Nuclear Instrumentation – NNPSS 2oo9

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Radiation Detection – Some Basics & Generalities
with auxiliary information & refs.

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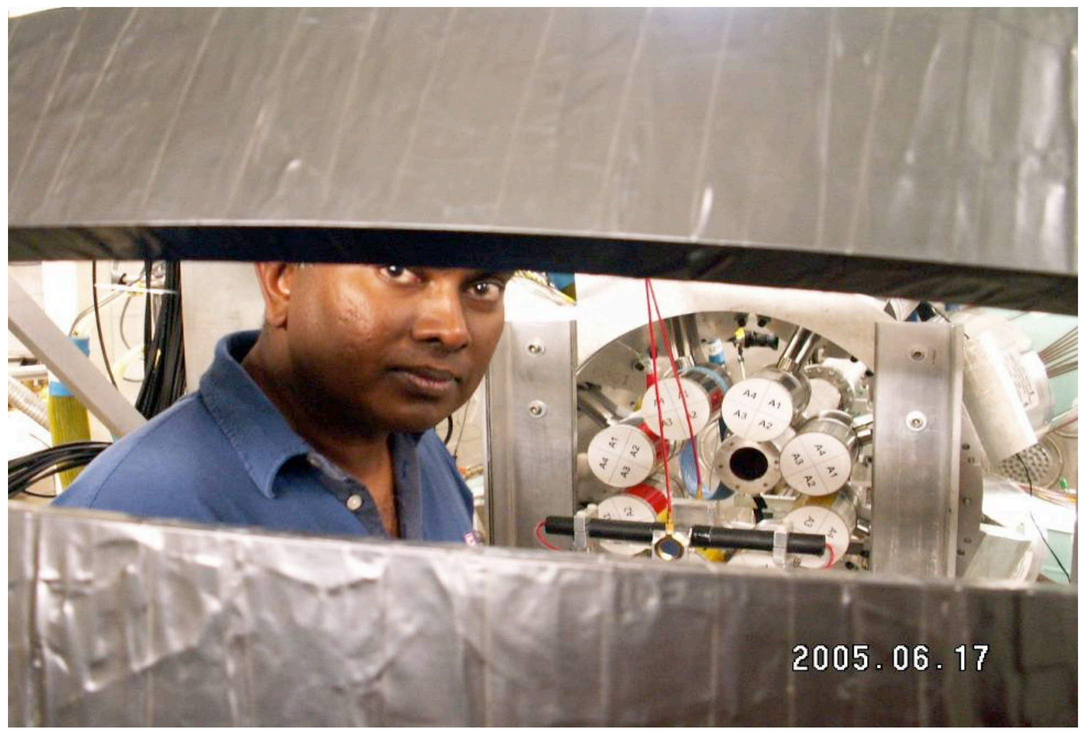
Many people's view of detectors



Chandana Sumithrarachchi (grad student) with detectors for four different types of radiation

Classes of Radiation to Consider Detecting

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	zero mass	"low" mass	"high" mass
Neutral	Gamma rays (photons)		Neutrons
Charged		Electrons +/-	Massive Charged Particles Muons … Nuclei

"Force"
Electromagnetic
Coulomb
Strong (Nuclear)

Except neutrons, these particles interact *primarily* with the electrons in materials that they enter … they are energetic enough to ionize the materials. A photon can only "collide" with one electron and the interaction creates a moving electron and a cation essentially at rest. On the other hand, the coulomb interaction has an infinite range so charged particles interact with a large number of electrons and a moving charged-particle continuously slows down until it stops. This process creates a host of ion pairs with a variety of excitation energies. Finally, neutrons only interact with nuclei and are detected through the secondary products of nuclear reactions.

The observation of this ionization is the fundamental operating basis for radiation detectors. The amount of ionization is sometimes strongly, other times weakly related to the incident *kinetic energy* of the particle but always depends on the stopping medium.

E.g, solid Silicon:

Overview of Whirlwind Presentation

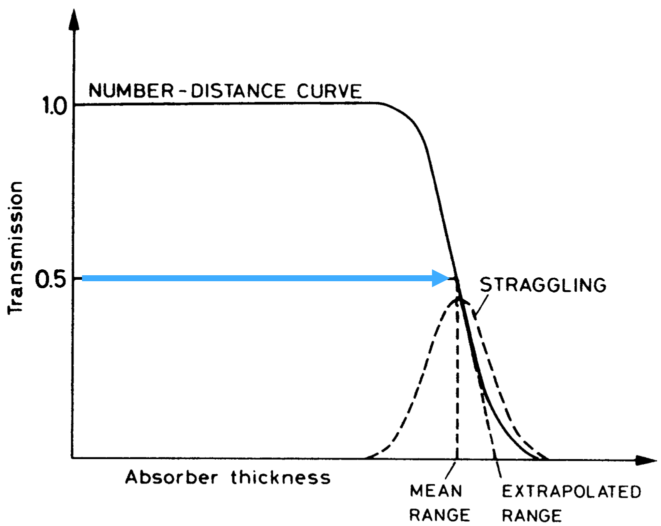
Reference material on Interaction of Radiation with Materials
heavy charged particles / electrons / photons / neutrons

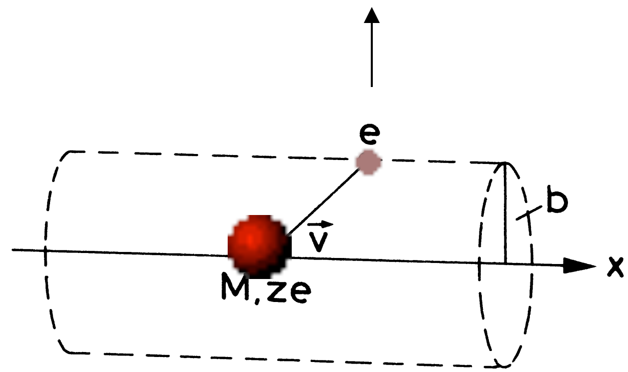
Primary Ionization Detectors (charged particles, photons)
Ion collection, gas-filled & solid state
Ion multiplication, gas-filled
Ion conversion, scintillation
Secondary Ionization Detectors (neutrons)
Neutron reaction basics

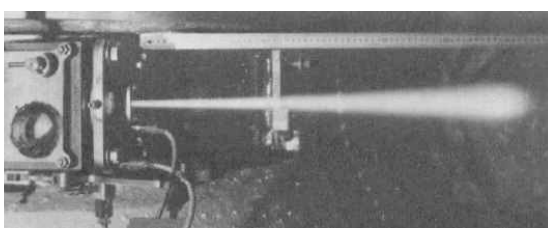
Pulse processing
Pulse shape, shaping, and timing
Electronic components, linear chain, ADCs, etc.

Interaction of massive C.P. with Matter

Massive charged particles interact with the electrons in the bulk material but the very large ratio of masses (e.g., the smallest ratio is $m_p/m_e \sim 1800$) means that the ions will travel on straight lines, continuously slow down by kicking out electrons, and finally stop at some point after a huge number of interactions.







Deuterons in air from:
A.K. Solomon, "Why Smash Atoms?" (1959)

We expect that the ion intensity remains essentially constant with depth until the end of the range when the ions come to rest.

On the other hand the kinetic energy of the ion will drop continuously in tiny increments until it stops.

The energy change is small in any single collision.

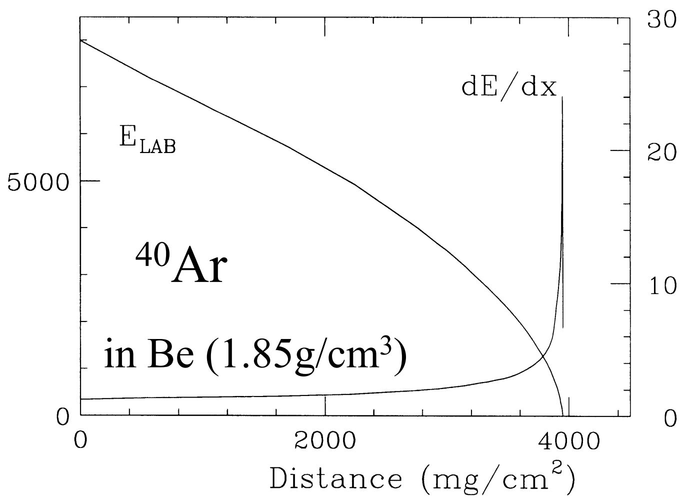
Interaction of massive C.P. with Matter -1-

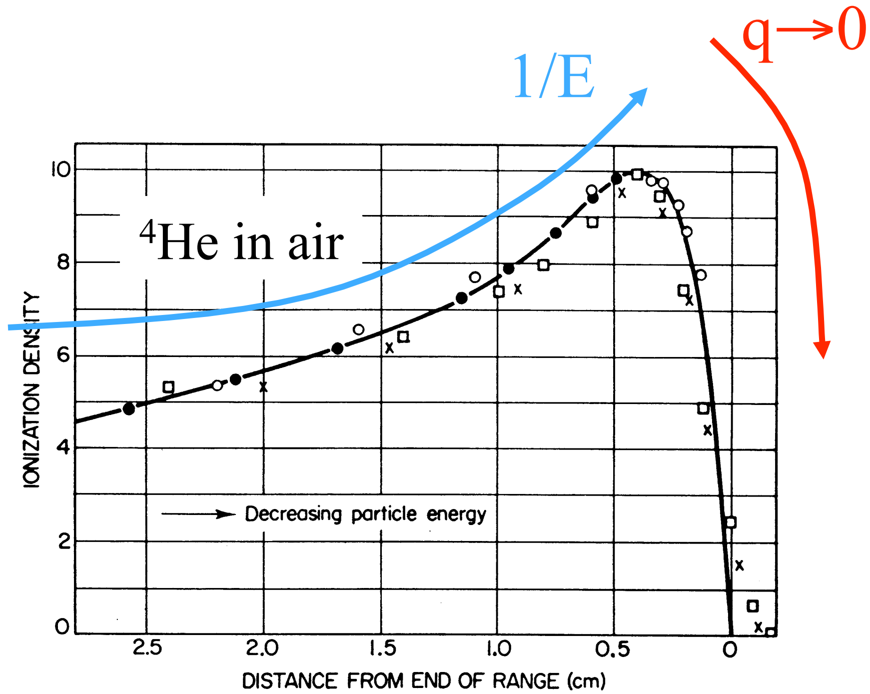
Rate of energy loss, dE/dx, for a heavy charged particle is called the stopping power and it is made of three terms. The electronic stopping is the most important, the nuclear reaction part is generally very small, and the nuclear-atomic part is only important at the end of the range (misnomer in my opinion).

$$\frac{-dE}{dx} = S_{electronic} + S_{\substack{nuclear\\reaction}} + S_{\substack{nuclear\\atomic}}$$

Bethe-Bloch Eq.
$$\frac{-dE}{dx} = \left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \frac{4\pi}{m_e}\left(\frac{q^2}{v^2}\right) Z_{Tar}\rho_{Tar}\left(\ln\left[\frac{2m_e c^2\beta^2}{I_{Tar}}\right] - \ln[1-\beta^2] - \beta^2\right)$$

$$\frac{-dE}{dx} \propto K\frac{Aq^2}{E}$$





Interaction of massive C.P. with Matter -2-

The charge state of an ion moving through a medium will depend on the kinetic energy of the ion. In the simplest approximation a fully-stripped ion will start to capture electrons from the medium as it slows down when the ion's velocity approaches the Bohr velocity for a K-electron in that element.

$$v_{Bohr}(N) = \frac{Z e^2}{4\pi\varepsilon_0 \; n\hbar}$$

Where n is the principal Quantum Number

$$\beta_{Bohr}(N) = \frac{Z}{n\alpha} = \frac{Z}{n}\frac{1.439 MeV\,fm}{197.5 MeV\,fm} = \frac{Z}{n}0.0729$$

There are empirical expressions for the "equilibrium charge state" of a moving ion based on measurements, e.g.,
Winger, et al. NIM B142 (1998) 441; NIM B70 (1992) 380
Leon, et al. AD&ND Tables 69 (1998) 217
Schiwietz & Grande, NIM B175 (2001) 125

Codes for "high energy ions"

CHARGE – Scheidenberger, et al. NIM B142 (98) 441
GLOBAL – Meyerhof (loc. cit.)
ETACHA – Rozet, et al. NIM B107(1996) 67

Interaction of e's with Matter

Rate of energy loss, dE/dx, for fast electrons (+ or -) is made of only two terms. The electronic stopping is the most important, the second term is a radiative term due to Bremsstrahlung that is important for high energies and high Z materials. The electronic term is similar to the Bethe-Bloch formula but the experimental situation for e- is complicated due to scattering by identical particles and the fact that the electrons are relativistic ($m_e c^2 = 0.511$ MeV).

$$\left(\frac{-dE}{dx}\right)_e = S_{electronic} + S_{radiative}$$

$$\frac{S_{radiative}}{S_{electronic}} \approx \frac{T + m_e c^2}{m_e c^2} \frac{Z_{tar}}{1600} \rightarrow \frac{3\, Z_{tar}}{1600} \; at \; T = 1\, MeV$$

$$\frac{S_{radiative}}{S_{electronic}} \approx \frac{T\, Z_{tar}}{700}$$

Interaction of Photons with Matter –1–

A beam of photons passes through material until each undergoes a collision, at random, and is removed from the beam. Thus, the intensity of the beam will continuously drop as the beam propagates through the medium but the energy of the photons will remain constant. This degradation of the beam follows the Beer-Lambert exponential attenuation law:

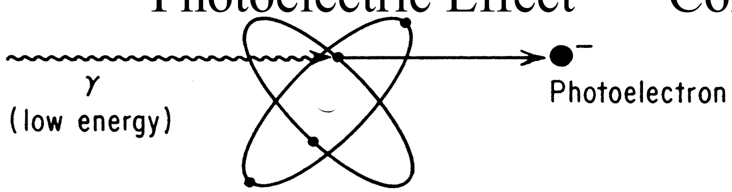
$$I = I_0 \, e^{-\mu x} \qquad \mu = 1/\lambda$$

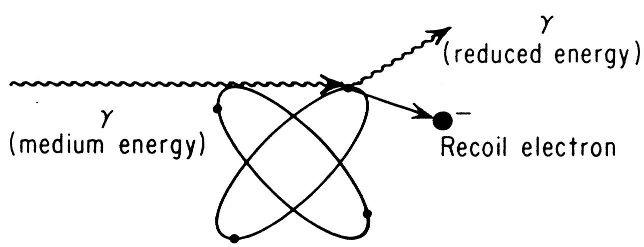
μ attenuation coefficient; λ mean free-path

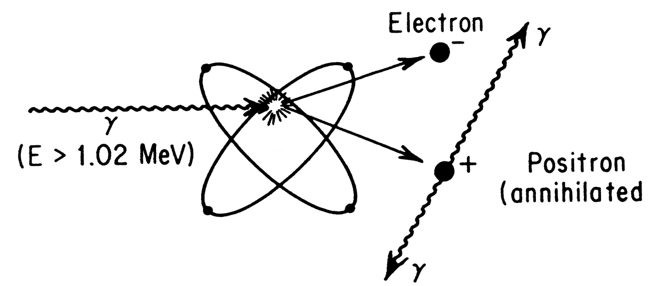
http://physics.nist.gov/PhysRefData/XrayMassCoef/cover.html

Three interaction processes:

Photoelectric Effect Compton Scattering Pair-production



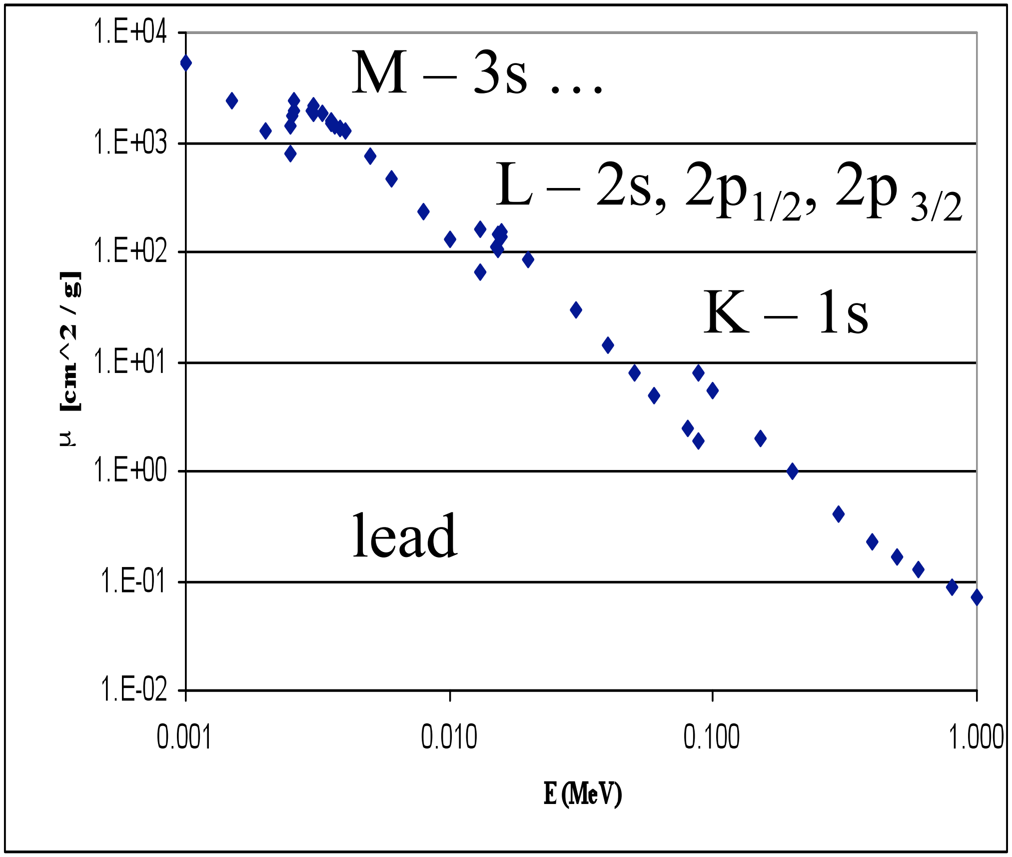




Interaction of Photons with Matter –2–

Photoelectric Effect: process originally described by Einstein, most efficient conversion of photon into a moving electron. [Electron then goes on to ionize the medium as just discussed.] Atomic scale (square angstroms) cross sections that decrease sharply with photon energy with steps at the electron shell energies.

PE effect generates
One electron with:
$E_e = h\nu - BE_e$



"Edges" in data due to a threshold at each electron shell.

