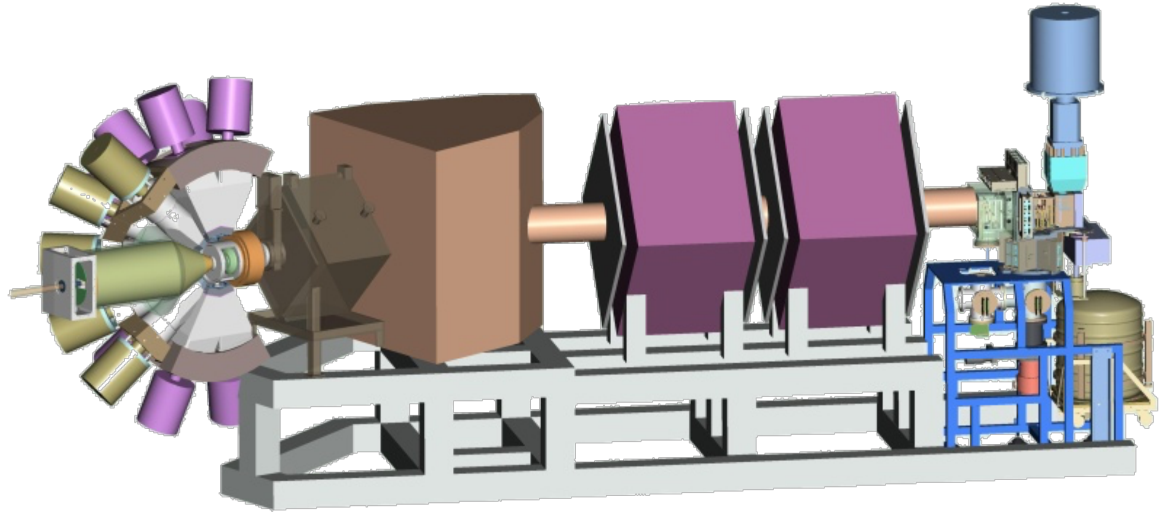

Experimental Probes for Nuclear Structure Studies: Gamma and Electron Spectroscopy

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Outline

1. Gamma Ray detection — Lecture 1&2
2. Gamma Ray Spectroscopy
    1. Gamma Ray Transitions — Lecture 3&4
    2. Coincidence Techniques — Lecture 5
    3. Angular Corellations — Lecture 6
    4. Polarisation — Lecture 7
3. Gamma Ray Tracking — Lecture 8
4. Conversion Electrons
    1. Multipolarities — Lecture 9
    2. E0 Transitions — Lecture 10

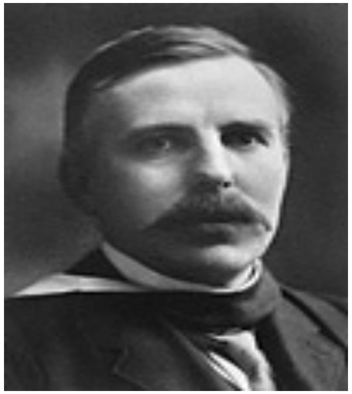
1) Gamma Ray Detection

A little bit of history…

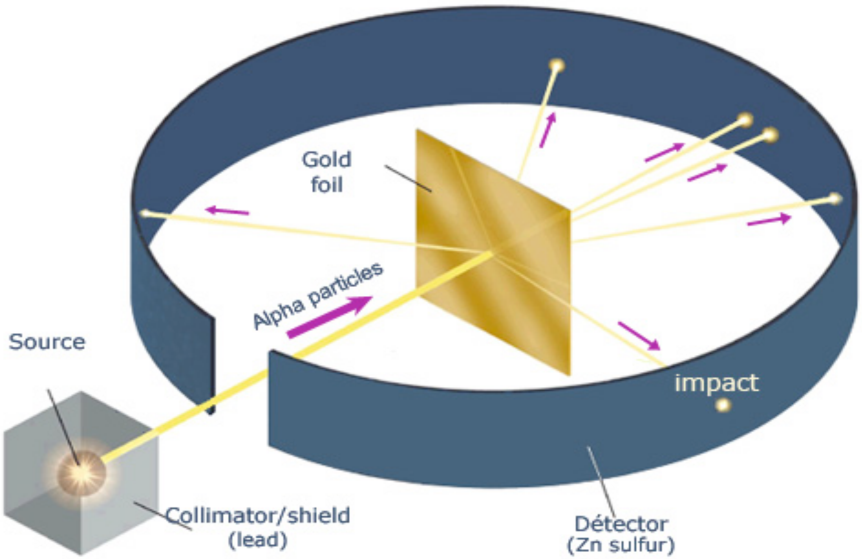
• Physicists of the XIXth century understood quite quickly that the atoms had a sub-structure. Towards the end of the XIXth century, after the discovery of the electron, several atomic models are developed (Thompson …).

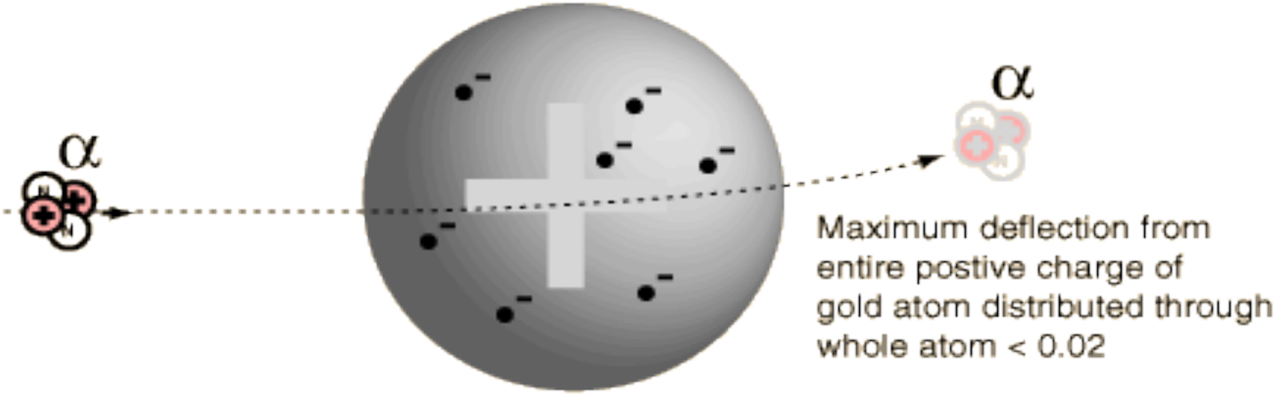
Plum pudding model

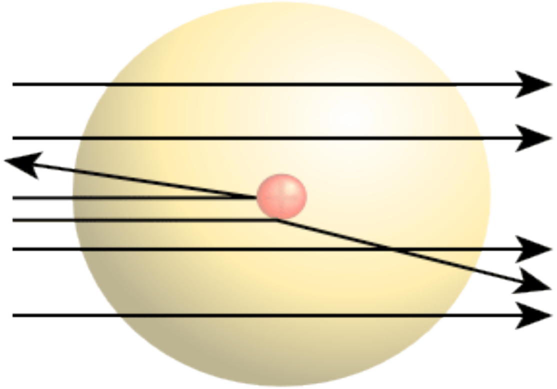
• In 1911, Rutherford demonstrates the existence of a nucleus at the centre of the atom by bombarding atoms with a particles.



Sir Ernst Rutherford (1871-1937)
Chemistry Nobel Prize winner in 1908

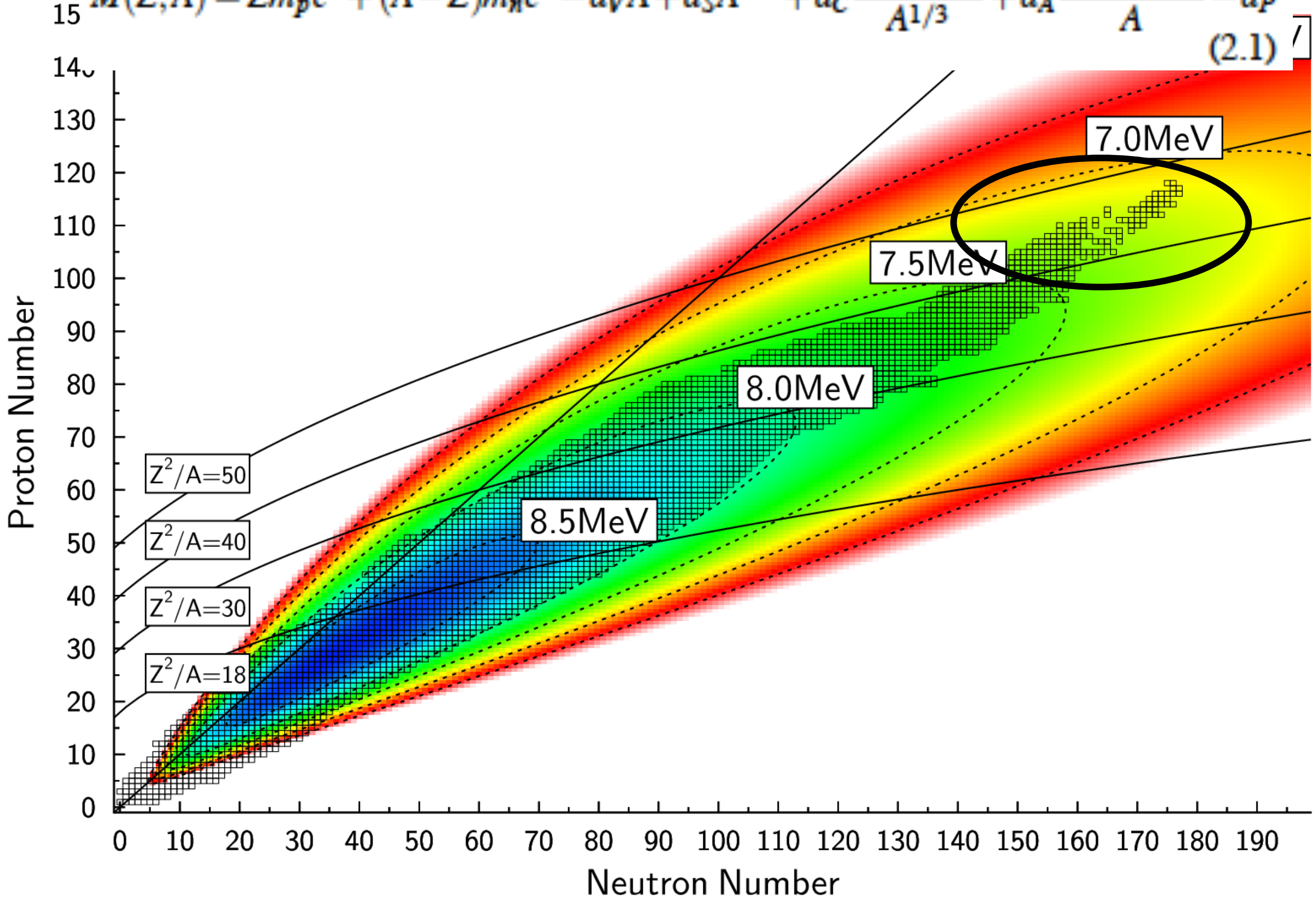




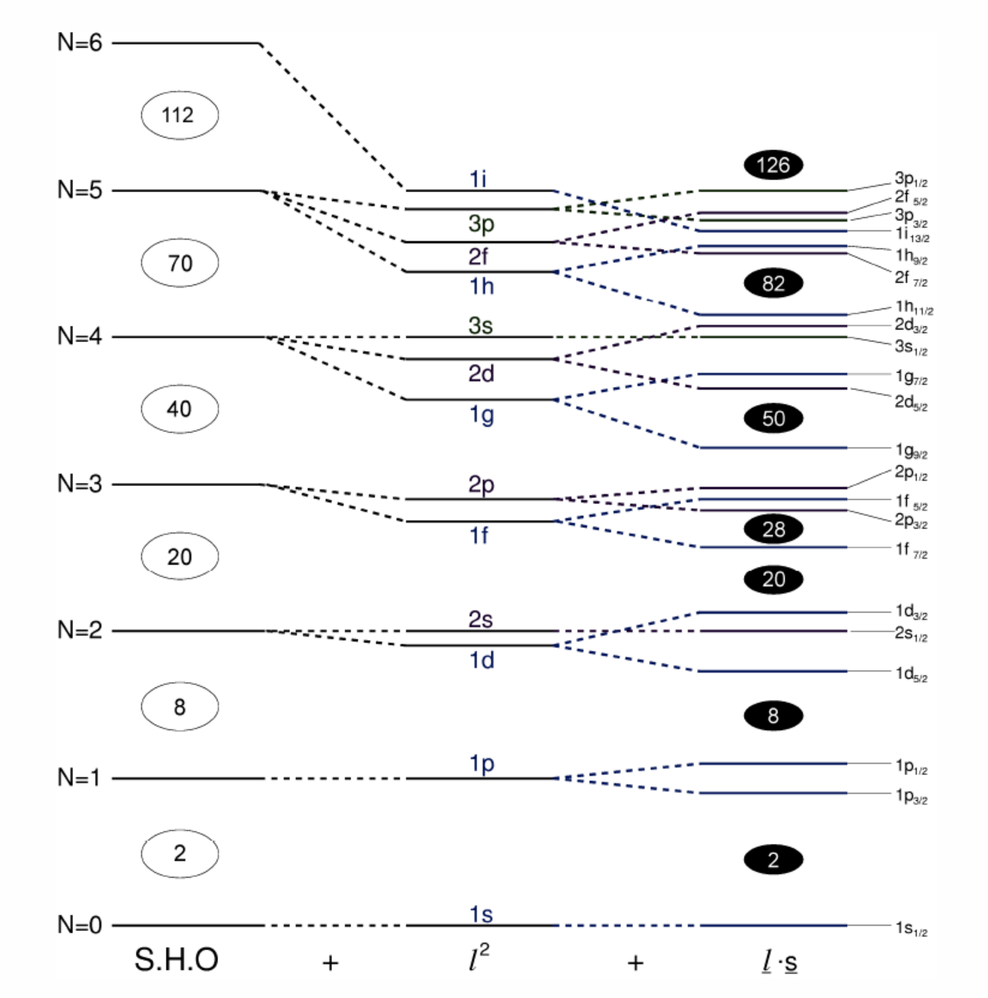


Liquid Drop Model

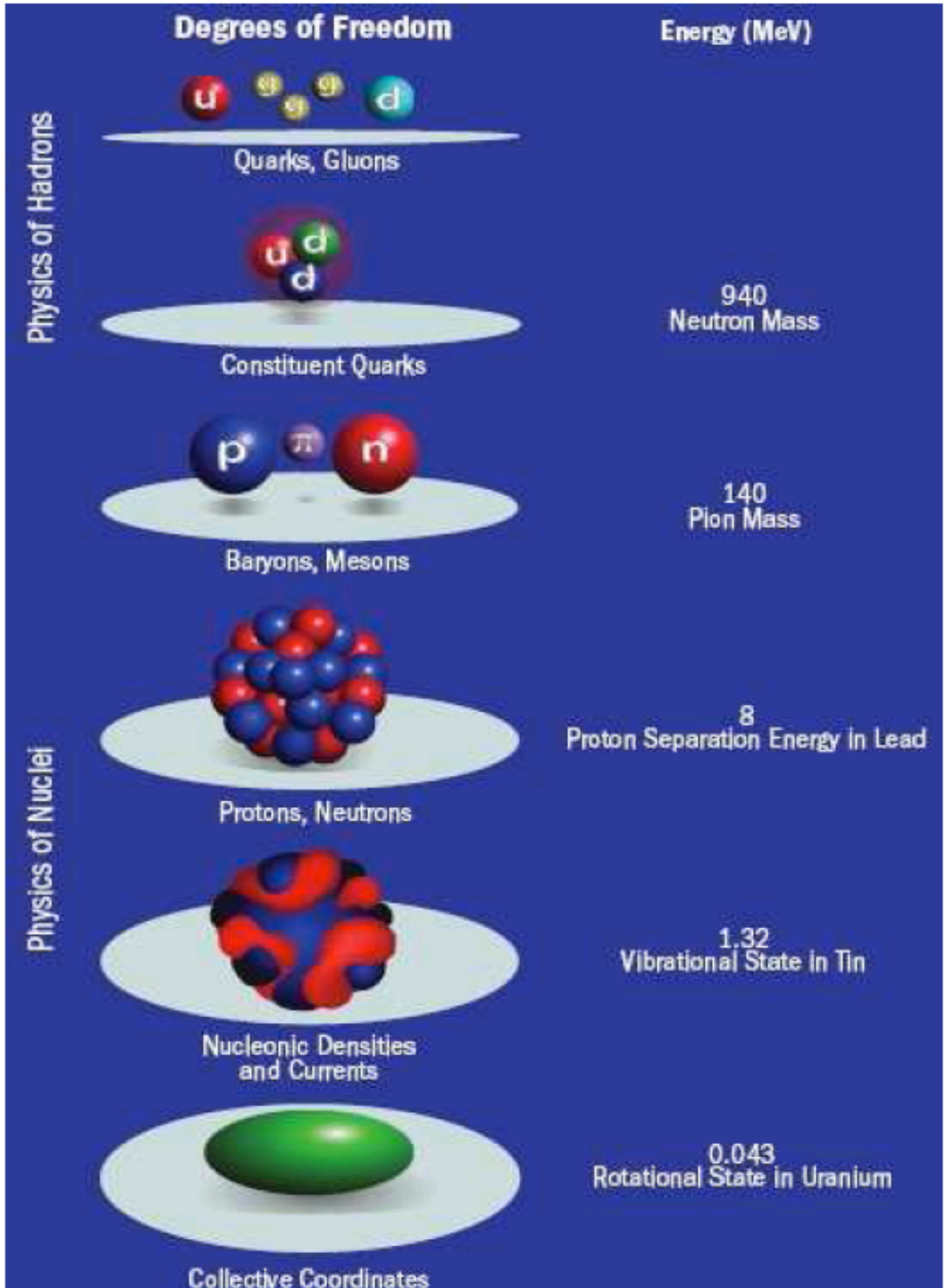
$$M(Z,A) = Zm_pc^2 + (A-Z)m_nc^2 - a_VA + a_SA^{2/3} + a_C\frac{Z(Z-1)}{A^{1/3}} + a_A\frac{(A-2Z)^2}{A} - a_P \quad (2.1)$$



Shell Structure



Maria Goeppert-Mayer (1906-1972), walking in to the Nobel ceremony with King Gustaf Adolf (1963)


Degrees of Freedom
Energy (MeV)
Physics of Hadrons
Quarks, Gluons
Constituent Quarks
940
Neutron Mass
Baryons, Mesons
140
Pion Mass
Physics of Nuclei
8
Proton Separation Energy in Lead
Protons, Neutrons
1.32
Vibrational State in Tin
Nucleonic Densities
and Currents
0.043
Rotational State in Uranium
Collective Coordinates

Fundamental interactions

In the 1960's, 4 types of fundamental forces enable to explain all the known phenomena.

