Detectors for Slow Neutrons

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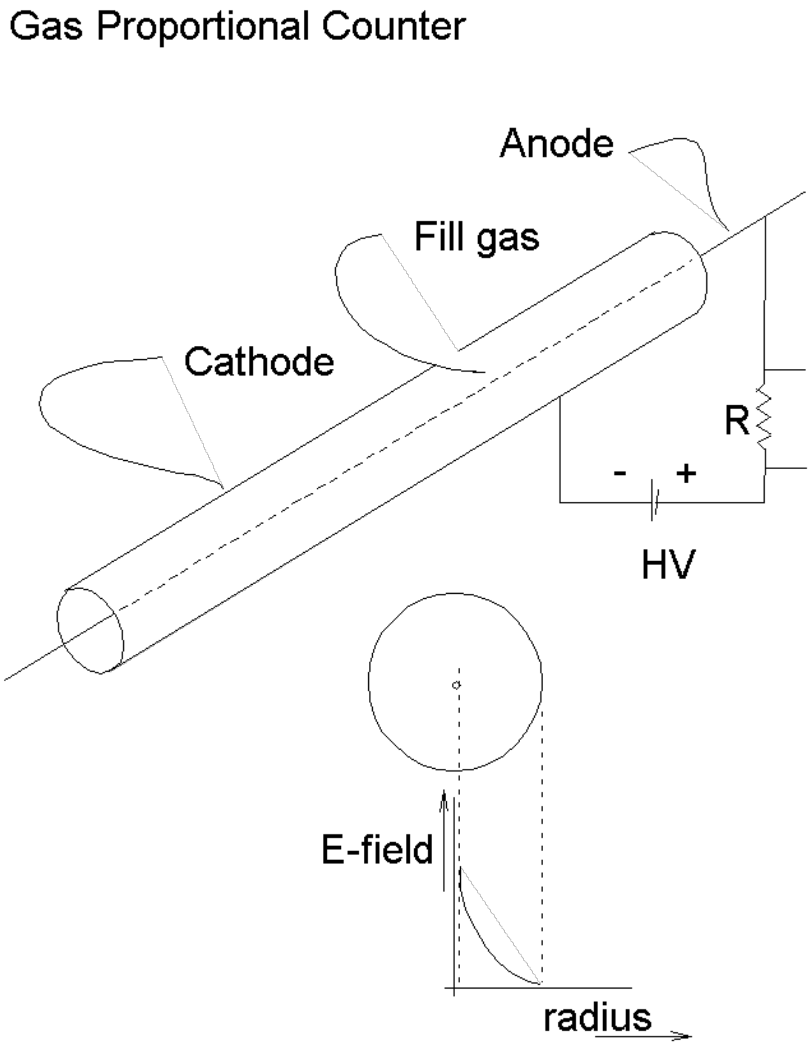
Neutron Detectors

- How does one “detect” a neutron?
  - Can’t directly detect slow neutrons (neutrons relevant to materials science, that is)—they carry too little energy
  - Need to produce some sort of measurable quantitative (countable) electrical signal
- Need to use nuclear reactions to convert neutrons into charged particles
- 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 Detectors

- $n + {}^{3}He \rightarrow {}^{3}H + {}^{1}H + 0.764$ 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
- $n + {}^{155}Gd \rightarrow Gd^{*} \rightarrow$ gamma-ray spectrum + conversion electron spectrum (~70 keV)
- $n + {}^{157}Gd \rightarrow Gd^{*} \rightarrow$ gamma-ray spectrum + conversion electron spectrum (~70 keV)
- $n + {}^{235}U \rightarrow$ xn + fission fragments + ~160 MeV (<x> ~ 2.5)
- $n + {}^{239}Pu \rightarrow$ xn + fission fragments + ~160 MeV (<x> ~ 2.5)
- ^{197}Au(4.906 eV), 115In(1.46 eV), ^{181}Ta(4.28 eV), ^{238}U(6.67, 10.25 eV); energy-selective detectors, narrow resonances, prompt capture gamma rays

Gas Detectors



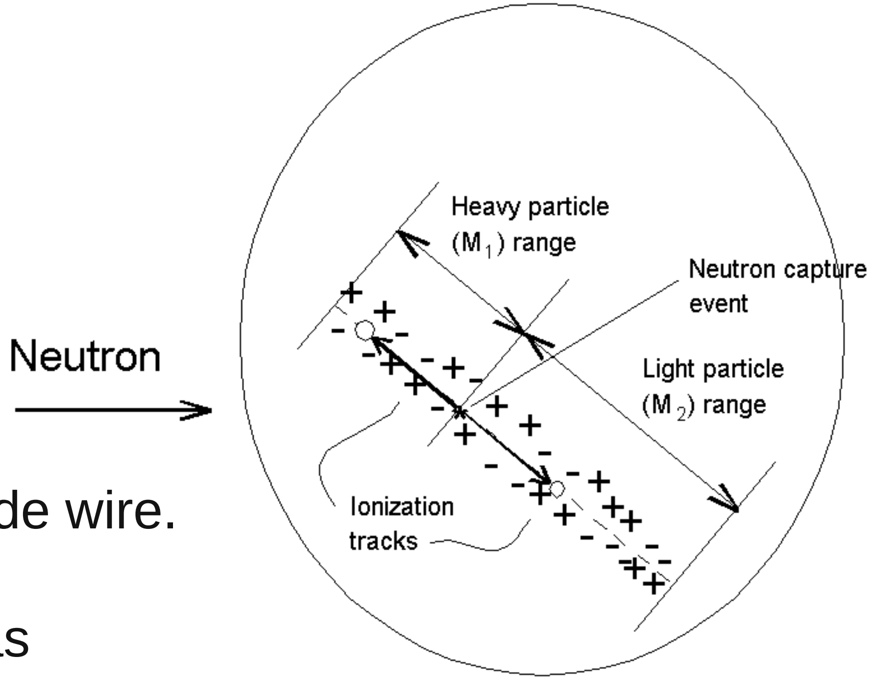
$$n + {}^{3}\mathrm{He} \rightarrow {}^{3}\mathrm{H} + {}^{1}\mathrm{H} + 0.76\ \mathrm{MeV}$$

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

~25,000 ions and electrons (~4´10^{-15} coulomb) produced per neutron

Gas Detectors

Ionization tracks in
proportional counter 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 the number many-fold, about x10^3. Separation of these charges puts a charge on the detector, which is a low-capacitance capacitor, causing a pulse in the voltage that can be amplified and registered electronically.

