Detector physics – NPAC 2023-2024

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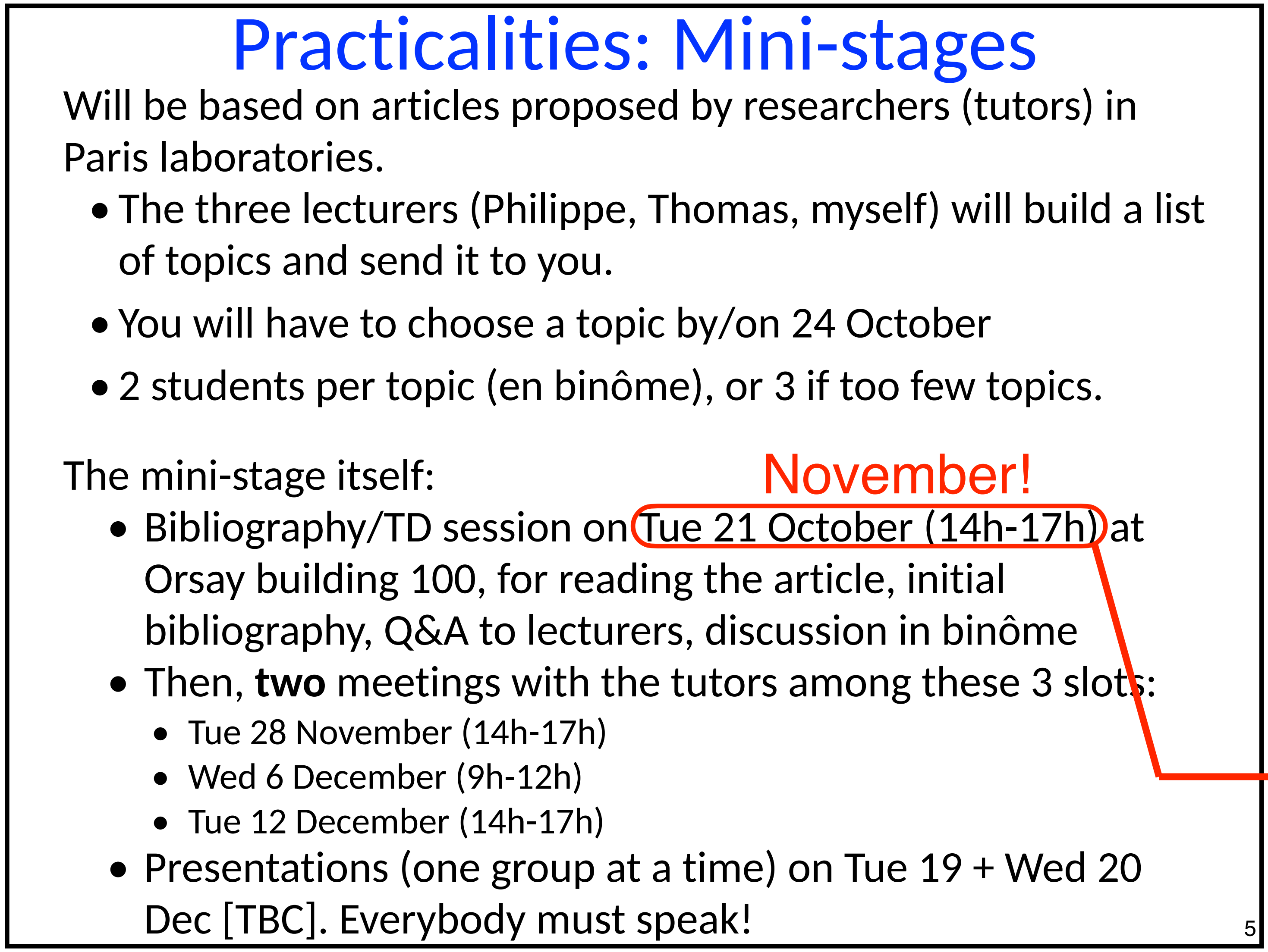
Plan

- Second lecture: intro, interaction of charged particles in matter
- Third lecture (this one):
  - Interactions of photons in matter
  - Start of scintillators & photodetectors
- Fourth lecture: photodetectors, interactions of other neutral particles in matter

Questions & corrections on lecture 2

- First, there was a typo on slide 5. The bibliography will be on Tue 21 November (not October). You can also see it in the planning:



Practicalities: Mini-stages

Will be based on articles proposed by researchers (tutors) in Paris laboratories.

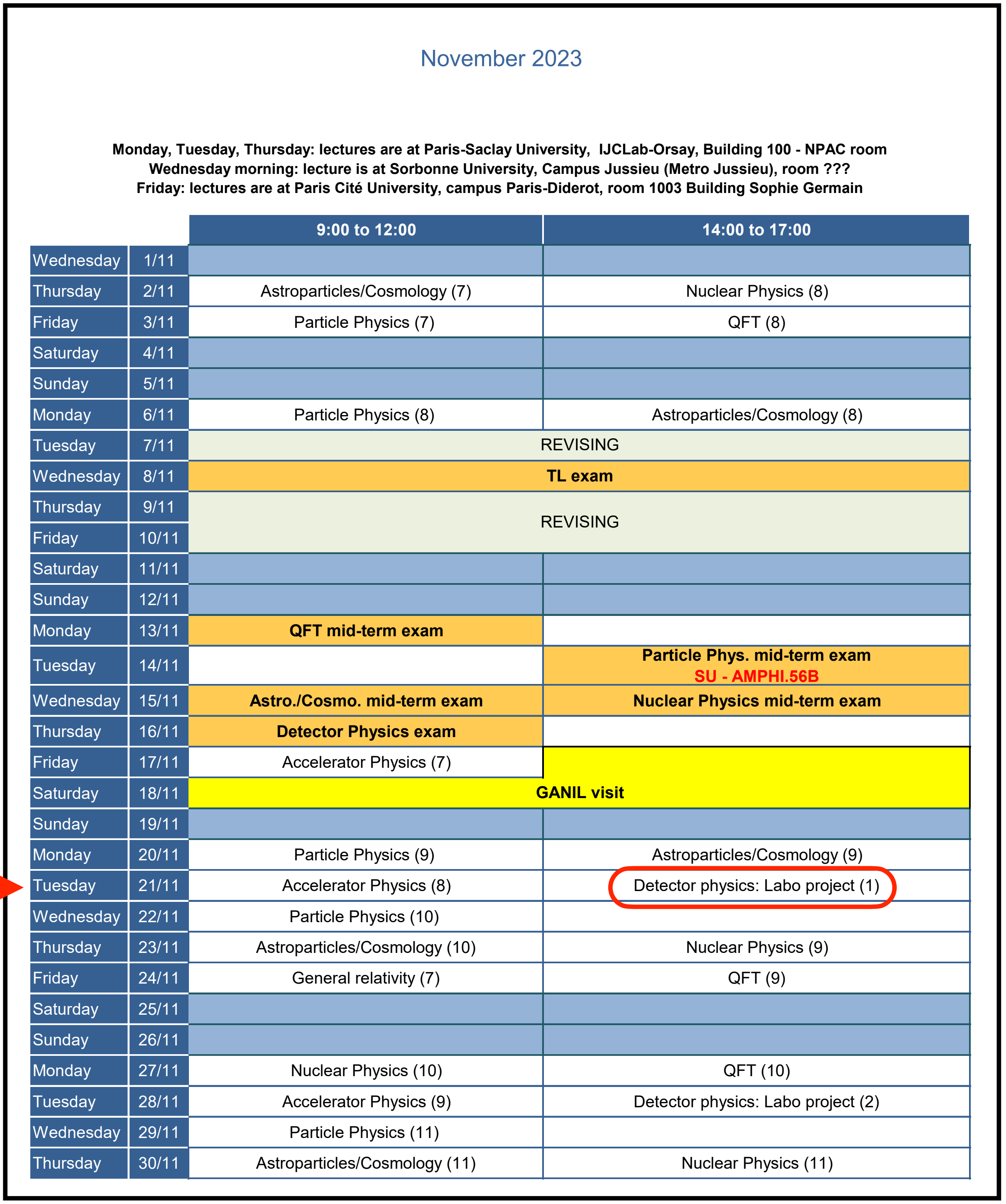
- The three lecturers (Philippe, Thomas, myself) will build a list of topics and send it to you.
- You will have to choose a topic by/on 24 October
- 2 students per topic (en binôme), or 3 if too few topics.

The mini-stage itself:

November!

- Bibliography/TD session on Tue 21 October (14h-17h) at Orsay building 100, for reading the article, initial bibliography, Q&A to lecturers, discussion in binôme
- Then, **two** meetings with the tutors among these 3 slots:
  - Tue 28 November (14h-17h)
  - Wed 6 December (9h-12h)
  - Tue 12 December (14h-17h)
- Presentations (one group at a time) on Tue 19 + Wed 20 Dec [TBC]. Everybody must speak!

5



November 2023

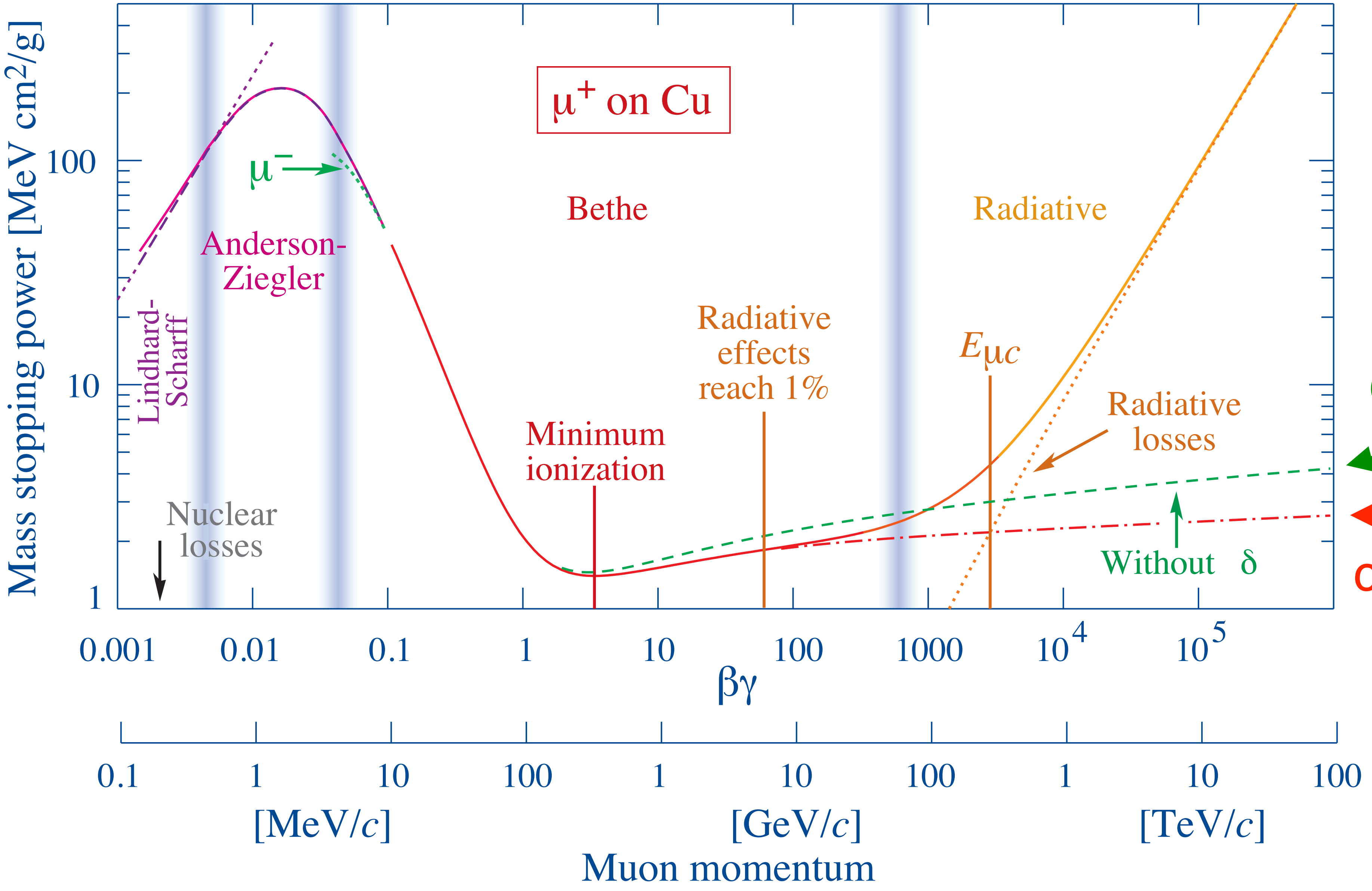
Monday, Tuesday, Thursday: lectures are at Paris-Saclay University, IJCLab-Orsay, Building 100 - NPAC room
Wednesday morning: lecture is at Sorbonne University, Campus Jussieu (Metro Jussieu), room ???
Friday: lectures are at Paris Cité University, campus Paris-Diderot, room 1003 Building Sophie Germain

		9:00 to 12:00	14:00 to 17:00
Wednesday	1/11		
Thursday	2/11	Astroparticles/Cosmology (7)	Nuclear Physics (8)
Friday	3/11	Particle Physics (7)	QFT (8)
Saturday	4/11		
Sunday	5/11		
Monday	6/11	Particle Physics (8)	Astroparticles/Cosmology (8)
Tuesday	7/11	REVISING	
Wednesday	8/11	**TL exam**	
Thursday	9/11	REVISING	
Friday	10/11		
Saturday	11/11		
Sunday	12/11		
Monday	13/11	**QFT mid-term exam**	
Tuesday	14/11		**Particle Phys. mid-term exam** **SU - AMPHI.56B**
Wednesday	15/11	**Astro./Cosmo. mid-term exam**	**Nuclear Physics mid-term exam**
Thursday	16/11	**Detector Physics exam**	
Friday	17/11	Accelerator Physics (7)	**GANIL visit**
Saturday	18/11		
Sunday	19/11		
Monday	20/11	Particle Physics (9)	Astroparticles/Cosmology (9)
Tuesday	21/11	Accelerator Physics (8)	Detector physics: Labo project (1)
Wednesday	22/11	Particle Physics (10)	
Thursday	23/11	Astroparticles/Cosmology (10)	Nuclear Physics (9)
Friday	24/11	General relativity (7)	QFT (9)
Saturday	25/11		
Sunday	26/11		
Monday	27/11	Nuclear Physics (10)	QFT (10)
Tuesday	28/11	Accelerator Physics (9)	Detector physics: Labo project (2)
Wednesday	29/11	Particle Physics (11)	
Thursday	30/11	Astroparticles/Cosmology (11)	Nuclear Physics (11)

Questions & corrections on lecture 2

- There was also a question about the density correction (δ) and how it varies with energy. As a reminder, here's the B-B formula:

$$-\frac{1}{\rho}\left\langle\frac{\mathrm{d}E}{\mathrm{d}x}\right\rangle = \frac{2\pi z^2 e^4}{m_e v^2}\frac{Z}{A}N_A\left[\ln\left(\frac{2m_e\gamma^2 v^2 W_{\max}}{I^2}\right) - 2\beta^2 \boxed{-\,\delta} - 2\frac{C}{Z}\right]$$



Green line: before correction

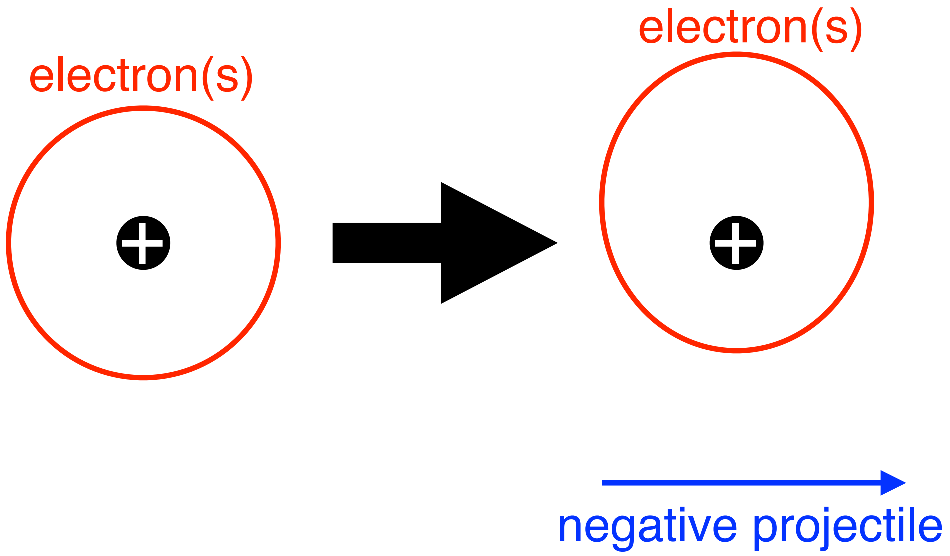
Red line: after correction (it's negative)

Effect is small for $\beta\gamma \leq 1$ but increases with momentum

Questions & corrections on lecture 2

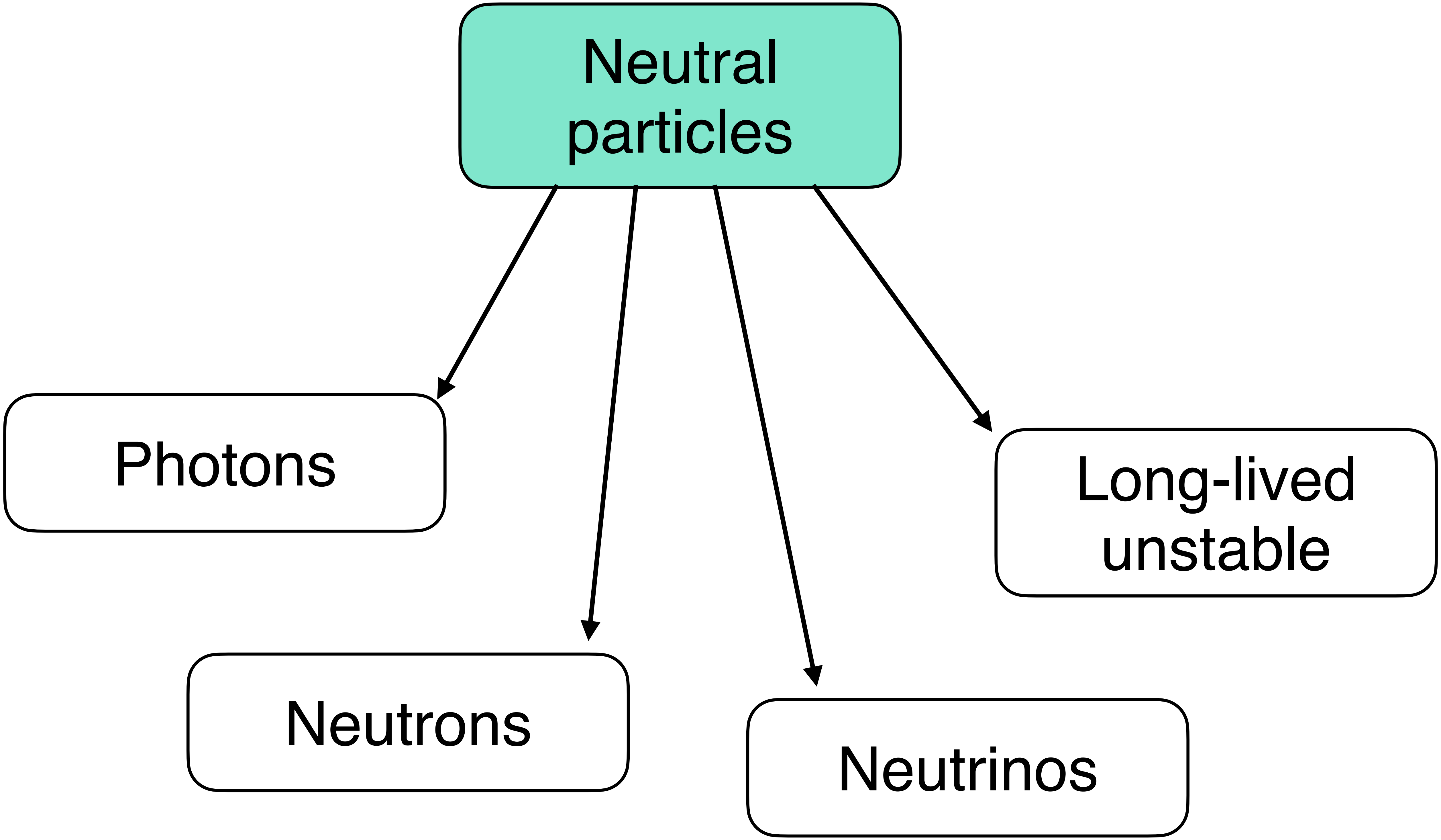
$$-\frac{1}{\rho}\left\langle\frac{\mathrm{d}E}{\mathrm{d}x}\right\rangle = \frac{2\pi z^2 e^4}{m_e v^2}\frac{Z}{A}N_A\left[\ln\left(\frac{2m_e\gamma^2 v^2 W_{\max}}{I^2}\right) - 2\beta^2 \boxed{-\,\delta} - 2\frac{C}{Z}\right]$$

- As a reminder, the physical origin of this term is the shielding effect, in which electrons in the material adjust positions to [partly] compensate for the EM field of the charged projectile.



- The shielding effect is larger for electrons further away -- and as $\beta\gamma$ increases, the energy loss calculation includes more and more distant electrons.
  - Recall $b_{\max} = \frac{\gamma v}{\bar{\nu}} \propto \beta\gamma$ characterises the outer radius cut-off, due to minimum quantised energy transfer.

Interactions of neutral particles in matter



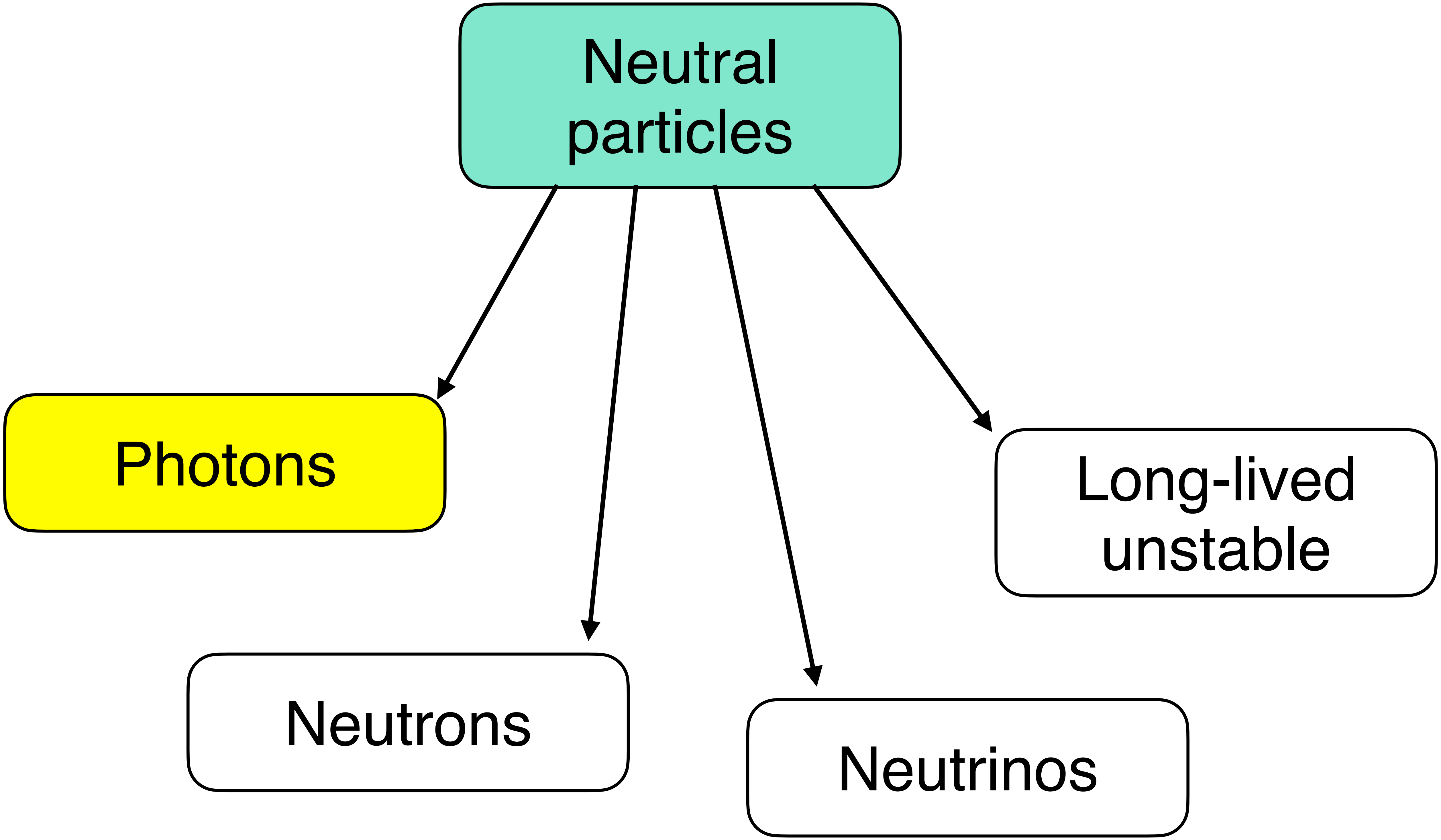
Neutral particles

Photons

Neutrons

Neutrinos

Long-lived unstable

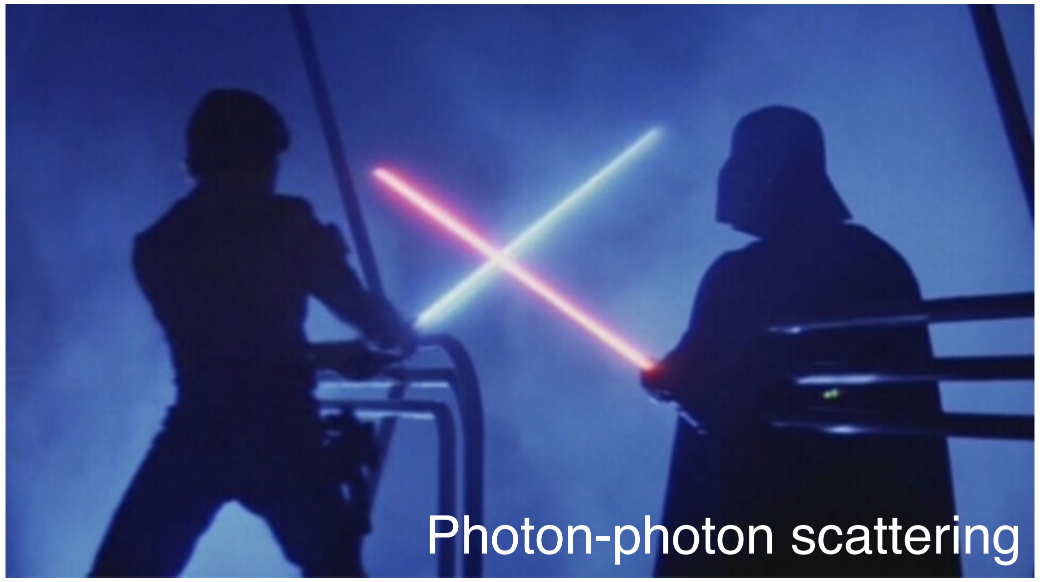


Neutral particles

- Photons
- Neutrons
- Neutrinos
- Long-lived unstable

Interaction of photons with matter

- Principal characteristic:
  A single interaction removes photon from beam (not the case for heavy charged particles)
- Possible interactions:
  - Photoelectric effect ($\gamma A \rightarrow A^{+} e^{-}$; A = atom)
  - Compton scattering ($\gamma e \rightarrow \gamma e$; inelastic)
  - Pair production ($\gamma N \rightarrow e^{+} e^{-} N$; N = nucleus)
  - Rayleigh Scattering ($\gamma A \rightarrow \gamma A$; coherent)
  - Thomson Scattering ($\gamma e \rightarrow \gamma e$; elastic)
  - Photo Nuclear Absorption ($\gamma N \rightarrow pN'$ or nN')
  - Nuclear Resonance Scattering ($\gamma A \rightarrow A^{*} \rightarrow \gamma A$)
  - Hadron/Lepton Pair production ($\gamma N \rightarrow h^{+} h^{-} N$)
  - Delbruck Scattering ($\gamma N \rightarrow \gamma N$; coherent scattering due to the vacuum polarization in a Coulomb field of a nucleus)
  - ...