Interaction	Relative Strength	Range	
Strong	1	short ~ 1 fm = 10^{-15} m	
Electromagnetic	~ 10^{-2}	long	$\propto \frac{1}{r^2}$
Weak	~ 10^{-14}	short ~ 10^{-2} fm = 10^{-17} m	
Gravitational	~ 10^{-44}	long	$\propto \frac{1}{r^2}$

Long range forces were known at the end of the XIXth century.

The strong and weak interactions were necessary to explain the cohesion of the atomic nuclei (strong) and the radioactive processes like b-radioactivity (weak).

The electromagnetic force is linked to the charge of the interacting particles.

On the nuclear and sub-nuclear scale the gravitational force can be neglected.

Units adapted to the field of Nuclear Physics

- length: Fermi (or femtometre) $1 \text{ fm} = 10^{-15}$ m
- energy: electron-volt $1 \text{ eV} = 1.6\text{x}10^{-19}$ J

energy gained by a charge e moving through a potential difference of 1 V

and multiples keV (10^3), MeV (10^6), GeV (10^9)

Typical values

- radius of a nucleus — a few fm
- volume of a nucleus — $\sim 10^{-44}$ m^3
- mass of a nucleus — $\sim 2\text{x}10^{-26}$ kg (^{12}C)
- density of nuclear matter — $\sim 2\text{x}10^{18}$ kg/m^3
  $\sim 2\text{x}10^{8}$ tons/cm^3

about 10^{15} times greater than normal matter!

Gamma Ray Transitions:

Spin in nuclei: 0 – 70 ħ

Transition energies: 0 – 20 MeV

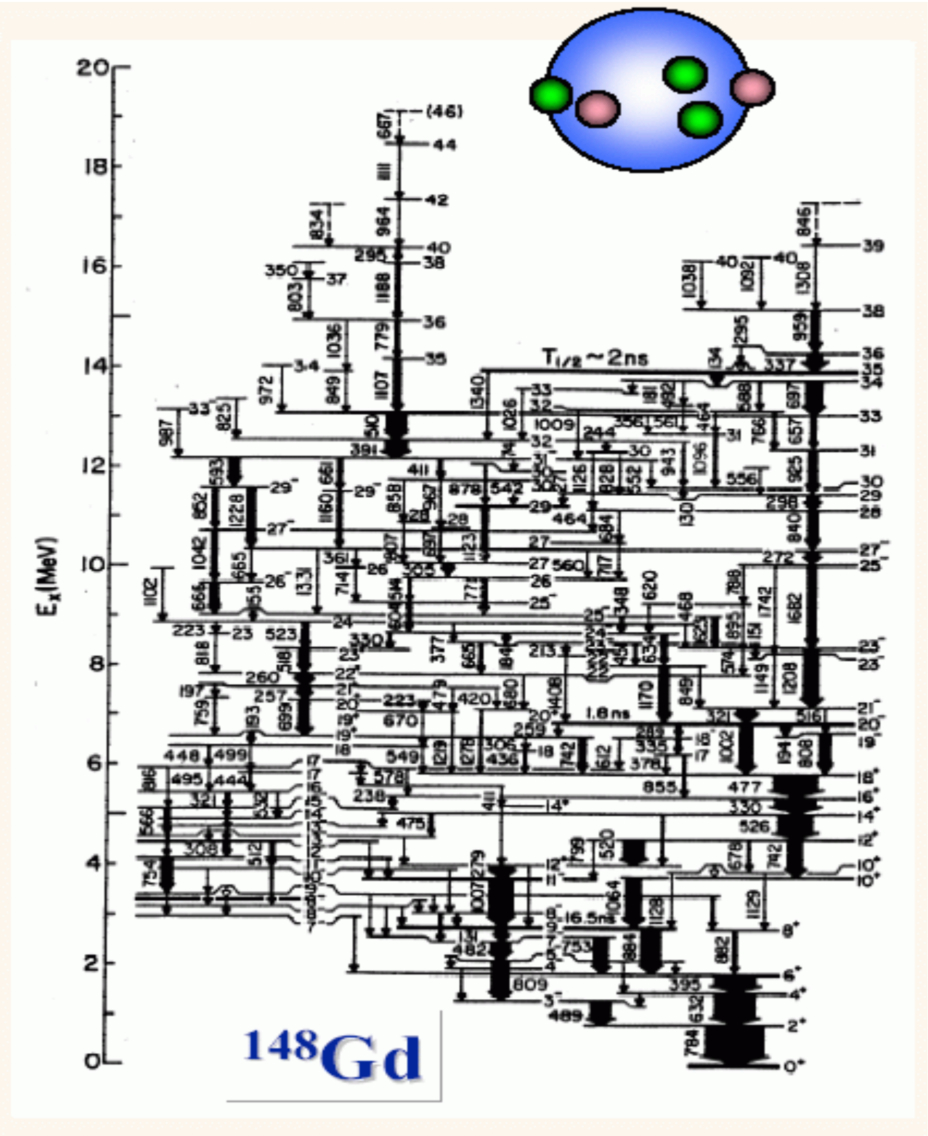
Lowest:	^{229}Th:	<10 eV (?)
Highest:	^{8}Be:	18129 keV

Typical: 40-2000 keV

Multipolarities: Mostly E2, followed by M1
E0, E1, E3, M2 are rarer

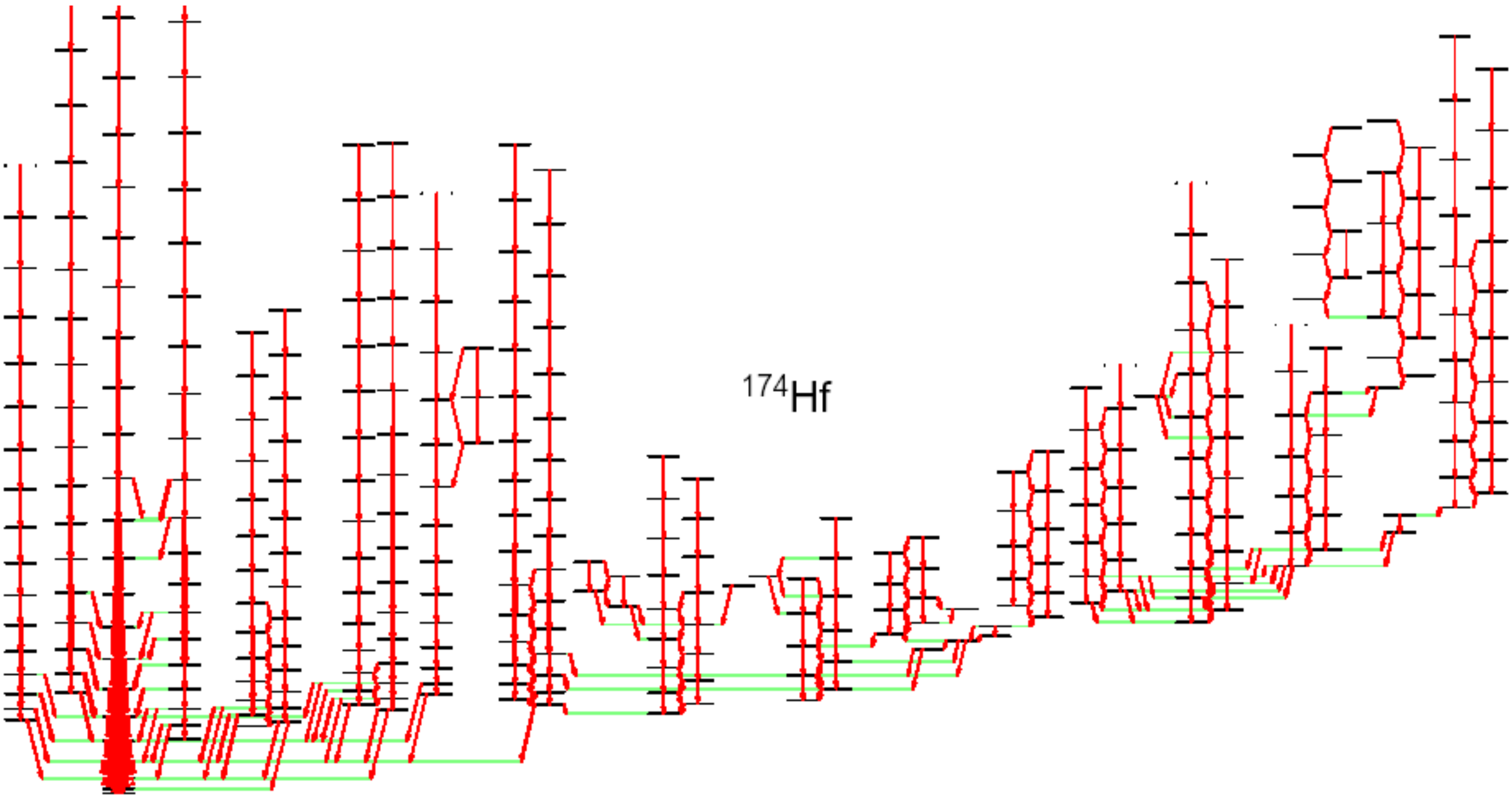
Timescales: ps, but with a huge spread (fs – ms)

Noncollective level scheme



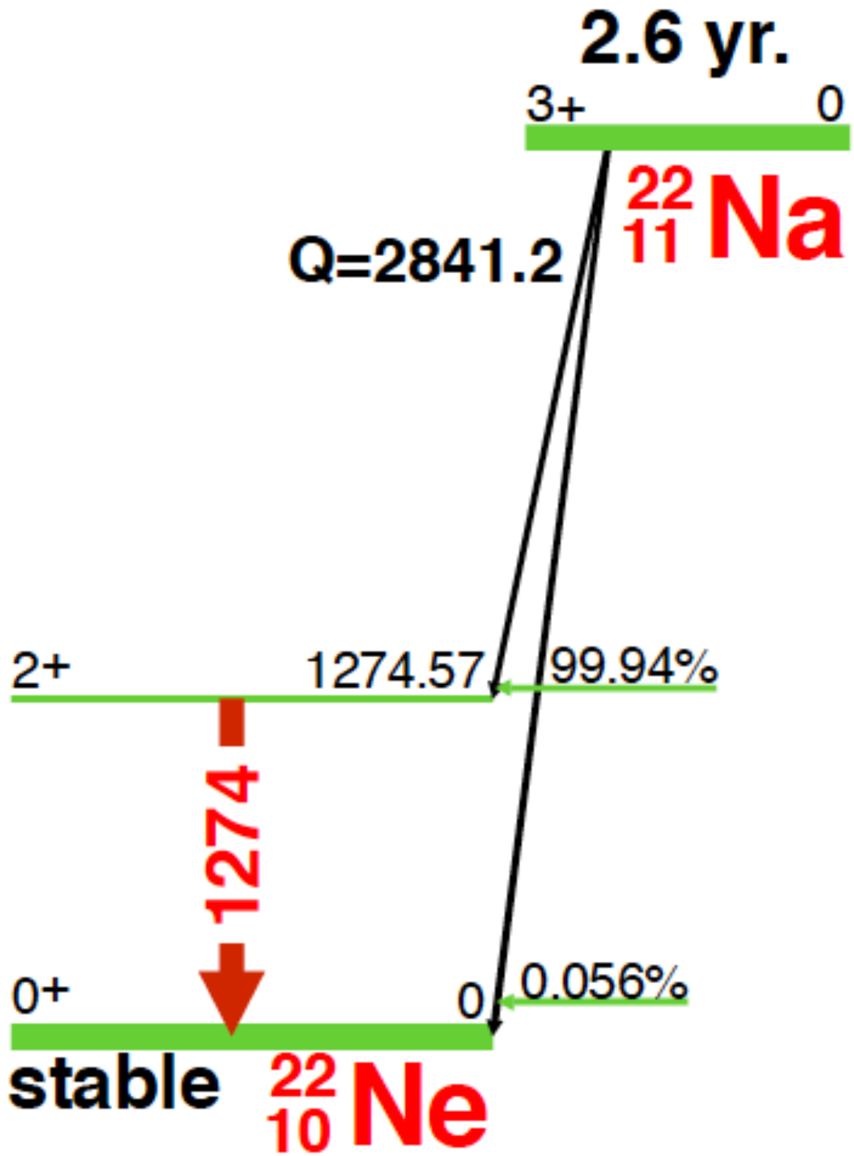
- ^{148}Gd is an example of a nucleus showing single-particle behaviour
- Complicated set of energy levels
- No regular features e.g. band structures
- Some states are isomeric

Collective level scheme

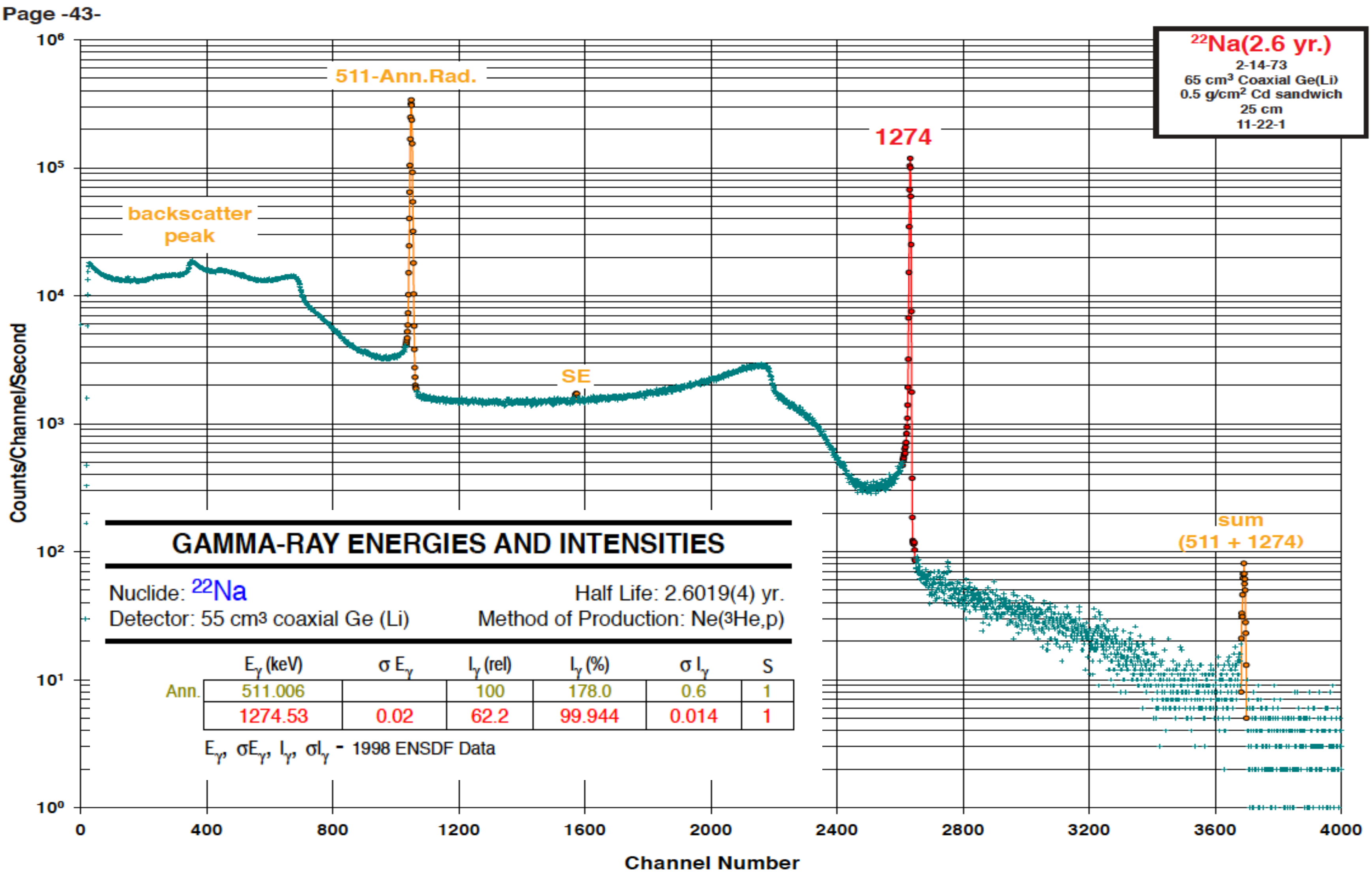


This nucleus has 347 known levels and 516 gamma rays !

