



Elettra Sincrotrone Trieste



Elettra  
Sincrotrone  
Trieste

# Radiation-matter interaction

# IAEA training workshop on synchrotron technologies and techniques and their applications

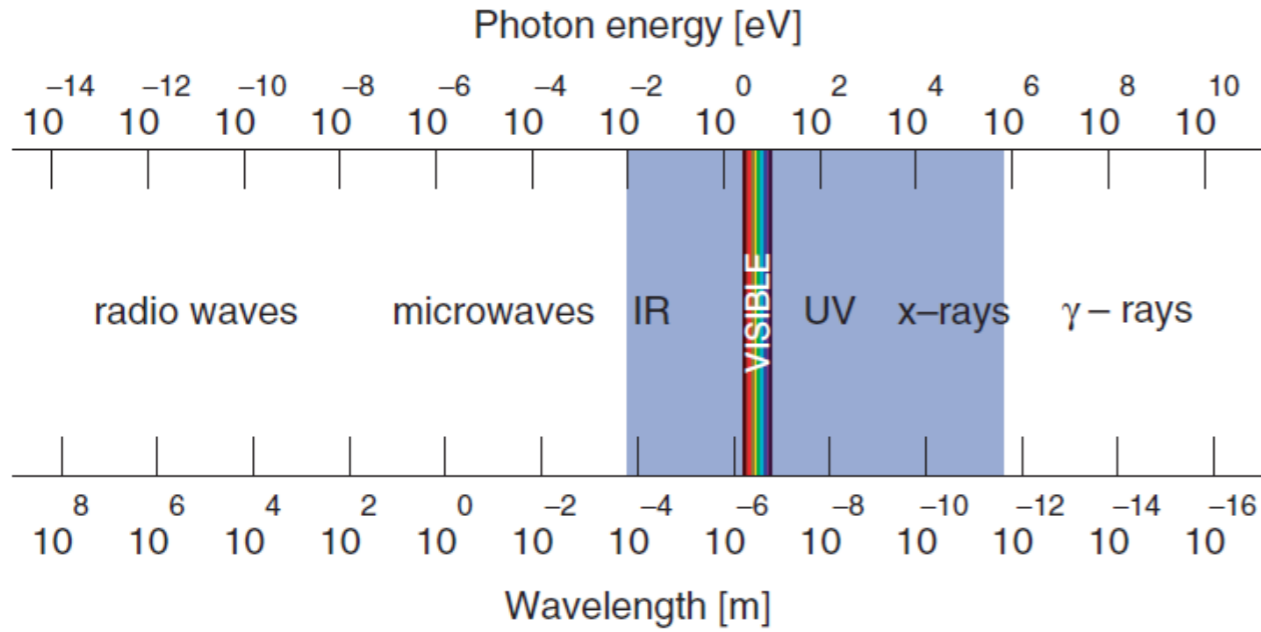
The lectures and Q&A sessions will take place in the training room.



23/10/2023	Monday	24/10/2023	Tuesday	25/10/2023	Wednesday	26/10/2023	Thursday	27/10/2023	Friday
8:30 - 8:45	Welcome L. Gregoratti - Elettra	9:00 - 9:30	Q&A	9:00 - 10:00	XAS theory G. Agostini - Elettra	9:00 - 9:30	Q&A	9:00 - 13:00	Proposals presentations and discussion
8:45 - 9:30	Introduction A. Migliori - IAEA	9:30 - 12:30	Hands on XRD and proposal writing (G1 XRD; G2 proposal)	10:00 - 11:00	XRF theory A. Migliori - IAEA	9:30 - 12:30	Hands on XAS and XRF beamlines (G1 XAS; G2 XRF)	13:00 - 14:00	Lunch
9:30 - 10:30	Students presentations	12:30 - 14:00	Lunch	11:00 - 11:30	Coffee break	12:30 - 13:00	Photo shooting	14:00 - 14:15	Farewell
10:30 - 11:00	Coffee break	14:00 - 17:00	Hands on XRD and proposal writing (G1 proposal; G2 XRD)	11:30 - 12:30	XRD applications J. Plaisier - Elettra	13:00 - 14:00	Lunch		
11:00 - 12:00	Radiation-matter interaction I. Carlomagno - Elettra	17:00 - 17:30	Break and feedback of the day	12:30 - 13:30	Lunch	14:00 - 17:00	Hands on XAS and XRF beamlines (G1 XRF; G2 XAS)		
12:00 - 13:30	Lunch			13:30 - 14:15	XAS applications: material science G. Aquilanti - Elettra	17:00 - 17:30	Break and feedback of the day		
13:30 - 14:30	Synchrotron radiation G. Aquilanti - Elettra			14:15 - 15:00	SR applications in bio- anthropology and heritage sciences Simone Lemmers - Elettra				
14:30 - 15:15	Beamlines: introduction G. Das - Elettra			15:00 - 15:30	Coffee break				
15:15 - 15:30	Coffee break			15:30 - 16:15	XRF applications G. Das - Elettra				
15:30 - 16:30	XRD Theory L. Gigli - Elettra			16:15 - 17:00	Combined XRF and XAS applications S. Pollastri - UniMoRe				
16:30 - 17:15	How to write a good proposal I. Carlomagno - Elettra			17:00 - 17:30	Break and feedback of the day				
17:15 - 17:45	Break and feedback of the day								