Photon-photon scattering

Interaction of photons with matter

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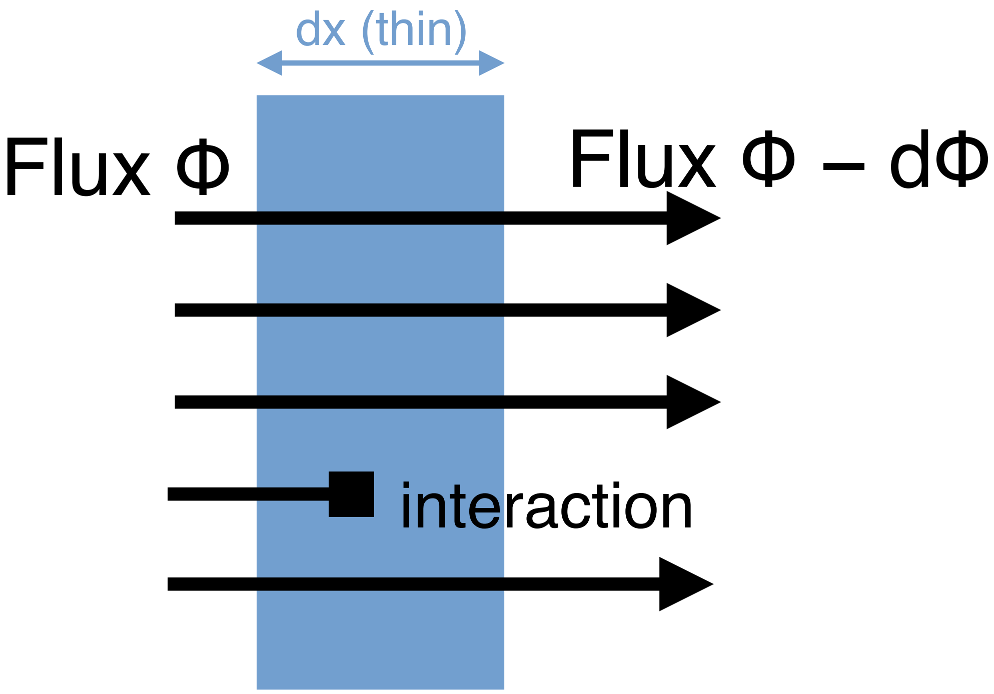


with $d\Phi = \mu \, \Phi \, dx$,

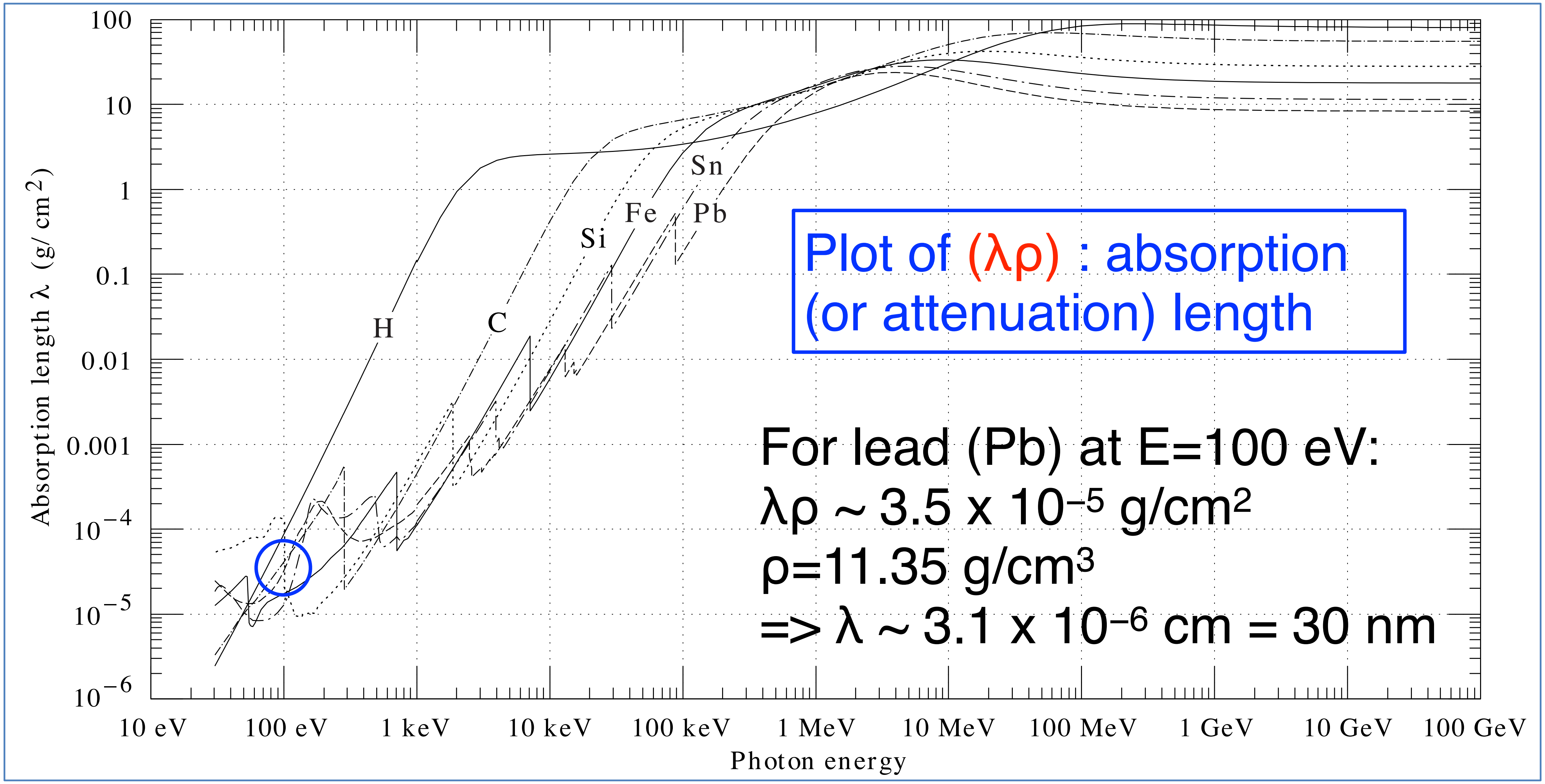
where μ is the absorption coefficient and depends on E, Z, and target density n [with $n = \rho N_A / A$ for atoms]

You can show $d\Phi = -\,\Phi \, n \, \sigma \, dx$, and thus the mean free path is

$\lambda = 1/\mu = 1 \,/\, (n\sigma)$

for total absorption cross-section σ

Interaction of photons with matter



Plot of (λρ) : absorption (or attenuation) length

For lead (Pb) at E=100 eV:
$\lambda\rho \sim 3.5 \times 10^{-5}$ g/cm^2
ρ=11.35 g/cm^3
=> $\lambda \sim 3.1 \times 10^{-6}$ cm = 30 nm

Figure from PDG: K.A. Olive et al. (Particle Data Group), Chin. Phys. C, 38, 090001 (2014) and 2015 update

- Interaction probability of low-energy photons is very high ($\lambda \sim$ 30nm in lead at 100 eV)
- Peaks are observed
- Saturation at high energy

Caution: watch out for notation/units difference (our mean free path λ in cm).

Interaction of photons with matter

The dominant interaction is one of these three for photon energies above 10 eV.

- Possible interactions:
  - Photoelectric effect ($\gamma A \to A^+ e^-$; A = atom)
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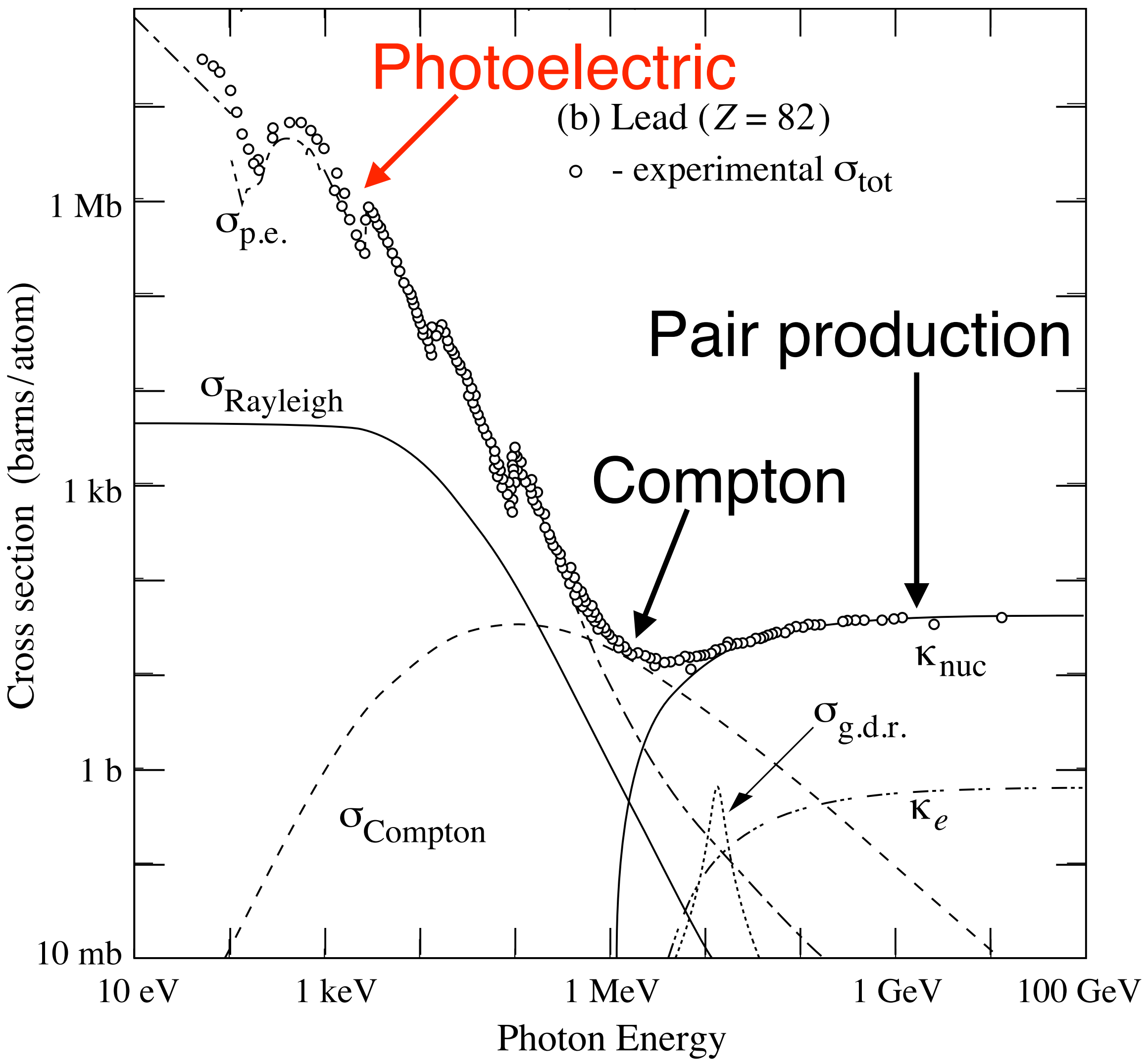

$\sigma_{\rm p.e.}$ = Atomic photoelectric effect (electron ejection, photon absorption)
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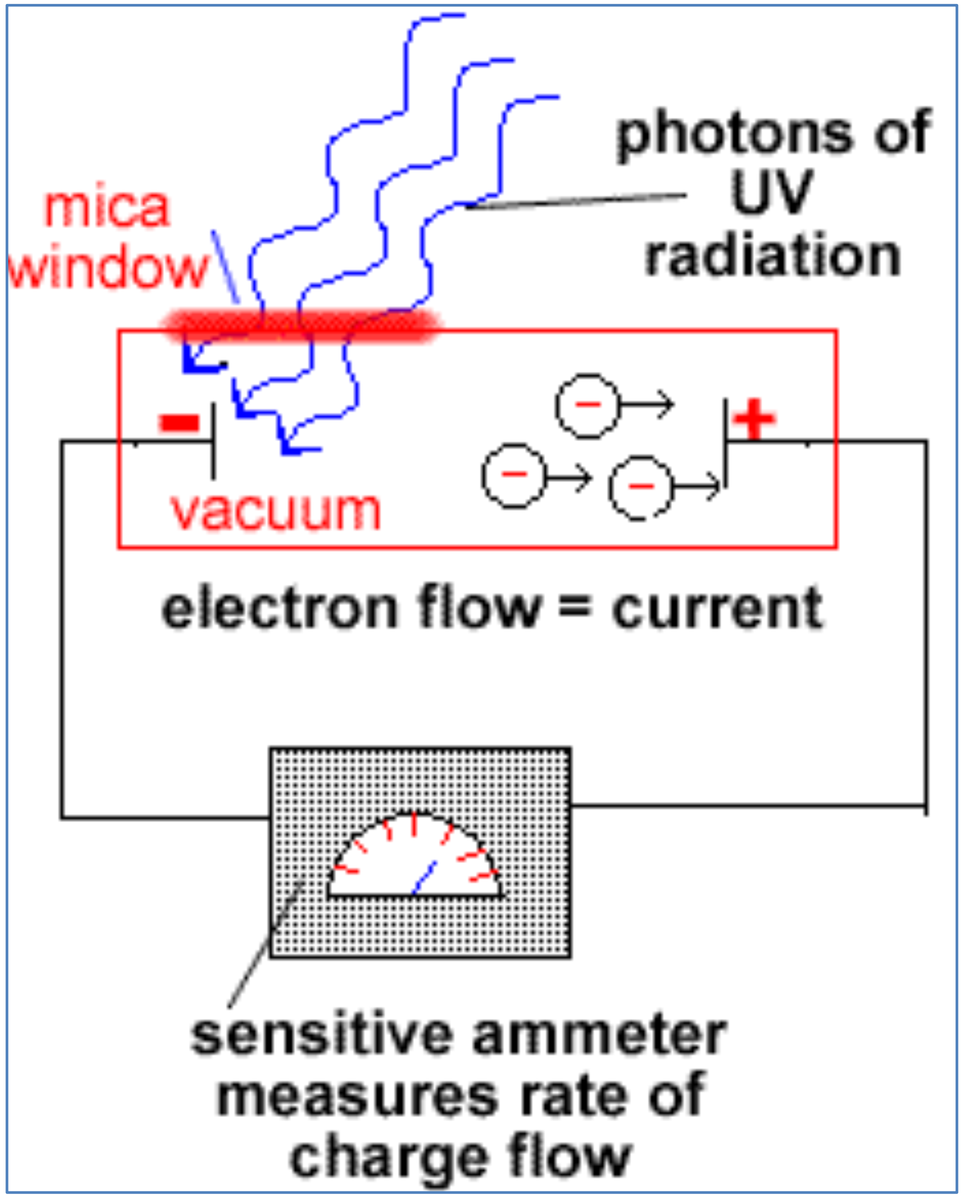
$\kappa_{\rm nuc}$ = Pair production, nuclear field
κ_e = Pair production, electron field
$\sigma_{\rm g.d.r.}$ = Photonuclear interactions, most notably the Giant Dipole Resonance [52]. In these interactions, the target nucleus is broken up.

Original figures through the courtesy of John H. Hubbell (NIST).

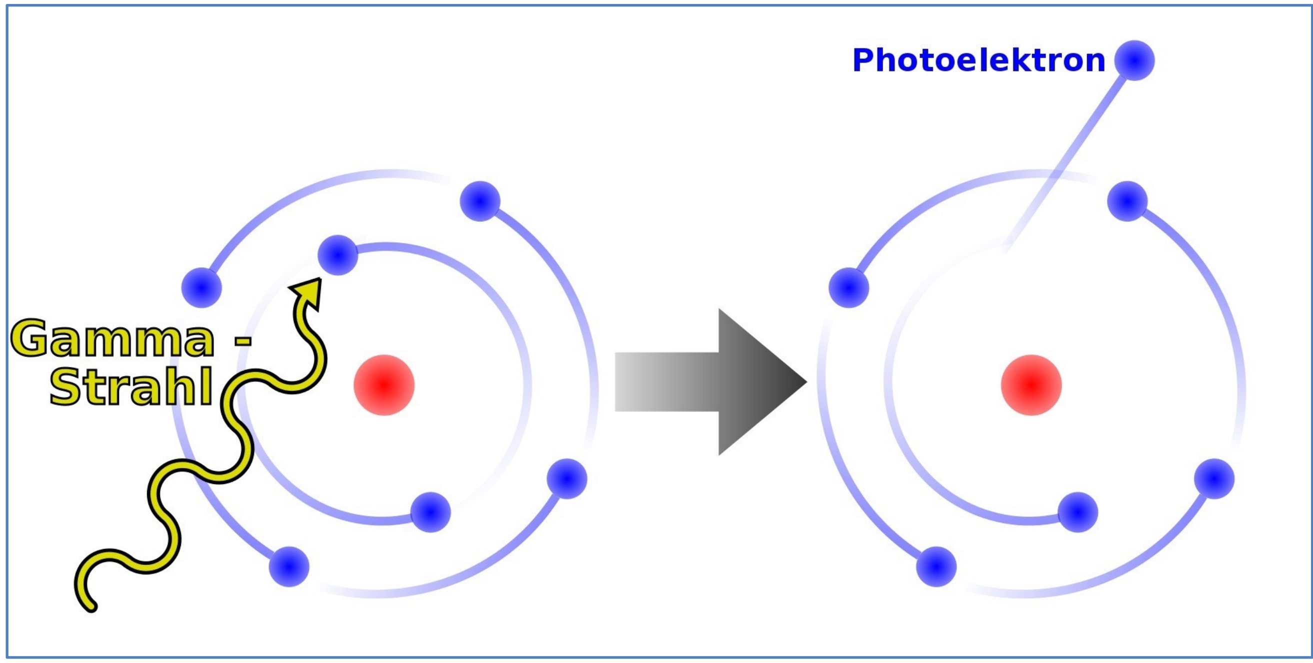
Figure from PDG: K.A. Olive et al. (Particle Data Group), Chin. Phys. C, 38, 090001 (2014) and 2015 update

Photons & matter: Photoelectric Effect

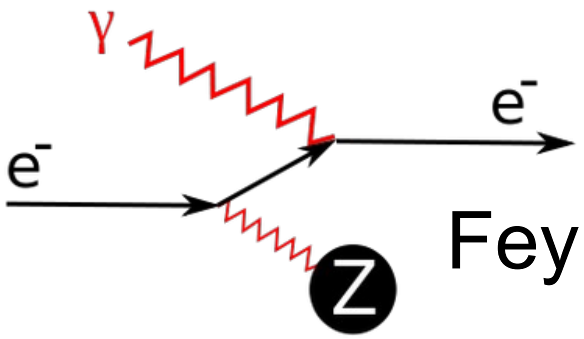
Discovered before 1900.



Naïve picture:



$\gamma + \text{atom} \rightarrow e^- + \text{atom}^+$



Feynman diagram

Q: Why is the reaction $\gamma e^- \rightarrow e^-$ impossible? What is the role of the nucleus in the photoelectric effect?

Photons & matter: Photoelectric Effect

Kinetic energy of outgoing electron:

$$T_e = h\nu - I_b$$

Photon energy E_γ

Binding energy

Typical energy dependence:

$$\sigma_{\mathrm{ph}} = 2\pi\, r_e^2\, \alpha^4 Z^5 mc^2/E_\gamma \qquad \text{for } E_\gamma \gg mc^2$$

$$\sigma_{\mathrm{ph}} = \pi\, \alpha\, r_{\mathrm{B}} Z^5 (I_b/E_\gamma)^{7/2} \qquad \text{for } I_b \ll E_\gamma \ll mc^2$$

Example:

$r_B = 0.53 \times 10^{-10}$ m

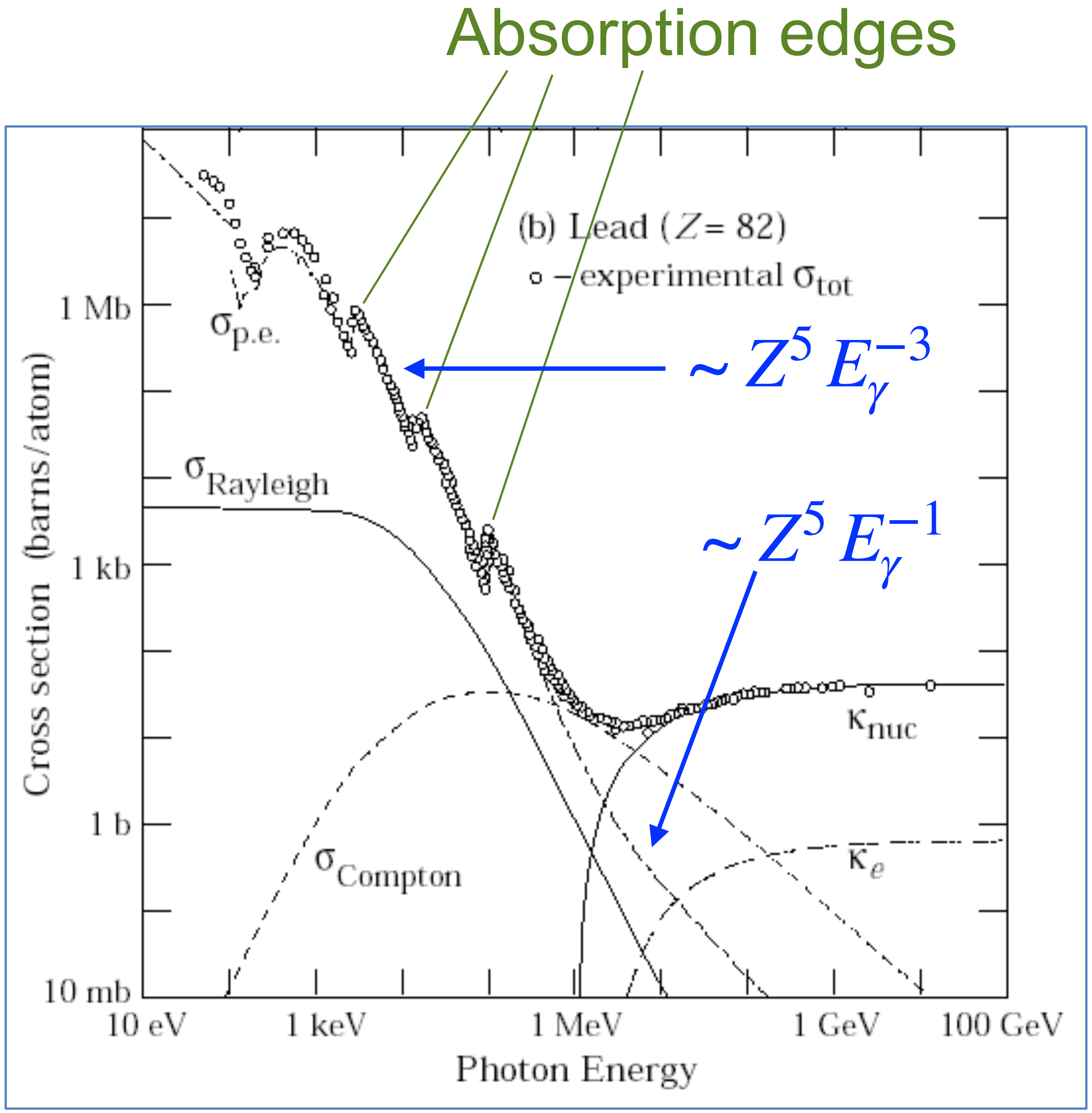
$I_b = 13.6$ eV

$E_\gamma = 100$ keV :

$\sigma_{ph}(\mathrm{Fe}) = 29$ barn

$\sigma_{ph}(\mathrm{Pb}) = 5000$ barn

Strong dependence on Z !



Absorption edges

$\sim Z^5 E_\gamma^{-3}$

$\sim Z^5 E_\gamma^{-1}$

(NB: 1b = 1 barn = 10^{-24} cm^2 = 10^{-28} m^2)

Photons & matter: Photoelectric Effect

Kinetic energy of outgoing electron:

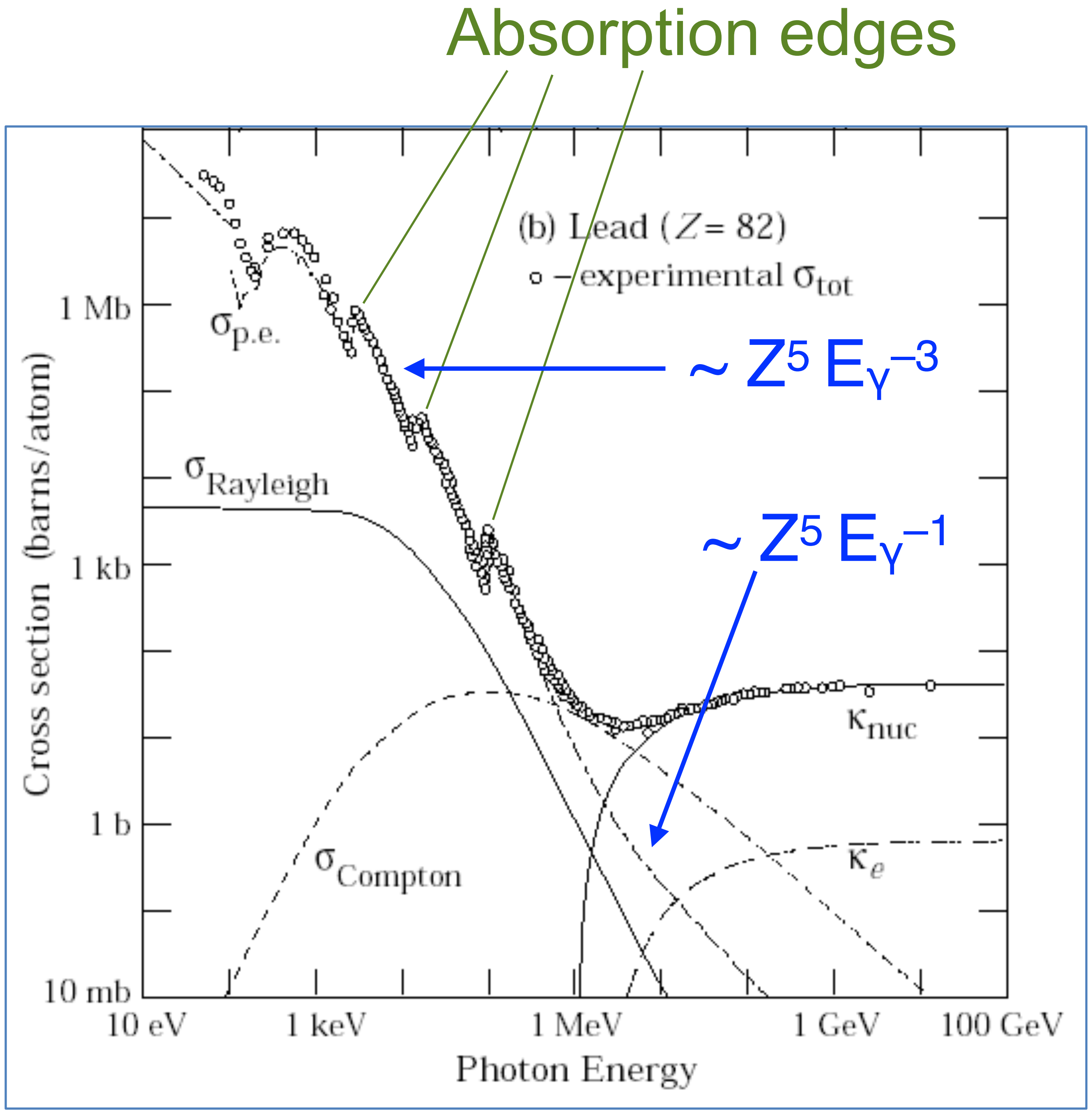
$$T_e = h\nu - I_b$$

Photon energy E_γ

Binding energy

Reaction is only possible if $E_\gamma > I_b$

The absorption edges correspond to the binding energies of different atomic shells -- there are extra turn-on points at which $E_\gamma > I_b$ for another shell, and so total cross-section increases.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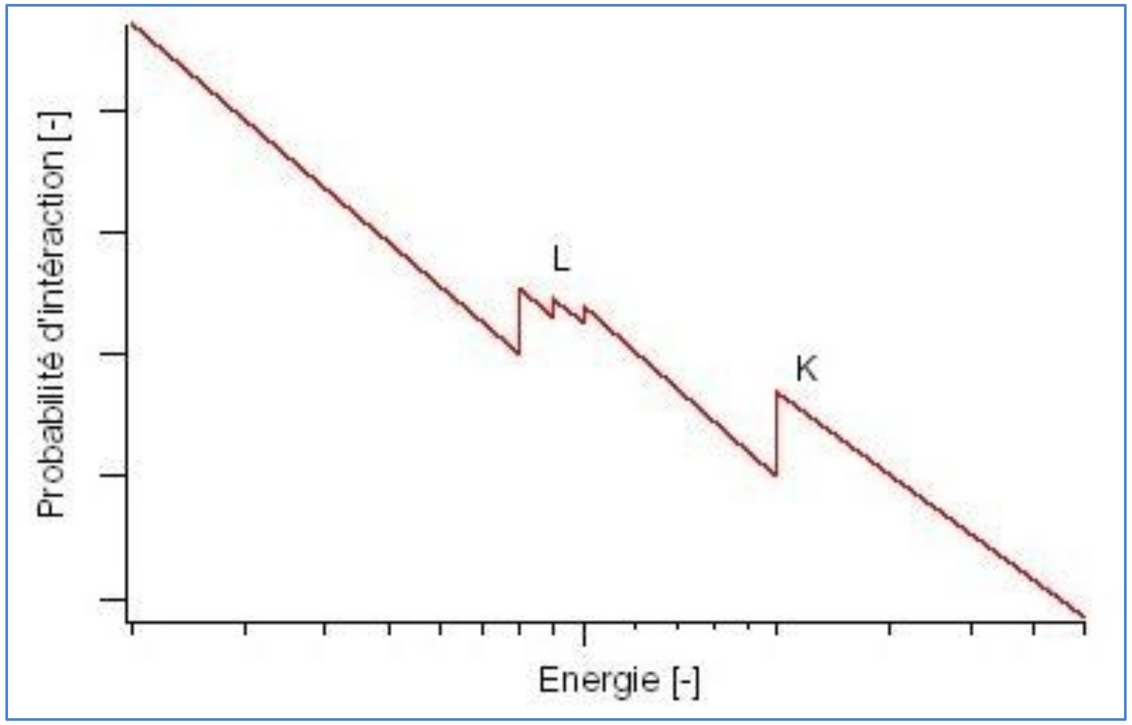
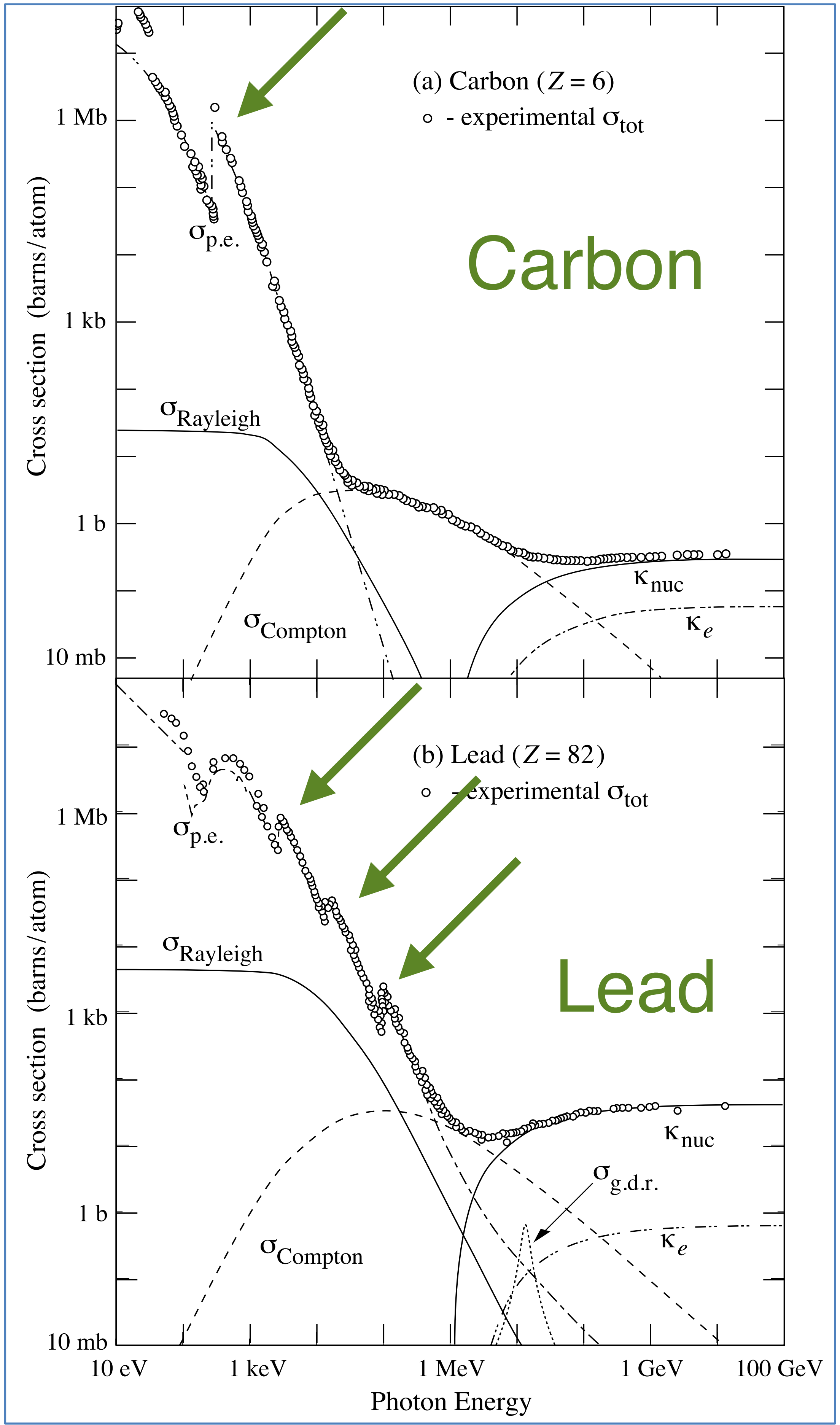


