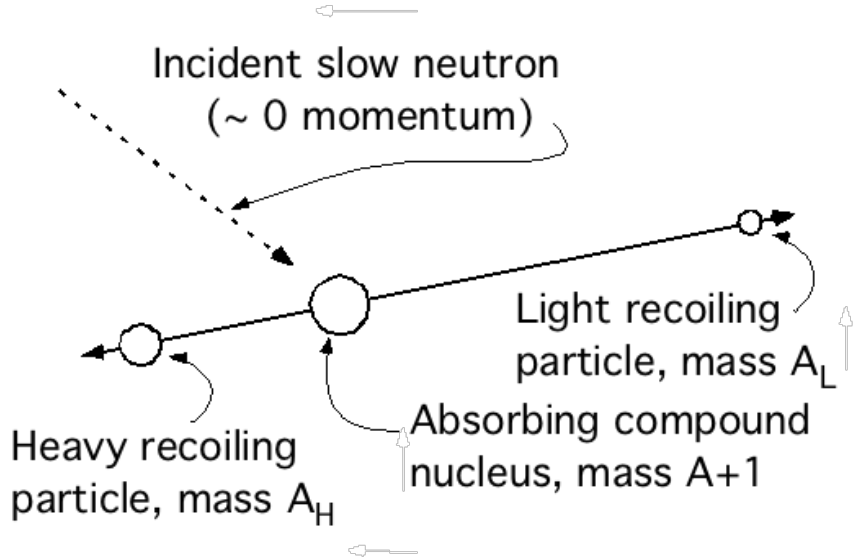
$\rightarrow {}^{7}Li + {}^{4}He + 2.79$ MeV (7%)

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

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

Nuclear Reactions for Neutron Detection

Atomic recoil (mostly observable among light atoms, mass number A)

When the struck particle is initially at rest,

$n(E_n) + A \rightarrow A(E_R) + n(E'_n)$ and, when θ is the scattering angle, the recoil energy depends on the scattering angle

$$E_R = \frac{2A}{(A+1)^2}(1 - \cos\theta)E_n \qquad E_{R\,Max} = \frac{4A}{(A+1)^2}E_n$$

Nuclear Recoil Energies

Struck atom	Fractional average recoil energy, $\frac{E_{R\ Ave}}{E_n}$
H	0.5
D	0.444
^{3}He	0.375
^{4}He	0.32
^{12}C	0.142
^{16}O	0.1107
^{57}Fe	0.034
^{238}U	0.00833

Nuclear Reactions for Neutron Detection

Capture gamma rays Prompt capture gamma spectra ~ 6 MeV total energy; registered in detector

n + $^{natural}Cd \rightarrow {}^{113}Cd^*$ → gamma-ray spectrum (mostly used for shielding)

n + $^{155}Gd \rightarrow Gd^*$ → gamma-ray spectrum + conversion electron spectrum

n + $^{157}Gd \rightarrow Gd^*$ → gamma-ray spectrum + conversion electron spectrum

Nuclear Reactions for Neutron Detection

Fission

n + ^{235}U → xn + 2 fission fragments + ~160 MeV

n + ^{239}Pu → xn + 2 fission fragments + ~160 MeV

n + ^{238}U → xn + 2 fission fragments + ~ 160 MeV (threshold ~ 0.5 MeV)

[<x> ~ 2.5 neutrons per fission, but most neutrons escape]

Energy-Selective (Resonance) Nuclear Reactions

Resonance capture reactions Narrow resonances, prompt emission, total prompt gamma energy ~ 6 MeV.

Energy-selective resonance-capture detectors

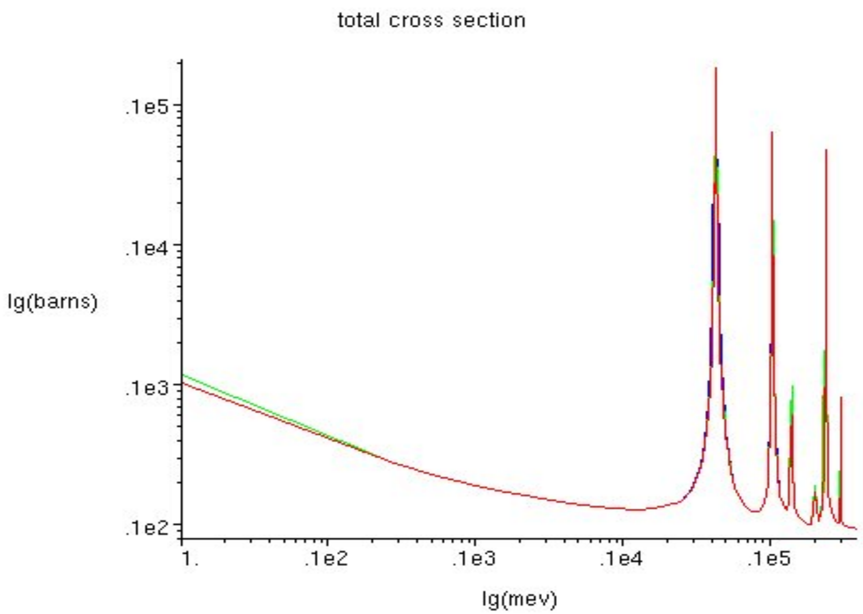
Isotope	Resonance Energy (eV)	Resonance Total width (meV)
^{115}In	1.46	75
^{181}Ta	4.28	57
^{197}Au	4.906	143
^{238}U	6.67	25
"	20.87	34

Cross sections

Most of the neutron-detection reactions tabulated have cross sections proportional to the wavelength, “1/v” cross sections.

Tables of cross sections usually quote the cross section for the specific energy of *nominally thermal* 293-K neutrons, wavelength 1.80 Å, energy 25. meV, speed 2200 m/s, even for non-1/v cross sections.

Cross section of Tantalum



Narrow isolated resonance at 4.28 eV

^3He Gas-filled Detectors

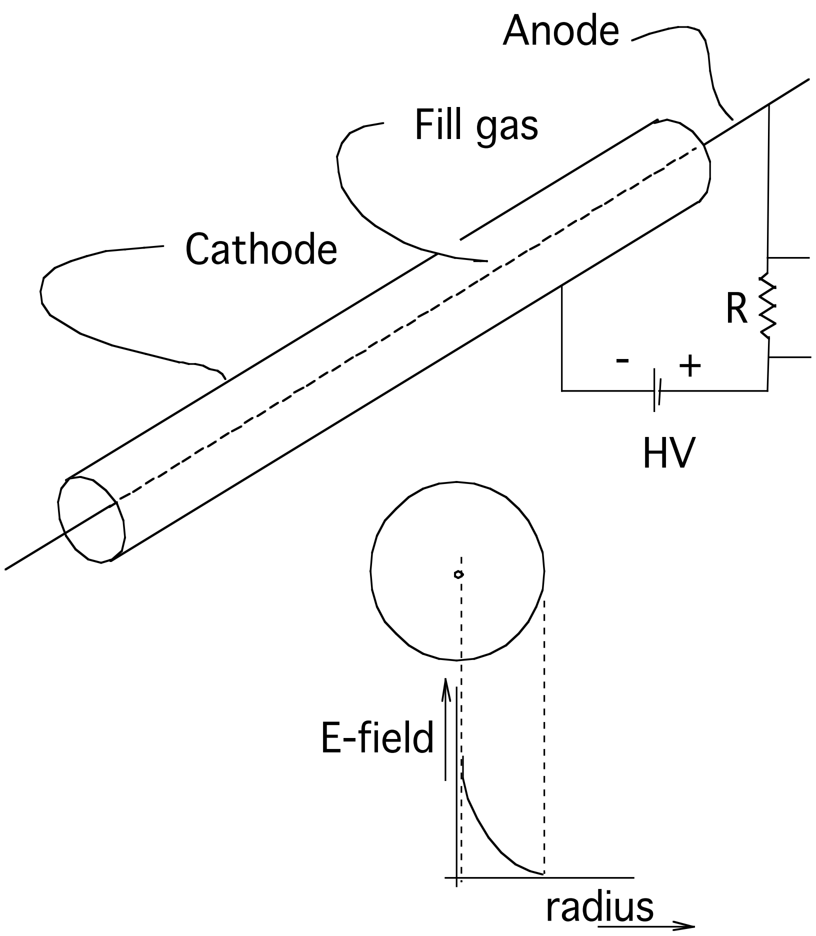
^3He is the converter material most used today. Before ~1960 when ^3He became widely available, $^{10}BF_3$ was commonly used. But because $^{10}BF_3$ is poisonous, corrosive and otherwise dangerous, it was replaced in most applications by ^3He, which is benign.

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

Students: these developments may lie in your future.