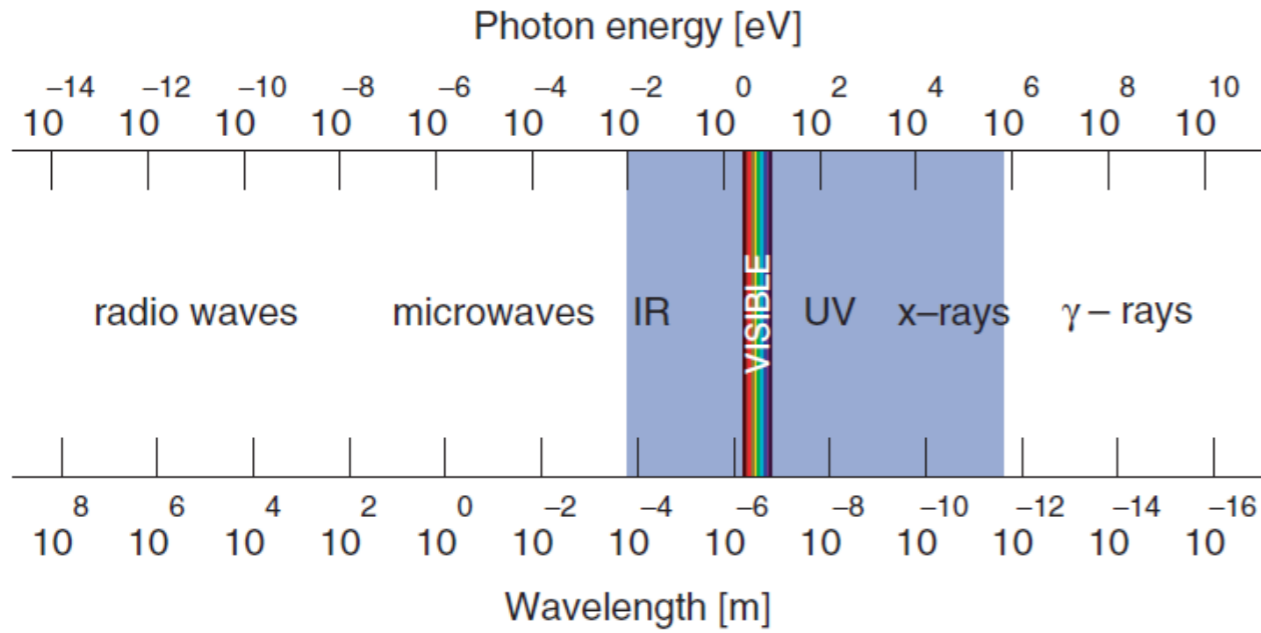
# Our subjects: light and matter



**Take home message:**  
Interaction depends on  $\lambda$ !



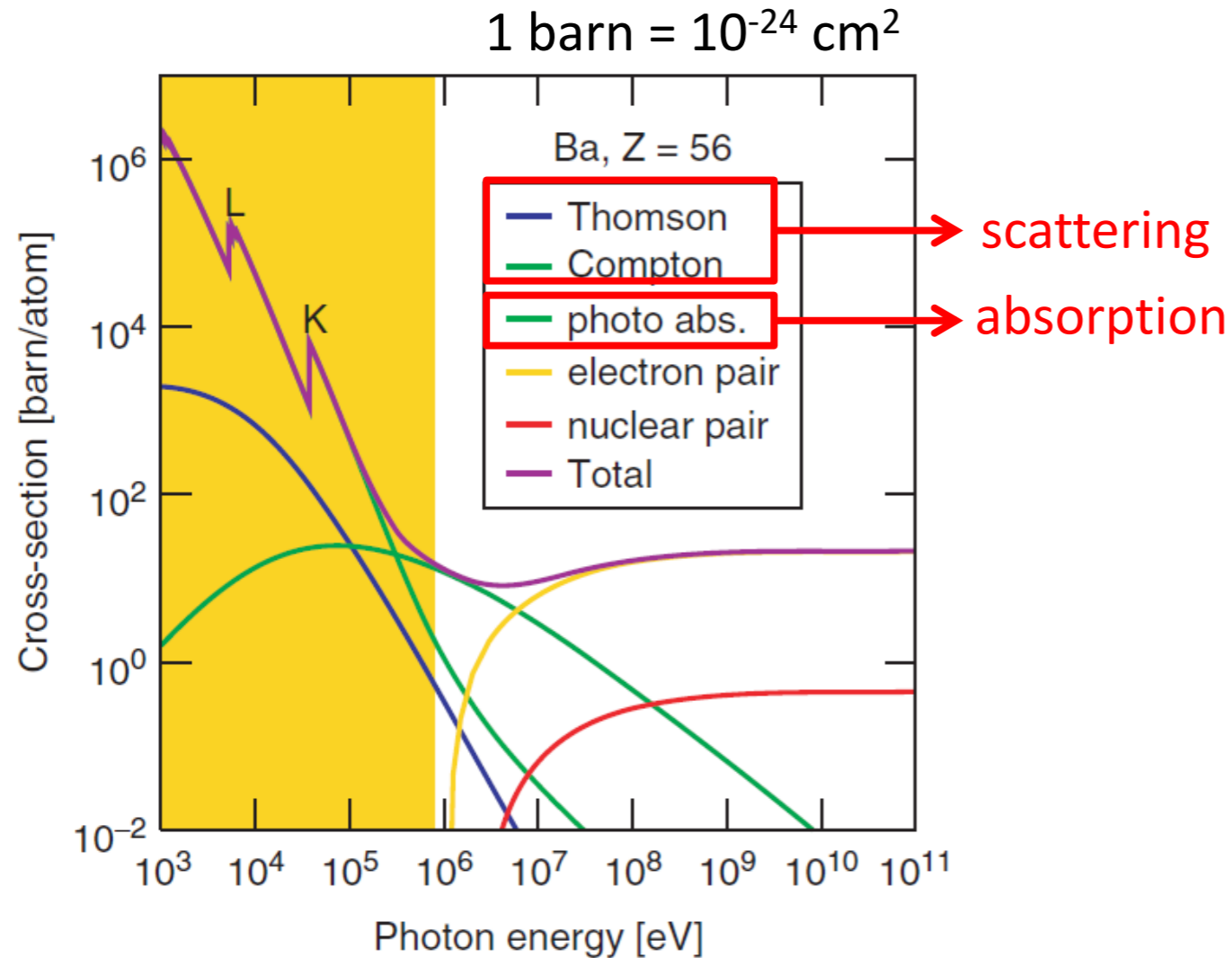
# Energy-frequency-wavelength



Energy of a photon       $E = h\nu = hc/\lambda$   
Planck's constant       $h = 6.626 \times 10^{-34} \text{ J s}$   
Frequency of the radiation       $\nu$ [Hz]  
Speed of light       $c = 2.9979 \times 10^8 \text{ m/s}$   
Wavelength of light in vacuum       $\lambda$ [m]

