Detectors for ionizing radiation: An introduction

presented today

by

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Literature

- "Techniques for Nuclear and Particle Physics Experiments" by W.R. Leo
  (my recommendation, but out-of-date in some areas)
- "Measurement And Detection Of Radiation" by N. Tsoulfanidis and S. Landsberger
  (recent 3rd edition, I didn't read it yet, but it's pretty up-to-date)
- "Radiation Detection And Measurement" by G. Knoll
  (The device physicists' bible, but beginners may get lost soon…)

(most pictures presented in this lecture are taken from those books and referenced as [LEO], [TSO], [KNO])

Aim of this lecture is …

… to give an introduction and overview on radiation detectors.

In this lecture following color coding is used:

- red boxes: This YOU HAVE to know (I think)
- green boxes: You should have heard about it, if you need it you look it up
- everything else: Considered as ‘yellow’ box somewhere between red and green…..

Talking about detectors….

…for ionizing radiation we have to discuss two major questions:

How does radiation interact with matter?

And

How does a detector generate a signal?

Energy loss of charged particles in matter

Protons, Alphas, heavy particle (mostly) interact with electrons of the absorber. The energy loss along dx is described by the **Bethe-formula**:

$$-dE/dx = z^2/E * N Z B$$

E: Kinetic energy of particle; z: charge of the particle; N Z : Density/Z of absorber

B: Some wild expression you'll find in any textbook

Notice: For heavy ion with < MeV/A "Nuclear Stopping" becomes dominant

Essential: $\mathbf{dE/dx \sim z^2/E}$

This relationship let you understand most particle ID (pid) techniques

At NSCL we usually deal with particle energies >> 10MeV/A

Electrons: also Bremsstrahlung has to be taken into account. For our purpose we need to know that a 1MeV electron is stopped within ~1mm or less in a solid.

Example: Range of charged particles in Si

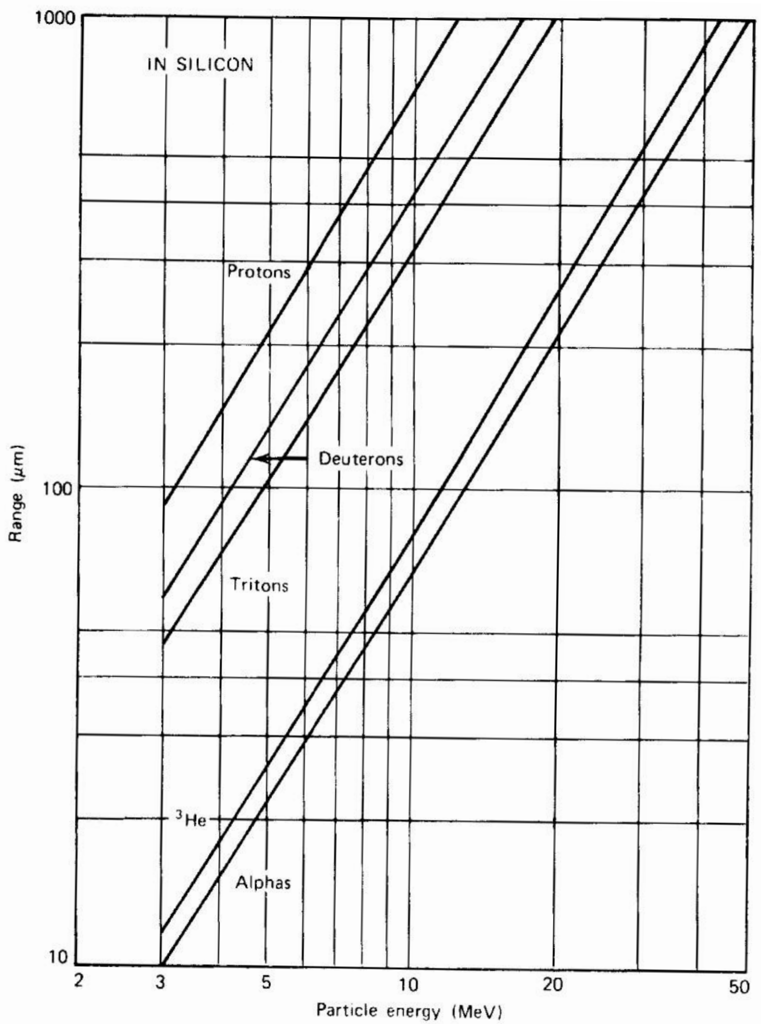
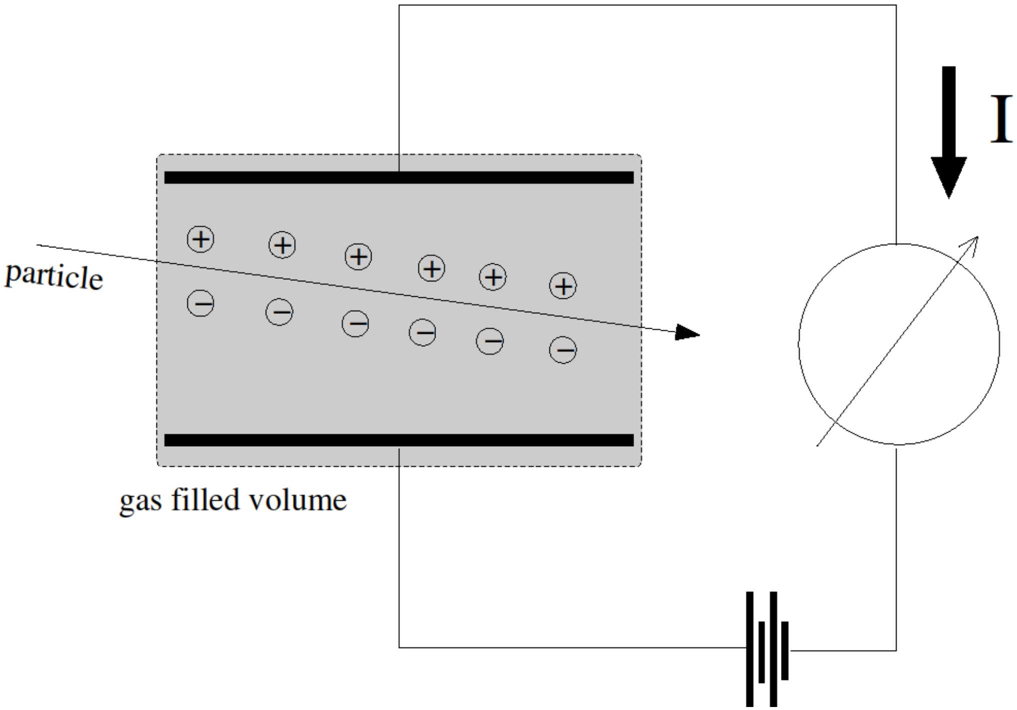


Figure 2-7 Range–energy curves calculated for different charged particles in silicon. The near-linear behavior of the log–log plot over the energy range shown suggests an empirical relation of the form $R = aE^b$, where the slope-related parameter b is not greatly different for the various particles. (From Skyrme.[3])

[KNO]

A good tool to calculate energy loss is the "physical calculator" in LISE++ (**http://groups.nscl.msu.edu/lise/lise.html**)

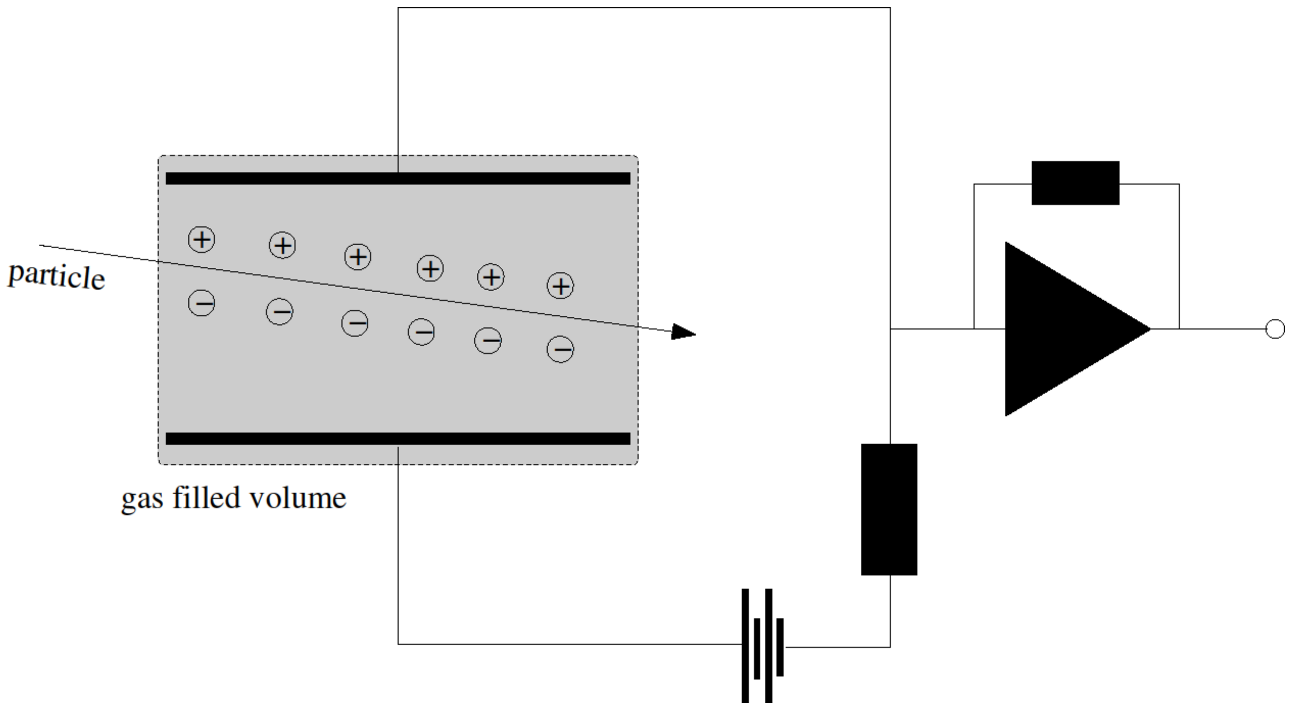
Our first detector: Ionization Chamber



A charged particle travels through a gas filled volume. According Bethe formula it does produce ion-electron pairs. An applied electric field let the charges drift to the electrodes and an electric current will flow.