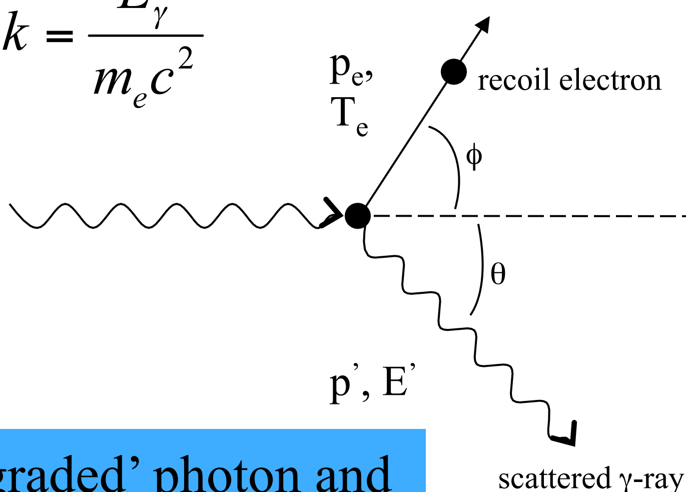
Interaction of Photons with Matter –3–

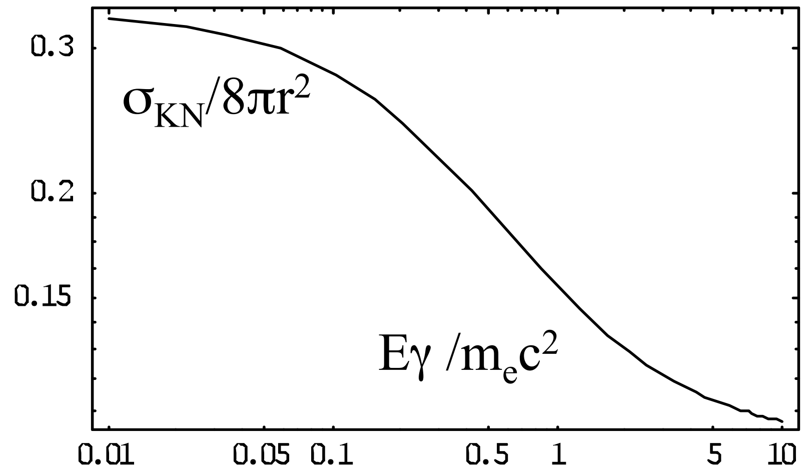
Compton Scattering: scattering of a photon by a (free) electron that leads to a moving electron *and* a lower energy photon. The two-body scattering leads to a correlation between angle and electron kinetic energy. The total cross section for the scattering is given by the Klein-Nisihna formula:

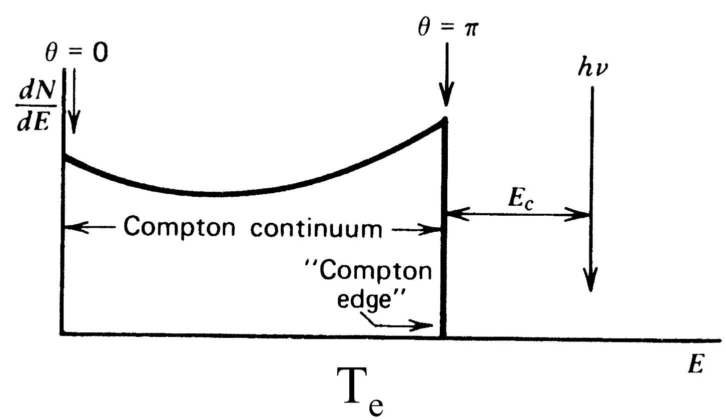
$$\sigma_{KN} \cong 8\pi\, r_e^2 \frac{1+2k+1.2k^2}{3(1+2k)^2}$$

$$r_e = \frac{e^2}{m_e c^2} = 2.818x10^{-15}\, m$$

$$k = \frac{E_\gamma}{m_e c^2}$$





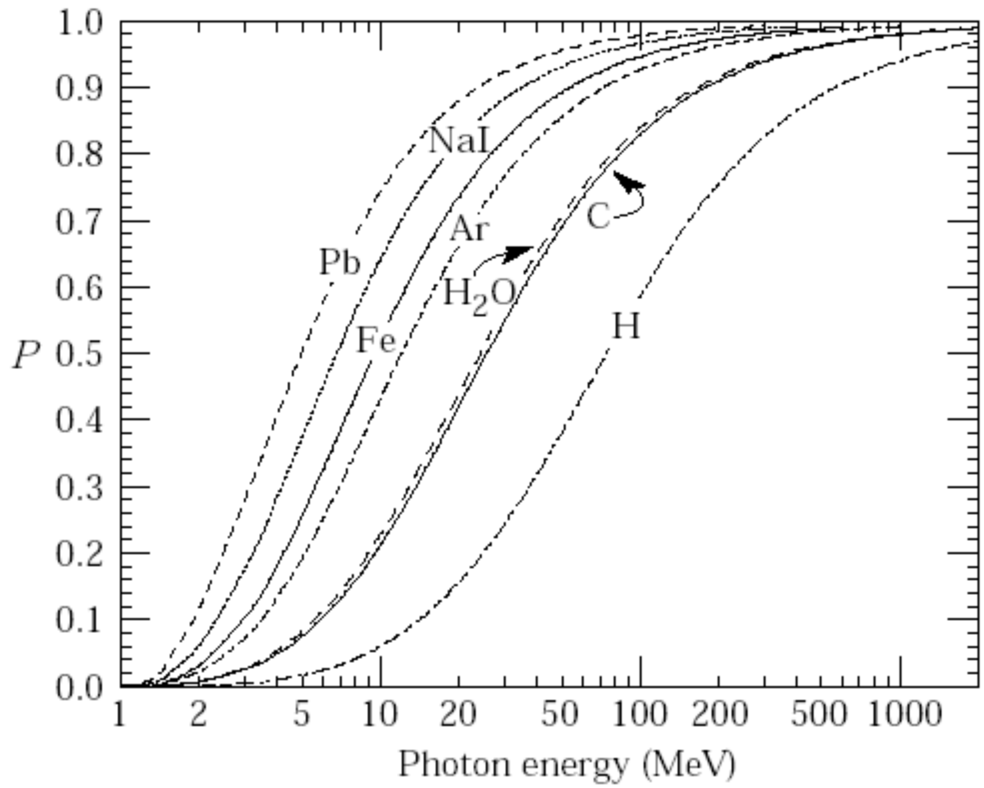


'Degraded' photon and one moving electron.

Interaction of Photons with Matter –4–

Pair production: $E_\gamma > 1.022$ MeV, the conversion of a photon into a matter/antimatter pair of electrons in the presence of a nucleus (or an electron). The process generally depends on the Z^2 of the medium and grows with photon energy. The two moving electrons share the remainder of the initial photon energy. Eventually the positron annihilates at the end of its range giving two 511 keV photons.

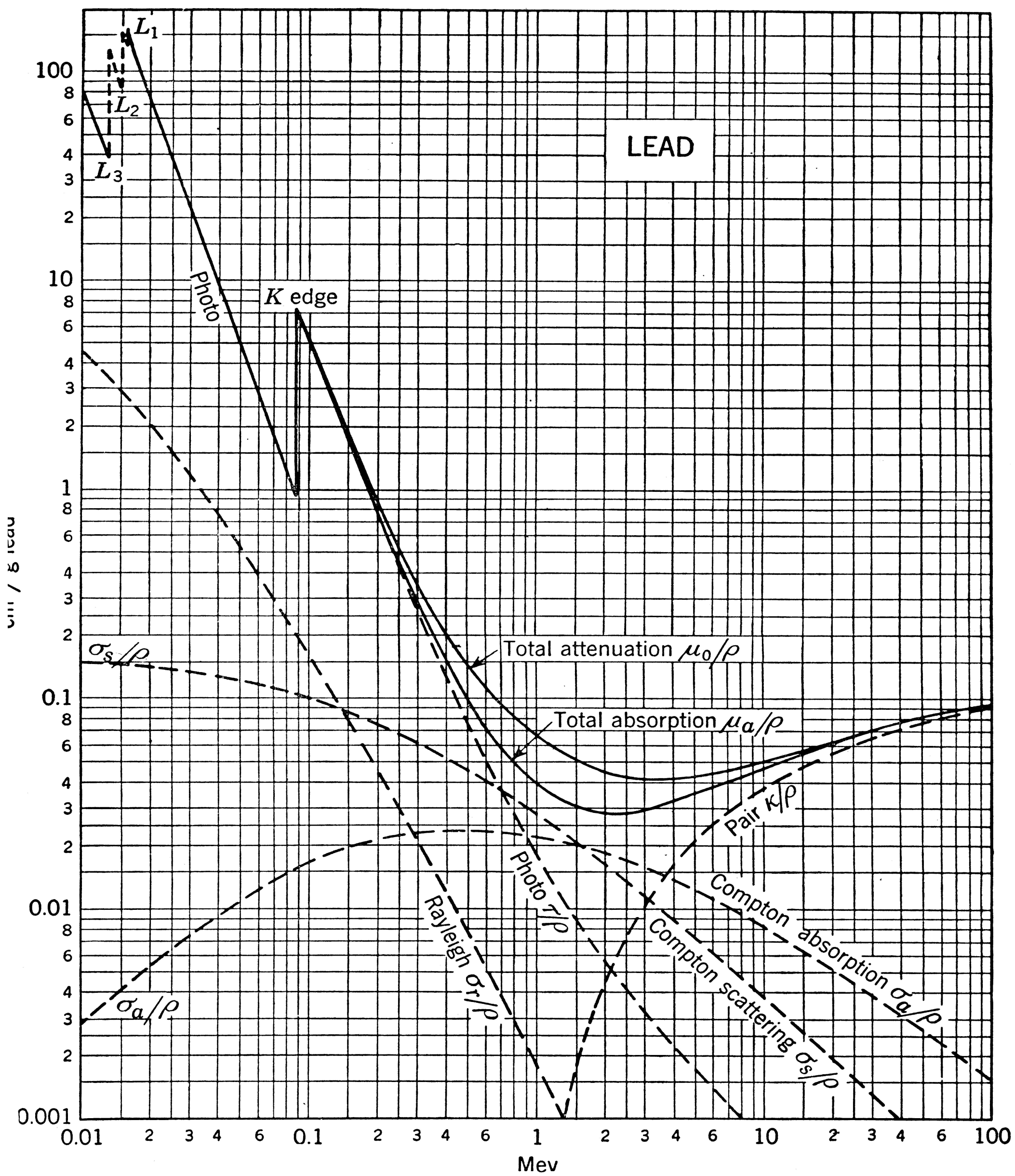
Probability of conversion, to be multiplied by a geometric cross section.



Interaction of Photons with Matter –5–

The full-deal:
μ/ρ mass-attenuation coefficient from *The Atomic Nucleus* by R.Evans

Overall, the photon beam is converted into a variety of fast electrons.



Interaction of Neutrons with Matter –1–

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A beam of neutrons passes through material until each undergoes a collision at random and is removed from the beam. In contrast to photons, the neutrons are 'scattered' by nuclei and usually only leave a portion of their energy in the medium until they are very slow and are absorbed. Thus, the intensity of the beam will continuously drop as the beam propagates through the medium and the mean kinetic energy of the neutrons will also generally decrease. The degradation of the beam intensity follows the Beer-Lambert exponential attenuation law and is characterized by an attenuation coefficient.

$$I = I_0 \, e^{-\mu x} \qquad \mu = 1/\lambda = N_0 \sigma_{Total}$$

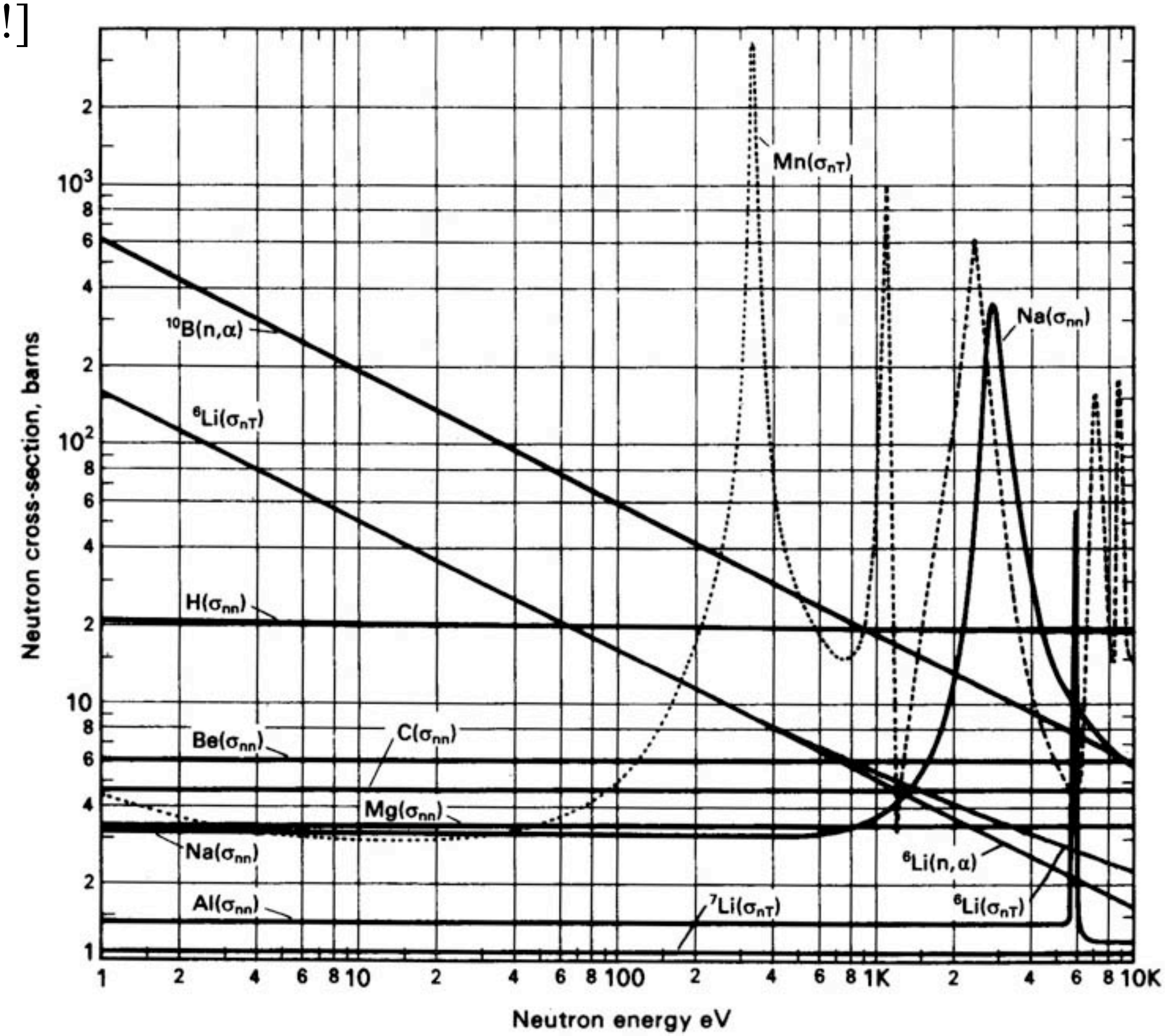
Hierarchical List of neutron reactions:

A(n,γ) A+1 -- radiative capture
A(n,n) A -- elastic scattering
A(n,n') A* -- inelastic scattering
A(n, 2n) A-1
A(n,p) A(Z-1) A(n,np)A-1(Z-1) etc.
A(n,α)
A(n,f)

Note that the H(n,n)H produces a recoil proton

Interaction of Neutrons with Matter –2–

Neutron reaction cross sections have a characteristic shape, one or more Breit-Wigner resonances and then a 1/v dependence at the lowest energies.
[More on this if you want!]

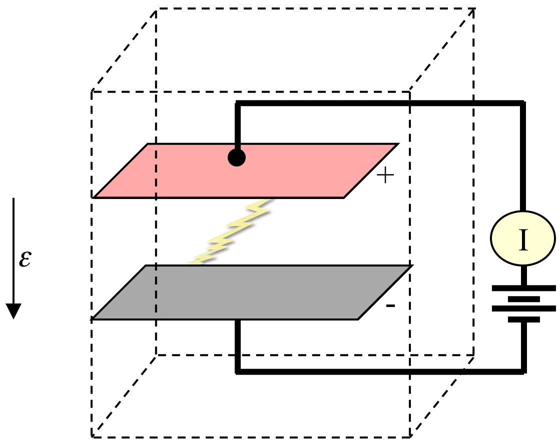


General Features of Detectors

Primary Ionization is created by the interaction of the radiation in the bulk material of the 'detector' – then what?

Rate	Technique	Device	Energy Proportionality?	Temporal Information?	Position Information?
Individual	View Ions	Cloud/Bubble Chamber, Film	Small range	Little or None	Very good
Low	Collect ions	Ion Chamber	Can be Excellent (0.001)	Generally Poor	Average (mm)
	Multiply & Collect ions	Proportional counter	Very good	Average (μs)	Good (10's μm)
Medium	Convert into photons	Scintillation counter	Acceptable (0.05)	Good (0.1 ns)	Varies
	Create discharge	Geiger-Mueller Ctr. Spark chamber	No	Good to excellent	None Excellent (μm)
High	Collect current	Ion Chamber	Radiation Field	None	None

Ion Chambers – Drift ions



Two parallel plates, ions will drift towards plates between collisions with the fill-gas. These collisions randomize the velocity and restart drift.

$v_{drift} = K\,\varepsilon$; $K = eD / k_B T = \mu/p$, μ is *ion mobility*

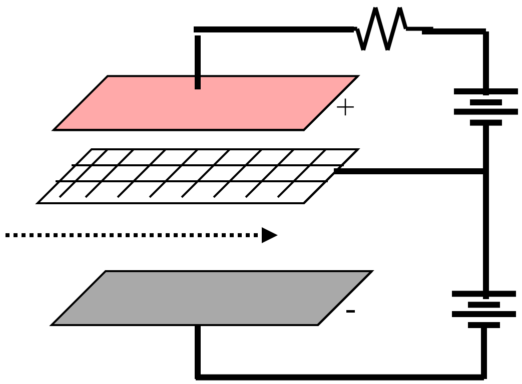
e.g., O_2^- $(\mu/p) = 2.5 \times 10^{-4}\ m^2/s\ V$ at 1 atm

Typical (large) value: 1kV across a 1.0 cm gap gives:
$v_{drift} = (2.5 \times 10^{-4}\ m^2/s\ V)^*\ (10^3\ V / 0.01m) \sim 25\ m/s < v_{thermal}$

$t_{collection} \sim 0.005\ m / 25\ m/s = 2 \times 10^{-4}\ s = 0.2\ ms$

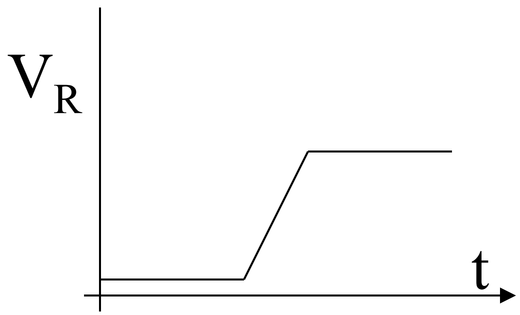
N.B. (μ/p) for an electron is about $10^2 - 10^3$ x larger due to its smaller mass

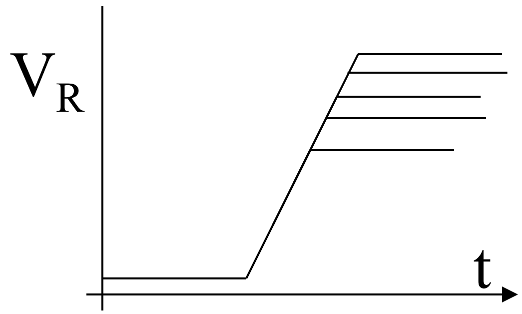
Ion Chambers – Frisch Grid



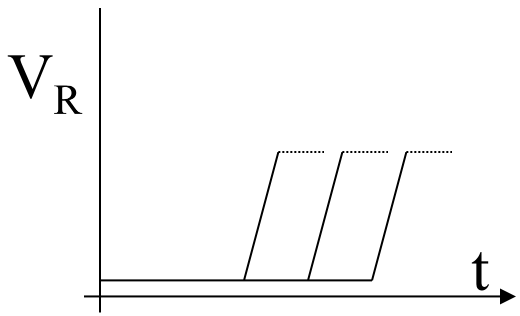
Give up the cations …

Add a grid at position between the anode and cathode but closer to the anode. The grid needs a high transmission but it will shield the anode electrically from the primary ionization.





} various pulse heights on central axis give energy dependence – spectroscopy

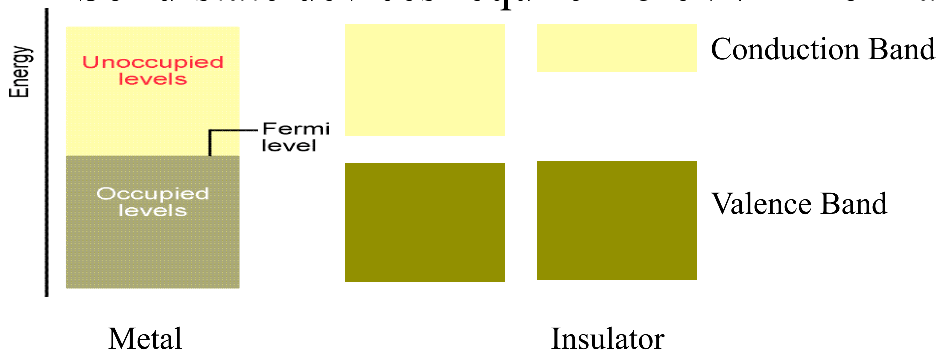


} uniform pulse height at various positions from grid gives drift time differences – positional information.

Semiconductor Diodes – Solid State Detectors

Semiconductor diodes provide the best resolution for energy measurements, silicon based devices are generally used for charged-particles, germanium for photons.

- Scintillators require ~ 100 eV / "information carrier" .. Photoelectrons in this case
- Gas counters require ~ 35 eV / "information carrier" .. Ion-pair
- Solid-state devices require ~ 3 eV / "information carrier" .. Electron/hole pair



A semiconductor is an insulator with a small band gap, ~1.2eV for silicon. Generally want smallest band gap ***but*** thermal excitation across the gap provides a leakage current. N.B. the actual band gap depends on the direction relative to the lattice (Si and Ge do not crystallize in cubic lattices) and the gap decreases slowly with temperature.

The ratio of 'w' to band gap is approximately constant for a wide range of materials – division of excitation energy between e/h pair and phonons, etc. is ~ constant.