In practical units for x-rays

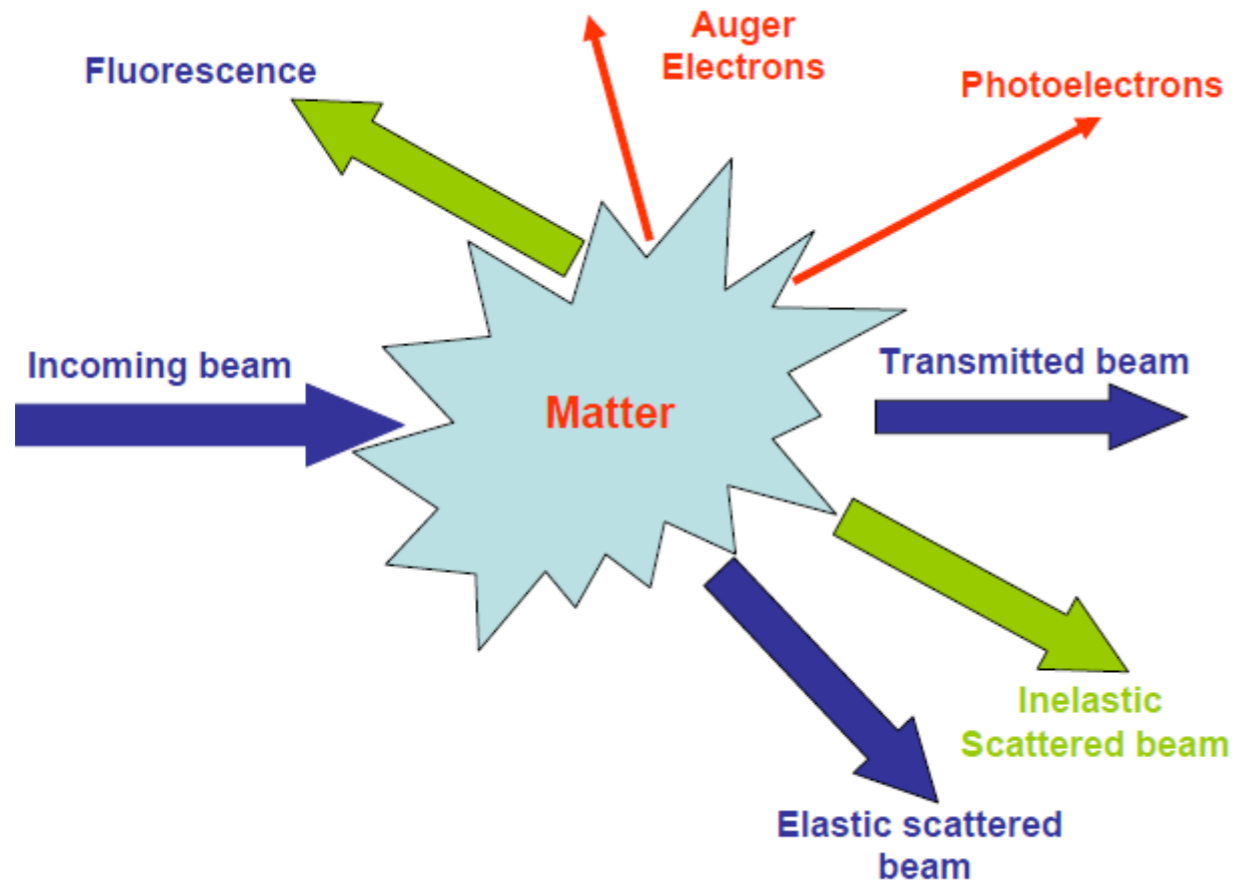
$$\lambda[\text{\AA}] = \frac{12.3984}{E[\text{keV}]}$$



Due to their  $\lambda$   
x-rays interact  
mainly  
with electrons in  
matter



# Interactions and their effects



Interactions:

- Scattering
- Absorption

Observed phenomena:

1. Transmission
2. Elastic scattering
3. Inelastic scattering
4. Fluorescence
5. Auger electrons
6. Photoelectrons

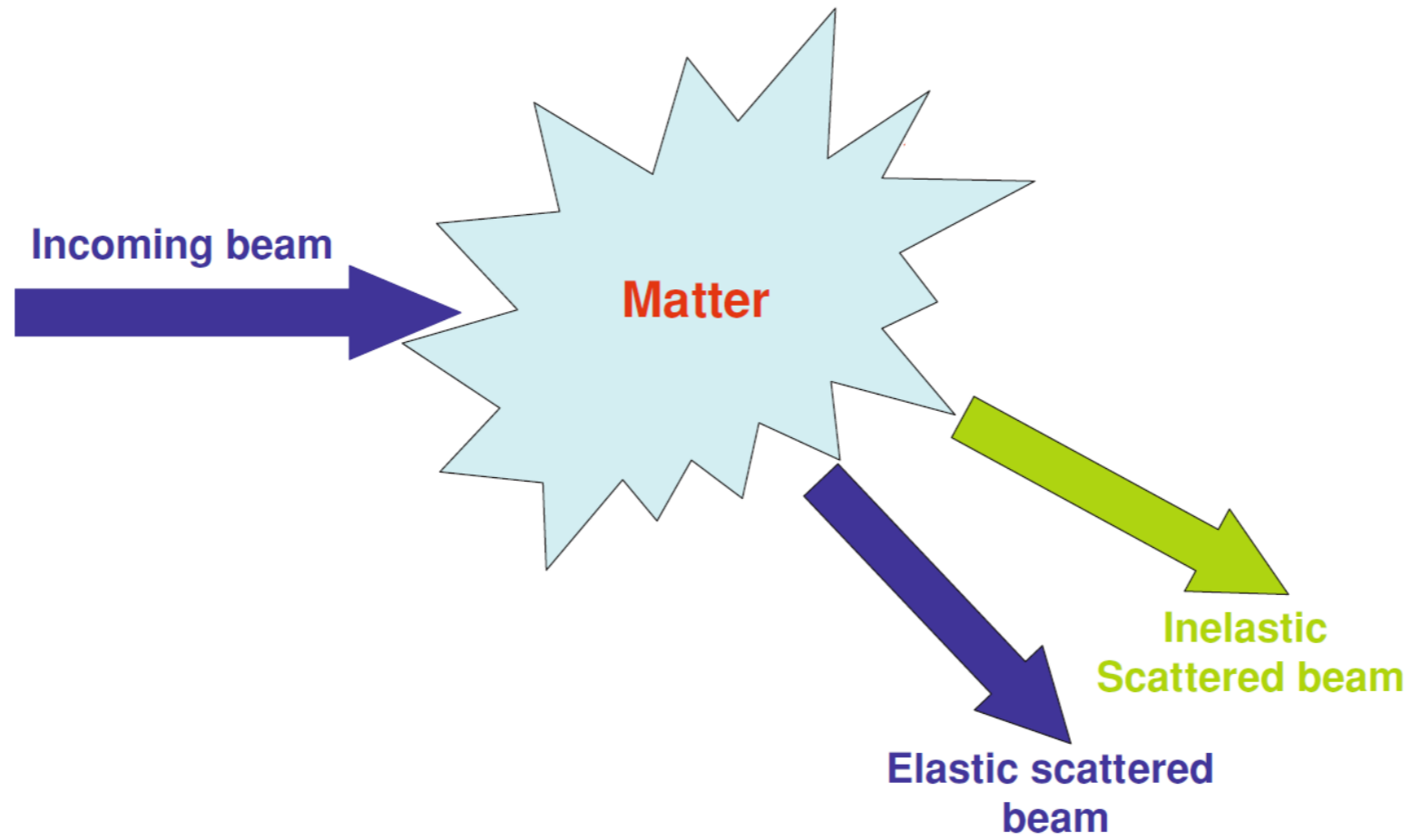


# Matter-radiation interaction: scattering



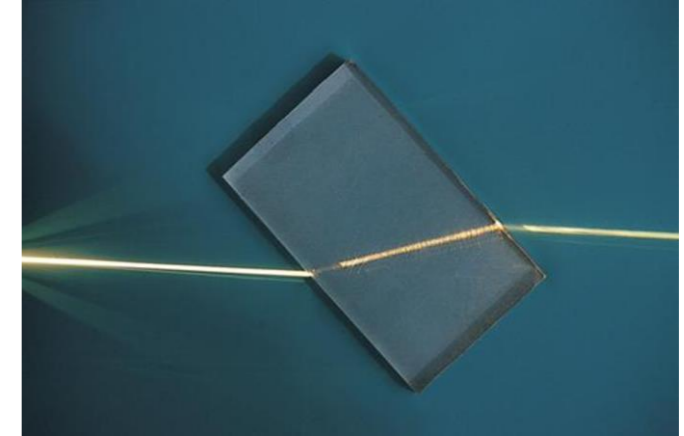


# Scattering



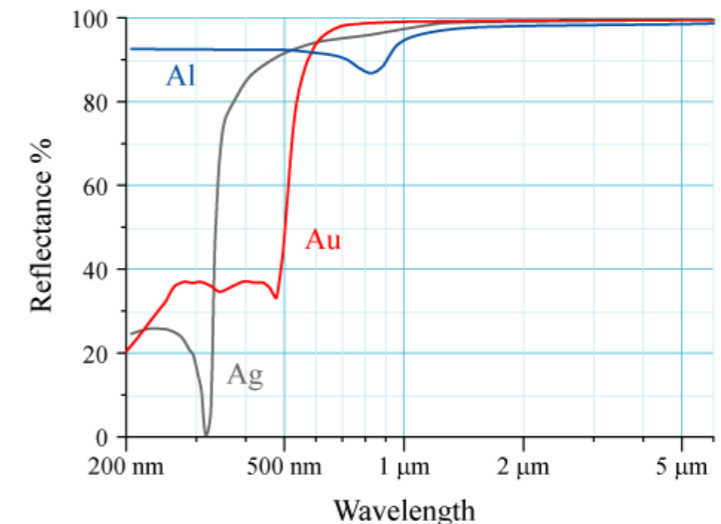
## Refraction

- The higher the refractive index, the slower the light travels
- Light path bends when crosses the boundary between two media
- Depends on wavelength!



## Reflection

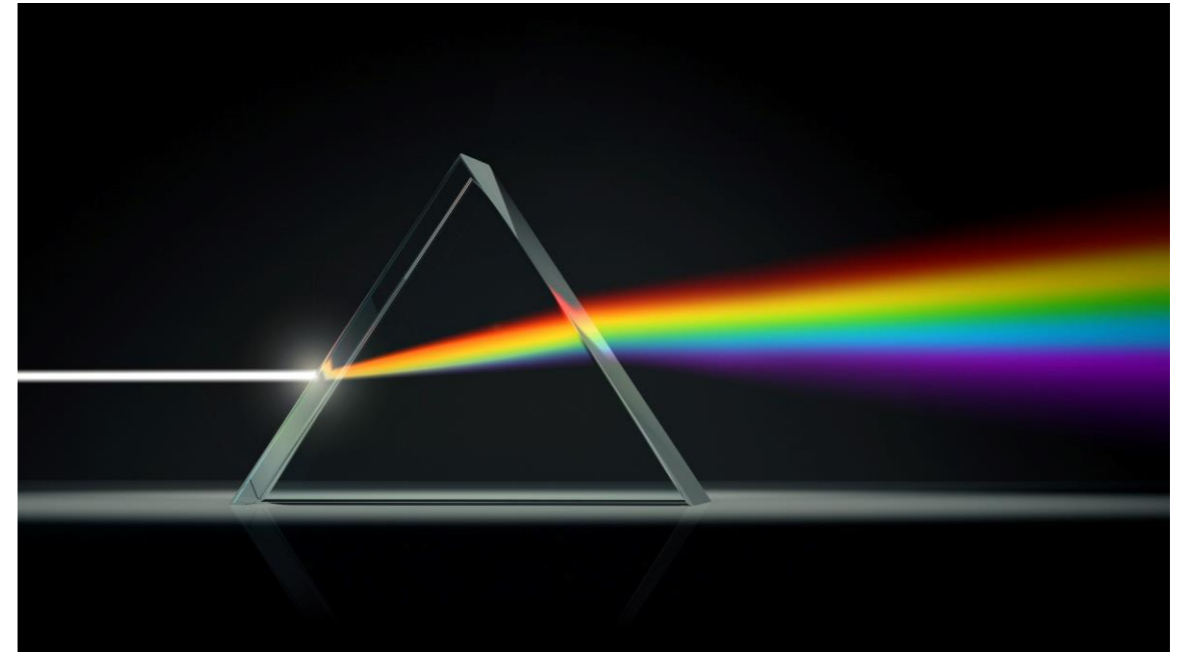
- Below the critical angle, light is completely reflected off a surface
- Conductive materials reflect light efficiently at any angle
- The reflectivity of Al is  $\sim 1$  in the VIS and UV range
- Au reflects less well and has a yellow appearance, because of an absorption band in the blue



Visible light: 400 – 800 nm = few eV

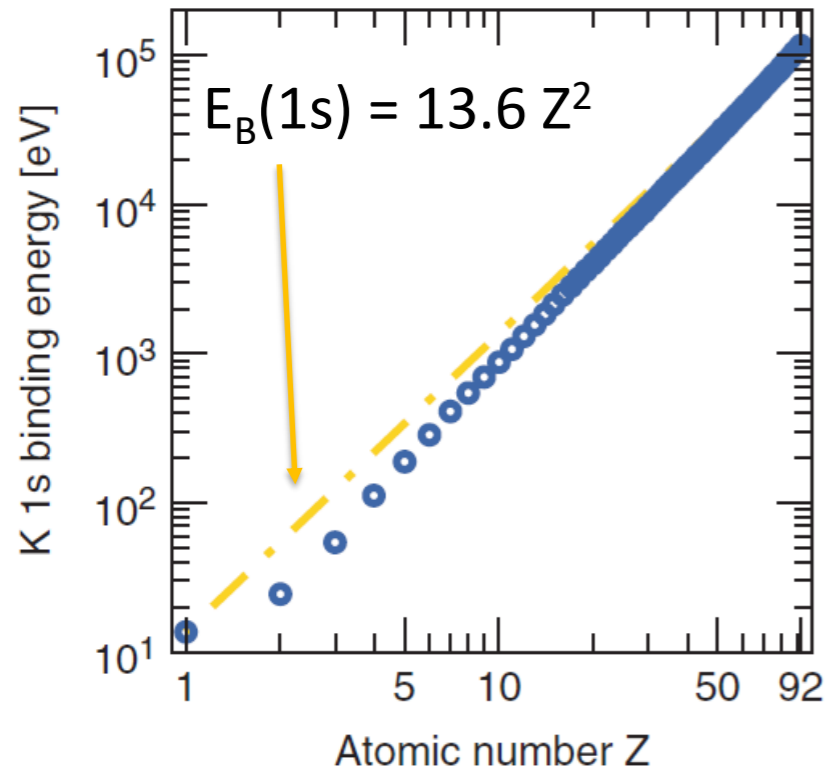
- Small energy: enough to interact with free or valence electrons
- Inner (“core”) electrons are tightly bound to nuclei: weak interaction, if any!
- Depends on...?