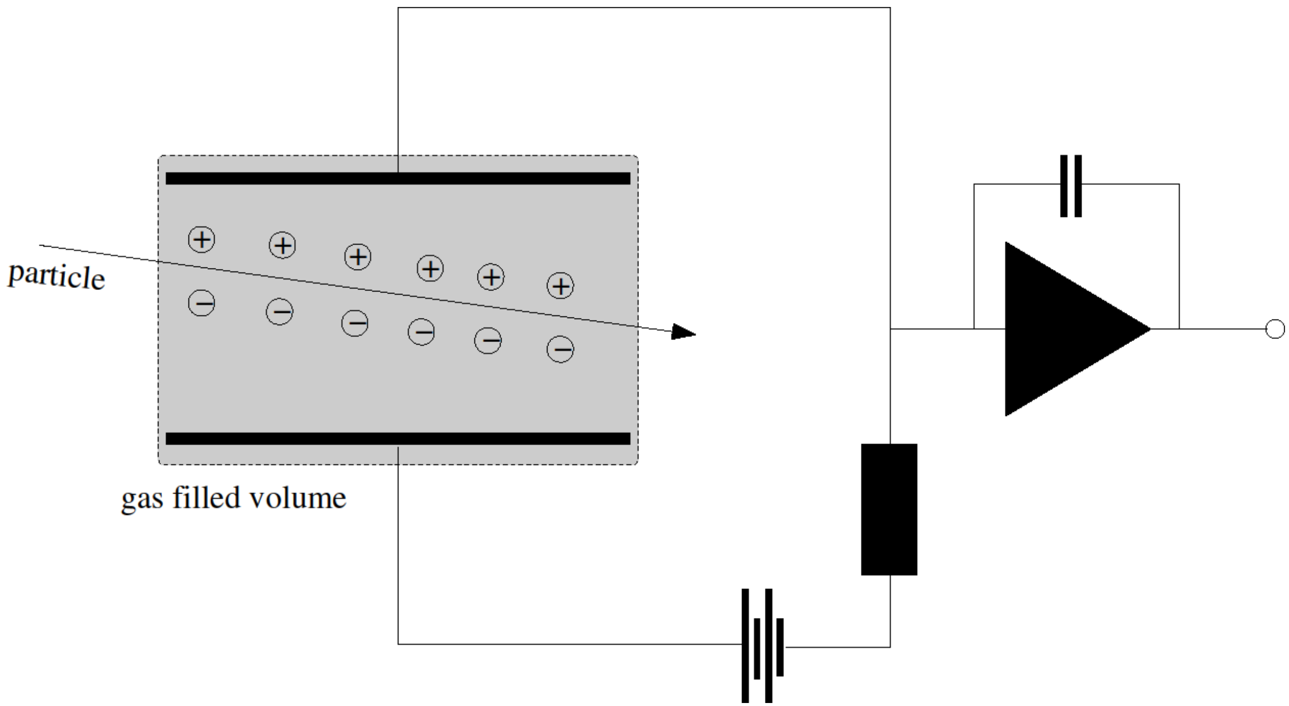
Typically 30-40eV are needed to create an ion pair.

Ionization Chamber: Current signal



Sitting with an amperemeter next to the chamber is NOT convenient. Therefore a **Current-to-Voltage converter** is used (simple resistor and U=RI) and voltage is transmitted to processing electronics (Remco's lecture) via a **Linear Preamplifier**