^{3}He Gas Detectors

Gas Proportional Counter



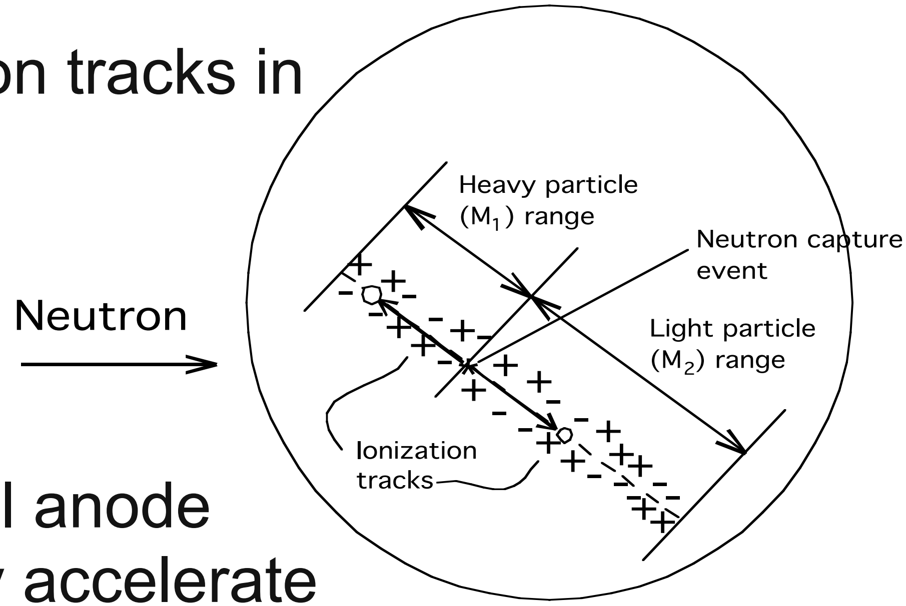
$$n + {}^3\text{He} \rightarrow {}^3\text{H} + {}^1\text{H} + 0.76\ \text{MeV}$$

$$\sigma = 5333 \frac{\lambda}{1.8} \quad \text{barns}$$

These particles recoil from the point of capture, which produce ~25,000 ions and electrons (~ 4×10^{-15} coulomb) per neutron captured.

Gas 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.

Gas Detectors

Ionization Mode

- Electrons drift to the anode, producing a charge pulse with no gas multiplication–no Townsend avalanche.
- Typically employed in low-efficiency beam-monitor detectors.

Proportional Mode

- If the voltage is high enough, electron collisions ionize gas atoms producing even more electrons.
  - *Gas amplification increases the collected charge proportional to the initial charge produced.*
  - *Gas gains of up to a few thousand are possible, above which proportionality is lost.*

At high anode voltage, proportionality is lost: the Geiger mode.

Gas Detectors

- Proportional counters (PCs) come in a variety of different forms.
- Simple detector (shown previously) and pancake
- Linear position-sensitive detector (LPSD):
  - The anode wire is resistive, read out from both ends—the charge distributes between the ends according to the position of the neutron capture event in the tube.
  - Usually cylindrical.

Gas Detectors

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

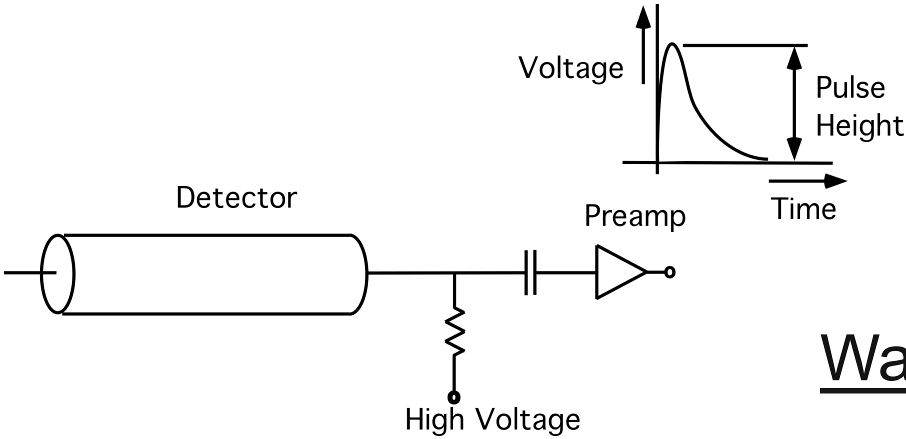
- Many parallel resistive wires extend across a large thick area of fill gas. Each wire operates either as in an LPSD

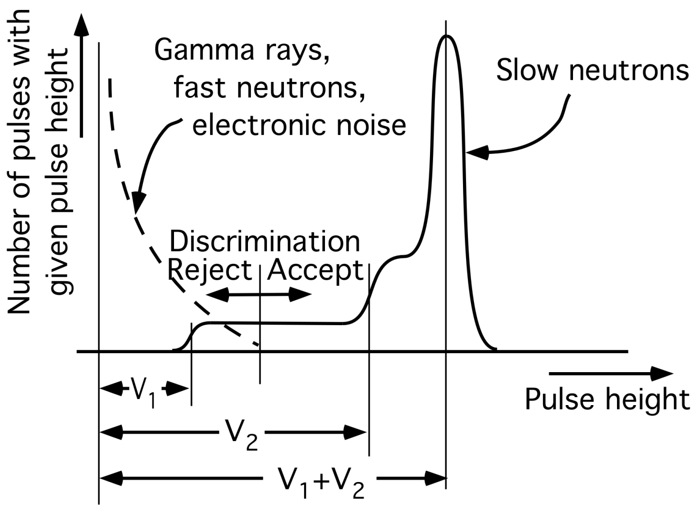
or

- 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.

Pulse Height Discrimination





Wall effect

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

Pulse Height Discrimination

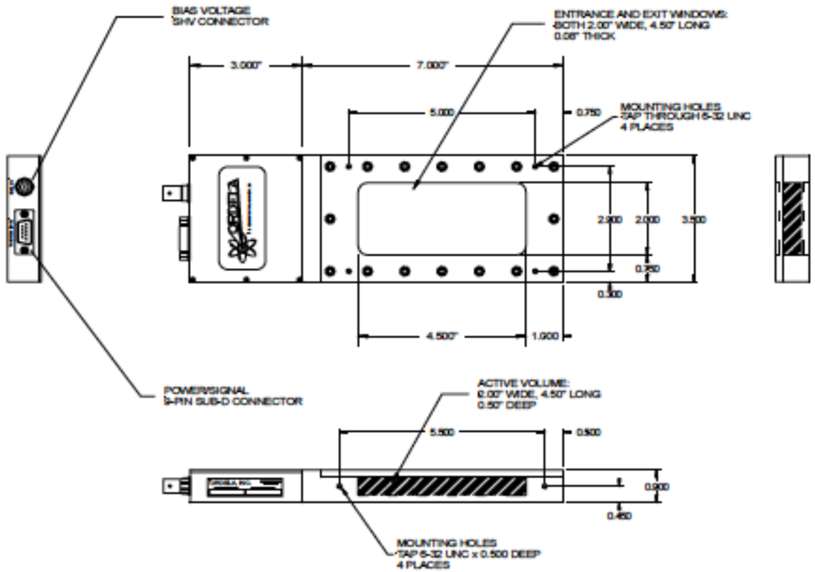
- Can set discriminator levels to reject undesired events (fast neutrons, gammas, electronic noise).
- Pulse-height discrimination can make a large improvement in background.
- Discrimination capabilities are an important criterion in the choice of detectors (^{3}He gas detectors are very good).

Stopping Gas

Sometimes, a heavy-atom or molecular gas is added to the fill gas, which reduces the range of the charged particles and therefore reduces the energy lost in the wall effect. Examples are Ar, CO_2, propane (C_3H_8), and CF_4.

Carbonaceous gases are sometimes problematic because molecules ionized, especially in the Townsend avalanche, recombine into solid polymers that precipitate on the anode wire, inhibiting performance.

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

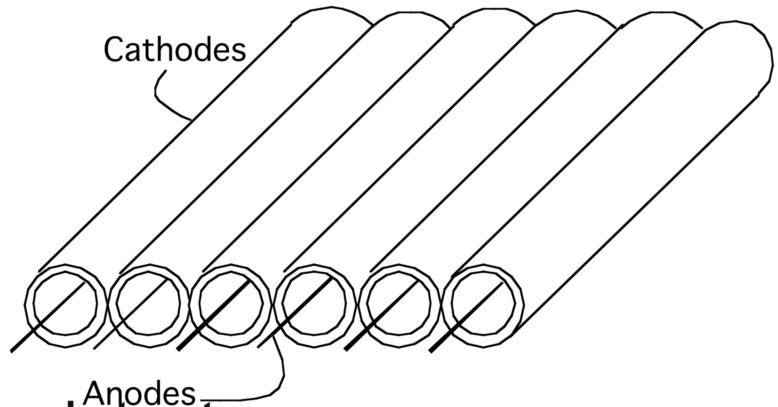
Common fill gases contain ^{3}He or $BF_{3,}$ sometimes in P-10 (90% argon + 10% CH_4) gas, or ^{4}He and CF_4, or pure nitrogen. Some detectors employ converter surface coatings of boron or ^{235}U.

Beam Monitor Detectors (Pancake Detectors)

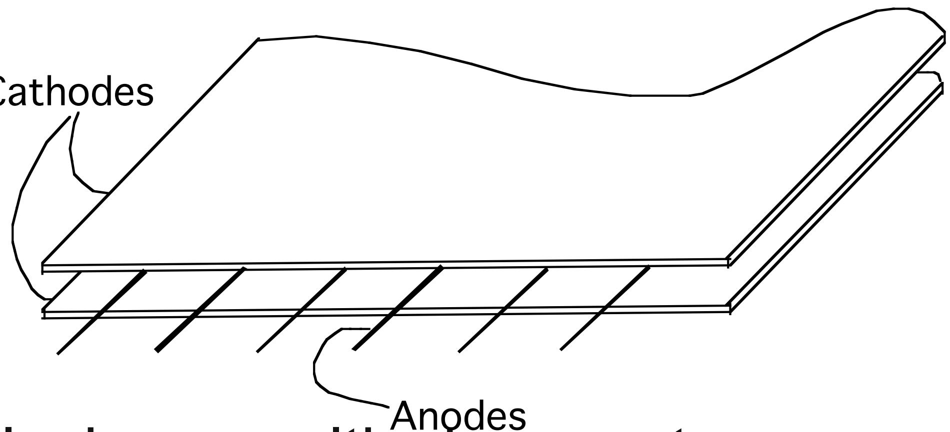
Instrument operators and designers often rely on accurate knowledge of the absolute efficiency of beam monitor detectors.