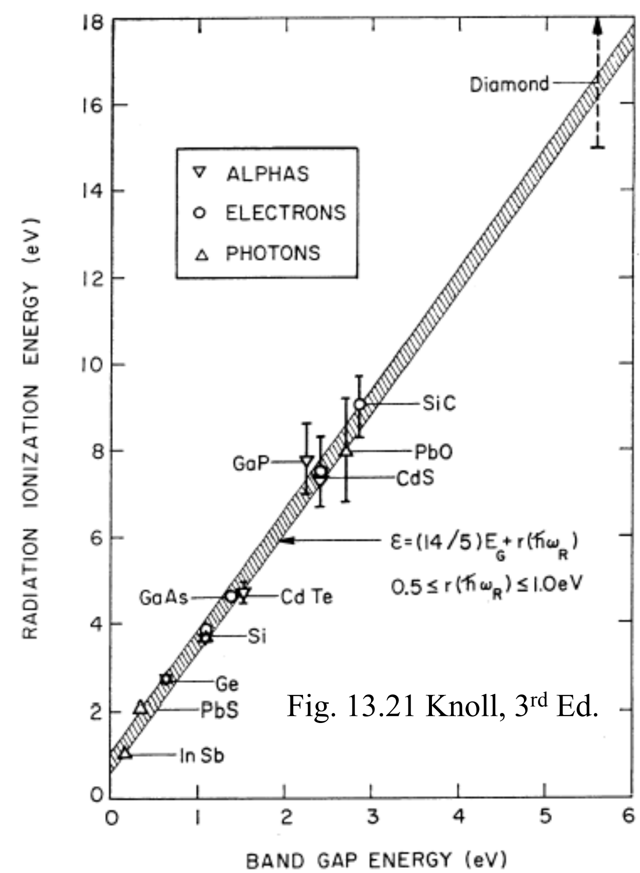


Fig. 13.21 Knoll, 3rd Ed.

C.A.Klein, J.App. Phys. 39 (1968) 2029

Semiconductor Diodes – 2

Some properties of the junction:

$$d \sim \sqrt{\frac{2\varepsilon V}{q_e N_A}} \quad \& \quad \rho = \frac{1}{q_e N_D \mu_e}$$

$$d \sim \sqrt{2\varepsilon V \rho \mu} \quad \& \quad C = \frac{\varepsilon A}{d}$$

$$E = \Delta V / \Delta x \quad \rightarrow \quad E_{max} = \frac{2V}{d}$$

Rectifying contact

ohmic or blocking contact

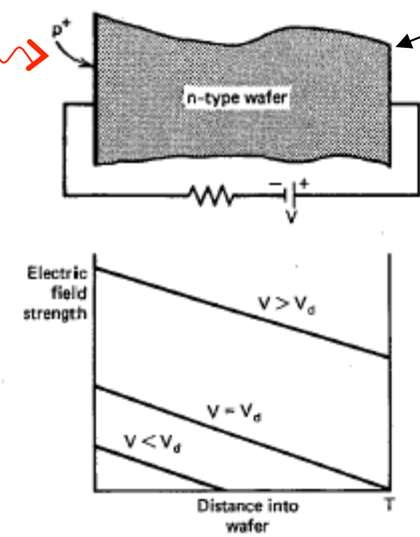
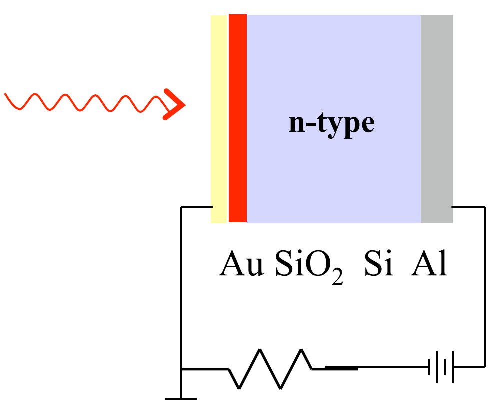


Fig. 11.12 Knoll, 3rd Ed.

One can apply an external (reverse) bias voltage such that the depletion layer extends from the junction to the full thickness of the device

Silicon Surface Barrier Device



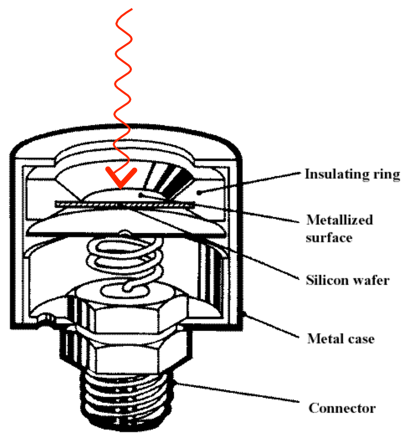


Fig. 11.11 Knoll, 3rd Ed.

(From EG&G Ortec)

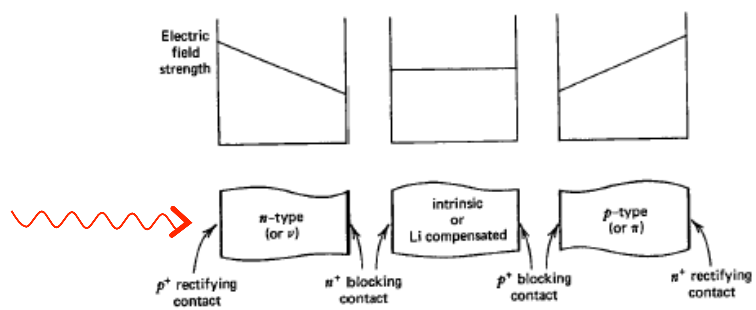
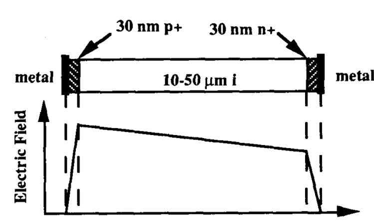


Fig. 11.13 Knoll, 3rd Ed.



Solid State – Germanium Based Detectors

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The semiconductors provide the lowest value of "w" and thus the highest resolution for the energy, Silicon has become widely available in thin disks but the low atomic number (14) limits its use for photon detection – a higher Z is needed.

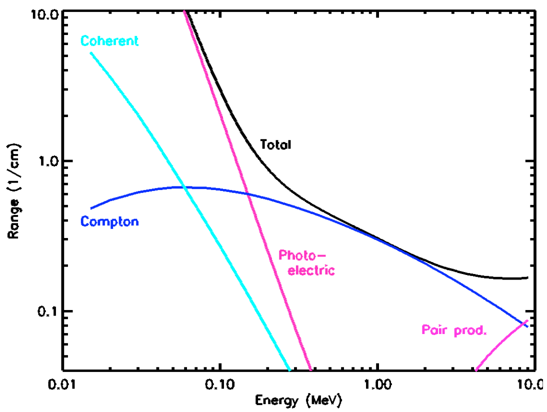
13	14	15
5 B 10.811	6 C 12.011	7 N 14.007
13 Al 26.982	14 Si 28.086	15 P 30.974
31 Ga 69.72	32 Ge 72.59	33 As 74.922
49 In 114.82	50 Sn 118.69	51 Sb 121.75
81 Tl 204.37	82 Pb 207.19	83 Bi 208.98

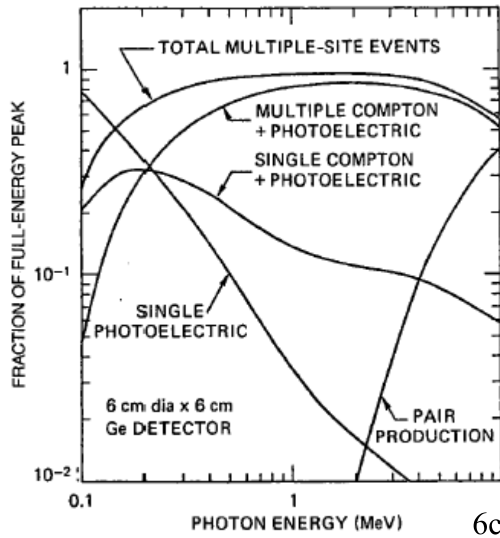
- Sn & Pb are "metallic"
- Ge is only elemental option
- GaAs, InSb are used somewhat
- CdZnTe is a "new" material

Germanium is more metallic than silicon – band gap is lower, higher signals, higher thermal noise, easier to purify, donor/acceptor level must be lower

Large volumes are available (~1 L) from zone refining
n-type usually has Oxygen in the matrix
p-type usually has Aluminum in the matrix
"hyperpure" material is readily available .. Intrinsic.

Germanium Based Detectors – contacts





6cm x 6cm Fig. 12.16 Knoll, 3rd Ed.

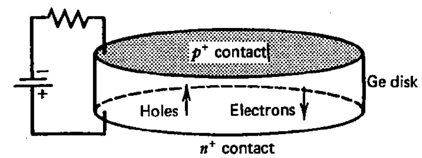
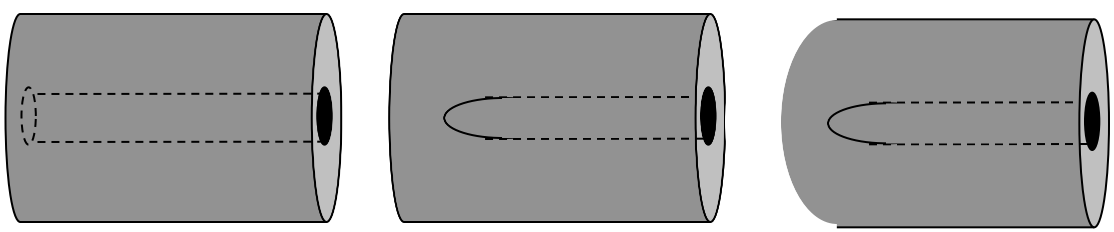
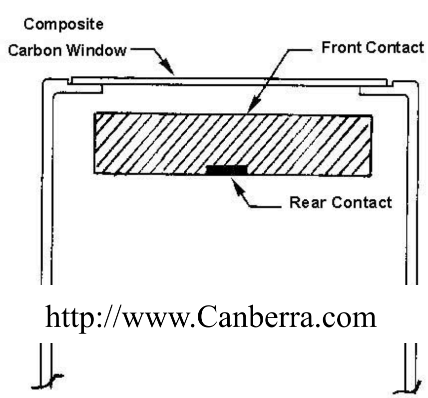


Fig. 12.2 Knoll, 3rd Ed.

Multiple Compton Scattering is most likely process in "nuclear regime"
Planar devices: low energy photons.

Intrinsic or high purity germanium can be formed into coaxial shapes with radial electric fields but end-caps are often left on and they are often "bulletized"





http://www.Canberra.com

Extremely low capacitance device with unusual electrode design but funky electric field

Shape, material and contacts are separate variables.

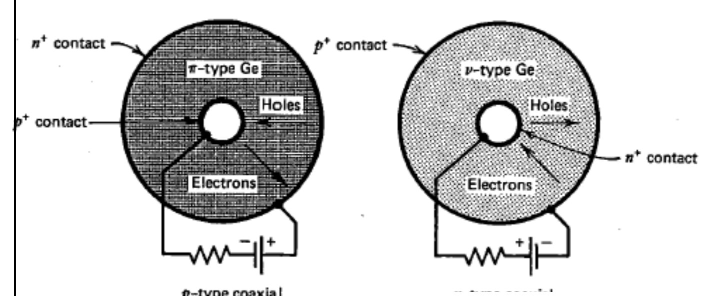
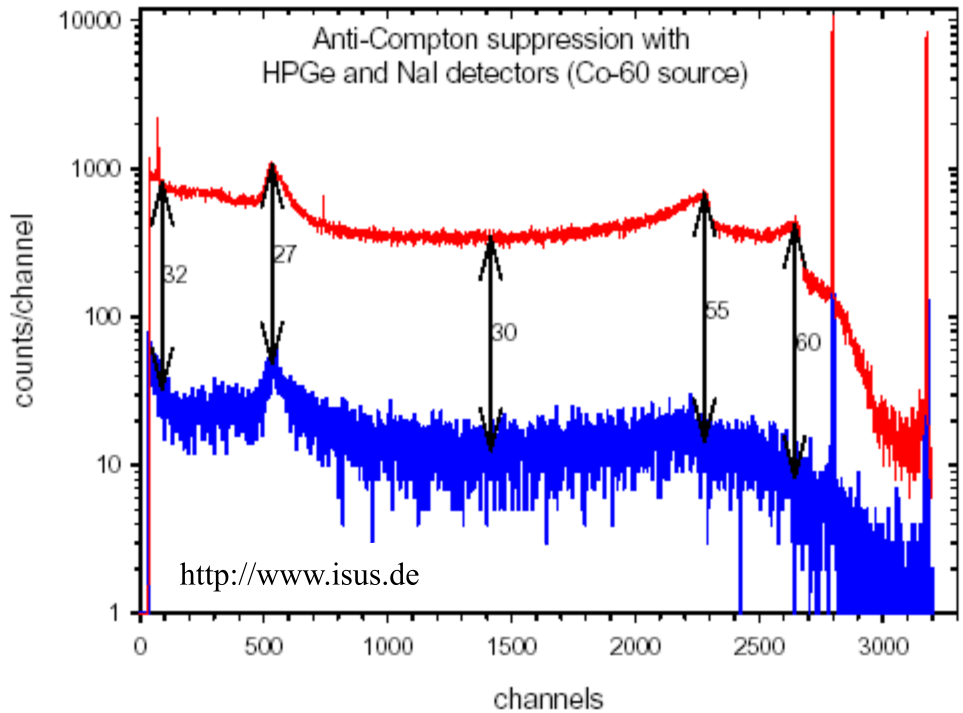
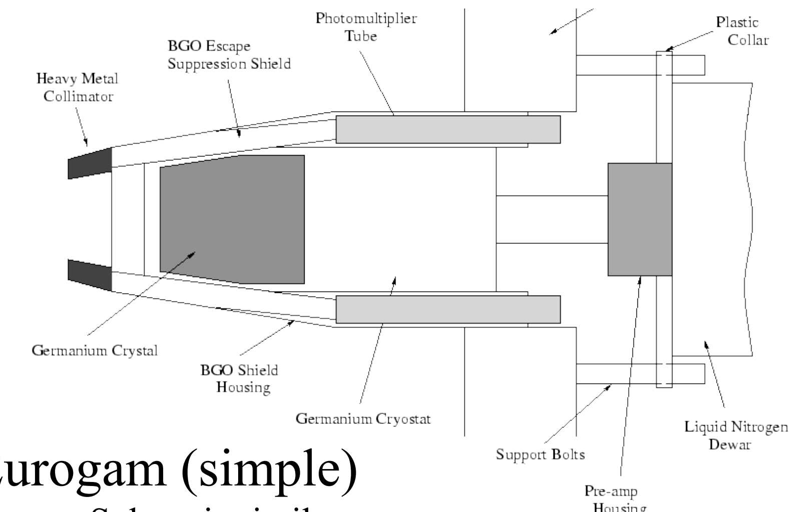


Fig. 12.3 Knoll, 3rd Ed.

Germanium Based Detectors – Anticompton

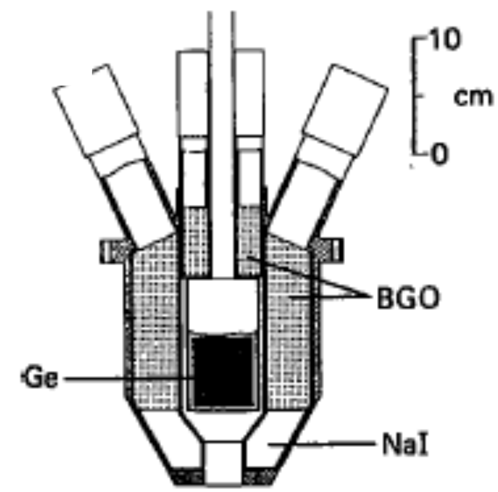


Anticompton shields: Improve the quality of the signal by rejecting events when (Compton-scattered) photons leave the Ge crystal.



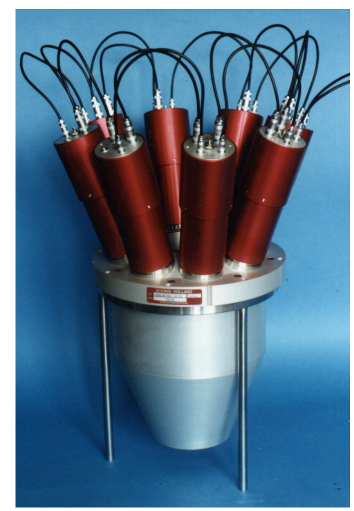
Eurogam (simple)

GammaSphere is similar



"Tessa" mixed shield

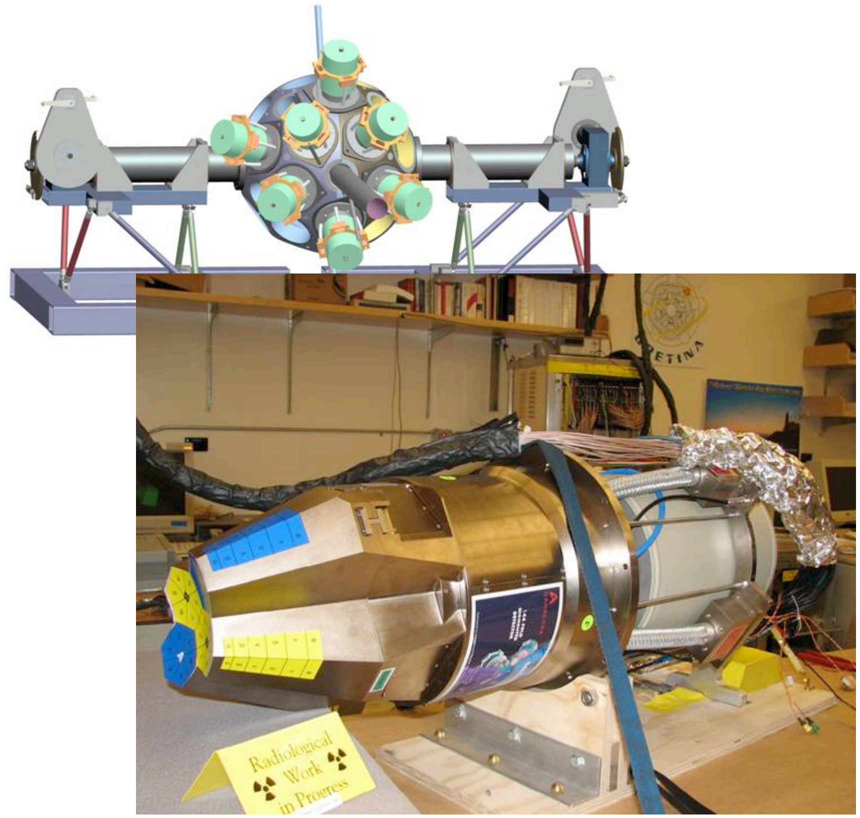
Fig. 12.25 Knoll, 3rd Ed.