Photons & matter: Photoelectric Effect



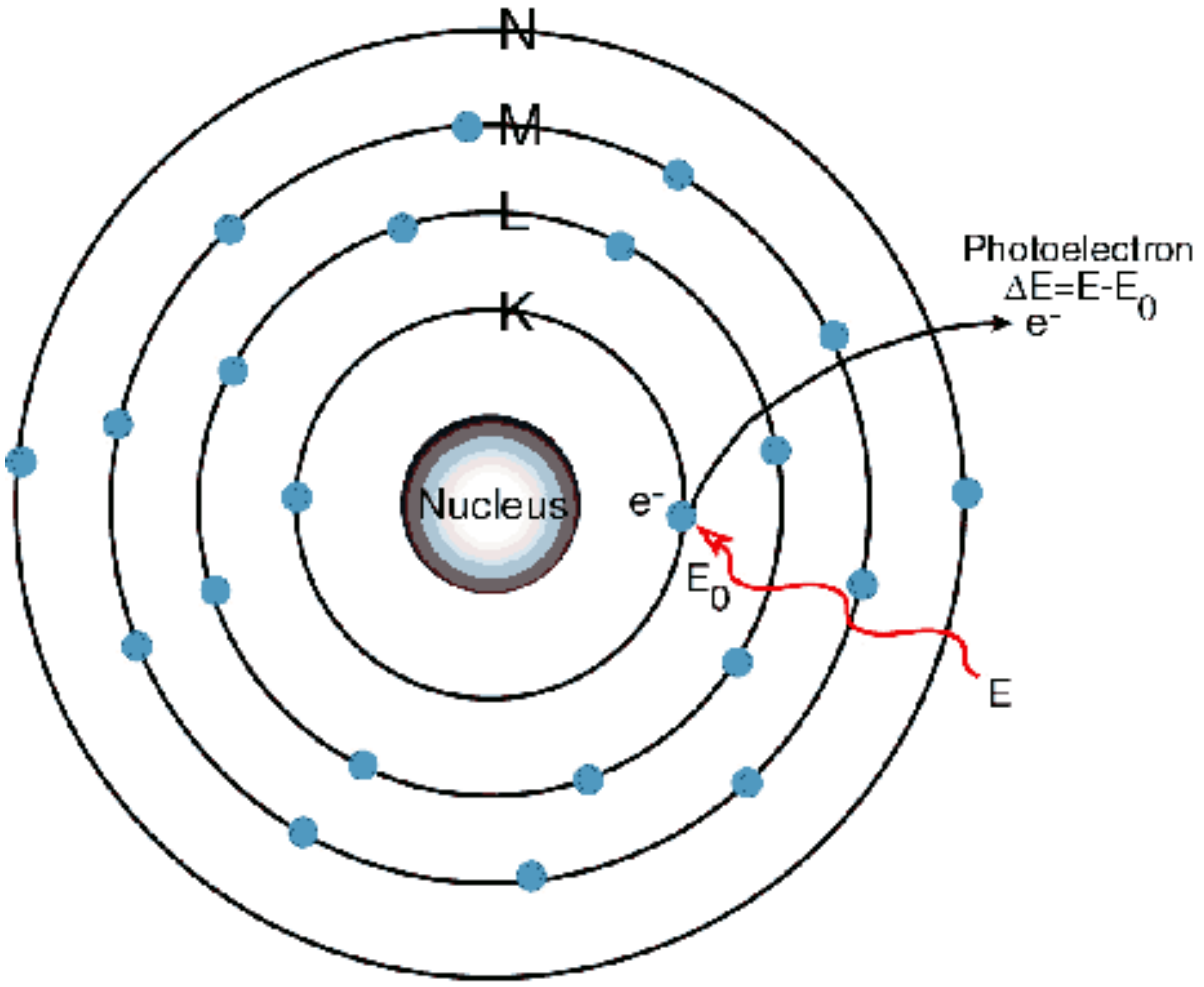
Different elements have different electron shell structures

=> The photoelectric absorption edges are at different energies.

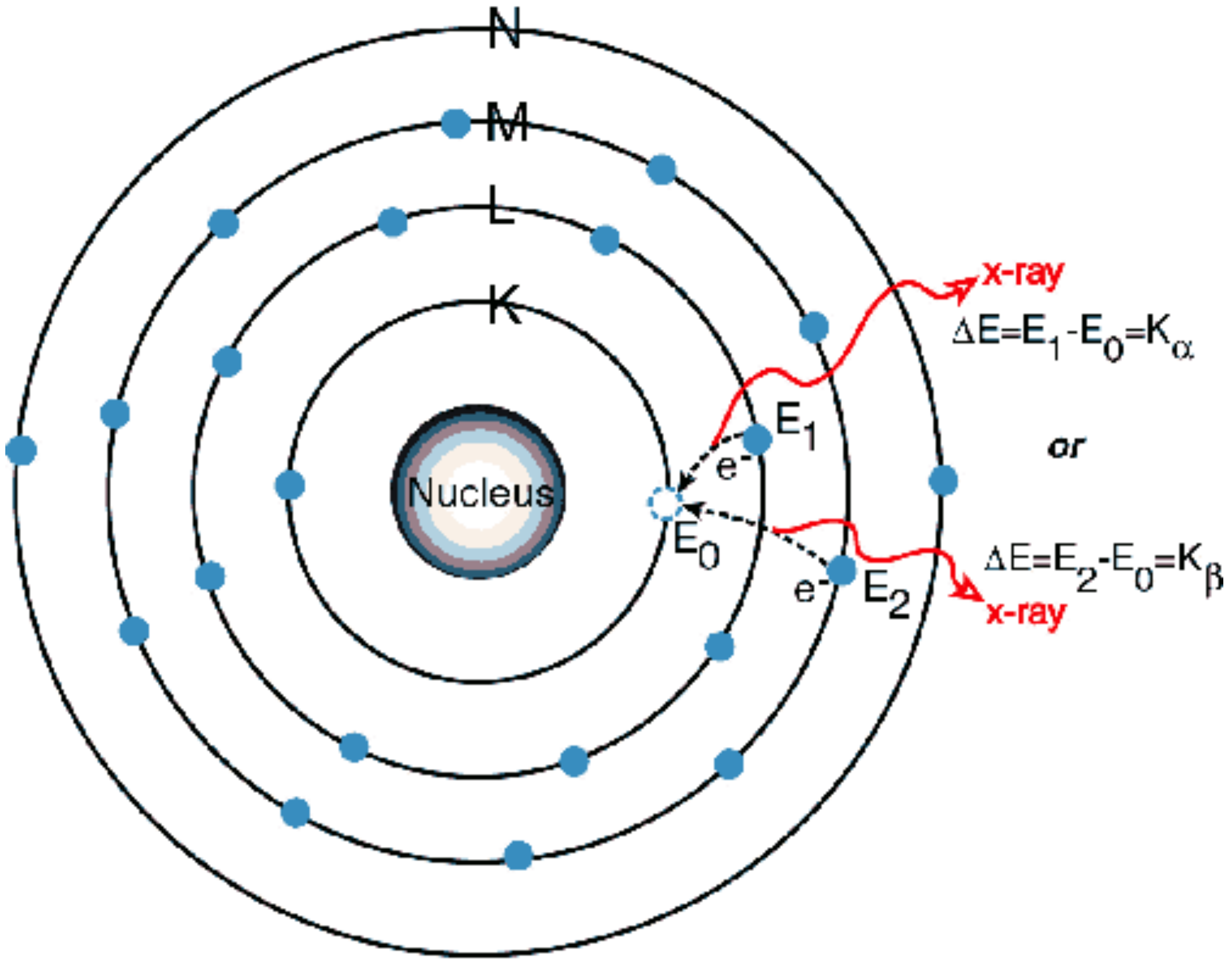
Can use these characteristic energies to identify elements.

Photons & matter: Photoelectric Effect
Characteristic X-ray energies

(Figures from Amptek, Inc.)



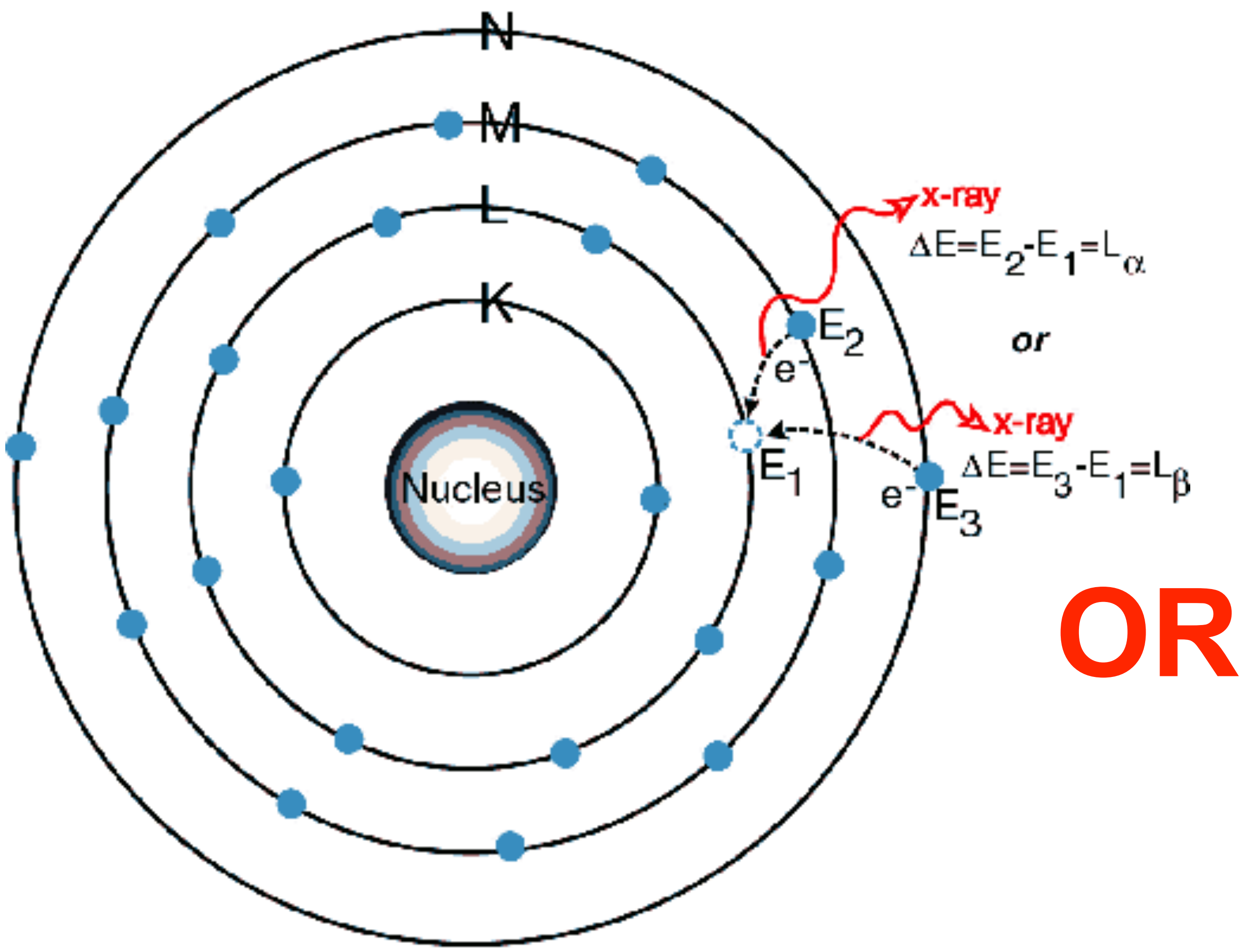
Step 1: Photoelectric effect knocks out an electron in one shell, leaving a vacancy.



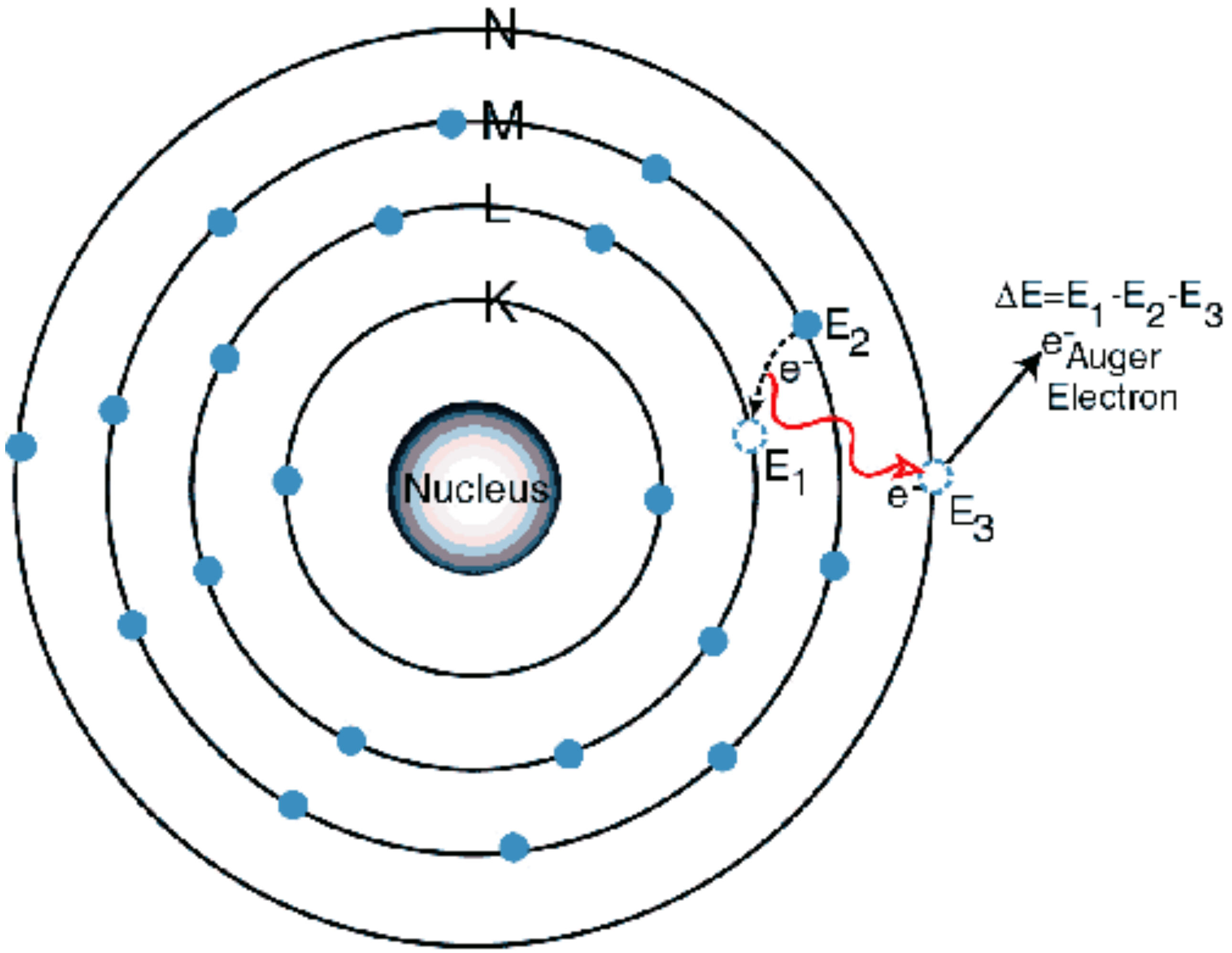
Step 2: An electron from a higher shell drops down to fill the vacancy. Potential energy is converted into an X-ray whose energy is characteristic of the element's electron shell structure. Leaves vacancy in an outer shell.

Photons & matter: Photoelectric Effect Characteristic X-ray energies

(Figures from Amptek, Inc.)



OR



Step 3: Same process can repeat for the vacancy left in an outer shell => two (or more) X-rays emitted with a characteristic pattern of energies.

=> X-ray spectroscopy

Step 3: An electron drops down, but the potential energy is instead used to liberate an electron from an outer shell (ionisation + kinetic energy). Kinetic energy of the electron is characteristic of the element.

=> Auger spectroscopy

Photons & matter: Photoelectric Effect

Last words: note that

- The full energy of the incoming photon is absorbed by the material
- Most* of this energy (E_γ - I_b) is immediately transferred to the ejected electron
- Most of the rest (I_b) is reemitted as lower-energy X-rays and/or an Auger electron (likely to be recaptured)
- Therefore: essentially 100% of the photon's energy is seen by the detector**.

* For the energies we work with, $E_\gamma \gg I_b$

** Can fail if detector is not large compared to depth of EM shower, e.g. for very high energy photons/electrons at a collider.

Photons & matter: Compton Scattering

The dominant interaction is one of these three for photon energies above 10 eV.

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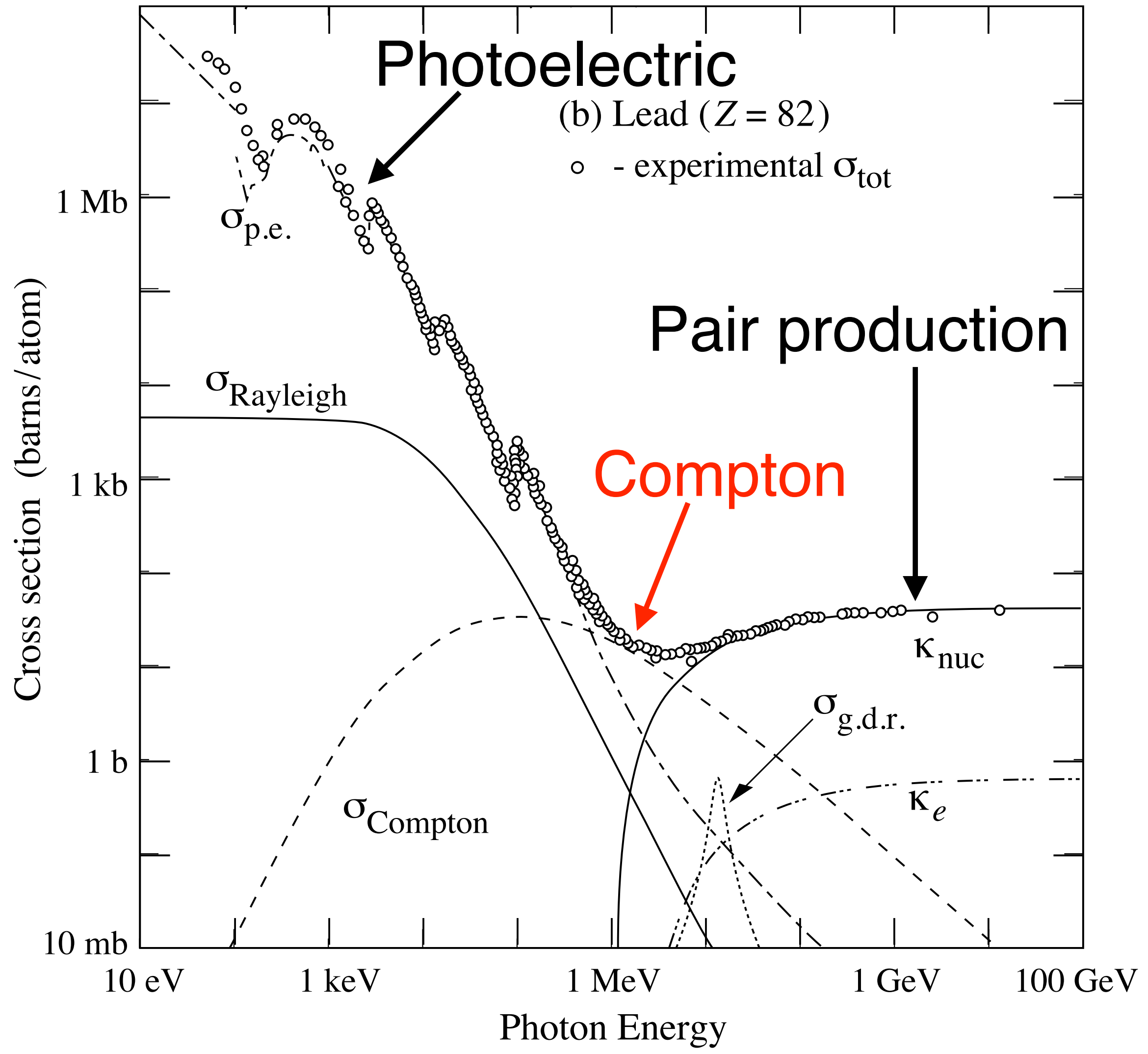

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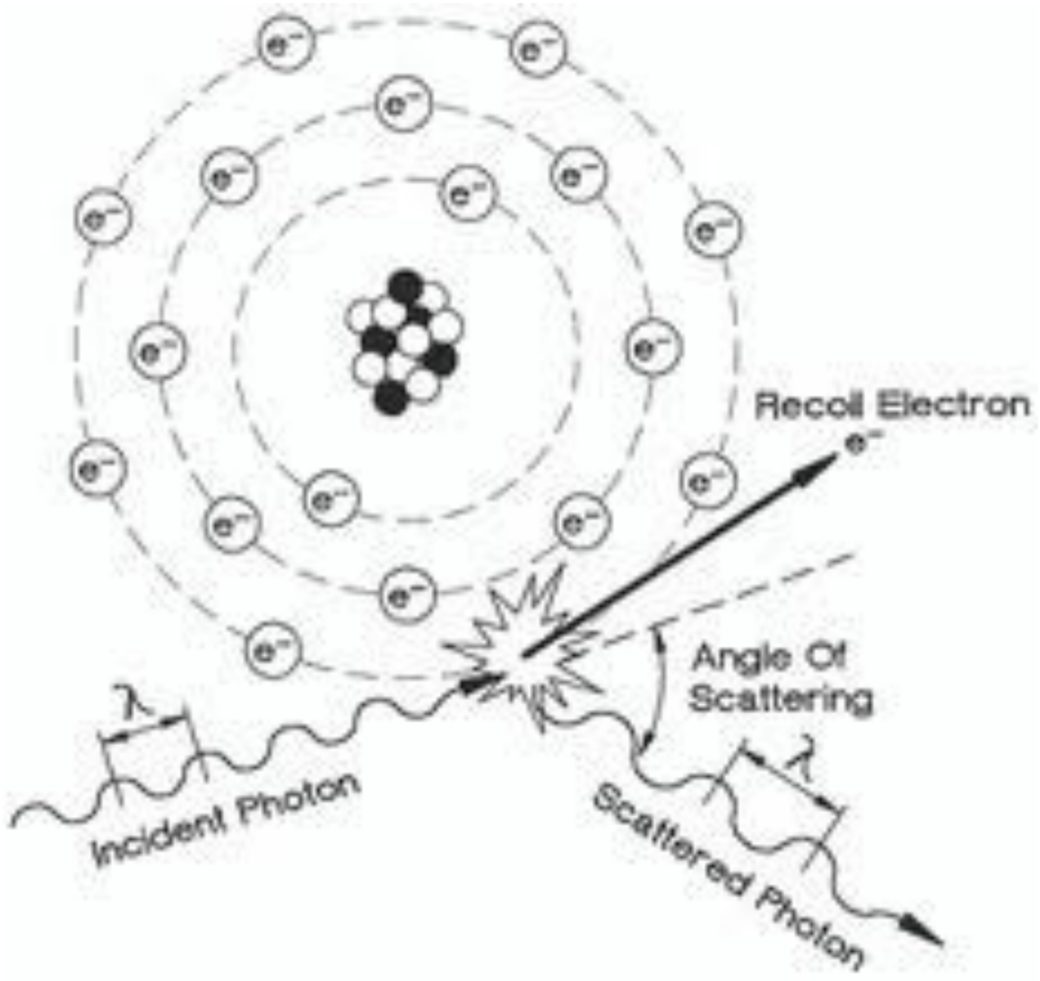
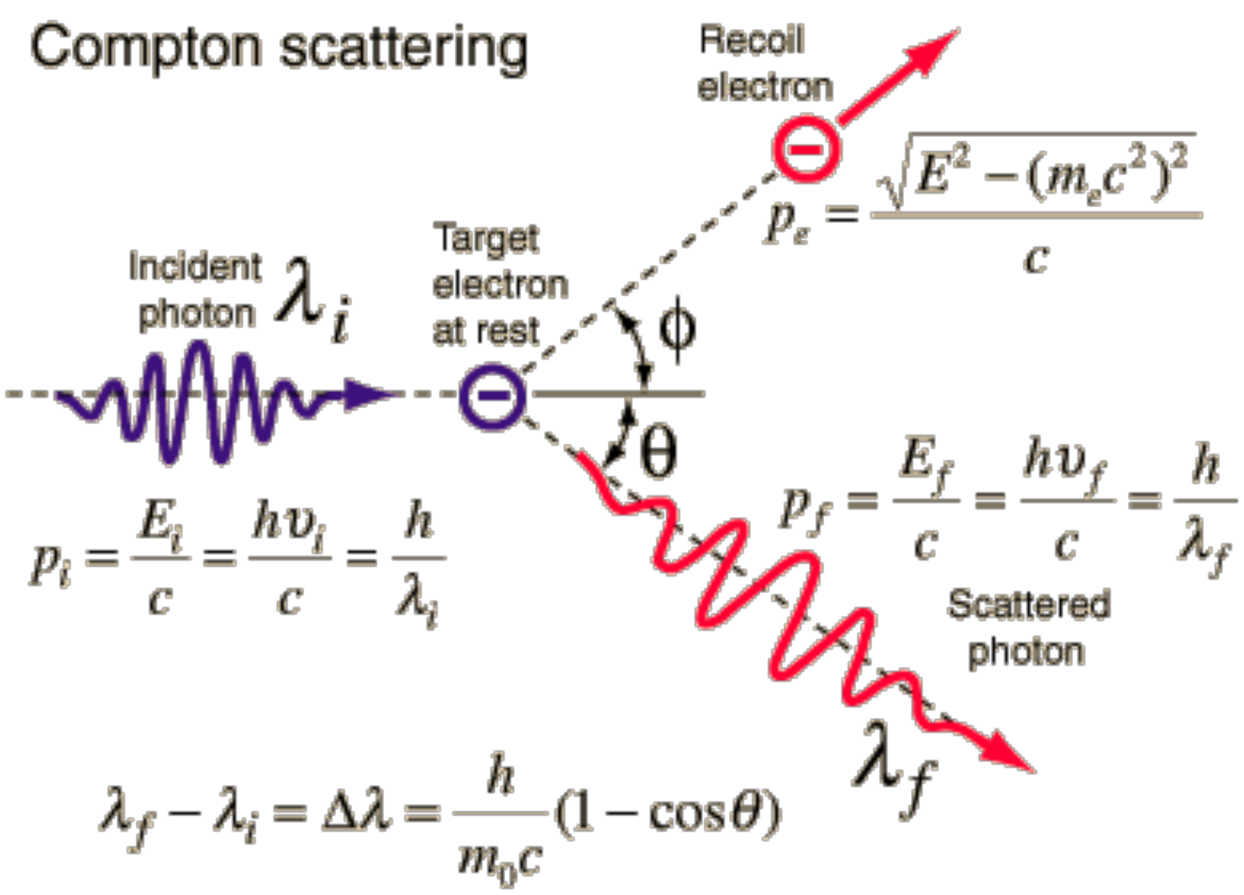
Photons & matter: Compton Scattering

Compton scattering is elastic scattering of a photon on a free charged particle, usually an electron.





