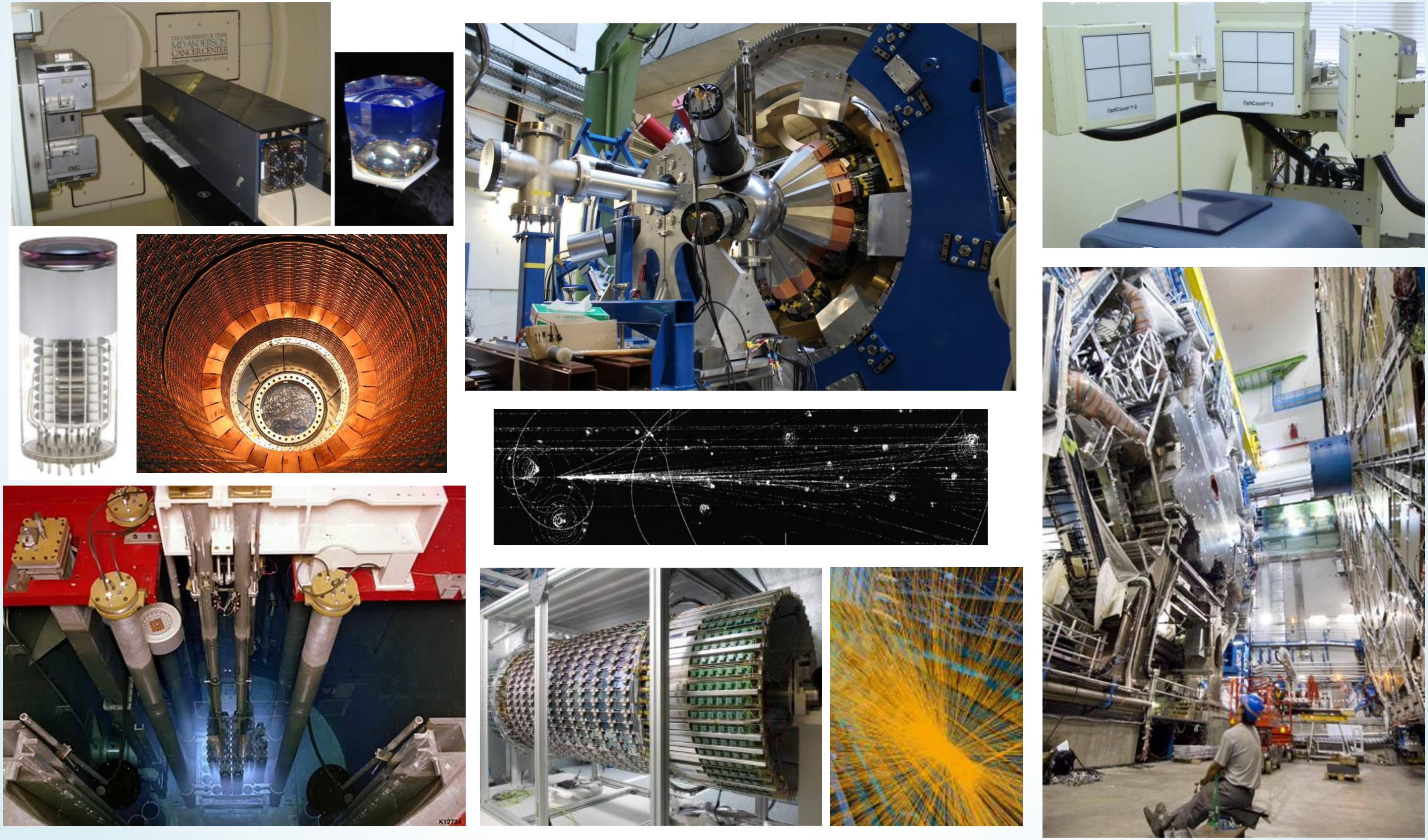
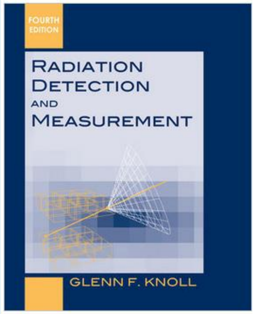
Interactions of Particles with Matter-I

Phil Allport (allport@cern.ch) University of Birmingham

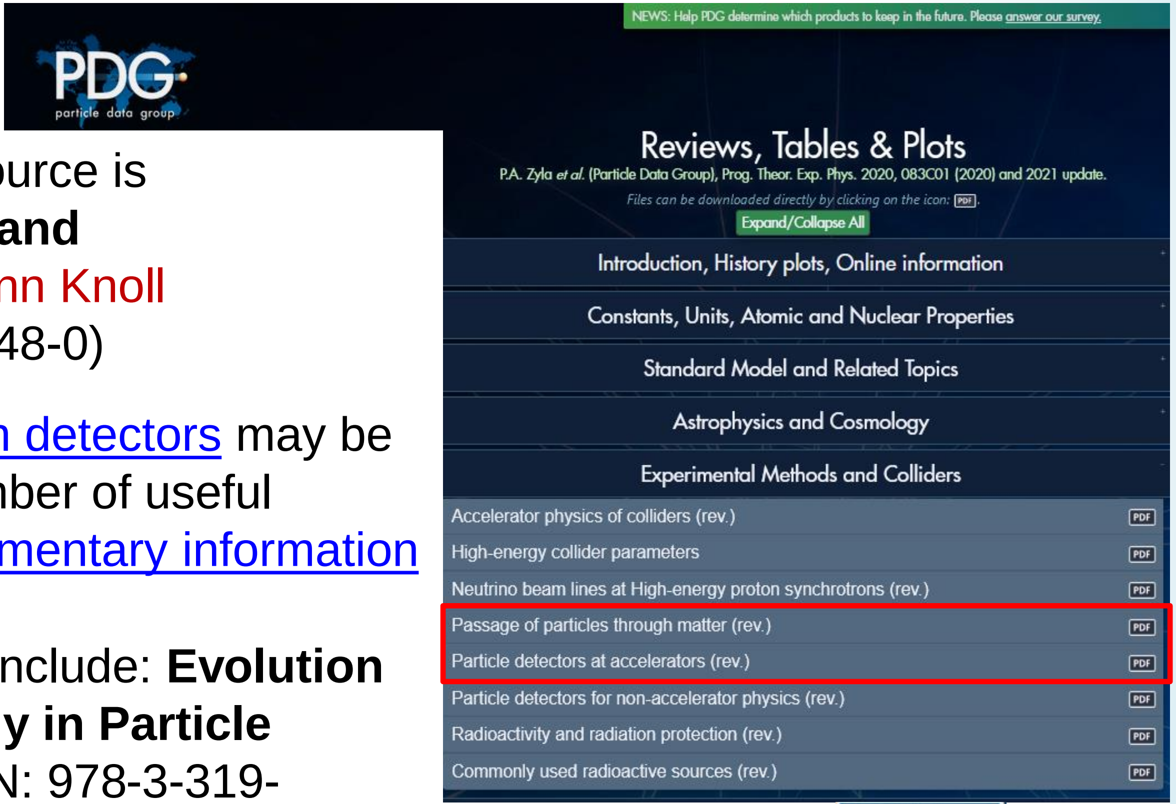


General Approach Used in these Lectures

- These lectures will concentrate on physics rather than formulae and assume students seeking formulae will refer to the appropriate literature and primary sources, many of which can be found in the reviews at https://pdg.lbl.gov/



Another excellent resource is **Radiation Detection and Measurement** by Glenn Knoll (ISBN: 978-0-470-13148-0)



NEWS: Help PDG determine which products to keep in the future. Please answer our survey.

Reviews, Tables & Plots

P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020) and 2021 update.

Files can be downloaded directly by clicking on the icon: PDF.

Expand/Collapse All

Introduction, History plots, Online information

Constants, Units, Atomic and Nuclear Properties

Standard Model and Related Topics

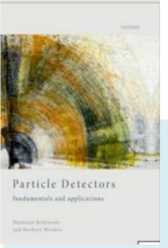
Astrophysics and Cosmology

Experimental Methods and Colliders

- Accelerator physics of colliders (rev.) PDF
- High-energy collider parameters PDF
- Neutrino beam lines at High-energy proton synchrotrons (rev.) PDF
- Passage of particles through matter (rev.) PDF
- Particle detectors at accelerators (rev.) PDF
- Particle detectors for non-accelerator physics (rev.) PDF
- Radioactivity and radiation protection (rev.) PDF
- Commonly used radioactive sources (rev.) PDF

- A fairly recent review of silicon detectors may be of interest as it contains a number of useful references and links to supplementary information

- Further recommended books include: **Evolution of Silicon Sensor Technology in Particle Physics** by F. Hartmann (ISBN: 978-3-319-64436-3) and **Particle Detectors: Fundamentals and Applications** by H. Kolanoski and N. Wermes (ISBN-13: 9780198858362)



Overview of Topics to be Covered

Lecture I

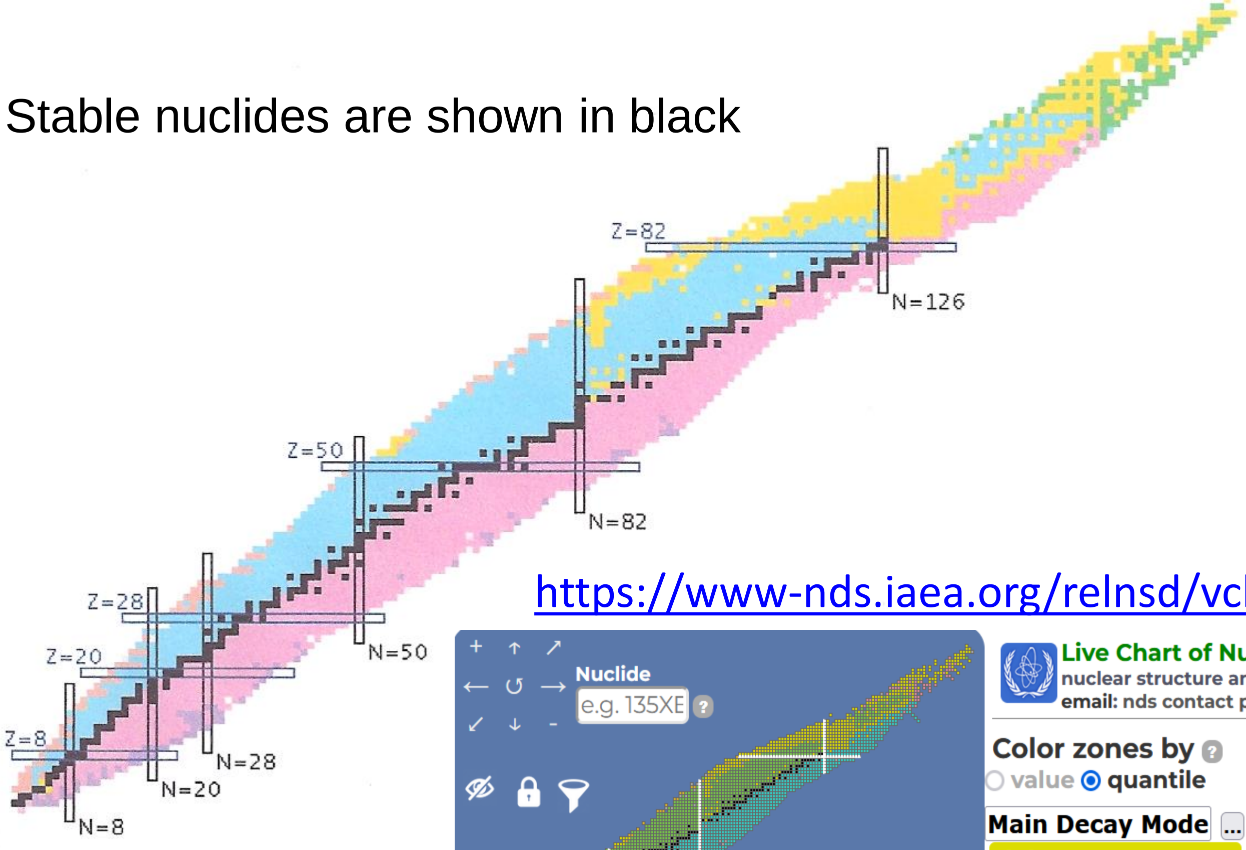
- Natural sources of radiation and their detection
  - Important in its own right and essential for understanding tools for testing detectors
- Ionising radiation
  - Charged particle interactions (ions and electrons)
  - Neutral particle detection (indirect detection)
- Non-ionising interactions with matter
  - Lower energy phenomena
  - Higher energy interactions
  - Factors affecting EM and hadron calorimetry