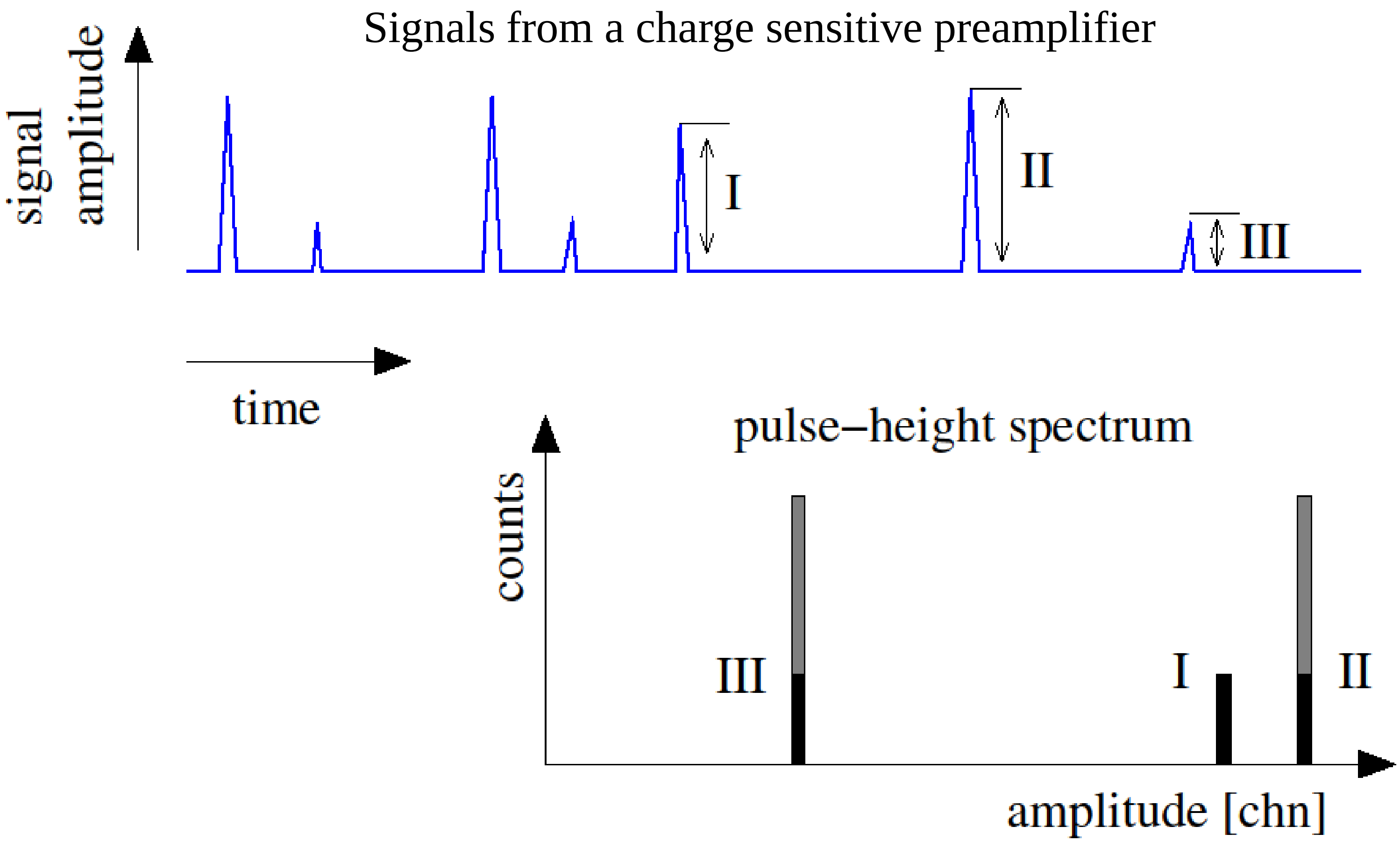
Ionization Chamber: Charge signal



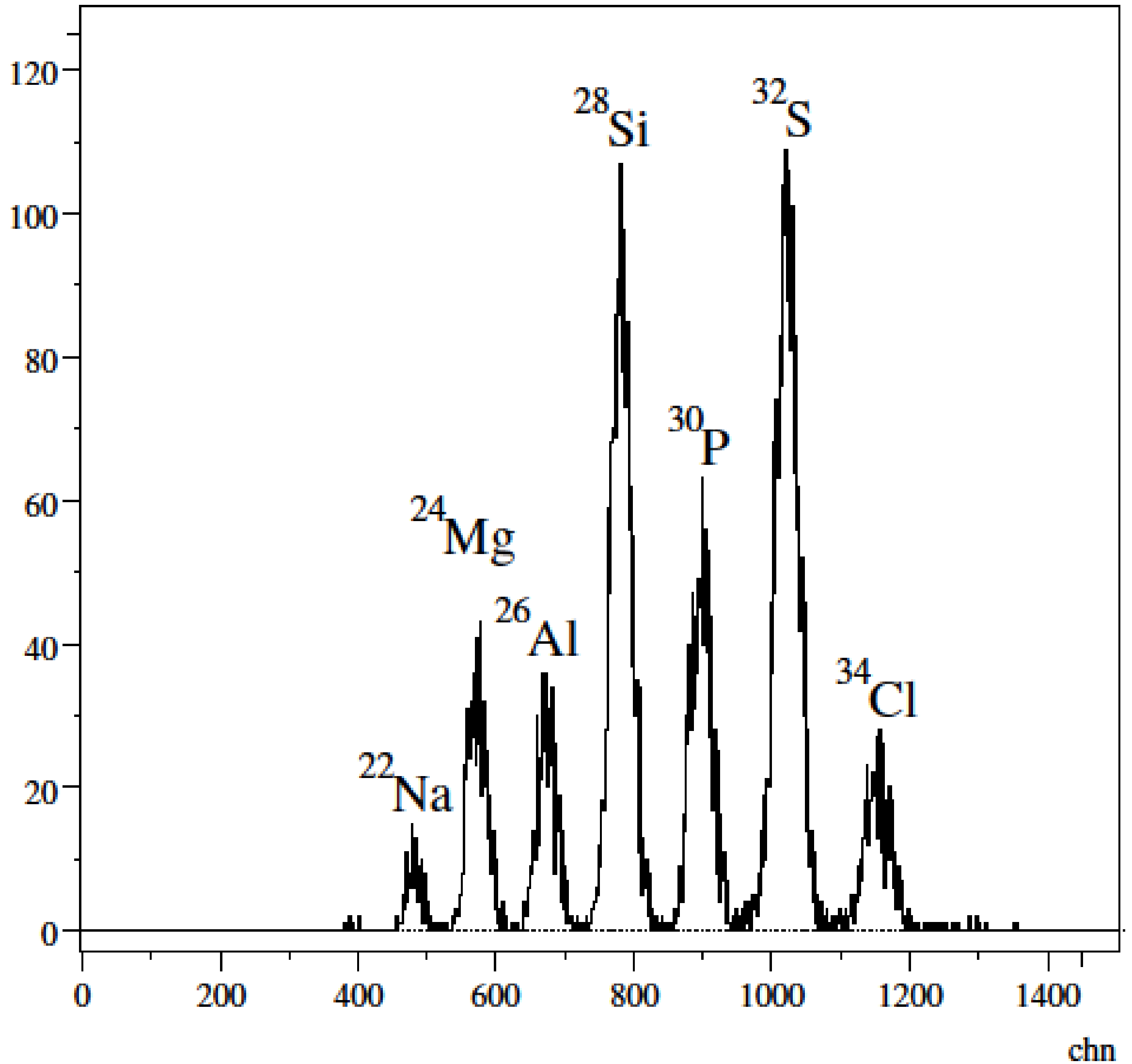
Actually the total charge collected gives the energy deposited in the chamber ($E \sim q = \int I dt$). A **Charge-Sensitive Preamplifier** carries out this integration.

Not shown: The preamplifier would saturate after many events. Additional circuits reset the integrating stage.

How a pulse-height spectrum is made

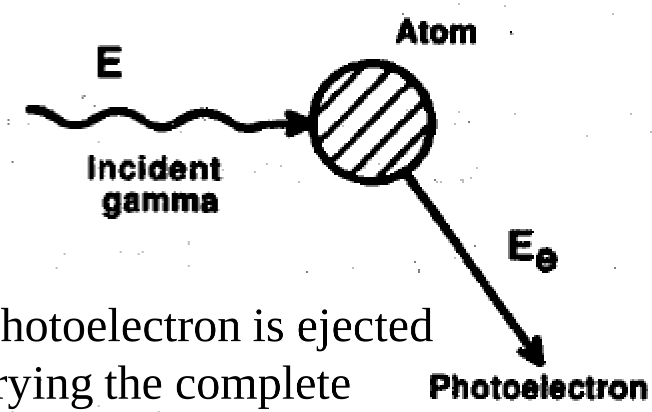


Pulse-height spectrum (S800 ion chamber)



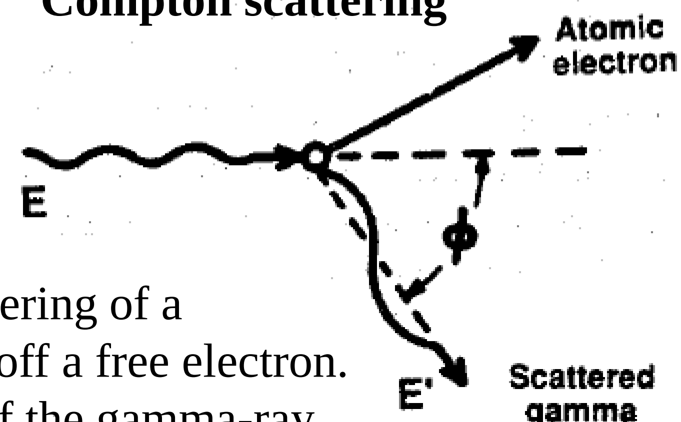
Interaction of gamma rays with matter

Photo effect



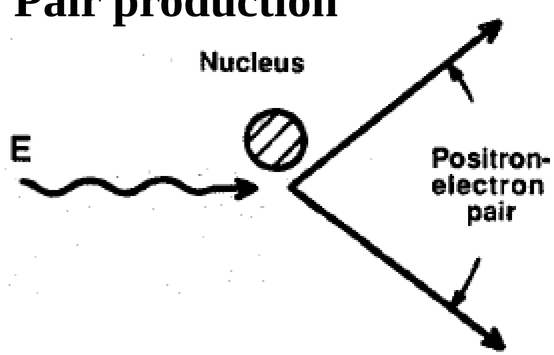
A photoelectron is ejected carrying the complete gamma-ray energy (- binding)

Compton scattering



Elastic scattering of a gamma ray off a free electron. A fraction of the gamma-ray energy is transferred to the Compton electron

Pair production



If gamma-ray energy is >> 2 $m_o c^2$ (electron rest mass 511 keV), a positron-electron can be formed in the strong Coulomb field of a nucleus. This pair carries the gamma-ray energy minus 2 $m_o c^2$.

Compton scattering: More Details

Compton formula:

$$E' = \frac{E}{1 + \frac{E}{m_0 c^2}\,(1 - \cos\theta)}$$

Special case for E>>1:
gamma-ray energy after 180^o scatter is approximately

$$E' = \frac{m_0 c^2}{2} = 256\ \text{keV}$$

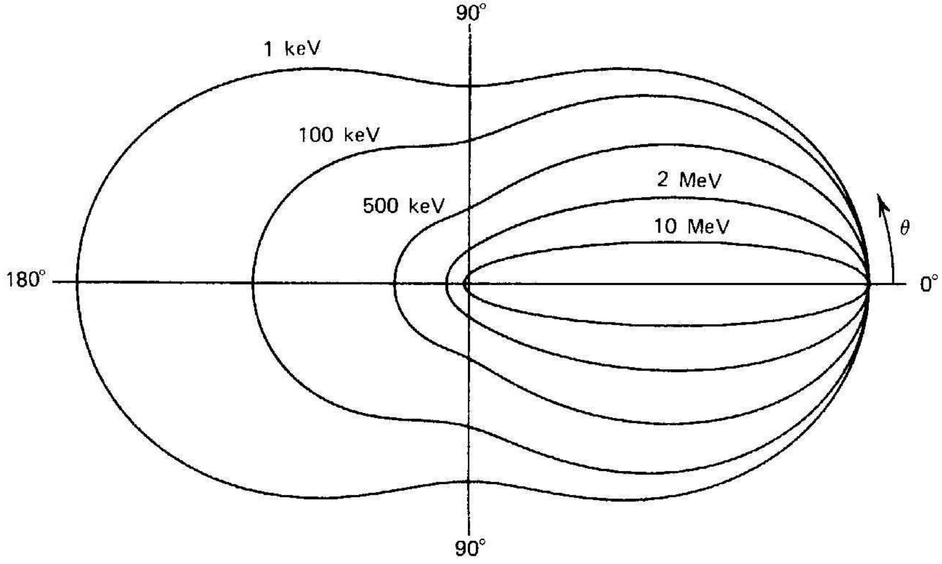


Figure 2-19 A polar plot of the number of photons (incident from the left) Compton scattered into a unit solid angle at the scattering angle θ. The curves are shown for the indicated initial energies.