This **requires accurate knowledge of the converter gas concentration. This is sometimes problematical** and may require careful attention, but is easy with N_2 gas filling.

Multi-Wire Proportional Counter

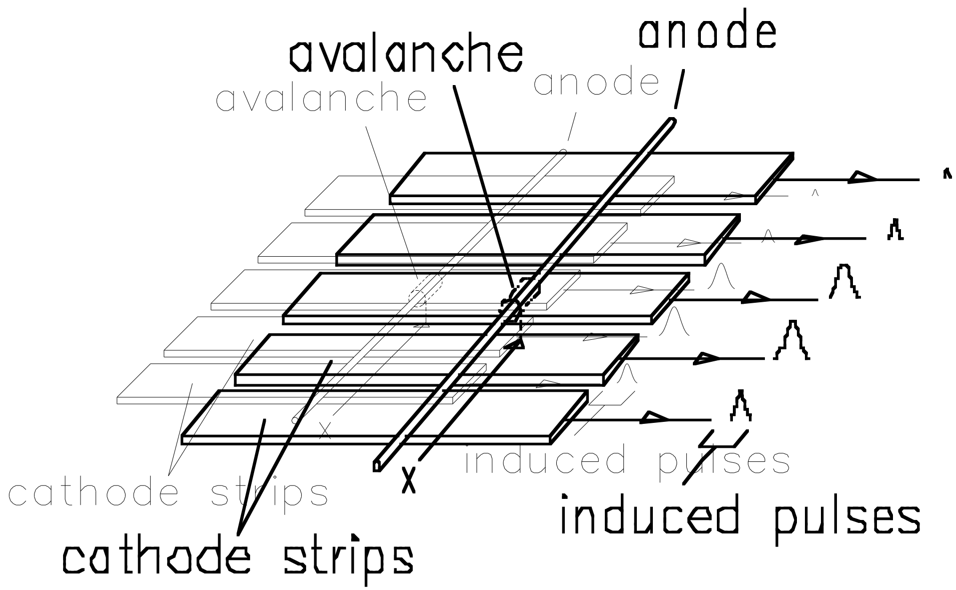


Array of discrete detectors.



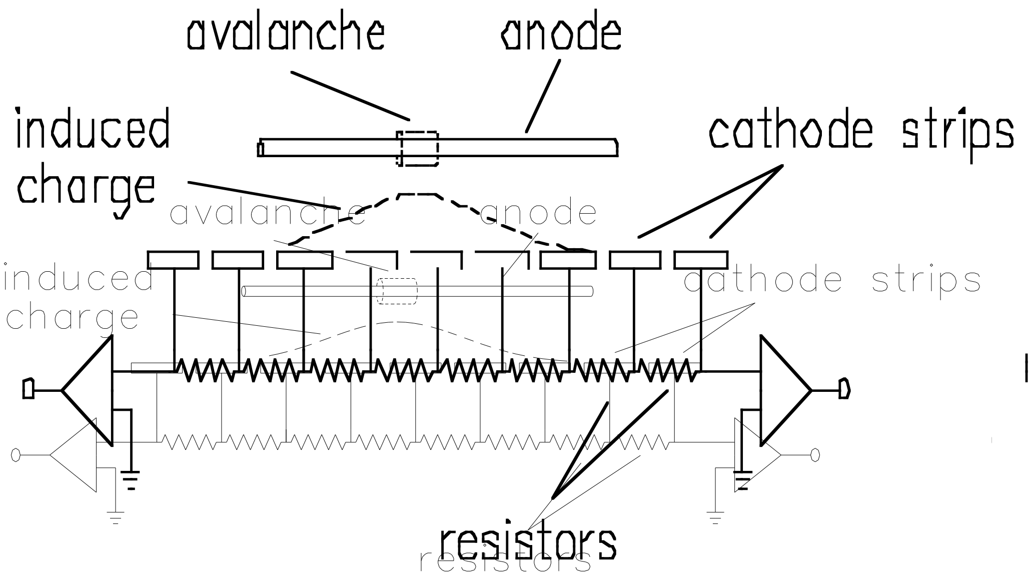
Without walls, have multi-wire counter.

MWPC



Segment the cathode to get x-y position

Resistive Encoding of a Multi-Wire Detector



- Instead of being read individually, the cathode strips can be resistively coupled (cheaper & slower) and read together.
- Position of the event can be determined from the fraction of the charge reaching each end of the resistive network (<u>charge-division encoding</u>)
  - Used on the GLAD and SAND linear PSDs at IPNS.

Resistive Encoding of a Multi-Wire Detector

The position of the event can be determined from the relative time of arrival of the pulse at the two ends of the resistive network (rise-time encoding). A pressurized gas mixture surrounds the electrodes

- Used on the POSY1, POSY2, SAD, and SAND 2-D PSDs.

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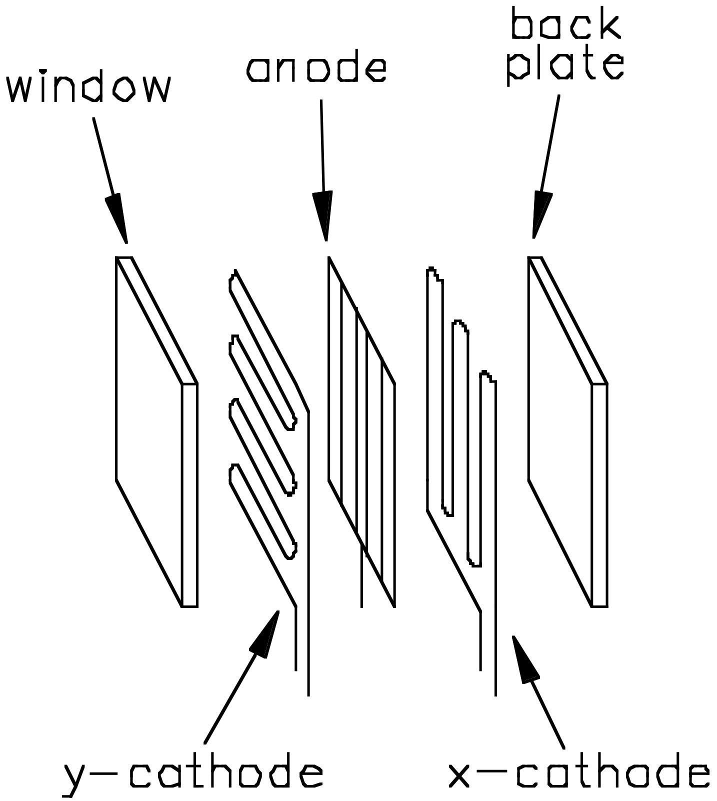
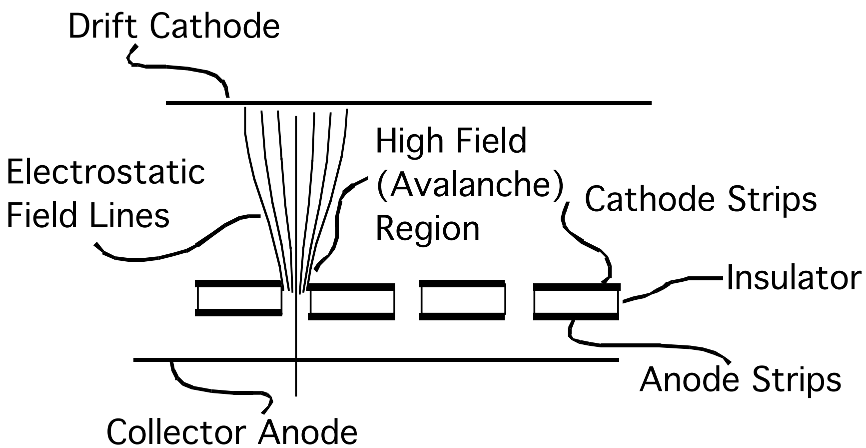