^{22}Na(2.6 yr.) Decay Scheme



Simple Gamma Ray Spectra



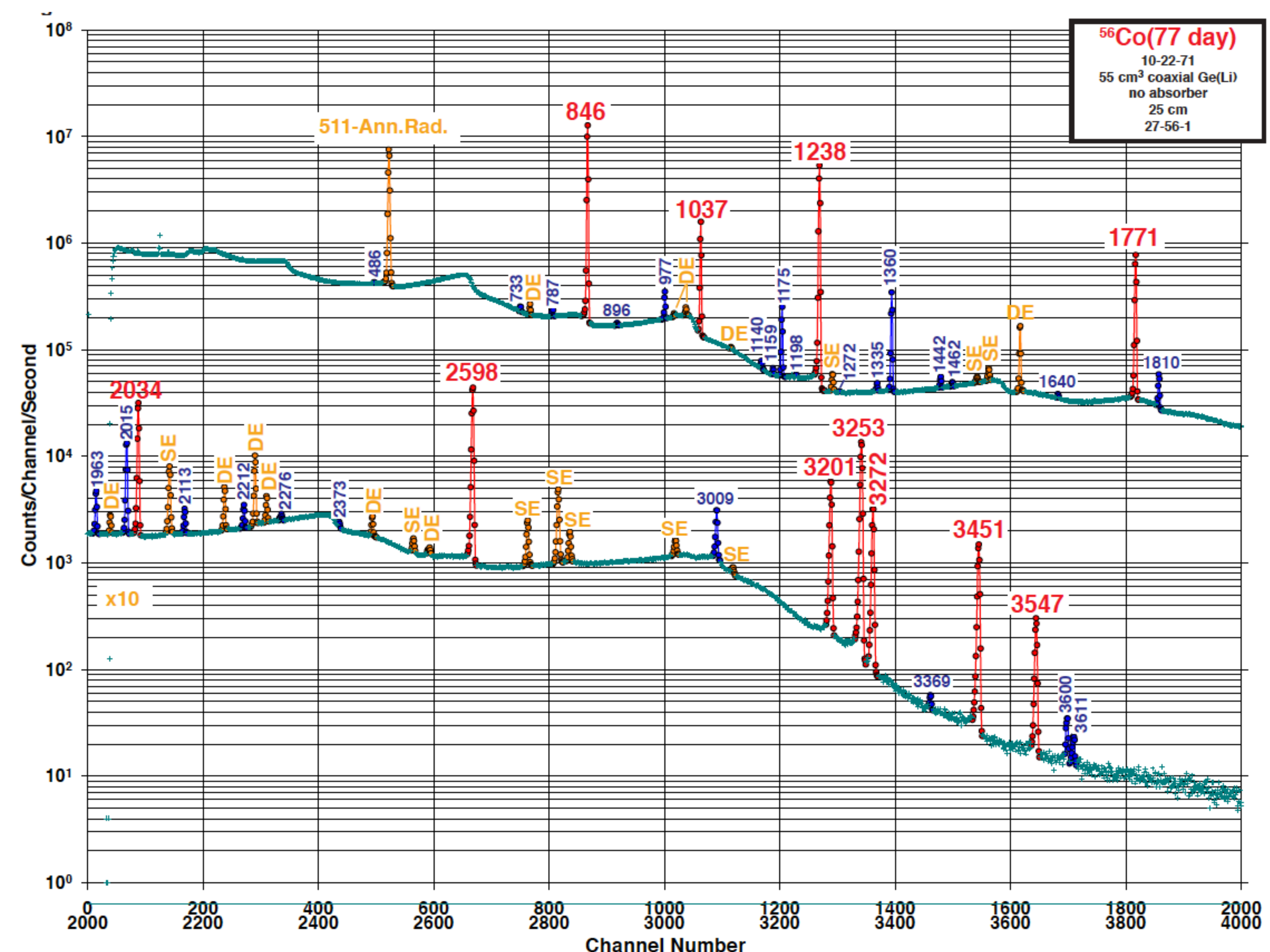
GAMMA-RAY ENERGIES AND INTENSITIES

Nuclide: ^{22}Na — Half Life: 2.6019(4) yr.

Detector: 55 cm³ coaxial Ge (Li) — Method of Production: Ne(^{3}He,p)

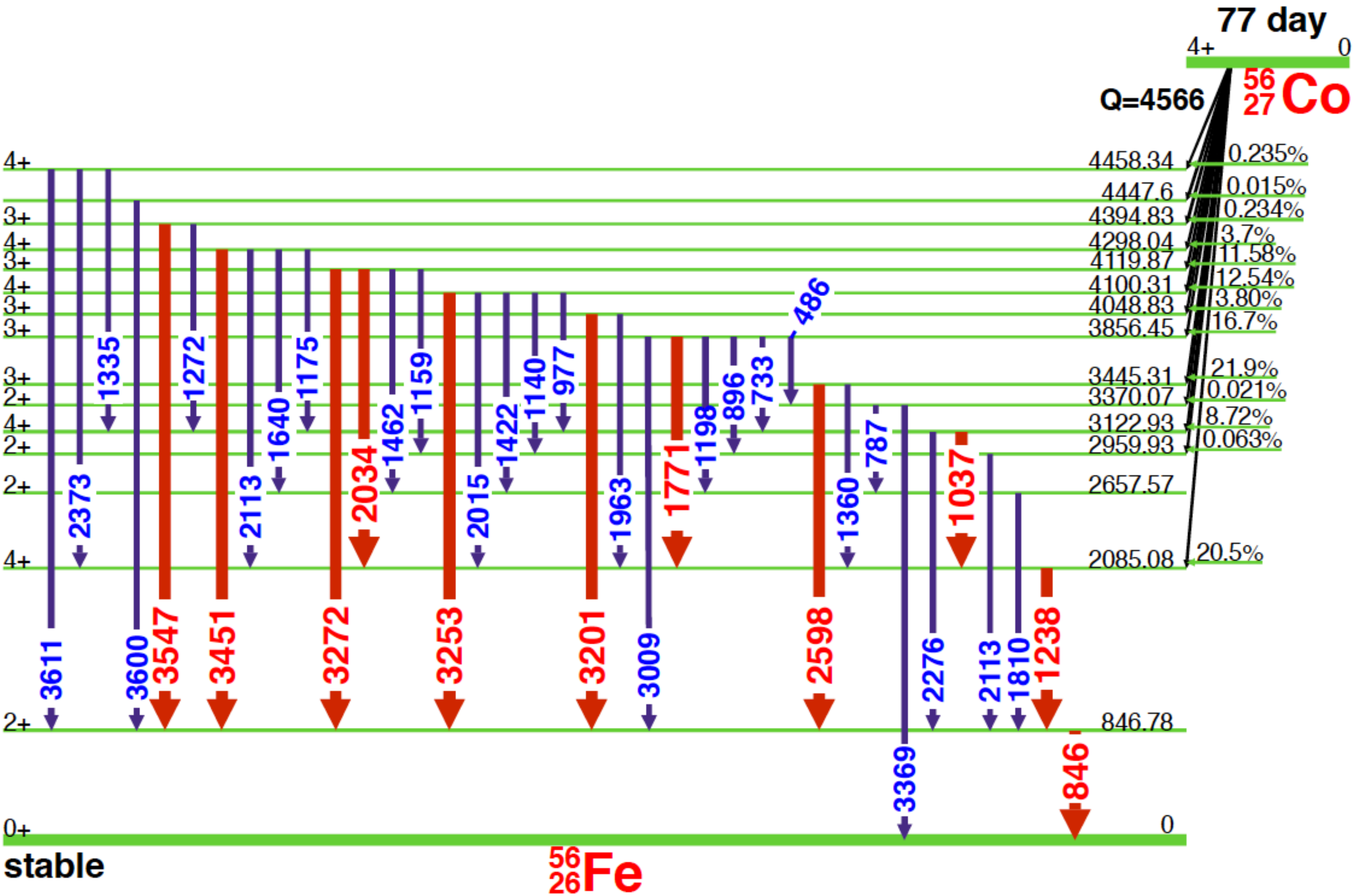
	E_γ (keV)	σE_γ	I_γ (rel)	I_γ (%)	σI_γ	S
Ann.	511.006		100	178.0	0.6	1
	1274.53	0.02	62.2	99.944	0.014	1

E_γ, σE_γ, I_γ, σI_γ - 1998 ENSDF Data



^{56}Co(77 day)
10-22-71
55 cm^3 coaxial Ge(Li)
no absorber
25 cm
27-56-1
511-Ann.Rad.
846
1037
1238
1771
486
733
DE
787
896
977
DE
1140
1159
1175
1198
SE
1272
1335
1360
1442
1462
SE
SE
DE
1640
1810
2034
2015
1963
DE
SE
2113
DE
2212
DE
DE
2276
2373
DE
SE
DE
2598
SE
SE
SE
SE
3009
SE
3201
3253
3272
3369
3451
3547
3600
3611
x10
Counts/Channel/Second
Channel Number

^{56}Co(77 day) Decay Scheme



Ingredients required:

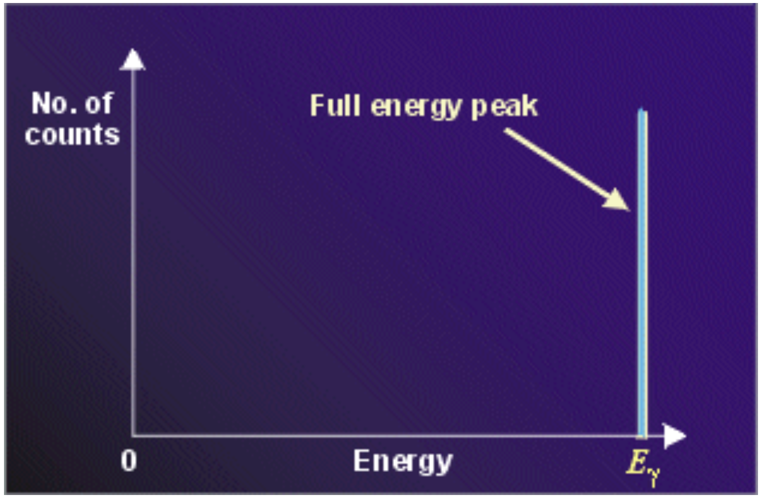
- Detectors for gamma rays
  - semiconductor detectors (HPGe)
  - szintillator detectors (NaI, BaF, BGO)

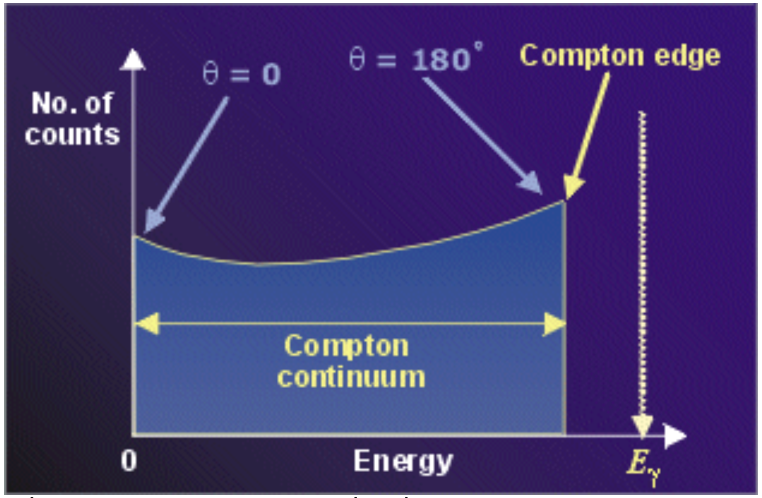
Selection rules and properties of gamma rays

Experimental techniques

How do γ rays interact with matter?

- Gamma-ray photons can interact with matter through 3 primary processes:
  - Photo-electric absorption.
  - Compton Scattering
  - Pair Production.
- An electron with a finite energy will be left in the semiconductor material.





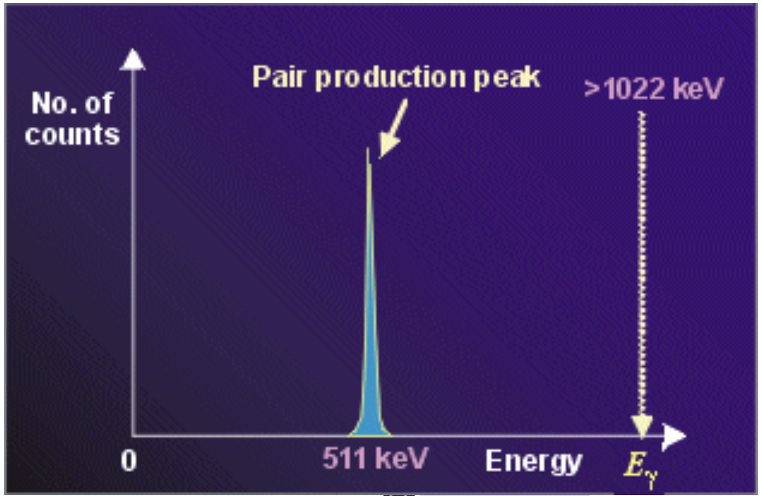


Photo-electric absorption

- The gamma ray transfers **<u>all</u>** its energy to a bound atomic electron. Ie the photon completely disappears and is replaced by an energetic photoelectron.

- The energy of the photoelectron can be written:

$$E_e = E_\gamma - E_b$$

- The incident gamma-ray photon minus that of the binding energy of the electron (12eV in germanium).

- [Photo-electric absorption](#)

Photo-electric absorption

- The photoelectric cross section is approximately proportional to Z^5 where Z is the atomic (proton) number of the absorber material.

- This interaction is important at low energies ($E\gamma < 500$ keV).

- Photoelectric cross section decreases with increasing energy.

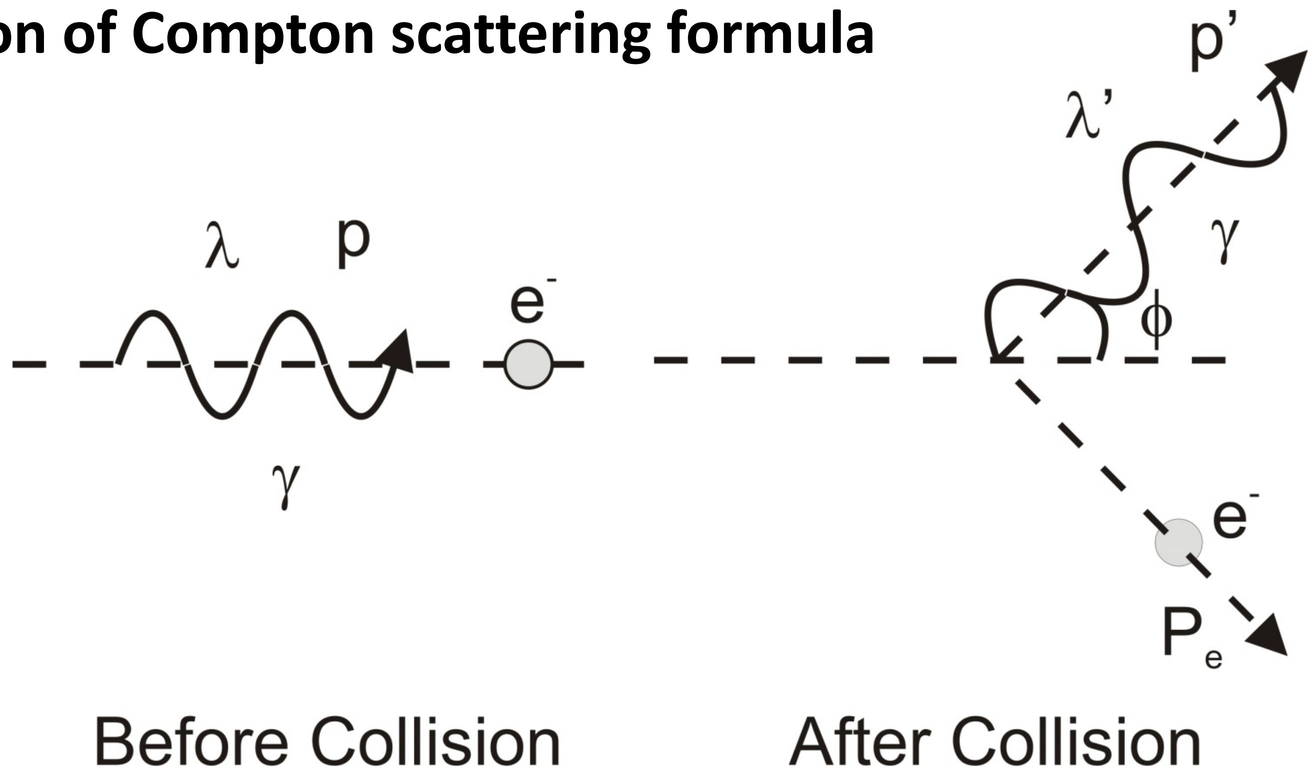
Compton Scattering

- The gamma ray interacts with a loosely bound atomic electron.
- The incoming gamma ray is scattered through an angle ϕ with respect to its original direction.
- The photon transfers a proportion of its energy to a recoil electron.
- The expression that relates the energy of the scattered photon to the energy of the incident photon is:

$$E_s = \frac{E_\gamma}{1 + \frac{E_\gamma}{m_0 c^2}(1 - \cos\theta)}$$

- The Compton scattering cross section is proportional to Z.
- This interaction is important at gamma-ray energies around 1MeV.
- Compton Scattering

Derivation of Compton scattering formula



Use conservation laws for Energy and momentum 4-vectors $P = (E/c, \mathbf{p})$:

$P_e = (mc\ ,\ \mathbf{0})$

$P_\gamma = (E_\gamma/c\ ,\ \mathbf{p}_\gamma)$

$P'_e = (E_e/c\ ,\ \mathbf{p_e})$

$P'_\gamma = (E'_\gamma/c\ ,\ \mathbf{p'}_\gamma)$

$P_\gamma^2 = P'^2_\gamma = 0 \qquad P_e^2 = P'^2_e = (mc)^2$

$E^2 = p^2c^2 + m^2c^4$

Derivation of Compton scattering formula

$P_e + P_\gamma = P'_e + P'_\gamma \quad \leftrightarrow \quad P'_e = P_e + P_\gamma - P'_\gamma$