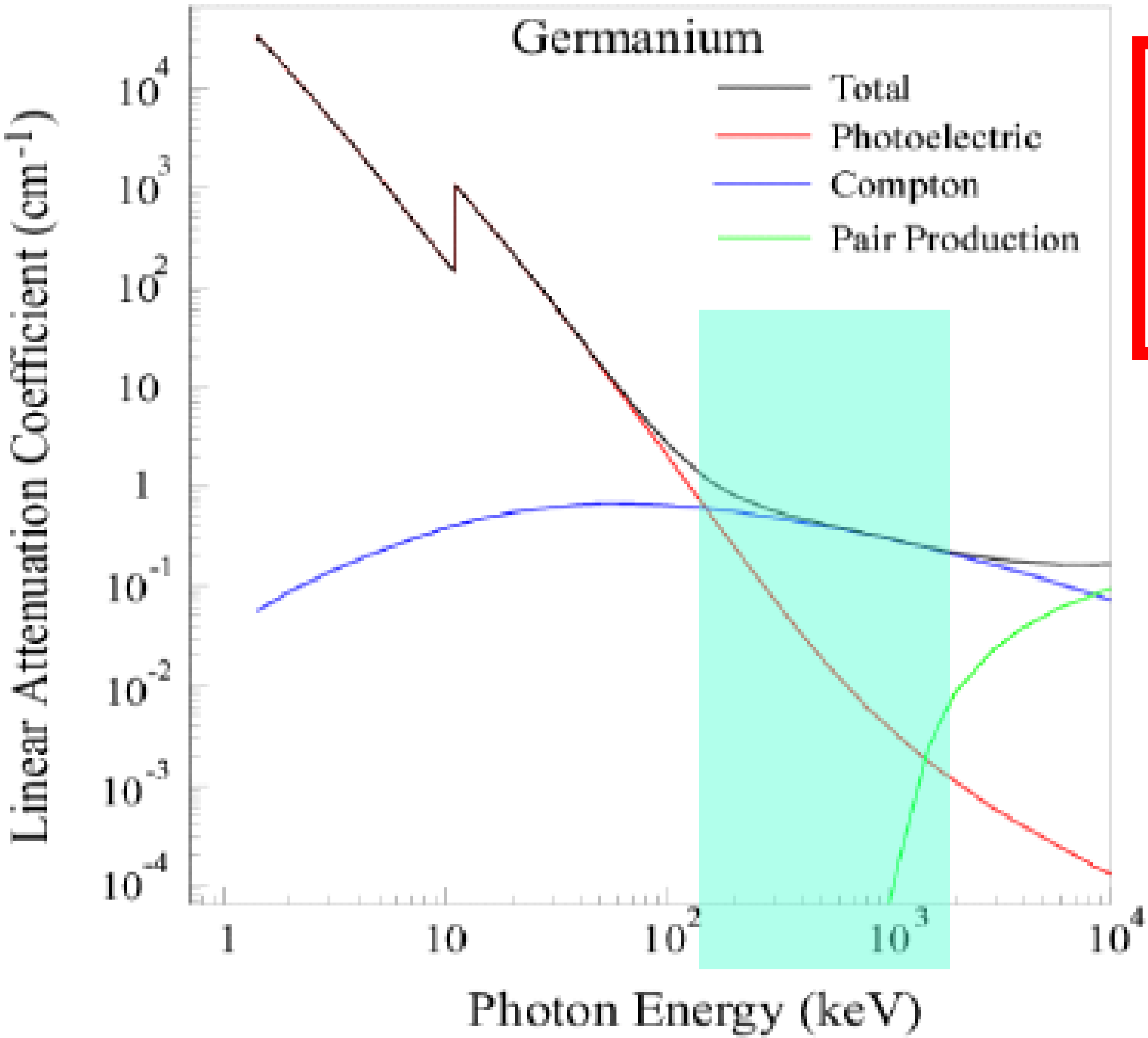
[KNO]

The angle dependence of Compton scattering is expressed by the

Klein-Nishina Formula

As shown in the plot **forward scattering** (θ small) is dominant for E>100keV

Gamma-ray interaction cross section



300keV-2MeV is typical gamma-ray energy range in nuclear science. Compton scattering is dominant!

Photo effect: ~$Z^{4\text{-}5}$, $E_\gamma^{-3.5}$

Compton: ~Z, E_γ^{-1}

Pair: ~Z^2, increases with E_γ

Structure of a gamma-ray spectrum

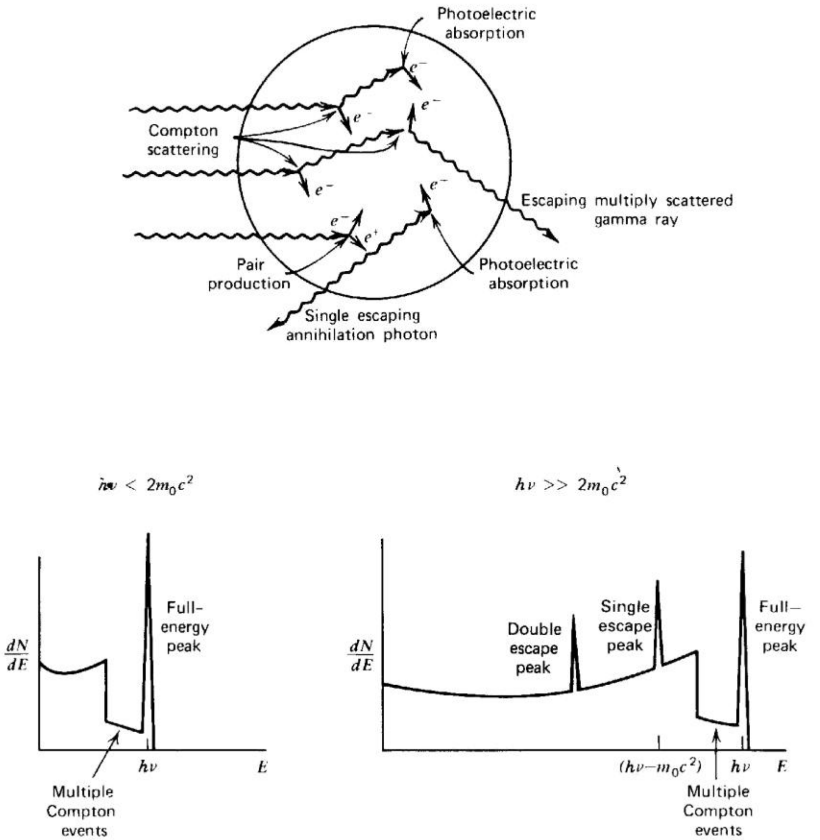


Figure 10-4 The case of intermediate detector size in gamma-ray spectroscopy. In addition to the continuum from single Compton scattering and the full-energy peak, the spectrum at the left shows the influence of multiple Compton events followed by photon escape. The full-energy peak also contains some histories that began with Compton scattering. At the right, the single escape peak corresponds to initial pair production interactions in which only one annihilation photon leaves the detector without further interaction. A double escape peak as illustrated in Fig. 10-2 will also be present due to those pair production events in which both annihilation photons escape.

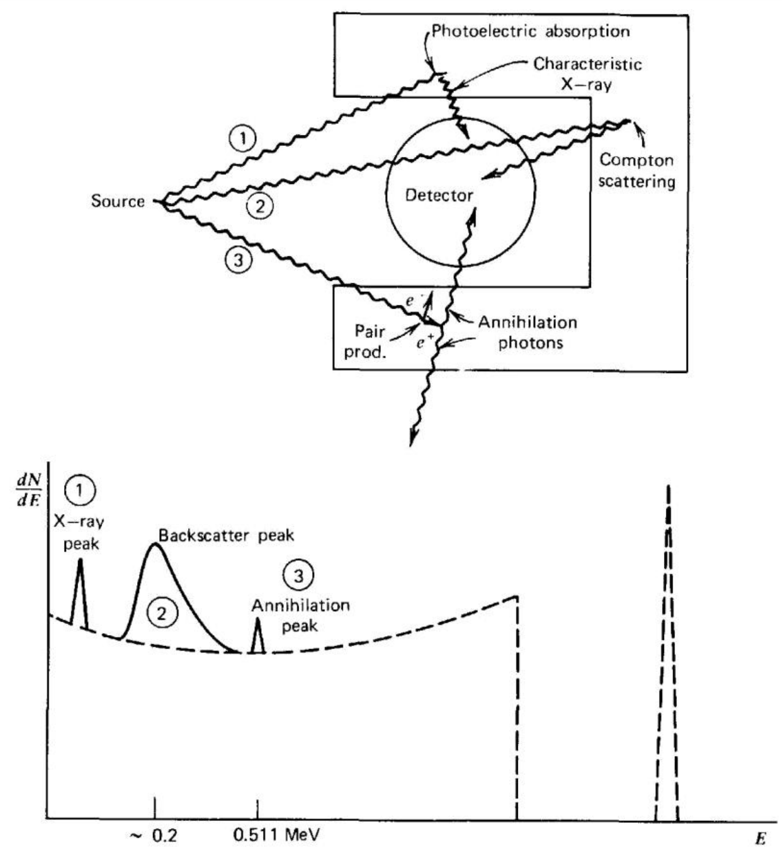


Figure 10-6 Influence of surrounding materials on detector response. In addition to the expected spectrum (shown as a dashed line), the representative histories shown at the top lead to the indicated corresponding features in the response function.

[KNO]

Scintillator

Scintillators are materials that produce 'small flashes of light' when struck by ionizing radiation (e.g. particle, gamma, neutron). This process is called '**Scintillation**'.

Scintillators may appear as solids, liquids, or gases.