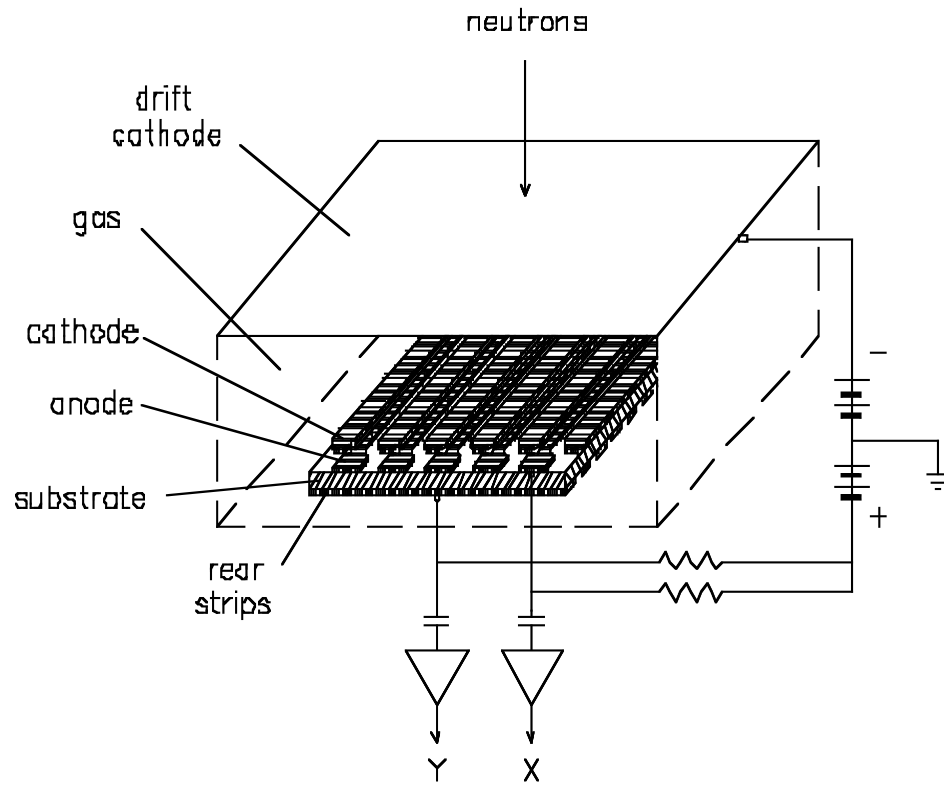
Micro-Strip Gas Counter



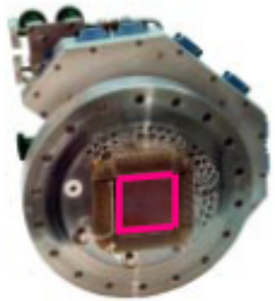
Electrodes printed lithographically, producing accurate, small features.

Implies

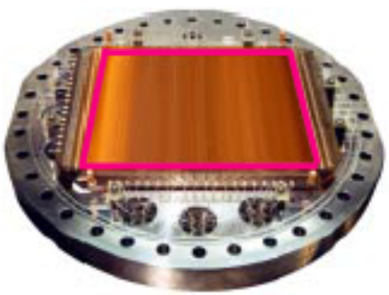
- High spatial resolution.
- High field gradients.
- Charge localization.
- Fast recovery.



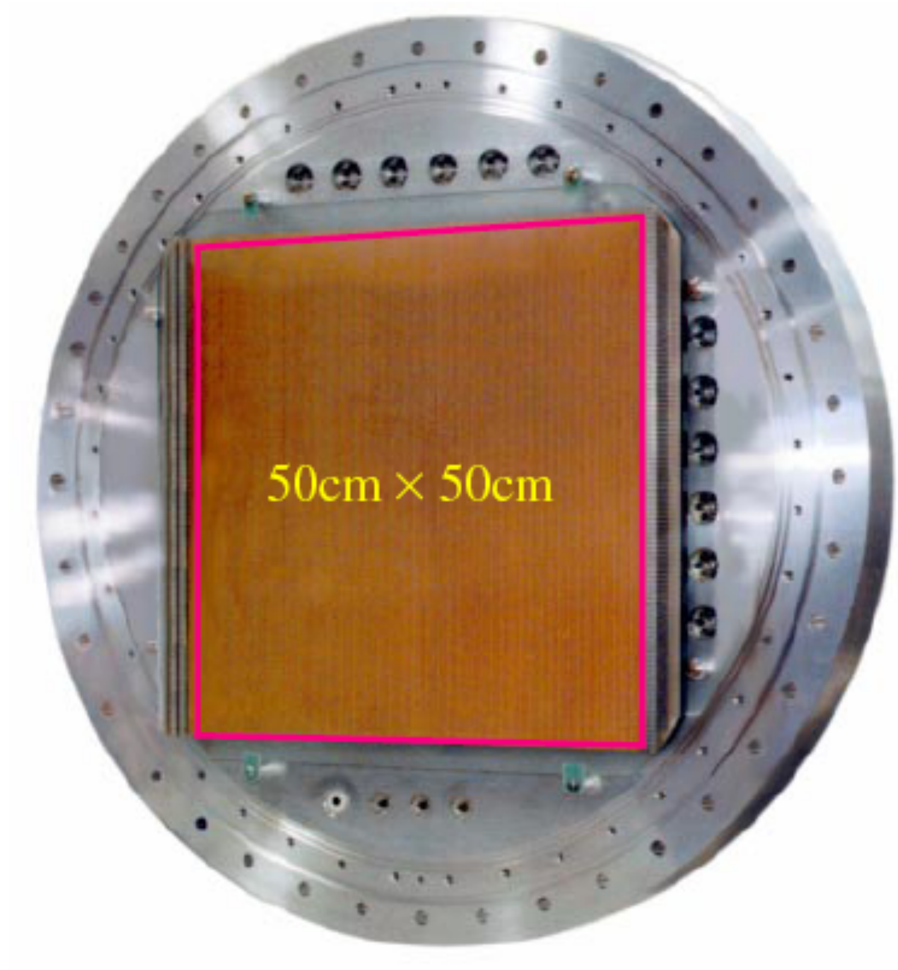
Brookhaven MWPCs



5cm × 5cm



20cm × 20cm



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 = 2.7×10^{19} cm^{-3} per atm for a gas at 300 K.

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

Efficiency of Detectors

The efficiency is easy to compute in a planar detector, but more complicated in a cylindrical one:

$$\eta(\lambda) = 1 - \frac{1}{R}\int_0^R e^{-2\Sigma\sqrt{R^2 - x^2}}dx$$

Here, R is the radius of the detector and $\Sigma(\lambda)$ is the macroscopic capture cross section of the fill gas.

Expanding the exponential in a power series gives

$$\eta(\lambda) = \sum_{n=1}^{\infty} \frac{(-x)^{n+1}}{n!} Z_n$$

where $x = \Sigma(\lambda)R$ and $Z_n = \frac{\sqrt{\pi}}{2}\frac{\Gamma\left(\frac{n}{2}+1\right)}{\Gamma\left(\frac{n}{2}+\frac{3}{2}\right)}$.

Spatial Resolution of Proportional Counters

Spatial resolution (how well the detector tells the location of an event) is always limited by the charged-particle range and by the range of neutrons in the fill gas, which depend on the pressure and composition of the fill gas.

And also limited by the geometry:

Simple PCs: dx ~ diameter; 6 mm - 50 m*m.*

LPSDs: dx ~ diameter, dz ~ diameter ; 6 mm - 50 mm.

MWPC: dx and dy ~ wire spacing; 1 mm - 10 mm.

And also by statistics; the number of charges collected. In PCs, the number is usually so large that this is insignificant.

Time Resolution of Detectors

The time resolution, that is, the variance of the time of arrival of a neutron compared to the time that it passes its mean distance, is

$$s_t^2 = [\langle t^2\rangle - \langle t\rangle^2] = [\langle x^2\rangle - \langle x\rangle^2]/v^2 = s_x^2 / v^2.$$

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

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

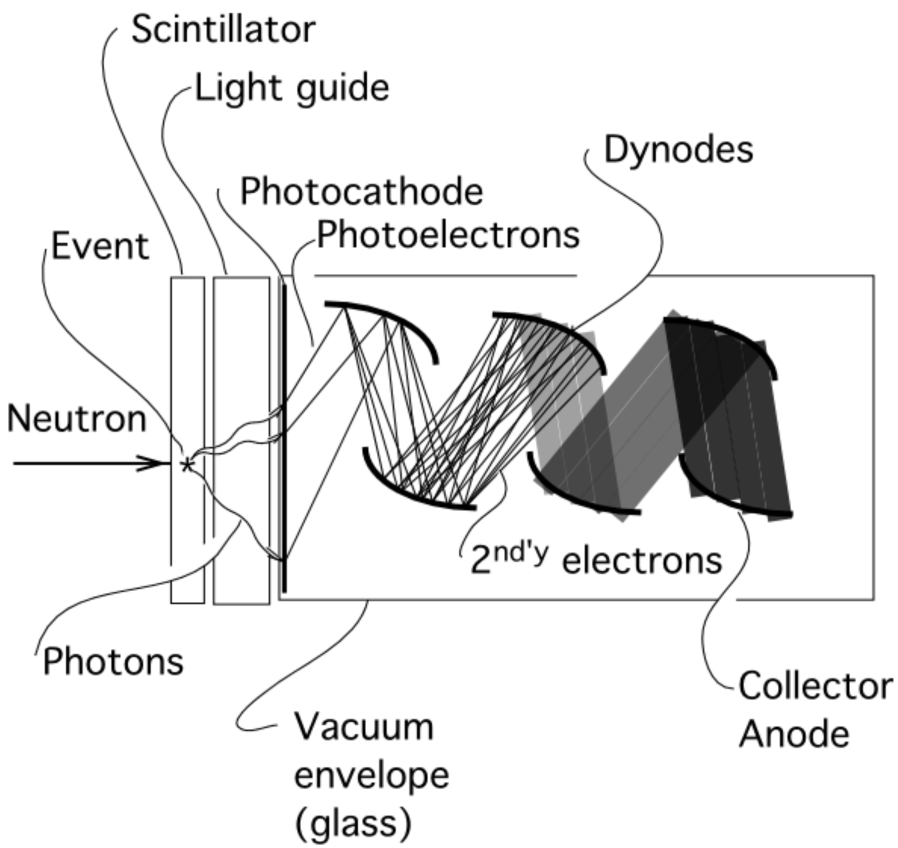
Time Resolution of Detectors

The time resolution depends entirely on the geometric part s_x^2, but because s_x^2 depends on (v) in a more-or-less complicated way, s_t^2 also depends on the speed.