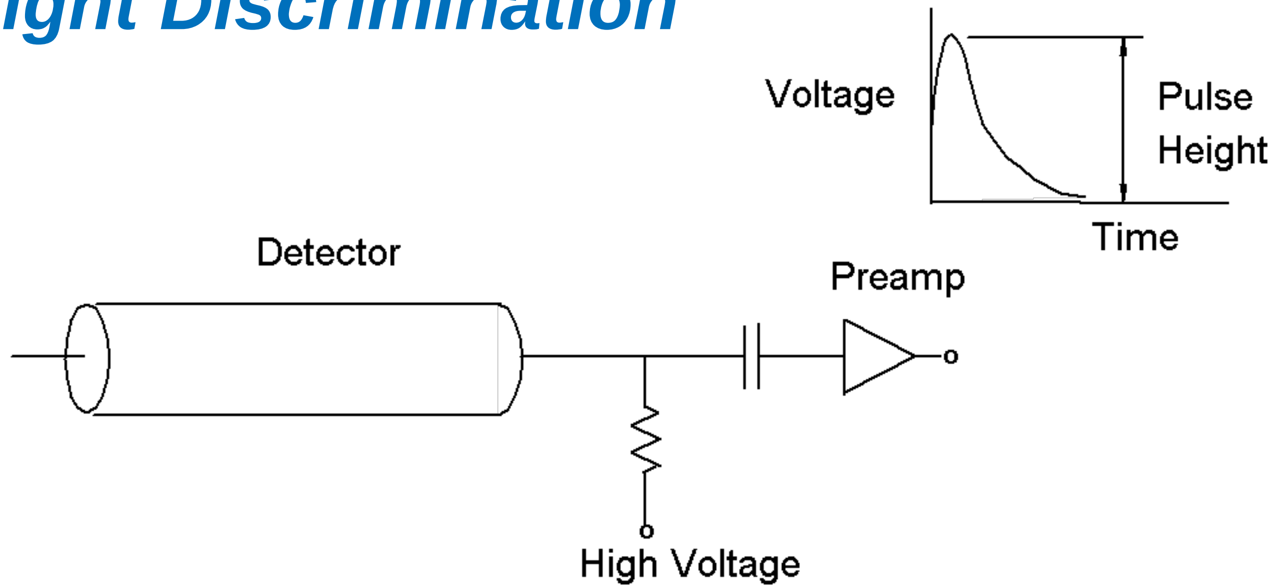
Gas Detectors – cont'd

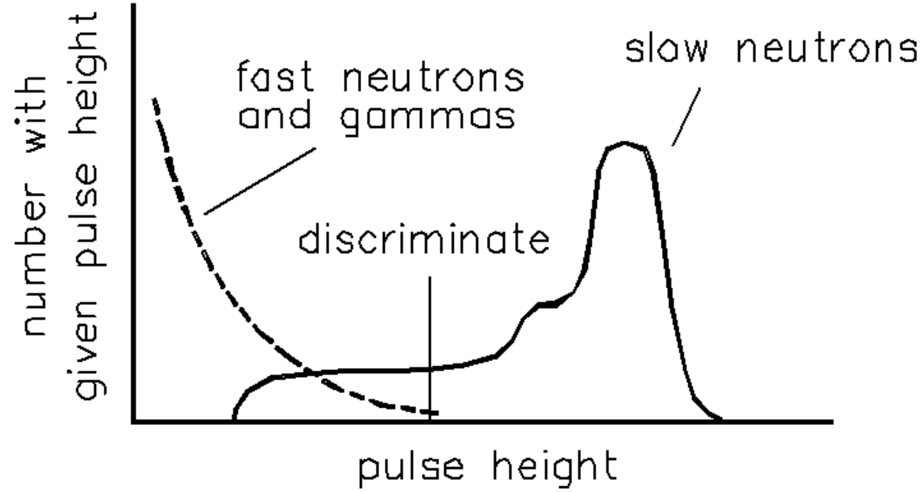
- Proportional counters (PCs) come in a variety of different forms.
- Simple detector (shown previously)
- Linear position-sensitive detector (LPSD):
  - *The anode is resistive, read out from both ends—the charge distributes between the ends according to the position of the neutron capture event in the tube.*
  - *Usually cylindrical.*
- 2-D position-sensitive detector (MWPC).
  - *Many parallel resistive wires extend across a large thick area of fill gas. Each wire operates either as in LPSD or without position information as in a simple PC.*

  or

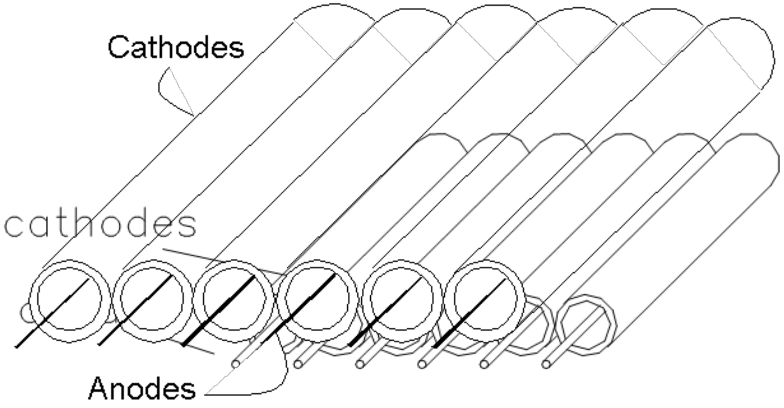
  - *Two mutually perpendicular arrays of anode wires. Each is read separately as an LPSD to give two coordinates for the neutron capture event.*
  - *MWPCs usually have a planar configuration.*