Refraction and reflection occur also in the X-rays and UV range





## Introduction – X-rays



X-rays energies are similar to or larger than core electrons binding energies  
(Binding energy of electron in H atom: 13.6 eV)

$$E_B(1s) = 13.6 \cdot Z^2$$

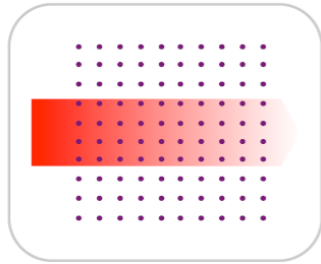
easy approximation ignoring any Coulomb interaction

Interaction strength or “cross section” is stronger for core electrons than for valence ones

Basic requirement for a good probe  
 $\text{wavelength} \leq \text{interatomic distances}$

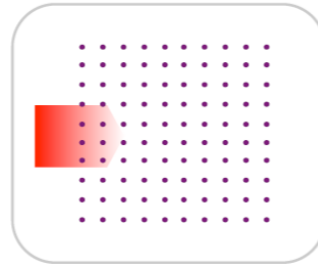


Weak interaction  
 Large penetration depth



Bulk probes

Strong interaction  
 Small penetration depth



Surface probes

- Structural properties
  - Macroscopic
  - **Atomic level**
- Electronic properties
- Vibrational properties

wave-particle duality

“Radiation”

- Microwaves
- Infrared
- Visible
- UV
- **X-ray**

- **Electrons**
- Positrons
- **Neutrons**
- Ions
- .....



Upon interaction, photons change their direction of propagation

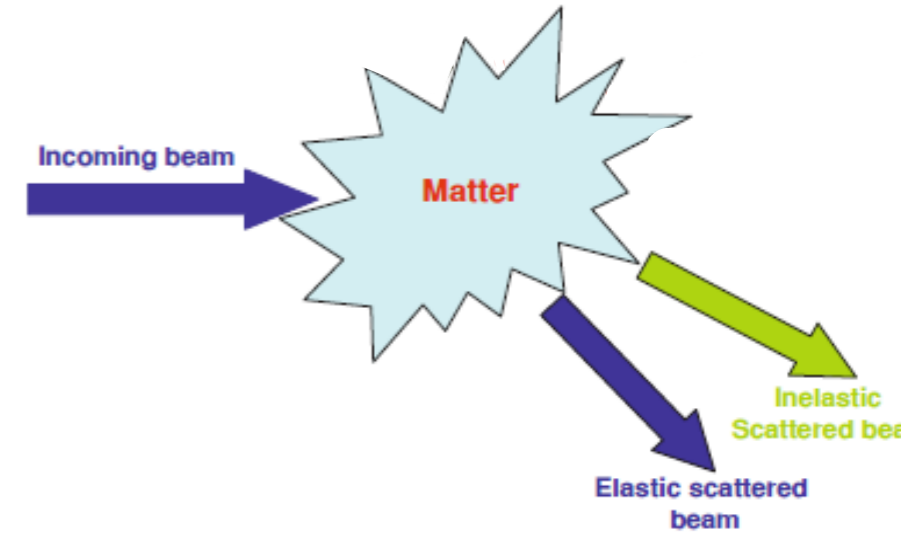
The scattering can be:

### *Elastic:*

- no exchange of energy:  $\Delta E = 0$
- diffused photons have the same energy of the incoming ones
- “coherent” because the waves scattered by different parts of the system interfere