However, for infinitely thick detectors, the time resolution is constant and is equal to the lifetime of neutrons in the medium,

$$1/[v\, s\mathit{Sigma}(v)] = 1/[v_o \mathit{Sigma}(v_o)].$$

Scintillation Detectors



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

$$\sigma = 940 \frac{\lambda}{1.8}\ \text{barns}$$

Some Common Scintillators for Neutron Detectors

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.

Some Common Scintillators for Neutron Detectors (Continued)

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

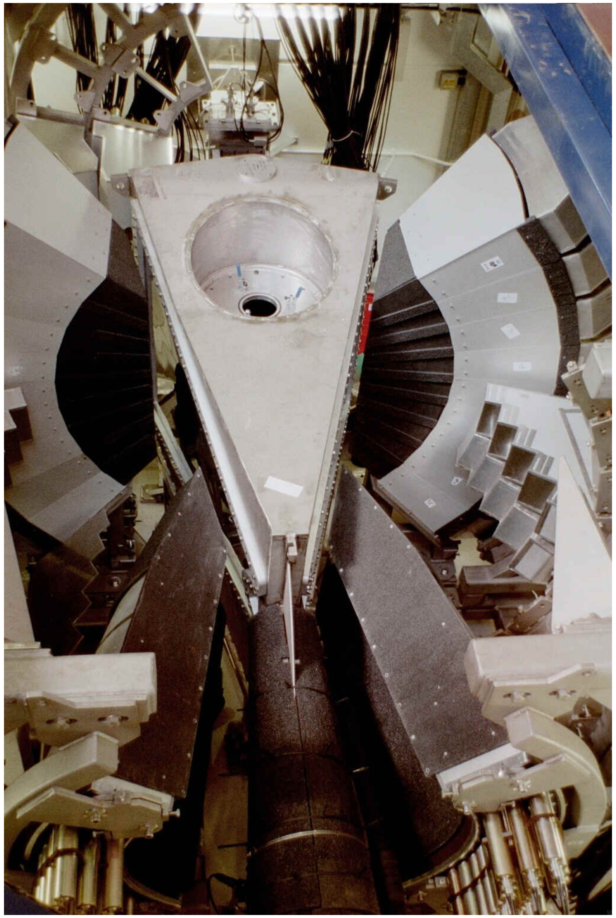
$Li_6Gd(BO_3)_3$ (Ce^{3+}) (including ^{158}Gd and ^{160}Gd, ^{6}Li ,and ^{11}B rare because ^{158}Gd and ^{160}Gd are rare.), and $^{6}LiF(Eu)$ are intrinsic scintillators that contain high proportions of converter material and are typically transparent.

An efficient gamma ray detector with little sensitivity to neutrons, used in conjunction with neutron capture gamma-ray converters, is YAP (yttrium aluminum perovskite, $YAl_2O_3(Ce^{3+})$).

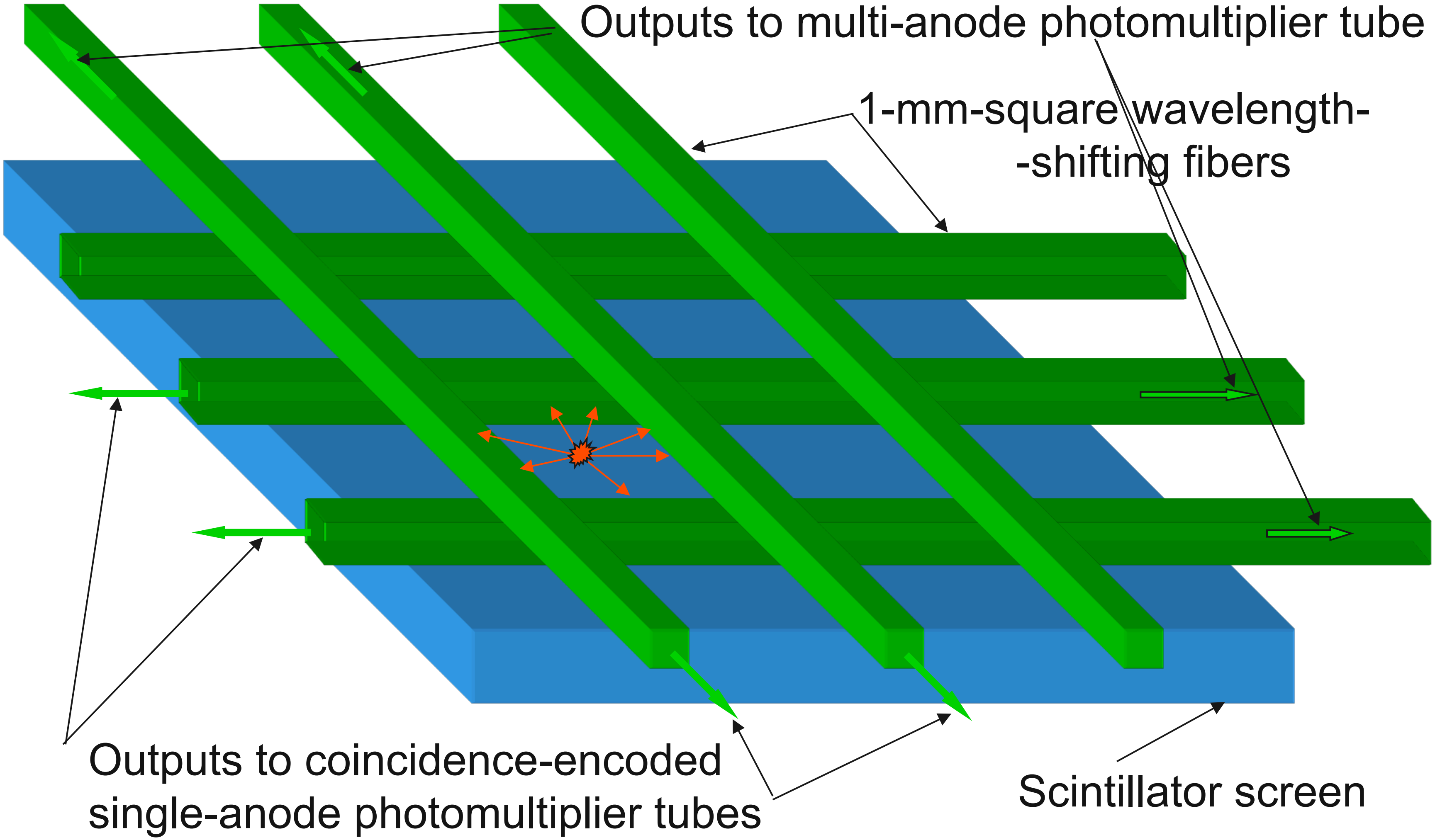
Some Common Scintillators for Neutron Detectors

Material	Density of ^{6}Li atoms (cm^{-3})	Scintillation efficiency	Photon wavelength (nm)	Photons per neutron
Li glass (Ce)	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

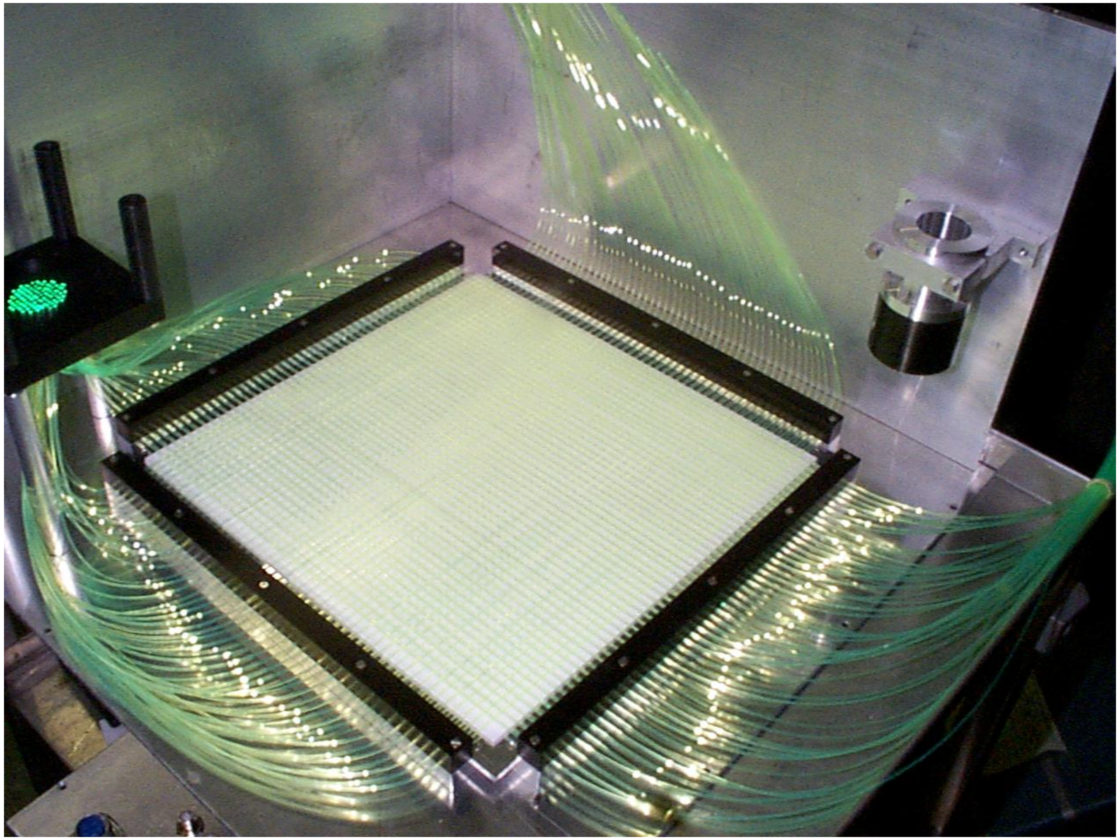
GEM Detector Module (ISIS)



Principle of Crossed-Fiber Position-Sensitive Scintillation Detector



SNS 2-D Scintillation Detector Module



Scintillator plate with all fibers installed and connected to multi-anode photomultiplier mount.