Lecture II

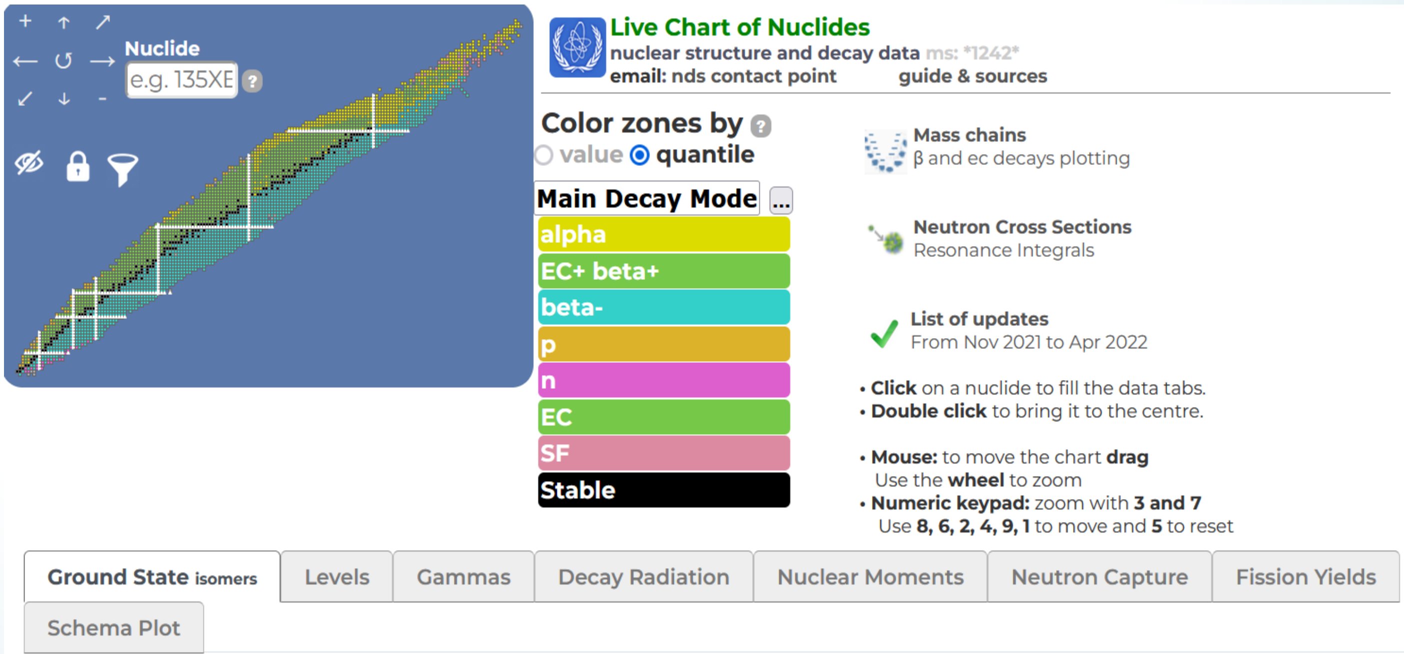
- Efficiencies and energy resolutions for individual sensors
- Brief overview of silicon sensor technologies
  - Overview of different types of sensors
  - Recap of operating principles
- Digressing into gaseous tracking detectors
  - Signal formation in sensors without and with gain
- Application for signal formation in simple diode (two terminal) case

Chart of Nuclides: Plot of Z Versus N

Stable nuclides are shown in black



https://www-nds.iaea.org/relnsd/vcharthtml/VChartHTML.html



Nuclide

e.g. 135XE ?

Live Chart of Nuclides

nuclear structure and decay data ms: *1242*

email: nds contact point **guide & sources**

Color zones by ?

○ value ● **quantile**

Main Decay Mode ...

- alpha
- EC+ beta+
- beta-
- p
- n
- EC
- SF
- Stable

Mass chains
β and ec decays plotting

Neutron Cross Sections
Resonance Integrals

List of updates
From Nov 2021 to Apr 2022

- **Click** on a nuclide to fill the data tabs.
- **Double click** to bring it to the centre.

- **Mouse:** to move the chart **drag**
  Use the **wheel** to zoom
- **Numeric keypad:** zoom with **3 and 7**
  Use **8, 6, 2, 4, 9, 1** to move and **5** to reset

Types of Natural Radiation

Ions (alpha particles, fission fragments,
also protons etc. in nuclear physics)
Straight tracks

Electrons (beta particles) (+ve and -ve)
Highly scattered tracks

Charged: directly ionising,

along track of particle

Neutrons
Interact only with nuclei: to give ion tracks

Photons: gamma-rays and X-rays
Interact with atoms/electrons: to give electron tracks

Uncharged: indirectly ionising,

along tracks of secondary radiation following interactions

Ions:

slow down gradually through thousands of collisions with atomic electrons.

When a non-relativistic ion of mass *M* and kinetic energy E collides with an electron of mass m_e , the maximum energy transferred (head-on collision) is

$4\frac{Mm_e}{(M+m_e)^2}\mathrm{E}$ and, since $(m_e \ll M)$, this $\boxed{\approx 4\frac{m_e}{M}\mathrm{E}}$

Since an alpha-particle is around 8000 times more massive than an electron, in each collision it loses only a tiny fraction of its energy (and is deviated by a very small angle).

The slowing down process is random (stochastic) but because the number of collisions is so large the variations (“straggling”) are relatively small.

To a first approximation, alpha particles are undeviated and slow down at a predictable rate.

The Bethe-Bloch Formula

Stopping power (average rate of energy loss per unit distance) is predicted by the Bethe-Bloch formula as given approximately by:

$$S = -\frac{d\mathrm{E}}{dx} \cong \left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \frac{4\pi z^2}{m_e v^2} NZ \left[ln\frac{2m_e v^2}{I} - ln\left(1 - \frac{v^2}{c^2}\right) - \frac{v^2}{c^2}\right]$$

e, me are charge and mass of electron, ε_0 is the vacuum permittivity

z, v are atomic number and velocity of the particle

Z, N are atomic number and number density of medium (atoms per unit volume)

I is an effective average ionisation potential for the atoms of the medium (usually taken as an empirical parameter:

for hydrogen $I \approx 20$ eV, for other elements $I \approx 10 \times Z$ eV).

The Bethe-Bloch Formula

Stopping power (average rate of energy loss per unit distance) is predicted by the Bethe-Bloch formula as given approximately by:

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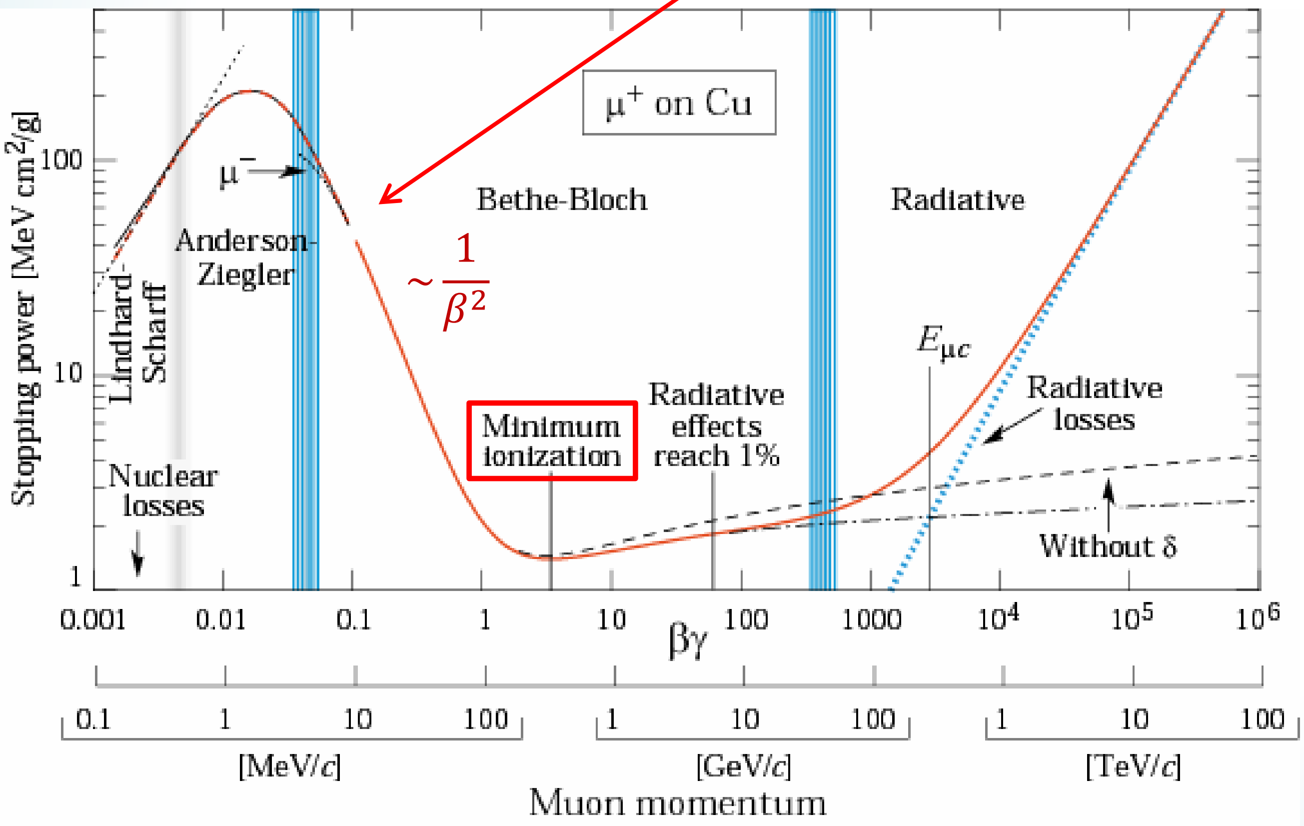


"Stopping power" for positive muons in copper as a function of $\beta\gamma = p/m_\mu c$ over nine orders of magnitude. **Note definition in plot independent of density**

Full relativistic formula at https://pdg.lbl.gov/

The Bethe-Bloch Formula

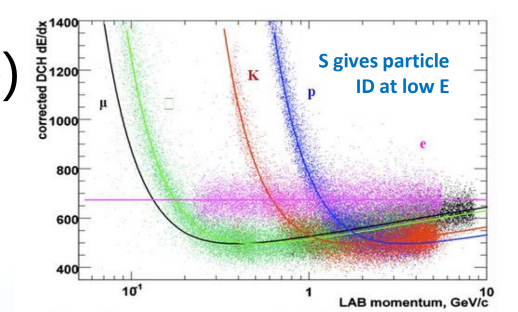
For non-relativistic particles/ions, the last two terms in the square bracket are high energy corrections that can be neglected.

Using this approximation for the Bethe-Bloch formula:

$$\boxed{S = -\frac{dE}{dx} \approx \left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \frac{4\pi z^2}{m_e v^2} NZ \cancel{\left[ln\frac{2m_e v^2}{I}\right]}}$$

and ignoring the slowly-varying logarithmic term, the formula says:

- For non-relativistic particles: $S \mathrel{\overset{\sim}{\propto}} {}^{z^2}\!/_{v^2} \propto {}^{Mz^2}\!/_{E}$ (particle mass M)
- For the medium: $S \mathrel{\overset{\sim}{\propto}} NZ$ (electrons / unit volume)



S gives particle ID at low E

A simultaneous measurement of dE/dx and momentum can provide particle identification.

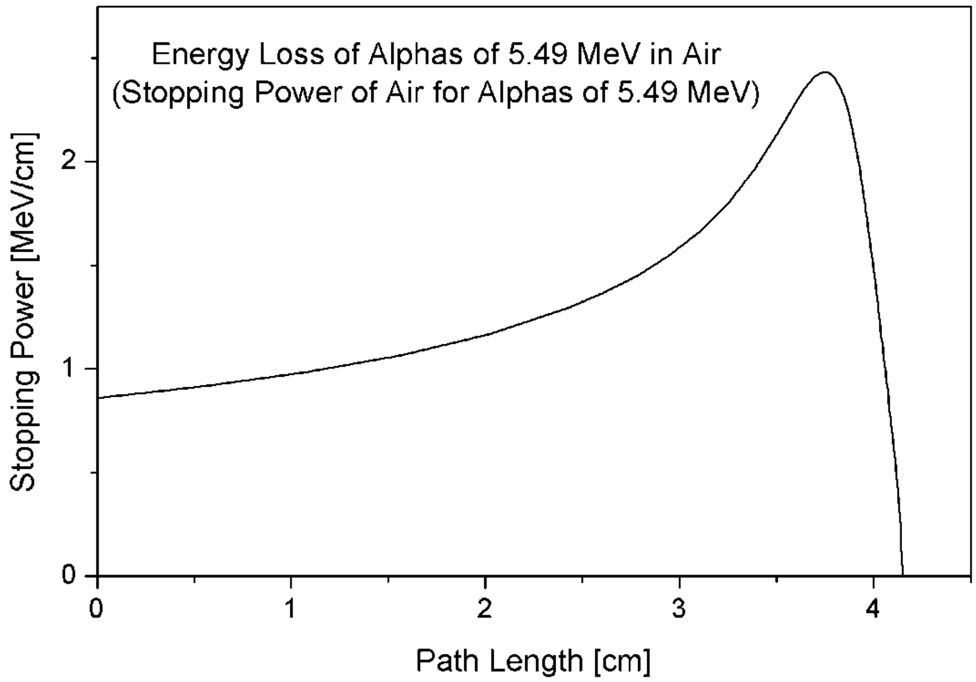
The Bragg Peak:

As energy reduces, stopping power increases.

Bethe-Bloch (B-B) predicts stopping power peaks at very low energy.

In practice at low energy, stopping power is lower than B-B prediction because ion starts to pick up electrons from medium and is no longer fully-ionised: for alpha particles, stopping power peaks at around 1 MeV.