Major properties for different scintillating materials are:

- Light yield and linearity **(energy resolution)**
- How fast the light is produced **(timing)**
- Detection efficiency

Organic Scintillators ("plastics"):
Light is generated by fluorescence of molecules; usually fast, but low light yield

Inorganic Scintillators:
Light generated by electron transitions within the crystalline structure of detector; usually good light yield, but slow

Properties of some Scintillator materials

Organic Scintillators	density [g/cm3]	Light yield per keV γ	Prim. Decay time [ns]	wavelength max [nm]	
BC400	1.032	11	2.4	423	Plastic
BC444	1.032	7	285	434	Plastic
BC505	0.877	13	2.5	425	Liquid
BC509	1.61	3-4	3.1	425	F-loaded liquid

Inorganic Scintillators	density [g/cm3]	Light yield per keV γ	Prim. Decay time [ns]	wavelength max [nm]	hygroscopic
NaI(Tl)	3.67	38	250	415	YES
CsI(Na)	4.51	41	630	420	YES
BaF_2	4.88	10	0.7	310	slightly
BGO	7.13	10	300	480	no
$LaBr_3$(Ce)	5.08	63	16	380	YES

Data from Saint-Gobain Scintillators data-sheets; BCxxx are manufacturer-specific names

Photo-Multiplier Tube (PMT)

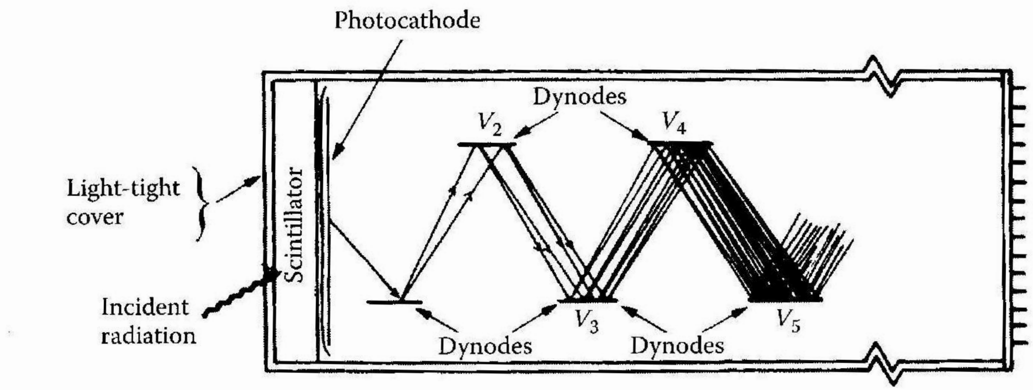
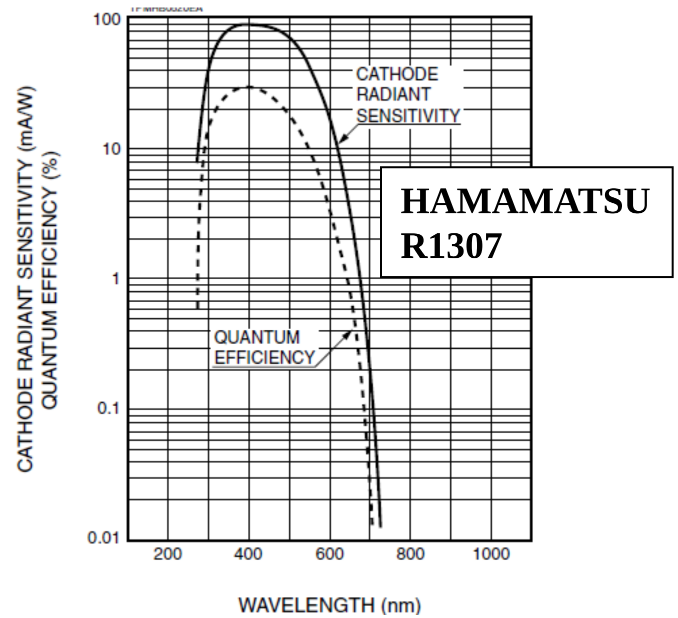


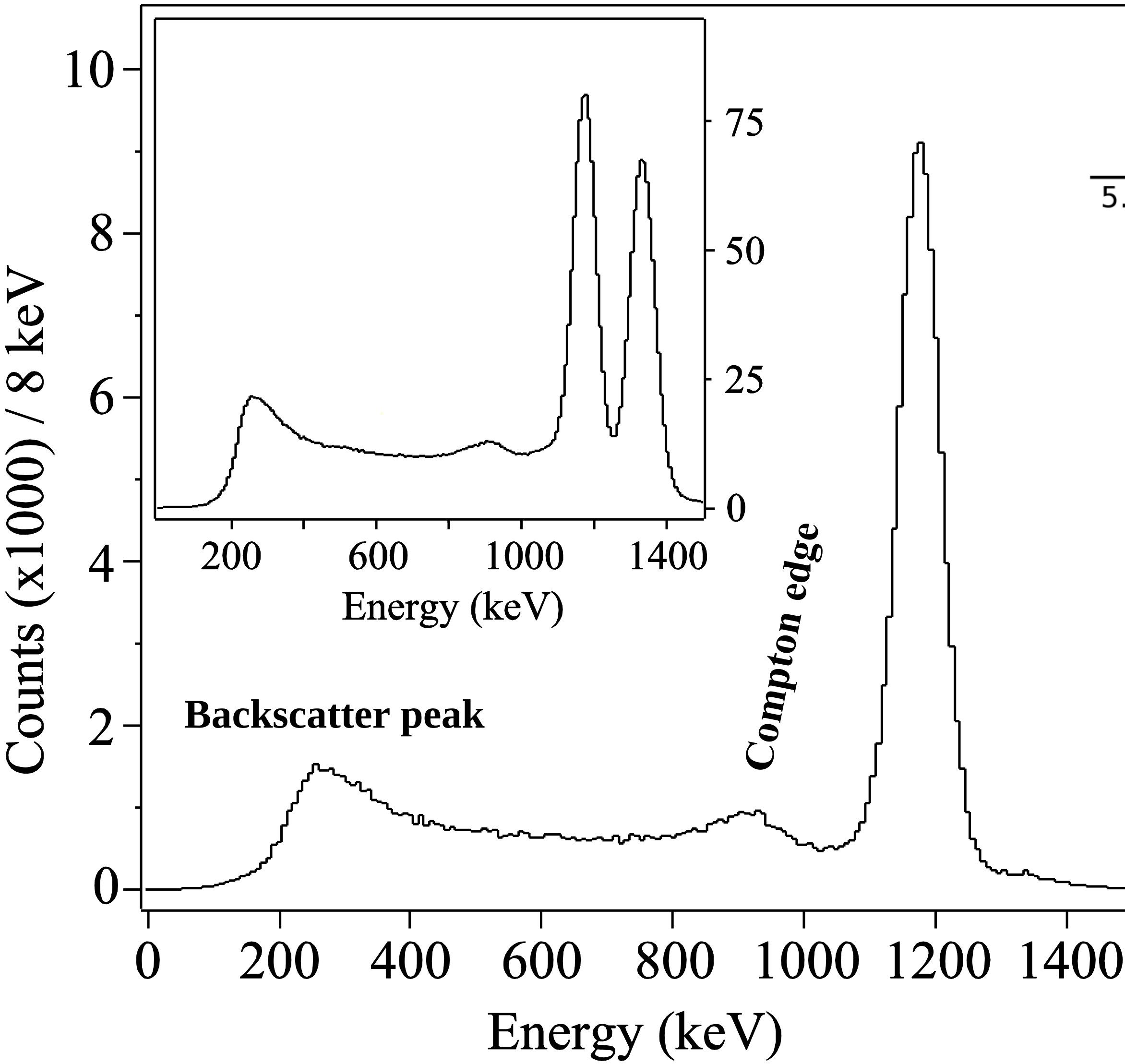
Figure 6.13 Schematic diagram of the interior of a photomultiplier tube. [TSO]

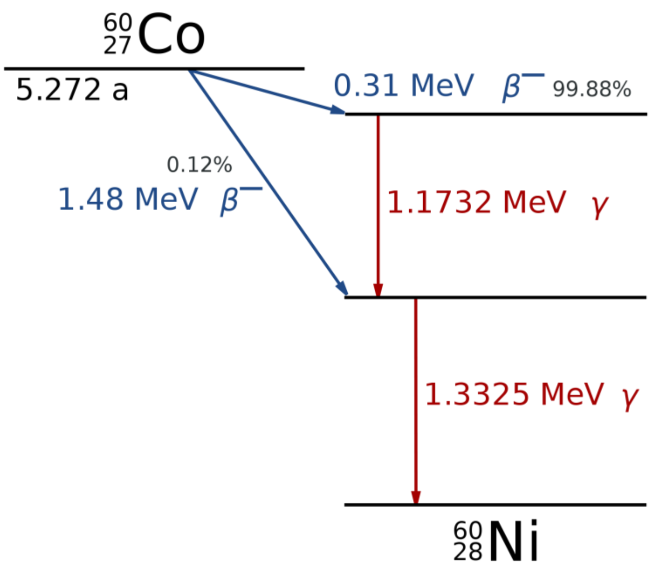


A PMT converts (visible) photons into an electron current. High Voltage is applied at the dynodes to multiply the initial photoelectrons produced at the photocathode.

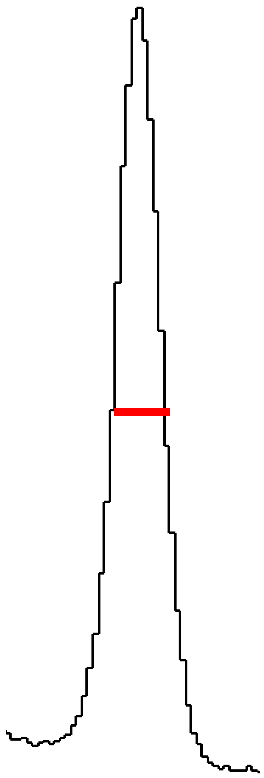
Photocathodes of modern PMTs convert 2-3 out of 10 photons into a photoelectron. This characteristic is called **Quantum Efficiency**, and it is strongly dependent on the wavelength of the photon.
Other devices for converting scintillation photons are Photo-Diodes, Avalanche Photo-Diodes (APD), and Silicon Photo-Multiplier (SiPM).