Coincidence Encoding

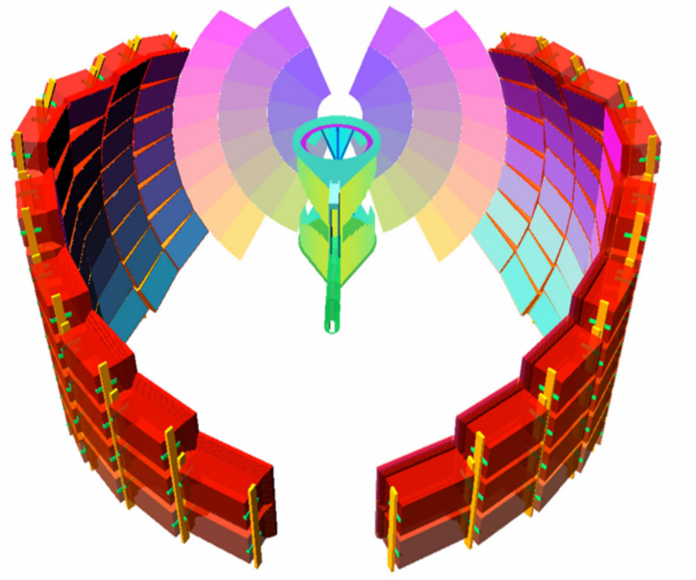
Several optical fibers attached to each scintillator tile lead to a group of photosensors. Each sensor is attached to several distinct scintillation tiles. The pattern of attachments uniquely relates pairs or higher multiples of light sensors to each individual tile.

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,

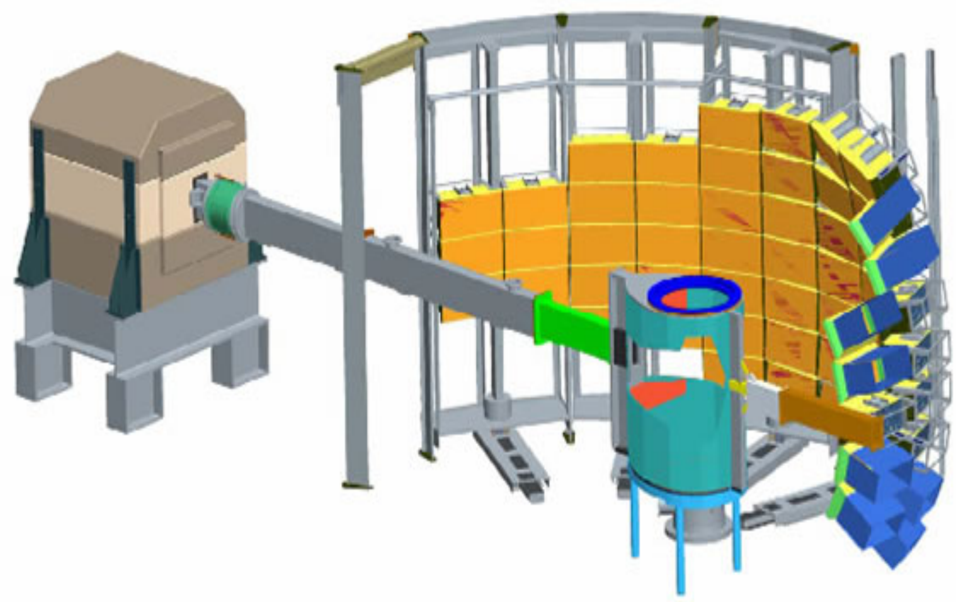
$$N_t = N_s! / [(N_s - 2)!2!].$$

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

POWGEN Powder Diffractometer at SNS (~ 40 m^2 when complete)



Looking into the Instrument from upstream



Neutron beam comes from the upper left

Spatial Resolution of Area Scintillation Detectors

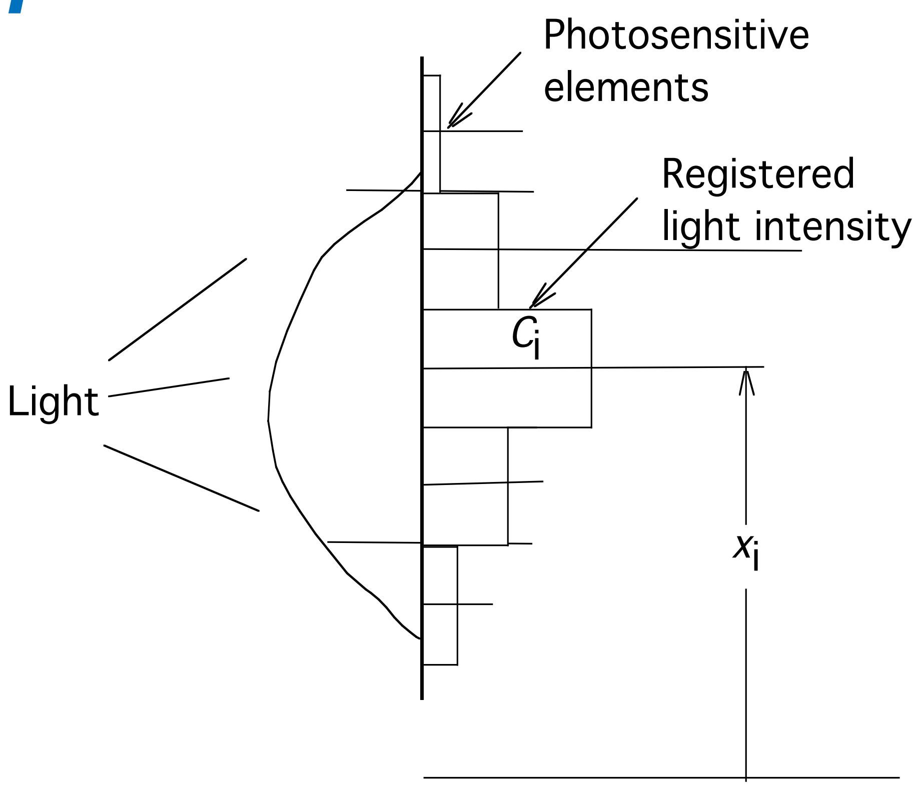
The spatial resolution accomplishable in SDs is typically better than in gas detectors. The range of neutrons is smaller and the range of ionizing particles is smaller in solid materials than in gases.

However, the localization of the light source (an optical process) imposes the limit on position resolution. This in turn depends statistically on the number of photons produced in the scintillator (more is better, of course, and usually is the limiting factor in determining position resolution).

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

$$\langle x \rangle = \frac{\sum_i x_i C_i}{\sum_i C_i} \ .$$

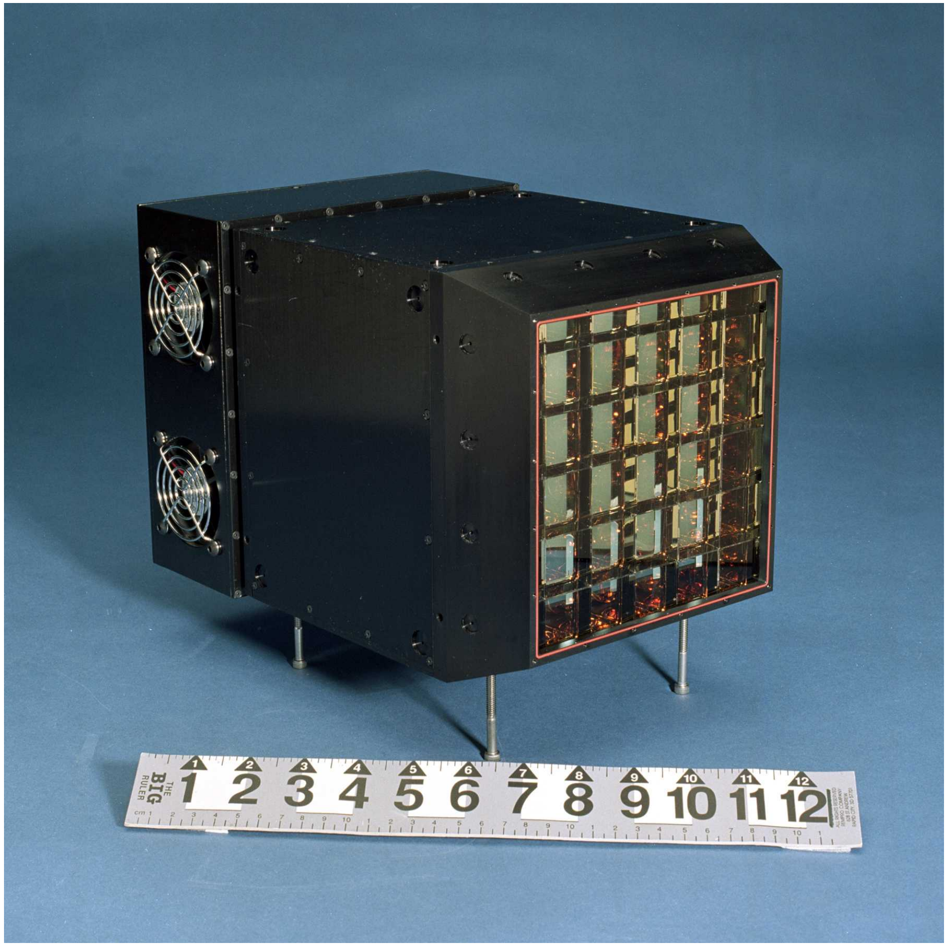


The result is an electronic signal that is binned more finely than the size of the photosensitive elements, with a precision limited by the number of photons collected as C_i.