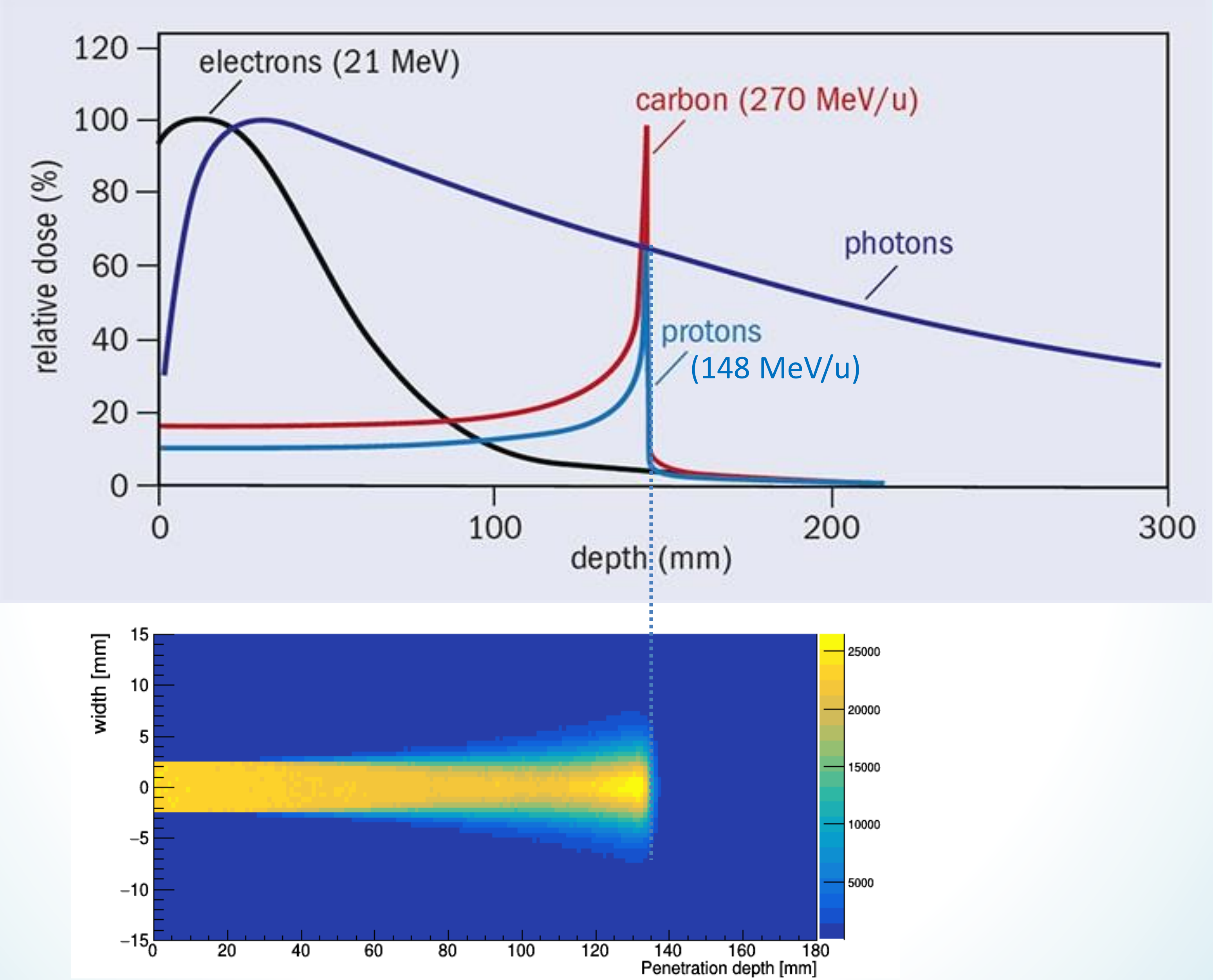
For ions slowing down in a medium, because stopping power increases with depth, so do ionisation and dose: get “Bragg peak”.



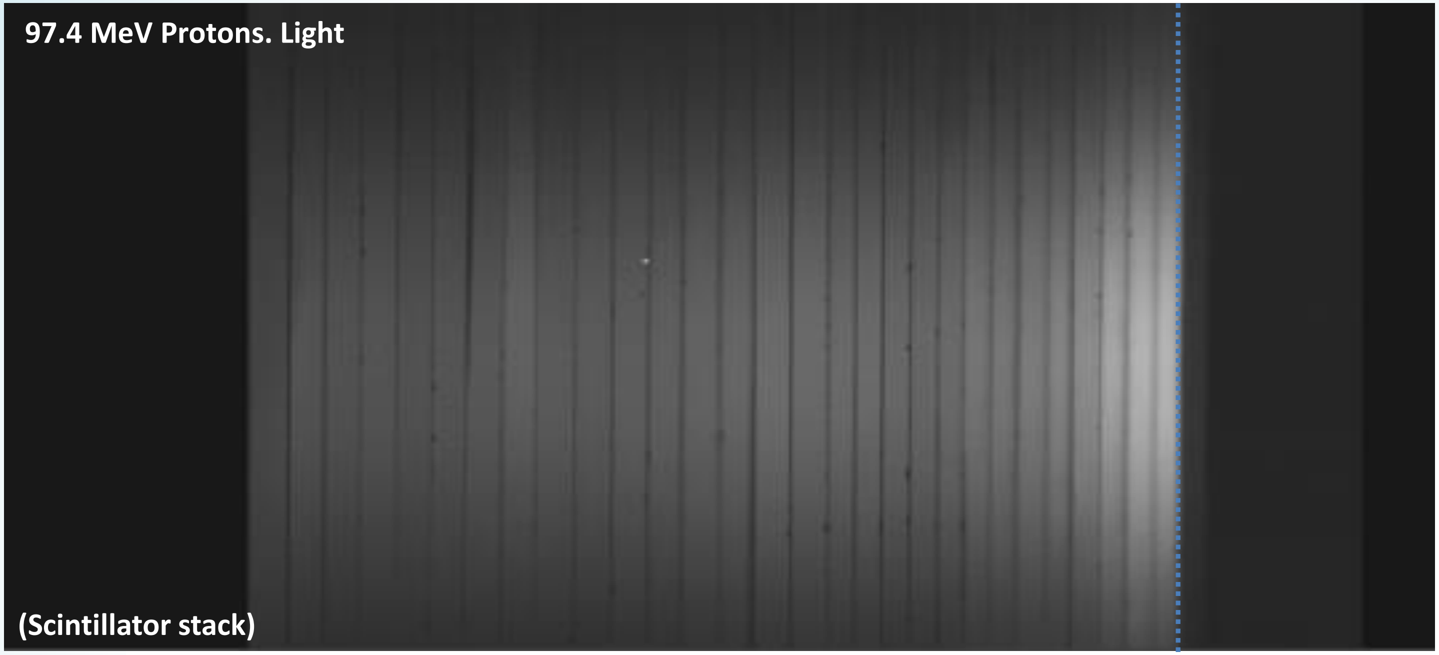
The Bragg Peak:

Proton p

(Plastic)

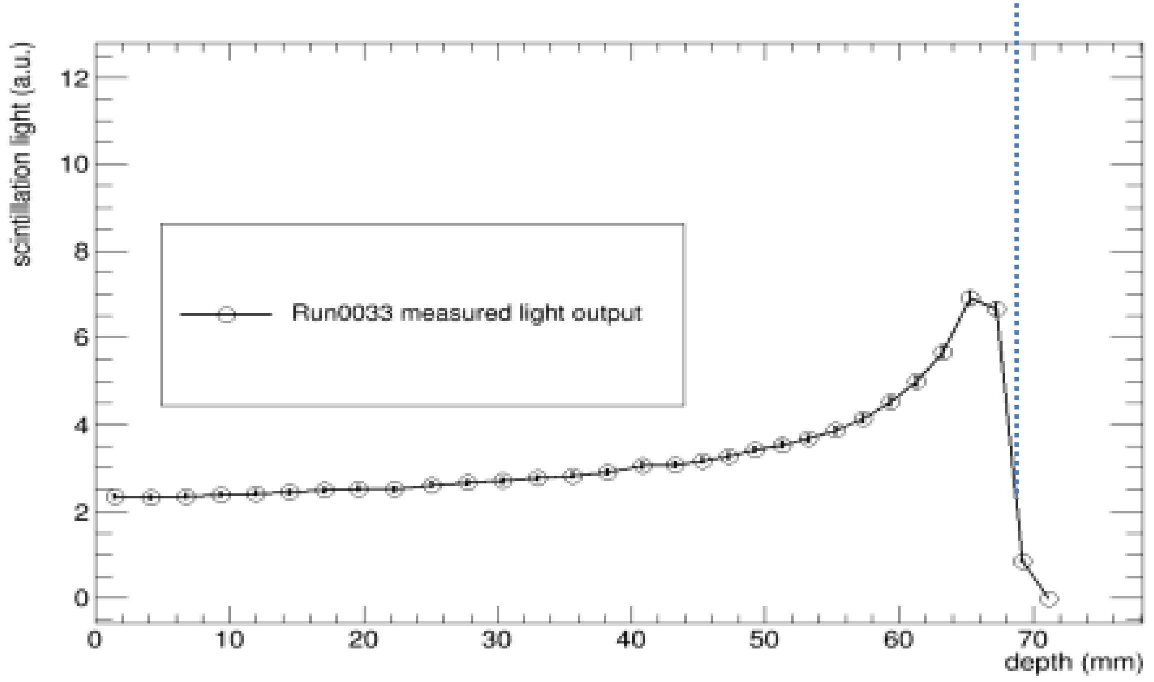


The Bragg Peak:



97.4 MeV Protons. Light

(Scintillator stack)



A beam of mono-energetic ions, such as alpha-particles, entering a medium will slow down gradually and stop at an average depth of

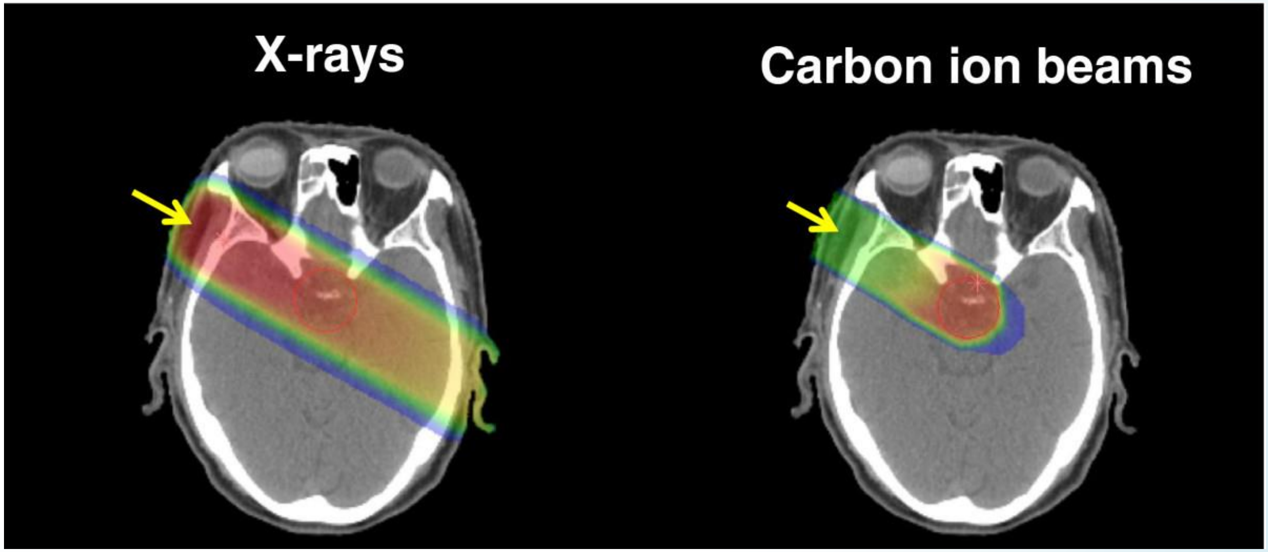
$$R = \int_0^E \left(\frac{dE}{dx}(E')\right)^{-1} dE'$$ (the alpha-particle range)

Because the slowing down process is random, individual alpha-particles will slow down slightly faster or slower. There will be a small spread in the depths reached (the "range straggling"). Similarly if one measured the alpha energies at a particular depth, one would find a small spread (the "energy straggling").

For ions, the range straggling is typically a few per cent of the ion range.

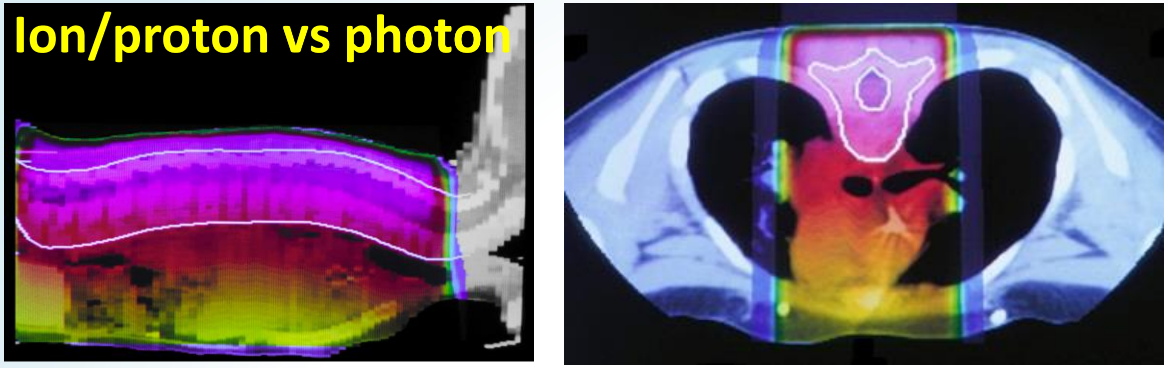
Example of hadron radiotherapy using carbon ions compared with conventional radiotherapy.

→ Even with range straggling, much better defined dose.