A bit of algebra =>

$$h\nu = \frac{h\nu_0}{1+\alpha(1-\cos\theta)} \quad [\mathrm{keV}]$$

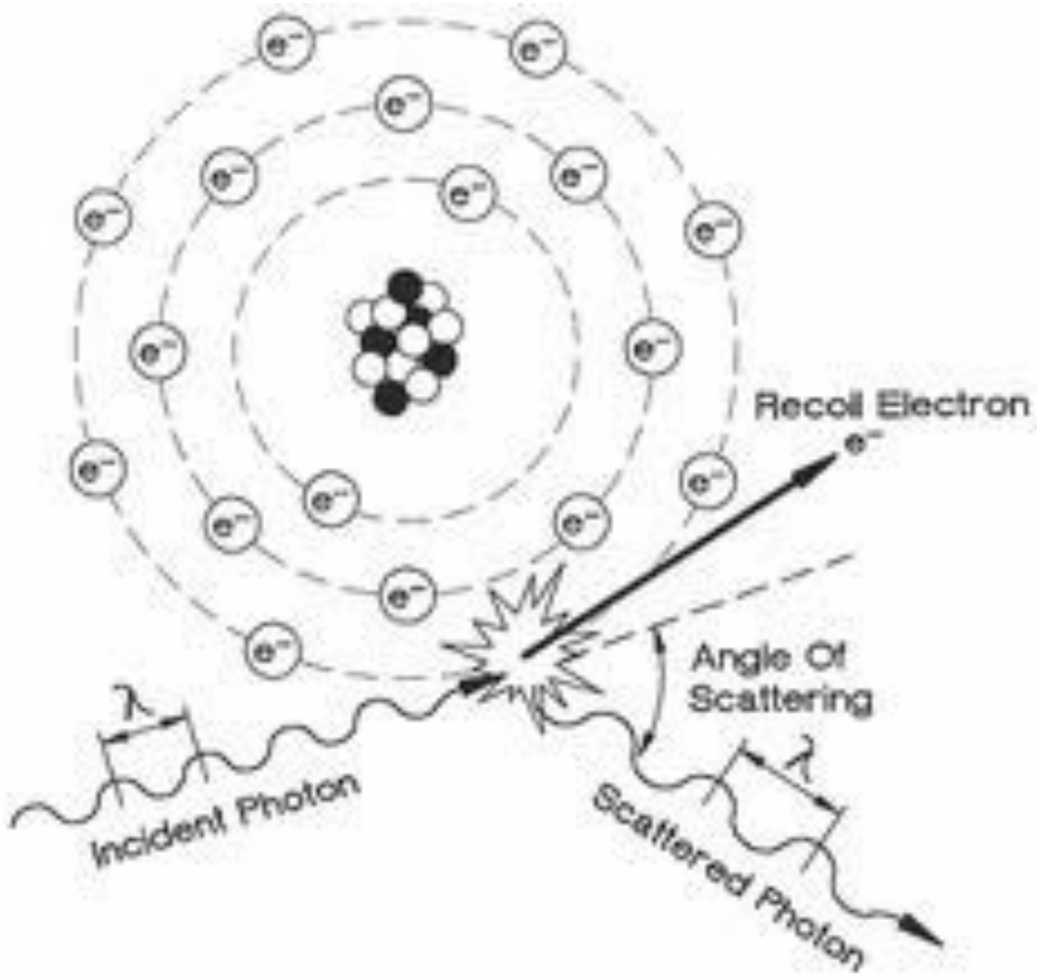
$$T_e = \frac{h\nu_0\,\alpha(1-\cos\theta)}{1+\alpha(1-\cos\theta)} \quad [\mathrm{keV}]$$

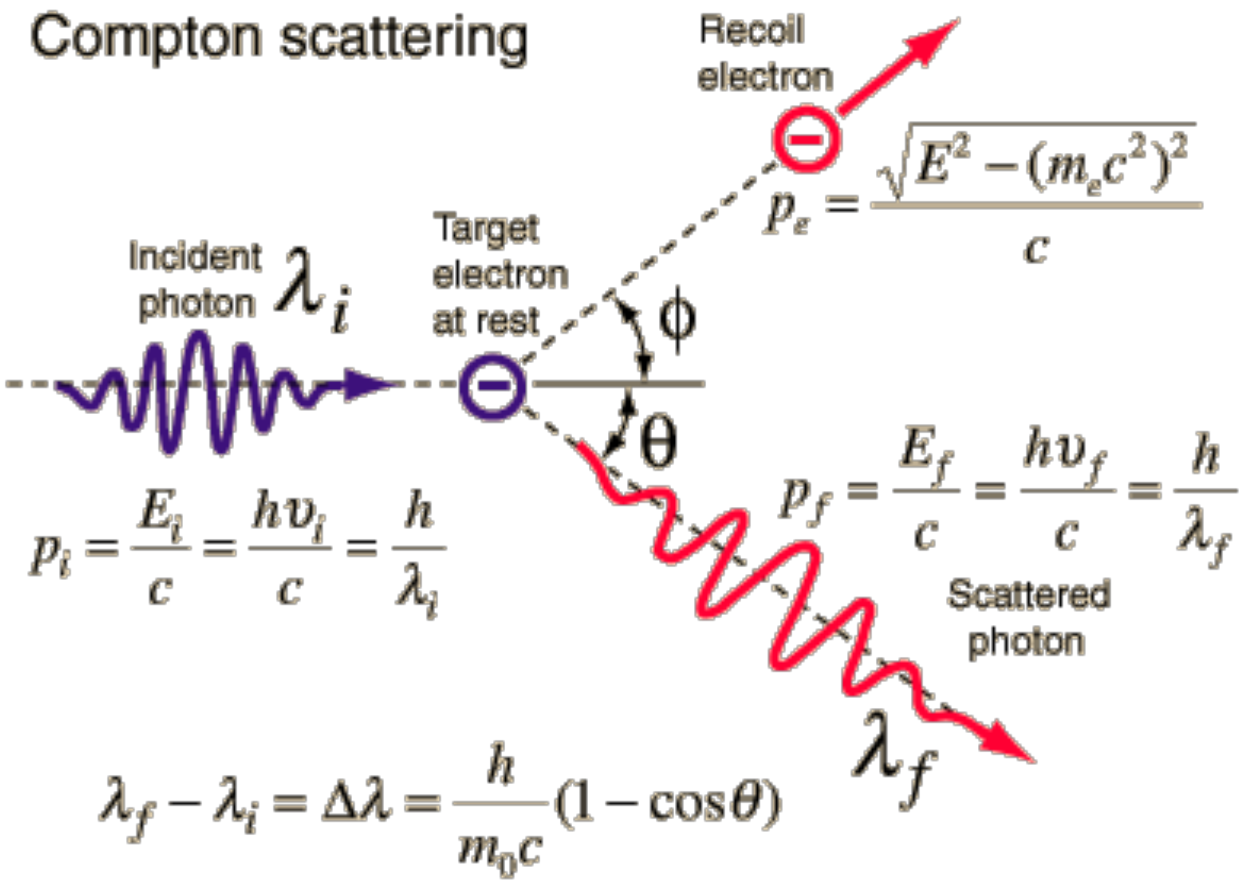
where

- $h\nu_0$ = incoming photon energy
- $h\nu$ = outgoing photon energy
- $\alpha = h\nu_0 / (m_e c^2)$
- T_e = outgoing electron kinetic energy

Photons & matter: Compton Scattering

Compton scattering is quasi-elastic scattering of a photon on a quasi-free* charged particle, usually an electron. * initial photon energy >> electron binding energy





$$p_e = \frac{\sqrt{E^2 - (m_e c^2)^2}}{c}$$

$$p_i = \frac{E_i}{c} = \frac{h\upsilon_i}{c} = \frac{h}{\lambda_i}$$

$$p_f = \frac{E_f}{c} = \frac{h\upsilon_f}{c} = \frac{h}{\lambda_f}$$

$$\lambda_f - \lambda_i = \Delta\lambda = \frac{h}{m_0 c}(1 - \cos\theta)$$

A bit of algebra =>

$$h\nu = \frac{h\nu_0}{1 + \alpha(1 - \cos\theta)} \quad [\mathrm{keV}]$$

$$T_e = \frac{h\nu_0\,\alpha(1 - \cos\theta)}{1 + \alpha(1 - \cos\theta)} \quad [\mathrm{keV}]$$

where

- $h\nu_0$ = incoming photon energy
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- $\alpha = h\nu_0 / (m_e c^2)$
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Photons & matter: Compton Scattering

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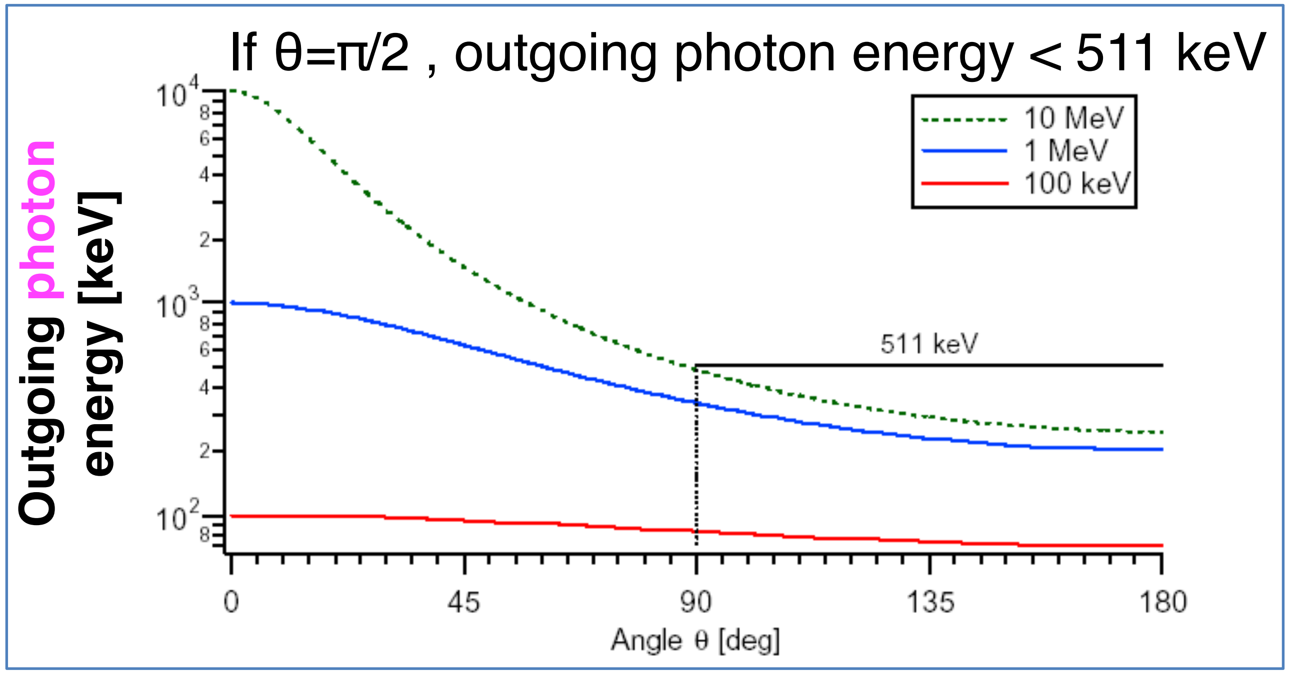
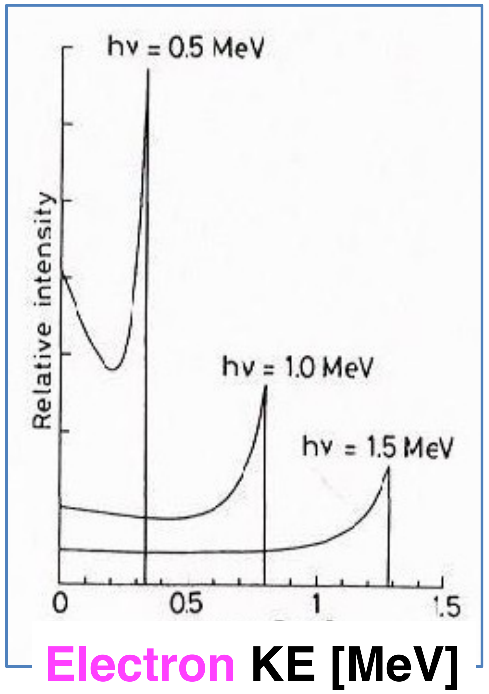
where

- $h\nu_0$ = incoming photon energy
- $h\nu$ = outgoing photon energy
- $\alpha = h\nu_0 / (m_e c^2)$
- T_e = outgoing electron kinetic energy

Bounding cases:

- $\theta=0$: $h\nu = h\nu_0$; $T_e = 0$ => infinitely weak scatter, photon undeflected
- $\theta=\pi$: $h\nu=h\nu_0/(1+2\alpha)$ and $T_e=T_{e,max}=2ah\nu_0/(1+2a)$
  => maximum recoil energy (Compton edge)


If θ=π/2 , outgoing photon energy < 511 keV



Note: photon always exits with some energy ($T_e < h\nu_0$)

=> If photon doesn't interact again, the detector won't see the remaining energy ($h\nu$).

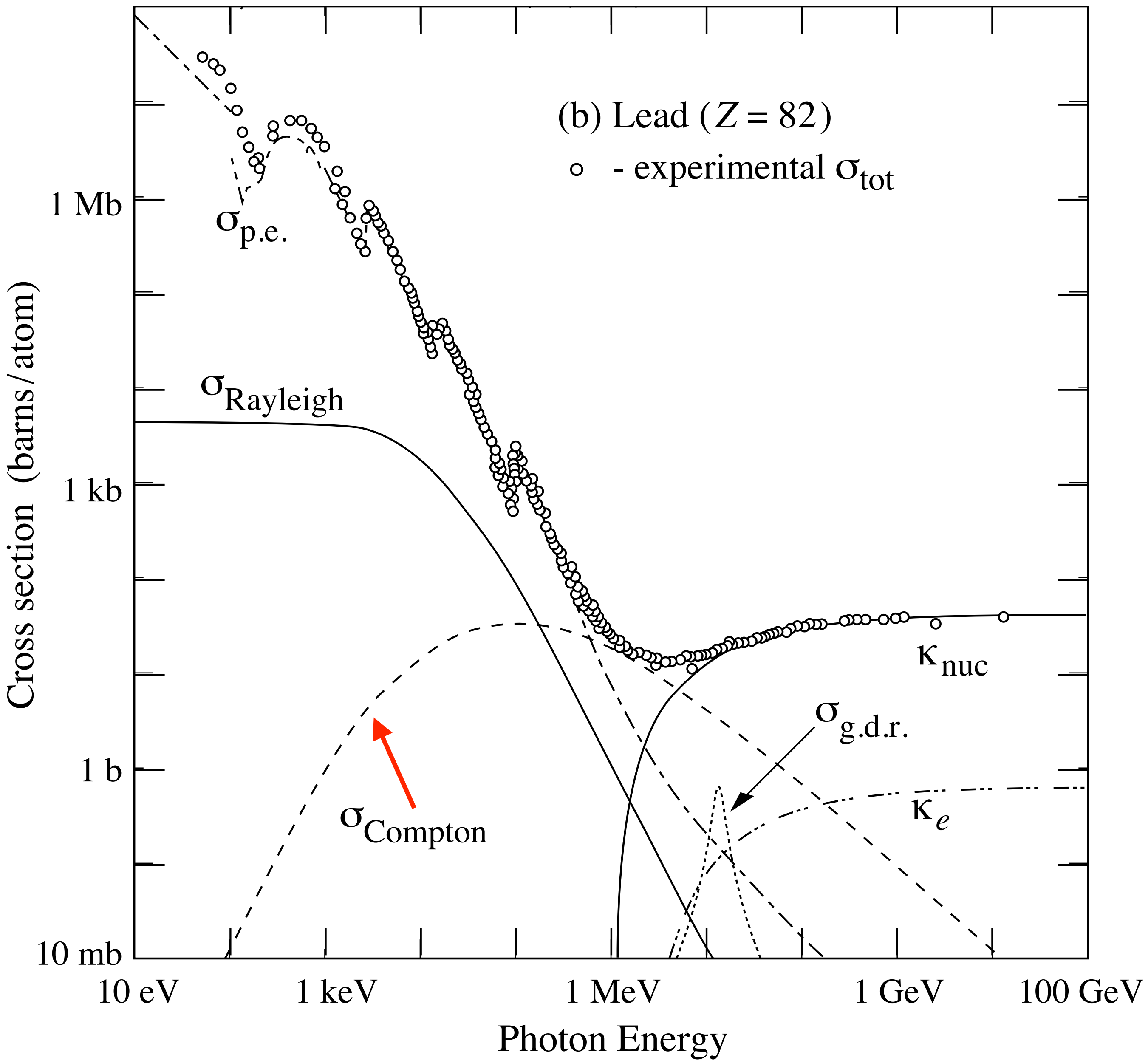
Photons & matter: Compton Scattering

Cross-section calculated by Klein & Nishina (1929):

$$\frac{d\sigma_{KN}(h\nu_0,\theta)}{d\Omega}=\frac{r_e^2}{2}\left(\frac{1+\cos^2\theta}{(1+\alpha(1-\cos\theta))^2}+\frac{\alpha^2(1-\cos\theta)^2}{(1+\alpha(1-\cos\theta))^3}\right)$$

where r_e is the classical electron radius.
(Formula assumes initial electron is free; corrections required if incoming photon energy is low or Z is high.)

Compton effect is important from (10-100 keV) up through (10-100 MeV), depending on the material.

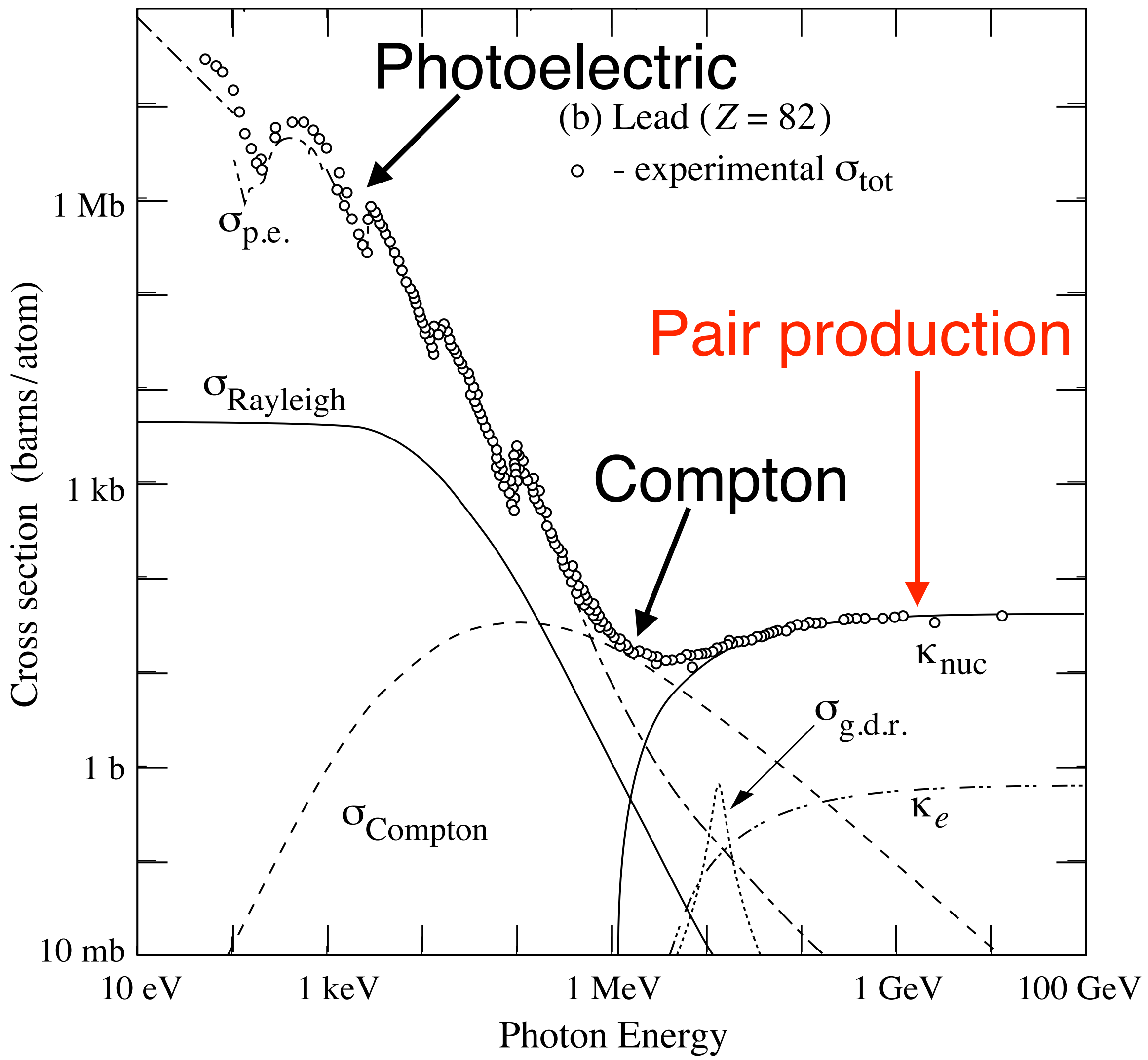


$$r_e = e^2/4\pi\varepsilon_0 m_e c^2 \approx 2.82\,\text{fm}$$

Photons & matter: Pair production

The dominant interaction is one of these three for photon energies above 10 eV.

- Possible interactions:
  - Photoelectric effect (γA → $A^+ e^-$; A = atom)
  - Compton scattering (γe → γe ; inelastic)
  - Pair production (γN → $e^+ e^-$ N ; N = nucleus)
  - Rayleigh Scattering (γA → γA; coherent)
  - Thomson Scattering (γe → γe ; elastic)
  - Photo Nuclear Absorption (γN → pN' or nN')
  - Nuclear Resonance Scattering (γA → A* → γA)
  - Hadron/Lepton Pair production (γN → $h^+ h^-$ N)
  - Delbruck Scattering (γN → γN ; coherent scattering due to the vacuum polarization in a Coulomb field of a nucleus)
  - ...

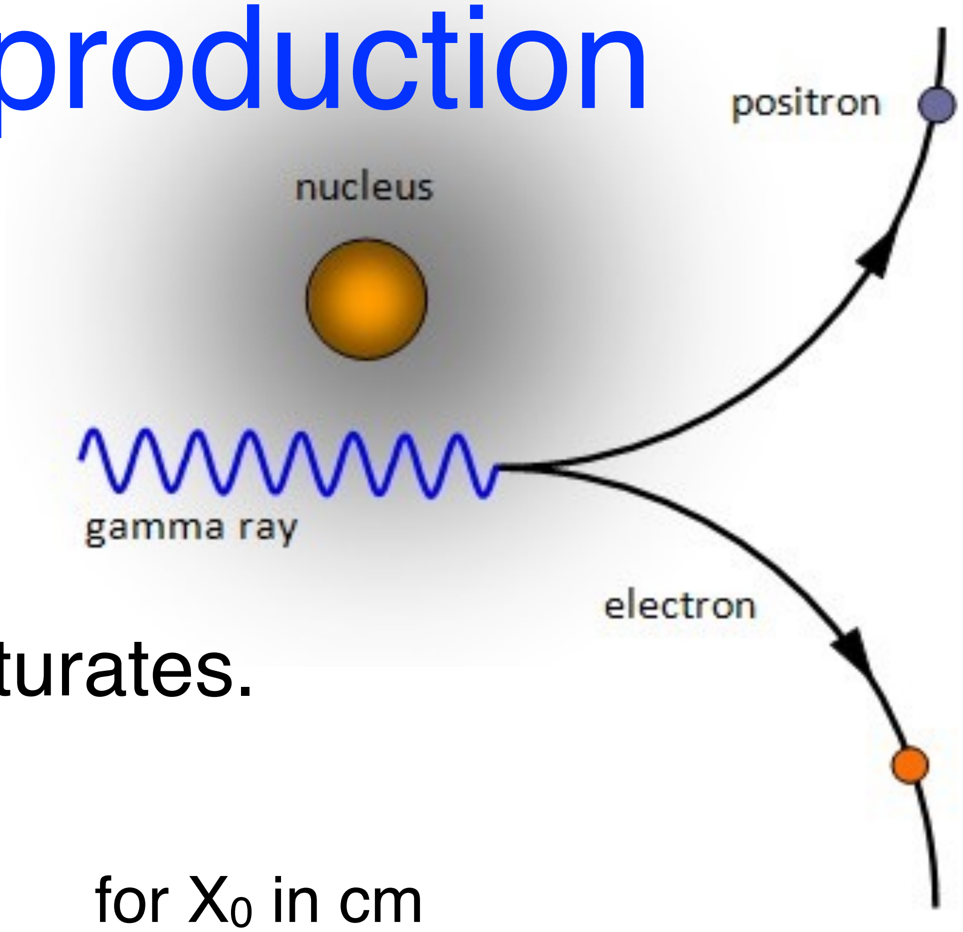


$\sigma_{\text{p.e.}}$ = Atomic photoelectric effect (electron ejection, photon absorption)
σ_{Rayleigh} = Rayleigh (coherent) scattering–atom neither ionized nor excited
σ_{Compton} = Incoherent scattering (Compton scattering off an electron)
κ_{nuc} = Pair production, nuclear field
κ_e = Pair production, electron field
$\sigma_{\text{g.d.r.}}$ = Photonuclear interactions, most notably the Giant Dipole Resonance [52]. In these interactions, the target nucleus is broken up.

Original figures through the courtesy of John H. Hubbell (NIST).

Figure from PDG: K.A. Olive et al. (Particle Data Group), Chin. Phys. C, 38, 090001 (2014) and 2015 update

Photons & matter: Pair production



Energy threshold for pair production:

$$E_\gamma \geq 2m_e c^2 \left(1 + \frac{m_e}{m_N}\right)$$

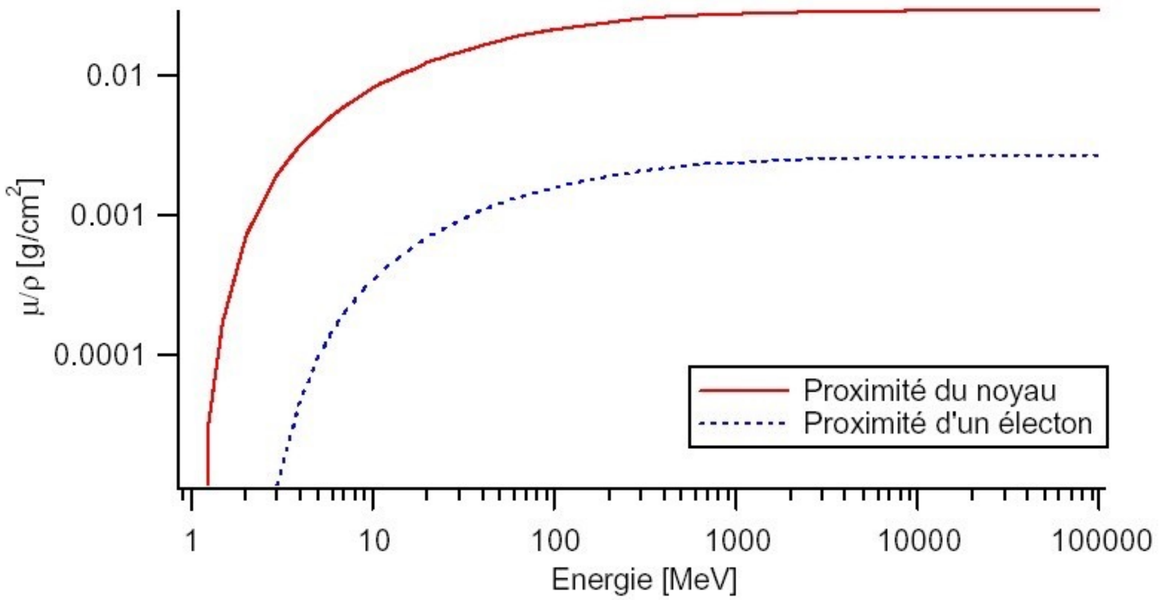
Cross-section ramps up from threshold, then saturates.
For $E_\gamma \geq 2m_e c^2$,

$$\sigma_{\text{pair}} = 4\alpha\, r_e^2 Z^2 \left(\frac{7}{9}\ln\frac{183}{Z^{1/3}} - \frac{1}{54}\right) \approx \frac{7}{9}\frac{A}{N_A}\frac{1}{\rho X_0}\ \text{cm}^2$$

for X_0 in cm
[caution!]