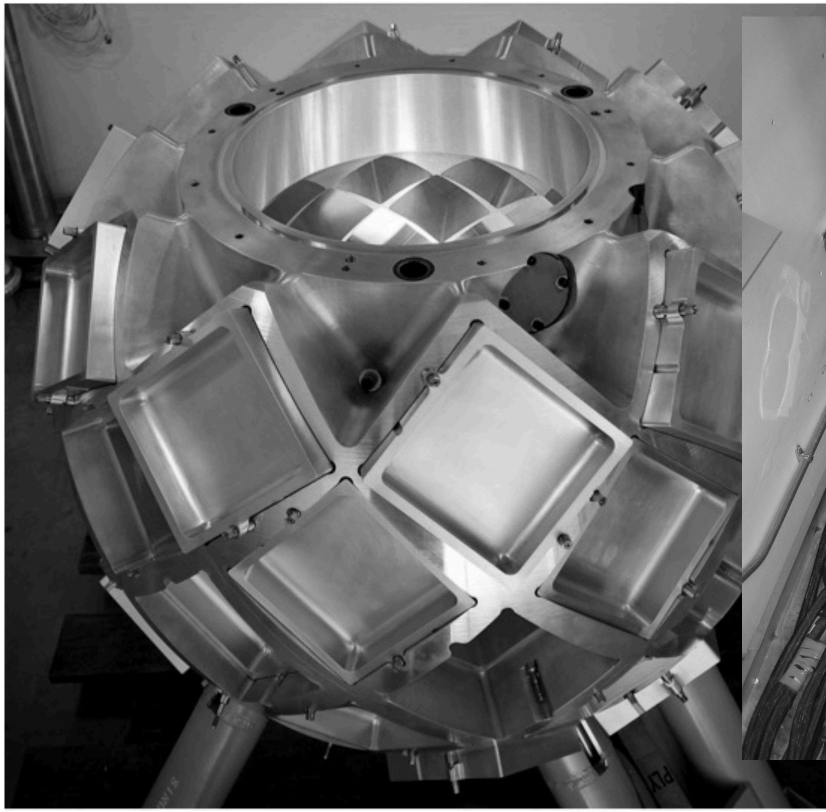
The process is actually carried out in two dimensions.

Anger Camera for the IPNS Single-Crystal Diffractometer at IPNS

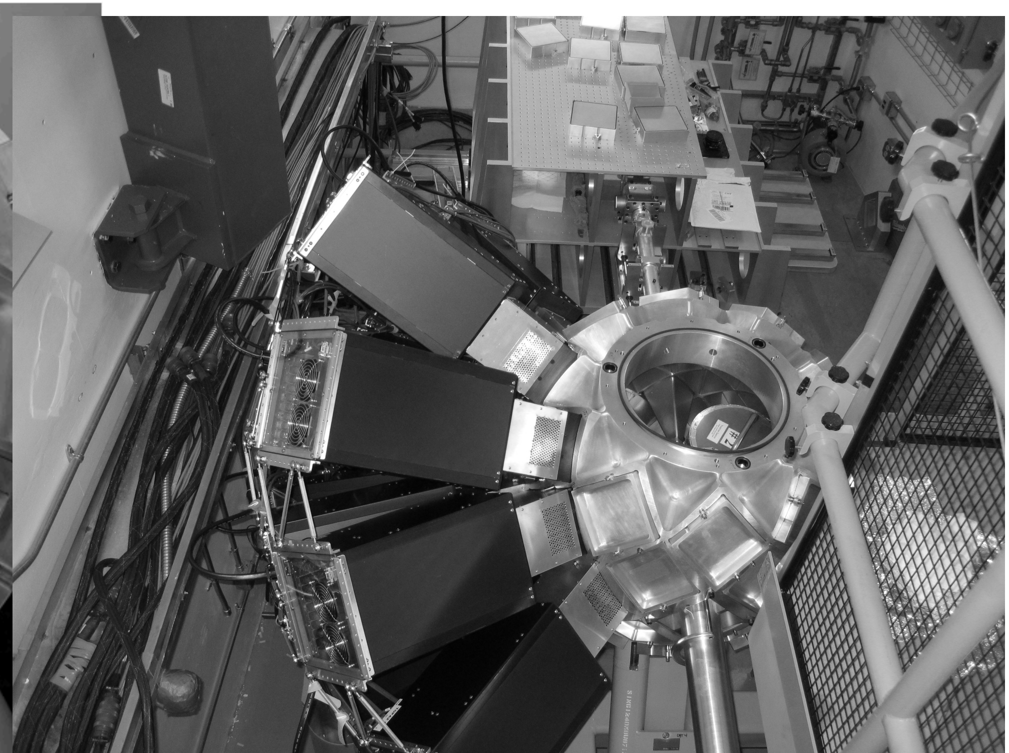
The photomultipliers are nominally 1 inch square. Scale is in inches.



TOPAZ Single Crystal Diffractometer at SNS

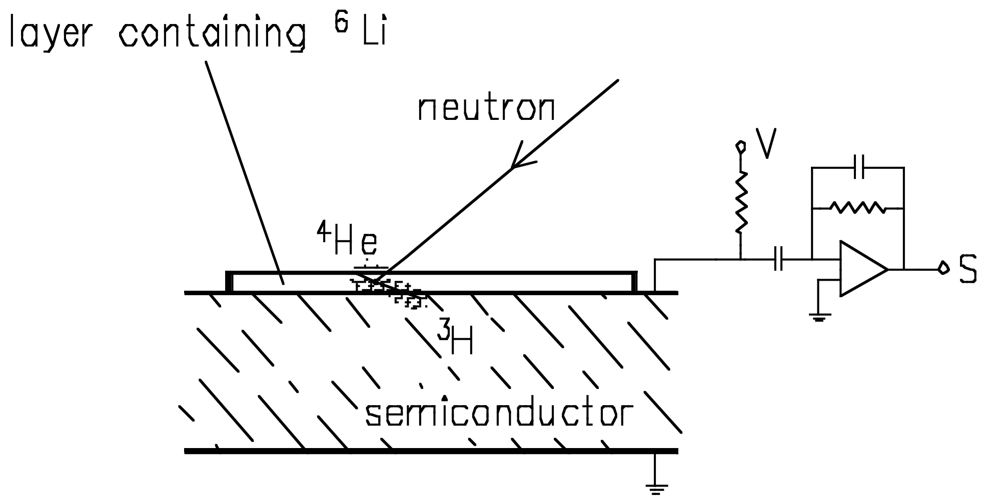


Looking down into the sample chamber



TOPAZ detector array with 14 Anger cameras mounted on the sample chamber

Coating with Neutron Absorber-Surface-Barrier Detectors



The sensitive layer (^{6}Li or ^{10}B) must be thin (a few microns) for charged particles to reach the detector.

- Detection efficiency is low.

Most of the deposited energy doesn't reach detector.

- Poor pulse-height discrimination.

Image Plates or Imaging Plates

Neutron-sensitive image plates (IPs) are relatively new on the scene. The converter is gadolinium, in which the capturing isotopes are ^{155}Gd and ^{157}Gd, which have huge low-energy cross sections because of resonances at about 100 meV.

At higher energies, the cross sections fall off from their low-energy resonance values, so IPs are mostly useful for slow neutrons.

Sensitivity returns at eV energies because of capture resonances there.

Image Plates

Neutron capture produces prompt “conversion electrons” of rather low energy, ~ 70 keV, as well as a cascade of higher energy gamma rays. These have short range in the medium.

The image plate consists of finely mixed particles of converter, Gd_2O_3, with “storage phosphors” such as $BaFBr:Eu^{2+}$ having long-lived light-emitting states that are excited by the 70-keV electrons, bonded and supported by a flexible polymer sheet.

IPs are time-integrating detectors, providing no useful timing signals. Moreover, they are slightly sensitive to gamma rays.

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.

Very Intense Vertical Axis Laue Diffractometer VIVALDI at ILL

A large cylindrical neutron image plate detector surrounds the sample.

A built-in image plate reader scans and records the Laue spots.