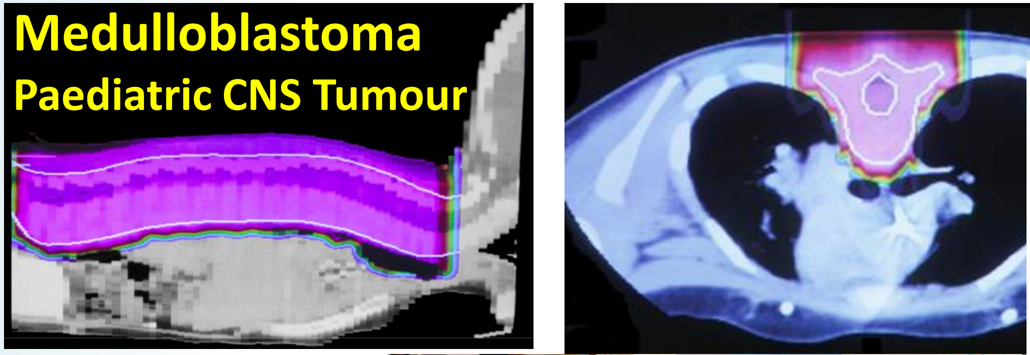
Ohno, T. EPMA Journal (2013) 4: 9. https://doi.org/10.1186/1878-5085-4-9

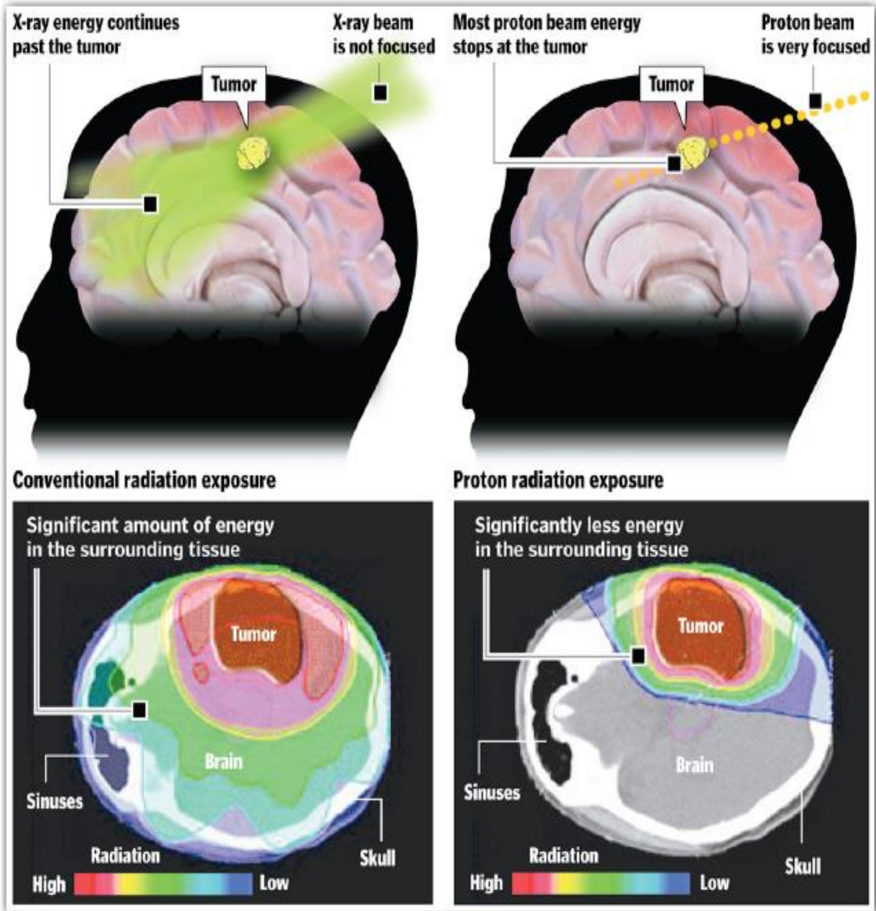
Ion/proton vs photon



Medulloblastoma

Paediatric CNS Tumour





Even with intensity-modulated radiation therapy (IMRT) protons/ions spare healthy tissue much better → **especially important for treating tumours near critical organs or for paediatrics**

Electrons:

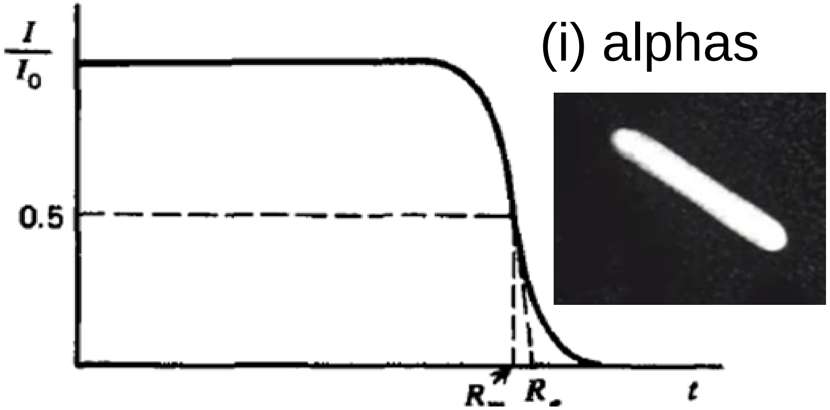
In principle electrons slow down in the same way as ions, through large numbers of collisions with atomic electrons, which can be described by the Bethe-Block formula.

BUT

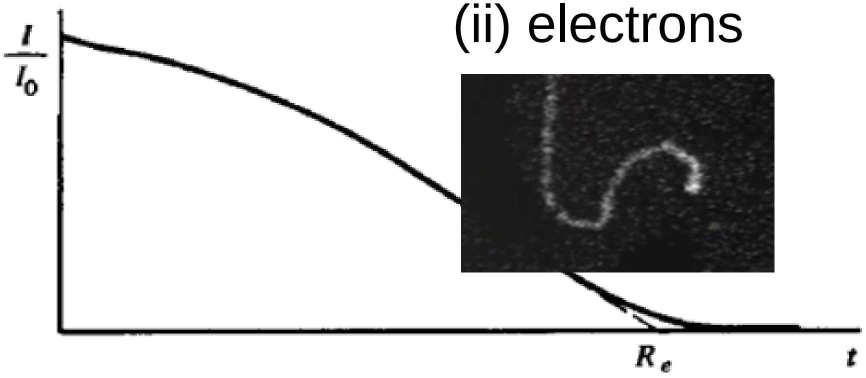
- Electrons, even from radioactive decays, are often highly relativistic.
- In a collision with another electron, the electron can lose any fraction of its energy (up to and including all of it) and is likely to be deviated by a large angle. Electron tracks are wiggly and unpredictable. The depth reached is typically much less than the range travelled.

  → **Energy straggling and range straggling are large**.

Transmission vs depth (figures from Knoll): for mono-energetic beams of:



(i) alphas



(ii) electrons

Photographs: http://microcosm.web.cern.ch/en/cloud-chamber-video#overlay-context=en/cloud-chamber

Neutrons:

are uncharged and do not interact with atomic electrons.

Only interactions are with nuclei in medium, and since nuclear force is short-range, probability of interaction per unit length is low.

When considering detection, useful to consider the following types of interaction at moderate energies:

- Scattering (elastic or inelastic): energy is transferred to a recoiling target nucleus. For large energy transfer, the target nucleus needs to be light (hydrogen is best). Can then detect the ionisation produced by the recoil nucleus. Unless one also knows the recoil angle, this does not uniquely determine the neutron energy. Cross-sections for scattering are often inversely proportional to neutron velocity.
- Radiative capture: nucleus captures a low energy (thermal) neutron and a gamma-ray is emitted. Not very useful for detection.
- Reactions like (n, p), (n, α), (n, fission) are much more useful, as they release charged particles which can be detected. Generally the reaction cross-sections peak for thermal neutrons and have a +ve Q-value, so the energy of the products is only indirectly related to the neutron energy.

Photon Interactions:

Three important interaction processes for high energy photons passing through matter:

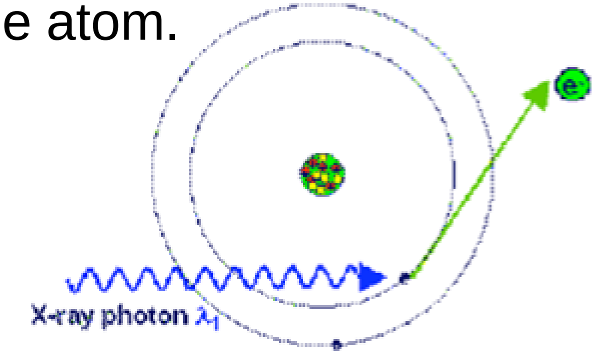
Photoelectric absorption – low energy, high Z

Compton scattering – always

Pair-production – only at high energy

Photoelectric Absorption:

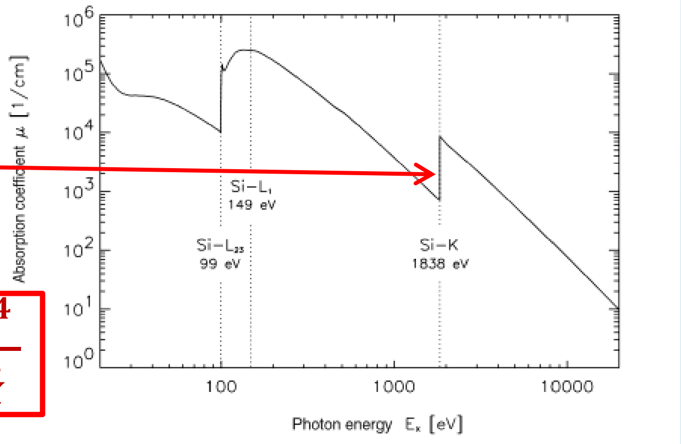
Photon (energy $\mathbf{E_X}$) is completely absorbed by an atom and an atomic electron is emitted with energy $\mathbf{E_X - E_{BE}}$, where $\mathbf{E_{BE}}$ is the binding energy of the atomic electron to the atom.



The process involves the whole atom, including the nucleus (must absorb momentum).

For this reason, mainly occurs for inner-shell electrons (K electrons).

Exception is when X-ray energy is less than K electron binding energy – then only outer electrons can be involved. There is a sharp drop (discontinuity) in cross-section at this energy, called the "K edge"

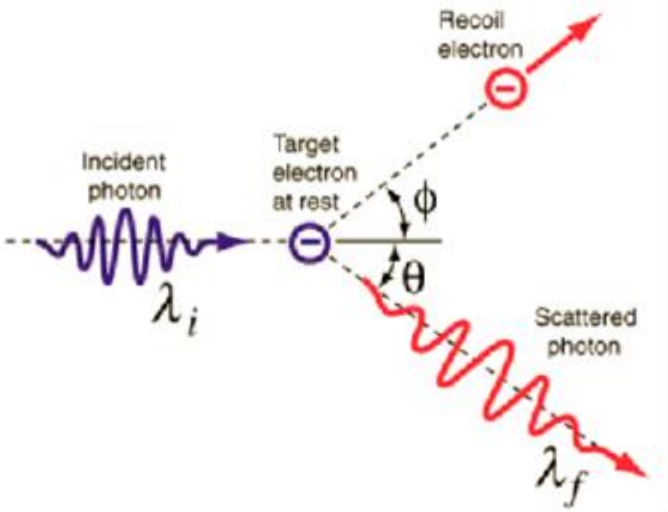


Cross-section depends strongly on Z and drops rapidly with X-ray energy, approximately as $\boxed{\sigma \propto \frac{Z^4}{E_X^3}}$

Compton Scattering:

Photon scatters off an individual electron, transferring some of its energy and momentum to the electron.

In general the binding energy of the electron can be neglected.



$$\boxed{\frac{1}{E_f} - \frac{1}{E_i} = \frac{1}{m_e c^2}(1 - \cos\theta)}$$

Cross-section reduces slowly with photon energy (Klein-Nishina formula).

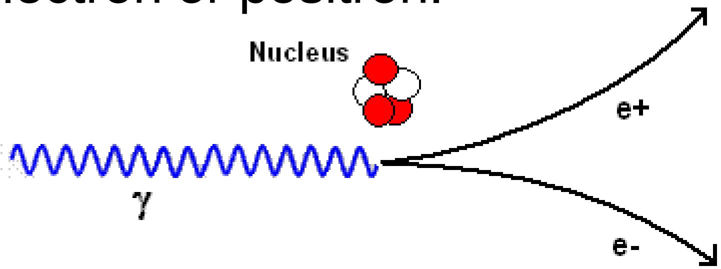
Cross-section proportional to number of electrons (cross-section per atom $\propto Z$).

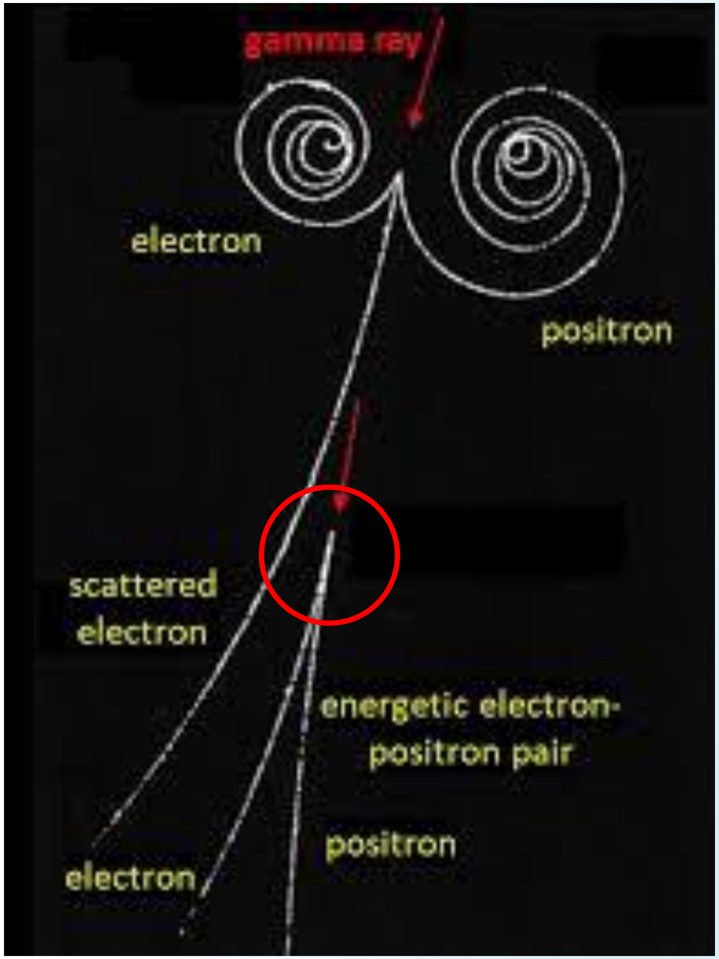
Linear attenuation coefficient $\mu = n\sigma$ where $n = \frac{\rho N_A}{A}$ is no of atoms per unit volume.