Pulse Height Discrimination

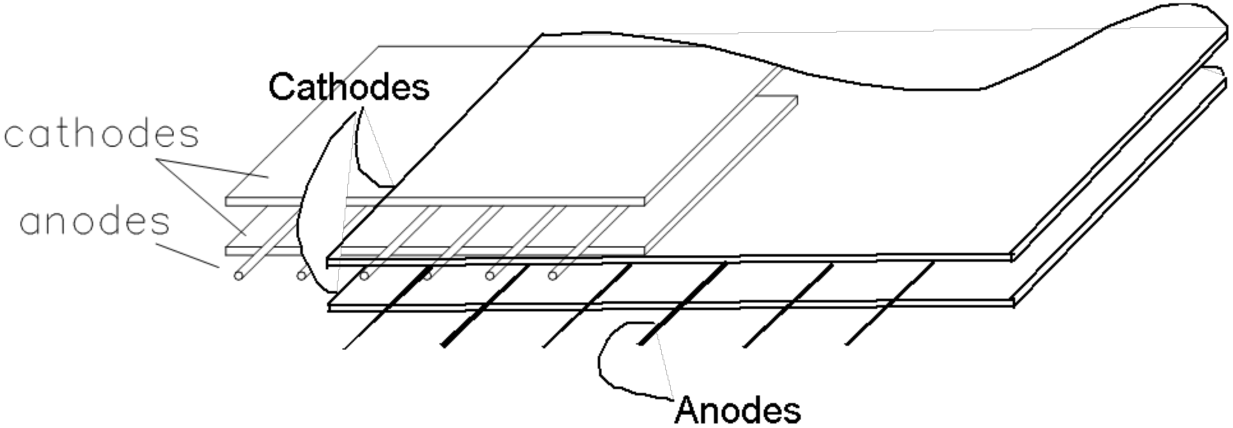




Multi-Wire Proportional Counter



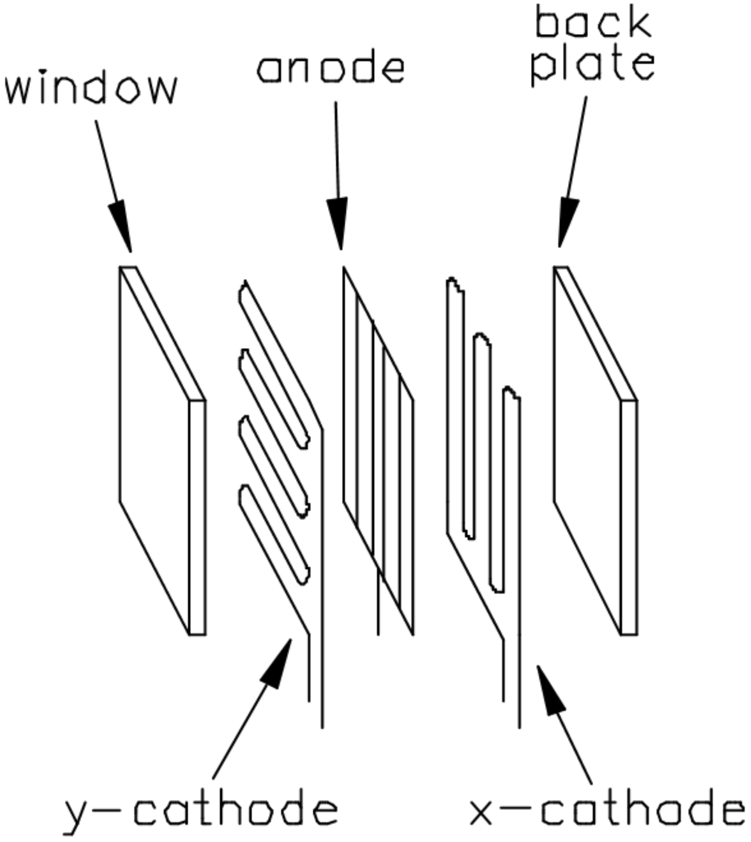
- Array of discrete detectors.



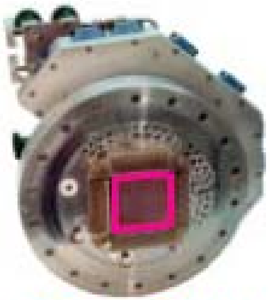
- Remove walls to get multi-wire counter.

Resistive Encoding of a Multi-Wire Detector-cont'd

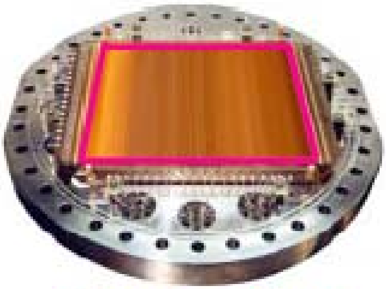
- Position of the event can also be determined from the relative time of arrival of the pulse at the two ends of the resistive network (rise-time encoding).
  - Used on the POSY1, POSY2, SAD, and SAND 2-D PSDs.
- A pressurized gas mixture surrounds the electrodes.