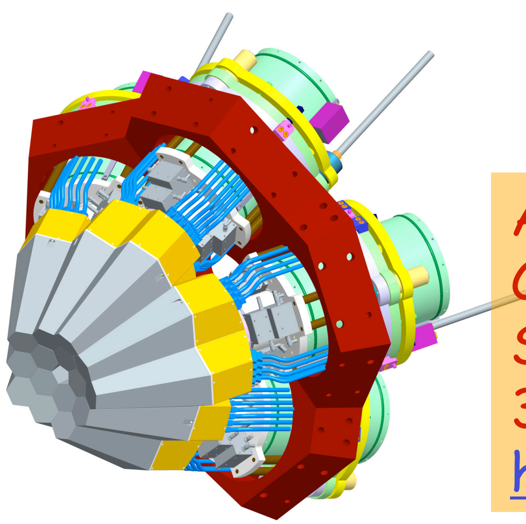


http://www.Scionix.com

Germanium Detectors: Spheres

Gretina (USA):
Cover $\frac{1}{4}$ of 4π solid angle
Seven 4-crystal detector modules
7% efficiency at 1 MeV [17 M$ TEC]
Start of operation Feb 2011
http://grfs1.lbl.gov/

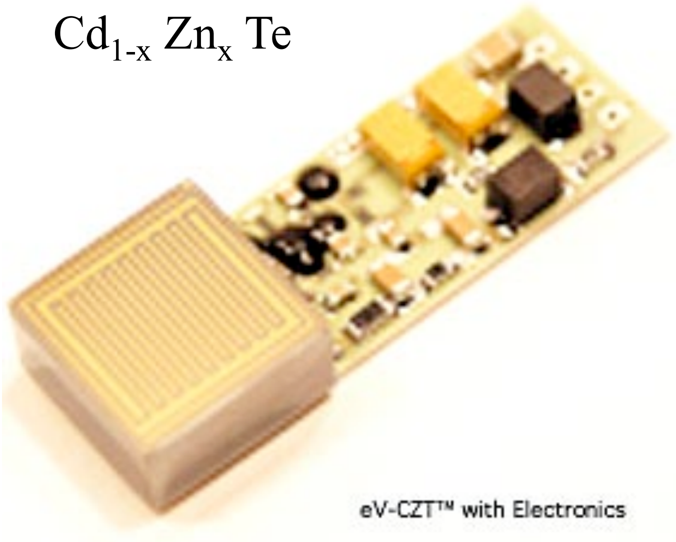


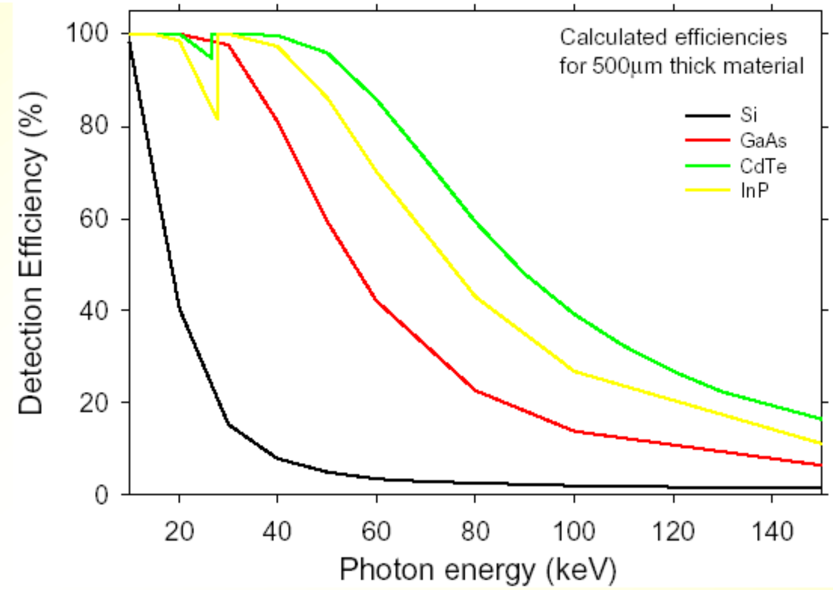


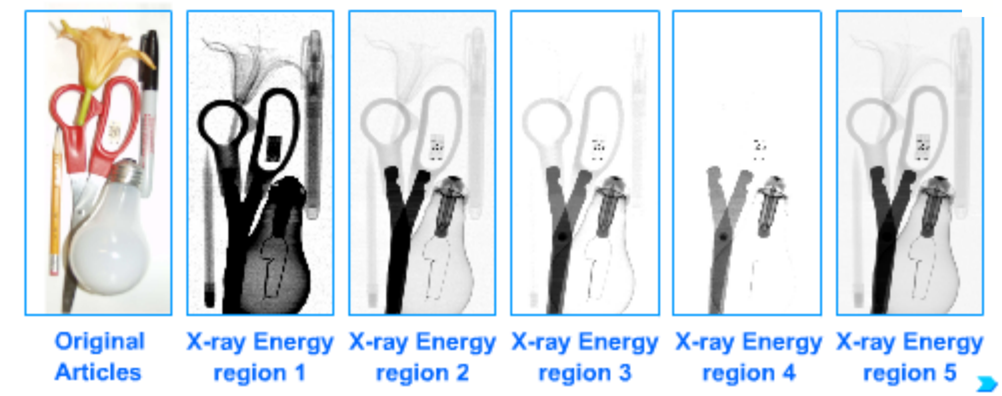
Agata Demonstrator (Europe):
Cover ~10% of 4π solid angle
Six triple-crystal detector modules
3-8% efficiency for M=1 [6 M Euro for parts]
http://www-w2k.gsi.de/agata/

Other Semiconductors – CZT

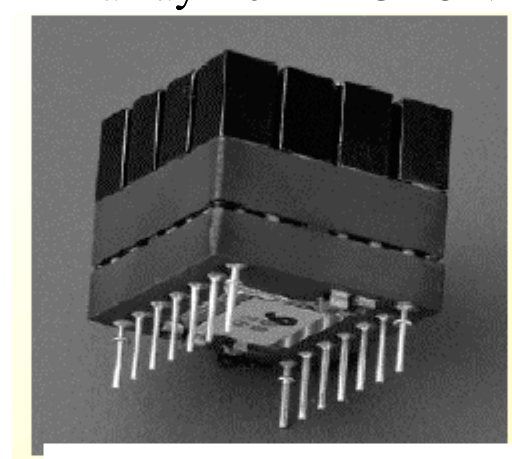
$Cd_{1-x}Zn_xTe$







Imaging device, 4.5x4.5x6 mm^3
in 4x4 array from BICRON



C.Mestais, NIM A458 (2001) 62

Typical sensitivity of integrated device:
0.1 mRem/hr to 1 Rem/hr
(Exercise to show this is ~3×10^7 MeV/s)

Proportional Counters, multiply electrons

Consider the drift motion of an ion in a simple ion chamber. The ions will have a thermal velocity plus a component along the field lines. Then after traveling for a mean-free-path they will undergo a collision that will randomize their velocity and they start over. What if the energy gain in one step is greater than the FIP of the buffer gas?

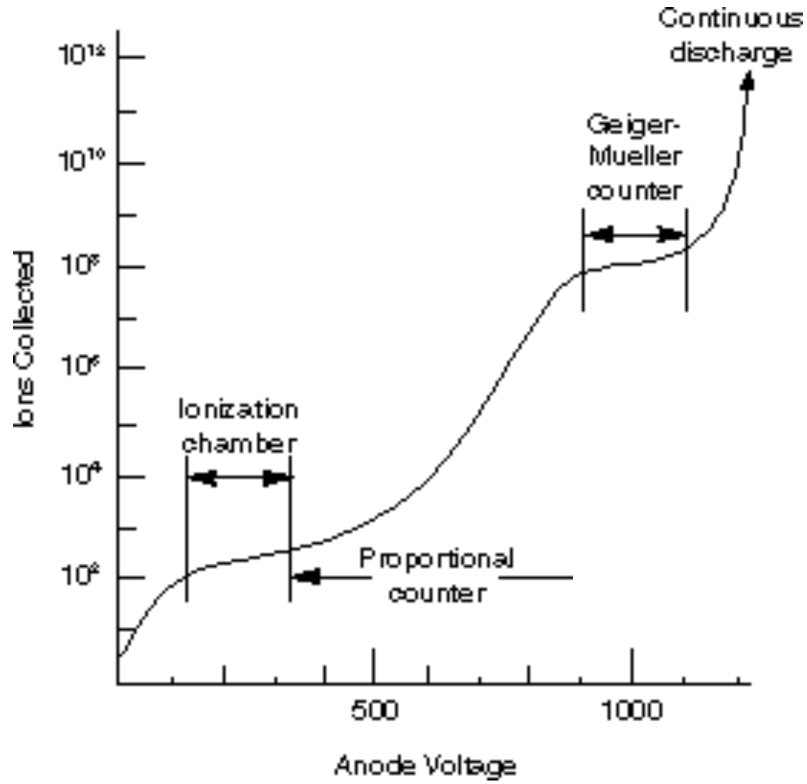
$$\Delta E \sim q_e\, \varepsilon\, \Delta x \quad where \quad \Delta x \sim \lambda_{MFP} \qquad \rightarrow \quad q_e\, \varepsilon \sim \frac{\Delta E}{\lambda_{MFP}}$$

$$\lambda_{MFP} = \frac{1}{\sqrt{2}\,\pi d^2 \rho_n} \qquad \text{(for molecules)}$$

$$\lambda_{MFP}(air) = 6.6\, mm/Pa \quad or \quad 6x10^{-8}\, m\ at\ 1atm$$

$$q_e\, \varepsilon \sim \frac{FIP}{6x10^{-8}\, m} \sim 200\, MV/m$$

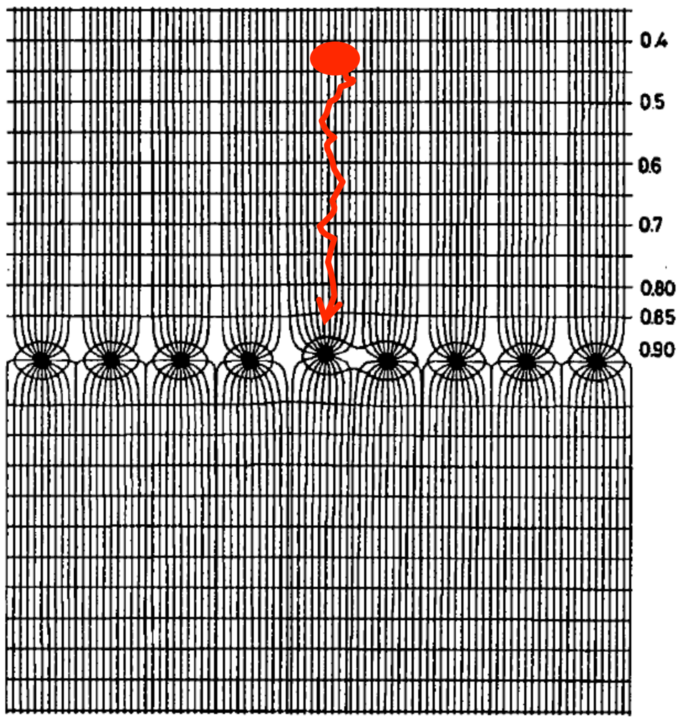
This value is too large for a nominal detector and so no multiplication of/by molecular ions.
However, MV/m = keV/mm is achievable.
Recall that the electrons will have much longer mean-free paths – electrons can be multiplied or "avalanched".

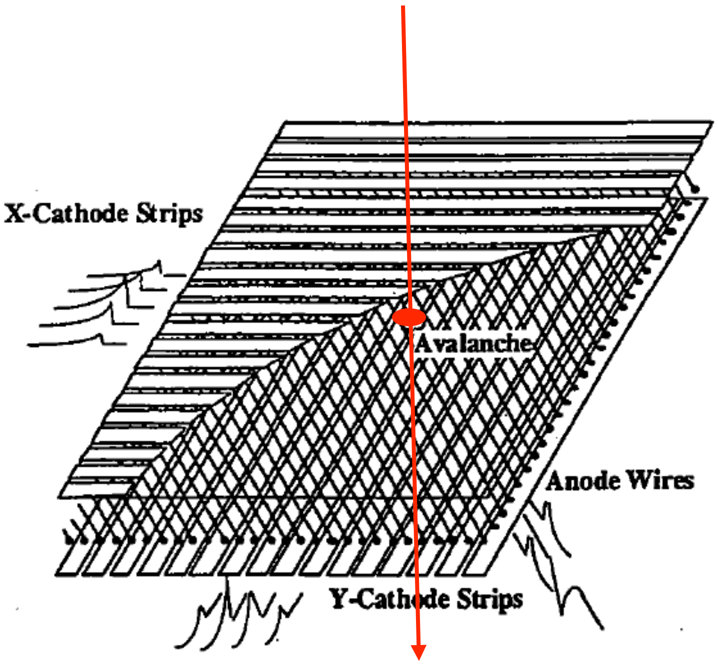


Similar to qualitative Fig. 6.2 Knoll, 3rd Ed.

Proportional Counters – Multiwires & Position

Field lines are approximately perpendicular to wire plane at large distances – electrons drift towards plane and retain position information. Many "wire chambers" have been developed to measure the positions of various particles.





Figs. 6.19 & 20 Knoll, 3rd Ed.

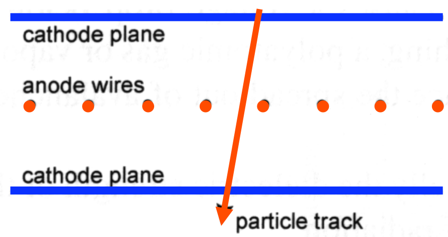
Read primary signal on wires, induced signals on cathode strips top and bottom – calculate 2D position.

Proportional Counters – Wires → Stripes

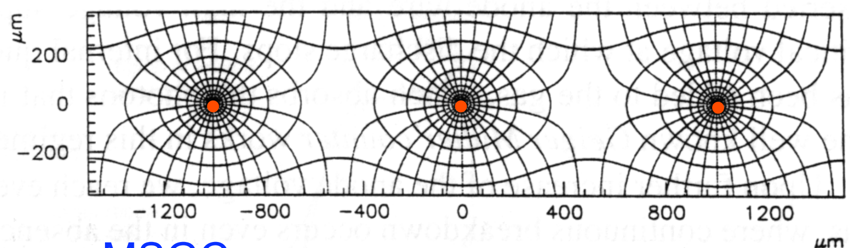
More sensitive detectors require more amplification – smaller "wires." Tiny anodes can be made by photoetching techniques but they must be supported on substrates (thick materials). Importantly the distance to the cathode traveled by the slow cations can be reduced enormously.

Multi-wire proportional chamber

Charpak

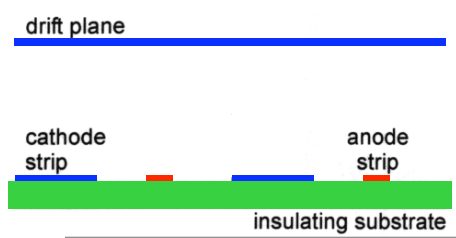


MWPC

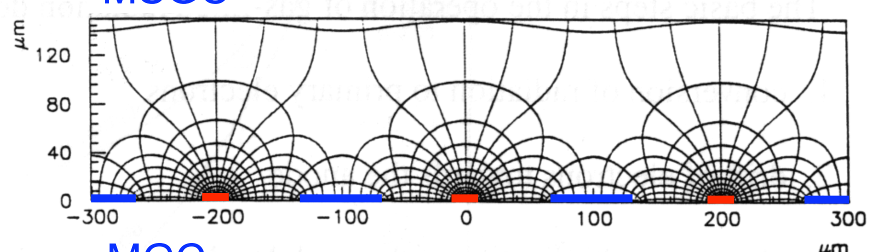


Micro-strip gas chamber

Oed

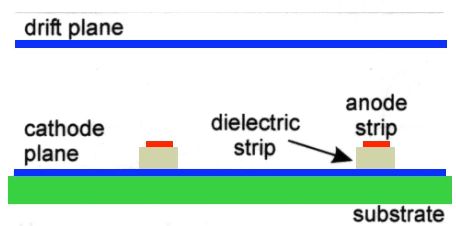


MSGC

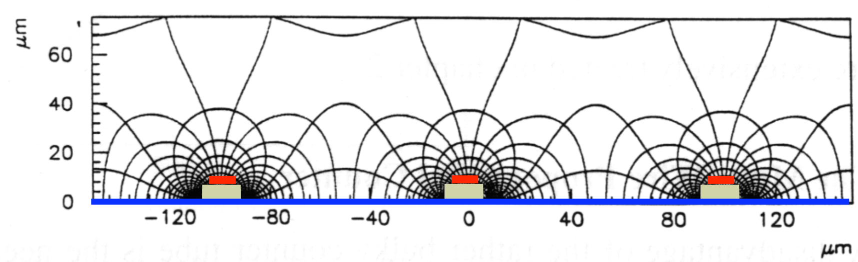


Micro-gap chamber

Bellazini

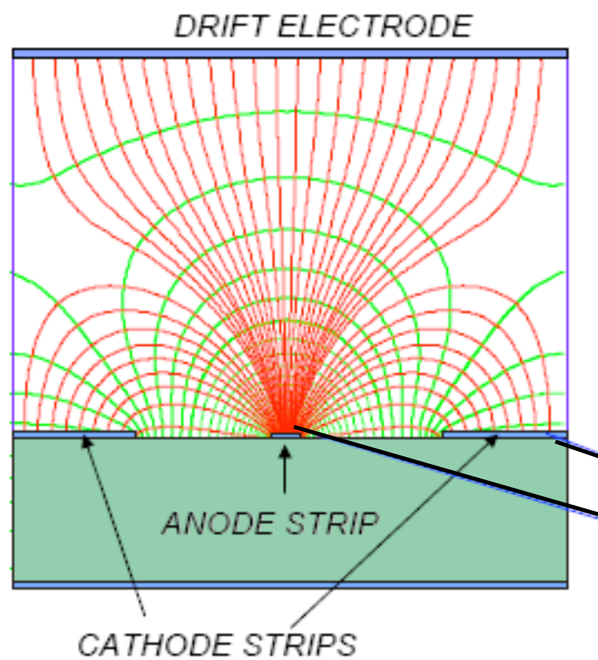


MGC



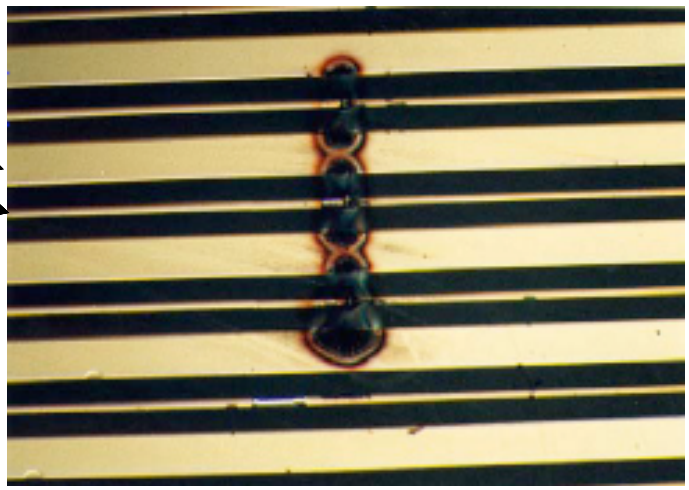
Proportional Counters – Wires → Stripes, Nope!

Thin metal strips on insulating support, generally resistive glass have a very high rate capability due to high fields and short distance of travel for the cations.



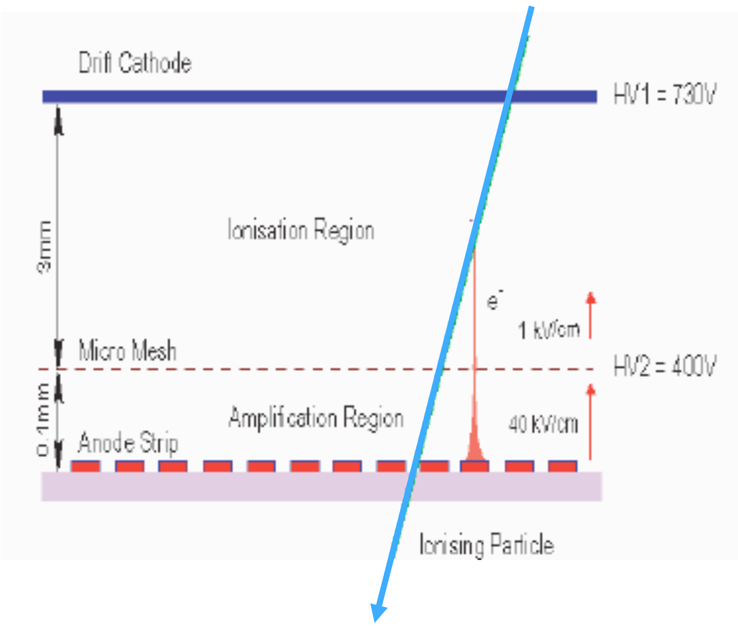
A.Oed, Nucl. Instr. and Meth. A263(1988)351

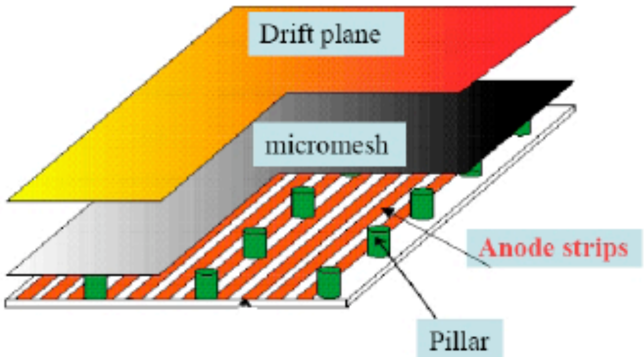
However, strips are permanently damaged by sparks or other discharges which then kills the detector.

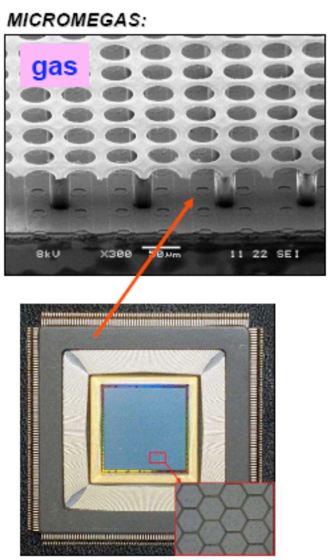


Proportional Counters – Micro Frisch Grid

MicroMeGas detectors are made on a tiny scale with micro fabrication techniques. These devices have high spatial resolution but may be gain limited because they are only one-stage by definition. Also they can be integrated with electronics, but they are generally small.







Y. Giomataris, et al. NIM A376 (1996) 239

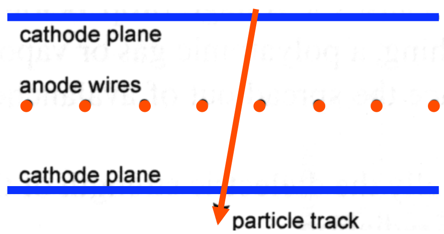
14x14 mm^2 , 256x256 pixels, 55x55 μm^2
H. Van der Graaf, IEEE-NSS workshop, 2007

Proportional Counters – Wires → Holes

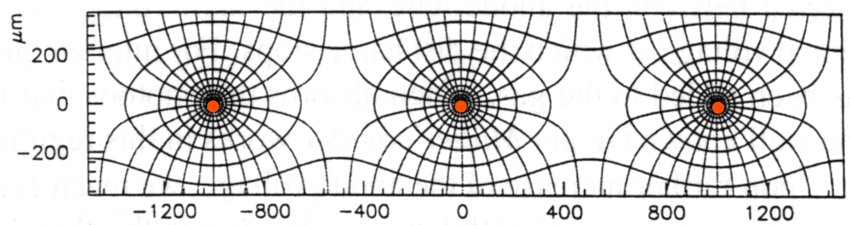
Get rid of the wires and use holes in an insulator… Gas Electron Multiplier (GEM). Typically a plastic foil, Kapton 50 μm, metal plated on both sides with small holes ~50 μm diameter. This creates a very high electric field 'in' the holes, perhaps 20kV/cm depending on the details. They can be stacked to get high gain.