So if $\sigma \propto Z$ then $\boxed{\frac{\mu}{\rho} \propto \frac{Z}{A}}$ which is similar for all elements (except hydrogen).

Pair production:

In the field of a nucleus, photon converts into an electron and positron (particle and antiparticle). The kinetic energies of the electron and positron sum to $\mathbf{E_X} - 2mec^2$ where $m_e c^2 = 0.511$ MeV is the rest mass energy of an electron or positron.



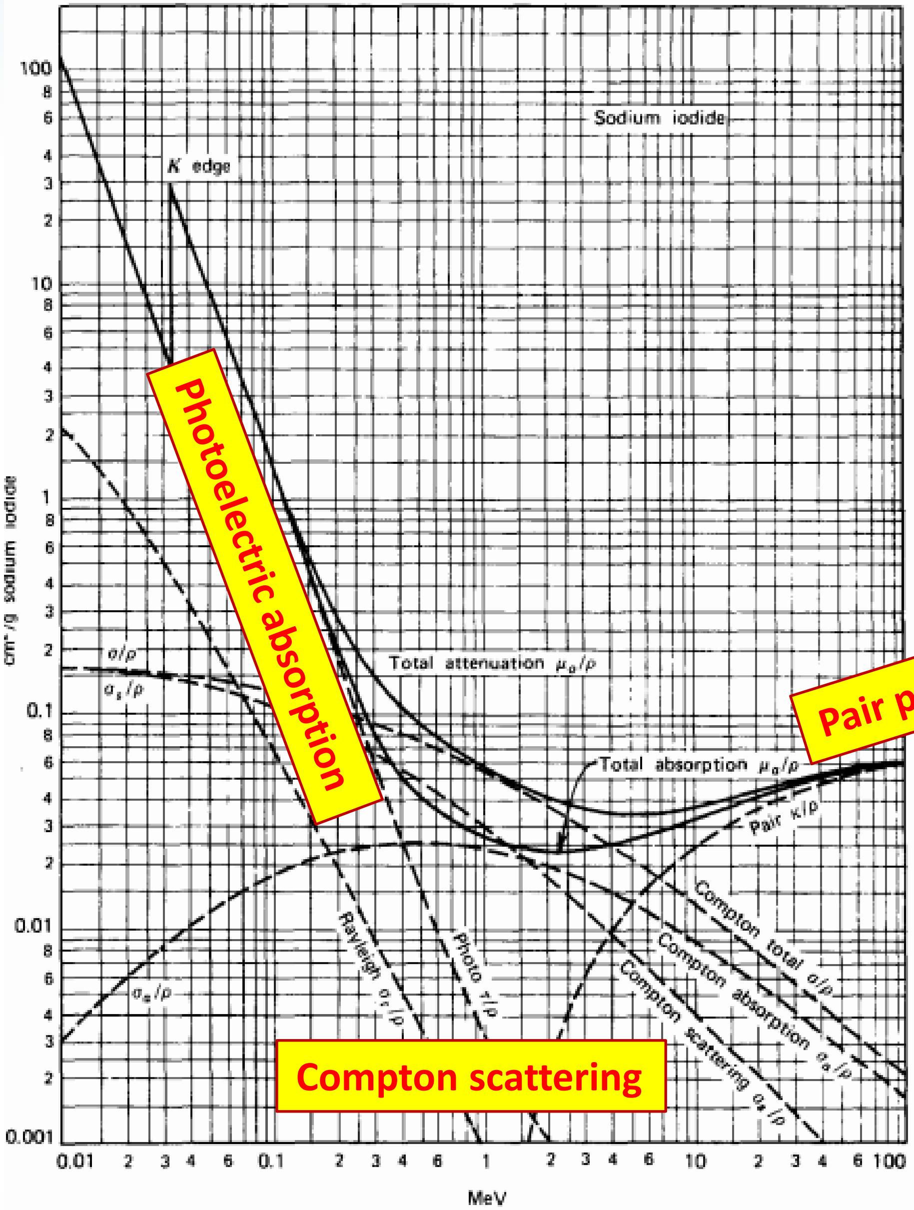


Process is only possible if $\mathbf{E_X} > 1.022$ MeV

Above this threshold, the cross-section grows steadily with energy, and is only really significant above 5 MeV.

Nucleus is involved to conserve momentum.

Cross section approximately proportional to Z^2.



Photoelectric absorption

Pair production

Compton scattering

Figure 2.18 Energy dependence of the various gamma–ray interaction processes in sodium iodide. (From *The Atomic Nucleus* by R. D. Evans. Copyright 1955 by the McGraw-Hill Book Company. Used with permission.)

Gamma-ray Detection:

→ finite detector size means some secondary radiation can escape

Radiation Detection and Measurement. Third Edition. Glenn F. *Knoll*. Professor of Nuclear Engineering and Radiological Sciences. University of Michigan.

$$\boxed{E_{e^-}\Big|_{\theta=\pi} = h\nu\left(\frac{2h\nu/m_0c^2}{1+2h\nu/m_0c^2}\right)}$$

Here E_e is KE of struck electron when photon recoils through 180°

From $p_e = \frac{h\nu}{c} + \frac{h\nu'}{c}$ and using formula for p_e in terms of E_e

Conservation of energy $\Rightarrow$

$$(h\nu + h\nu')^2 = E_e^2 + 2m_ec^2E_e$$

and substitute for $h\nu' = h\nu - E_e$

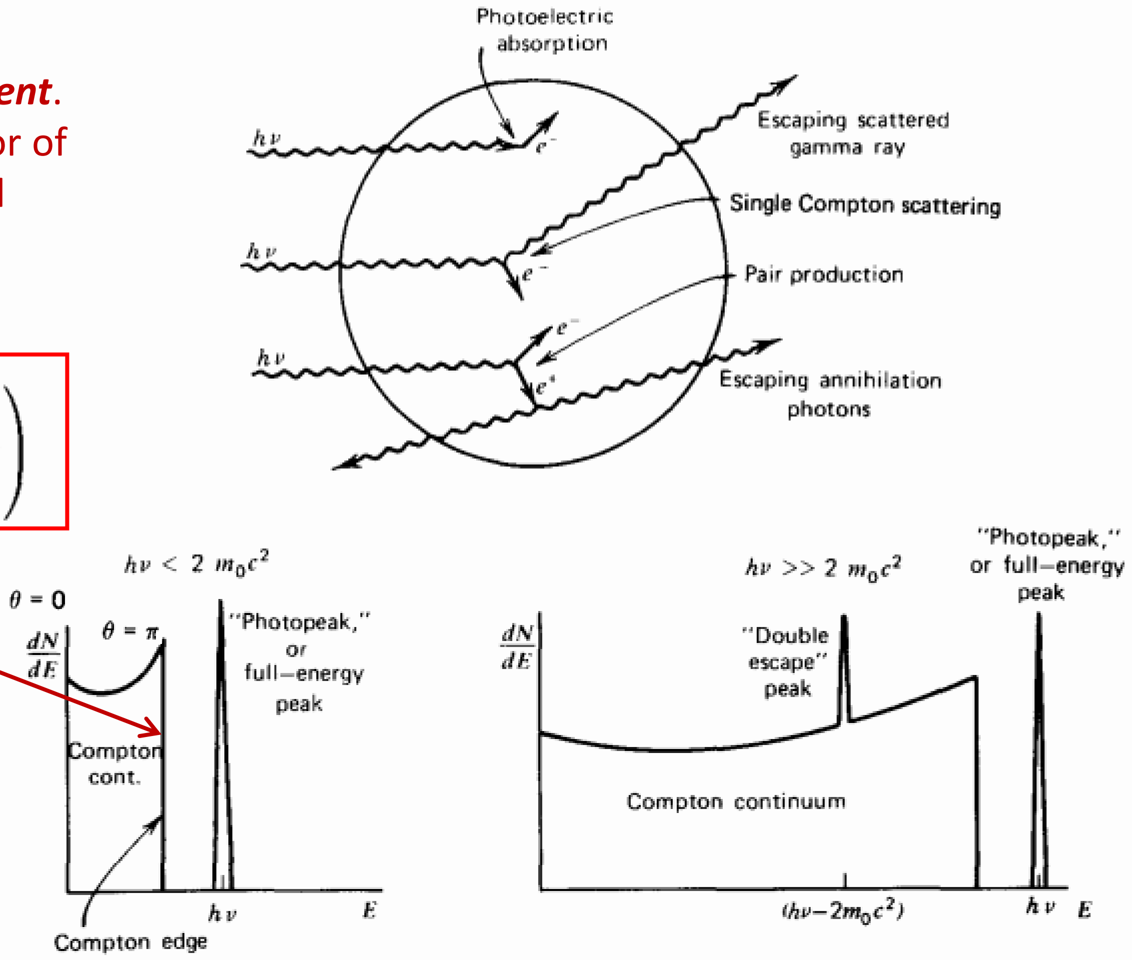


Figure 10.2 The "small detector" extreme in gamma-ray spectroscopy. The processes of photoelectric absorption and single Compton scattering give rise to the low-energy spectrum at the left. At higher energies, the pair production process adds a double escape peak shown in the spectrum at the right.

Gamma-ray Detection:

***Radiation Detection and Measurement*.** Third Edition. Glenn F. *Knoll*. Professor of Nuclear Engineering and Radiological Sciences. University of Michigan.

Note: Germanium ($Z = 32$) has higher efficiency than Si ($Z = 14$) so High-purity Ge (HpGe) is often used for detecting gamma-rays.

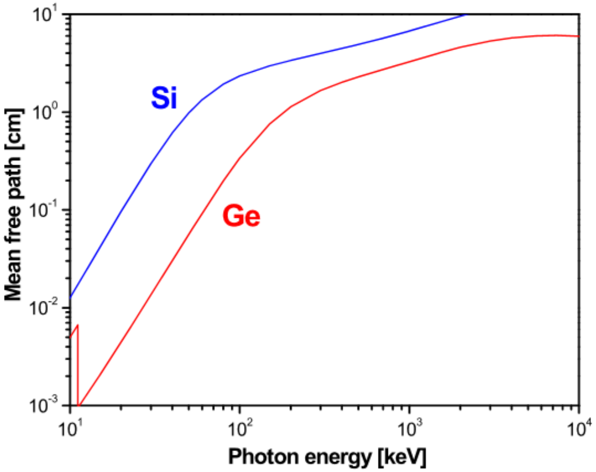


Fig. 8.1. Photon mean free paths in Si and Ge.

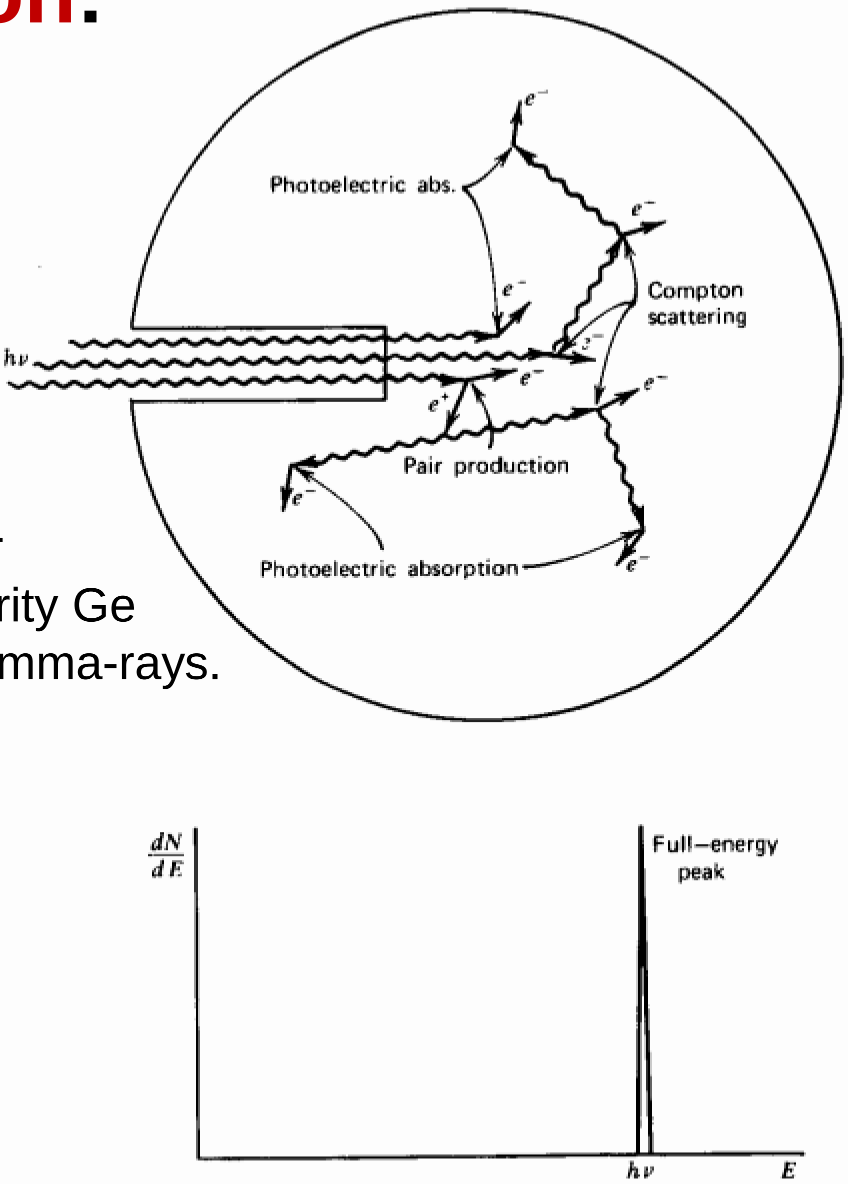


Figure 10.3 The "large detector" extreme in gamma-ray spectroscopy. All gamma-ray photons, no matter how complex their mode of interaction, ultimately deposit all their energy in the detector. Some representative histories are shown at the top.