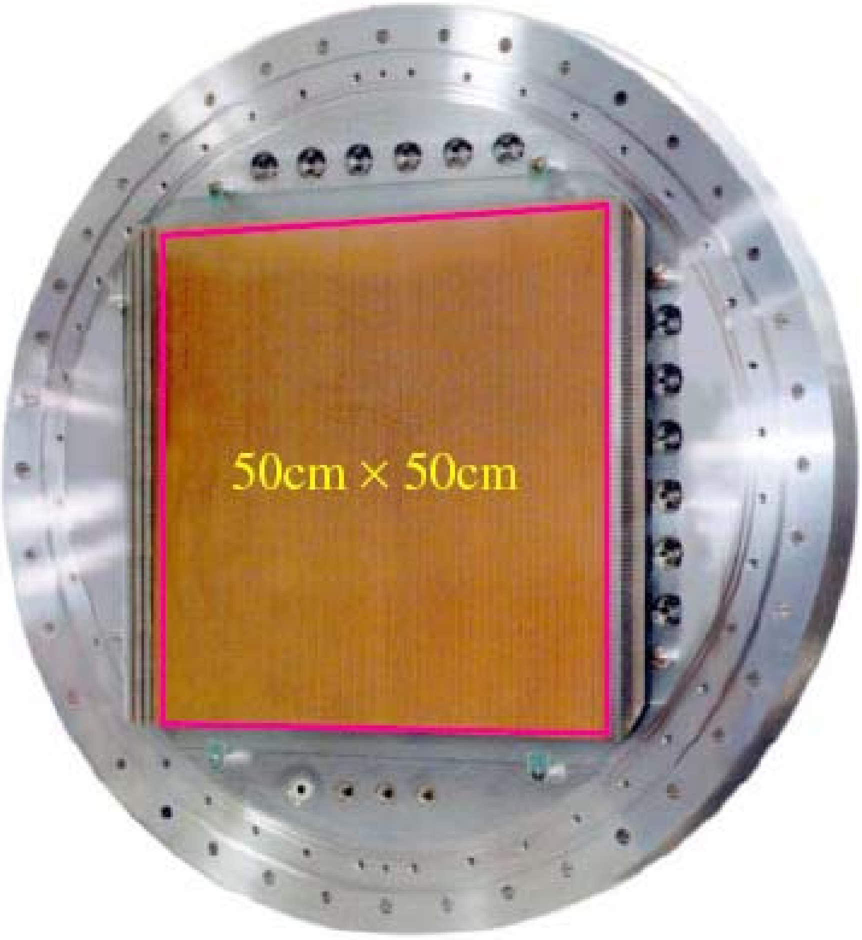
Brookhaven MWPCs



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.

- Full expression: $\varepsilon\phi\phi\psi = 1 - \exp(-N\ \sigma\iota\gamma\mu\alpha\ d)$.
  - Approximate expression for low efficiency:

$$\varepsilon\phi\phi\psi = N\ \sigma\iota\gamma\mu\alpha\ d.$$

  - Here:
    - $\sigma\iota\gamma\mu\alpha$ = absorption cross-section (function of
    - wavelength)

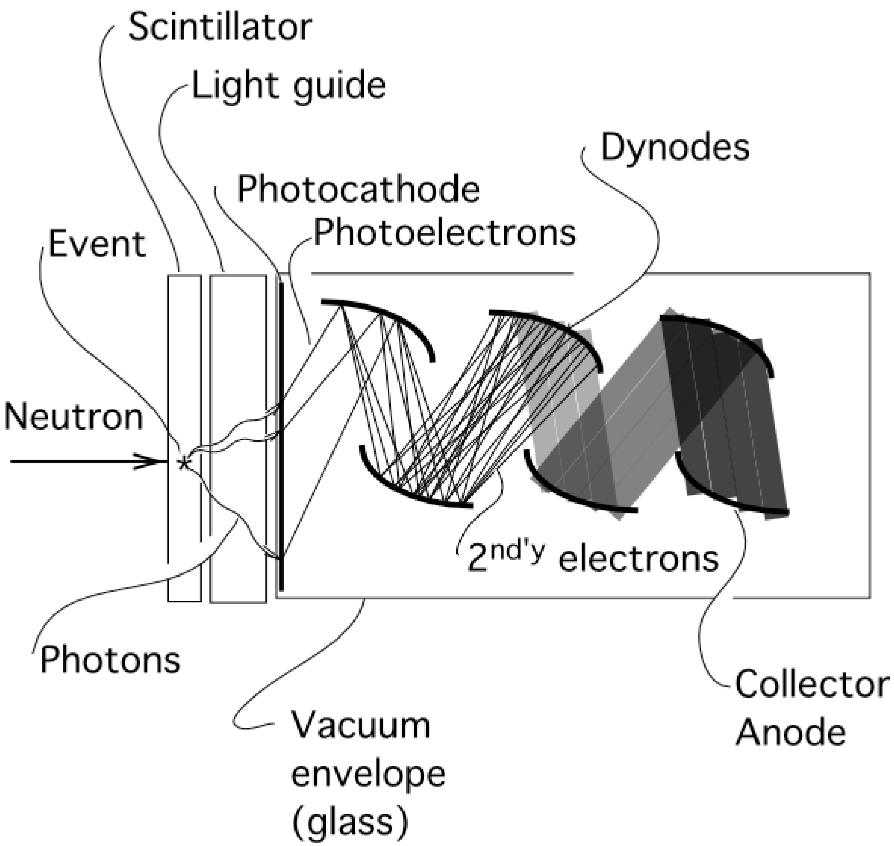
N = number density of absorber

d = thickness

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

- For 1-cm thick ^{3}He at 1 atm and 1.8-Å neutrons, effy = 0.13, so
- pressures are usually ~ 10 atm.

Scintillation Detectors



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

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

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.

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

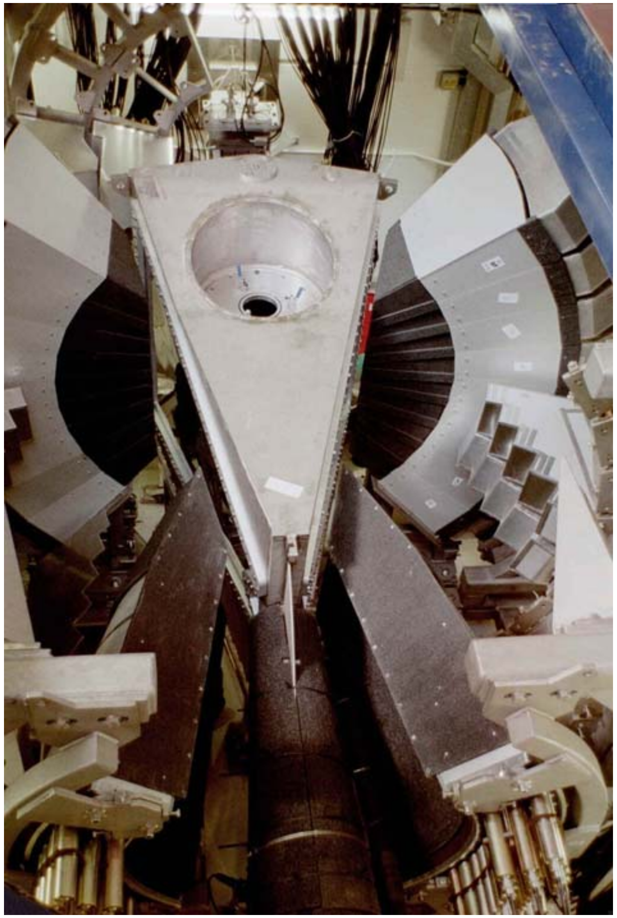
$Li_6Gd(BO_3)_3$ (Ce^{3+}) (including ^{158}Gd and ^{160}Gd, ^6Li ,and ^{11}B), and $^6LiF(Eu)$ are intrinsic scintillators that contain high proportions of converter material and are typically transparent.