Multi-wire proportional chamber

Charpak

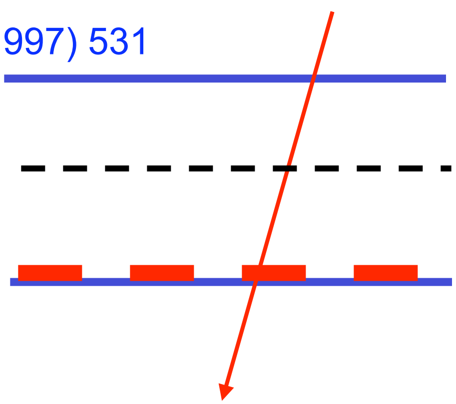


MWPC

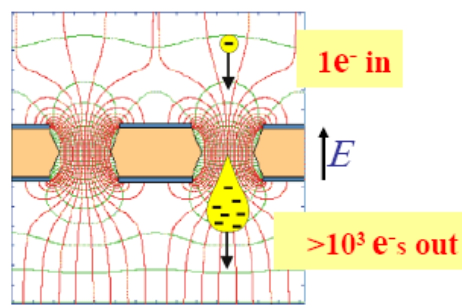


Gas Electron Multiplier

Sauli, NIM A433 (1997) 531

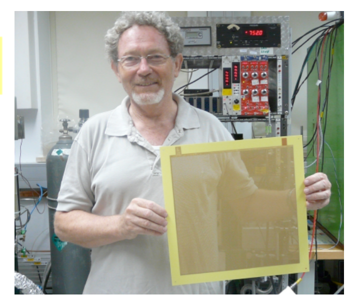


GEM



Electric field in the holes >20kV/cm

Amos Breskin,
Thick GEM, 2oo8



Geiger-Mueller Counters

Increase field in Proportional counter so that the avalanche spreads along the entire length of the wire … this will produce the largest signal but a sheath of cations will terminate the applied field, ending pulse.
Rutherford & Geiger, 1908

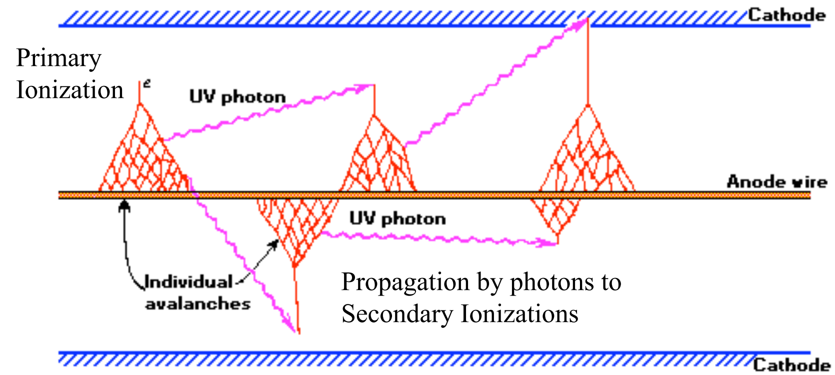
Recombination at the wall leads to “after pulse”

$He^+ + e^-$ (wall) $\rightarrow He^* \rightarrow He + h\nu$ (UV)

$He^+ + M \rightarrow He + M^+$

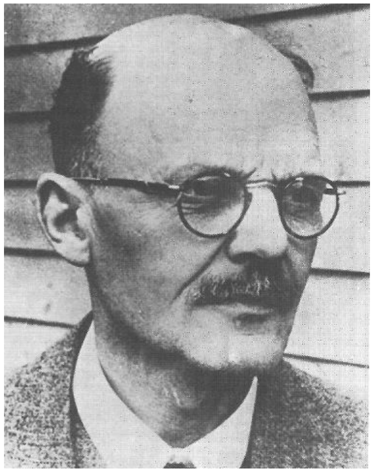
$M^+ + e^-$ (wall) $\rightarrow M^* \rightarrow M + h\nu$ (IR)

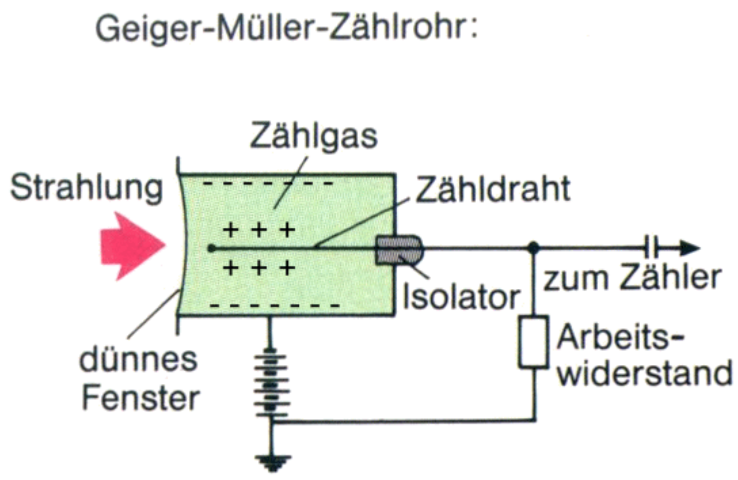
GM tubes are sealed … “M” gets burned up.



Beware of cartoon !

Hans Geiger (1882-1945) was a German physicist who introduced the first reliable detector for alpha particles and other ionizing radiation.His basic design is still used, although more advanced detectors also exist.
His first particle counter was used in experiments that identified alpha particles as being the same as the nucleus of a Helium atom.He accepted his first teaching position in 1925 at the University of Kiel, where he worked with Walther Müller to improve the sensitivity and performance of his particle counter.





Scintillation Counters

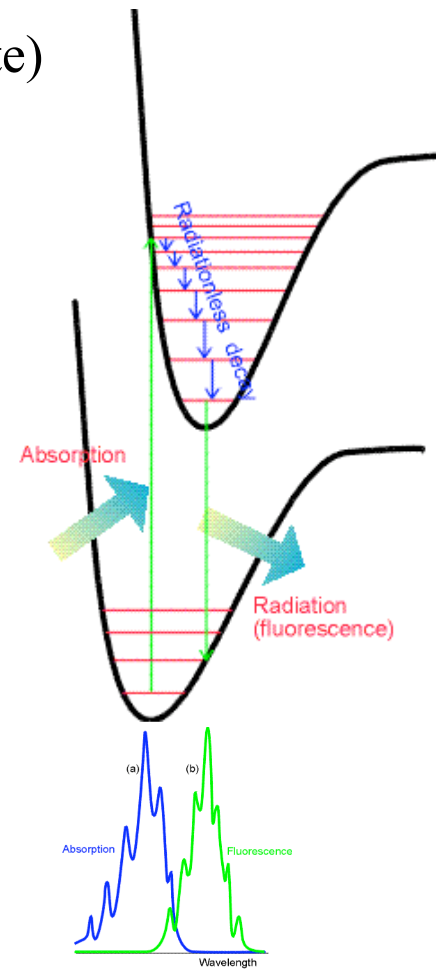
Photons can be produced during the deexcitation of the primary cations, scintillation devices rely on enhancing and detecting these photons. The primary ionization is ignored and these materials are generally insulators for reasons that we will discuss.

General requirements:

- Linear conversion of dE into photons (some only approximate)
- Efficient conversion into (near) visible light
  (e.g., NaI: 38k/MeV a value similar to N_{IP}/MeV)
- Transparent to scintillation photons, good optical medium
- Short decay time for fluorescence (ns OK, ps good)
- Good mechanical properties (n~1.5 for glass)

Scintillator classes:

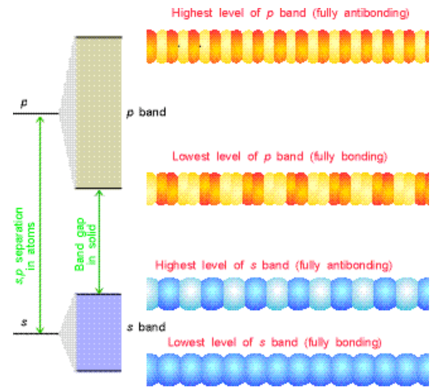
Organic molecules – molecular transitions in the fluor
Inorganic materials – transitions in atomic dopants

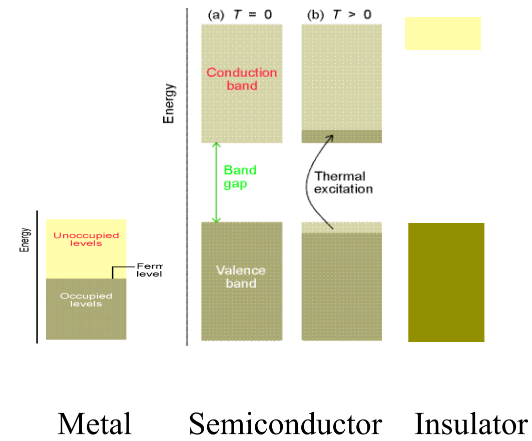


Molecular energy cycle for photon absorption/emission:
Notice that there is always a 'red-shift' in the emitted photons – energy loss, inefficiency!

Scintillation Counters – Inorganic Materials – 1

The band theory of solid materials in one sentence: the regular structure of the lattice and close proximity of atoms allows electron “molecular” orbitals that extend over the entire lattice whose energies merge into bands that preserve the underlying atomic orbital energy pattern.





The primary radiation creates an electron/hole pair which can recombine in various ways depending on the material and dopants or activators. The energy necessary to create a surviving pair is about 1.5-2 times the gap in ionic crystals and about four times the gap in covalent materials.

•Form an *exciton* (bound yet mobile e/hole pair) that decays directly, CdS

•Interleaved band structure of anions/cations in lattice, BaF_2

•Electron (or hole) is trapped by an impurity with levels in band-gap, NaI(Tl)

All of these processes emit photons with energies less than the size of the band gap. The impurity or “dopant” is chosen to provide visible photons.

Scintillation Counters – Light output/Track

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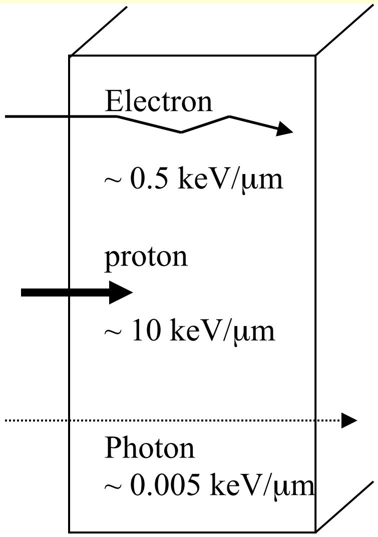


Consider the light output as a function of track length for three particles with 1 MeV incident on a (organic) scintillator:

$$\frac{dL}{dx} = S\frac{dE}{dx} \quad \textit{no recombination, etc.}$$

where L is the light output and S is the energy of the emitted photons compared to the energy of the incident radiation. $S = N_{h\nu} * (hc/\lambda) / E_{incident}$

In reality:

$$\frac{dL}{dx} = S\frac{dE}{dx}\Big/\left(1 + a\frac{dE}{dx}\right)$$

N.B. "a" is constant that depends on the material.

$$\frac{dL}{dx} = S\frac{dE}{dx} \quad \text{when} \quad \frac{dE}{dx} \text{ is small}$$

$$\frac{dL}{dx}\left(\frac{dE}{dx}\right)^{-1} = S \quad \text{or} \quad \frac{dL}{dE} = S$$

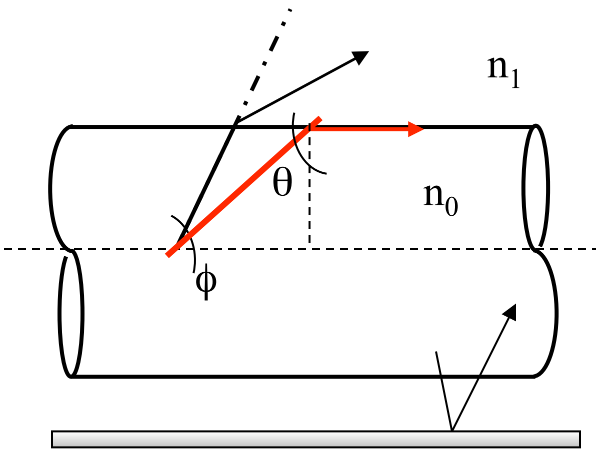
$$\int dL = \int S\,dE \quad \rightarrow \quad L = S * E$$

$$\frac{dL}{dx} = \frac{S}{a} \quad \text{when} \quad \frac{dE}{dx} \text{ is large}$$

$$\int dL = \int \frac{S}{a}dx \quad \rightarrow \quad L = \frac{S}{a}x$$

Scintillation Counters – Light Transmission

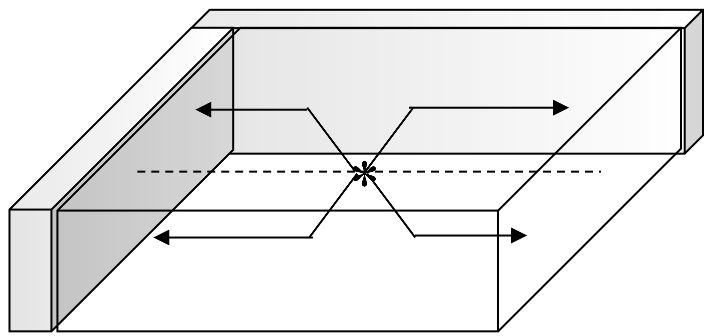
Round solid tube – light guide or scintillator – light pipe



Reflector – specular or *diffuse*

Internal reflection of light up to some critical angle, θ_c where $\sin\theta_c = n_1/n_0$ note that θ_c is normal to surface.

$$f = \frac{\Omega}{4\pi} = \frac{1}{4\pi}\int_0^{\varphi_C} 2\pi \sin\varphi \, d\varphi \rightarrow f = \frac{1}{2}\left(1-\cos\varphi_C\right) = \frac{1}{2}\left(1-\frac{n_1}{n_0}\right)$$



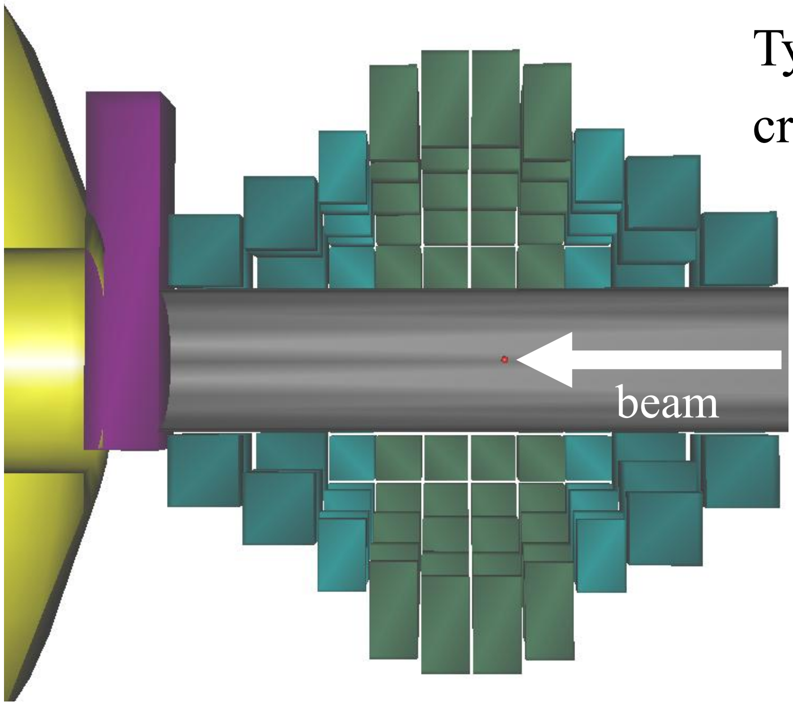
Slab: All edges

$$f = \frac{1}{2}\sqrt{1-\left(\frac{n_1}{n_0}\right)^2}$$

Attenuation Length: the light will suffer a Beer's Law attenuation along the path $I = I_0 e^{-x/L}$ where "L" is a characteristic attenuation length. L=2 m is good

The attenuation introduces a position sensitivity … allowing position measurement.

High-Efficiency Scintillator Array - CAESAR



Typical detector: 3”x 3” CsI(Na)

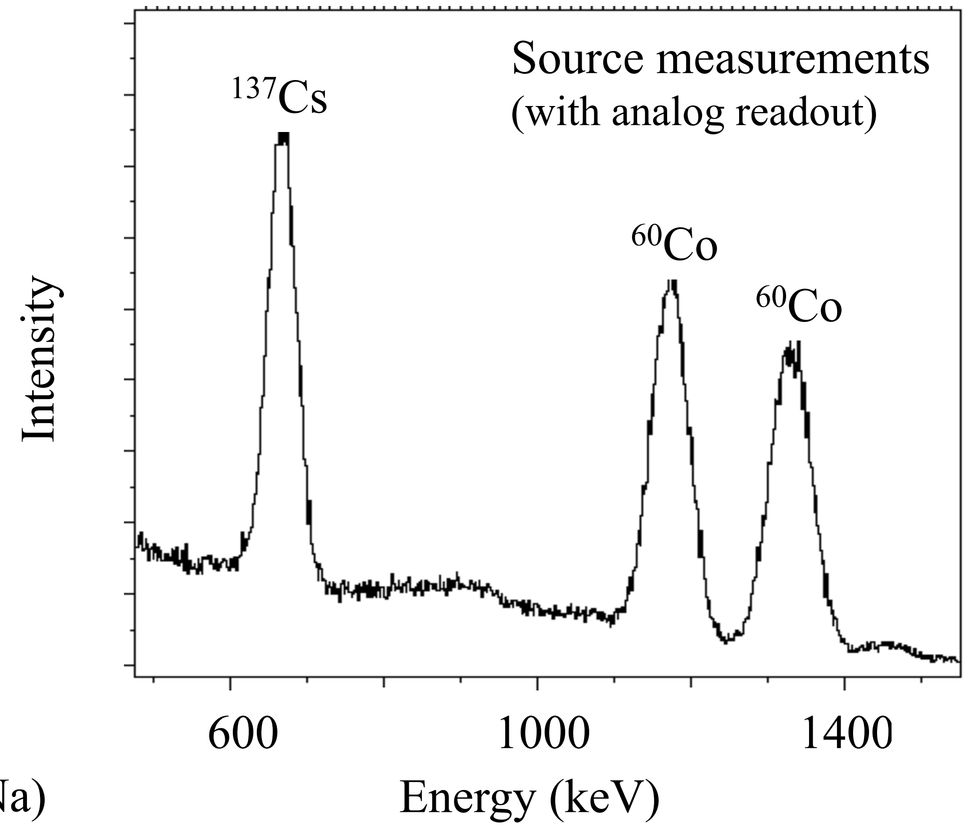
crystal+PMT/base+digital electronics (eMorpho)

Energy resolution (^{137}Cs):

6.6% (analog)   5.6% (digital)

Timing resolution:

7.0 ns (^{22}Na)   4.5 ns (^{60}Co)



GEANT simulations:

- Solid angle coverage 95%
- In-beam resolution (FWHM): 9.2% at 1 MeV
- Photopeak efficiency exceeding 40% at 1 MeV

Why CsI(Na) and not NaI(Tl)?

- 25-30% higher stopping power
- Superior resolution achieved with CsI(Na)

Scintillation Counters – Comparison

	Inorganic	Organic
Mechanism	Excitons recombine at dopants/color centers	Deexcitation of molecular π-electrons
Efficiency	Wide range: 0.1 NaI(Tl), 0.001PbWO4	Narrow range: 0.02 – 0.04
Track quenching ("a")	Small	Large
Time constant	Slow (~ μs)	Fast (tens of ns)
Temperature dependence	Large	Small
Radiation Damage	Creation of long term trapping centers	Destruction of primary fluors
Density	Generally high, 3.67 NaI(Tl), 8.28 PbWO4	Always low, 1 g/cm^3 ~ CH2
γ-ray detection	Important	Nearly insensitive
Pulse-shape discrimination	Possible in some cases	Fast/slow for γ/n

Neutron Detection – Nuclear Reactions

All neutron detection relies on observing a neutron-induced nuclear reaction.

The nuclear cross sections have a characteristic variation with energy:
•Charged particle reactions are dominated by the coulomb energy since both reaction partners have a positive charge: $\sigma(E) \sim \pi r^2 (1 - V/E)$ where "V" is the coulomb barrier.