$(P'_e)^2 = (P_e + P_\gamma - P'_\gamma)^2 = P_e^2 + P_\gamma^2 + P'^2_\gamma + 2P_eP_\gamma - 2P_eP'_\gamma - 2P_\gamma P'_\gamma$

$(mc)^2 \qquad = (mc)^2 + 0 + 0 \quad + 2mE_\gamma - 2mE'_\gamma - 2\mathbf{p}_\gamma \mathbf{p}'_\gamma$

$0 = m(E_\gamma - E'_\gamma) - E_\gamma E'_\gamma / c^2 + p_\gamma p'_\gamma \cos\phi$

Solve for E_γ:

Or for $E_e = E_\gamma - E'_\gamma$:

$$E_\gamma' = \frac{E_\gamma}{1 + \frac{E_\gamma}{mc^2}(1 - \cos\phi)}$$

$$E_e = E_\gamma \left[\frac{(1 - \cos\phi)}{1 + \frac{E_\gamma}{mc^2}(1 - \cos\phi)} \right]$$

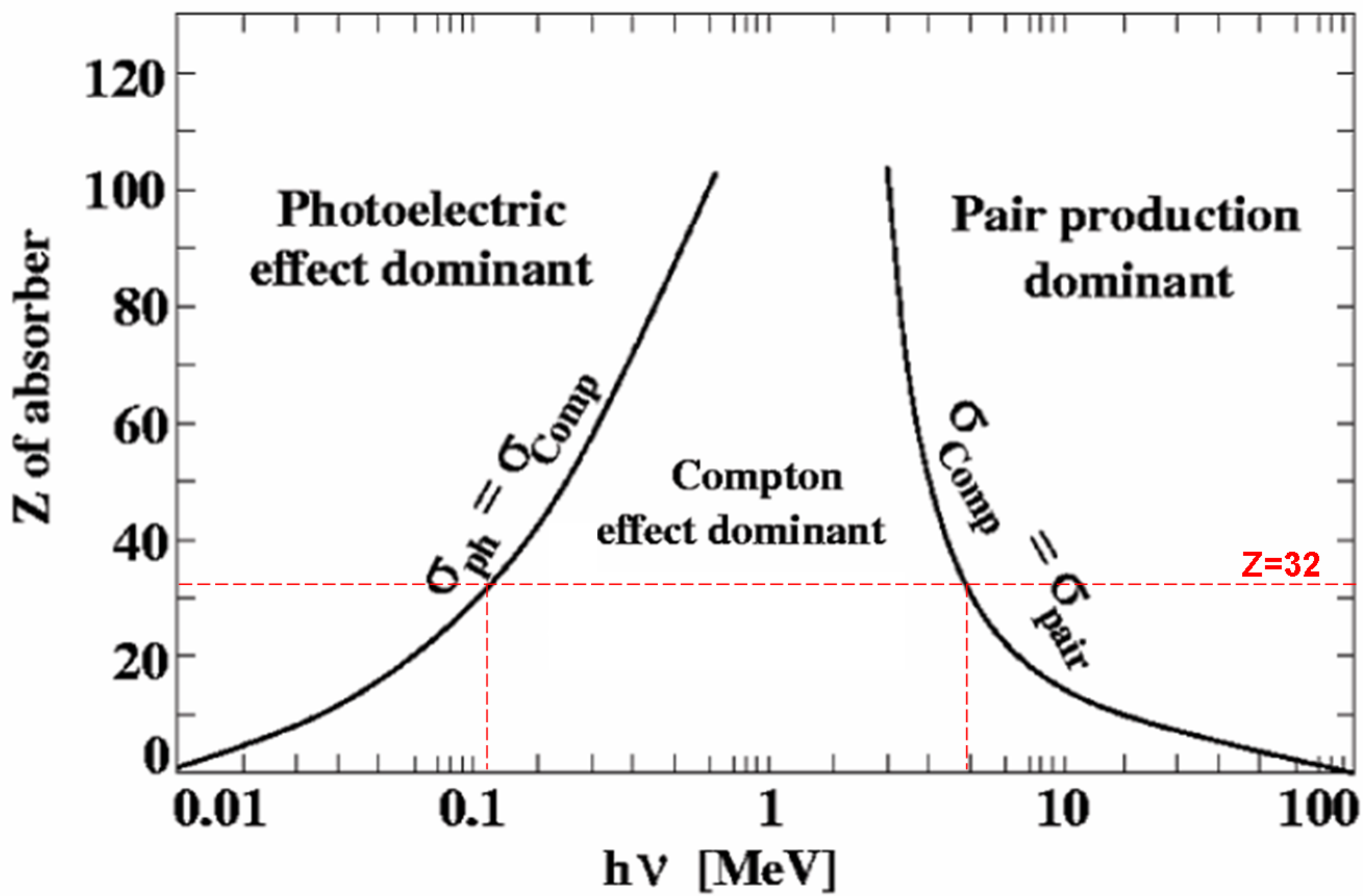
Pair Production

- If the energy of a gamma-ray exceeds twice the rest mass energy of an electron (1.02 MeV) the process of pair production is possible.

- A gamma-ray disappears in the Coulomb field of the nucleus and is replaced by an electron-positron pair.

- The excess energy above 1.02 MeV goes to the kinetic energy of the electron and the positron.

- The positron will subsequently annihilate after slowing down in the absorbing medium, producing two annihilation photons (511 keV) which may be subsequently detected.
- Pair Production



120
100
80
60
40
20
0
Z of absorber
Photoelectric effect dominant
Compton effect dominant
Pair production dominant
σph = σComp
σComp = σpair
Z=32
0.01
0.1
1
10
100
hν [MeV]

Other Gamma-ray interactions

Thomson Scattering

Low energy coherent scattering off **free** electrons.

Not important in the energy range concerned with most nuclear structure studies.

Nuclear Thomson Scattering

Low energy coherent scattering off nucleus.
Small effect.

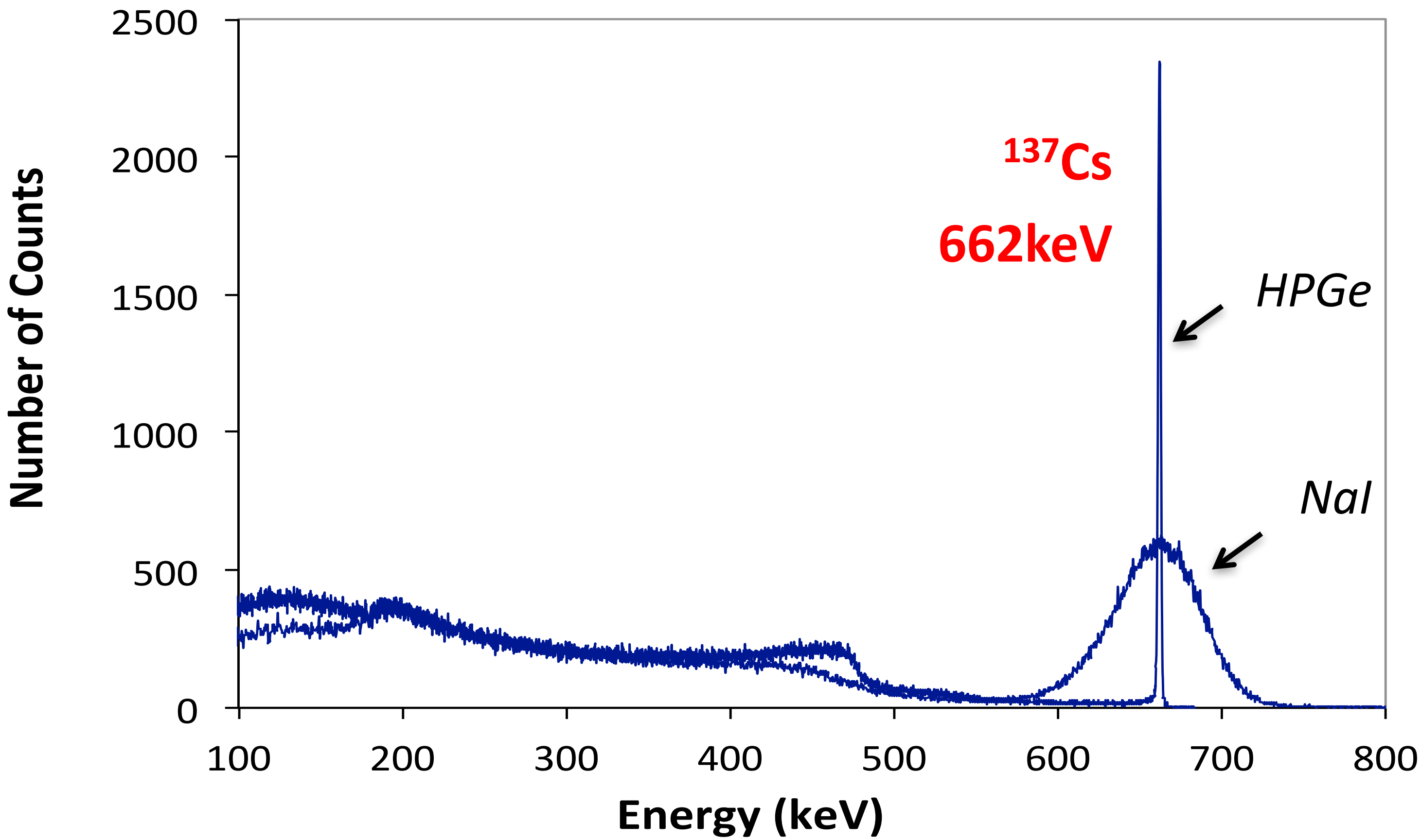
Dellbrück Scattering

Scattering in the Coulomb field of the nucleus.

Important at $E\gamma > 3$ MeV.

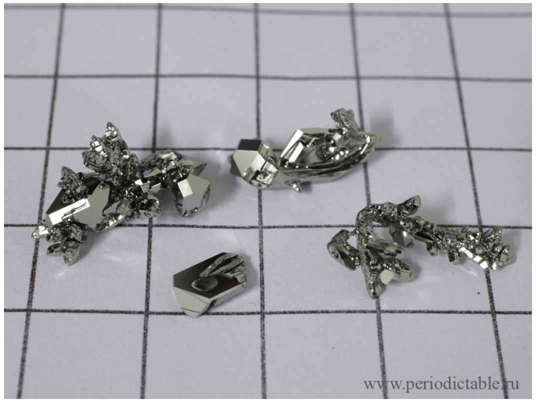
How do we build a detector?

- Semiconductor Detectors (Ge)
- Scintillator Detectors (NaI, BaF, CsI, plastic, etc.)



Ge detector

1) Start with hyperpure germanium

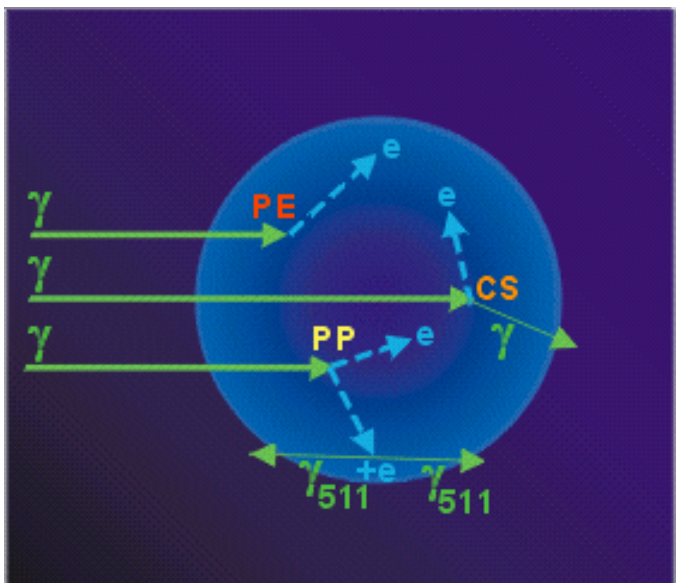


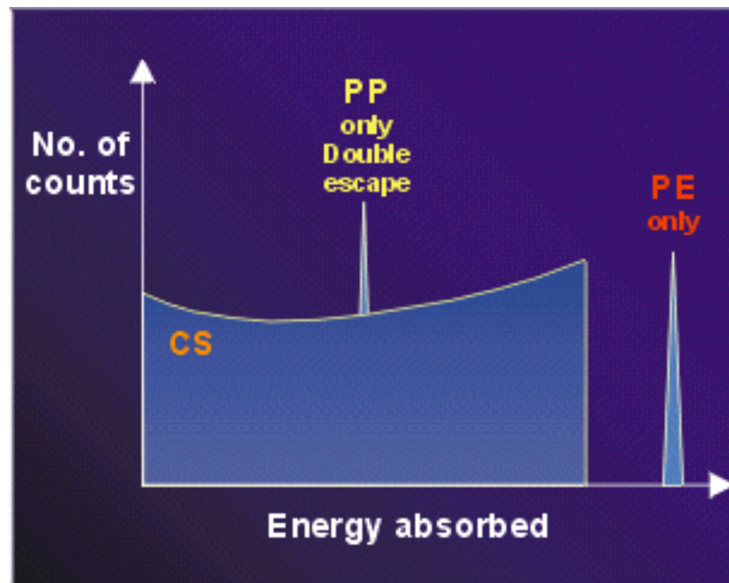
2) Form a HPGe crystal

3) Add cooling and electronics

Interactions in a small detector

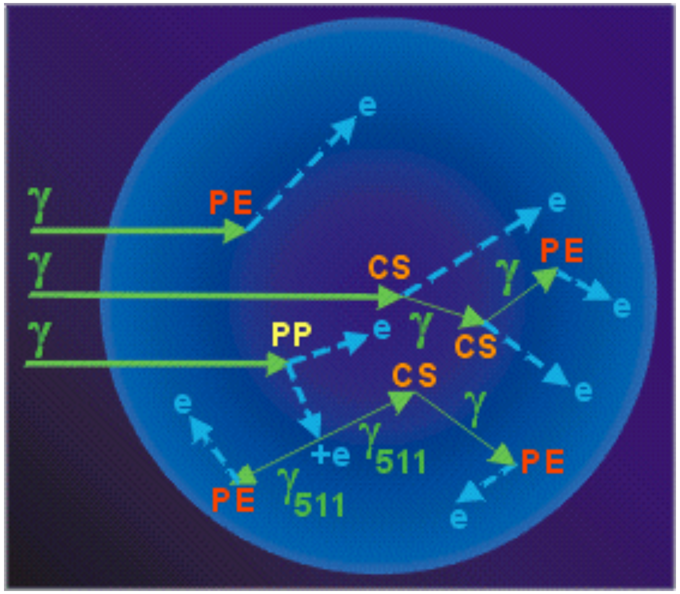
- A **small detector** is one so small that only one interaction can take place within it. Only the photoelectric effect will produce full energy absorption. Compton scattering events will produce the Compton continuum. Pair production will give rise to the double escape peak due to both gamma-rays escaping.

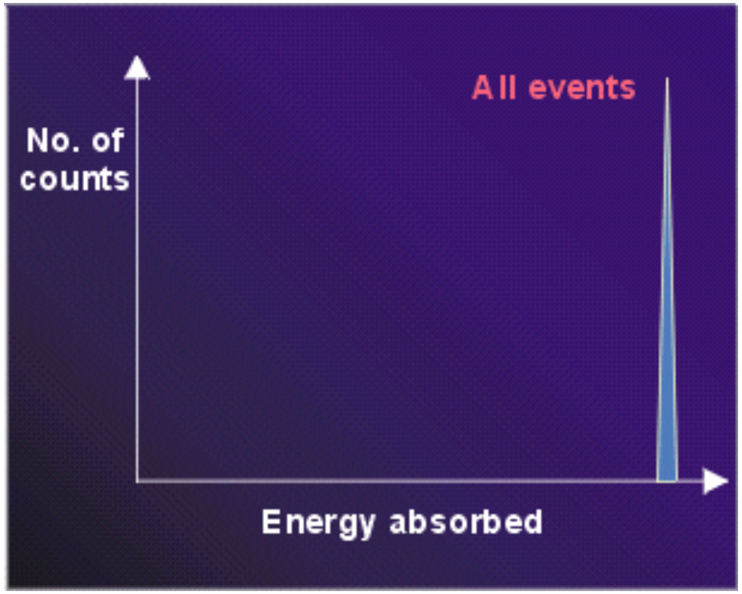




Interactions in a large detector

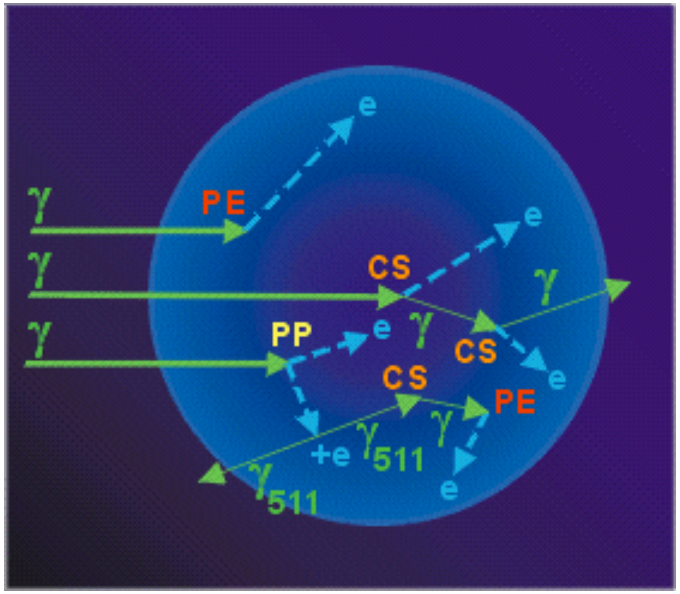
- A **large detector** is one in which we can ignore the surface of the detector. Various successive photoelectric absorption, Compton scattering and pair production interactions will occur. The result is complete absorption of the gamma ray and a single gamma-ray peak, referred to as the full energy peak.