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

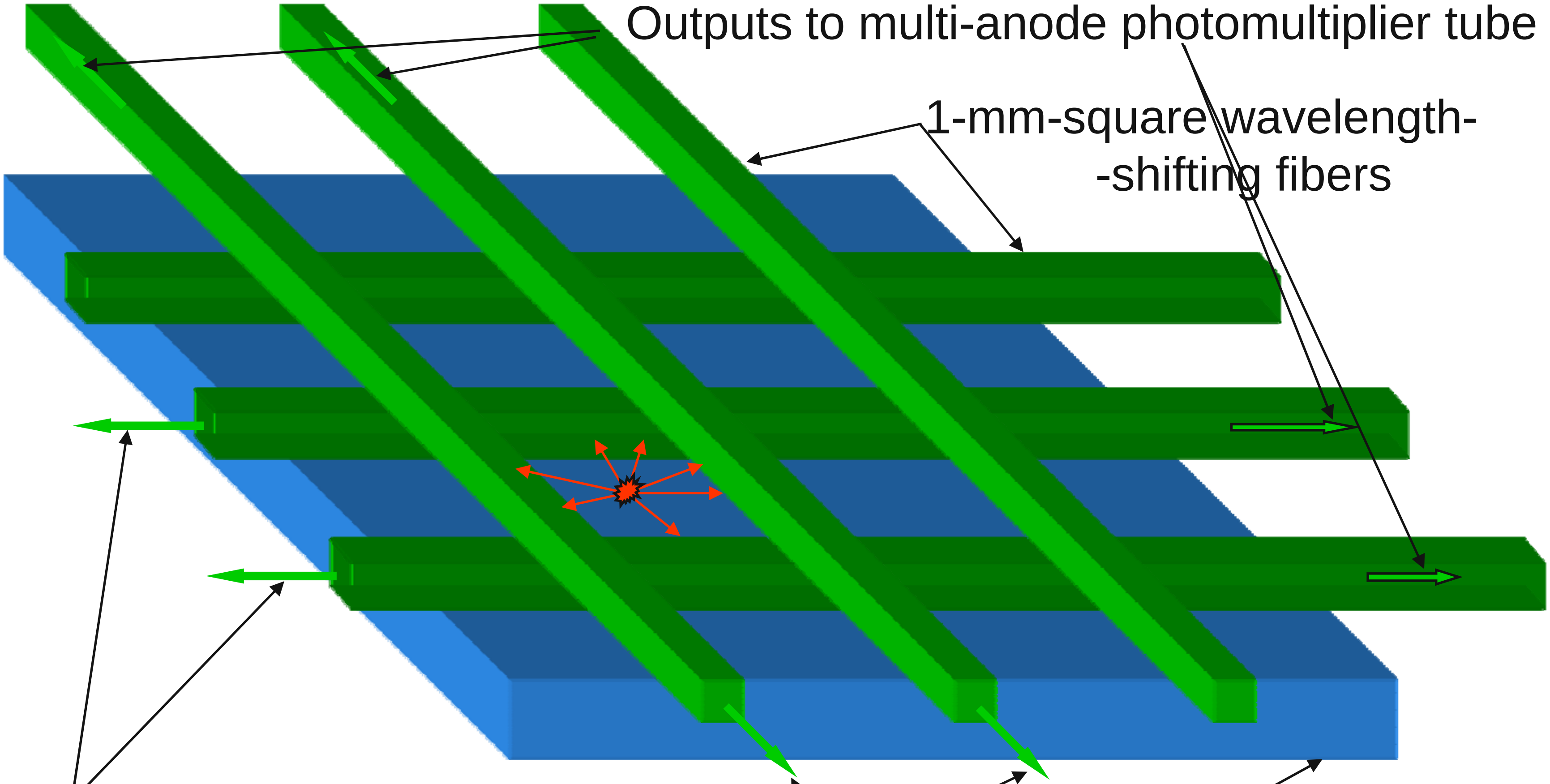
Some Common Scintillators for Neutron Detectors-cont’d

Material	Density of ^{6}Li atoms (cm^{-3})	Scintillation efficiency	Photon wavelength (nm)	Photons per neutron
Li glass (Ce)	$1.75x10^{22}$	0.45 %	395 nm	~7,000
LiI (Eu)	$1.83x10^{22}$	2.8 %	470	~51,000
ZnS (Ag) - LiF	$1.18x10^{22}$	9.2 %	450	~160,000
$Li_6Gd(BO_3)_3$ (Ce),	$3.3x10^{22}$		~ 400	~40,000
YAP	NA		350	~18,000 per MeV γαμμα