•Neutron-induced reactions also have a characteristic shape .. The interaction is always attractive and the cross section for l=0 capture reactions always grows with 1/v at (very) low energies. The form is derived from the Breit-Wigner lineshape:

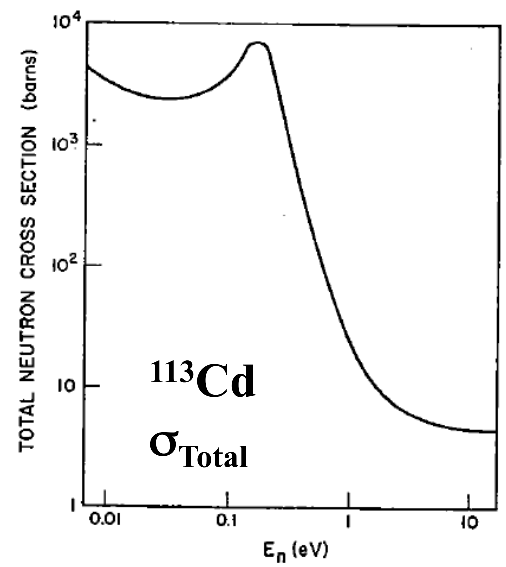
$$\sigma_{Cap} = \pi \bar{\lambda}^2 \frac{\Gamma_n \Gamma_\gamma}{(\mathbf{E} - E_0)^2 + (\Gamma/2)^2}$$

$$\sigma_0 = \pi \bar{\lambda}^2 \frac{4\Gamma_n \Gamma_\gamma}{\Gamma^2} \qquad \mathbf{E} = E_0; \Gamma = \Gamma_n + \Gamma_\gamma + \cdots \cong \Gamma_\gamma$$

$$\sigma_0 = 4\pi \bar{\lambda}^2 \frac{\Gamma_n}{\Gamma_\gamma} \qquad \bar{\lambda} = \frac{\hbar}{mv} \qquad \Gamma_n \sim v$$

$$\sigma_0 \sim \frac{1}{v}$$

$^{113}Cd + n \rightarrow {}^{114}Cd + \gamma$



Fast Neutron Detection

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All neutron detection relies on observing a neutron-induced nuclear reaction.

The capture cross sections for fast-neutron induced reactions are small compared to those at low energies (in the limit: geometric cross sections with occasional resonances).

Two approaches to detect fast neutrons:
– thermalized & capture which only provides a "count"

– Elastic scatter from protons at high energy – observe recoils for ToF techniques.

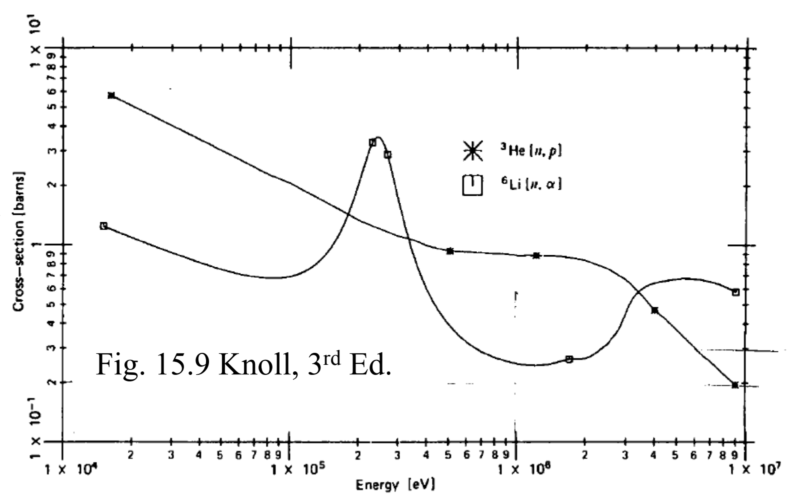

Fig. 15.9 Knoll, 3rd Ed.

Fast Neutron Detection: Scattering

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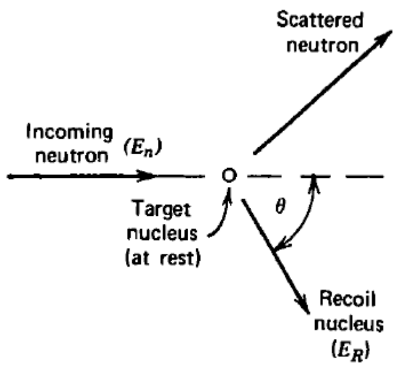


$$\frac{E_R}{E_n} = \frac{4A}{(1+A)^2} Cos^2\theta_{lab}$$

max at $\theta_{lab} = 0^o$ (neutron goes back, 180^o)

Tgt	A	$4A/(1+A)^2$
^1H	1	1
^2H	2	8/9=0.889
^4He	4	16/25=0.64
^{12}C	12	48/169=0.284

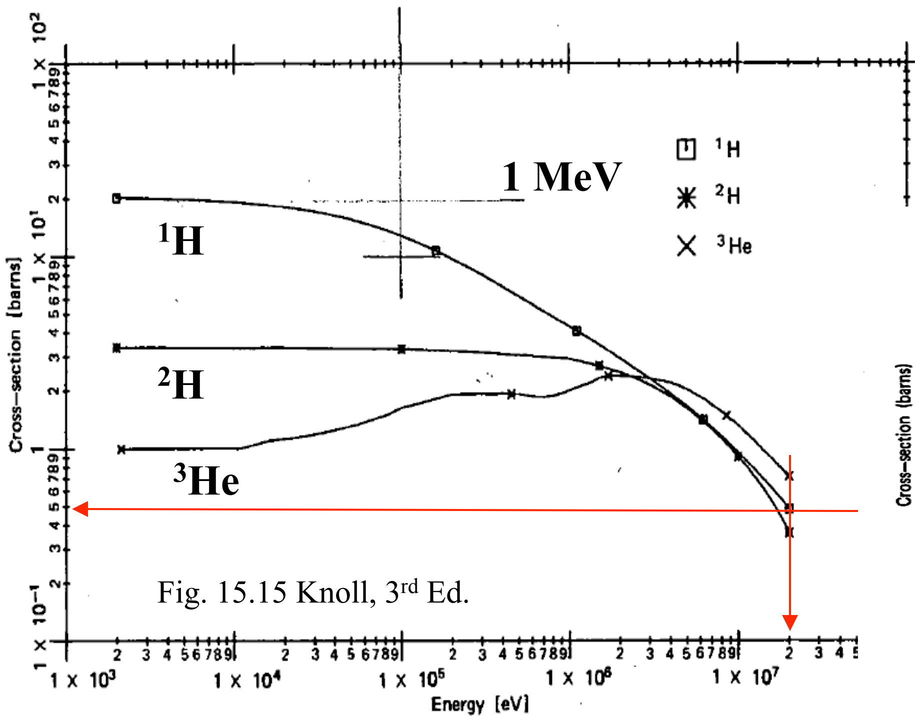
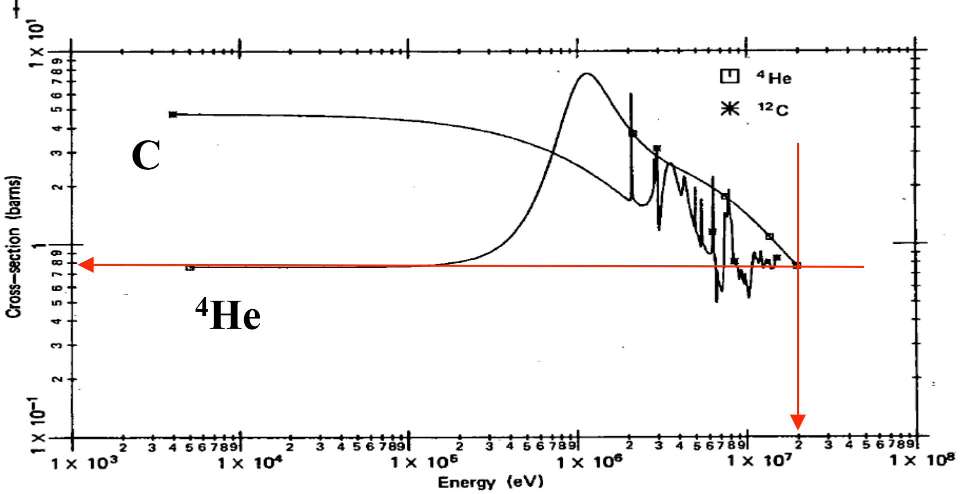


Fig. 15.15 Knoll, 3rd Ed.



Fast Neutron Detection: Scattering Pulse Height

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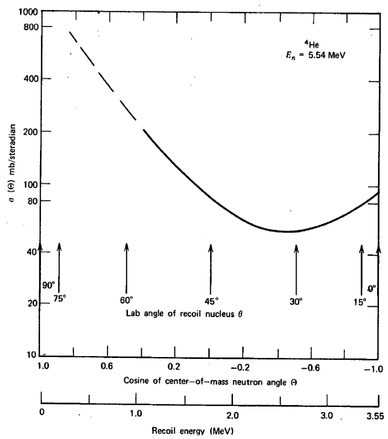
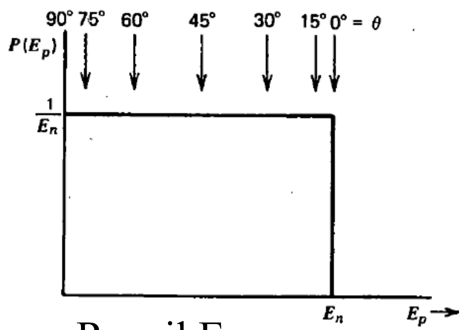




Recoil Energy

The ^{12}C(n,n') cross section has a modest angular distribution and small energy dependence on recoil angle.
The ^{1}H(n,n') distribution is flat.

Combine and fold with scintillator light output

2.6 MeV neutron
1"x1" stilbene

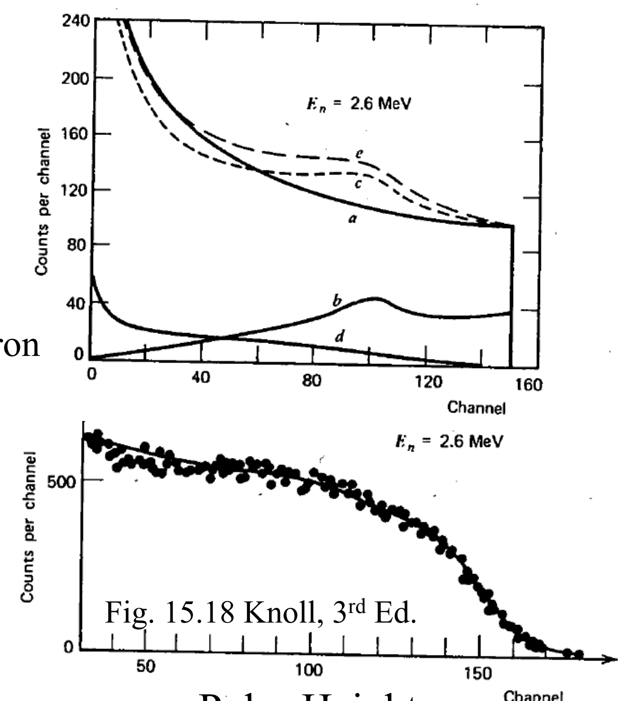
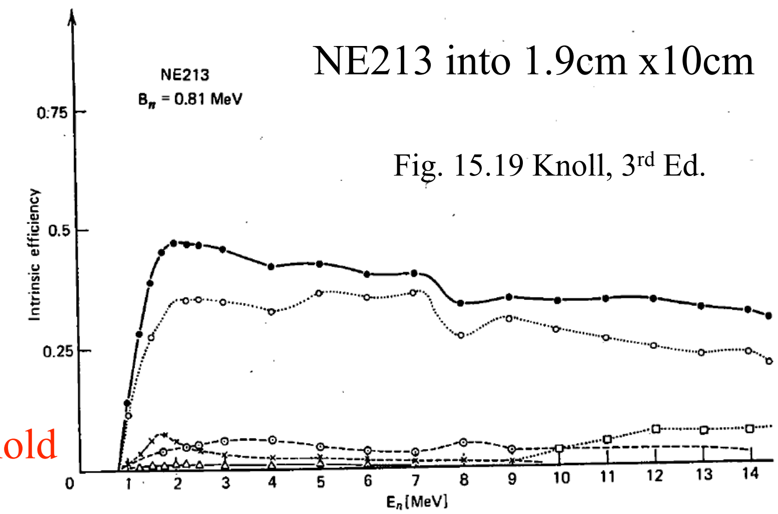


Fig. 15.18 Knoll, 3rd Ed.

Pulse Height

Channel

Set threshold to yield efficiency



NE213 into 1.9cm x10cm

Fig. 15.19 Knoll, 3rd Ed.

Fast Neutron Detection: Arrays for ToF

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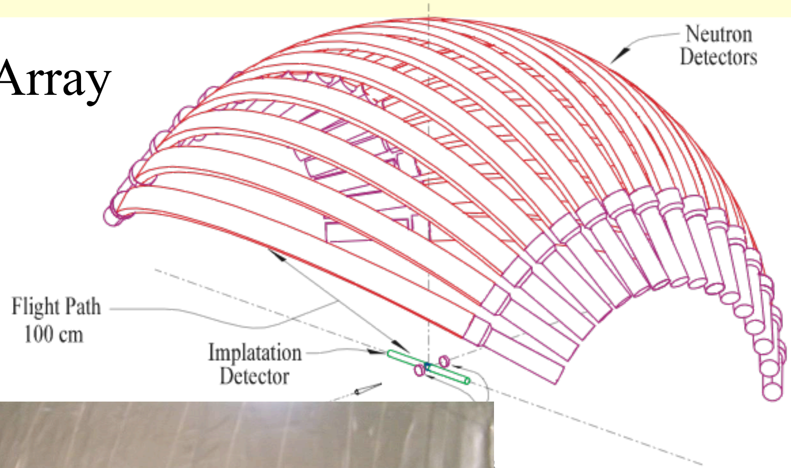
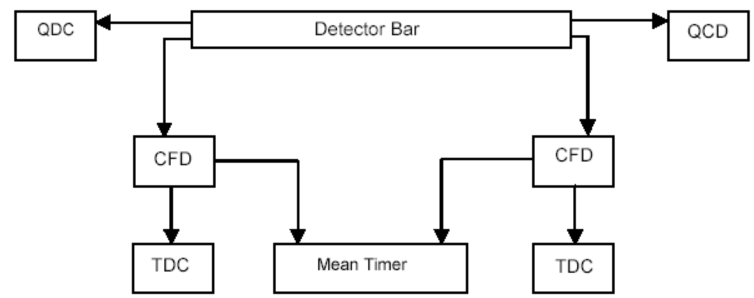
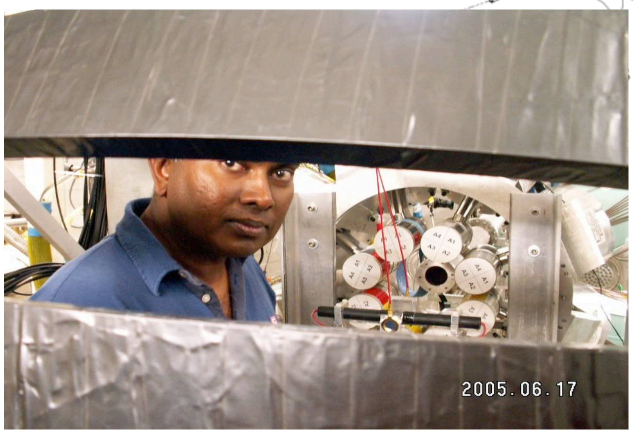
DNArray



$$E = \frac{m}{2}v^2 = \frac{m}{2}\left(\frac{L}{t}\right)^2 \qquad E_n << m_o c^2$$

$$\frac{dE}{dt} = \frac{-mL^2}{t^3} \rightarrow \frac{dE}{dt} = \frac{-2E}{t} \rightarrow \frac{dE}{E} = \frac{-2dt}{t}$$

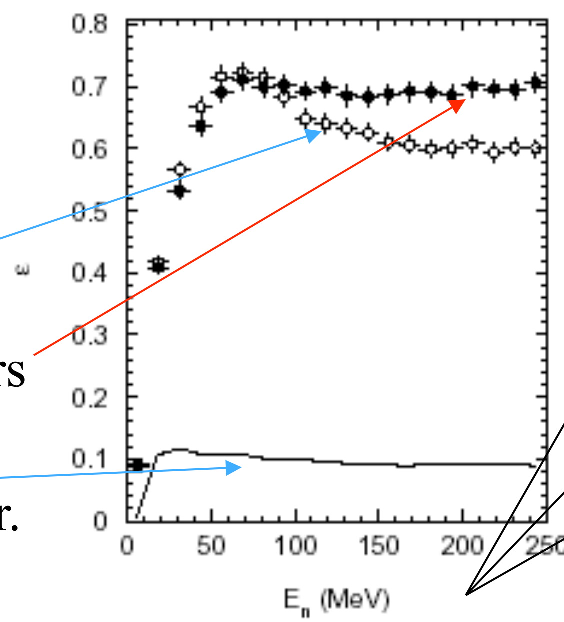


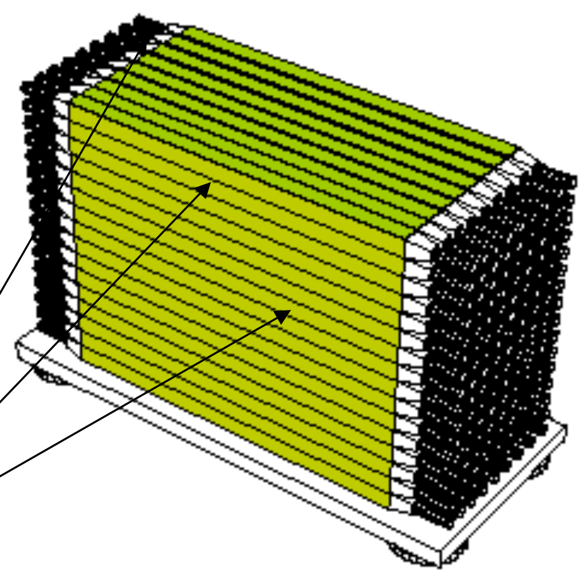


MoNA plastic scintillator
Ten layers – plastic scint.

Add Iron converter layers

NSCL "neutron wall"
One layer of liquid scintillator.





Pulse Processing: Active Pulse Shaping

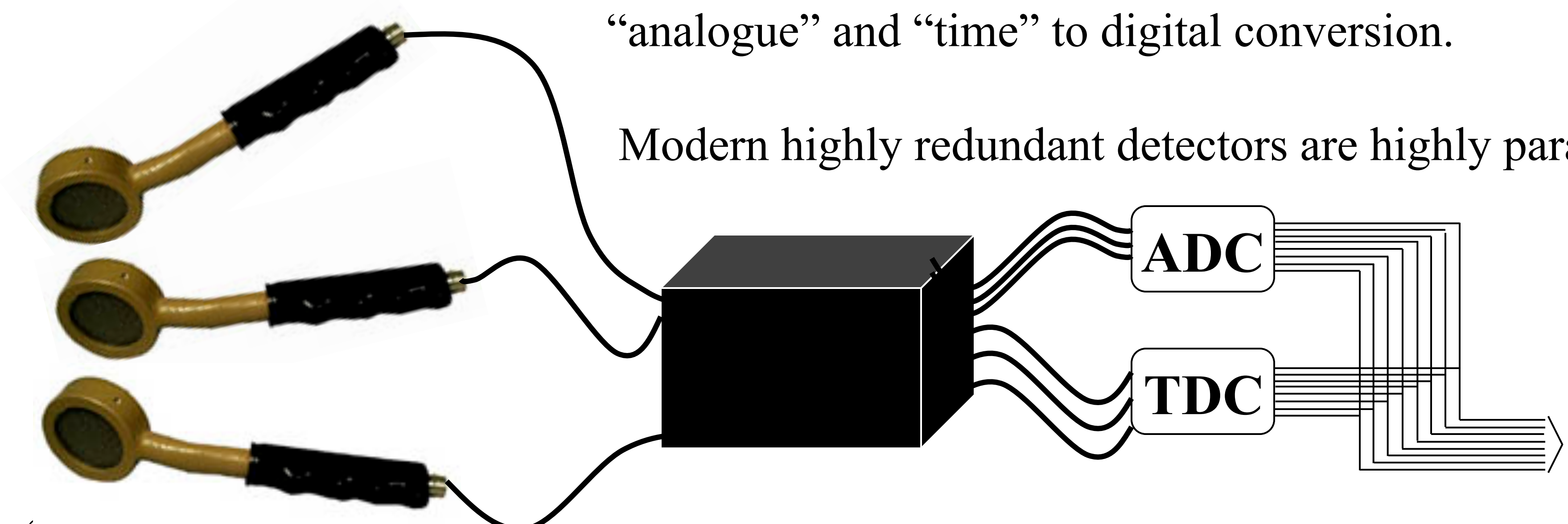
Why shape signals anyway?
The goal is to measure the charge created in the detector by the primary radiation and to maintain the time relationships of signals.

Pulses from detectors are generally small and either:
- Step functions, sharp rise, long pedestal or tail
- Very fast (sharp in time)
- Noise can be injected into the system at all levels

Time differences are best measured with logic pulses.

Modular electronic components are available for "analogue" and "time" to digital conversion.

Modern highly redundant detectors are highly parallel.