Scintillator spectrum (here CsI(Na))





Resolution



Our peak has a Gaussian shape with a FULL-WIDTH-HALF-MAXIMUM of 5% (dE/E).

Usually a (Gaussian) distribution is parameterized by its standard deviation σ.

Standard deviation σ and FWHM for a Gaussian have the relationship:

$$FWHM = 2.35\,\sigma$$

but can we understand the value of 5%.......?

Let's roll a dice: Binomial Distribution

What is the probability P(x) to roll x times a 'six' if you try n times?

Answer: The binomial distribution (with p = 1/6)

$$P(x) = \frac{n!}{(n-x)!\,x!}\, p^x (1-p)^{n-x}$$

The mean value

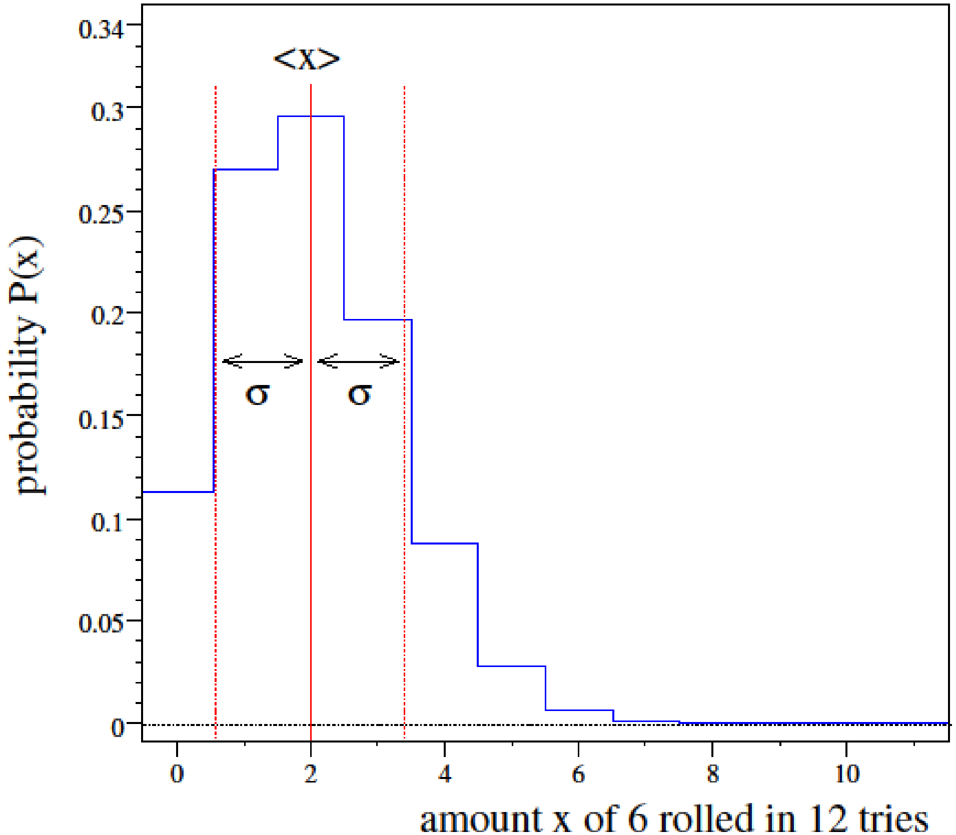
$$< x > = \sum_{x=0}^{n} P(x)\, x$$

for the bin. dist. is np

And the variance

$$\sigma^2 = \sum_{x=0}^{n} (x - < x >)^2 P(x)$$

is np(1-p).



Poisson statistics

Imagine a dice with 100 sides. And you try it 1000 times and ask again how often a six shows up.
In this case p << 1 and n large the binomial distribution reduces to the **Poisson distribution**:

$$P(x) = \frac{(pn)^x e^{-pn}}{x!}$$

For the Poisson distribution still holds <x> = np and the variance is σ^2= np (= <x>)!!

The **standard deviation** of a **Poisson distribution** is:

$$\sigma = \sqrt{< x >}$$

Poisson statistic and nuclear science

Mostly counting experiments are done like “How many events C do I count if a beam of nuclei B hit a target A ?” The cross section for producing event C is low, beam means many nuclei B are shoot on target nuclei A. So the counting statistics will follow the Poisson Distribution and if we count N events C, its error is $\sqrt{N}$.

Same applies for our scintillation detector:
An energetic particle is traveling through the detector (e.g. electron from gamma ray interaction). Per travelling length dx this particle may produce a scintillation photon, which may make it to the photo-cathode, which may be converted into a photo-electron in the PMT and contribute to the signal.

Example: CsI(Tl) does 39.000 photons per 1 MeV gamma. Light collection and PMT quantum efficiency ~15% → ~6000 photons are collected in average. $\sigma = \sqrt{6000} = 77$.
FWHM=2.35 * 77 = 180. →dE/E = 180/6000 = 3%.

Semiconductor detectors

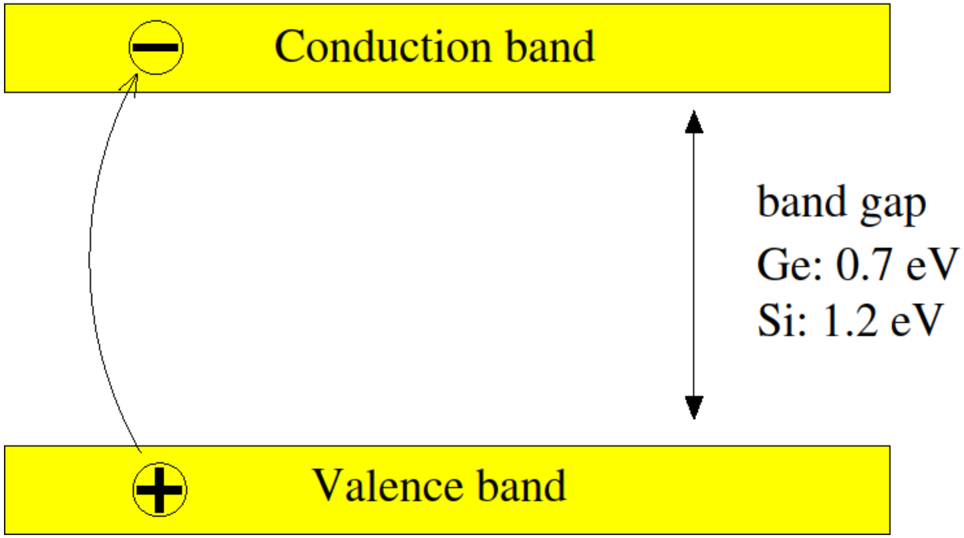
For **better energy resolution** Poisson distribution tells us:

We need a lot more (charge) carriers!

In a scintillator 1 carrier (photoelectron) cost us more than 150eV of incident energy.

Basic idea for using a semiconducter:

Because of the narrow band structure (~eV) it does cost us only a few eV to create an electron-hole pair!

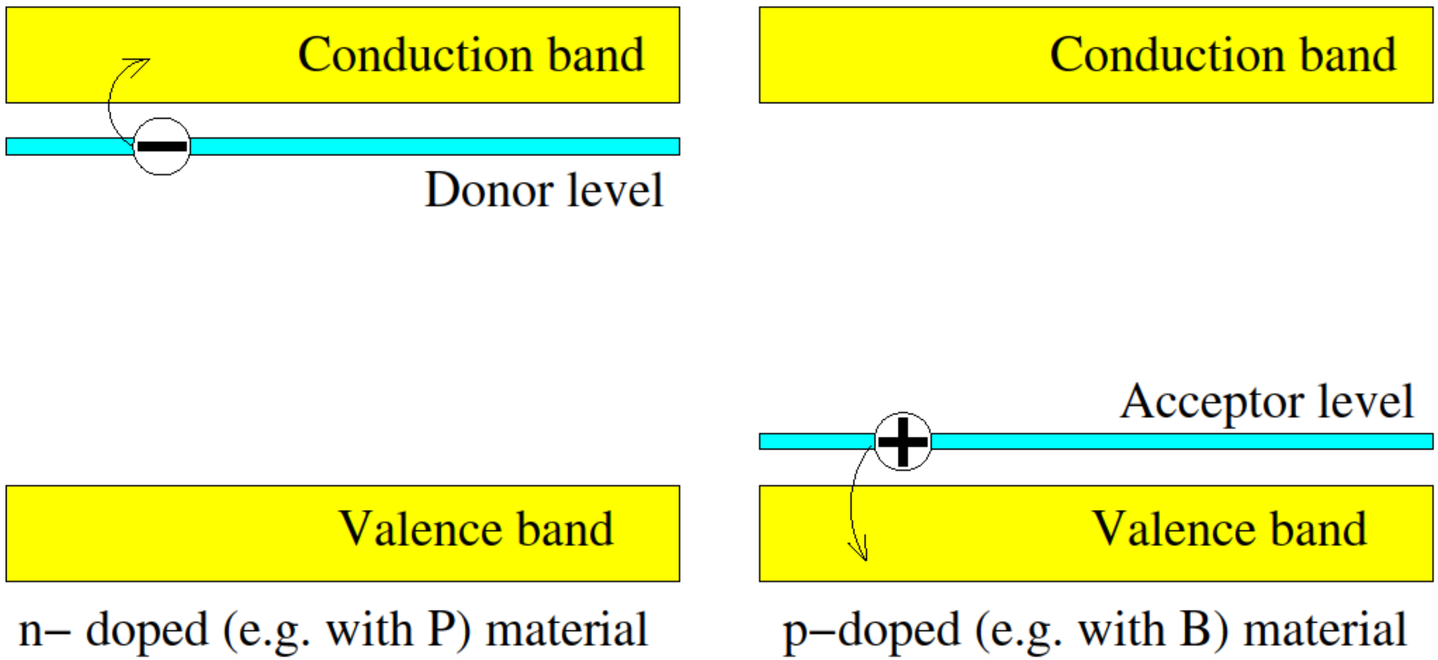


Real-life problems:

Lifetime of electron-hole pair has to long enough so we can collect them and

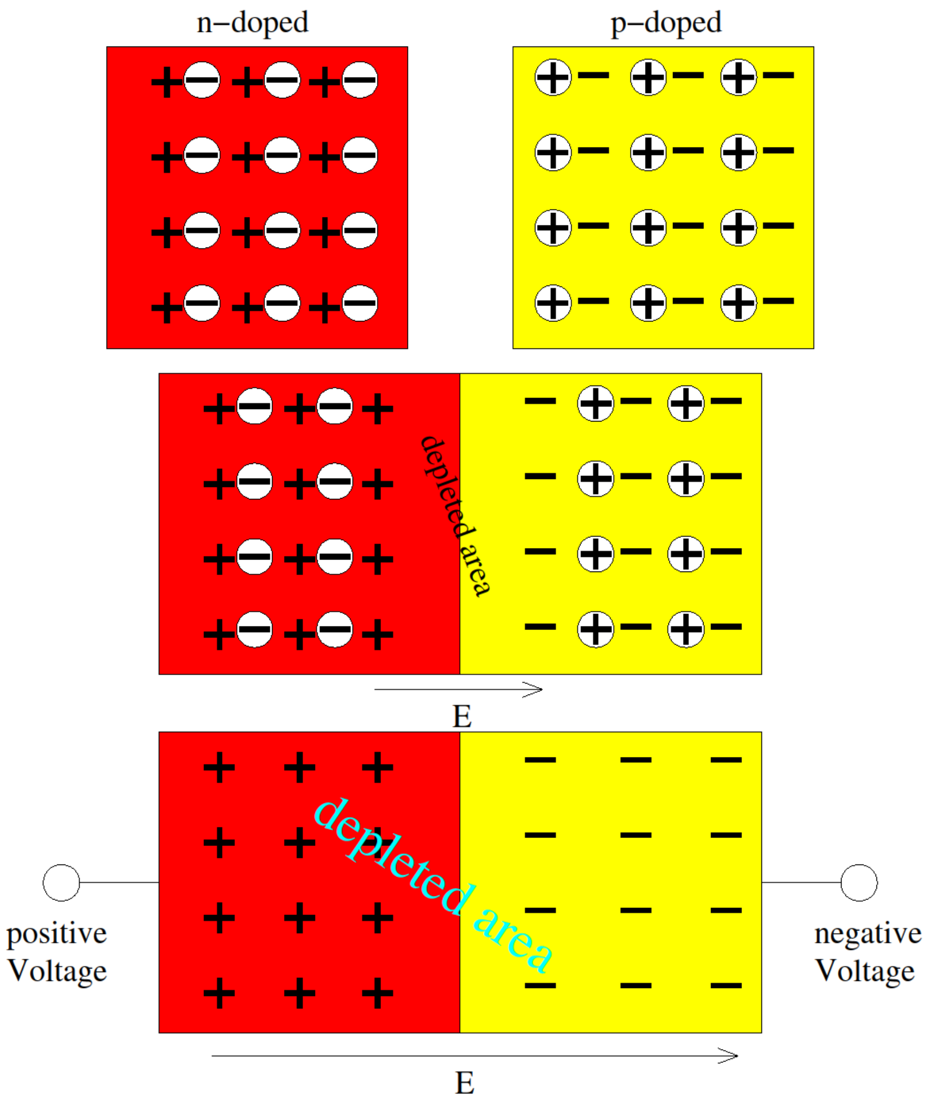
How do we collect them anyway?

n- and p-doped semiconductor material



Even the purest materials contain impurities which make them n- or p-doped. Purest materials obtained are germanium ($<10^{10}$ impurities per cm^3) and silicon (10^{12} impurities per cm^3). For comparison 1 cm^3 Ge or Si contains 10^{22} atoms!

Depletion and reverse biasing

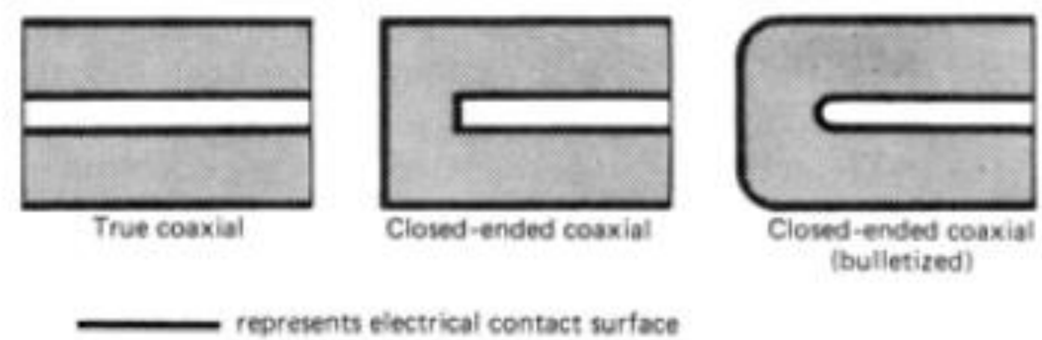


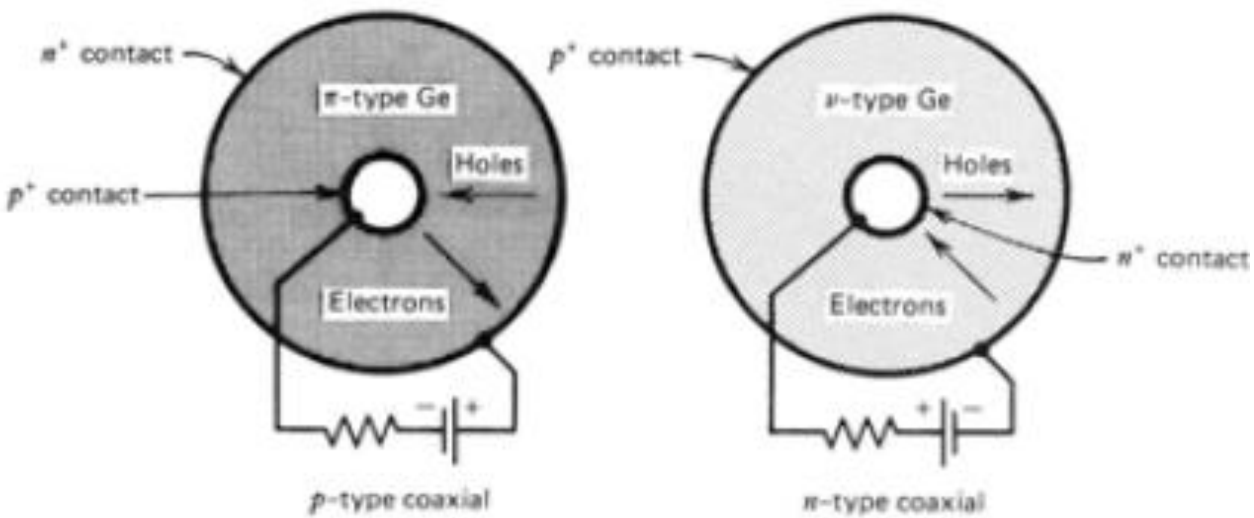
Doped material is electrical neutral.

If n- and p-doped material are brought in Contact diffusion of the mobile charge carriers starts. The ionized atoms remain and create and electric field E stopping further diffusion. A depleted area is formed (no free, mobile charges here)

Reverse biasing increases the depleted area. Charges created here will travel along electric field lines towards the electrodes. The achievable width depends on the doping concentration (lower concentration enables a wider depleted area)