GEM Detector Module



Principle of Crossed-Fiber Position-Sensitive Scintillation Detector



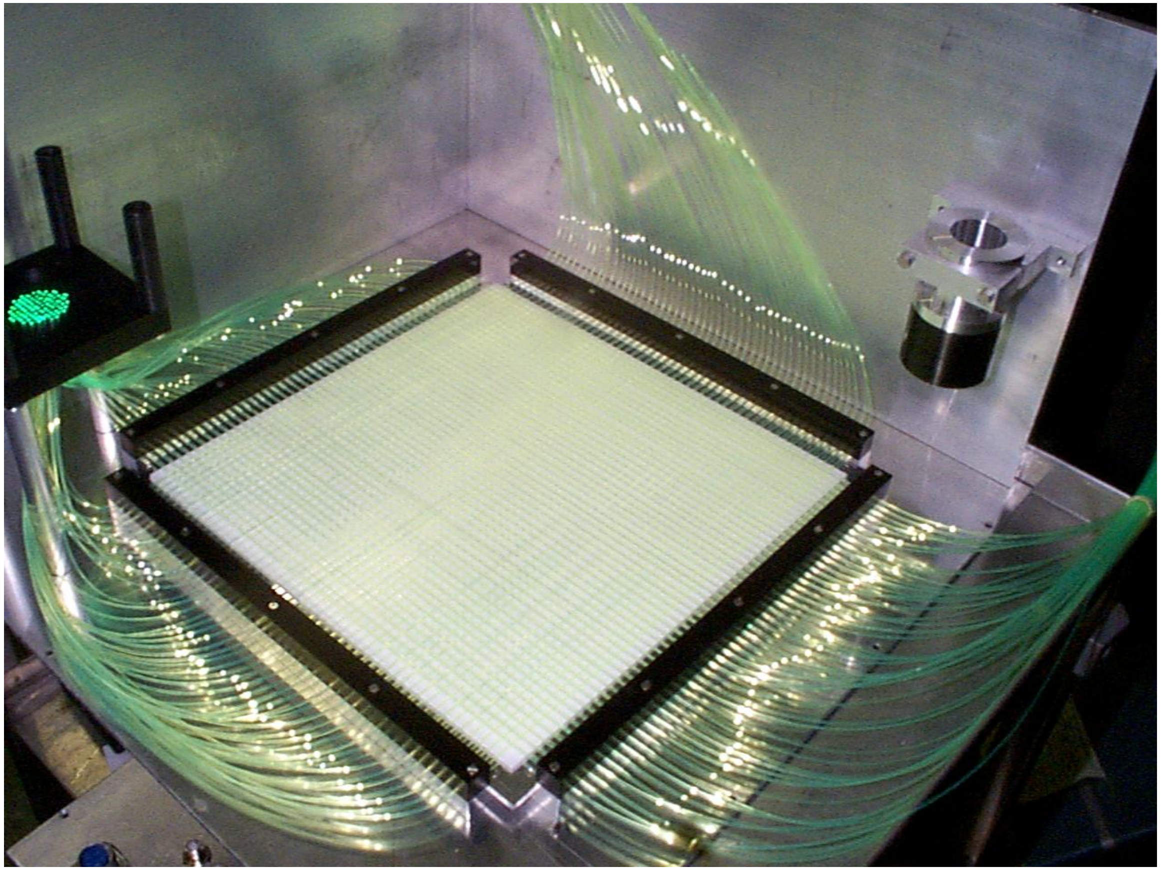
Outputs to multi-anode photomultiplier tube

1-mm-square wavelength-shifting fibers

Outputs to coincidence-encoded single-anode photomultiplier tubes

Scintillator screen

SNS 2-D Scintillation Detector Module

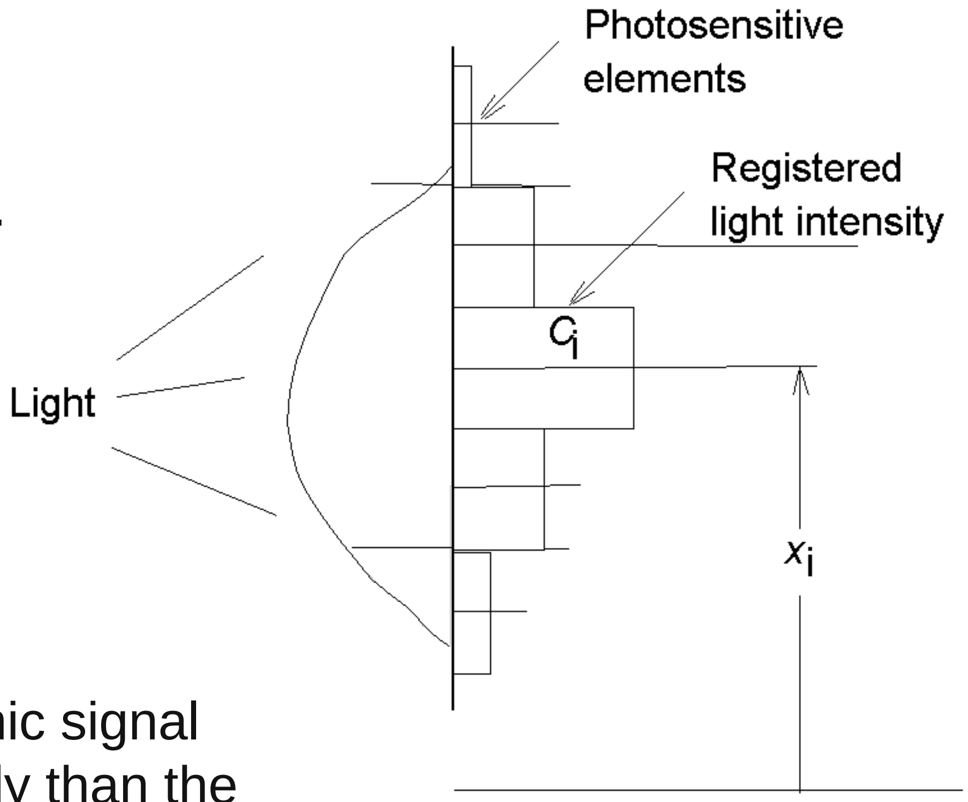


Shows scintillator plate with all fibers installed and connected to multi-anode photomultiplier mount.

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

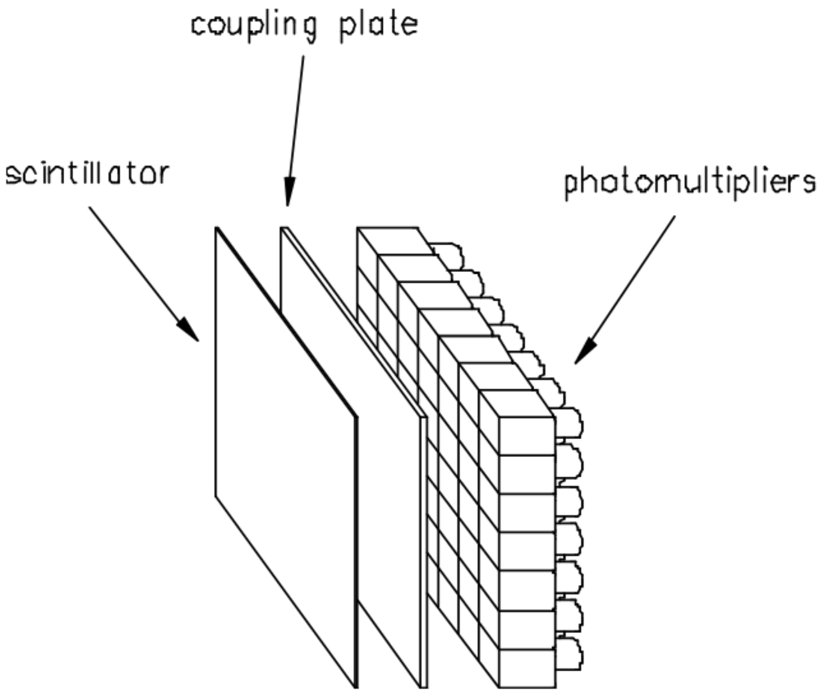
$$\langle x \rangle = \frac{\sum_i x_i C_i}{\sum_i C_i} \; .$$



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.