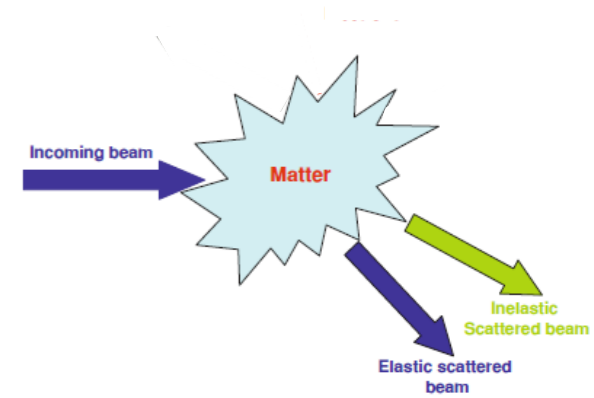
### *Inelastic:*

- $\Delta E =$  energy of an excited state of the sample

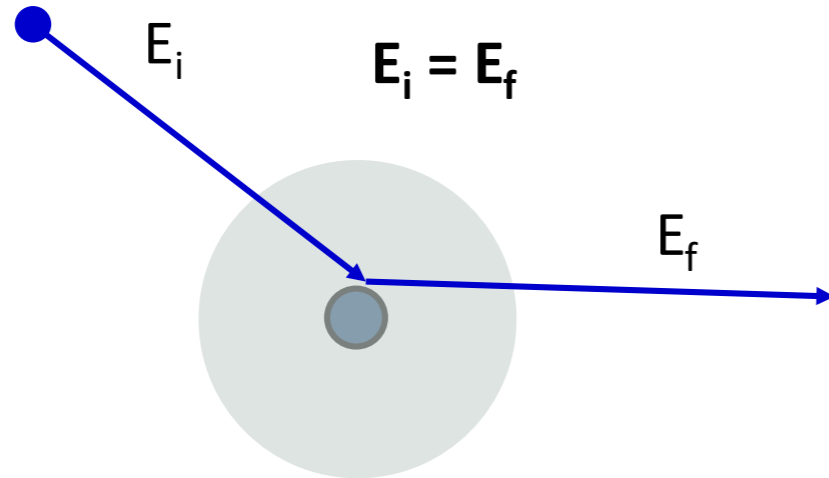




# Scattering



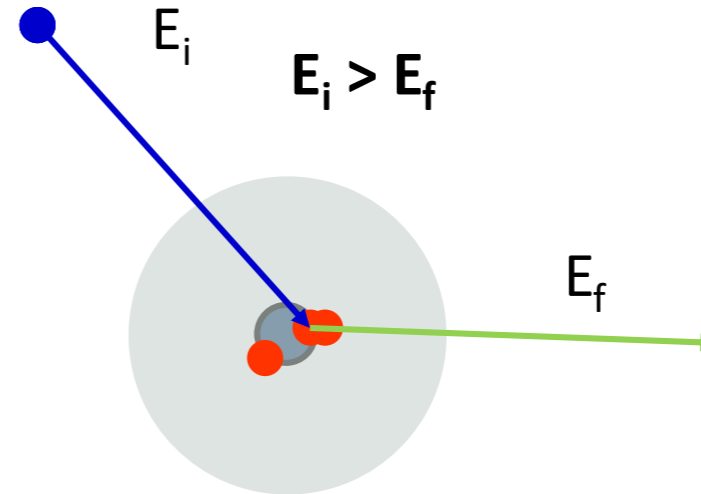
## Elastic



$$\Delta E = 0$$

The photons are re-emitted with a different direction of propagation

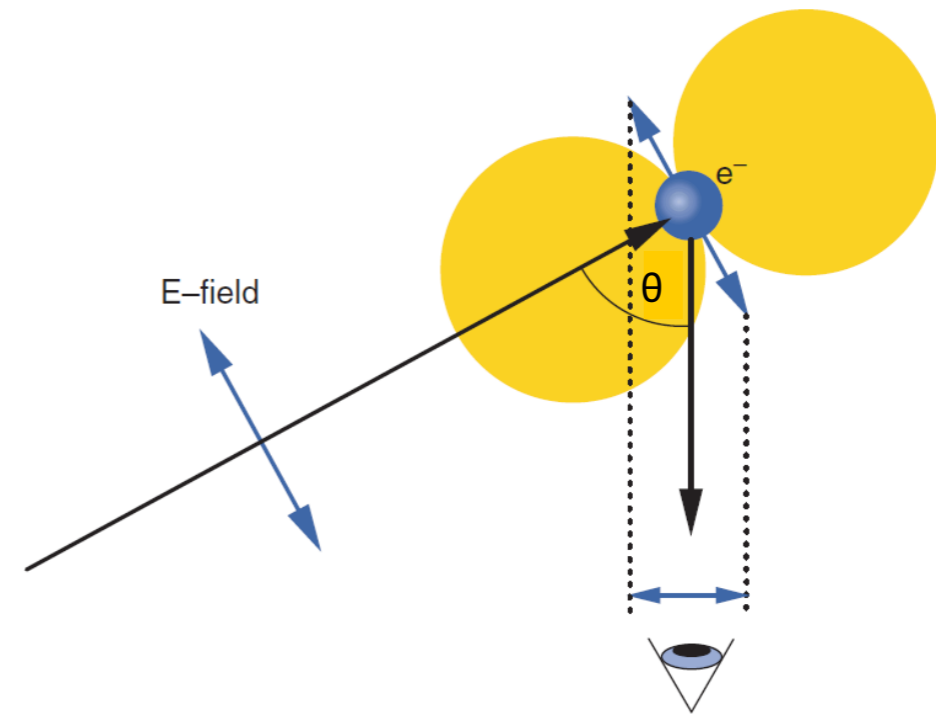
## Inelastic



$$\Delta E > 0$$

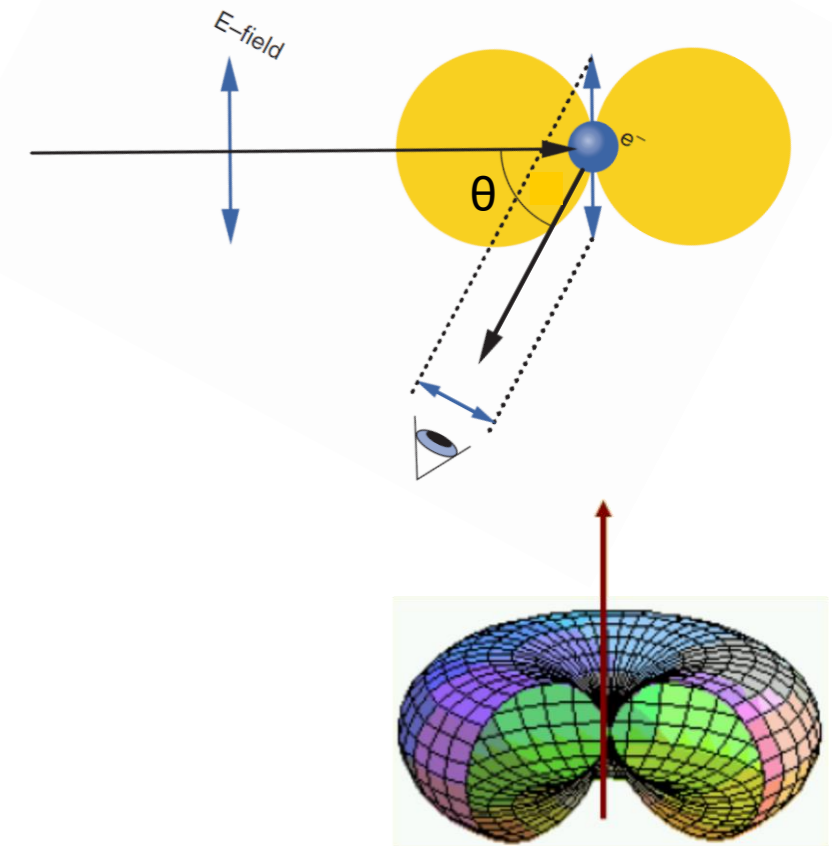
The photons are re-emitted in a different direction, with  $E_f < E_i$

- Classically, **elastic scattering** occurs when an electron is sinusoidally accelerated by the incoming electromagnetic field and reradiates light at the same frequency
- Emitted radiation: same frequency of the electromagnetic field (this is the scattered wave!)





- The strength of the re-emitted radiation depends on **the component of the electric field** seen from a given point
- **No scattering** occurs parallel to the electric field: no acceleration!  
( $\theta = \pi/2$ )
- **MAX scattering amplitude perpendicular to the electric field**
- **Scattering intensity**  $\sim E^2$  and to  $\cos^2\theta$   
( $\theta$ : angle between the plane perpendicular to the electric field and the direction of observation)



Electromagnetic *dipole* radiation

- **Scattering length**: ability of an electron to scatter an x-ray
- For an isolated electron **Thomson scattering length**: “classical radius” of a free electron
- The elastic scattering **amplitude** of an atom is proportional to the Thomson scattering length and **Z** (number of electrons in the atom)
- The elastic scattering **intensity** increases with **Z<sup>2</sup>**

$$r_0 = \left( \frac{e^2}{4\pi\epsilon_0 m_0 c^2} \right) = 2.82 \times 10^{-5} \text{ \AA}$$

Rest mass energy  
of the electron

The **Thomson scattering length** determines the **scattering amplitude** from a single electron

The scattering amplitude is proportional to:

$$-r_0 |\hat{\boldsymbol{\epsilon}} \cdot \hat{\boldsymbol{\epsilon}}'|$$

Polarization of the incident field      Polarization of the radiated field

(The factor -1 represents the 180° shift between incident and scattered waves)

## One more step: the differential scattering cross section

Efficiency of the scattering process normalized to the **flux** of the incoming beam and **size of the detector**

$$\frac{d\sigma}{d\Omega} = \frac{I_{sc}}{\Phi_0 \Omega}$$

$$\frac{d\sigma}{d\Omega} = r_0^2 |\hat{\boldsymbol{\varepsilon}} \cdot \hat{\boldsymbol{\varepsilon}}'|^2$$

### Thomson differential scattering cross section

$(\boldsymbol{\varepsilon} \cdot \boldsymbol{\varepsilon}')^2$  has to be considered for the optimal choice of experimental geometry!