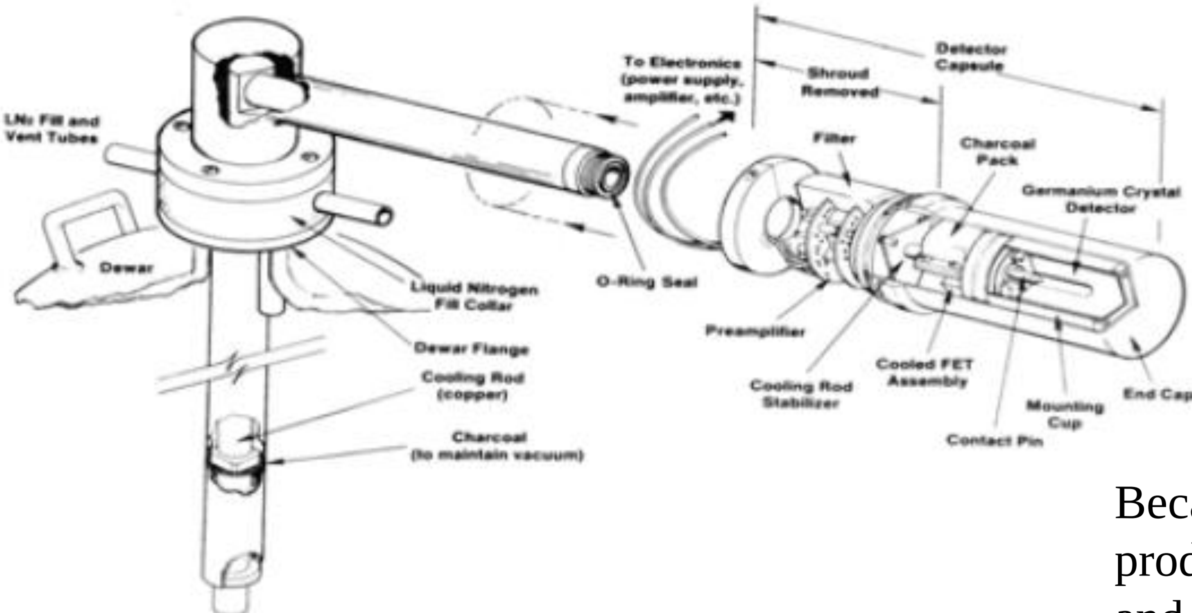
Coaxial germanium detector crystal

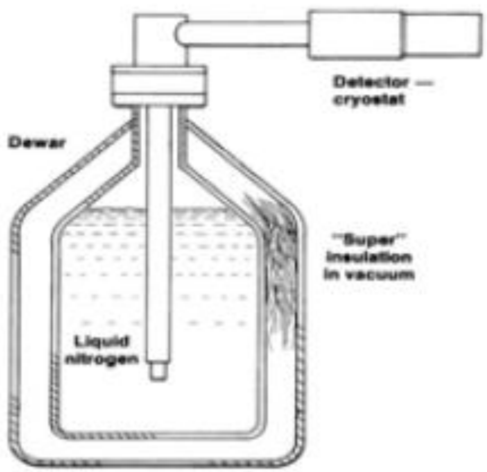




[KNO]

Germanium detector system





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Because thermal excitation produces electron-hole pairs and the narrow band gap of 0.7 eV in Ge the crystal has to be operated below 110K. Usually liquid nitrogen (77K) is used to cool the crystal down to ~90K.

Energy resolution Ge vs NaI(Tl) scintillator

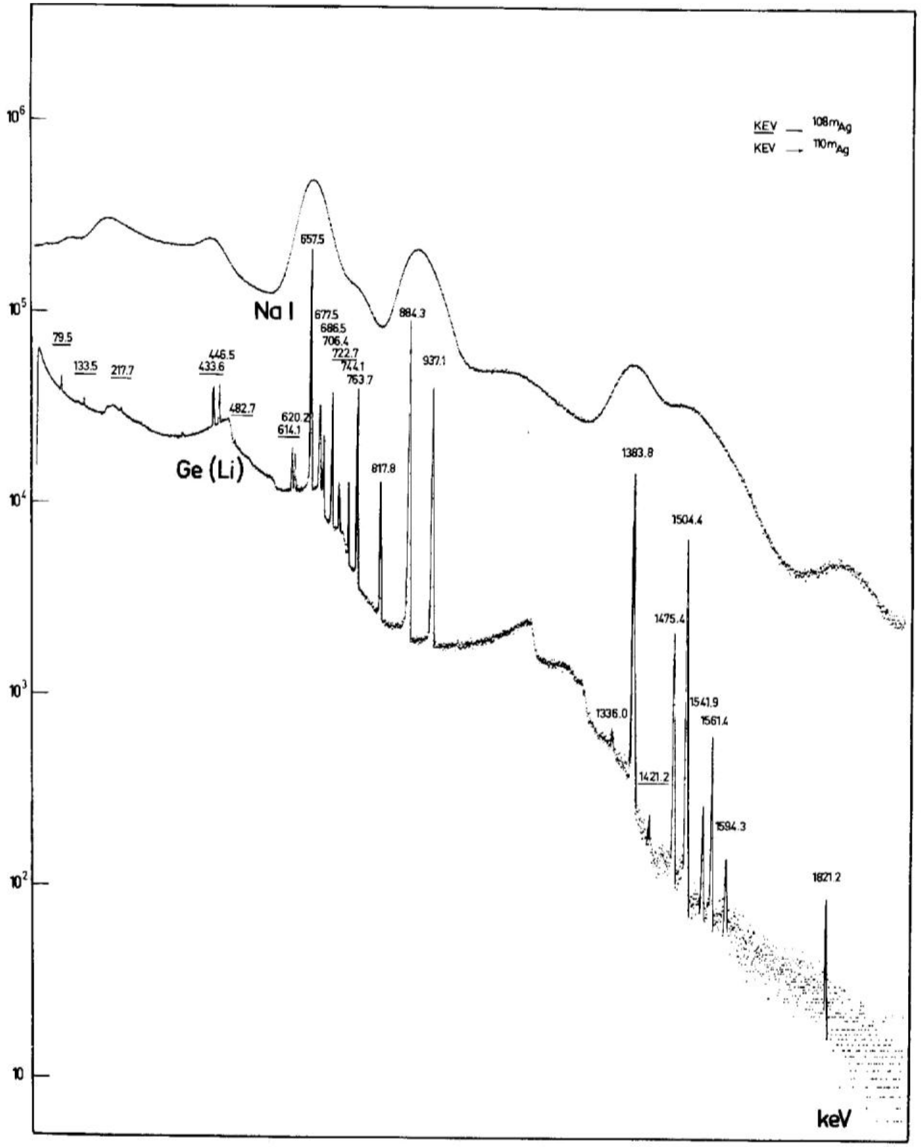


Figure 12-6 Comparative pulse height spectra recorded using a sodium iodide scintil-

Energy resolution for Ge is one order of magnitude better than scintillators.

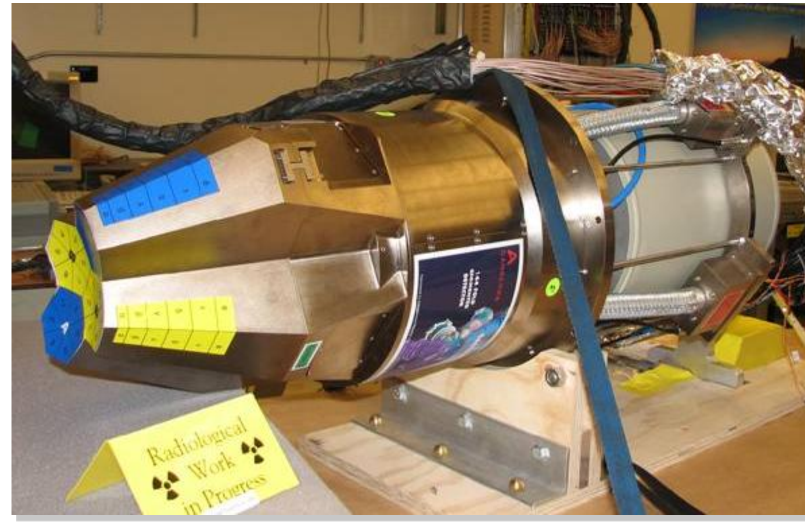
Why did we even talk about scintillators?

a) Ge detectors are VERY expensive and fragile devices (>> $10.000)
b) Ge detector crystals can't be made as big as scintillators. Scintillators offer higher Z materials.
c) Ge detectors need complex infrastructure (cooling).
d) Scintillators offer better timing (<<1ns). Ge: 5-10ns

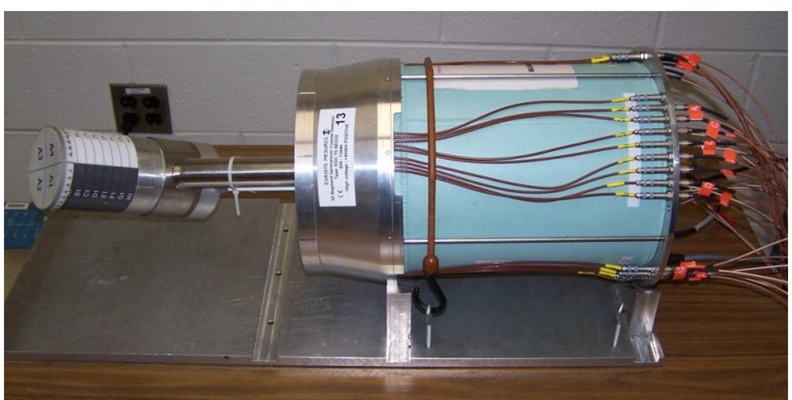
Energy resolution of a germanium detector is 2keV at 1MeV (0.2%)

Some Ge detectors at NSCL

Standard Ge detector
available for this class.
Value: several $10.000



GRETINA detector:
Most advanced Ge detector
Value: >$1.000.000



SeGA detector.
Value >$100.000

Summary

❖ Energy loss of charged particles in matter is described by Bethe-formula

❖ Gamma rays interact via Photo Effect, Compton Scattering, and Pair Production

❖ Scintillation detectors convert the energy deposited by an interaction in a proportional amount of light

❖ For scintillator detectors high voltage is used to operate the PMT, which converts the scintillation light in an electron current

❖ Various scintillator types exists

❖ Semiconductor detectors (Ge, Si) provide high-resolution energy measurement

❖ For semiconductor detectors high voltage is needed to deplete the detector.

❖ Ge detector crystals need to be operated at cryogenic temperatures (<110 K)

❖ Semiconductor detectors are fragile, expensive hardware

(Nonetheless we would get upset as well if a scintillator would break….)

ENJOY YOUR HANDS-ON !!!