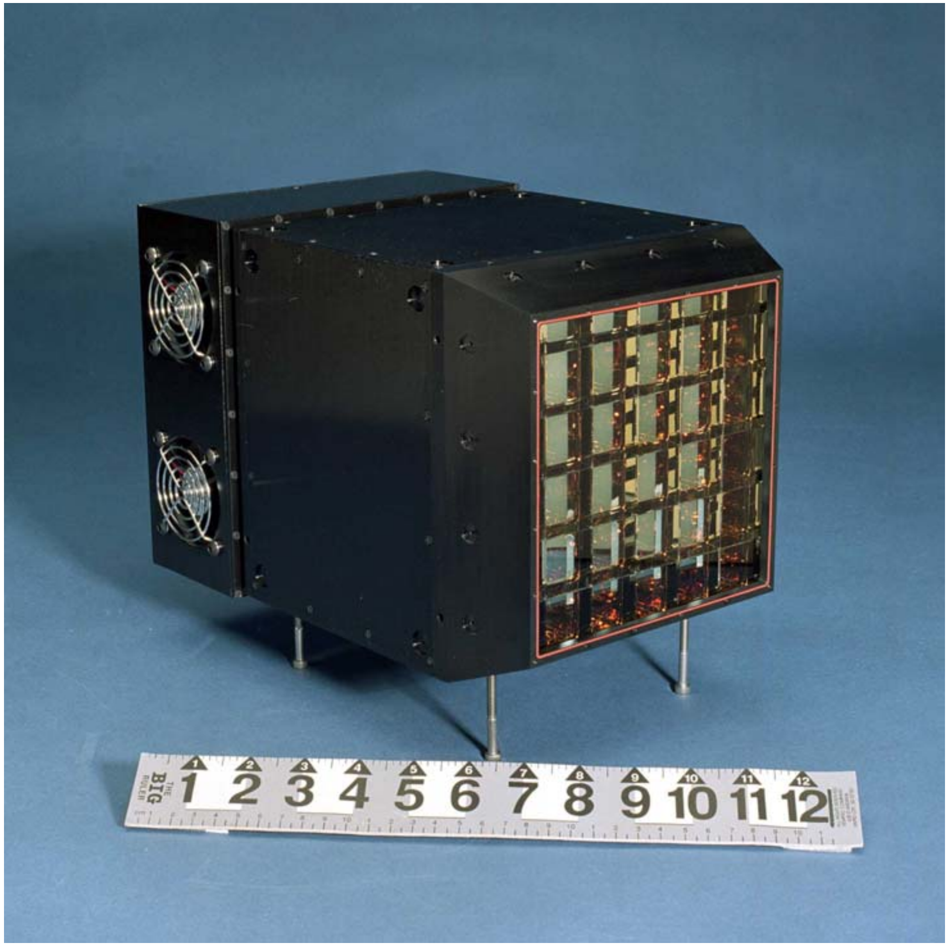
Anger Camera Concept for the Single-Crystal Diffractometer at SNS



- Air gaps and coupling plate thicknesses arranged to limit light spread
- Photomultiplier outputs are resistively encoded to give x and y coordinates.
- Entire assembly is in a light-tight box.

Anger Camera for the IPNS Single-Crystal Diffractometer at IPNS

The photomultipliers are nominally 1 inch square.

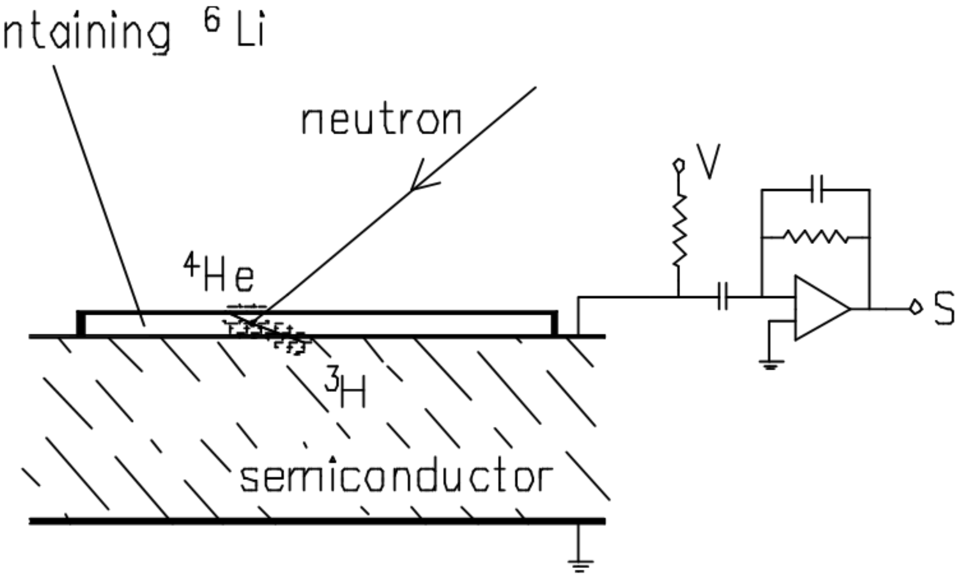


Hamamatsu Multicathode Photomultiplier

Compact photomultipliers are essential components of scintillation area detectors. The figure shows a recently developed multicathode photomultiplier, Hamamatsu model 8500.

256 ch Focusing Type **64 ch Focusing Type**

Coating with Neutron Absorber-Surface-Barrier Detectors



- 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

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.