SR is polarized horizontally, therefore...

- Scattering expt are done in the vertical plane, where  $(\boldsymbol{\varepsilon} \cdot \boldsymbol{\varepsilon}')^2 = 1$
- Fluorescence expt, on the contrary, avoid scattering and stay in the horizontal plane, where  $(\boldsymbol{\varepsilon} \cdot \boldsymbol{\varepsilon}')^2 = 0$



## X-ray scattering: some considerations

“X-rays interact  
mainly  
with electrons in matter”

$$r_0 = \left( \frac{e^2}{4\pi\epsilon_0 mc^2} \right)$$

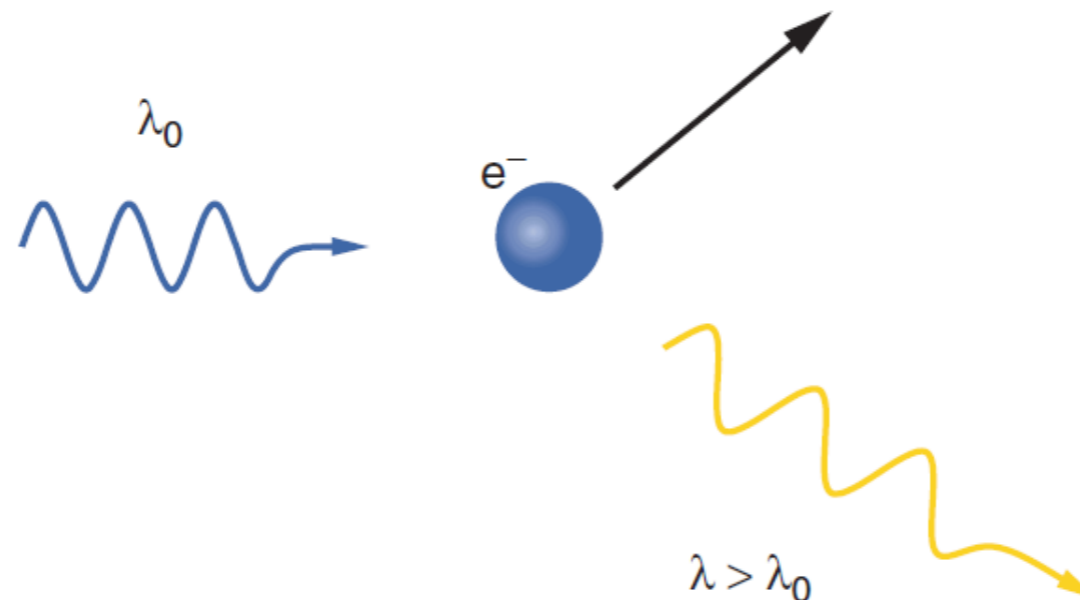
Scattering amplitude  $\sim$  (mass of the particle)<sup>-1</sup>  
Scattering cross section  $\sim$  (scattering length)<sup>2</sup>

$$m_{\text{nucl}} \sim 10^6 m_{el}$$

The nucleus can be completely ignored

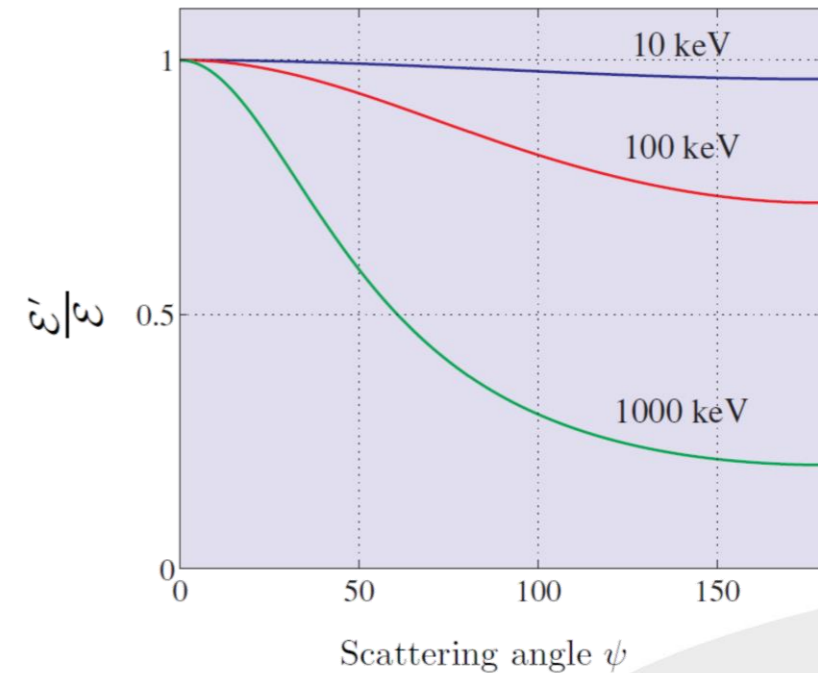
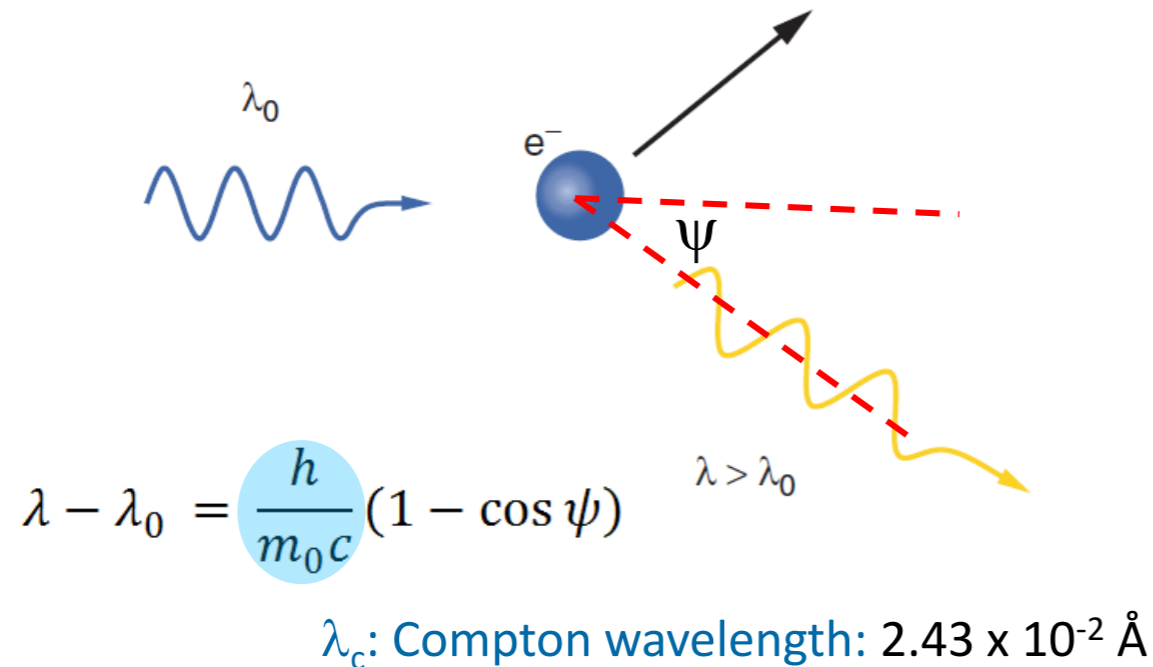
1. From quantum mechanics: x-rays = photons
2. The electron is free at rest