Gamma-ray Detection:

Radiation Detection and Measurement.
Third Edition. Glenn F. *Knoll*. Professor of
Nuclear Engineering and Radiological
Sciences. University of Michigan.

For HpGe need the maximum possible active volume. For a given thickness of depletion layer, can maximise the useful volume by using coaxial geometry.

With such large volumes, the leakage current due to injection of minority carriers from contacts means need to operate at liquid N_2 temperatures.

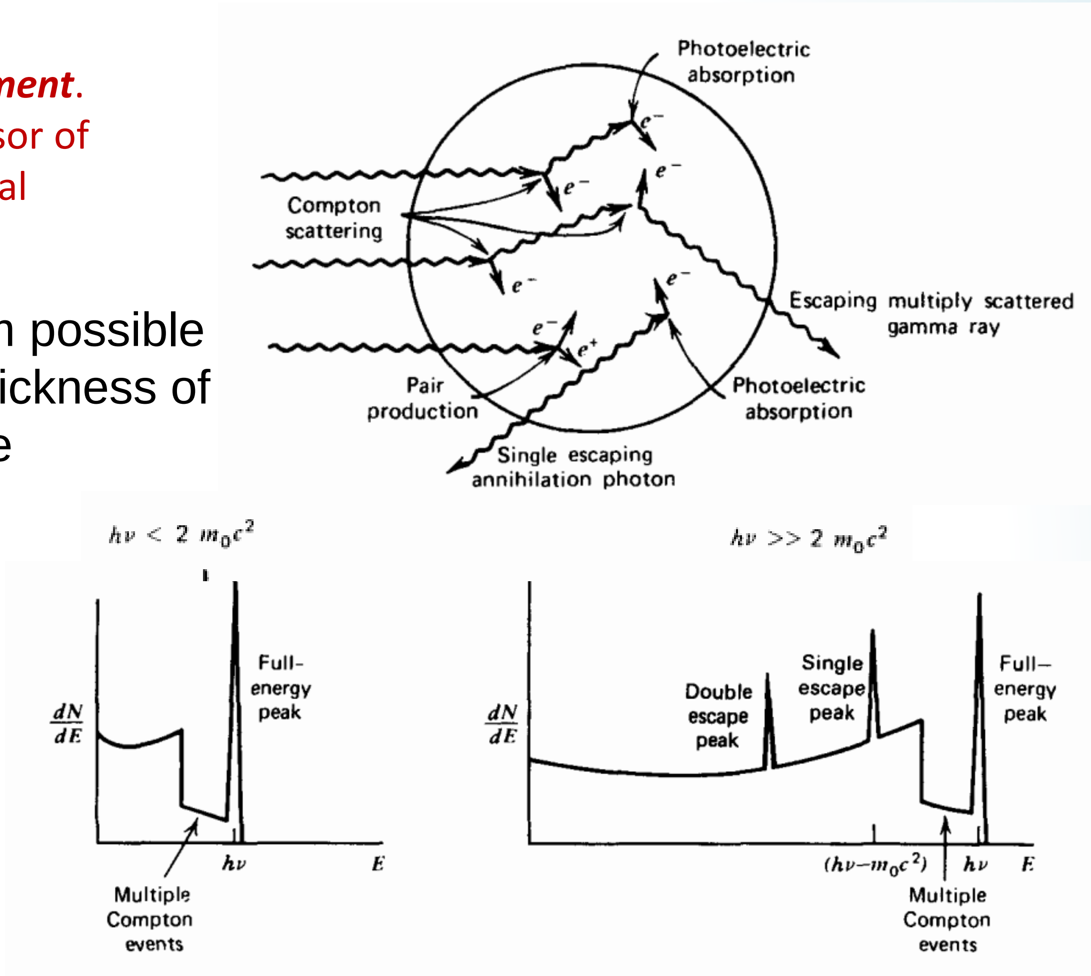
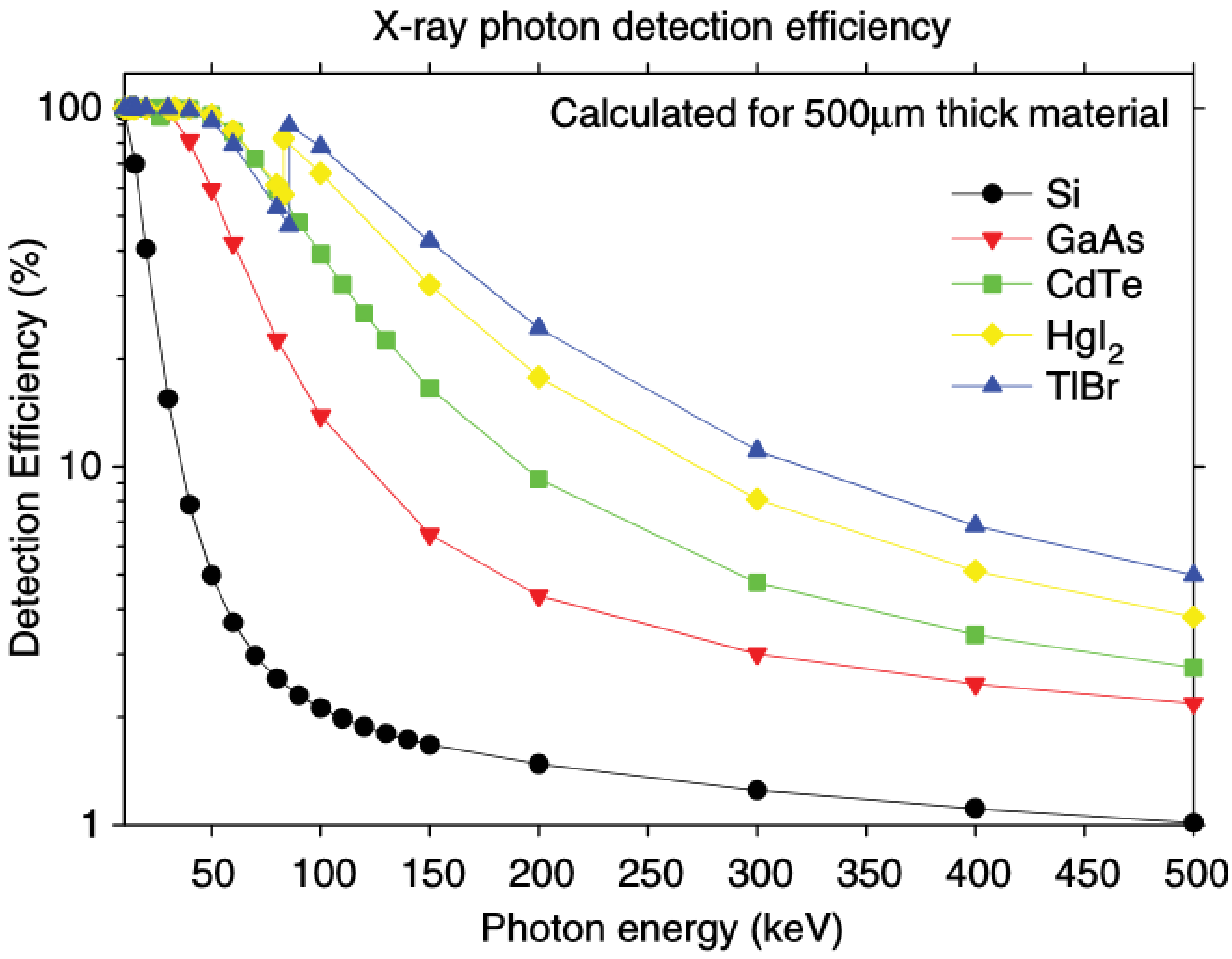


Figure 10.4 The case of intermediate detector size in gamma-ray spectroscopy. In addition to the continuum from single Compton scattering and the full-energy peak, the spectrum at the left shows the influence of multiple Compton events followed by photon escape. The full-energy peak also contains some 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.

Semiconductors for Photon Detection

Ideally would like higher Z (atomic number) materials to enhance γ efficiency at higher energies for thin and segmented (position sensing) detectors.

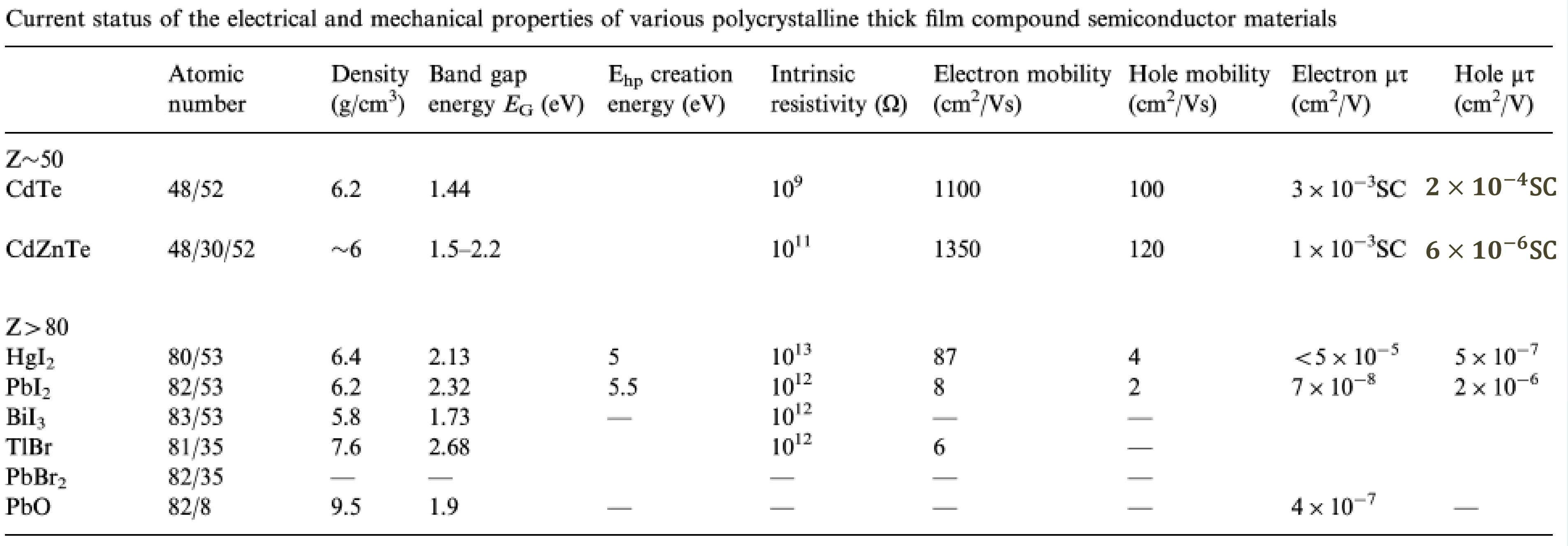
Typically need compound semiconductors to better achieve this.



P.J. Sellin
Nuclear Instruments and Methods in Physics Research A 563 (2006)

Semiconductors for Photon Detection

The problems is that some of these materials typically have **low mobilities** (compared with silicon: $\mu_e = 1400$ cm^2 V^{-1}s^{-1} and $\mu_h = 450$ cm^2 V^{-1}s^{-1}, germanium: $\mu_e = 3900$ cm^2 V^{-1}s^{-1} and $\mu_h = 1900$ cm^2 V^{-1}s^{-1} and gallium arsenide, GaAs: $\mu_e = 8500$ cm^2 V^{-1}s^{-1} and $\mu_h = 400$ cm^2 V^{-1}s^{-1}) along with poor typical carrier lifetimes and inhomogeneities.



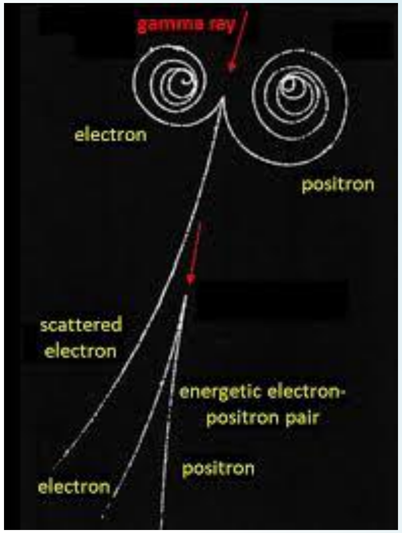
Current status of the electrical and mechanical properties of various polycrystalline thick film compound semiconductor materials

	Atomic number	Density (g/cm^3)	Band gap energy E_G (eV)	E_{hp} creation energy (eV)	Intrinsic resistivity (Ω)	Electron mobility (cm^2/Vs)	Hole mobility (cm^2/Vs)	Electron μτ (cm^2/V)	Hole μτ (cm^2/V)
Z~50									
CdTe	48/52	6.2	1.44		10^9	1100	100	3×10^{-3}SC	2×10^{-4}SC
CdZnTe	48/30/52	~6	1.5–2.2		10^{11}	1350	120	1×10^{-3}SC	6×10^{-6}SC
Z>80									
HgI_2	80/53	6.4	2.13	5	10^{13}	87	4	$<5 \times 10^{-5}$	5×10^{-7}
PbI_2	82/53	6.2	2.32	5.5	10^{12}	8	2	7×10^{-8}	2×10^{-6}
BiI_3	83/53	5.8	1.73	—	10^{12}	—	—		
TlBr	81/35	7.6	2.68		10^{12}	6	—		
$PbBr_2$	82/35	—	—		—	—	—		
PbO	82/8	9.5	1.9	—	—	—	—	4×10^{-7}	—

P.J. Sellin / Nuclear Instruments and Methods in Physics Research A 563 (2006)

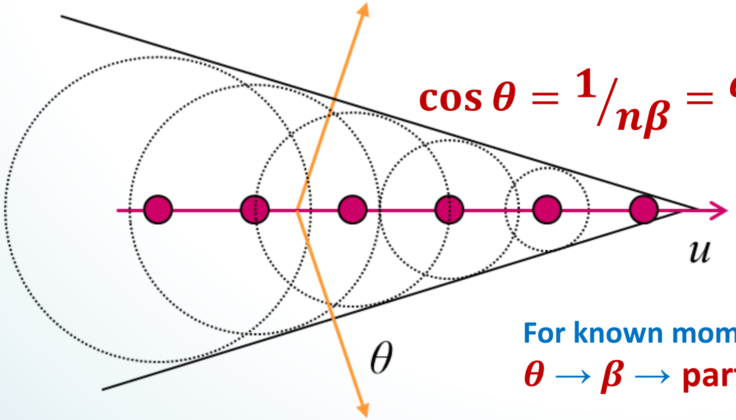
(**SC**: **S**ingle **C**rystals)

Relativistic Phenomena:



Bremsstrahlung. If a charged particle suddenly changes its velocity it produces a ripple in the electromagnetic field which radiates energy in the form of a photon. A fast electron passing close to a nucleus can do this. This radiation is referred to as *bremsstrahlung* ("braking radiation"). If photon scatters an electron or pair produces, and resulting e or $e^{\pm}$ interact → **electromagnetic cascade**.