Pulse Processing: Pulse Shape

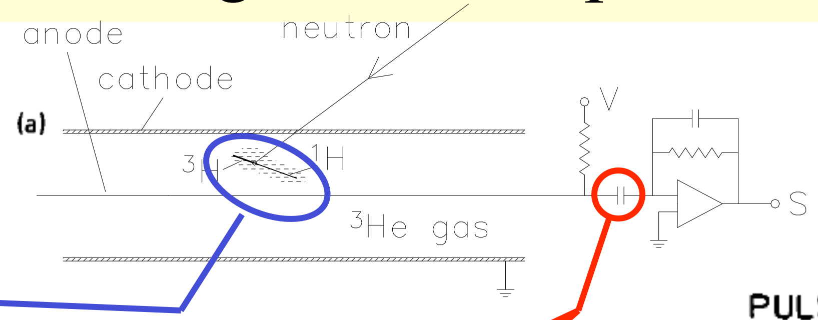
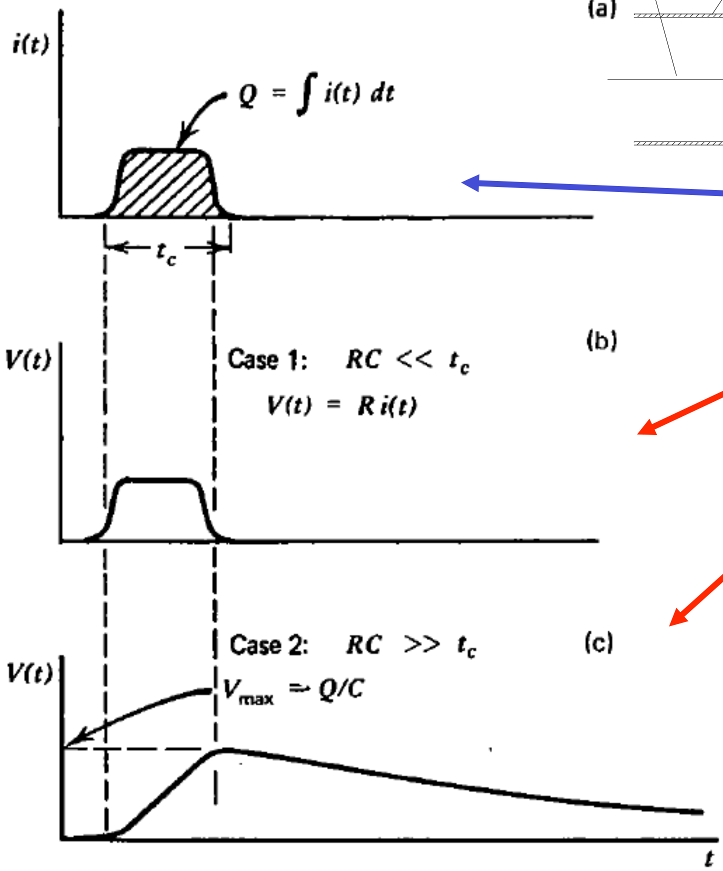
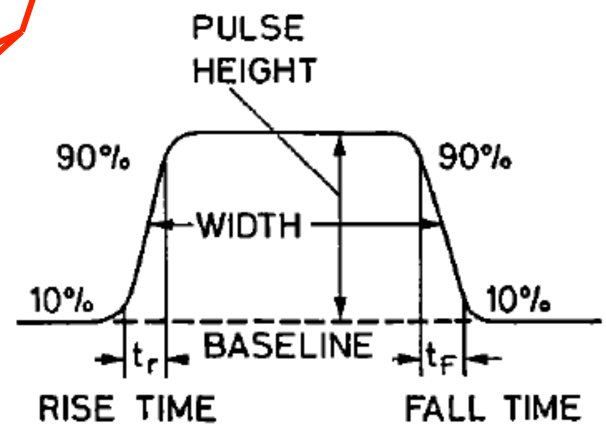


Fig. 4.1 Knoll, 3rd Ed.





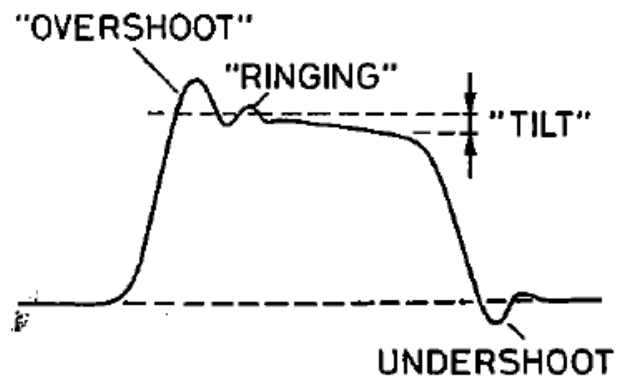


Fig. 11.1 Leo, 2nd Ed.

Leading or Falling edge
Rise or Fall time – 10:90%
(Uni or Bipolar // Analog or Digital)

Aside: Pulse Analysis & Noise

Noise in an electronic system is an unwanted signal that obscures the wanted signal.

For our purposes there are two classes of electronic noise:

•External noise: pickup of signals from sources outside the detector/electronics. Very often motors of various types, lights, ground loops. In principle, external noise can be avoided by careful construction, grounding and operation. (more on this in a moment)

•Internal noise: fundamental property of the detector/electronic components – can't be avoided by should be minimized by good design. There are three subclasses of internal noise:

Thermal noise (Johnson noise, series noise): mean value is zero but one expects fluctuations around zero. $\sigma(V) \sim \mathrm{Sqrt}(\ 4\ kT\ R\ \Delta f\ )$ where Δf is the frequency range of observation (bandwidth) – the variance tends to be small except for highest frequencies (fastest signals) – *a White Noise*

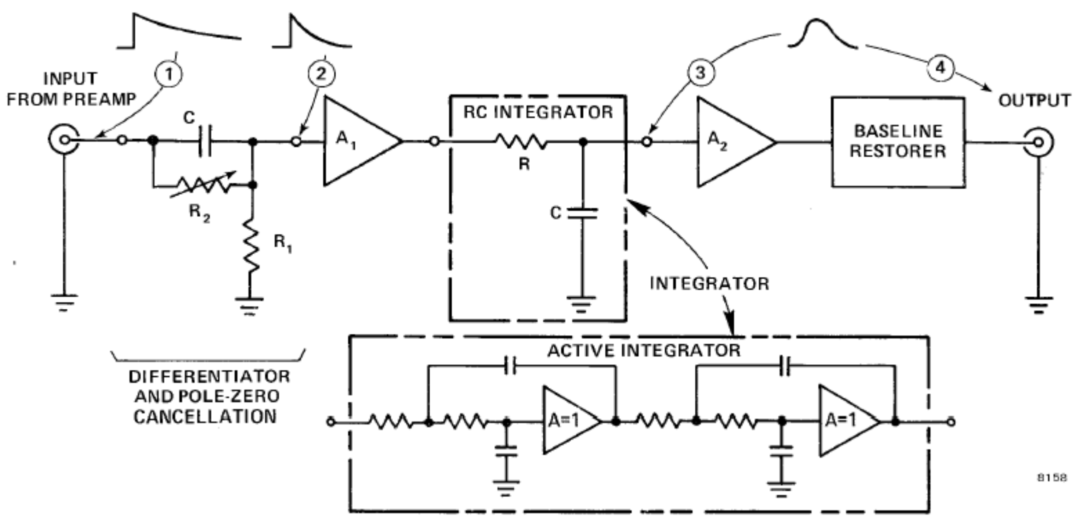
e.g. $\sigma(V) \sim \mathrm{Sqrt}(\ 4{*}0.026\ {*}1.6e\text{-}19{*}R{*}\Delta f\ ) \rightarrow 30\ \mu V$ at 50 Ω & 1ns at 300 K

Real components with R & C in parallel: $\sigma(V) \sim \mathrm{Sqrt}(\ kT/C\ )$

Shot noise (parallel noise): fluctuations in the current due to its quantization in electrons. $\sigma(V) \sim \mathrm{Sqrt}(\ 2\ q_e\ I_{DC}\ \Delta f\ )$ where I_{DC} is the (macroscopic) DC current – *a White Noise*

1/f noise: a catch-all for the fact that many sources of fluctuations have a exponential time dependence which transforms into a 1/f power spectrum.

Pulse Analysis: CR-(RC)^n shaper



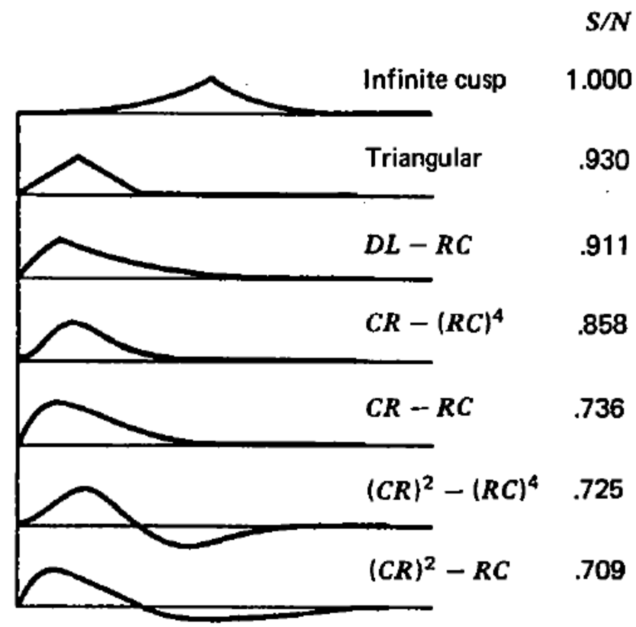


Fig. 17.15 Knoll, 3rd Ed.

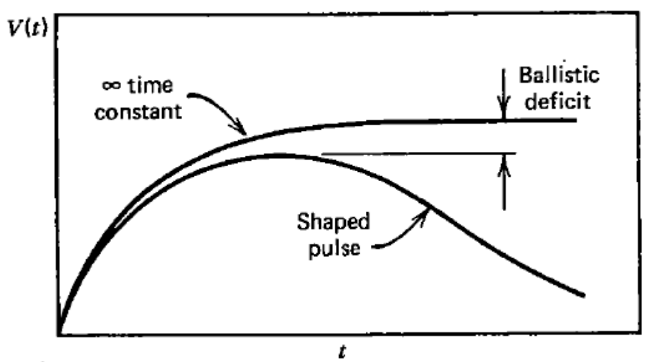


Fig. 17.13 Knoll, 3rd Ed.

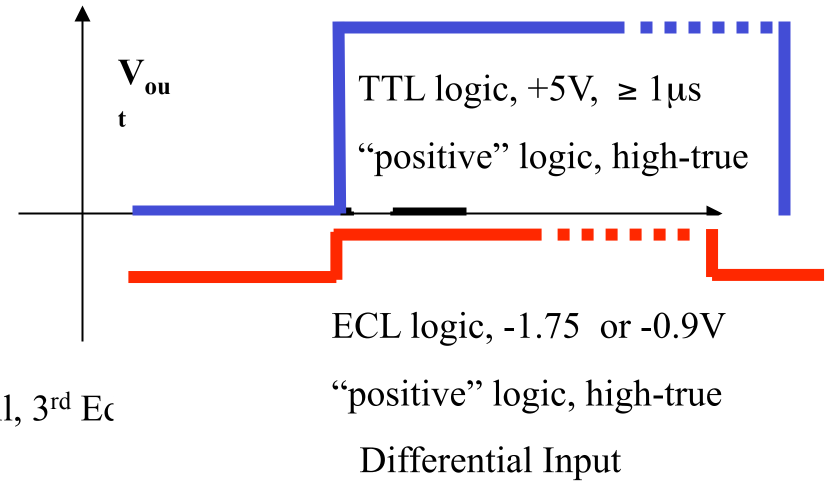
One more issue with shaping amps:

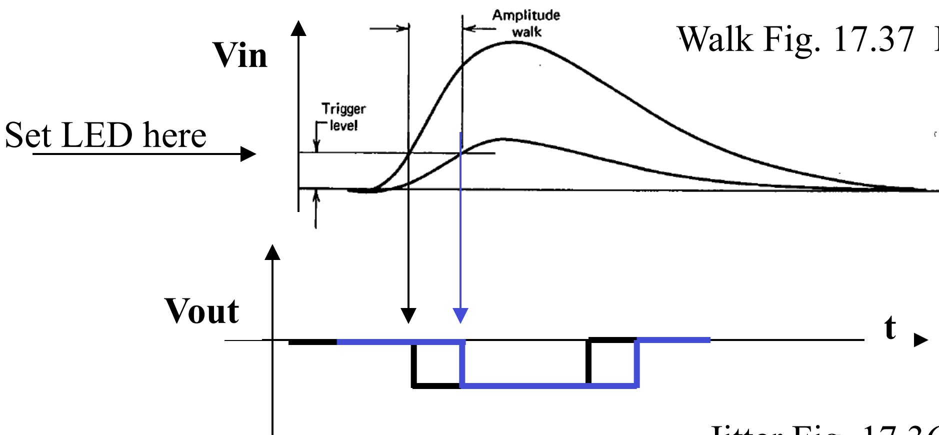
Can the shaping time be too short? Yes …

Thus, variations in the rise time will lead to signals with different pulse heights. Most significant for Ge detectors and proportional counters without grids.

Pulse Analysis: Leading Edge Discriminator

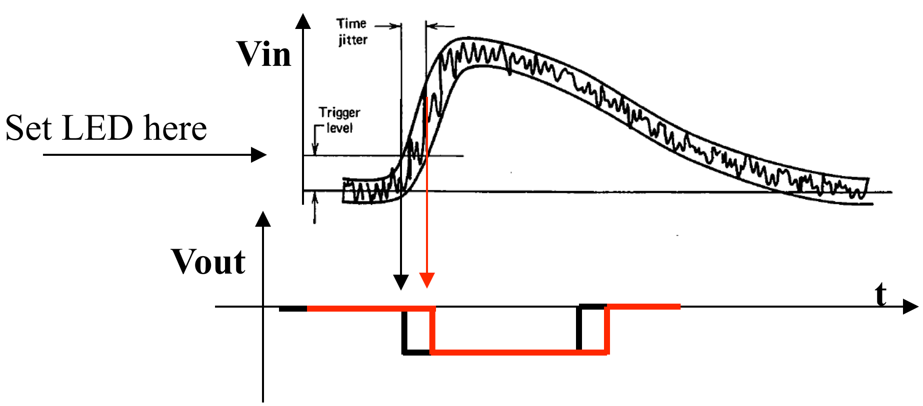
We need a way to generate a logic pulse that maintains a rigid time relationship to the interaction of the radiation in the detector.

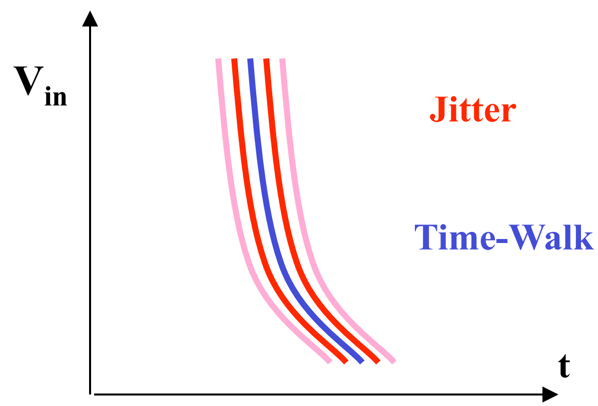




Walk Fig. 17.37 Knoll, 3rd Ec

Jitter Fig. 17.36 Knoll, 3rd Ed.





Z/C of bipolar pulse is constant in time but slow

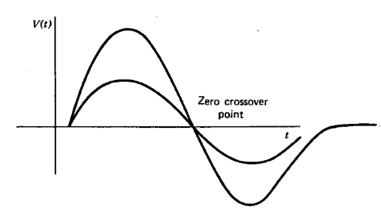


Fig. 17.39 Knoll, 3rd Ed.

Pulse Analysis: Linear Chains

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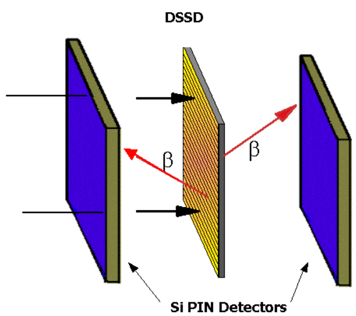
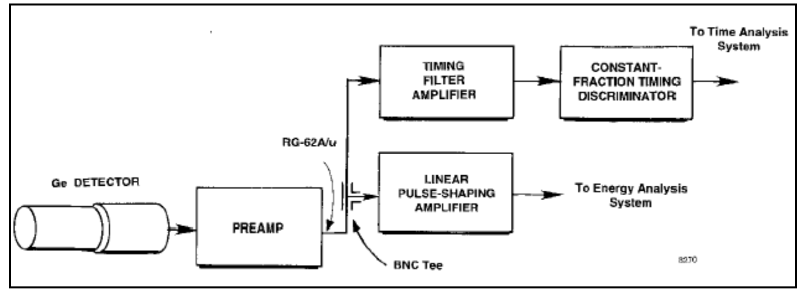
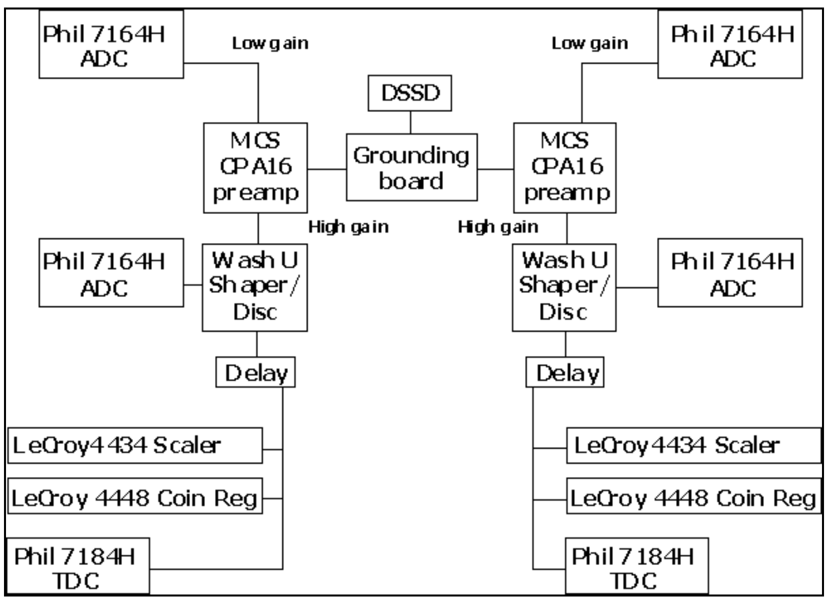




x 8 very high resolution (1/8192)



x 40 x 2 sides, High resolution (1/4096)
x 2 (low/high gains)

http://www.cem.msu.edu/~mantica/equip/betastrip.html

Analog to Digital Conversion

Final step in pulse processing is to convert the analog signal into a digital word.

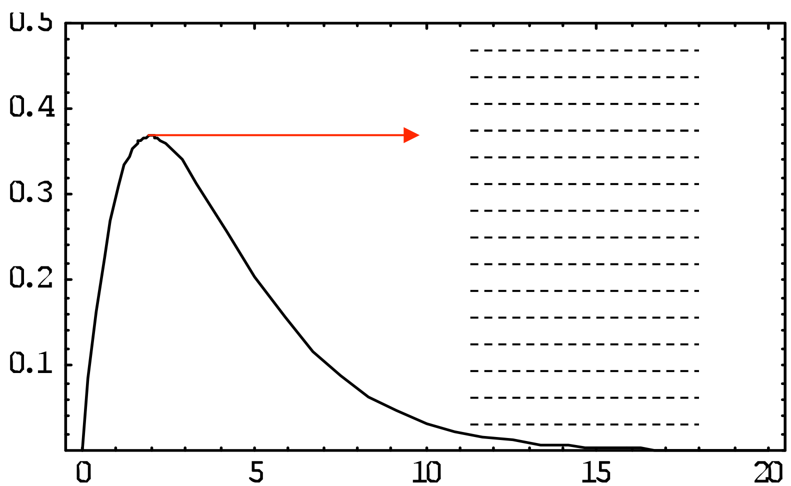
The input signal can be a voltage, charge or time difference and is compared to a reference voltage or charge by a variety of techniques. The choice of comparison circuit (procedure) generally determines:

Resolution, Non-linearity (integral and differential), and Conversion time

<u>Resolution:</u> the resolution of an ADC is specified in terms of both the (voltage) range and the digital range (number of bits).