Recall: mean free path $\lambda = 1/\mu = 1/(n\sigma)$
and $n = \rho N_A/A$ for atoms/nuclei, thus

$$\lambda_{\text{pair}} = \frac{1}{n\sigma} = \frac{1}{\frac{\rho N_A}{A}\frac{7}{9}\frac{A}{N_A}\frac{1}{\rho X_0}} = \frac{9}{7}X_0$$



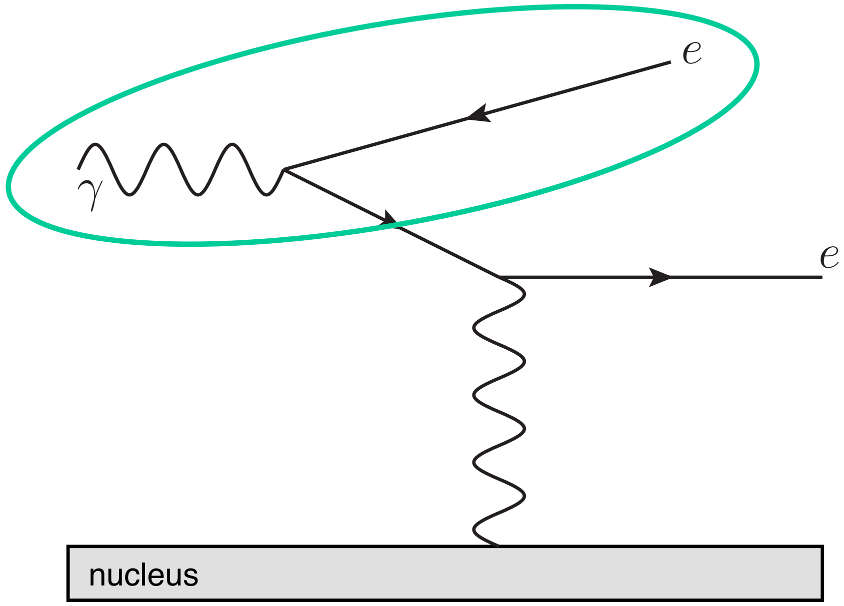
... so pair production mean free path ~ X_0
for $E_\gamma \geq 2m_e c^2$

Q: Why is the reaction $\gamma \rightarrow e^+ e^-$ impossible? What is the role of the nucleus in pair production?

Photons & matter: Pair production

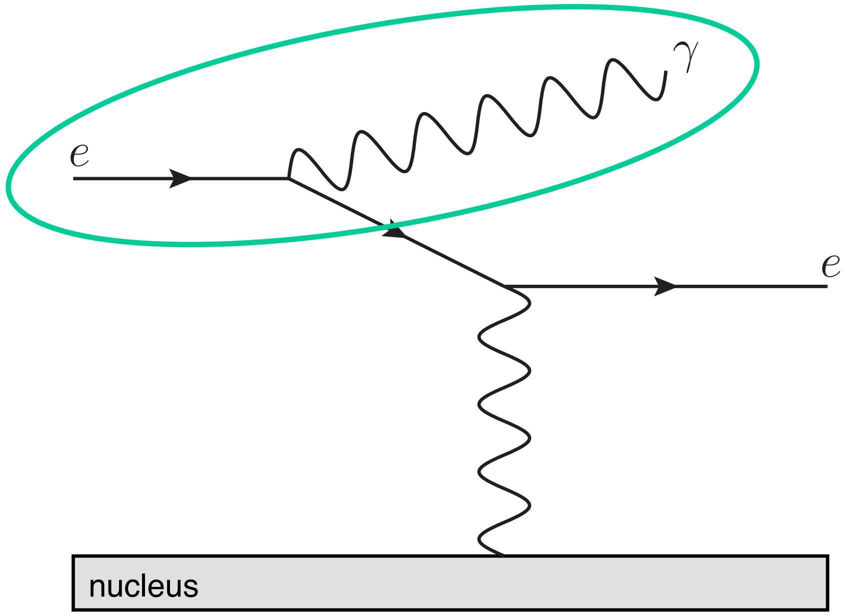
Remember that radiation length X_0 was defined as the distance over which the energy of an electron/positron is reduced by a factor of 1/e through **radiation** losses.

Fundamental connection between the two processes.



$$\lambda_{\text{pair}} = \frac{1}{n\sigma} = \frac{1}{\frac{\rho N_A}{A}\frac{7}{9}\frac{A}{N_A}\frac{1}{\rho X_0}} = \frac{9}{7}X_0$$

... so pair production mean free path ~ X_0 for $E_\gamma \geq 2m_ec^2$



Photons & matter: Pair production

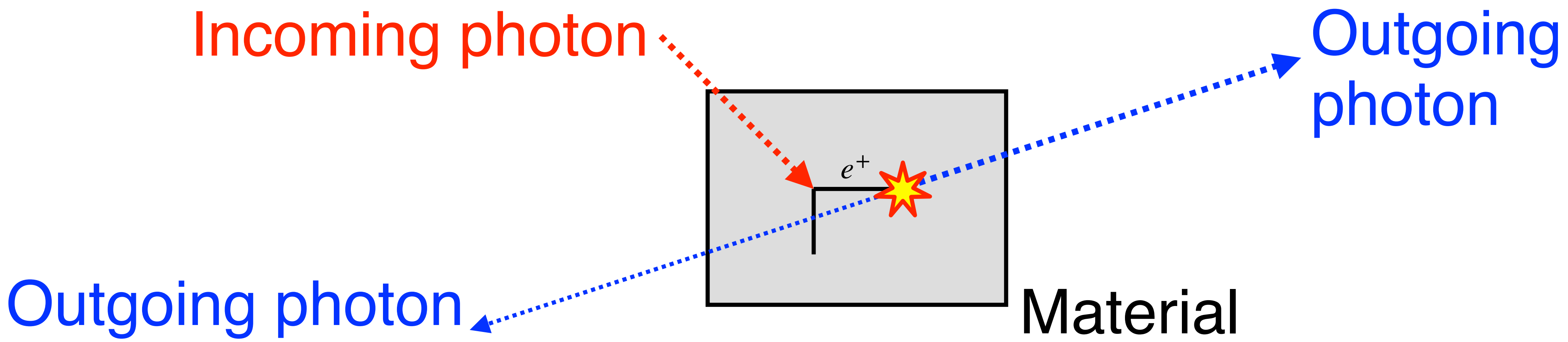
What happens to positrons emitted in pair production?

- They lose energy in matter (much like electrons)
- They annihilate with an electron
- Former is a stochastic process spread out over time; latter is all-or-nothing

In practice:

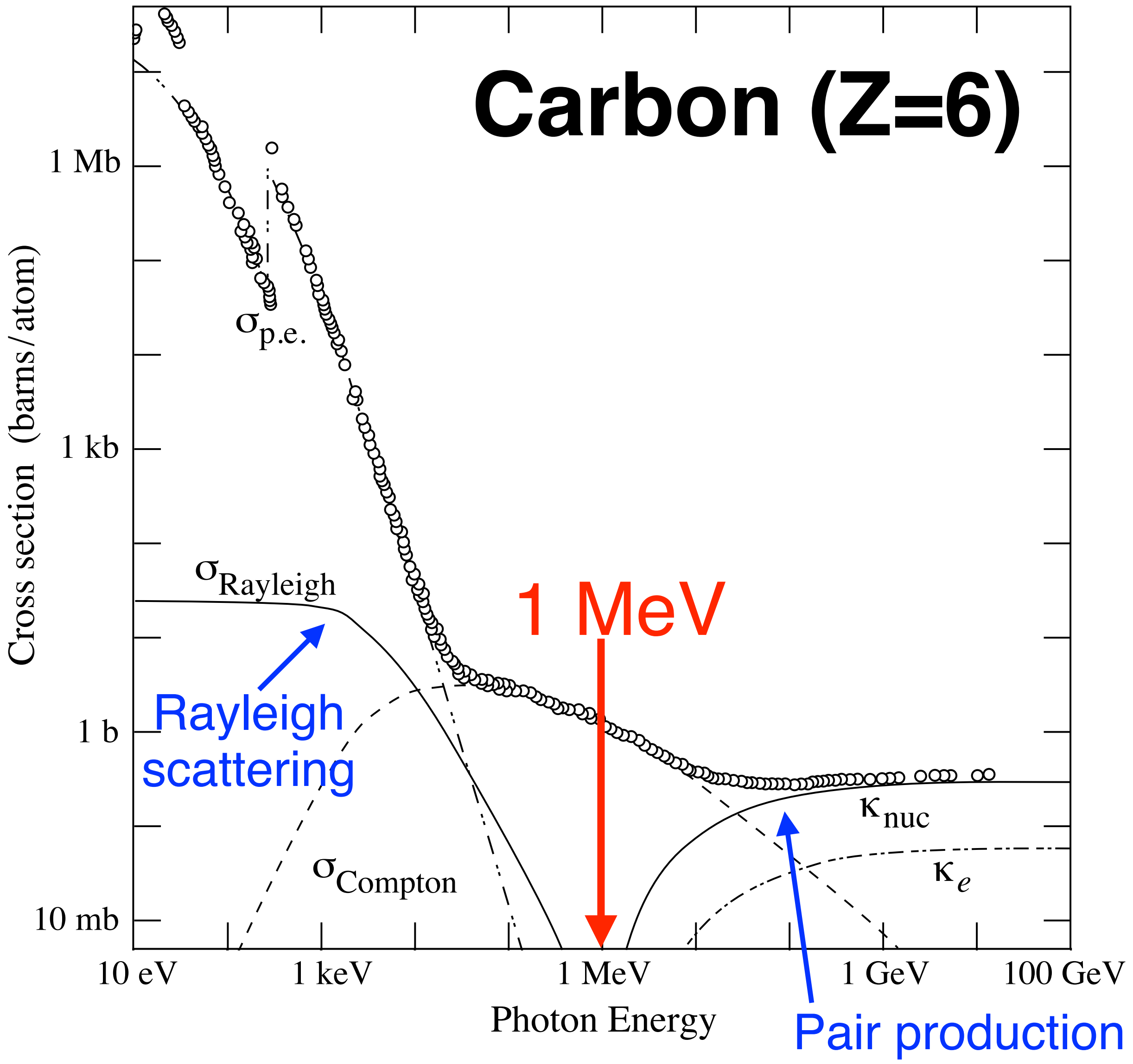
- The energy loss happens more quickly => positrons mostly stopped before annihilating with an electron
  - Stopping time ~ few ps in a solid state detector.
- Therefore, usually assume that the positrons annihilate **at rest** with a free electron and emit two photons (or more rarely 3+, but never only 1).
- Positron can also form bound a state of e^+e^- (positronium).

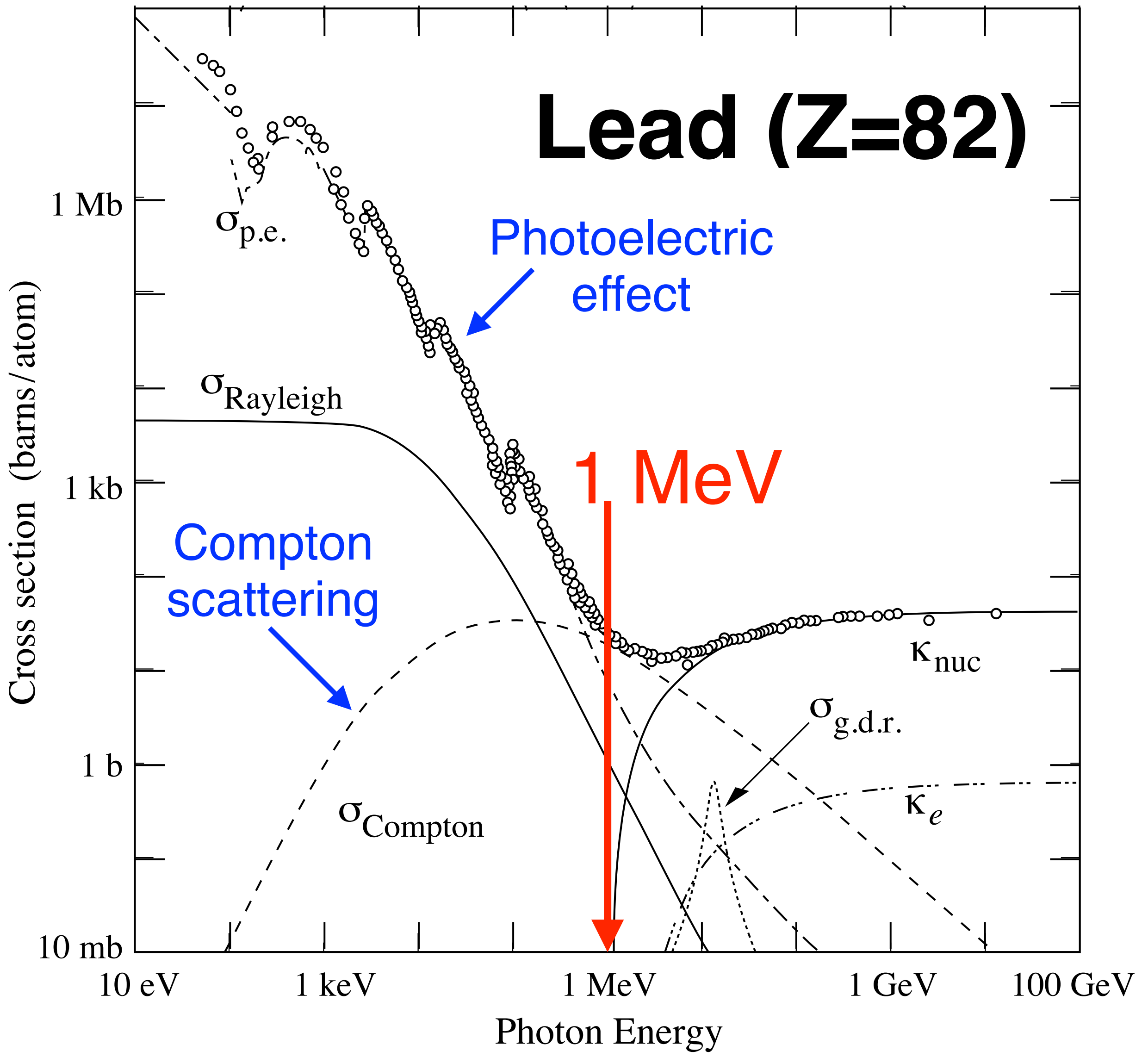
As the e^+ and free electron are at rest*, or the positronium is at rest, the two photons are emitted back-to-back*.

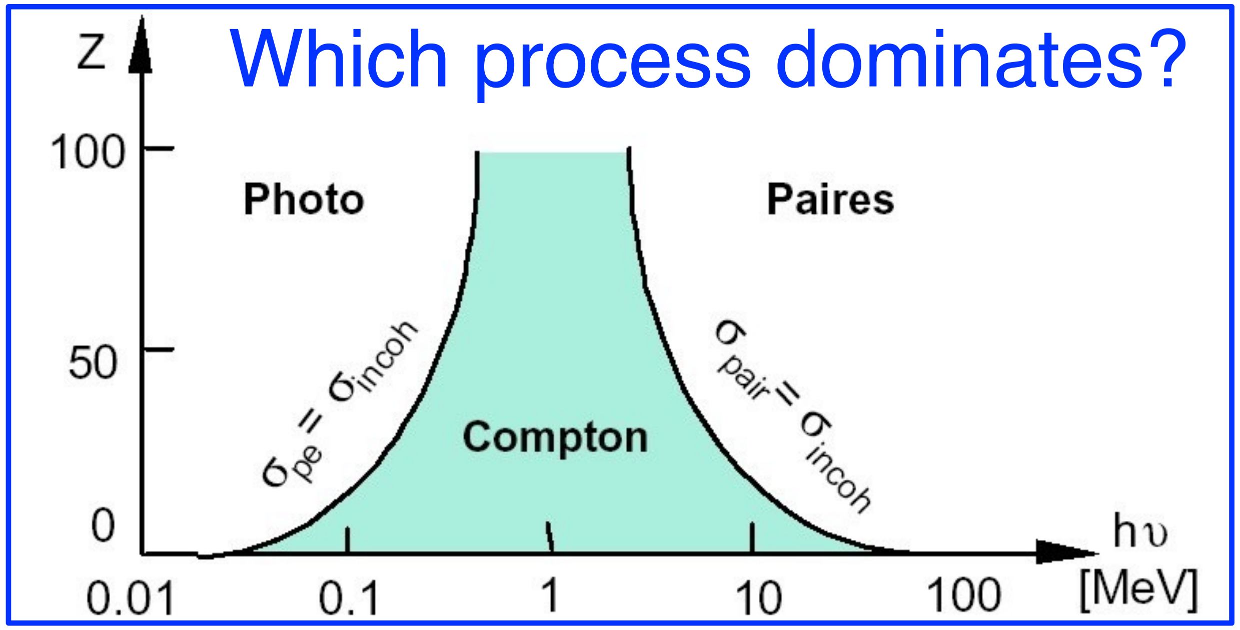


* almost

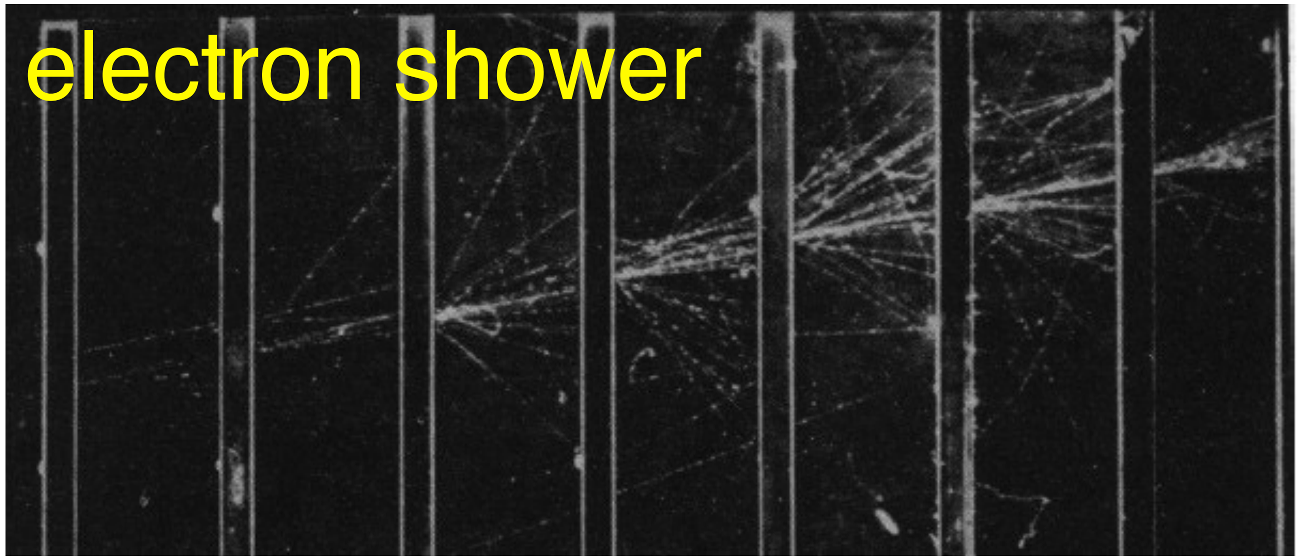
Photons & matter: Total photon x-sec







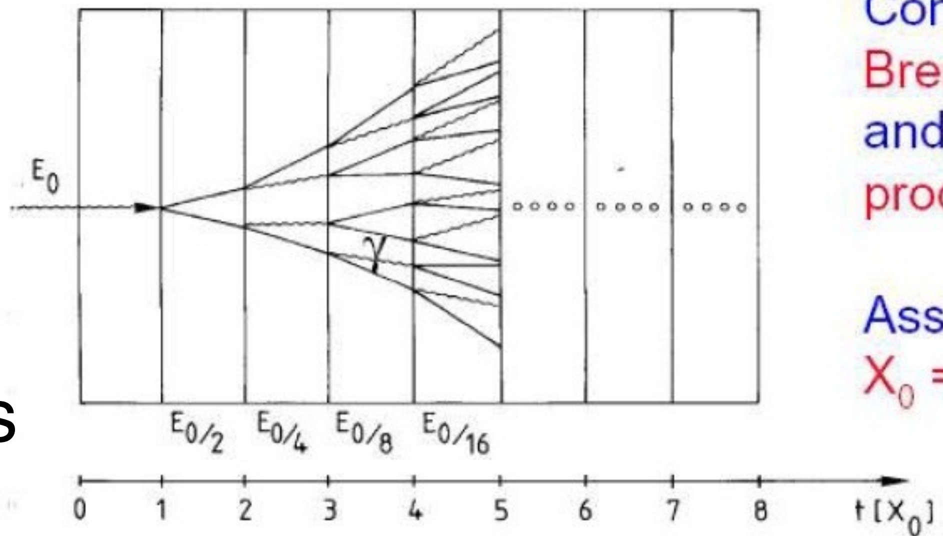
Electromagnetic showers



Electron shower in a cloud chamber with lead absorbers

For high energy γ and e± ($E \gg m_e c^2$), showers look very similar:

- An interaction happens (on average) once per radiation length, predominantly:
  - Bremsstrahlung ($e^\pm \rightarrow e^\pm \gamma$) or pair production ($\gamma \rightarrow e^+ e^-$) [quasi-spectator nucleon omitted]
- Both reactions are 1→2 for the EM shower particles ($\gamma/e^+/e^-$)
- So after t radiation lengths, $N(t) \sim 2^t$ particles, each of avg energy $E(t) \sim E_0/2^t$
- Shower stops at $t=t_{max}$, when E(t) falls below critical energy E_c needed to sustain it
  - $E(t_{max}) = E_0 / 2^{t_{max}} = E_c$
    $\Rightarrow \; t_{max} = \ln(E_0/E_c) / \ln(2) \propto \ln(E_0)$
  - $N(t_{max}) = 2^{t_{max}} = E_0/E_c \propto E_0$ -- and will be an ~ equal mix of e^+, e^-, γ => $^1/_3$ photons

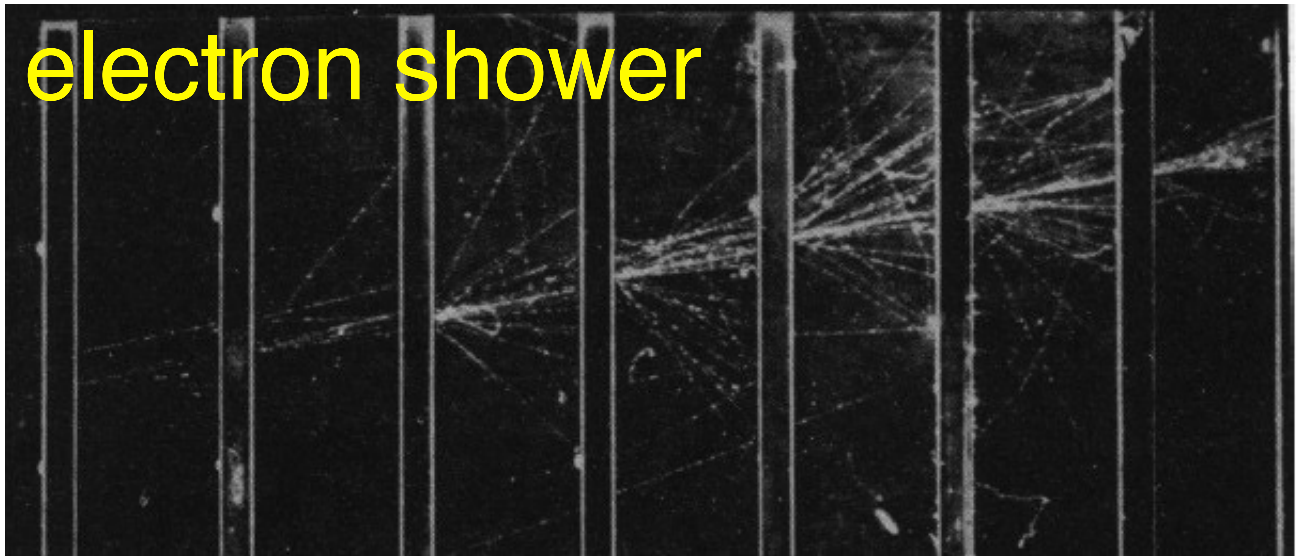


Consider only Bremsstrahlung and pair production.

Assume: $X_0 = \lambda_{pair}$

[$a\gamma + be^+ + be^- \rightarrow 2b\gamma + (b+a)e^+ + (b+a)e^-$ so equilibrium in ratio occurs when $a = b$.]

Electromagnetic showers

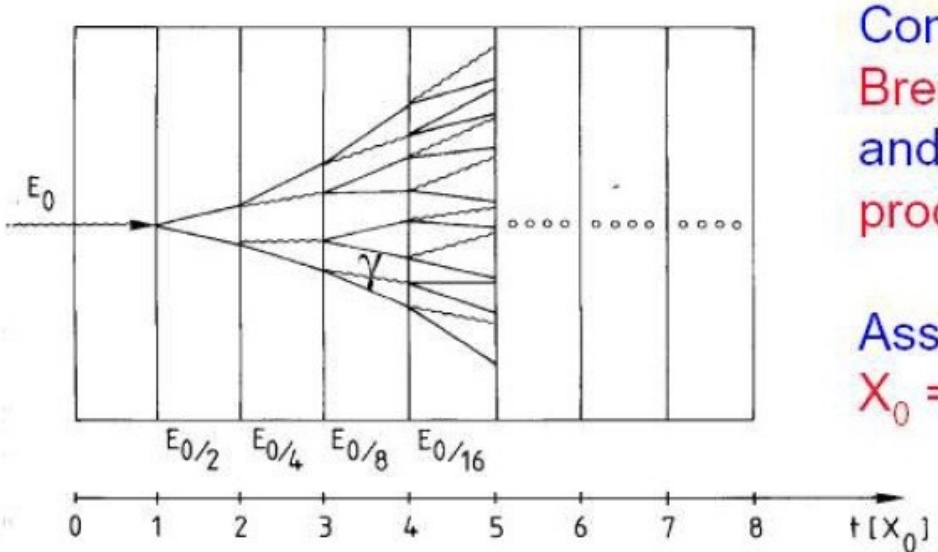


Electron shower in a cloud chamber with lead absorbers

For high energy γ and $e^{\pm}$ ($E \gg m_e c^2$), showers look very similar:

- Transverse development:
- 90% of particles stay within a cylinder of radius R_M (Molière radius) around shower axis.
- $R_M = X_0 \, E_s / E_c$ with E_s = 21 MeV

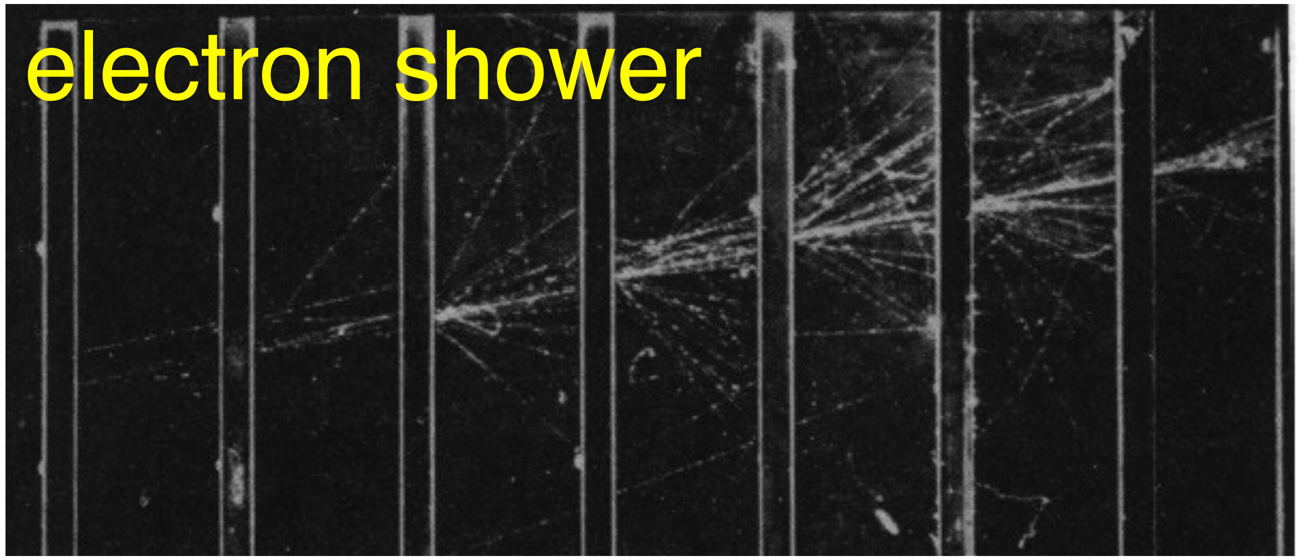
To distinguish photons from electrons/positrons, use a tracker or a thin preshower detector (thickness $\ll X_0$)



Consider only Bremsstrahlung and pair production.