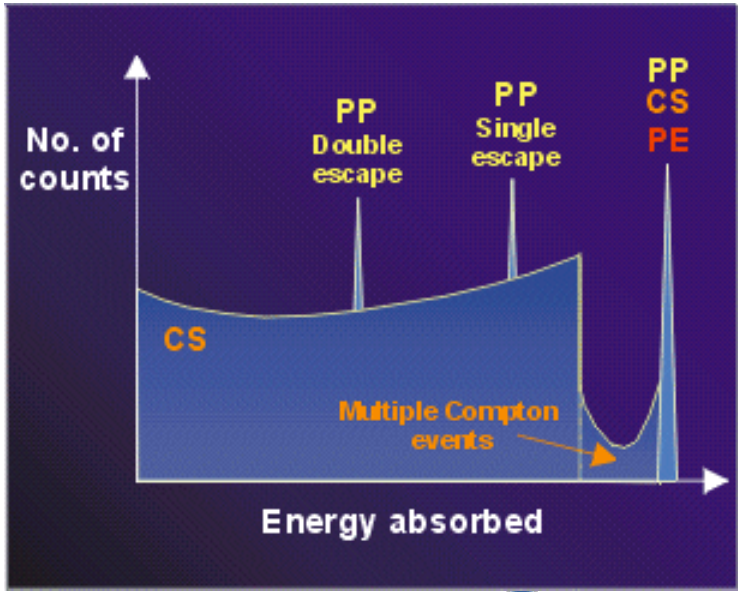




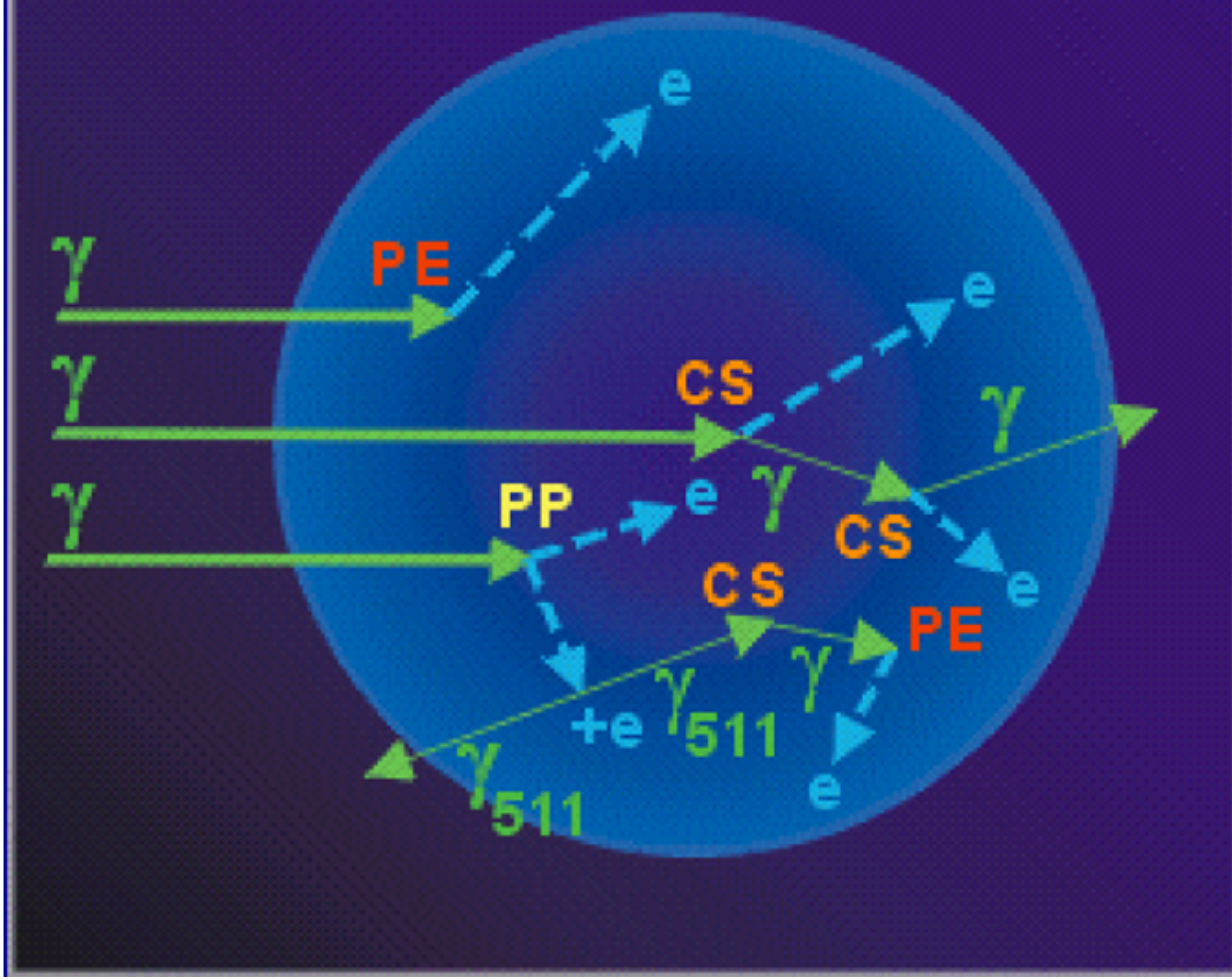
Interactions in a real detector

- Within a **real detector** the interaction outcome is not as simple to predict as the small or large detector case. Compton scattering may be followed by other Compton scatterings before the gamma-ray photon escapes from the detector. Also, pair production may be followed by the loss of only one annihilation gamma ray, resulting in a single escape peak as well as a double escape peak.

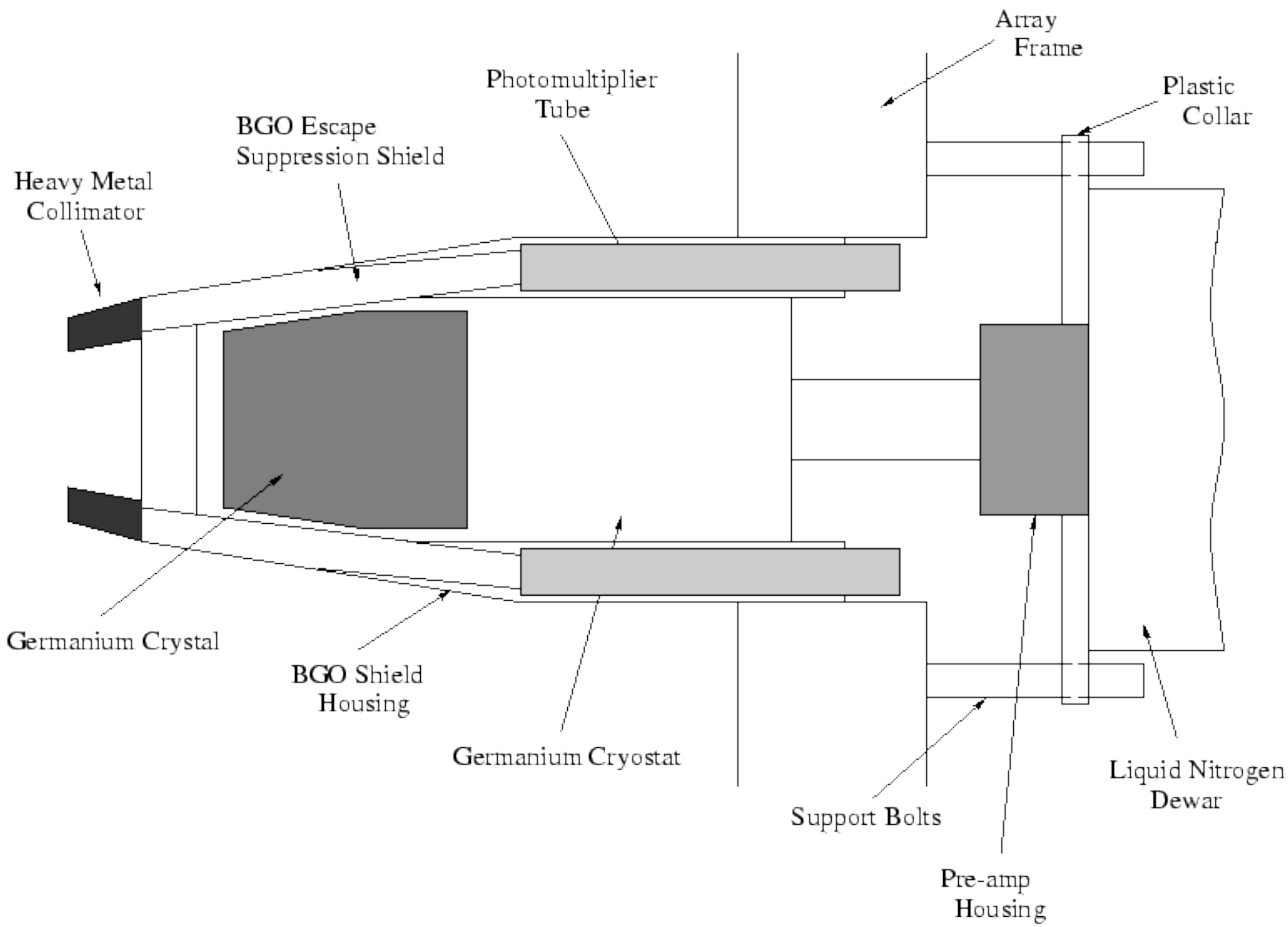


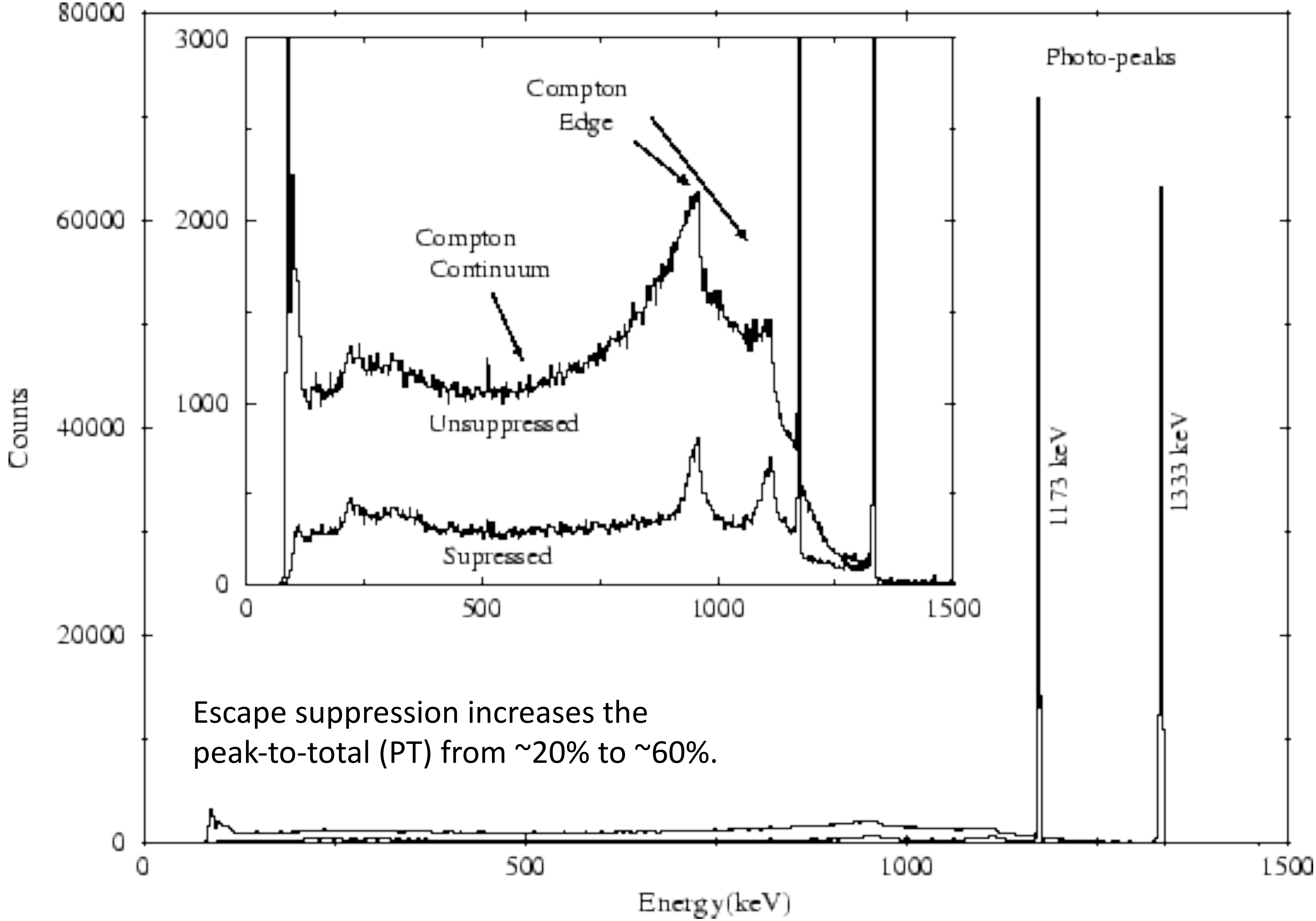


Gamma ray interactions in matter



HP Germanium detector with Compton suppression shield.





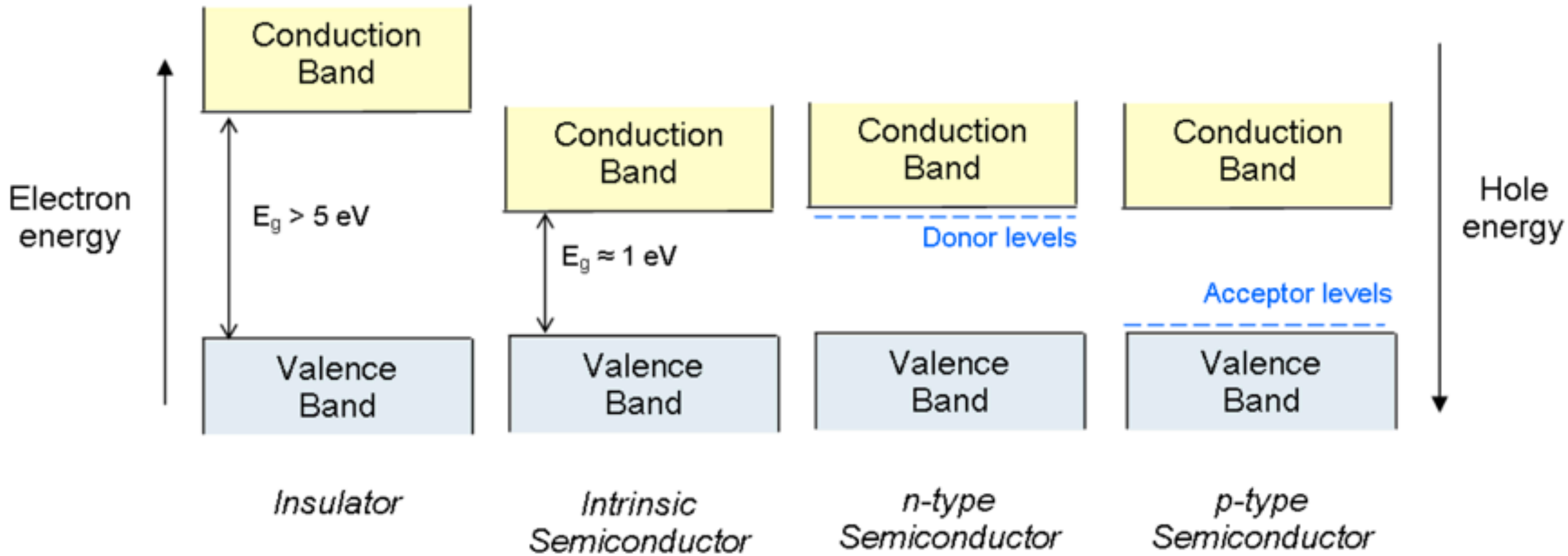
Escape suppression increases the peak-to-total (PT) from ~20% to ~60%.

Building a real semiconductor detector:

- Gamma ray transfers energy to an atomic electron
- Electron-hole pairs are created along the subsequent path of the atomic electron
- A potential difference is applied to the detector which produces an electric field
- The electron-hole pairs are swept from the active volume to the contacts, where the electrical signal is then read out.