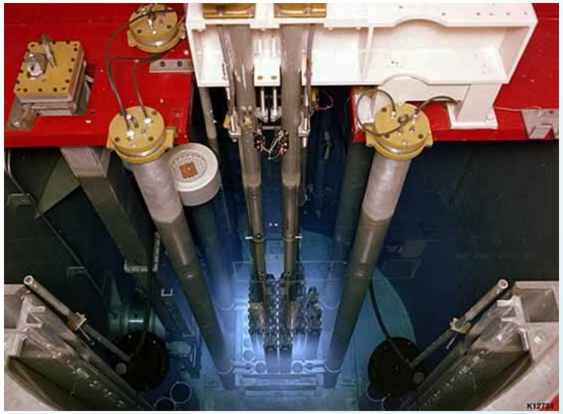
Cherenkov radiation. Inside a material the speed of light is less than the speed of light in vacuum (the ratio is the refractive index). So a highly relativistic particle may actually travel faster than the speed of light IN THAT MEDIUM. This causes a shock wave in the electromagnetic field leading to emission of a cone of visible or ultra-violet radiation.



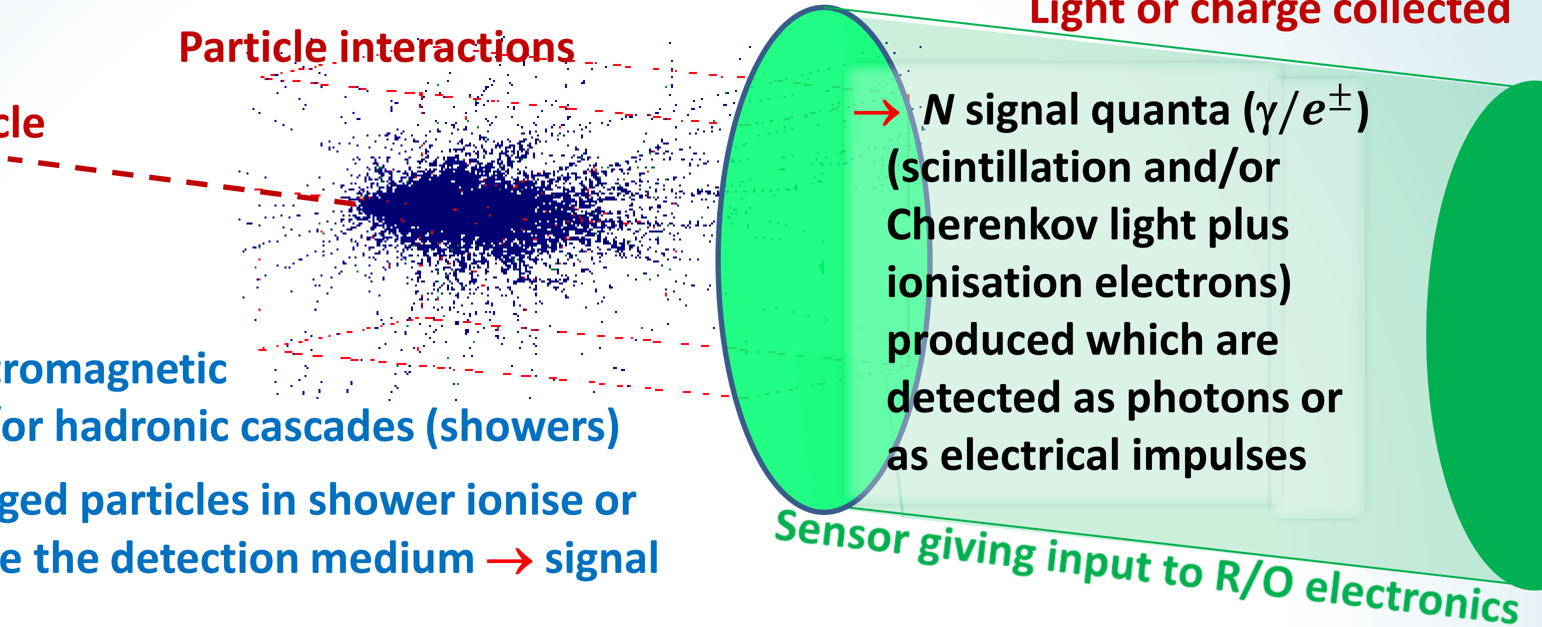
$$\cos\theta = {}^{1}/_{n\beta} = {}^{c}/_{(nv)}$$

For known momentum

$\theta \rightarrow \beta \rightarrow$ particle ID



High Energy Interactions:



Light or charge collected

Particle interactions

Incident particle
with energy E

$\rightarrow$ *N* signal quanta ($\gamma/e^{\pm}$) (scintillation and/or Cherenkov light plus ionisation electrons) produced which are detected as photons or as electrical impulses

Electromagnetic
and/or hadronic cascades (showers)

Charged particles in shower ionise or excite the detection medium → signal

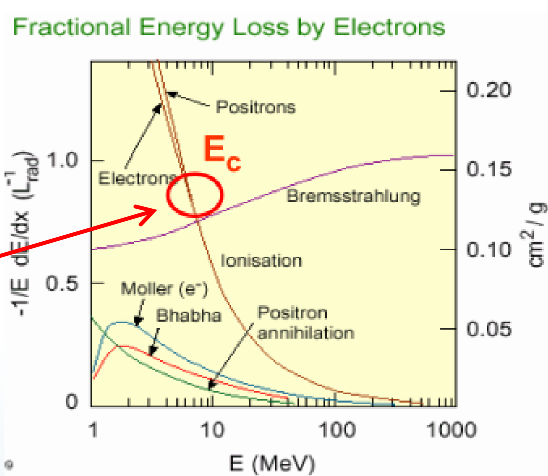
Sensor giving input to R/O electronics

For EM Shower: medium characterised by "radiation length": X_0 such that $E = E_0 e^{x/X_0}$.
X_0 : distance over which electron loses on averaged 63% of its energy by bremsstrahlung.

In 1 X_0 a 50 GeV $e^{\pm}$ loses 32 GeV; 46% * of γ's would pair-produce; but a minimum ionising particle would only lose a few 10s of MeV in 1 X_0 of Pb, ie ~ thousand times less.

*m.f.p. for $\lambda_{\text{pair}} = 9/7\ X_0$ (7.2 mm in Pb)

Shower characterised by "shower maximum", t_{MAX} , when $e^{\pm}$ energy losses through ionisation exceed bremsstrahlung at E_C and the shower starts to die away.



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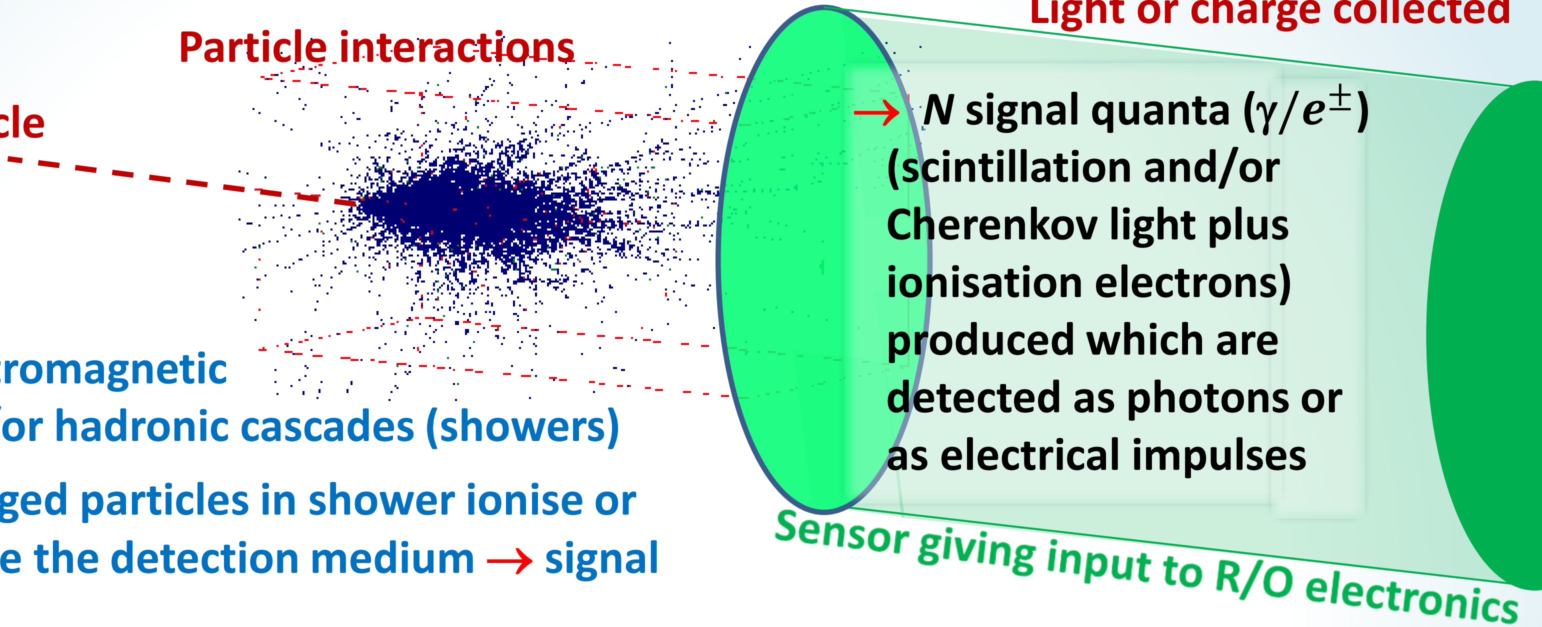

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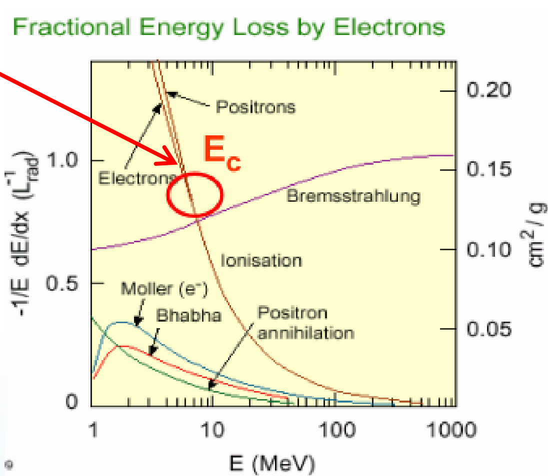
$$t_{\mathrm{MAX}} \approx X_0 \, {\ln\left(E_I/\mathrm{E_C}\right)}\Big/{\ln 2}$$

Shower width, "Moliere radius", R_M
(R_M ~1.6cm for Pb; 95% shower ≲ 3cm)
(**Note units: independent of density**).

$$R_M = \frac{21\,MeV}{\mathrm{E_C}} X_0 \;[\mathrm{g/cm^2}]$$



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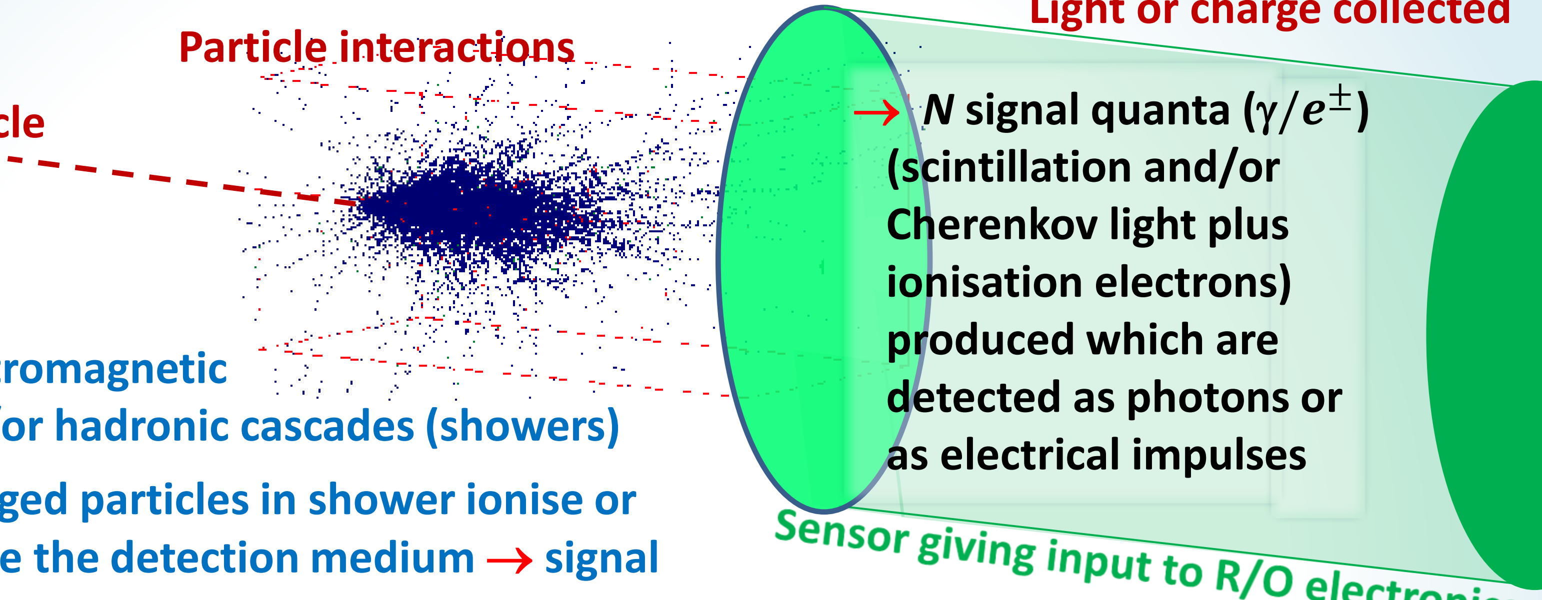

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For Hadronic Shower: medium characterised by "nuclear interaction length": $\lambda_I = {}^{A}\!/_{N_A \sigma_{\text{Inel}}} \approx 35 \times A^{1/3}$ [g/cm^2] (units independent of density) since roughly expect $\sigma_{\text{Inel}} \sim A^{2/3}$.