Assume:
$X_0 = \lambda_{pair}$

Electromagnetic showers



Electron shower in a cloud chamber with lead absorbers

We said:

- Shower stops at $t=t_{max}$, when $E(t)$ falls below critical energy E_c needed to sustain it

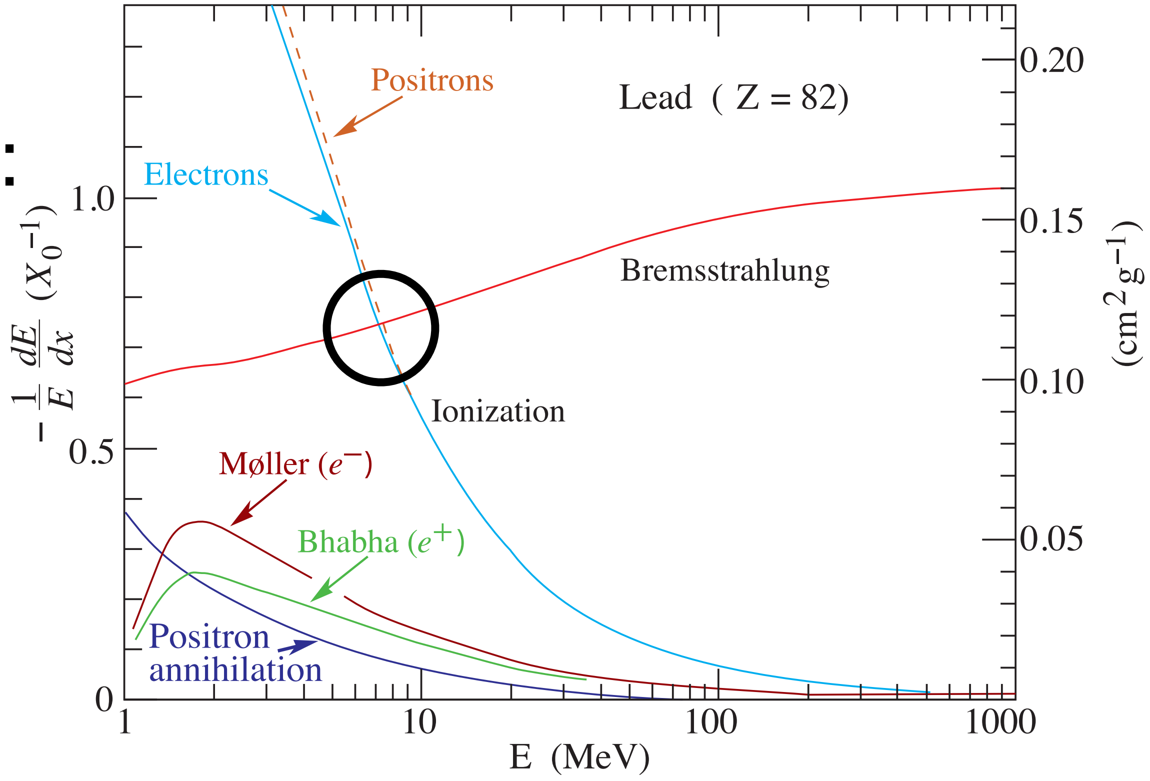
What is the critical energy?

Previous lecture: cross-over of energy loss:

- Below E_c, dominated by collision/ionisation
- Above E_c, dominated by bremsstrahlung

Typical value: $\sim 10^1 \text{ to } 10^2 \text{ MeV}$.

(For photons: changeover from Compton scattering to pair production occurs around few MeV too.)



Particle showers

High-energy hadrons (and...) can also shower.

Will hear more about particle showers in the calorimetry lectures.

Key difference is that the shower contains charged hadrons which have much bigger masses, and thus:

(1) dE/dx is typically smaller for the hadrons compared to $e^{\pm}$ (and they don't emit much brem), thus they can travel further.

(2) The number of particles inside the shower is smaller, so fluctuations are proportionately more important.

(Some of the hadrons are π^0 that decay to photons => local EM shower inside... but the *fraction* of π^0 fluctuates between hadronic showers.)

Net result: hadronic showers are broader, more "lumpy" (not uniform like EM), and vary a lot from one shower to another.

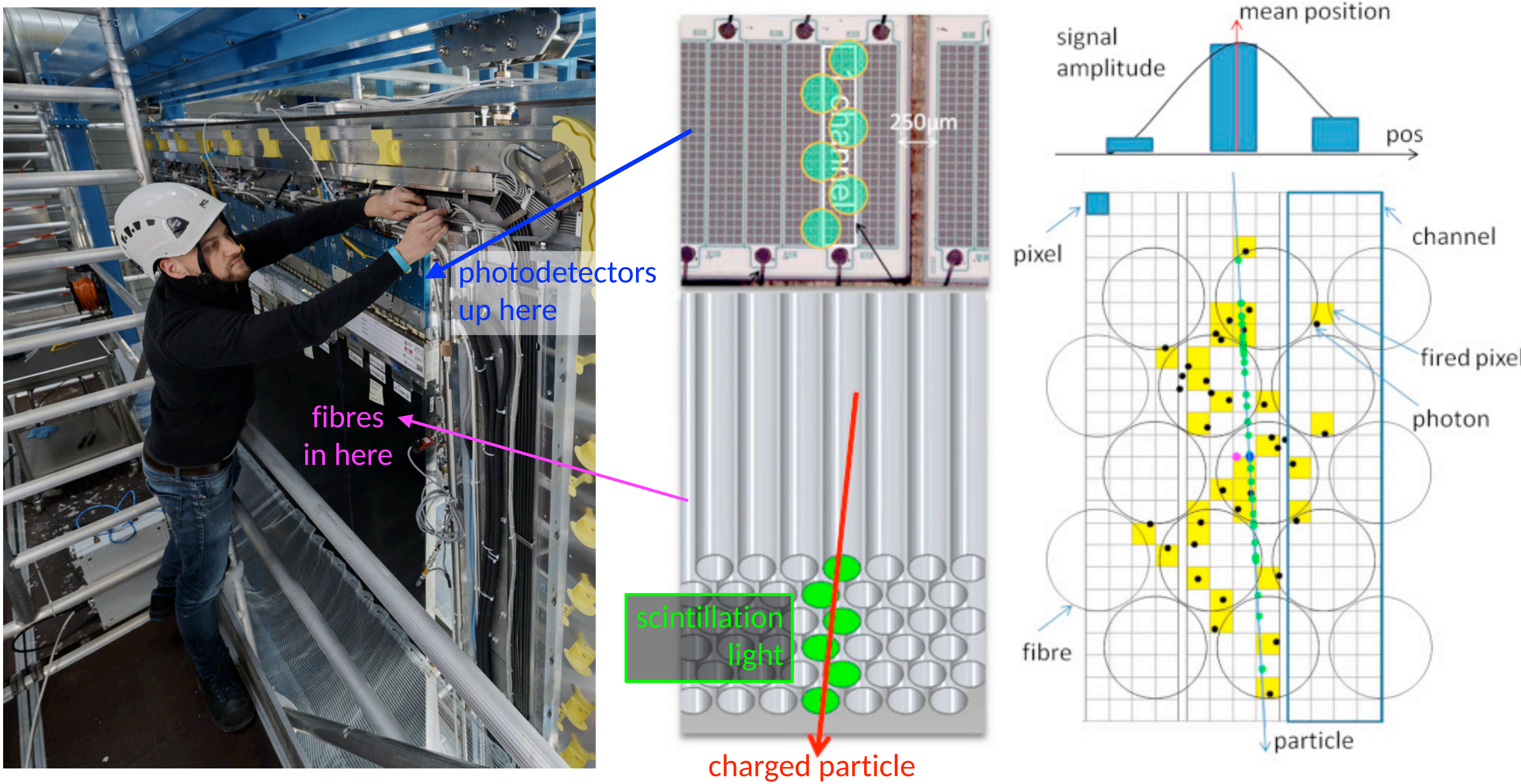
Scintillators

What are scintillators used for?

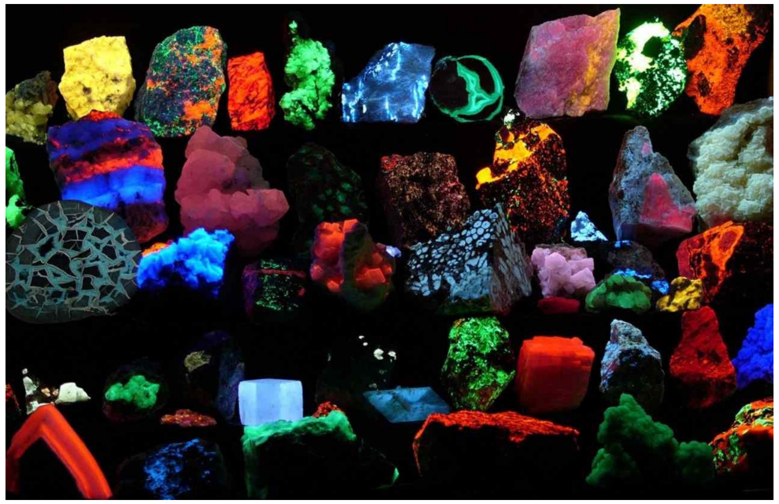
- We can detect and measure the energy of photons
  - ... though for low/medium energies, e.g. X-ray and gamma emission spectra, there are other options with better resolution -- see semiconductors lecture.
- We can use them in calorimeters, to detect and measure showers from high-energy particles
  - More in the calorimeter lectures, but this is a big application. Scintillators need to be rad-hard scintillator for most colliders. There are other options (e.g. gaseous, silicon) depending on the detector design.
- We can use them to tag or veto the passage of a charged particle
  - Just need a plane of silicon, with a thickness of perhaps mm to cm; charged particle deposits ionisation energy as it passes through, which is seen as scintillation light. Very efficient detection.
- And more, for example...

What are scintillators used for?

- … e.g. LHCb has recently installed and is now commissioning a scintillating fibre (SciFi) tracker:



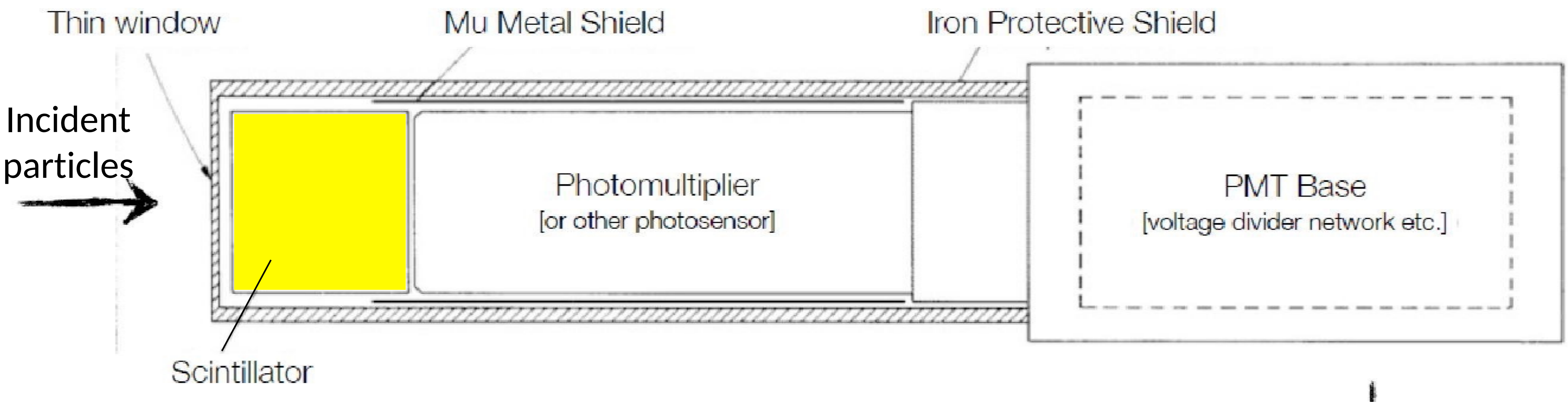
Scintillators



Minerals that emit visible light when exposed to ultraviolet light

- Basic principle:
  - A part of dE/dx is converted into visible light
  - Detected via a photosensor (eye, photomultiplier, ...)
- Properties we want in a scintillator:
  - **High efficiency** for conversion of excitation energy to prompt fluorescent radiation (vs delayed phosphorescent light)
    - Light yield (photons/MeV): Number of emitted photons per unit absorbed energy
    - Linearity between dE/dx and emitted light
  - **Transparency** to its fluorescent radiation, to allow transmission of light
  - **Frequency** of fluorescent light should be matched to photosensors
  - **Energy resolution** (in %) should be low, to measure photon energies
  - **Decay time** should be short, to avoid pile-up.
  - **Afterglow** (residual light output after the primary pulse) should be **small**
  - **Stopping power** (how much the incoming radiation is attenuated per unit thickness) should be high enough that we can capture photons with a reasonable crystal size.

Scintillators: Basic design

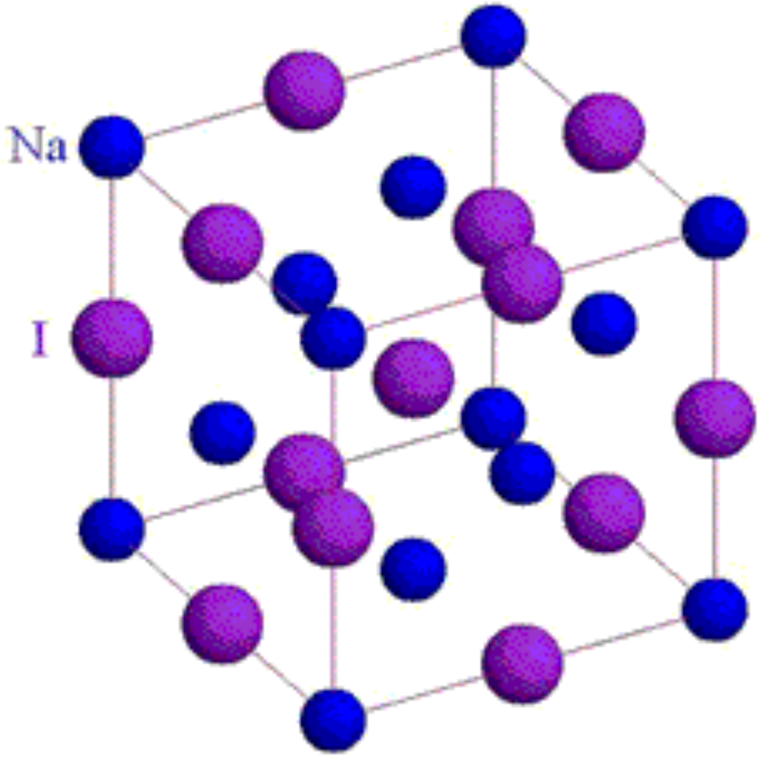


- Scintillator types:
  - Inorganic crystals
  - Organic scintillators
  - Gases
  - ... or even liquids (e.g. liquid Argon)
- Photodetectors:
  - Photomultipliers (PMTs)
  - Microchannel plates (MCPs)
  - Hybrid photodiodes (HPDs)
  - Silicon photomultipliers

Excitation/ionization → light → photo-sensor → electric signal

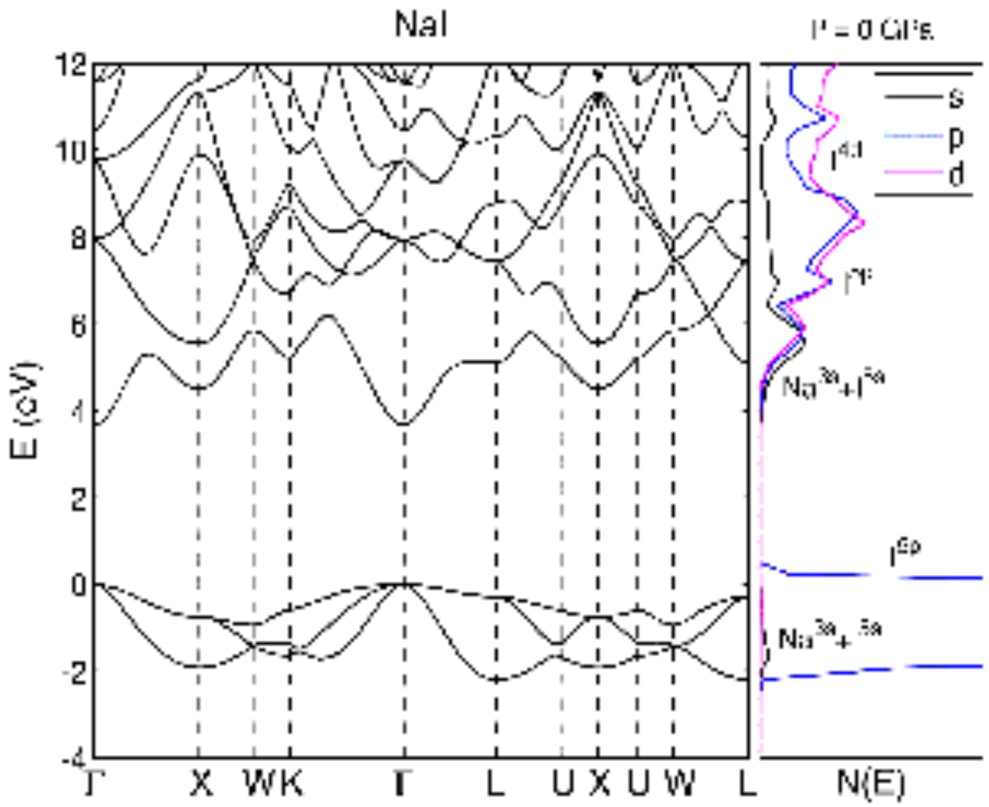
Scintillators: Inorganic crystals

- Different types*:
  - Alkali halide: NaI(Tl), CsI(Tl), CsI(Na), LiI(Ei)
  - Other slow inorganics: BGO, CdWO4, ZnS(Ag)
  - Cerium-activated fast inorganics: GSO, YAP, YAG, LSO, LuAP, LaBr3



- First, **excitation**:
  - Different bands
  - Energy deposition by ionization/excitation
  - Creation of electron-hole pairs
  - Thermalization: all theelectrons are at the bottom of the conduction band and the holes at the top of the valence band.

< 1ps



"BGO" = bismuth germanate, $Bi_4Ge_3O_{12}$

* You don't need to memorise all these! But you should know the key ones (mainly NaI(Tl)), and the common principles.

Scintillators: Inorganic crystals

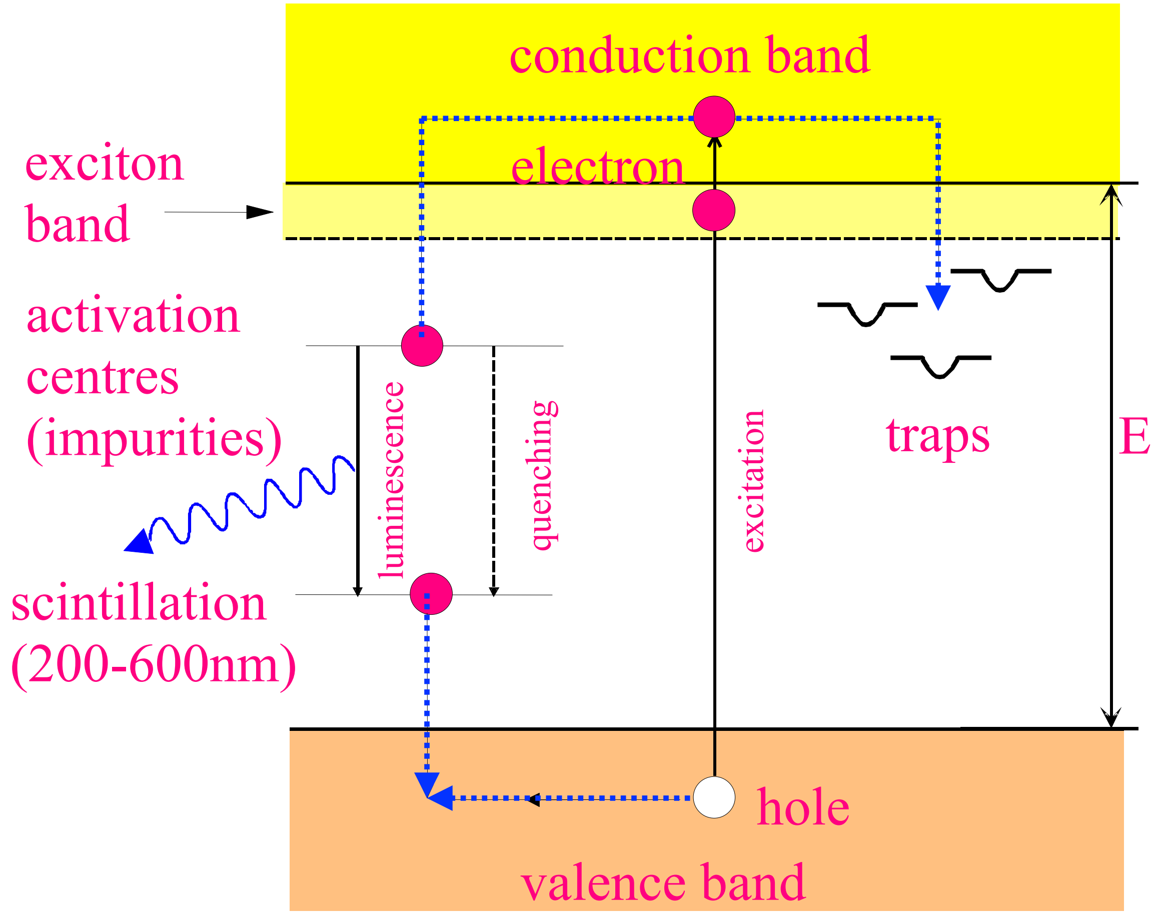
... then **de-excitation**:

- Pure crystals:
  - Emission of radiation not efficient, transparency problem
- Crystals with impurities:
  - Impurities => activation centres within the forbidden energy gap

10^{-12} to 10^{-8} s

  - After ionisation, the free electrons/holes migrate through the material and transfer their energy to the centres
  - De-excitation by photon emission (scintillation/luminescence) or by quenching (non-radiative processes in a trap)

>10^{-10} s (depending on scintillator)

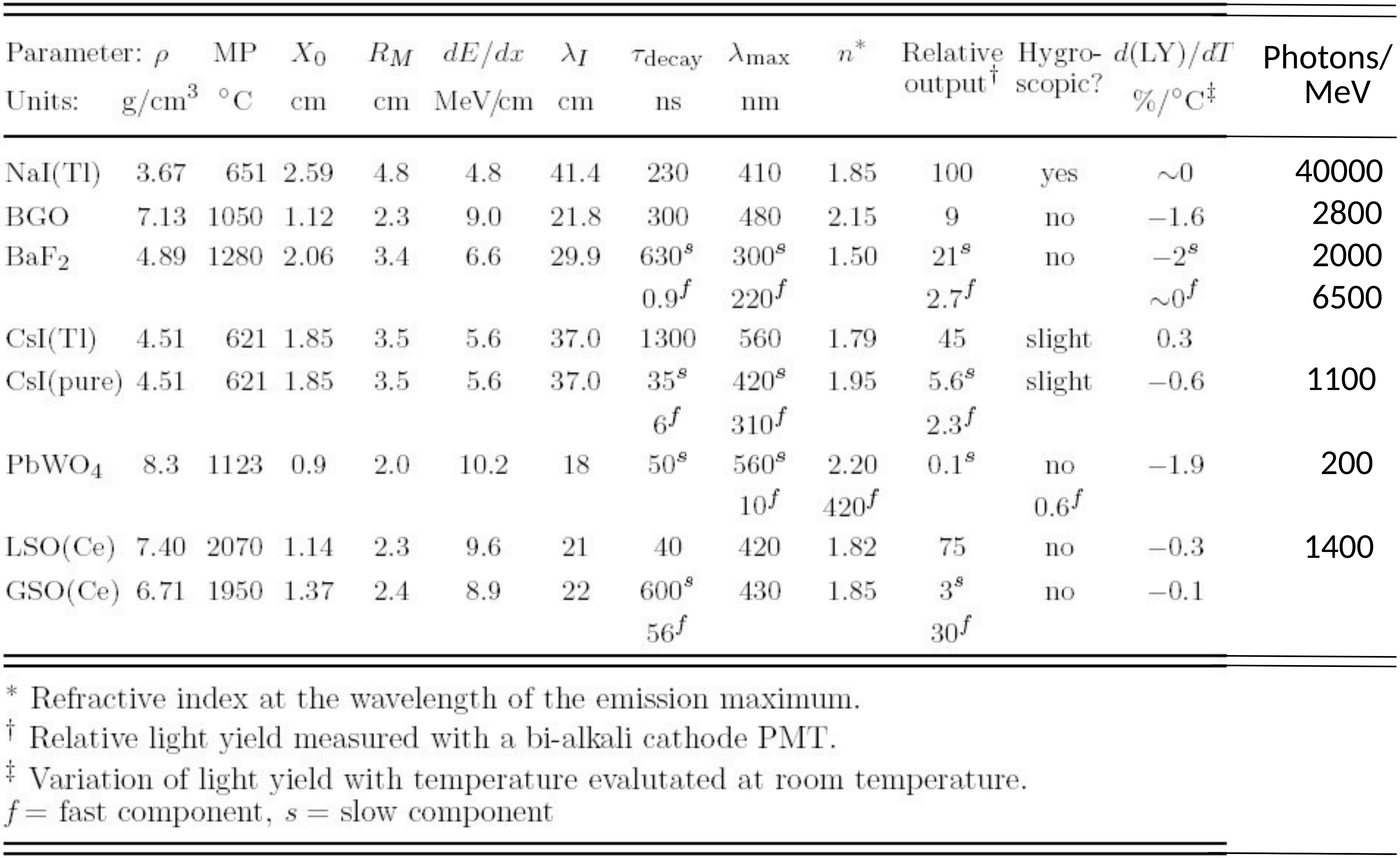


CERN Academic Training Program, C. D'Ambrosio

Example: NaI(Tl)

- Doped with Tl (Thallium), typical conc. 10^{-3}
- Gap 6 eV – photon 3 eV
- 13% of deposited energy converted to light (very high light yield!)

Inorganic crystals: Properties



Parameter:	ρ	MP	X_0	R_M	dE/dx	λ_I	$\tau_{\rm decay}$	$\lambda_{\rm max}$	n^*	Relative output†	Hygroscopic?	$d(LY)/dT$	Photons/ MeV
Units:	g/cm^3	°C	cm	cm	MeV/cm	cm	ns	nm				%/°C‡	
NaI(Tl)	3.67	651	2.59	4.8	4.8	41.4	230	410	1.85	100	yes	$\sim$0	40000
BGO	7.13	1050	1.12	2.3	9.0	21.8	300	480	2.15	9	no	-1.6	2800
BaF$_2$	4.89	1280	2.06	3.4	6.6	29.9	630^s 0.9^f	300^s 220^f	1.50	21^s 2.7^f	no	-2^s $\sim0^f$	2000 6500
CsI(Tl)	4.51	621	1.85	3.5	5.6	37.0	1300	560	1.79	45	slight	0.3	
CsI(pure)	4.51	621	1.85	3.5	5.6	37.0	35^s 6^f	420^s 310^f	1.95	5.6^s 2.3^f	slight	-0.6	1100
PbWO$_4$	8.3	1123	0.9	2.0	10.2	18	50^s 10^f	560^s 420^f	2.20	0.1^s 0.6^f	no	-1.9	200
LSO(Ce)	7.40	2070	1.14	2.3	9.6	21	40	420	1.82	75	no	-0.3	1400
GSO(Ce)	6.71	1950	1.37	2.4	8.9	22	600^s 56^f	430	1.85	3^s 30^f	no	-0.1	

[*] Refractive index at the wavelength of the emission maximum.

[†] Relative light yield measured with a bi-alkali cathode PMT.