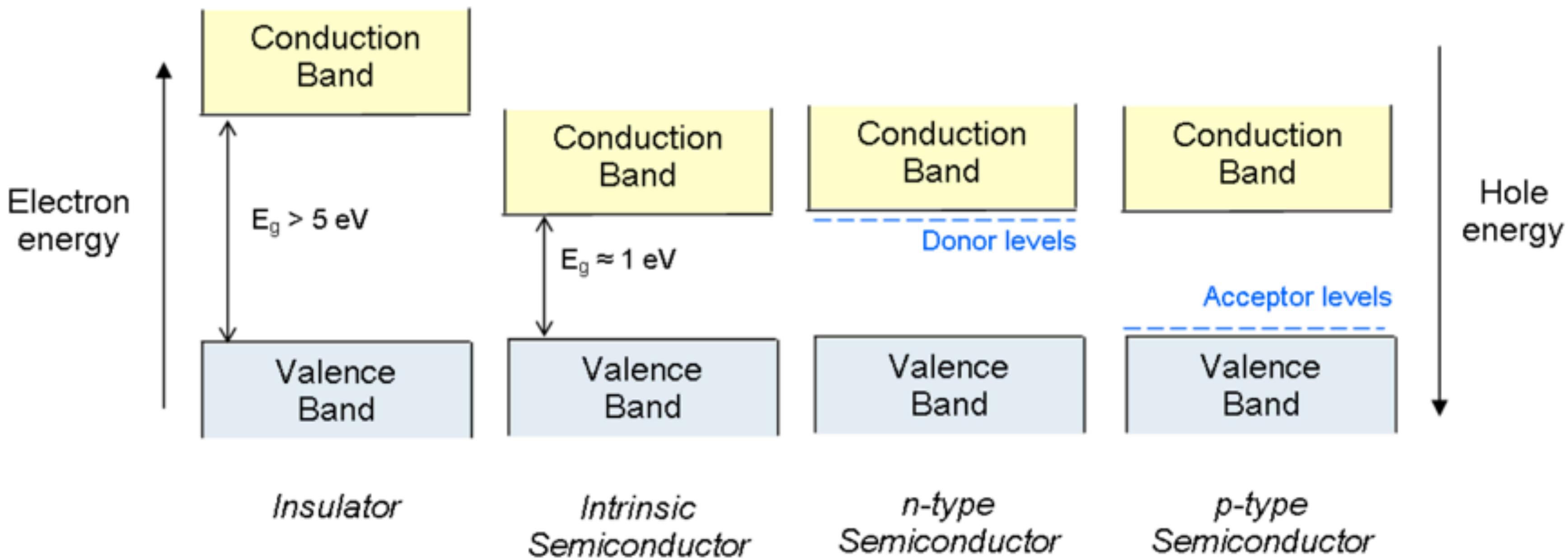
Building a real semiconductor detector:

- The band structure of permitted electron energies can be simplified to the conduction band, the valence band and the energy gap between them
- Bound outer shell electrons which occupy lattice sites within the crystal are situated in the energy region of the valence band.



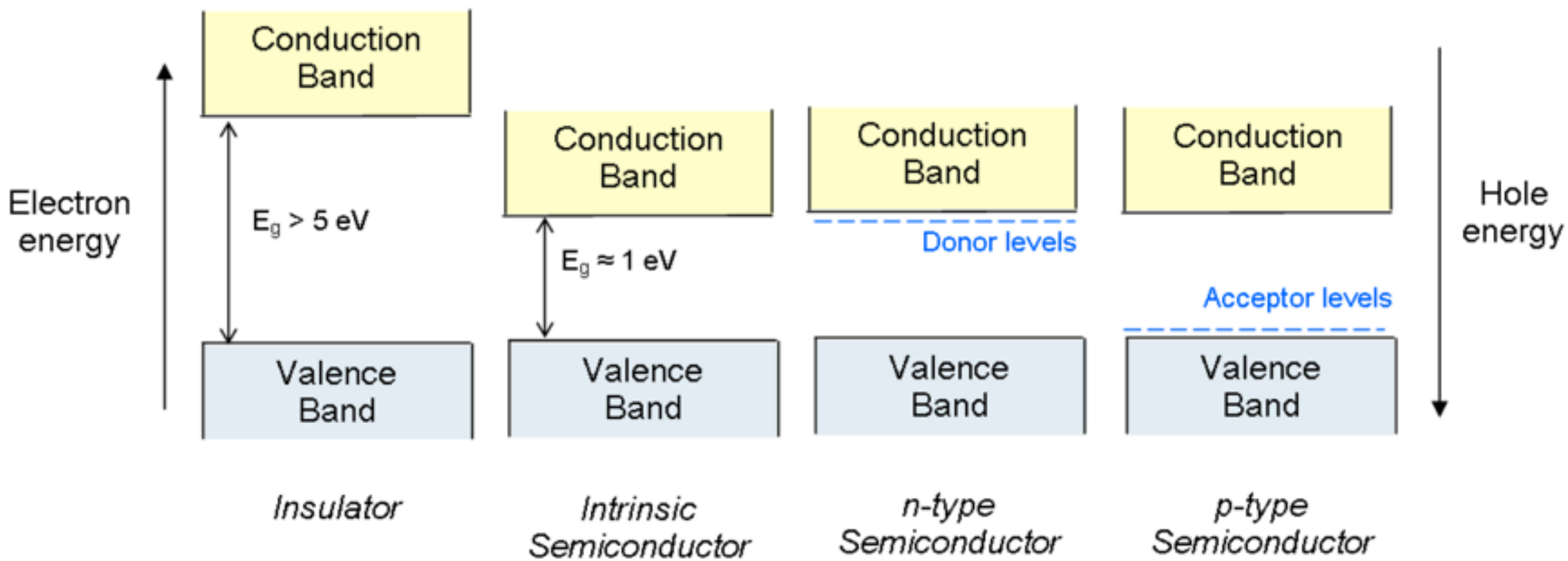
Building a real semiconductor detector:

- Electrons which are not bound to the crystal can travel freely in the conduction band, contributing to the conductivity
- The size of the energy gap, or bandgap, between the full valence band and empty conduction band determines whether the material is an insulator or semiconductor.



Building a real semiconductor detector:

- Under excitation, valence electrons are liberated, leaving a hole vacancy (charge carriers)
- Conductivity if electron energy > band gap
- Thermal excitations cause “thermal noise”



Some material constants

The average energy to produce an electron-hole pair:

- is bigger than the band gap
- it is temperature dependent

Silicon

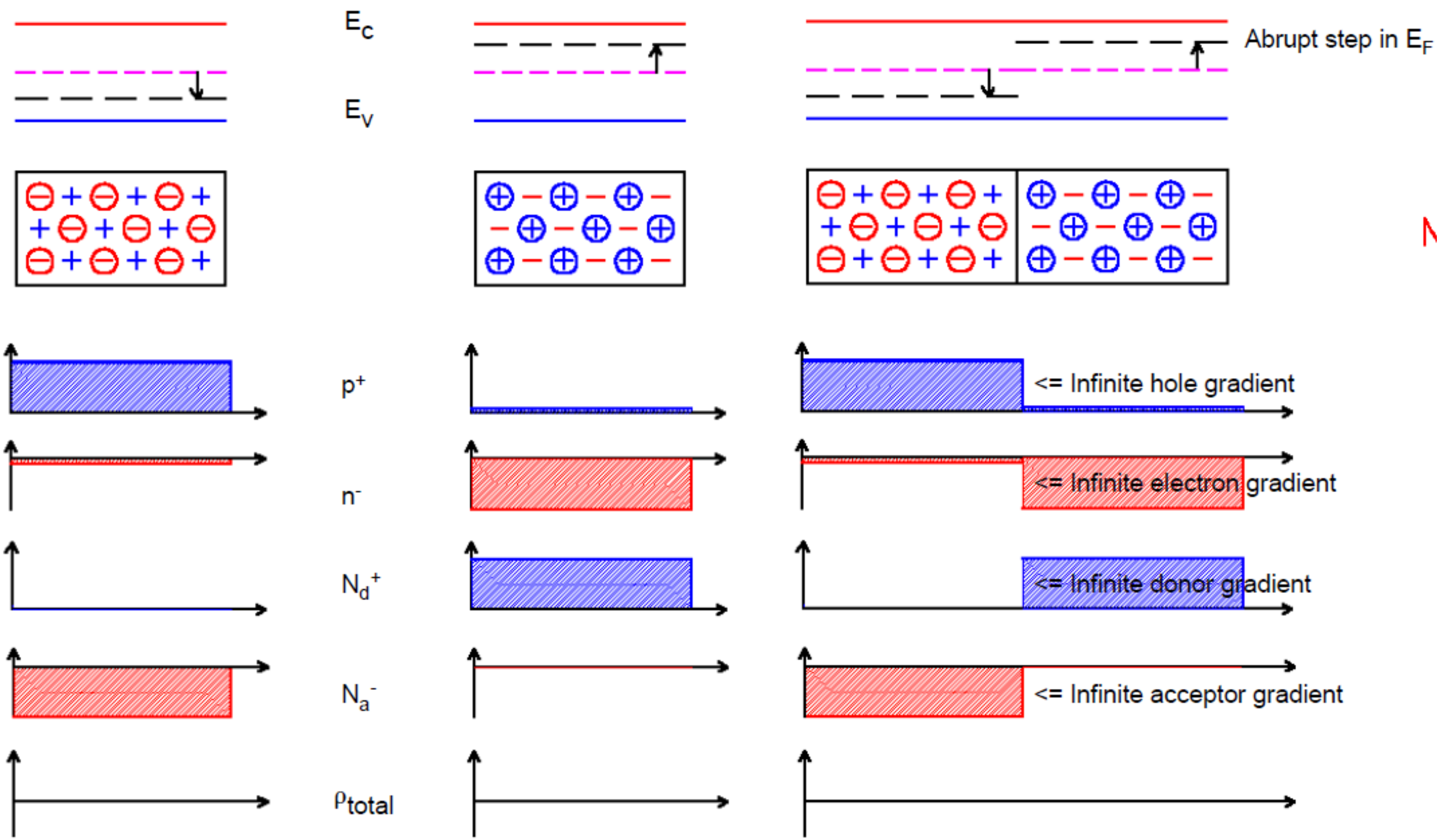
- 3.62 eV at 300K
- 3.76 eV at 77K

$$N = \frac{E_\gamma}{E_{pair}}$$

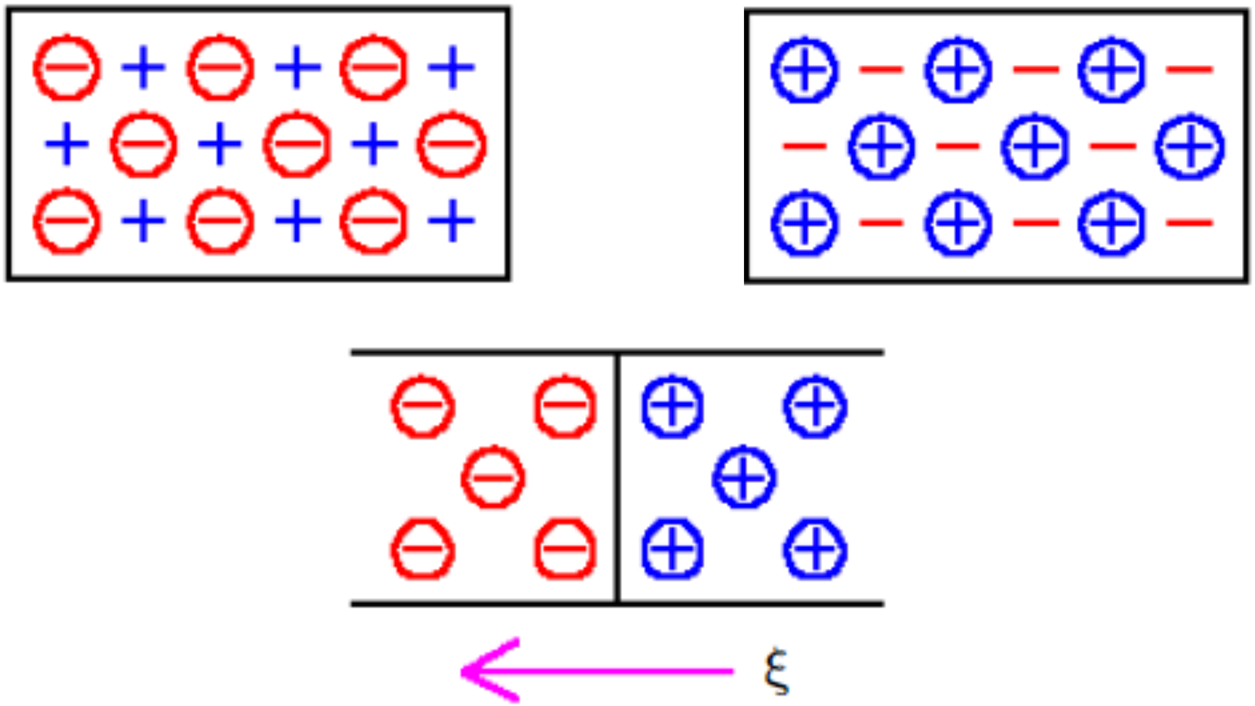
Germanium

- 2.96 eV at 77K

Building a diode



The Junction



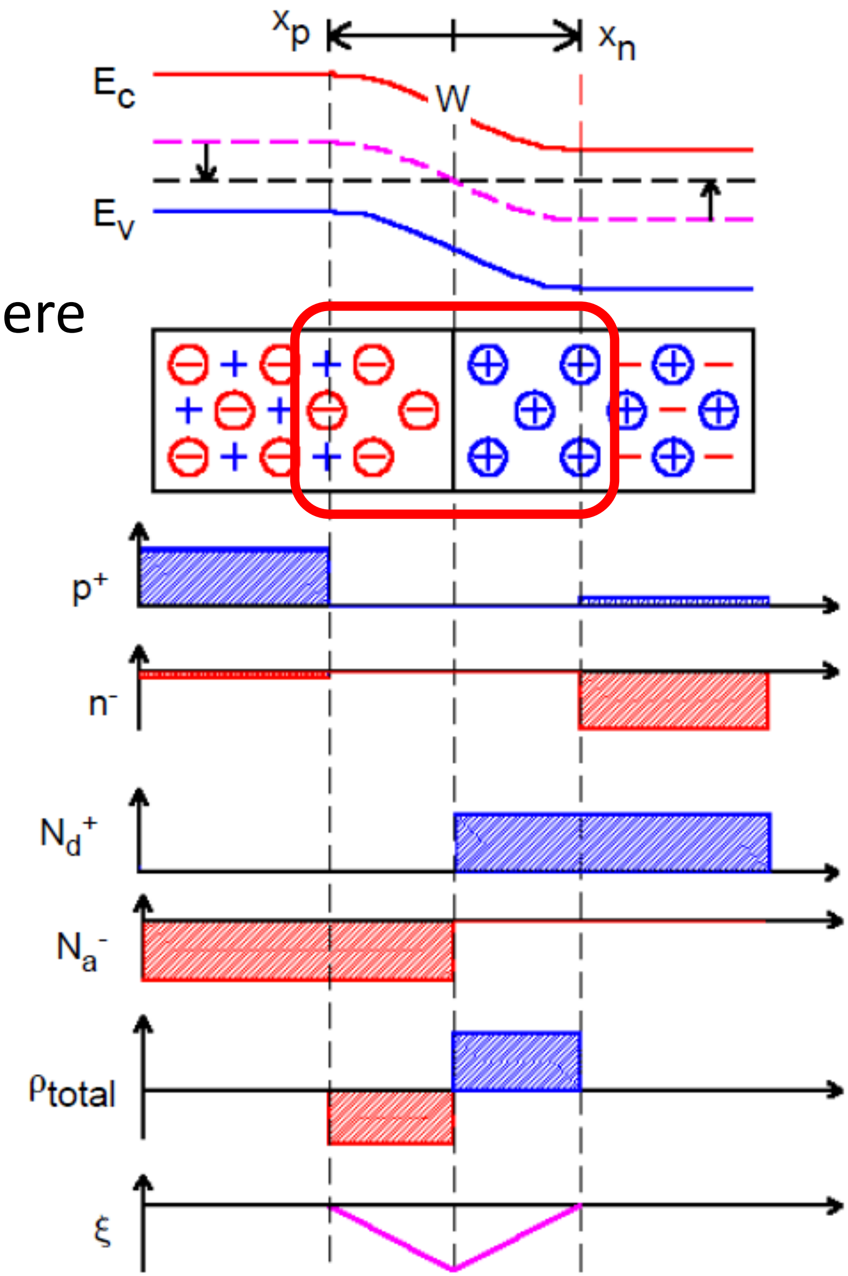
Dipole ions builds up an internal electric field
(eventually blocks further carrier crossing)

Full Junction

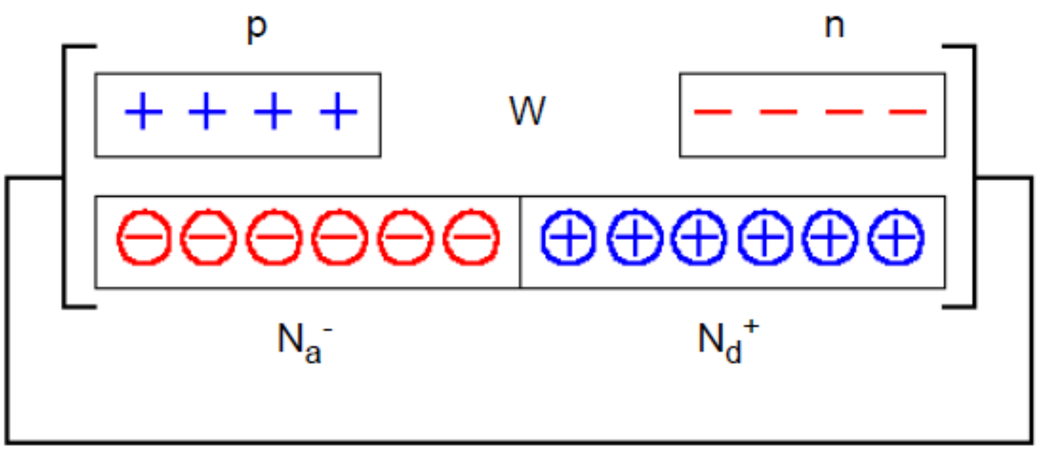
This depletion region is where we have a good detctor!

But it's small.

Apply reverse bias!