Hand-Held Neutron Monitor

CCD Neutron Camera

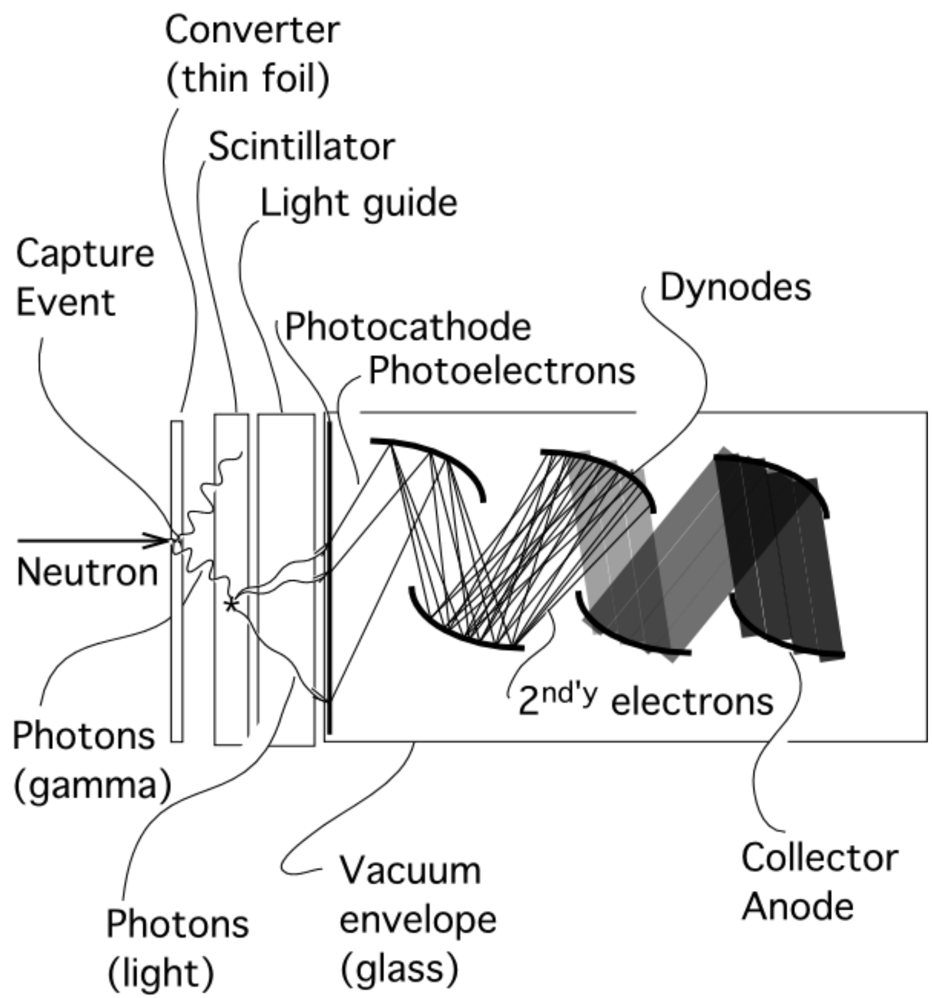
Resonance Capture Gamma-Ray Neutron Detectors

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).

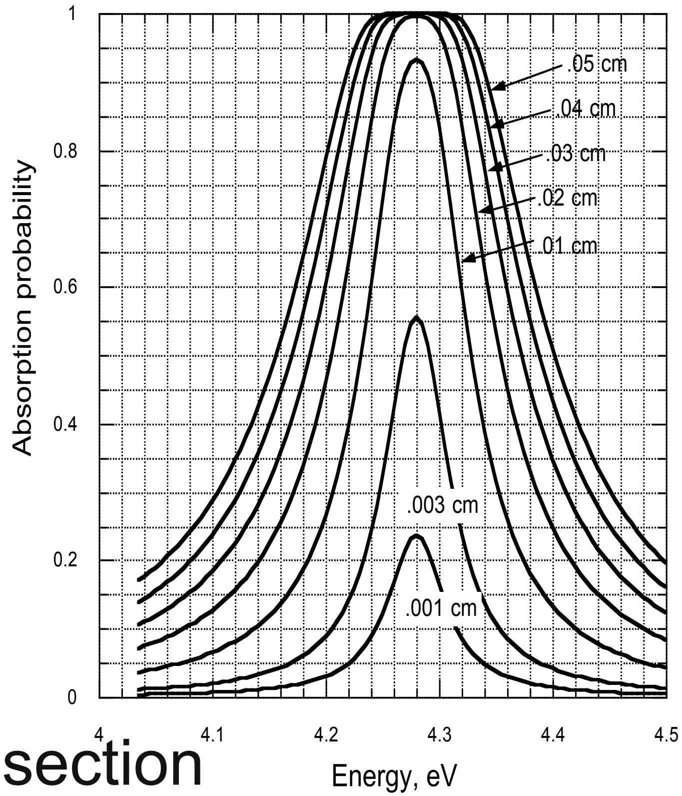
Capture Gamma-ray Detector



Resonance Neutron Detectors

In application, resonance absorption in a slab of material is further broadened by self-shielding effects. If the slab thickness is d, the transmission probability is

$$T(E) = \exp(-n\sigma(E)d).$$



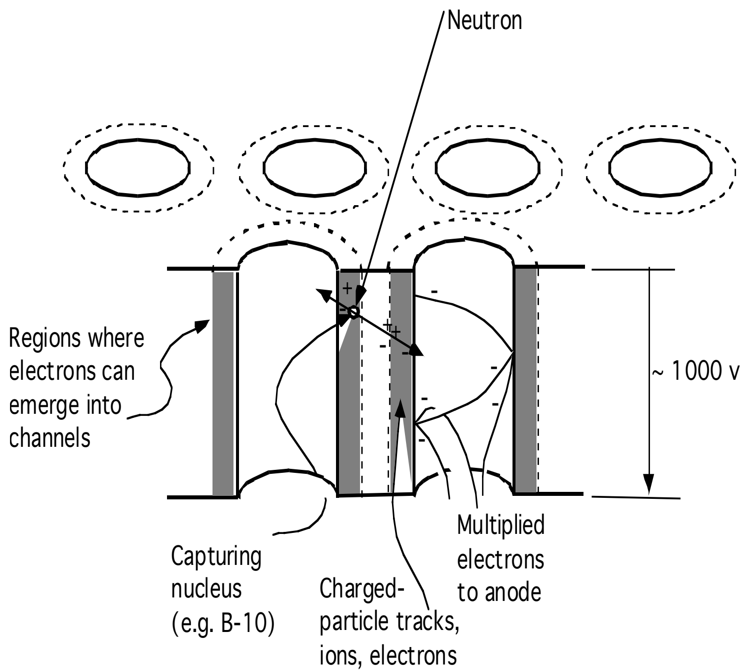
This is flatter on top and relatively higher in the wings than the cross section itself. This makes it profitable to take differences between spectra recorded with different absorber thicknesses, eliminating the wings and leaving a sharp response.

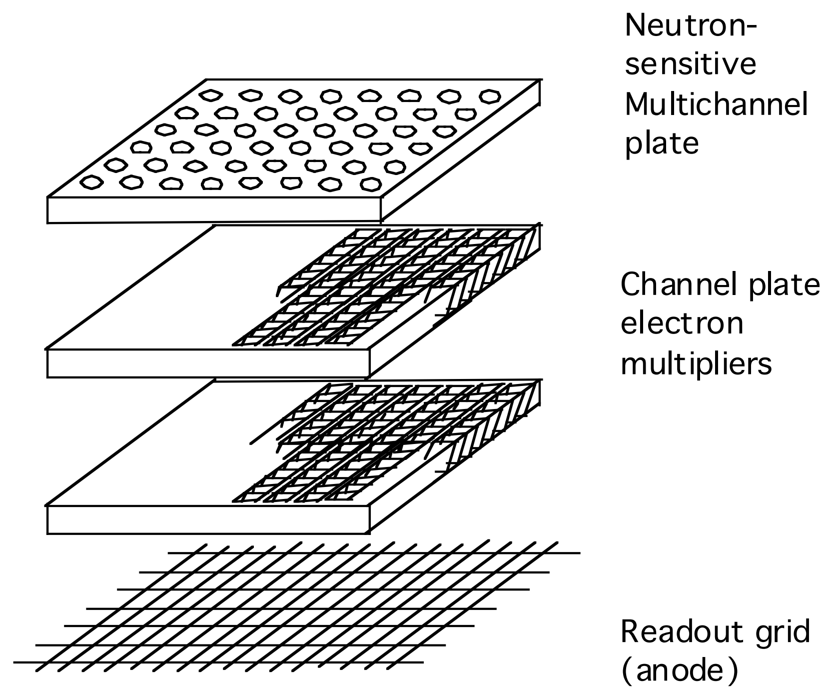
Microchannel Neutron Detectors

Microchannel amplifier (MCA) plates have had many applications for detecting photons and energetic ions with precise spatial resolution, fast response, and in compact size. MCAs are basically electron multipliers, consisting of plates of closely packed arrays of evacuated narrow channels coated with secondary-electron emitting material,

Workers have adapted MCAs to detecting neutrons with the same advantages, for example, incorporated into the neutron hand monitor.

Microchannel Neutron Detectors





Microchannel Neutron Detectors

As neutron detectors, neutron-absorbing material (^{6}Li, ^{10}B, Cd, Gd) incorporated in the channel material (glass or silicon) produces charged particles. If this occurs close enough to the channel wall, they produce electrons that are accelerated and multiplied in the channel. After several stages, these fall onto and register on a position sensitive anode.

Position resolution can be as good as 100 microns
but efficiency is low, ~10-20%

Summary

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

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.
- Spatial resolution.

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, to reduce the demands for that purpose.

We should devote strong efforts to develop non-^{3}He detectors suited to our applications, to reduce our dependence on ^{3}He.

End of Presentation

Thank you!