[‡] Variation of light yield with temperature evalutated at room temperature.

f = fast component, s = slow component

Light yield (ε_{sc}): fraction of energy loss going into photons

Consider a 1 MeV particle that deposits all of its energy in the scintillator:

NaI(Tl):
$$\lambda_{\rm max} = 410\,{\rm nm} \Rightarrow 3\,{\rm eV}$$
$$\varepsilon_{\rm sc} = \frac{(40000 \times 3\,{\rm eV})}{1\,{\rm MeV}} = 12\%$$

PbWO4:
$$\lambda_{\rm max} = 560\,{\rm nm} \Rightarrow 2.2\,{\rm eV}$$
$$\varepsilon_{\rm sc} = \frac{(200 \times 2.2\,{\rm eV})}{1\,{\rm MeV}} = 0.044\%$$

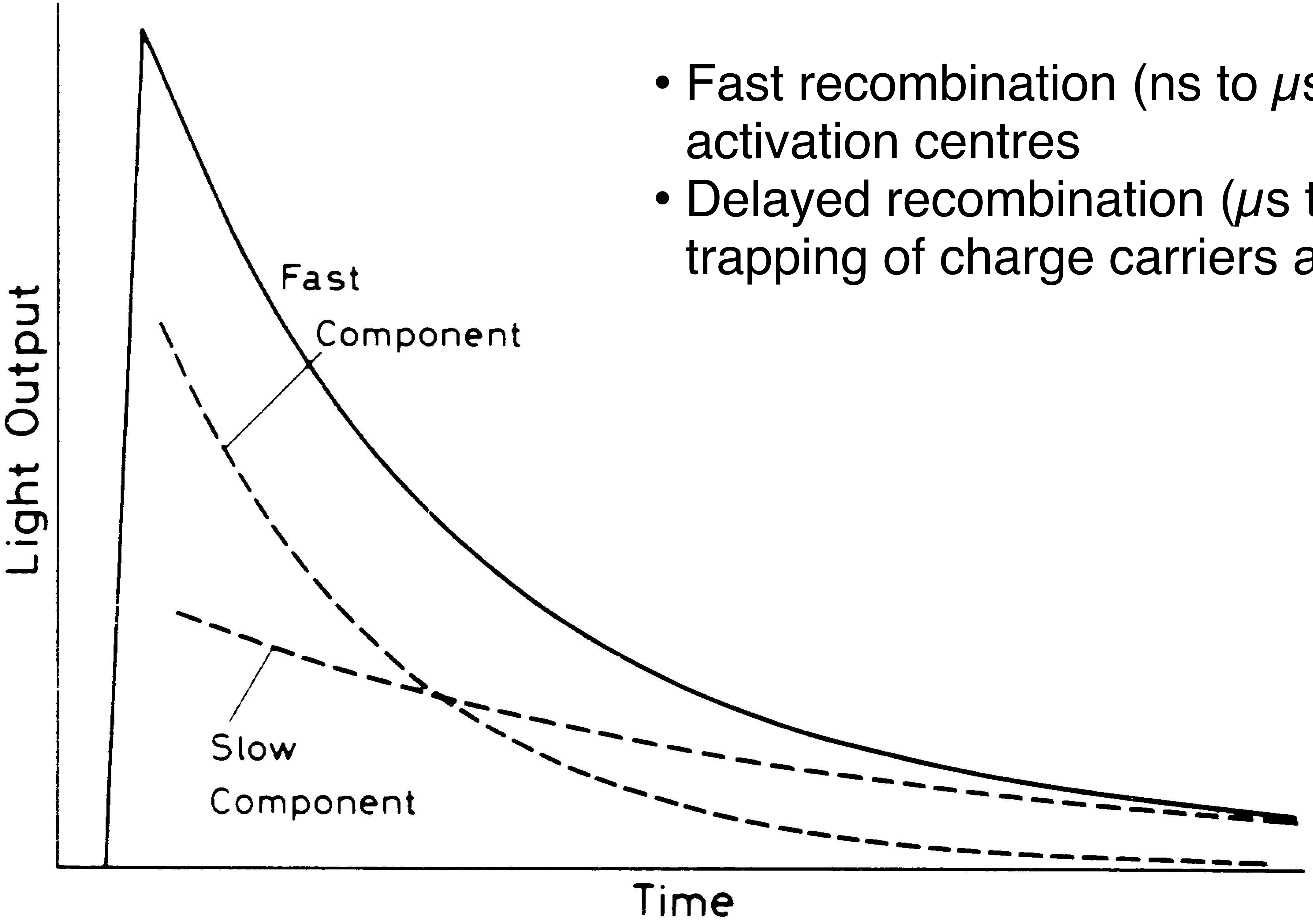
$$\hbar c \approx 197.3\,{\rm MeV\,fm}$$
$$E_\gamma = 2\pi\hbar c/\lambda$$

Inorganic crystals: Time response

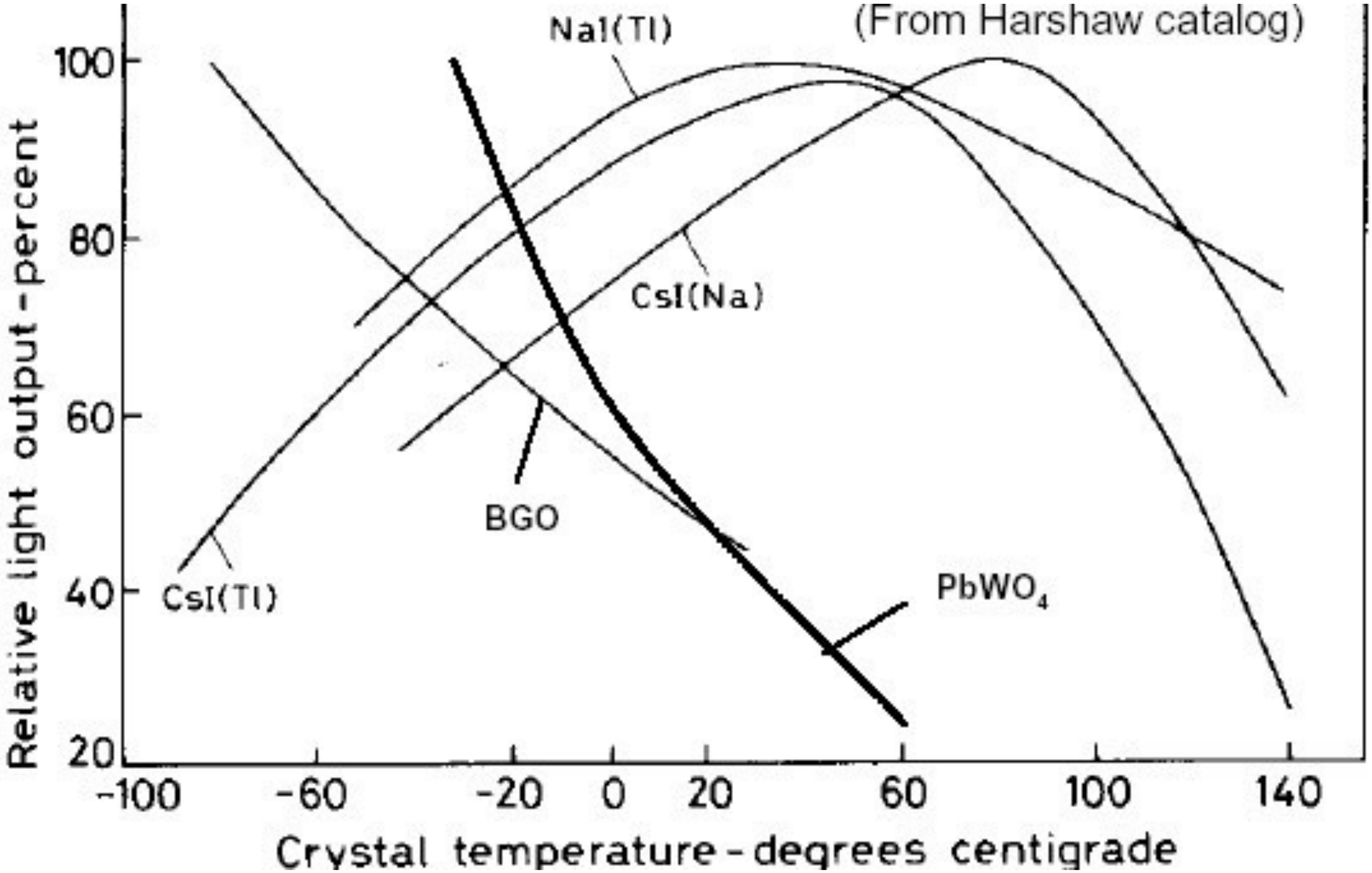
Time response usually has two components (fast & slow)

$$I(t) \propto A_\mathrm{f}\, e^{-t/\tau_\mathrm{f}} + A_\mathrm{s}\, e^{-t/\tau_\mathrm{s}}$$

- Fast recombination (ns to μs) from activation centres
- Delayed recombination (μs to ms) due to trapping of charge carriers at defects



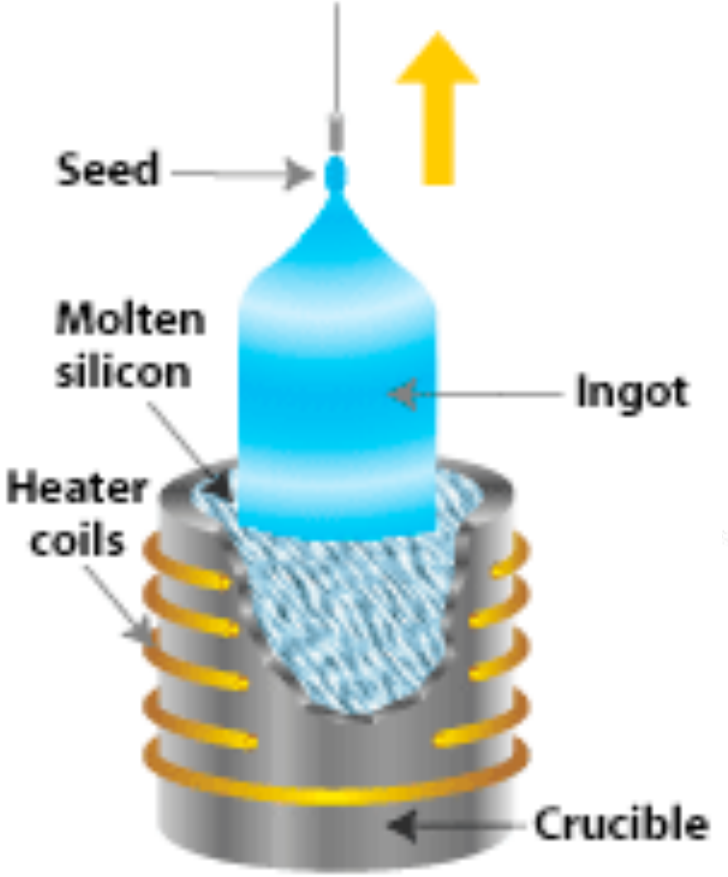
Inorganic crystals: Temperature

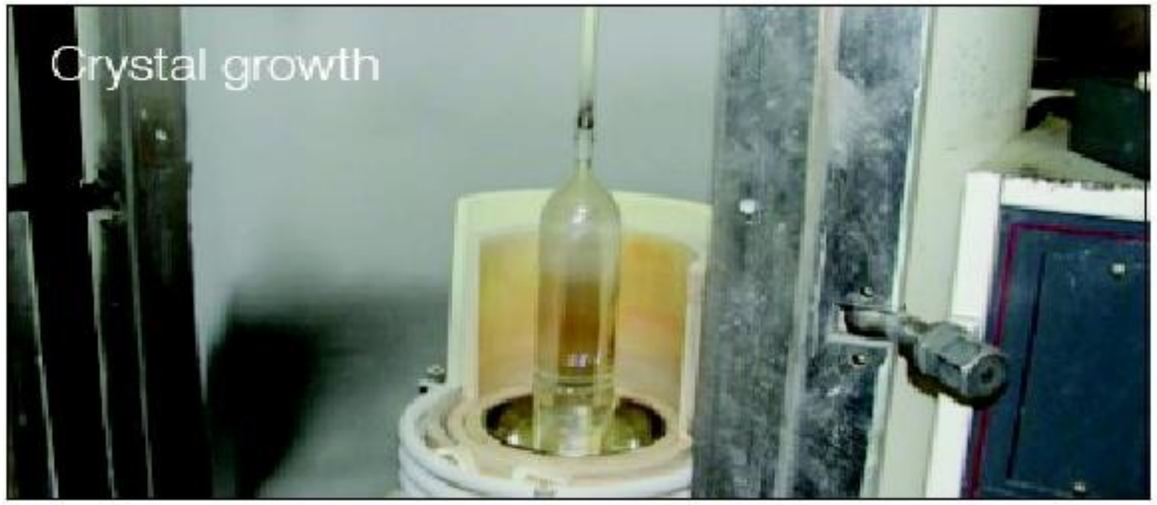


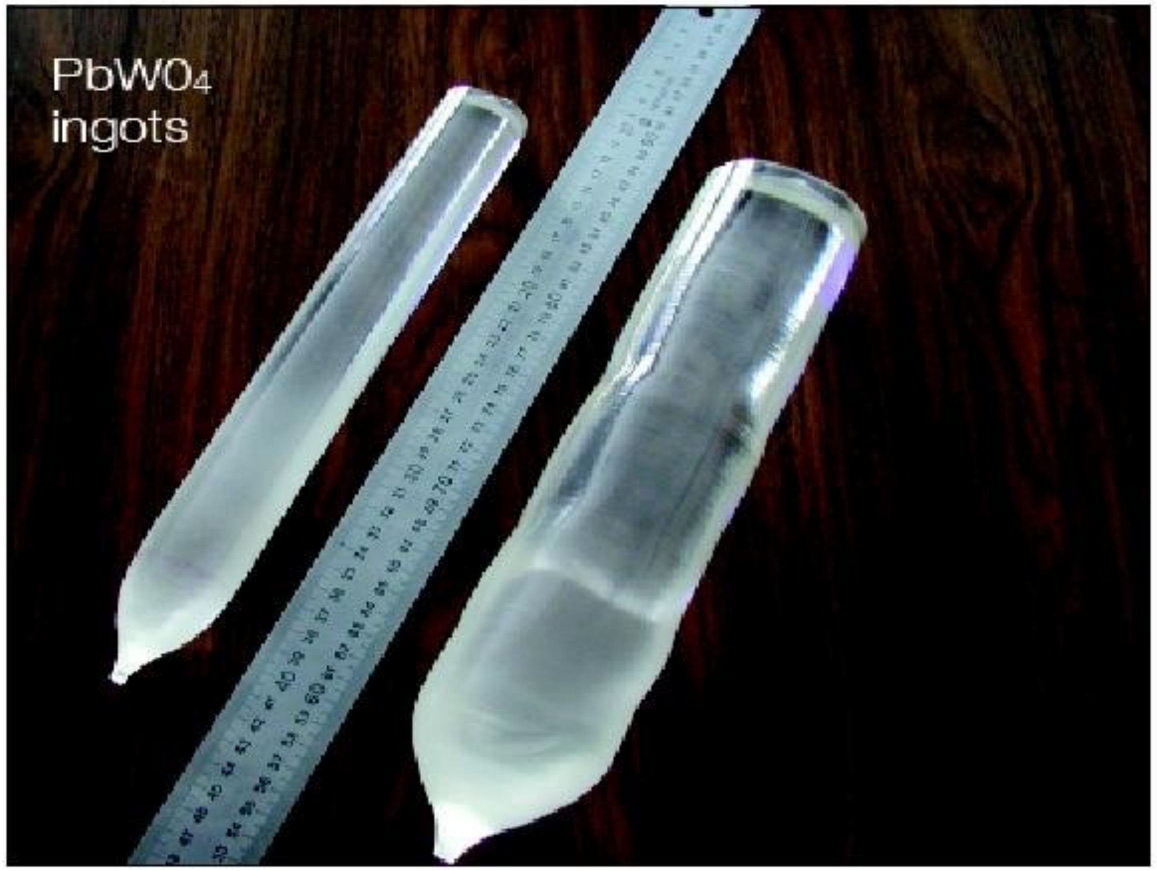
Strong (and material-dependent) temperature

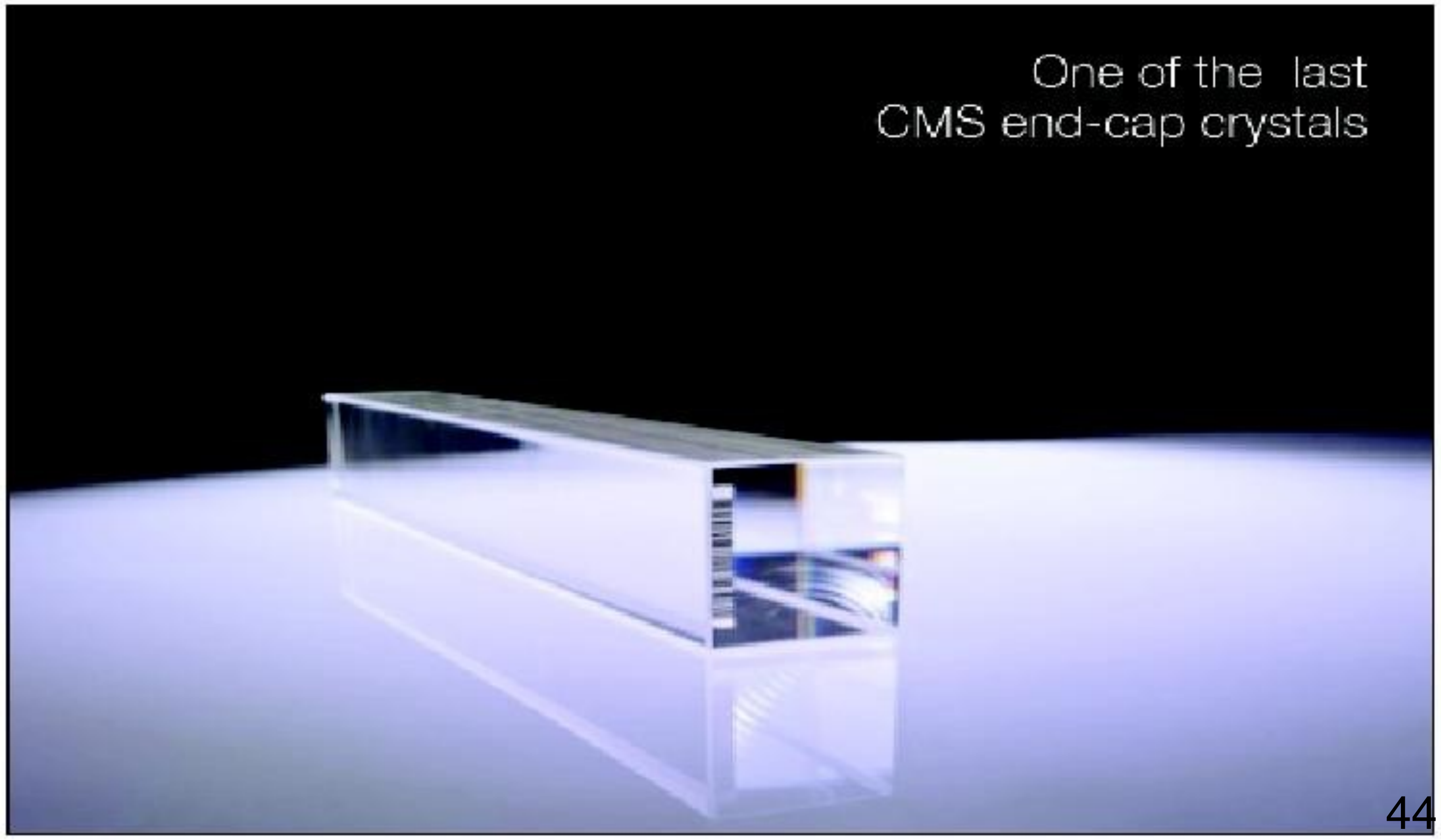
Inorganic crystals: CMS ECAL (example)

One attaches a seed crystal to the bottom of a vertical arm such that the seed is barely in contact with the material at the surface of the melt. The arm is raised slowly, and a crystal grows underneath at the interface between the crystal and the melt.





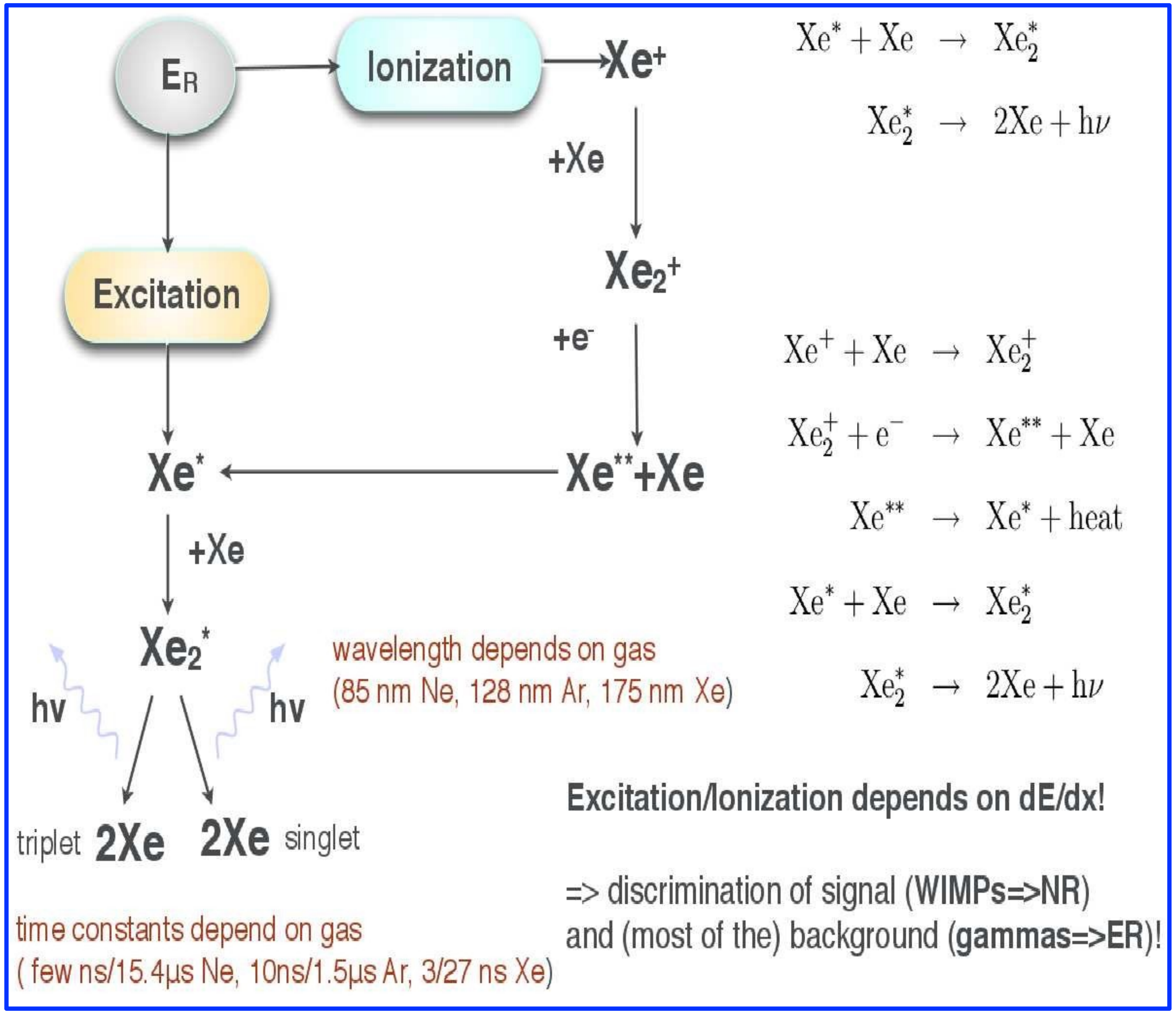




Scintillators: Liquid noble gases

- Several different types:
    - Helium (He)
    - Liquid Neon (LNe)
    - Liquid Argon (LAr)
    - Liquid Xenon (LXe)
    - ...
- Main features:
    - High scintillation light yields
    - Transparent to the scintillation light*
    - Large detector masses are feasible
    - Can be made very pure (important for eliminating radiological background in low-signal searches)

Example: use of LXe in WIMP searches



$$\mathrm{Xe}^* + \mathrm{Xe} \rightarrow \mathrm{Xe}_2^*$$
$$\mathrm{Xe}_2^* \rightarrow 2\mathrm{Xe} + h\nu$$

$$\mathrm{Xe}^+ + \mathrm{Xe} \rightarrow \mathrm{Xe}_2^+$$
$$\mathrm{Xe}_2^+ + e^- \rightarrow \mathrm{Xe}^{**} + \mathrm{Xe}$$
$$\mathrm{Xe}^{**} \rightarrow \mathrm{Xe}^* + \mathrm{heat}$$
$$\mathrm{Xe}^* + \mathrm{Xe} \rightarrow \mathrm{Xe}_2^*$$
$$\mathrm{Xe}_2^* \rightarrow 2\mathrm{Xe} + h\nu$$

wavelength depends on gas
(85 nm Ne, 128 nm Ar, 175 nm Xe)

time constants depend on gas
(few ns/15.4μs Ne, 10ns/1.5μs Ar, 3/27 ns Xe)

Excitation/Ionization depends on dE/dx!

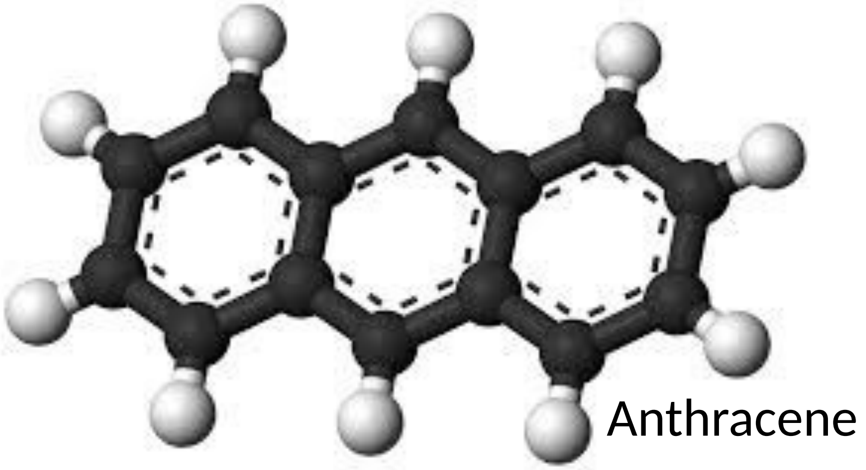
=> discrimination of signal (**WIMPs=>NR**)
and (most of the) background (**gammas=>ER**)!

NR = Nuclear recoil ; ER = Electronic recoil

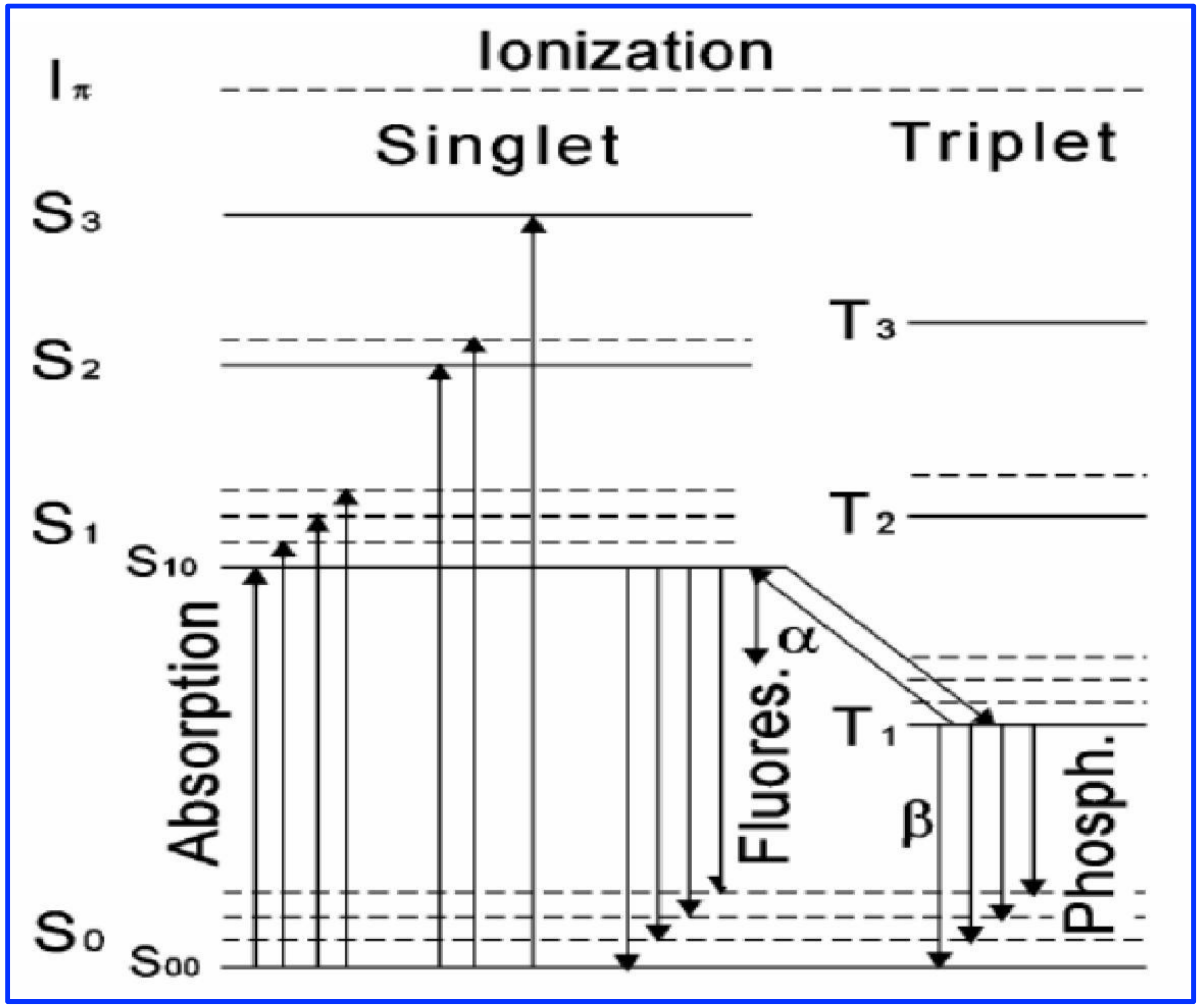
---

* The mechanism is a bit subtle, but this works when the emission step is not easily invertible. In the case shown, the excited state goes via a molecule of two Xe atoms that splits back apart, so to reabsorb the light you'd need two atoms in the right state and close together (and also in this case to collect TWO photons simultaneously to recombine them).