Bias

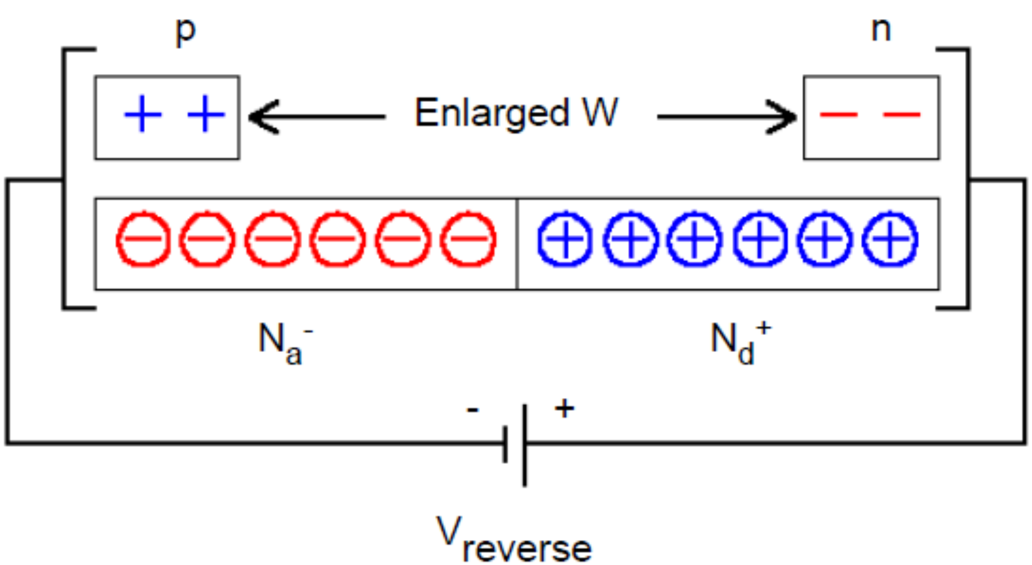


Zero applied voltage

$$W = \sqrt{\frac{2\varepsilon(V_{bi} - V_{appl})}{q}\left[\frac{1}{N_a} + \frac{1}{N_d}\right]}$$

$V_{appl} < 0$

Simplified:



$$d \cong \sqrt{\frac{2\epsilon V}{eN}}$$

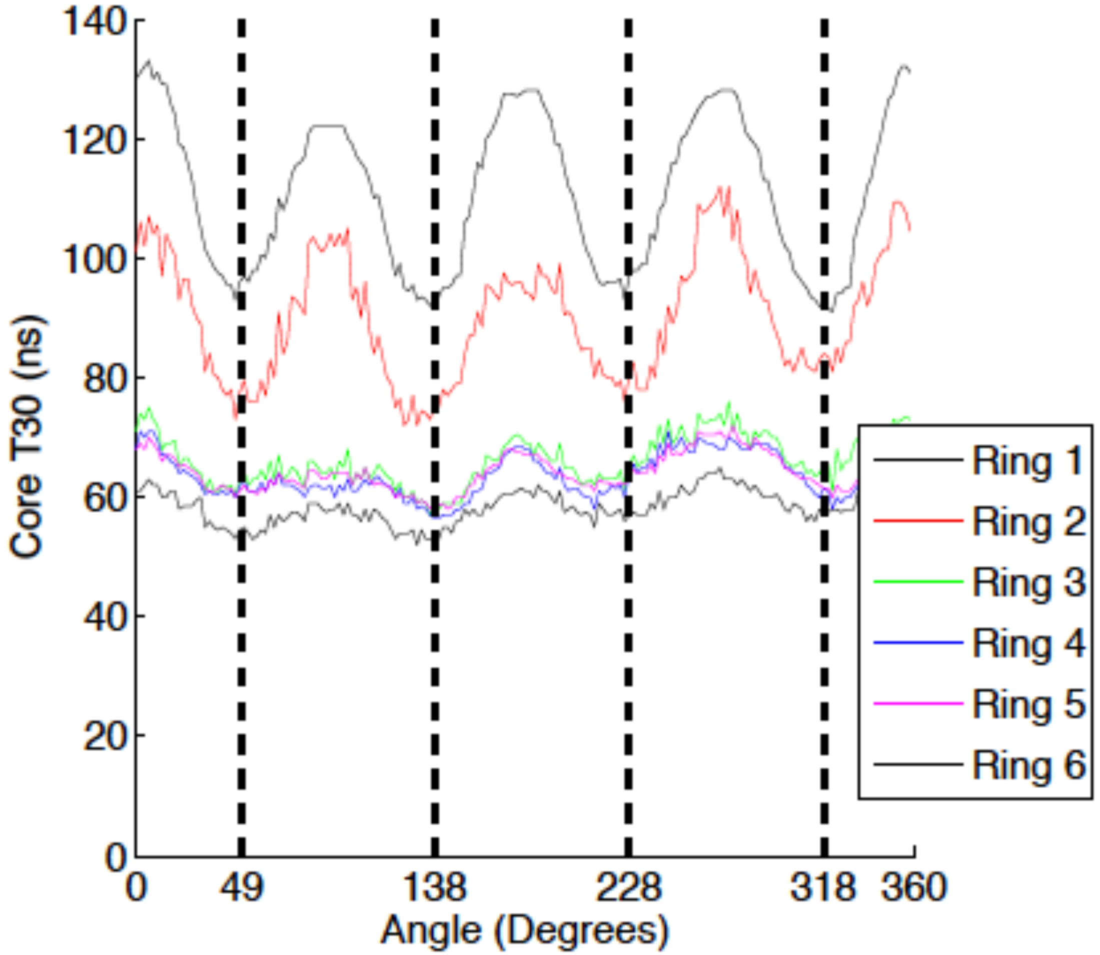
Charge collection takes time:

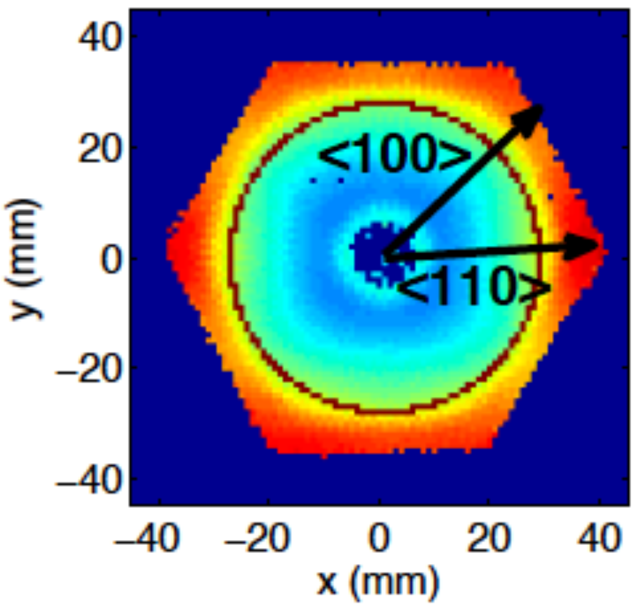
- Electron and hole diffuse from initial sites in random motion as function of time, eventually recombine
- However, if P.D applied, electrons and holes will migrate in opposite directions, parallel to the electric field
- Net average drift velocity of charges varies due to material type, according to the mobilities
- Drift velocity increases proportionally with electric field strength until saturation ~ 10^7 cm/s. Operate above this.

$$v_h = \mu_h \varepsilon \qquad v_e = \mu_e \varepsilon$$

Drift velocityin a Ge crystal

- Drift velocity varies as function of application of field to the





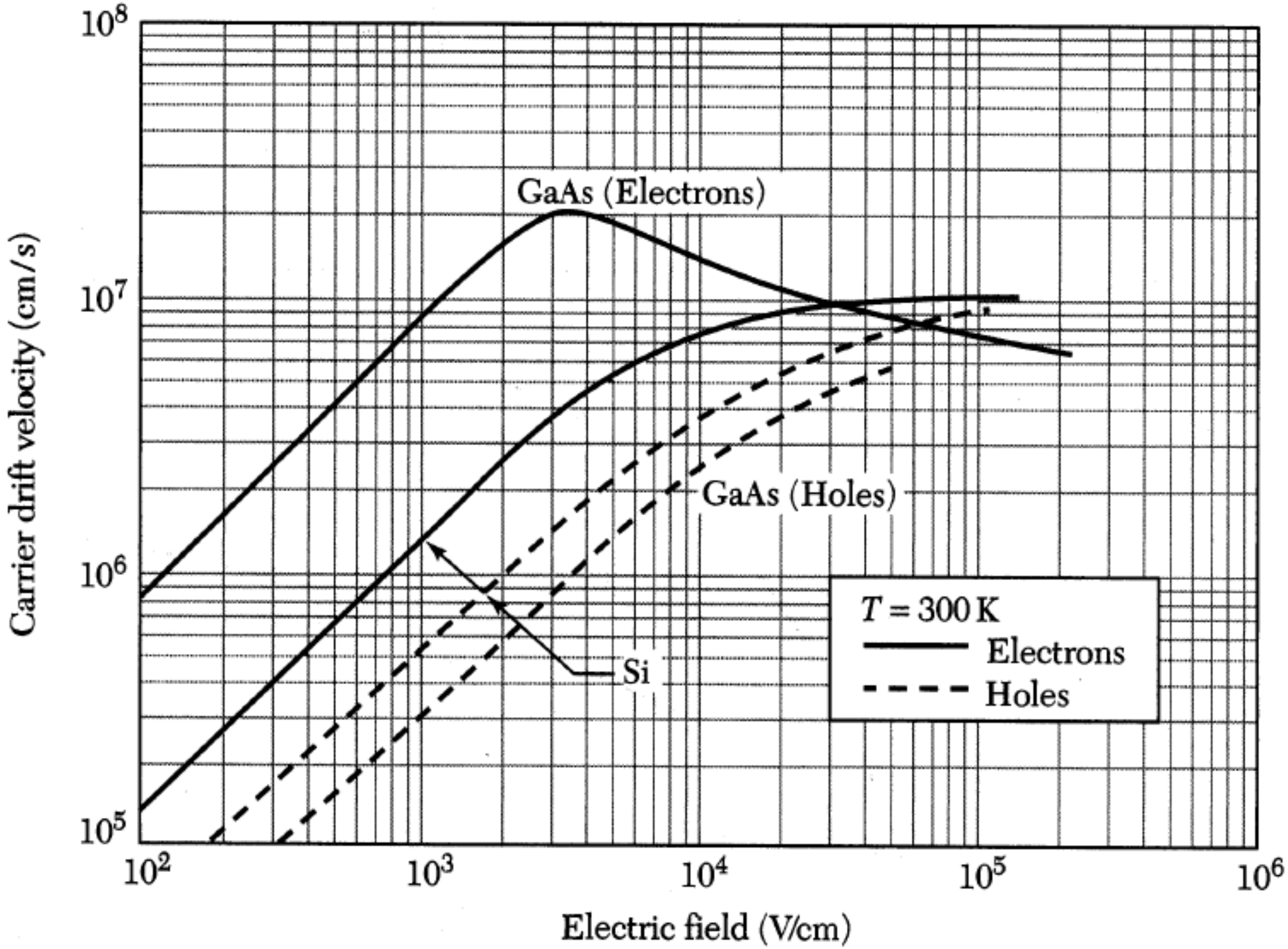
More material constants

Material	Carrier	Temp (K)	Mobility (cm^2/Vs)
Si	electron	300	1350
		77	21000
	Hole	300	480
		77	11000
Ge	electron	300	3900
		77	36000
	hole	300	1900
		77	42000

High electric field effects

- What is the dependence of the mobility as a function of electric field?
- This is important in most electronic devices.
  - At high fields *E* (~1-100kV/cm) electrons acquire a high average energy.
  - As the carriers gain energy they suffer greater scattering and the mobility starts to decrease.
  - At very high fields the drift velocity becomes saturated and therefore independent of *E.*
  - The drift velocities for most materials saturates to a value of ~10^7cm/s.

Drift of carriers in an Electric Field



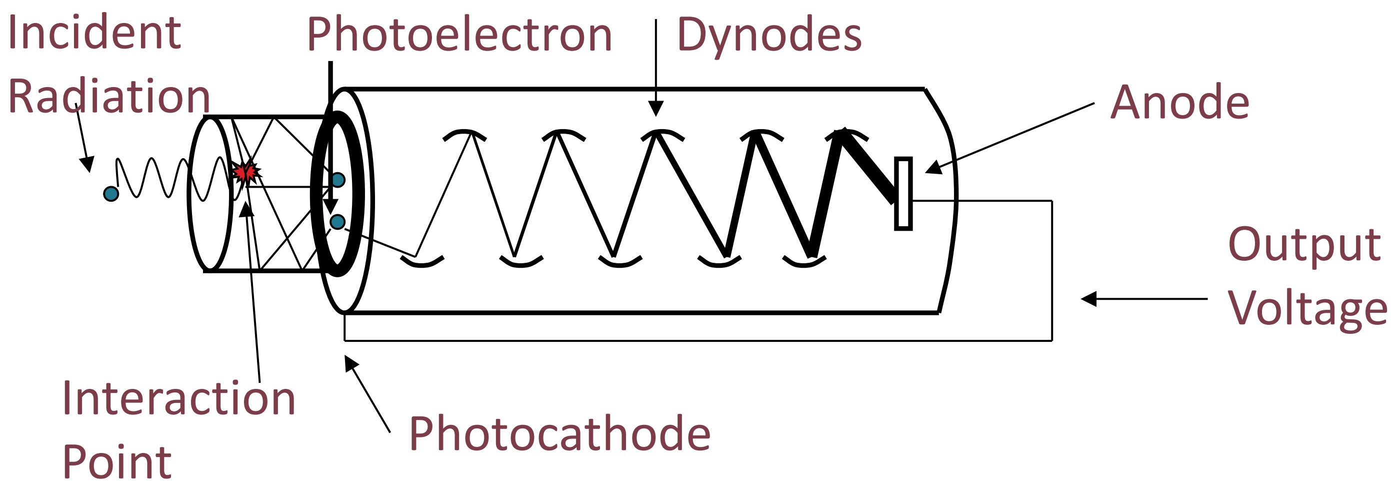
HP Ge detector

- Large depleted volume
- Good electron mobility

- Large Z, therefore high efficiency
- Cooled to LN2 temperatures
- Excellent energy resolution

Szintillator Detectors

- Energy deposition in scintillation material causes electronic transitions to excited states, which decay by emitting photons
- Amount of light produced is **proportional to energy deposited** by incident radiation but very small signal
- Light output converted into voltage pulses, e.g. PMT



Scintillation Materials

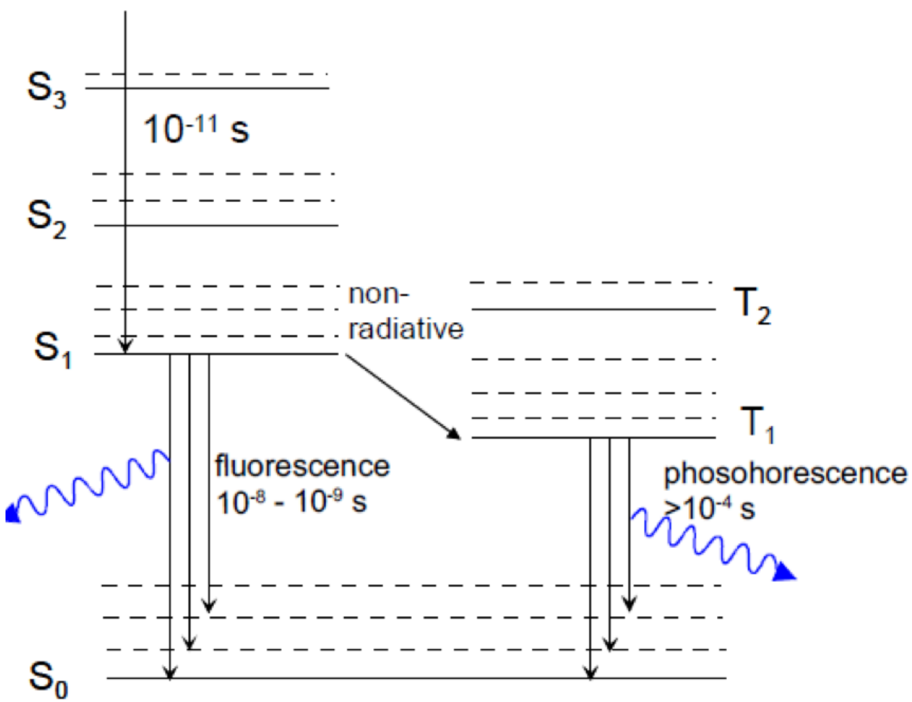
- ☺ Prompt fluorescence: prompt emission of visible radiation from a substance following excitation
- ☹ Delayed fluorescence: same emission spectrum as prompt but characterised by longer emission time following excitation
- ☹ Phosphorescence: emission of longer wavelength light than fluorescence, with longer characteristic time

Pulse shaping times much shorter than typical phosphorescence and delayed fluorescence decay times

Organic Scintillator

- Fluorescence process arises from transitions in the energy level structure of a single molecule, regardless of its physical state (solid, liquid etc)

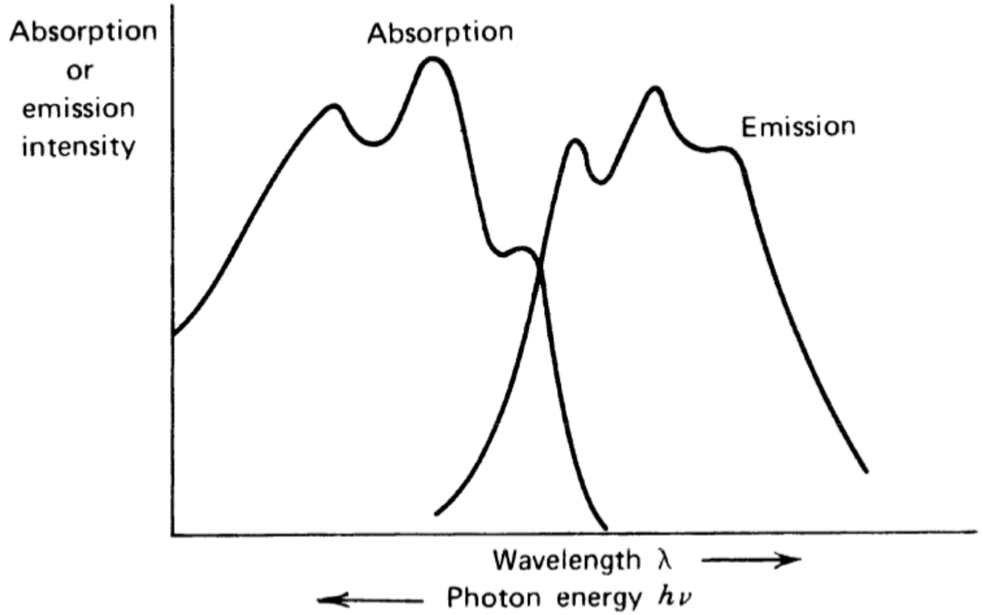
Singlet (Spin 0) **Triplet (Spin 1)**



- Energy can be absorbed by exciting the electronic configuration to any of the excited states
- S_0->S_1 ~3 or 4 eV
- Finer spacing is vibrational states (but larger than thermal 0.025eV)
- Room temperature molecules S_{00}

Emission - Absorption

- Principle scintillation light (prompt fluorescence) is emitted in transition from S_{10} state to a vibrational state of the ground electronic state S_{0n}
- Mostly self-transparent because all the fluorescence transitions have a lower energy than minimum required for excitation.