> Neutron capture produces prompt "conversion electrons" of rather low energy, ~ 70 keV, as well as a cascade of higher energy gamma rays. 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.

Image Plates-cont'd

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 that can be manipulated and displayed in computer-accessible format such as color-contour diagrams of the area density of the neutron capture intensity.

The plates are re-usable after "erasing" by exposure to UV light.

IPs are rather like x-ray film and available in ~ 300 x 400 mm^2 size.

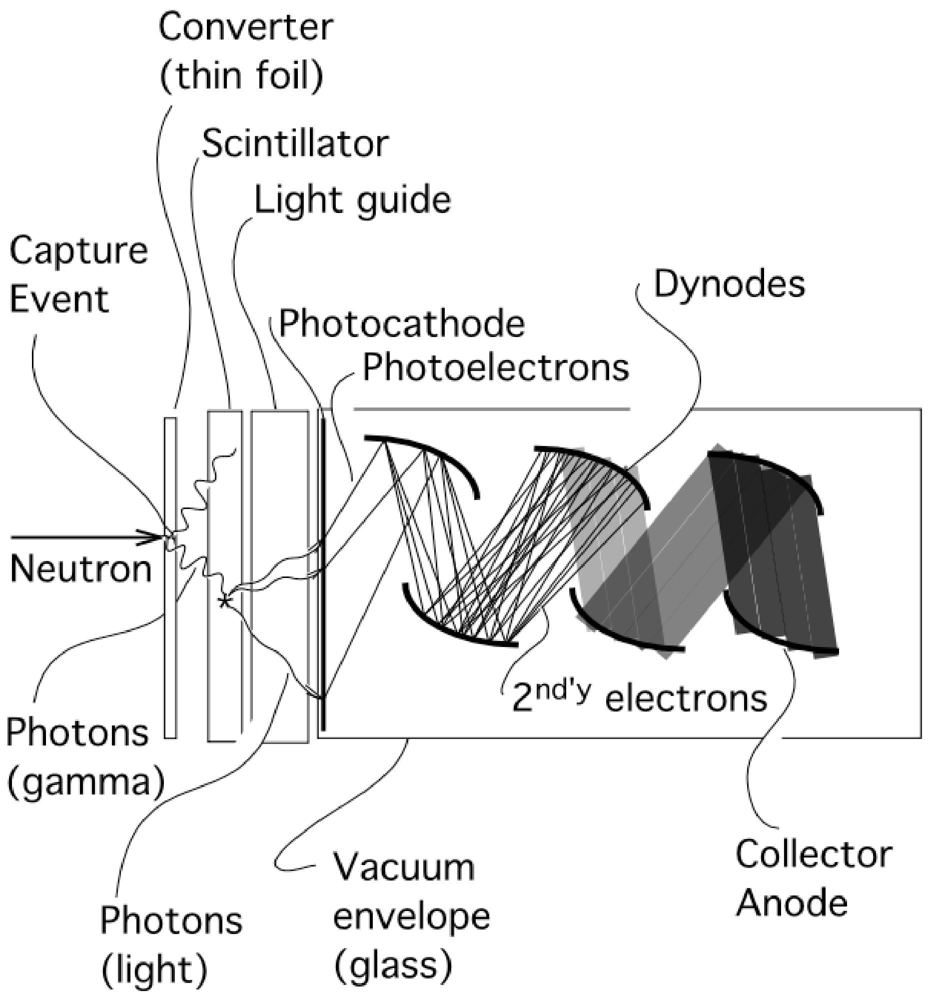
Position resolution is excellent, < 100 microns, because of the short range of the 70-keV electrons.

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.

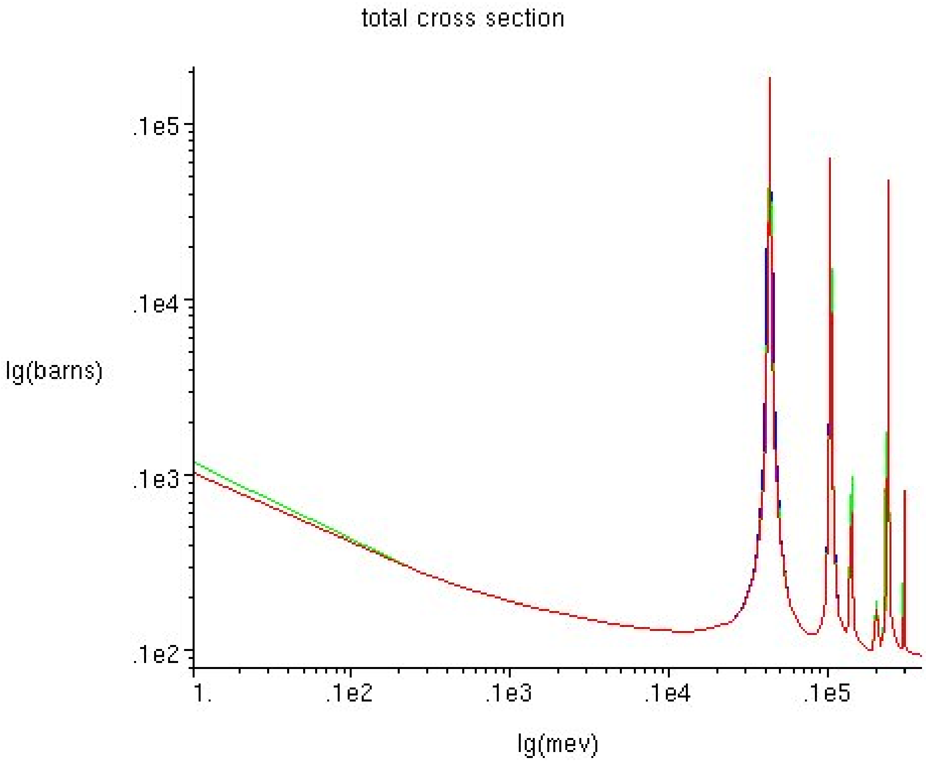

FUJIFILM

Capture Gamma-ray Detector



Total Cross Section of Tantalum

Tantalum is essentially monoisotopic ^{181}Ta and is often used as a neutron converter sensitive to energies near 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.
  - Spatial resolution.

- 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

- 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

End of Presentation

Thank you!