Scintillators: Organic



- Based on aromatic hydrocarbon compounds:
  - Organic -- composed of { C, H, O, N }
  - Examples: Anthracene [$C_{14}H_{10}$], Stilbene [$C_{14}H_{12}$], ...
  - Scintillation occurs at the level of a single molecule, so ~ independent of the physical state
- Mechanism
  - Delocalized electrons in π-orbitals
  - Light emitted in transitions between energy levels
  - S = singlet states (spin 0)
  - T = triplet states (spin 1)
  - Fine structure: each S/T state split into additional levels



Scintillators: Organic

1 Electrons excited to the upper levels

2 De-excite from higher state to S10 by radiationless transition (few ps)

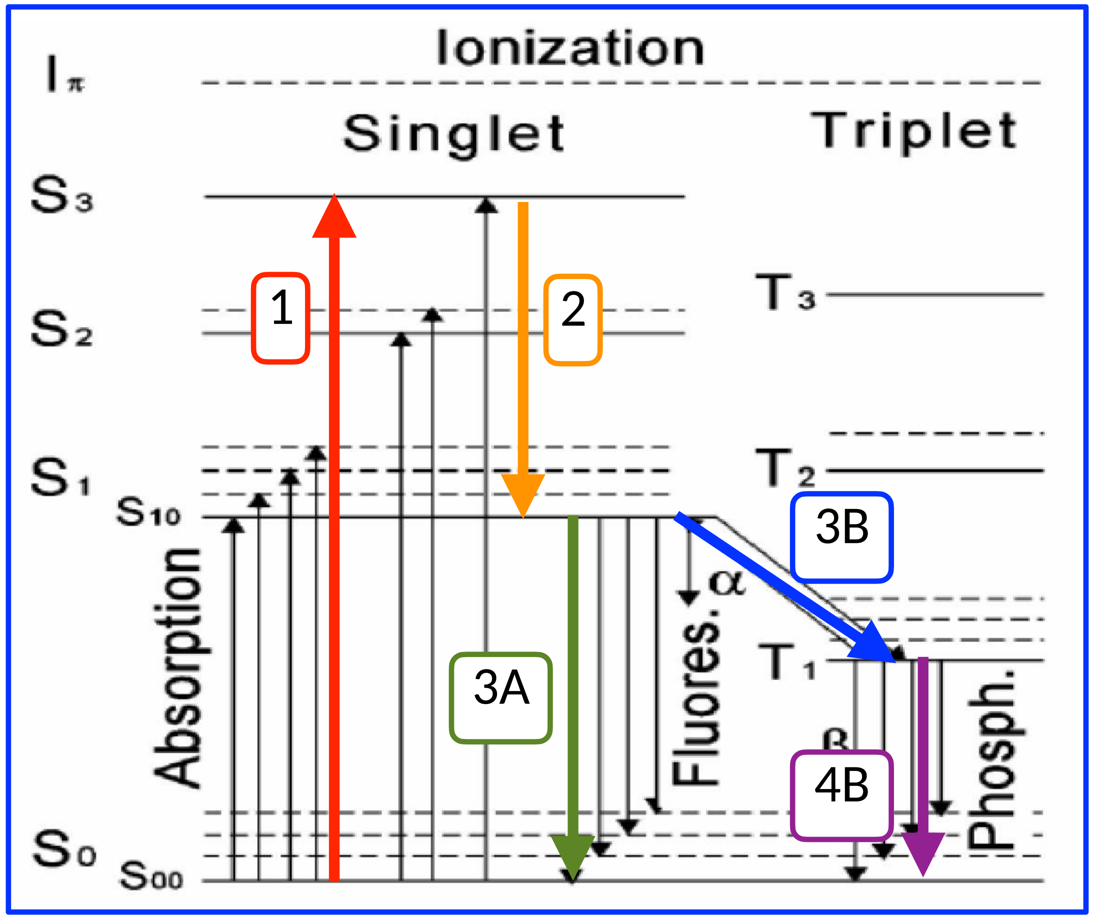
3A Prompt **fluorescence**: drop from S_{10} to ground level and emit photon

Time ~ few ns (fast!)
λ in UV range (~320 nm)

3B Intersystem crossing: drop from S10 to T1

4B **Phosphorescence**: drop from T1 to ground level and emit photon.

Time ~ few ms (slow)
λ longer than fluorescence



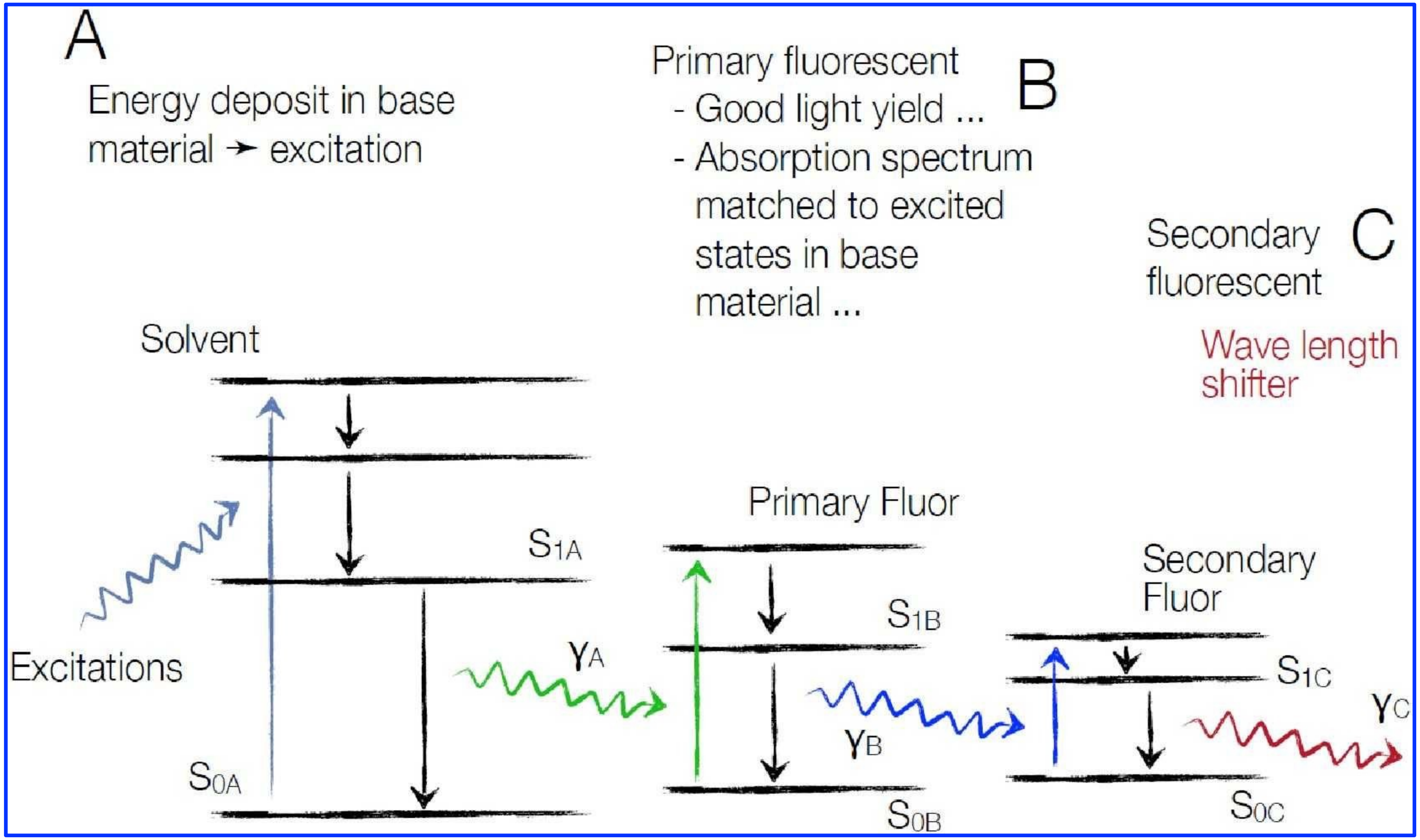
Problems:

- Light in UV range (harder to detect) => Use wavelength shifters (WLS)
- Prompt fluorescence yield low

Possible to distinguish fluorescence and phosphorescence based on timing, wavelength.

Scintillators: Organic: Wavelength shifting

From HansChristian SchultzCoulon
KirchhoffInstitut für Physik

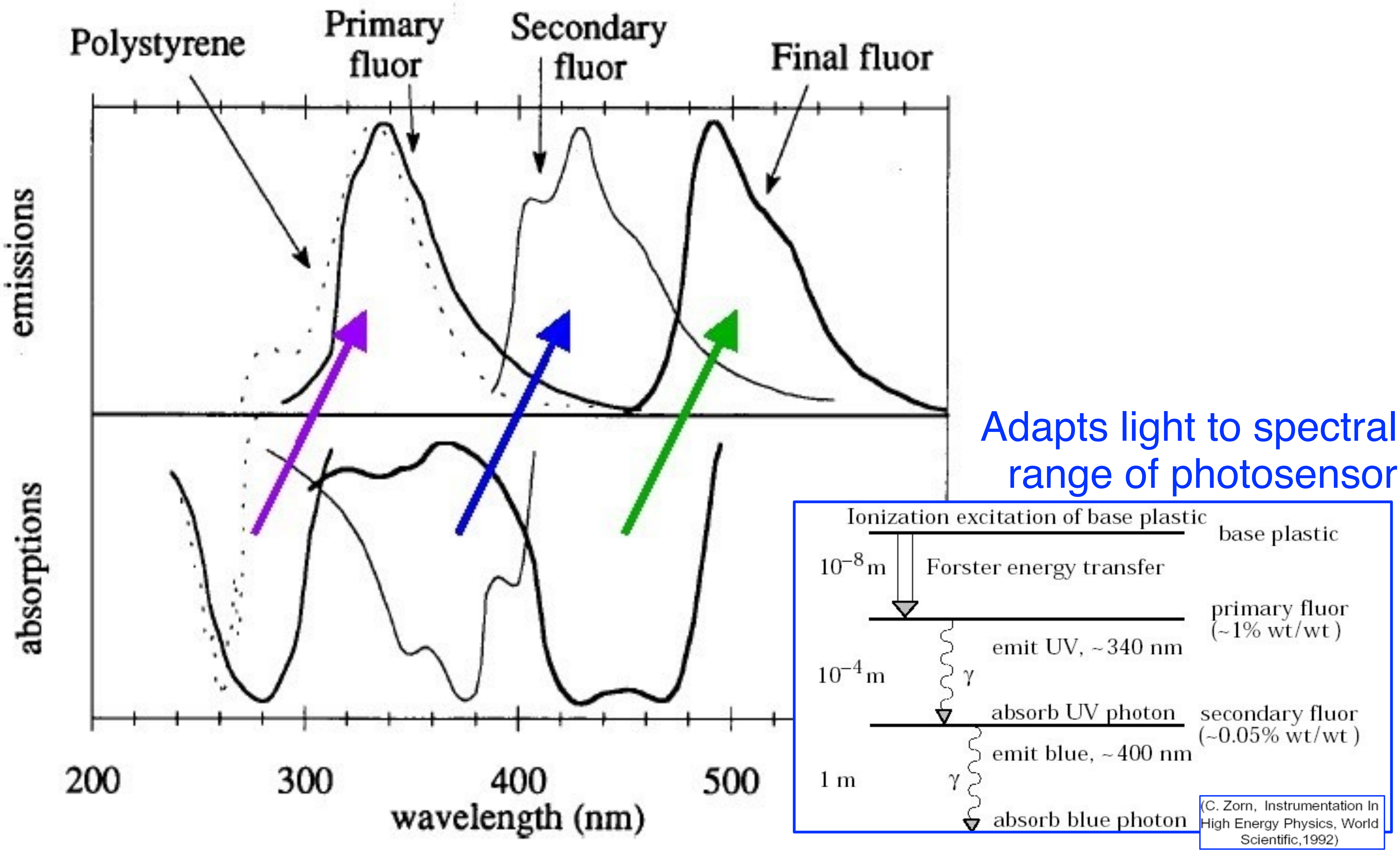


In practice:

Solution of organic scintillators [dissolved in plastic or liquid]
+ large concentration of primary 'fluor' (perhaps 1-3%)
+ smaller concentration of secondary 'fluor'
+ maybe more

=> step down the photon energy until λ is well matched to photodetector.
[Also helps avoid re-absorption of light]

Scintillators: Organic: Wavelength shifting



Adapts light to spectral range of photosensor

Ionization excitation of base plastic
base plastic
10^{-8} m
Forster energy transfer
primary fluor (~1% wt/wt)
emit UV, ~340 nm
10^{-4} m
γ
absorb UV photon
secondary fluor (~0.05% wt/wt)
emit blue, ~400 nm
1 m
γ
absorb blue photon

(C. Zorn, Instrumentation In High Energy Physics, World Scientific,1992)

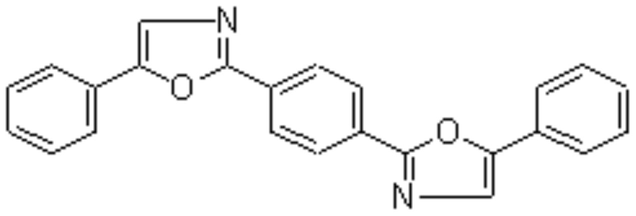
Emission spectrum for step (n) and absorption spectrum for step (n+1) must overlap.

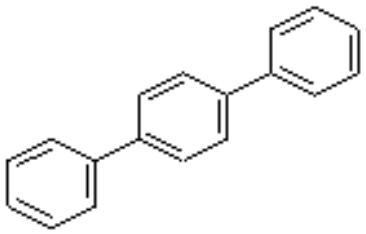
Scintillators: Organic: Composition

Some widely used solvents and solutes:

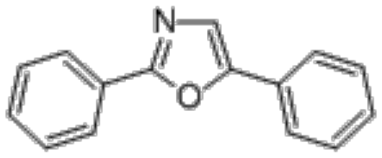
State	Solvent	Primary fluor	Secondary fluor
Liquid	Benzene	p-terphenyl	POPOP
	Toluene	DPO	BBO
	Xylene	PBD	BPO
Plastic	Polyvinylbenzene	p-terphenyl	POPOP
	Polyvinyltoluene	DPO	TBP
	Polystyrene	PBD	BBO or DPS

POPOP

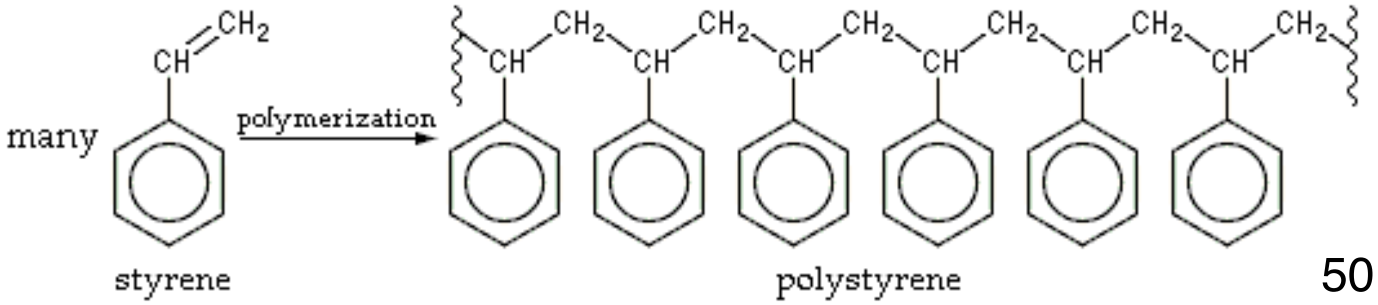




p-terphenyl

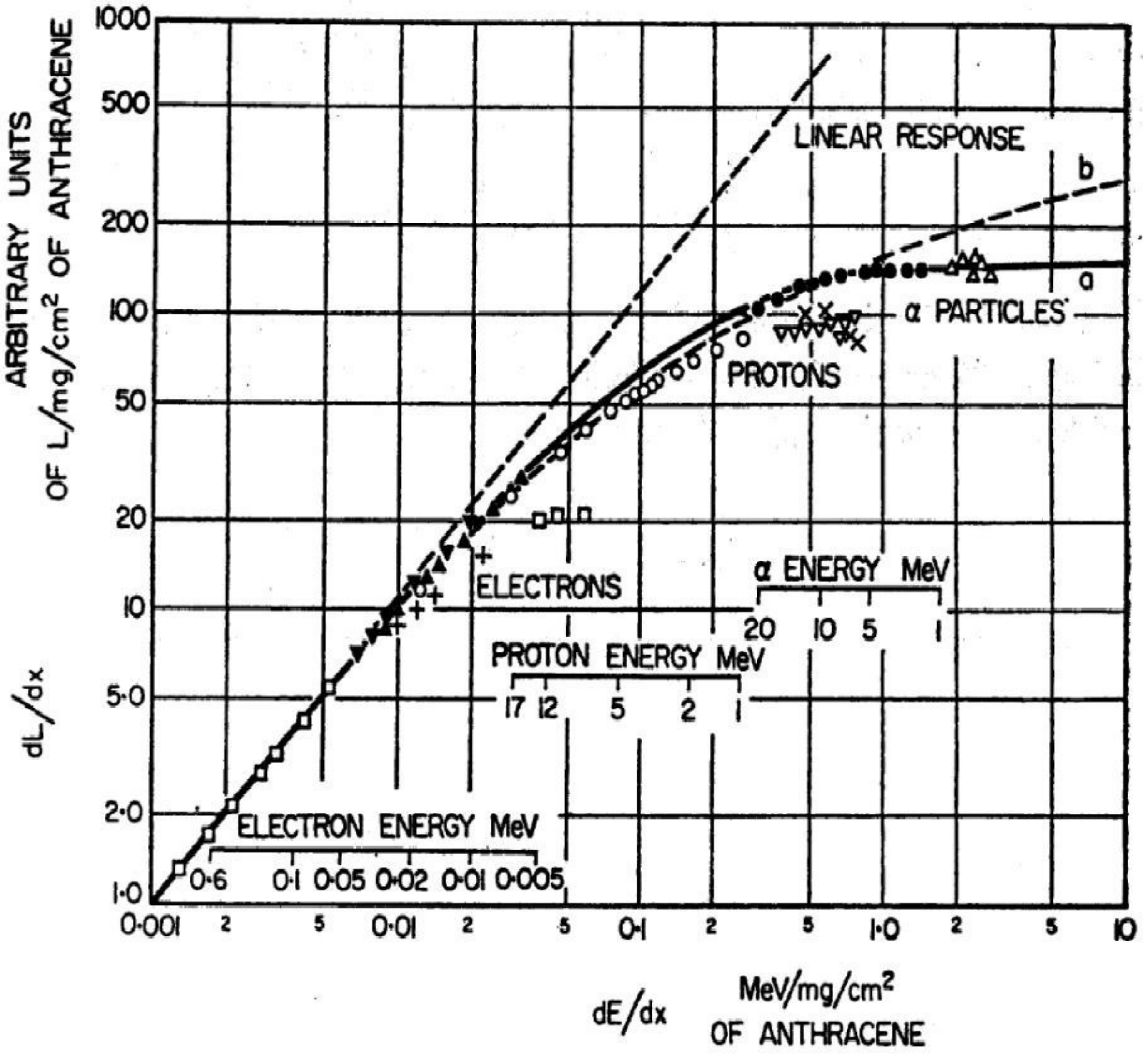


DPO



Scintillators: Organic: Light output

Fluorescent energy per unit path length dL/dx

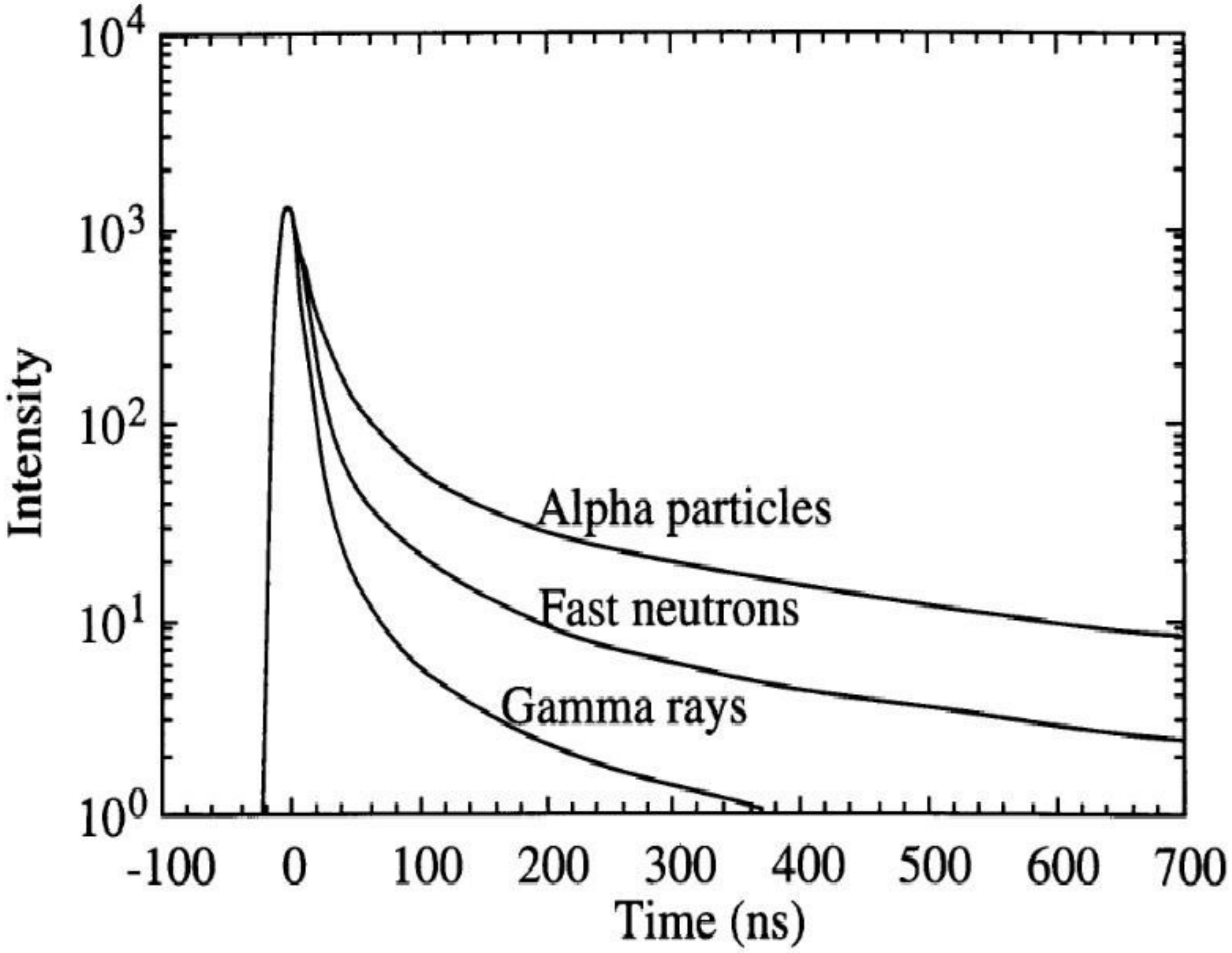


Variation of specific fluorescence dL/dx in anthracene with specific energy loss dE/dx (Brooks, from Birks)

Quenching: nonlinear response due to saturation of available states.

$$\frac{dL}{dx} = L_0 \frac{\frac{dE}{dx}}{1 + k_B \frac{dE}{dx}}.$$

Light output vs time for different particles



Discrimination between particles: time response varies according to incoming particle type.

(Caveat: may be affected by ageing, magnetic field effect, damage radiation, ...)

Scintillators: Organic: Properties

Scintillator material	Density [g/cm^3]	Refractive Index	Wavelength [nm] for max. emission	Decay time constant [ns]	Photons/MeV
Naphtalene	1.15	1.58	348	11	$4 \cdot 10^3$
Antracene	1.25	1.59	448	30	$4 \cdot 10^4$
p-Terphenyl	1.23	1.65	391	6-12	$1.2 \cdot 10^4$
NE102*	1.03	1.58	425	2.5	$2.5 \cdot 10^4$
NE104*	1.03	1.58	405	1.8	$2.4 \cdot 10^4$
NE110*	1.03	1.58	437	3.3	$2.4 \cdot 10^4$
NE111*	1.03	1.58	370	1.7	$2.3 \cdot 10^4$
BC400**	1.03	1.58	423	2.4	$2.5 \cdot 10^2$
BC428**	1.03	1.58	480	12.5	$2.2 \cdot 10^4$
BC443**	1.05	1.58	425	2.2	$2.4 \cdot 10^4$

* Nuclear Enterprises, U.K.
** Bicron Corporation, USA

c.f. NaI(Tl): ~ 40k photons / MeV

Scintillators: Pulse shape discrimination

- For multiple types of scintillator, we saw that time response can include fast and slow components
  - e.g. inorganic crystals like CsI(Tl)
  - e.g. organic scintillators like Stilbene
- We also saw that the mechanisms available can be influenced by nonlinear/saturation/quenching effects.
  - i.e. a large local energy deposit can exhaust all of the available states for a certain transition pathway.
  - Details are different for organic vs inorganic
- Some particles deposit energy faster
  - e.g. electrons vs muons vs alpha (z=2)
  - e.g. neutrons vs photons
- Consequence: time response can depend on particle type; can infer PID information from pulse shape.
- Not much used in high-rate, high-energy detectors today, but can be useful in low-rate or nuclear experiments.

Scintillators: Comparison

	Advantages	**Disadvantages**	**Used for**
Inorganic	Some have high light yield High density Good energy resolution	Complicated crystal growth Some have lower light yield	Calorimetry Gamma spectroscopy* Charged particle detection … * although really you'd use a semiconductor
Organic	Very fast Easily shaped Some have high light yield	Some have lower light yield Radiation damage (esp. for plastics; less for liquids) Aging	Time measurement Particle discrimination Charged particle detection …

"Typical" advantages & disadvantages; properties of individual materials vary a lot.

Scintillators: Comparison

	Advantages	**Disadvantages**	**Used for**
Inorganic	Some have high light yield	Complicated crystal growth	Calorimetry Gamma spectroscopy
Organic	Easily shaped Some have high light yield	Radiation damage (esp. for plastics; less for liquids) Aging	discrimination Charged particle detection ...

Practical points (cost, size, radiation hardness) can be the most important!

- e.g. in the TL we use NaI(Tl) to measure spectra but plastic for cosmic ray timing
- e.g. at accelerators, almost never use plastic

"Typical" advantages & disadvantages; properties of individual materials vary a lot.

Getting the light to a photodetector

Light must be guided to photosensor with minimal losses

=> use Total Internal Reflection, requires careful optimization of geometry.

Saint-Gobain:

Typical light pipe geometries include:

- ***Right Cylinders**: used when the light pipe diameter is the same as the scintillator diameter.*
- ***Tapered Cones**: transition pieces between square-to-round or round-to-round cross-sections*
- ***Fish Tail**: Transition pieces from thin, rectangular cross-sections to round cross-sections*
- ***Adiabatic**: provide the most uniform light transmission from the scintillator exit end to the PMT; the cross-sectional areas of the input and PMT faces are equal*

Next time: how to detect and measure the light once it reaches the photodetector

... and we'll come back to interaction of other neutral particles with matter.

Some useful further resources for scintillator info: Leo; PDG review "Particle detectors at accelerators" sections 35.3 + 35.4 + maybe 35.7.

Example exam questions from previous years

Note: The exam format has changed over time, and the syllabus has also evolved somewhat. The point is not to give you the exact style or content of this year's questions, but to help you prepare.

Exam questions

From 2016:

We consider photons in the energy range $10\,\text{eV} < E_\gamma < 100\,\text{GeV}$. For interactions with matter, the dominant processes in this region are the Compton effect, pair production, and the photoelectric effect.

(a) For each of these three processes, draw a Feynman diagram.

(b) Sketch a graph showing how the interaction cross-section of each of these three processes varies with E_γ on a log-log scale for a material of intermediate Z, labelling any important features.

Exam questions

From 2017:

A Higgs boson is produced inside a detector and decays to a pair of photons. Each of the photons enters an electromagnetic calorimeter, producing a shower.

(a) Explain briefly how the shower develops, in terms of the key physical processes involved.

(b) How do the dimensions of the shower relate to the radiation length X_0 and the critical energy E_c of the material?

Exam questions

From 2021:

Q3 (approx. 10–15 min)

We wish to study photons of energy E_γ between 10 eV and 10 keV. We use a thin plate of material.

(a) What is the most probable way for the photons to interact with the material? Identify the process and draw a Feynman diagram (including all participating particles).

(b) We have plates of various materials available (e.g. Si, Cu, Fe, Pb, ...), and plan to study how the interaction probability varies between them. What property of the *material* has the most influence on the interaction probability? Roughly how does the cross-section scale with this property? (The question refers to the physical properties of the material, not the dimensions of the plate.)

(c) We observe an event in which an incoming 18.0 keV photon produces a single electron of energy 9.0 keV and no other outgoing particles. What can we deduce from this? (The value of 9.0 keV represents the initial energy of the electron, ignoring any subsequent energy loss in the material.)

(d) For a particular material, we measure how the cross-section varies as a function of photon energy. We notice that the variation is not smooth but has a number of ridges/peaks in the plot of cross-section vs energy. Suggest a physical origin for these ridges.