The voltage associated with the least significant bit (LSB) is $(V_{max} - V_{min}) / 2^N$

Perfect device sorts the data into 2^N bins of equal width = 1 LSB



Example: $\Delta V = 0.5$ V

N=4, 2^N=16 V_{LSB}= 0.03125

Peak in bin #:

Decimal: 12 binary: 1100, Hex: C

Analog to Digital: conversion time

The input circuit can scale the input voltage range,
the number of bins and the conversion time (or input rate limit) are linked.
The following table is from the manufacturer *Analog Devices (www.analog.com)*

Analog-to-Digital Converters
Resolution/Throughput-Rate Selection Matrix

Resolution, Bits	<10 ksps	10 ksps to 100 ksps	100 ksps to 1 MSPS	1 MSPS to 10 MSPS	10 MSPS to 100 MSPS	100 MSPS +
17+	●	●	●	●		
14-16	●	●	●	●	●	●
12-13		●	●	●	●	●
10-11		●	●	●	●	●
8-9			●	●	●	●
<8					●	

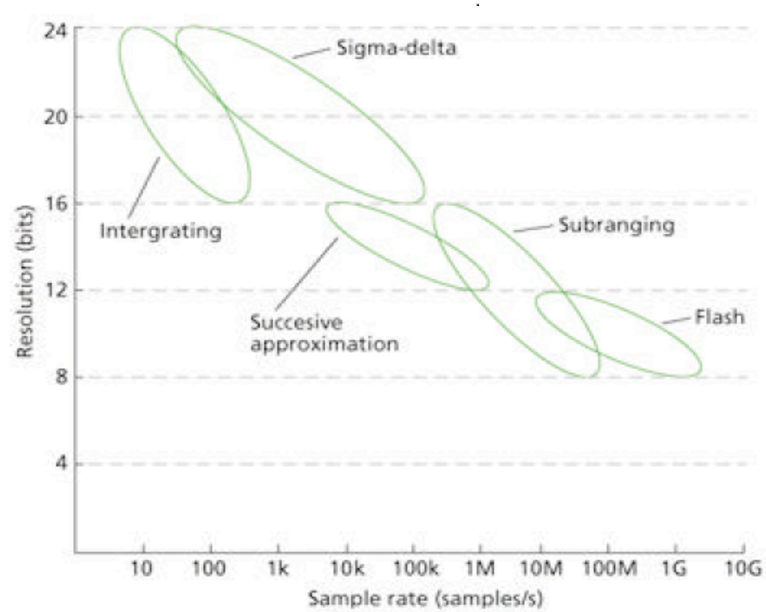
Throughput Rate

~ 10^8 b/s

~ 10 ns/b

SPS – samples / second

The algorithm used to convert the signal is correlated with the speed and resolution. Most modern devices are used in a nearly continuous mode, rather than in a pulse processing mode.



Typical nuclear physics pulsed device 12b /10 μs ~ 10^7 b/s

Data acquisition

The first question to ask is "do I have more than one detector?" ..

No – simple situation, use a multichannel analyzer (MCA). In a gross overview this is an ADC connected to a digital memory that keeps track of the number of signals that fall into each bin of the ADC. Most of the hardware is associated with the display of the data in memory. (Modern devices are contained on a PCI card that plugs into a PC.)

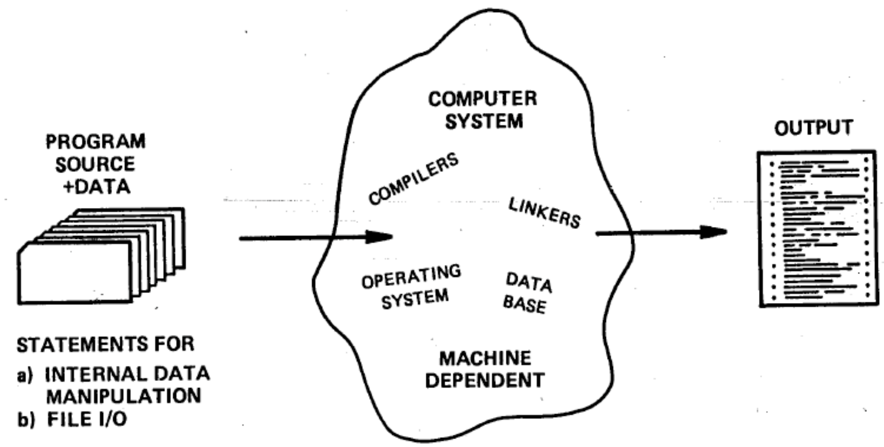
Fig. 18.7 Knoll, 3rd Ed.

Yes – more typical situation in nuclear science, generally want to retain correlations among the input signals. Up to present electronics/data recording are not fast enough to record everything (but getting closer). The experimenter has to set up some electronic logic to decide when to process and record the data.
This is called "Real Time" computing.

Data Acquisition: Real Time Computing

From LA-UR-82-2718 "CAMAC Primer"

Conventional Program runs (once) in a constrained world



Real-time Program has to respond to environment

Complex Detector Electronics: FPGA’s & ASIC’s

Complex systems and experiments with very high channel counts need to make a large number of logical decisions rapidly. Options for “electronic decision makers” include: a microprocessor (in CAMAC or VME), a field-programmable gate-array (FPGA), or an application-specific integrated-circuit (ASIC).

http://www.tutorial-reports.com/computer-science

	performance	NREs	Unit cost	TTM
High	ASIC	ASIC	FPGA	ASIC
	FPGA	FPGA	MICRO	FPGA
Low	MICRO	MICRO	ASIC	MICRO

ASIC = custom IC, MICRO = microprocessor

NRE’s – non-recurring engineering costs

TTM – time to market

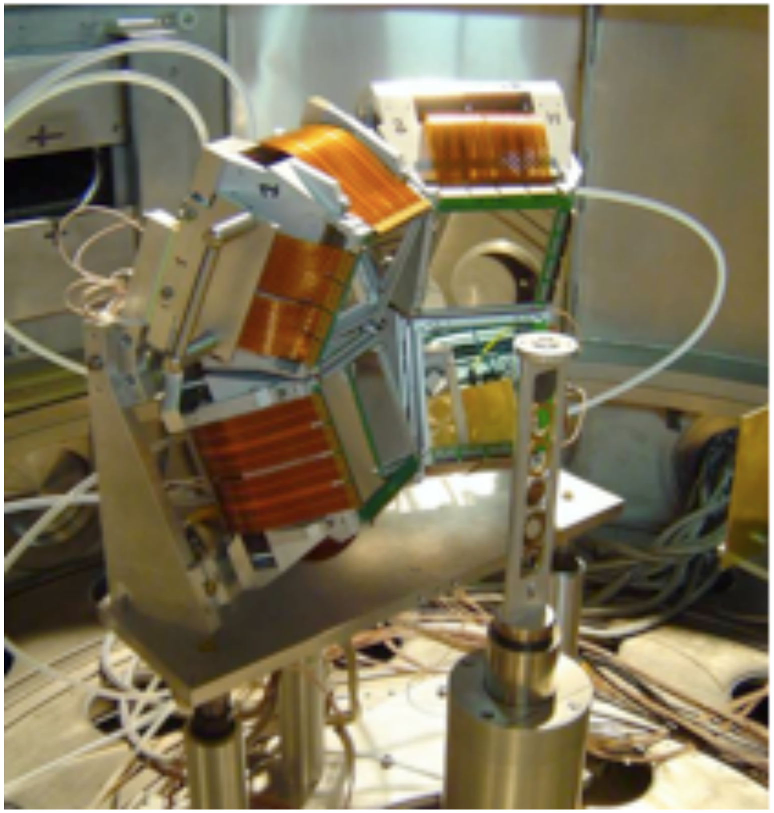
FPGA’s ... the manufacturer

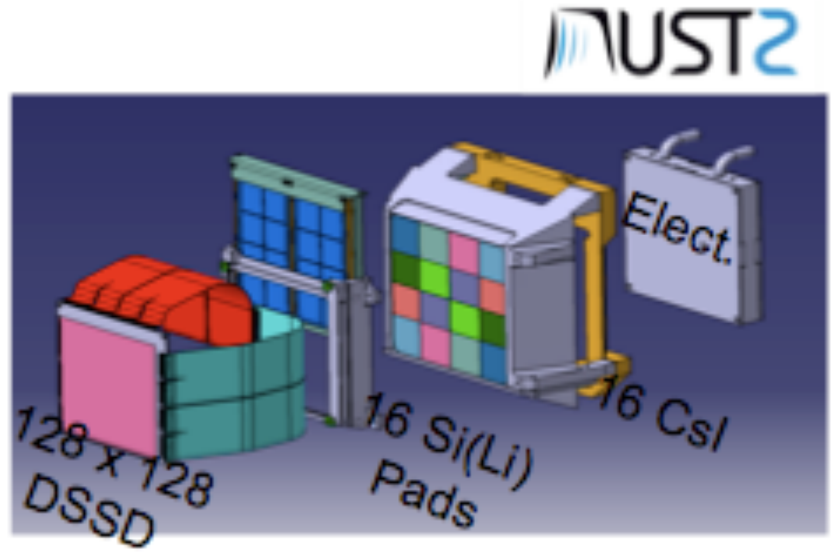
http://www.xilinx.com/

ASIC’s ... the website:

http://www-ee.eng.hawaii.edu/~msmith/ASICs/HTML/ASICs.htm

Complex Detector Electronics: MUST2





- 100 cm^2 area on front face
- 288 channels of Energy and Time (each)
- Si 300 μm / Si(Li) 5mm / CsI 4cm

Project **MUST2** (**MU**r à **ST**rips) is a multidetector of 10 telescopes; each telescope is made up with two X and Y plans of 128 Si tracks followed by 16 SiLi and 16 CsI. MUST2 is dedicated to the study of the light products produced from the interaction of radioactive beams with a target.

Complex Detector Electronics: MUST2

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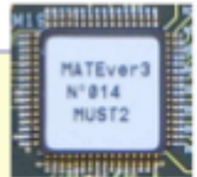
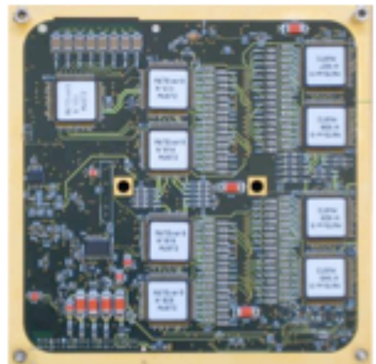
Asic solution for the Si, Si(Li) and CsI signals

MATE



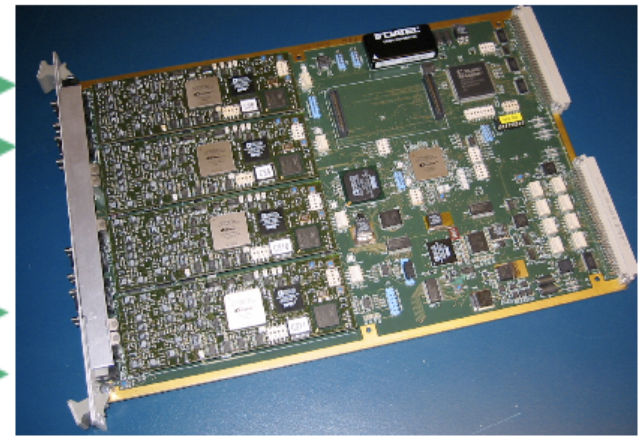
- 16 ch (E & T)
  - Bipolar
  - Energy
    - Shaping: 1μs/ 3μs
    - Range: 10 - 200 MeV
    - 20 keV FWHM (gene)
  - Time
    - Leading Edge
    - TAC (300 / 600 ns)
    - 300 ps FWHM (gene)
- Slow Control (I2C)
- Inspection (Debug)
- Chip 36mm²
  - BCMOS 0.8 μ
  - 16000 transistors
  - 35 mW/ch
- Serial output 2 MHz

MUFEE (2x per tel)



9x MATE
1x bus I2C
2x analog bus (Idif)
1x control line
Internal generator
Temperature probe

MUVI (4x tel)



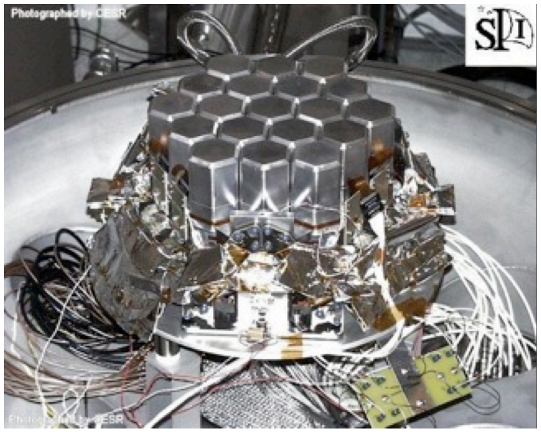
4x CAS
576 parameters
4 ADC 14 bits, **100μs DT**
Slow Control, C&C (DAC)
Scalers, Inspection
Time stamping (ATOM)

MUST2 Electronics is based on ASICs (Application Specific Integrated Circuit) so called **MATE**. MATEs are housed on **MUFEE** cards located closed to the detectors. In each MATE 16 detector channels are analog processed in order to get the 16 energy (E) and 16 time (T) analog steps . These steps are serially sent to MUVI.

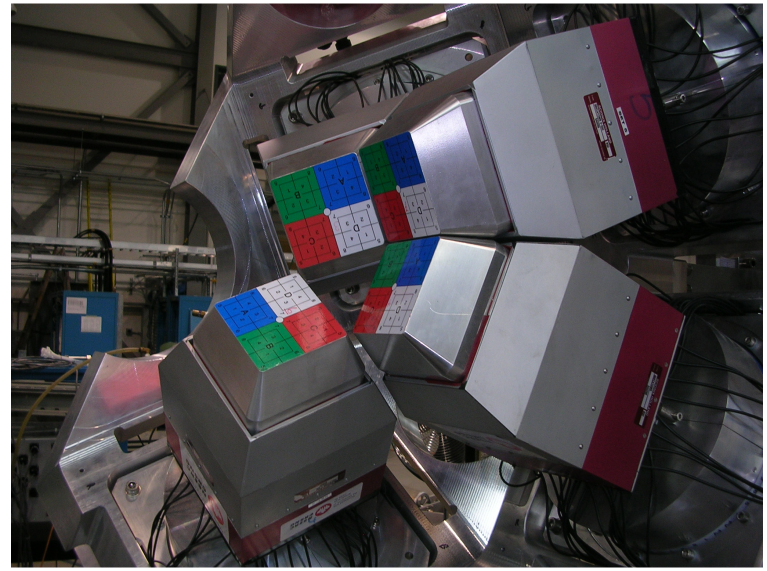
MUVI is a C sized VXI card in which are implemented the 14 bits analog to digital conversion, the digital processing, the physics parameters readout and the MATEs control. MUVI was specially designed in order to pay attention at the aspects of resolution, density of channel and reduction of the dead time of acquisition. It manages 4 telescopes and delivers more than 2000 E and T parameters processed in 4 **CAS** daughter cards.

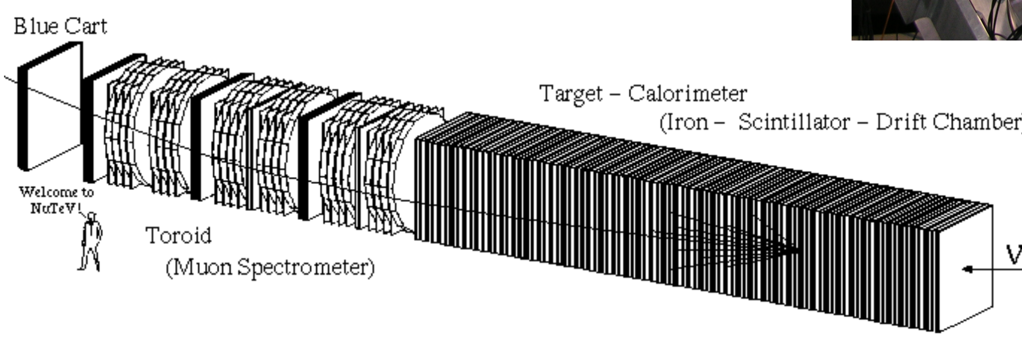
Overview of Whirlwind Presentation

Ge detectors on INTEGRAL spacecraft
for stellar nucleosynthesis detection



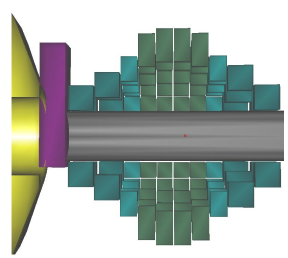
or in clusters for
nuclear rxn's





Stacks of scintillators and wire chambers for NuTeV experiment

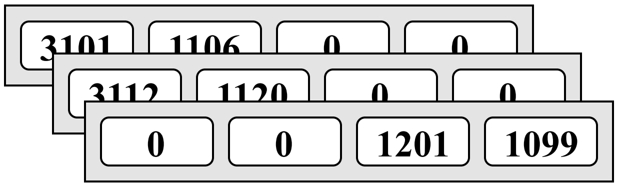
Barrel of CsI(Na) crystals for
nuclear structure studies



Aside: Data Acquisition: data stream

Options for Multidimensional data

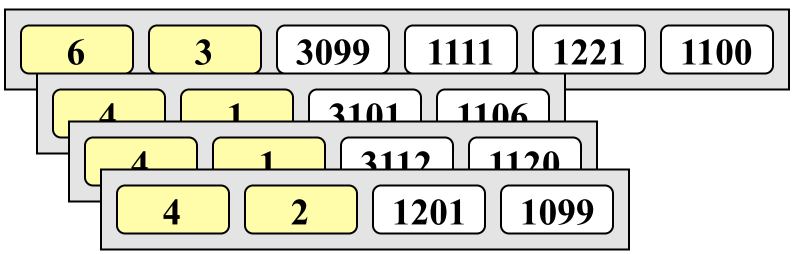
1) Record all values in order including zeros as placeholders (n-tuple)



Example of 2 detector data stream
Simple to interpret
"sparse" data (recall DSSD had 80 channels, only 2 valid)
error recovery from dropped words may be difficult

2) Record only non-zero words

A) imbed information in data stream (plus word count, pattern register)



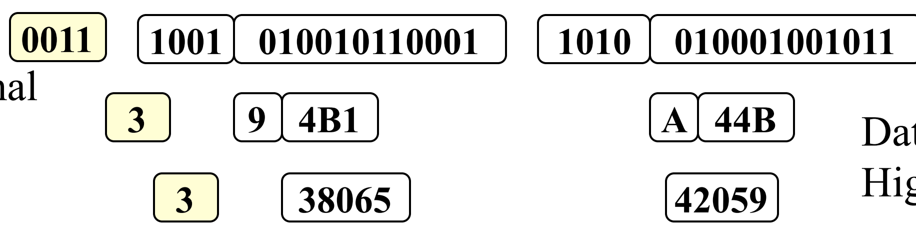
No gain for small experiments
Data needs to be "interpreted"
"dense" data

Problems from dropped words are localized

B) imbed information in data *words* (plus word count)

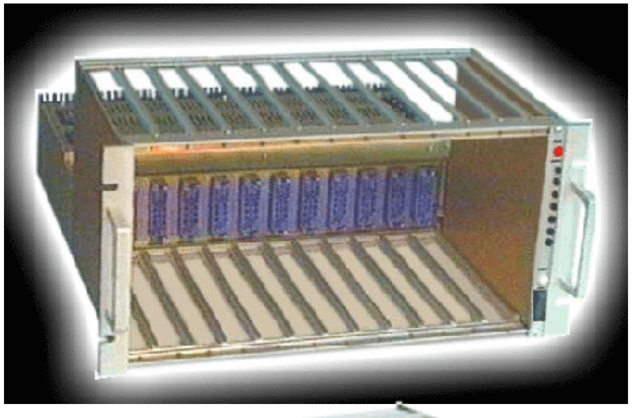
e.g. 16 bit word 4 bit ID, 12 bit data

Binary
Hexidecimal
Decimal



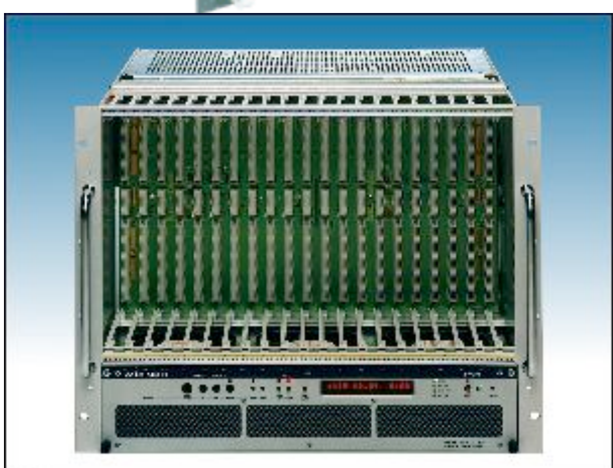
Data needs more "interpretation"
High level of error checking possible

Aside: Data Acquisition: Equipment Standards



NIM (nuclear instrumentation module):
Nuclear Physics standard container/voltages/power
Only signal lines are gate & clear (not geographic)
(not all pins on the connector block are used)

CAMAC (computer automated measurement and control):
Nuclear Physics standard container/voltages/power
Computer bus (back plane) with [86 lines]
Address lines / write / read (24b) / control lines
Bus speed 1 MHz .. Geographic: “BCNAF” “LAM”



VME (Versa Module Eurocard):
industry standard container/voltages/power
Computer bus
Address lines (32b) / data lines (32b) / control lines
Bus speed 20 MHz ..
Not geographic (unless JAUX bus is used),
Memory mapped … extensions VME64, VXI