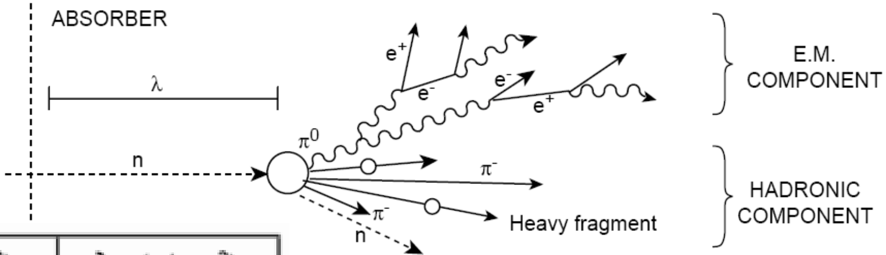
So λ_I ~ 17cm (lead or steel) cf X_0 of Pb ~0.6cm

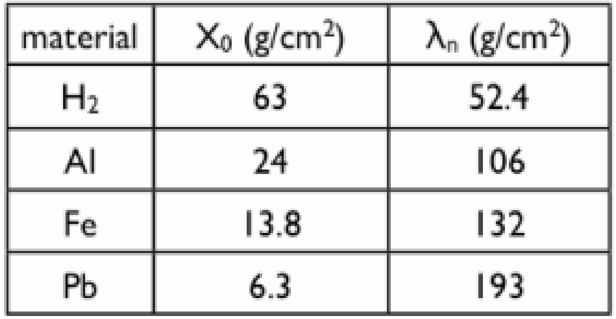
https://pdg.lbl.gov/2020/AtomicNuclearProperties/

Multiplicity of secondary particles $\sim ln(E)$

~$^{1}/_{3}$ hadrons produced are π^0s.

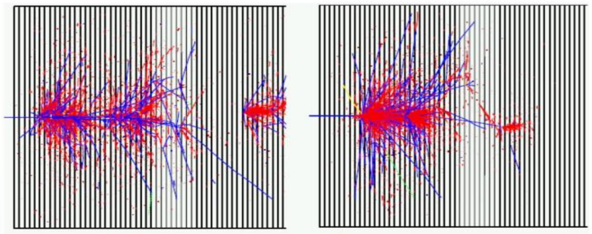
For 100 GeV hadron ~18 π^0 produced as secondaries.





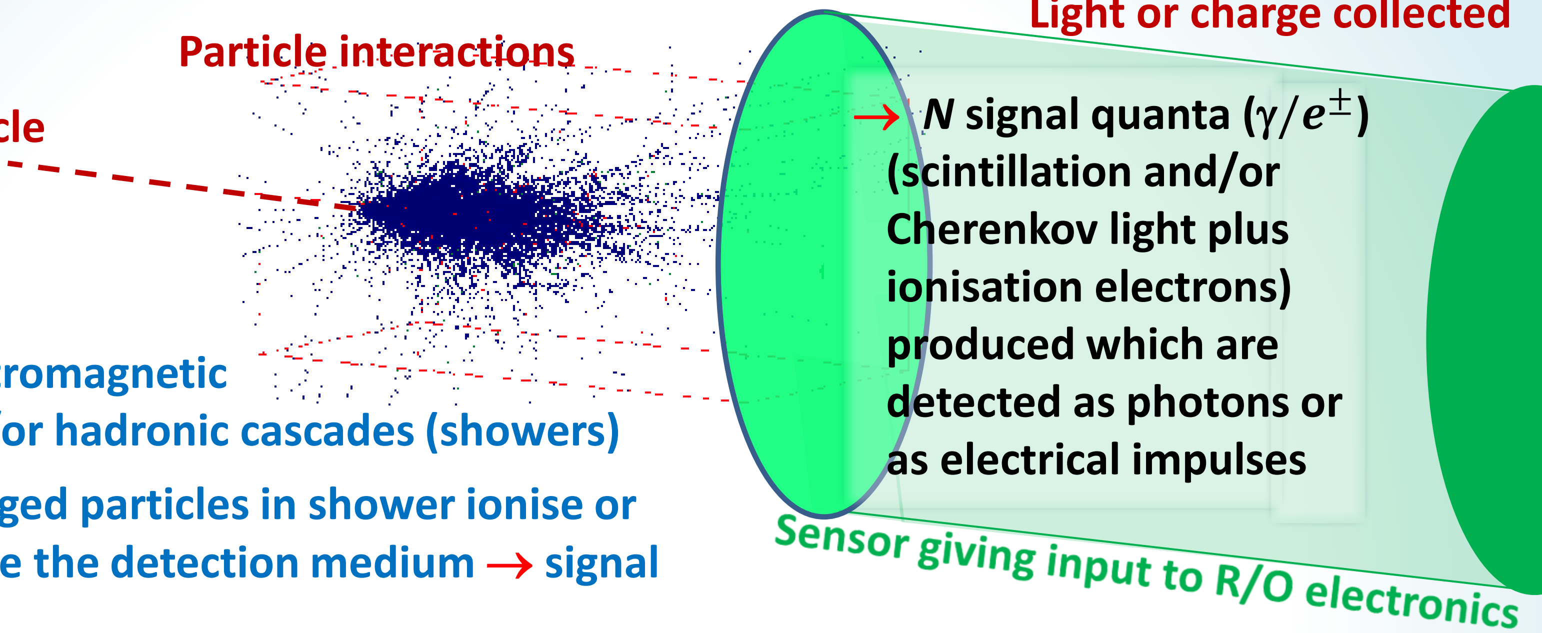
material	X_0 (g/cm^2)	λ_n (g/cm^2)
H_2	63	52.4
Al	24	106
Fe	13.8	132
Pb	6.3	193

Simulations of hadron showers



Red - e.m. component Blue – charged hadrons

High Energy Interactions:



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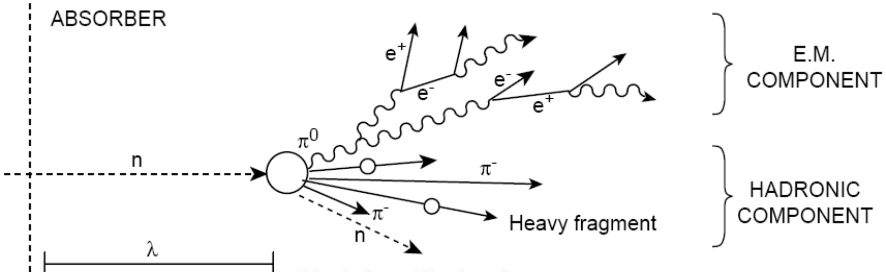
Depth of shower maximum:

$$t_{MAX} \approx \lambda_I \left(0.2 \times \ln(E\,[\text{GeV}]) + 0.7\right)$$
$$t_{95\%}(\text{cm}) \approx 9.4 \times \ln(E\,[\text{GeV}]) + 39 \text{ (Fe)}$$

100 GeV in Fe, $t_{95\%} \approx 80\text{cm}$

Shower width ~ λ_I ie ~17cm



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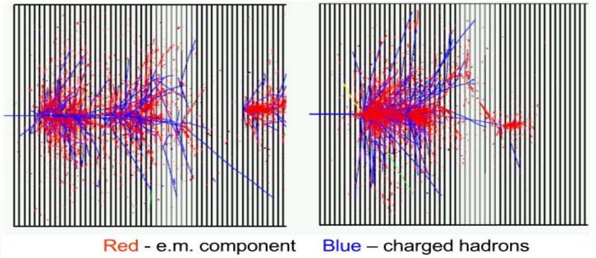


High Energy Interactions:

High energy charged particles passing through (as opposed to stopping in) a medium release different amounts of energy per unit length to ionisation as they transverse the sensor active material.

These fluctuations are described by the the highly asymmetric "Landau distribution" (see https://pdg.lbl.gov/ or textbooks).

In silicon, a typical peak energy loss in a 300µm thick detector is ~80keV.

Given that it takes on average about 3.6eV of deposited energy for each eh-pair, this gives ~22,500e of peak signal produced.

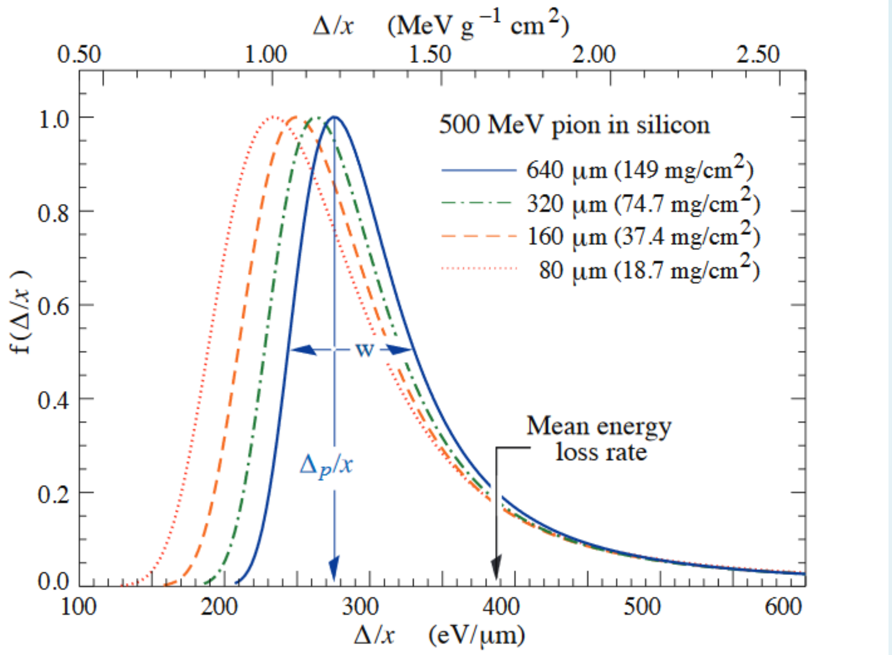


Figure 34.8: Straggling functions in silicon for 500 MeV pions, normalized to unity at the most probable value Δ_p/x. The width w is the full width at half maximum.

Crucially for tracking, relativistic particles undergo multiple Coulomb scattering which then introduces extrapolation (for vertexing) and curvature* (for momentum) measurement errors, with (for thickness, x, of material) angular scattering $\theta_{\mathrm{rms}} \approx \frac{13.6 MeV}{\beta c p} z \sqrt{\frac{x}{X_0}}$

* $p\, cos\lambda = \; 0.3z\, B\, R$ (momentum, p, in GeV/c; helix pitch angle, λ, B in T, R in m).

Interactions of Particles with Matter

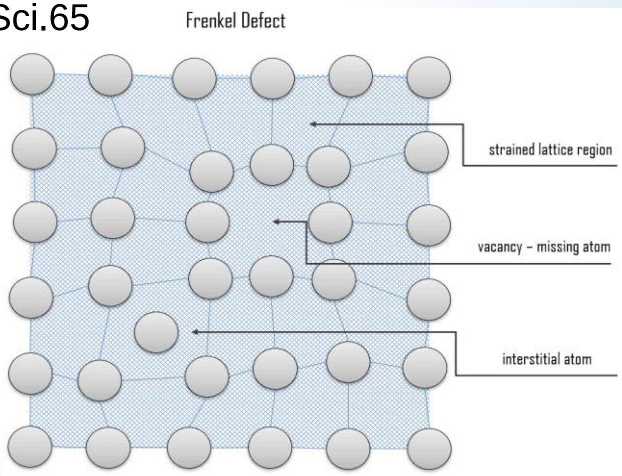
Radiation Damage

- There is another very important category of interactions that particle have with detectors and these are the ones that cause damage to the detectors.
- For sensors and electronics there are three key damage mechanisms*.

1. The ionisation itself results in charge being created and over time some of the charges may get trapped in structures (particularly at interfaces) giving a build up of problems with time. The integrated "**total ionising damage**" (often abbreviated TID) is basically the dose measured in unit of Gy or Rad (where 1Gy is 100 Rad).

2. The elastic collisions of particles with atoms in a crystal results in Frenkel pairs (vacancy + interstitial) being created. Such **displacement damage** (M. Moll, "Displacement Damage in Silicon Detectors for High Energy Physics", IEEE Trans.Nucl.Sci.65 (2018) no.8, 1561-1582, 2018) is conventionally related to the particle fluence scaled to that for 1MeV neutrons and so is quoted in units of 1MeV neutron equivalent per cm^2 (n_{eq}/cm^2).

3. **Nuclear interactions**, resulting in detectors or materials becoming radioactive, leading to handling issues and ultimately to changes in bulk chemistry.



* Huge topic: see Laura Gonella (17/5/22)