Scintillation Materials

MATERIAL	DENSITY [g/cm^3]	EMISSION MAXIMUM [nm]	DECAY CONSTANT (1)	REFRACTIVE INDEX (2)	CONVERSION EFFICIENCY (3)	HYGRO-SCOPIC
NaI(Tl)	3.67	415	0.23 ms	1.85	100	yes
CsI(Tl)	4.51	550	0.6/3.4 ms	1.79	45	no
CsI(Na)	4.51	420	0.63 ms	1.84	85	slightly
CsI (undoped)	4.51	315	16 ns	1.95	4 - 6	no
CaF_2 (Eu)	3.18	435	0.84 ms	1.47	50	no
^{6}LiI (Eu)	4.08	470	1.4 ms	1.96	35	yes
^{6}Li - glass	2.6	390 - 430	60 ns	1.56	4 - 6	no
CsF	4.64	390	3 - 5 ns	1.48	5 - 7	yes
BaF_2	4.88	315 220	0.63 ms 0.8 ns	1.50 1.54	16 5	no
YAP (Ce)	5.55	350	27 ns	1.94	35 - 40	no
GSO (Ce)	6.71	440	30 - 60 ns	1.85	20 - 25	no
BGO	7.13	480	0.3 ms	2.15	15 - 20	no
$CdWO_4$	7.90	470 / 540	20 / 5 ms	2.3	25 - 30	no
Plastics	1.03	375 - 600	1 - 3 ms	1.58	25 - 30	no

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Scintillation Materials

MATERIAL	IMPORTANT PROPERTIES	MAJOR APPLICATIONS
NaI(Tl)	Very high light output, good energy resolution	General scintillation counting, health physics, environmental monitoring, high temperature use
CsI(Tl)	Noon-hygroscopic, rugged, long wavelength emission	Particle and high energy physics, general radiation detection, photodiode readout, phoswiches
CsI(Na)	High light output, rugged	Geophysical, general radiation detection
CsI(undoped)	Fast, non-hygroscopic, radiation hard, low light output	Physics (calorimetry)
CaF_2(Eu)	Low Z, high light outut	b detection, a, b phoswiches
^{6}LiI(Eu)	High neutron cross-section, high light output	Thermal neutron detection and spectroscopy
^{6}Li - glass	High neutron cross-section, non-hygroscopic	Thermal neutron detection
BaF_2	Ultra-fast sub-ns UV emission	Positron life time studies, physics research, fast timing
YAP(Ce)	High light output, low Z, fast	MHz X-ray spectroscopy, synchrotron physics
GSO(Ce)	High density and Z, fast, radiation hard	Physics research
BGO	High density and Z	Particle physics, geophysical research, PET, anti-Compton spectrometers
$CdWO_4$	Very high density, low afterglow, radiation hard	DC measurement of X-rays (high intensity), readout with photodiodes, Computerized Tomography (CT)
Plastics	Fast, low density and Z, high light output	Particle detection, beta detection

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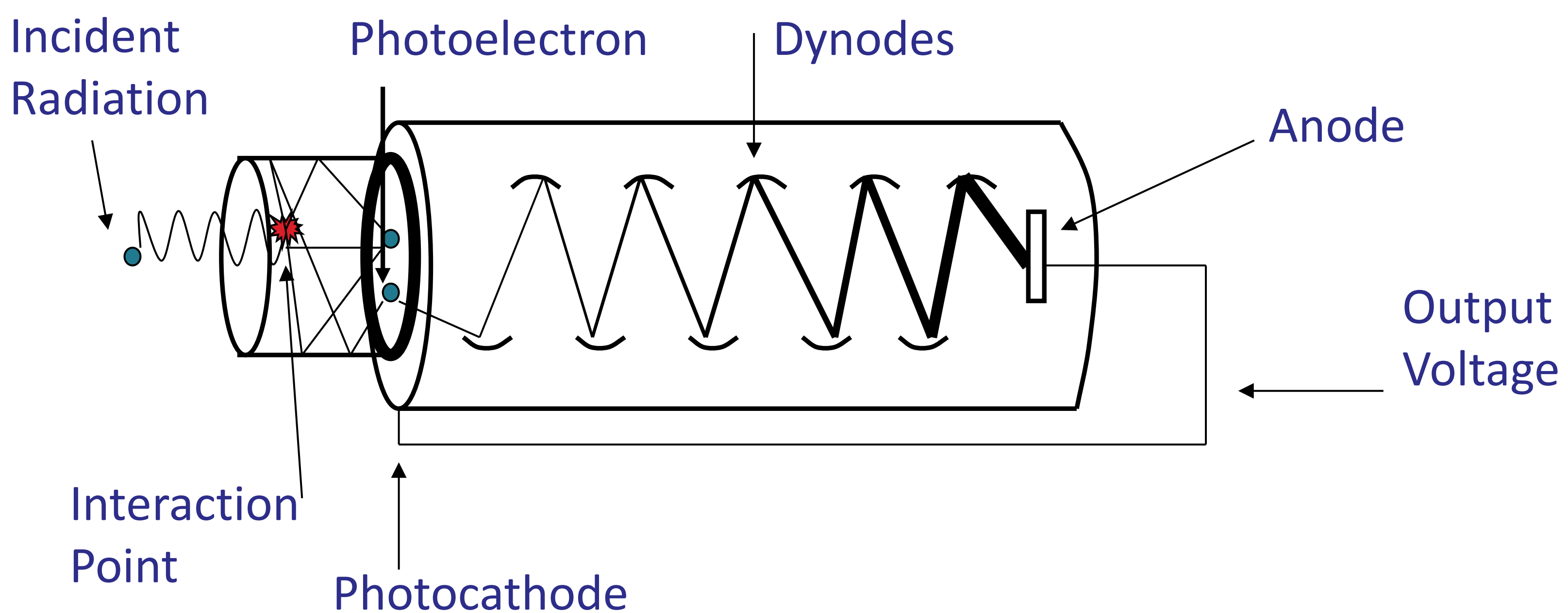
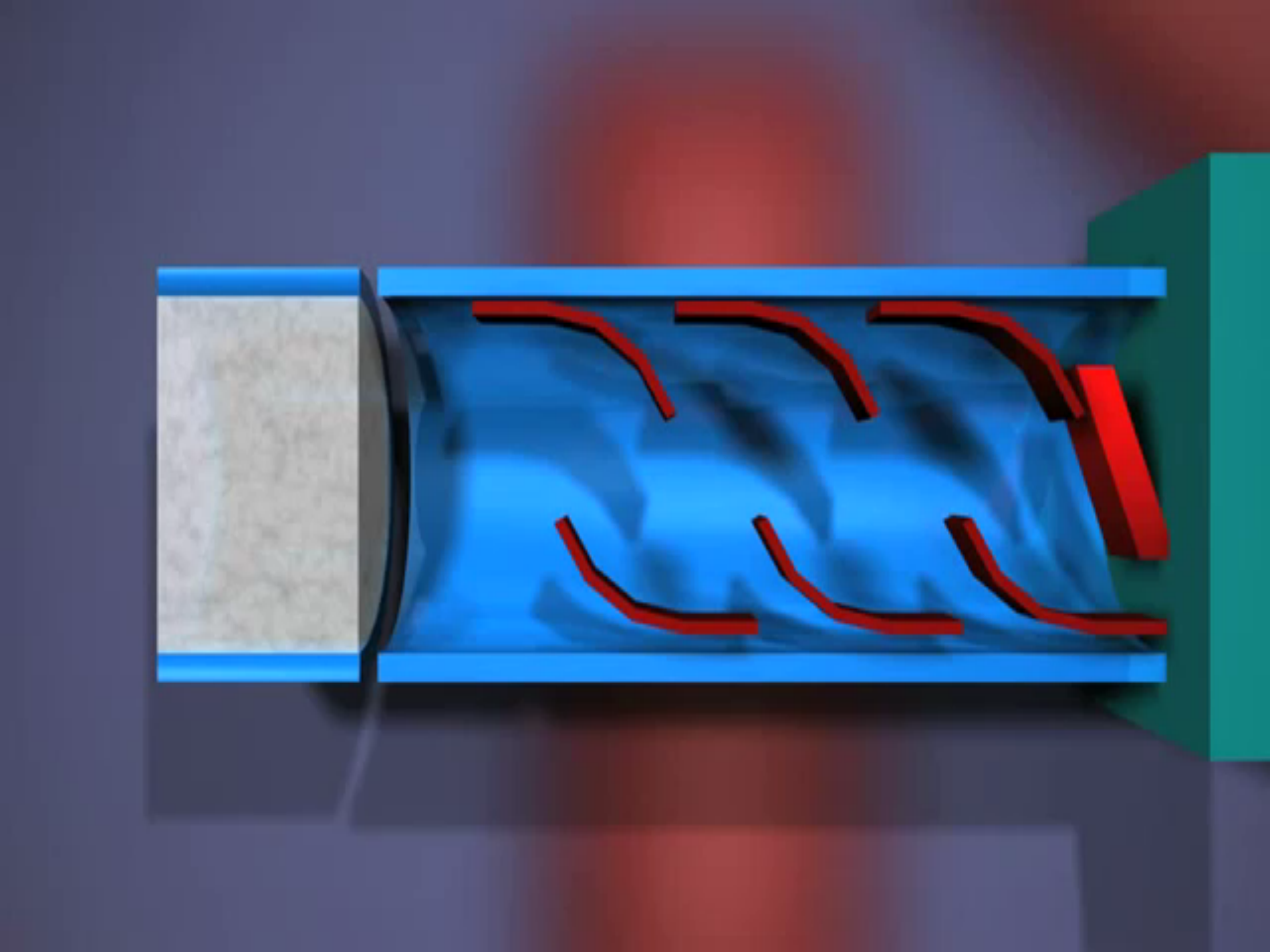
Scintillator Readout

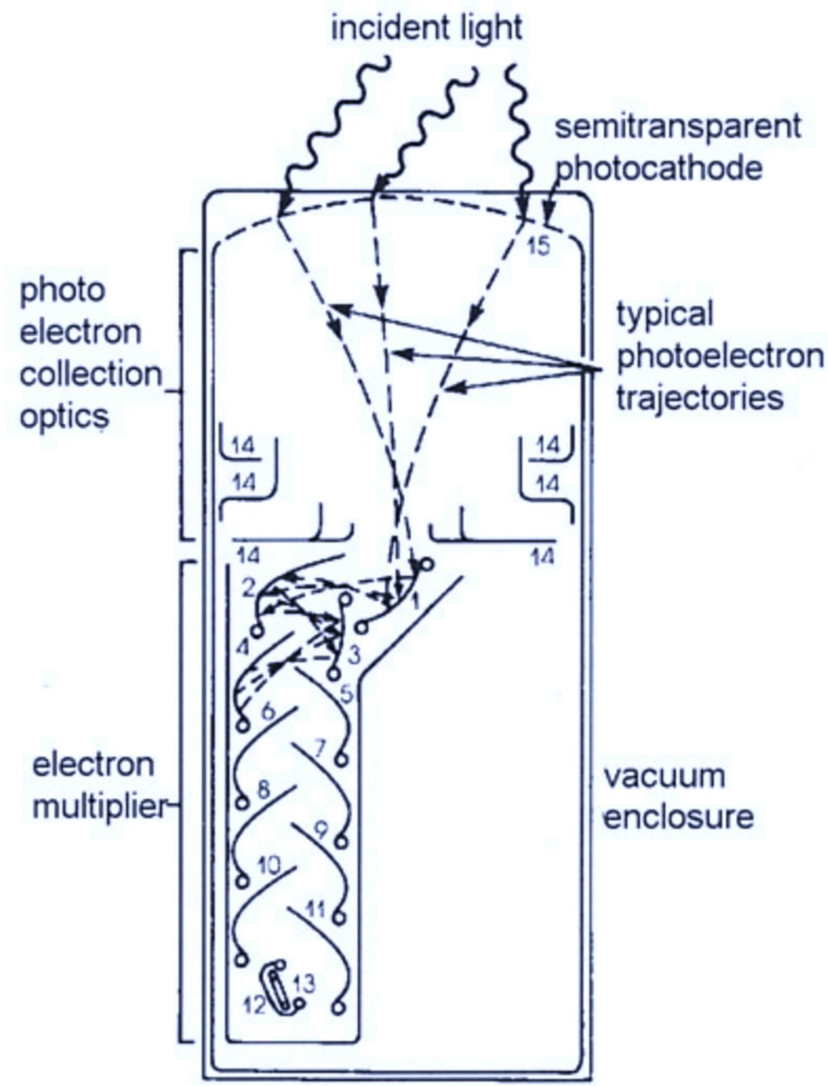
- Amount of light produced is **proportional to energy deposited** by incident radiation but very small signal
- Photomultiplier Tube (PMT) most common
- APD, SiPM……





Photomultiplier Tubes

- Photocathode converts as many incident light photons as possible to low-energy electrons
- Only few 100 electrons produced therefore electron multiplier used as an efficient collection geometry for the photoelectrons and an excellent amplifier
- After amplification, typical scintillator pulse ~ 10^7-10^{10} electrons
- Output pulse usually proportional to deposited energy



Photocathode

Photoemission:

1. Absorption of incident photon and transfer of energy to electron in medium (for blue light typically ~3eV)
2. Migration of the electron to the surface (with some energy loss)
3. Escape of the electron from the surface of the photocathode (must overcome work function energy, resulting in a low energy cut-off in red wavelength)
4. Quantum Efficiency typically ~ 20-30%

$$\text{Quantum Efficiency (QE)} = \frac{\text{number of photoelectrons emitted}}{\text{number of incident photons}}$$

Electron Multiplication

Secondary e^- emission:

1. Electrons (k.e. < 1eV) from photocathode accelerated towards the surface of an electrode (dynode) by positive potential of several hundred volts
2. Energy deposited by incident electron can result in excitation of more than one electron in the same surface (about 30 excited electrons per 100 V of accelerating voltage)
3. Some electrons are re-emitted (if can overcome work function of dynode and the direction of motion is appropriate)

$$\text{Multiplication factor for single dynode } \delta = \frac{\text{number of secondary electrons emitted}}{\text{primary incident electron energy}}$$

Electron Multiplication

Multiple stage multiplication:

1. All PMs employ multiple stages
2. At first dynode, δ electrons are produced per incident photoelectron
3. Secondary electrons guided to next dynode in repetitive process
4. If N stages of multiplication, overall gain is

$$\text{Overall gain} = \alpha\delta^N$$

where α is the fraction of all photoelectrons collected by the multiplier. Typically overall gain is 10^7

Alternatives to PMT : Photodiodes

- Alternative to PMTs, offer high quantum efficiency (potentially better energy resolution), lower power consumption, more compact size, improved ruggedness and insensitive to magnetic fields
- Conventional photodiodes: no internal gain, directly convert light photons to electron hole pairs
- Avalanche photodiodes: incorporate internal gain through higher electric fields that increase the number of charge carriers collected
- Silicon photomultiplier: operated in Geiger mode

Electronic Detector Spectral Sensitivities

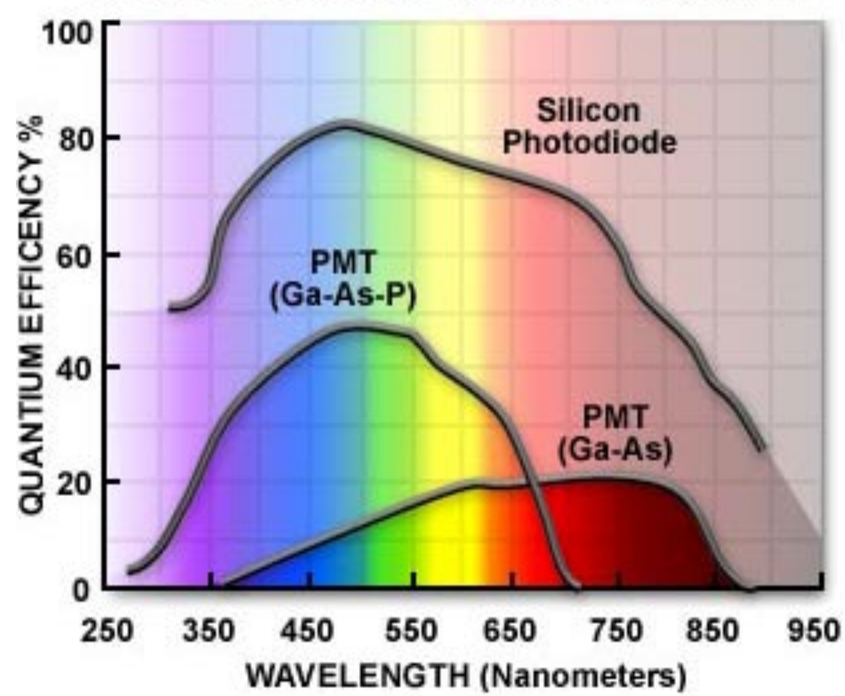


Figure 3