In a collision, the **energy** of the photon can be **transferred** to the electron, and the scattered photon has a lower energy than that of the incident one



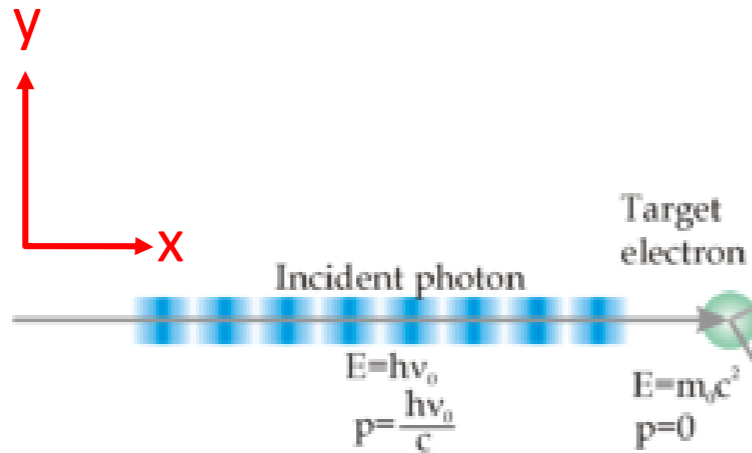
The photon energy loss increases with increasing scattering angle and incident photon energy

- For most applications using SR, the cross section for Compton scattering can be neglected





# Inelastic scattering from a free electron: Compton scattering - 3



## Energy conservation

$$h\nu_0 + m_0c^2$$

Rest mass  
of the electron

## Momentum conservation

x direction

$$\frac{h\nu_0}{c}$$

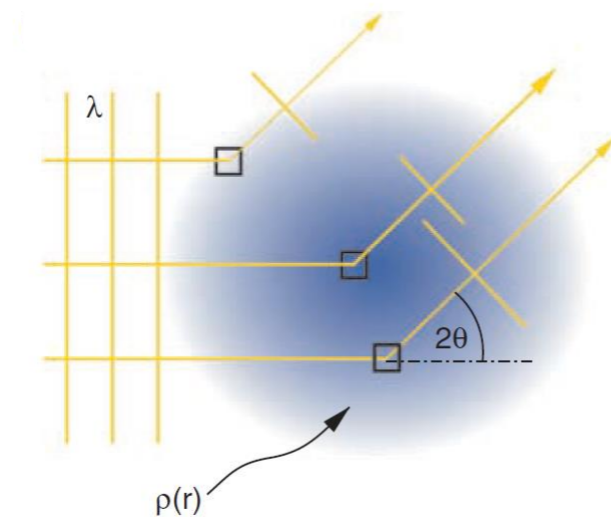
y direction

$$0$$



Assumption:

the electrons in an atom can move freely and are unaffected by being in bound states



Electron distribution  
 $\rho(r)$  = electron density

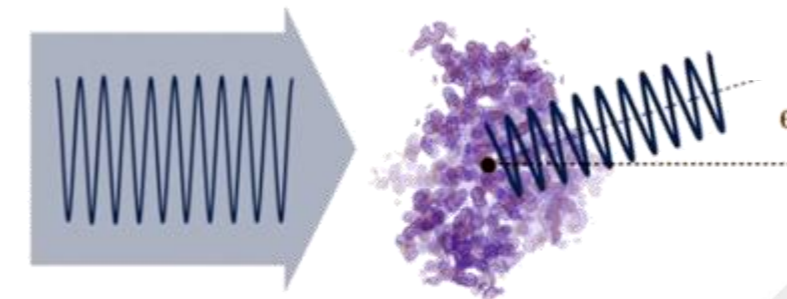
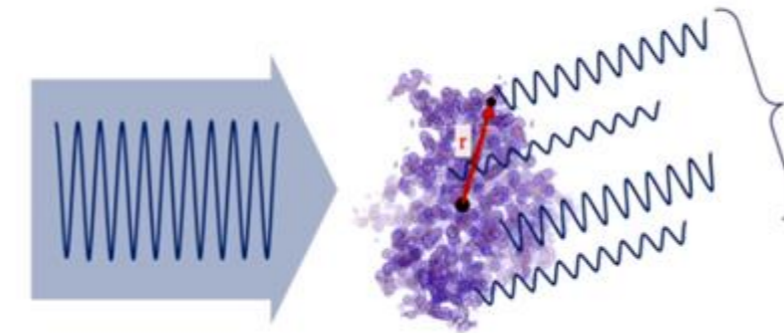
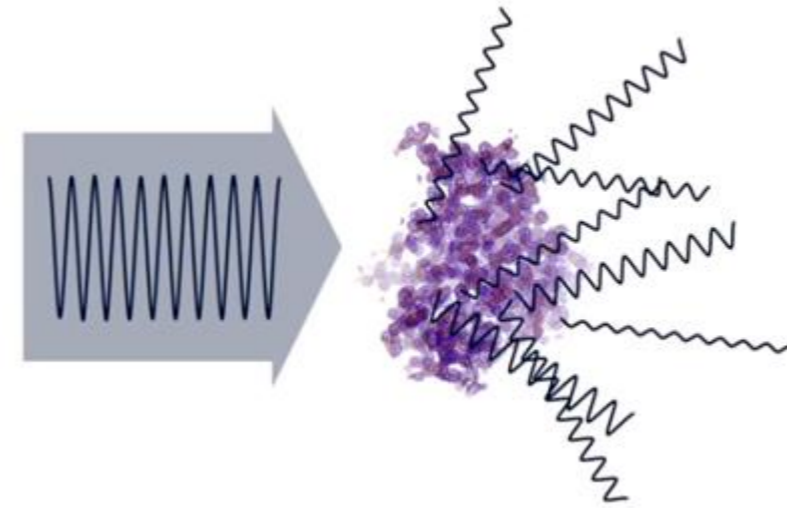
Scattered radiation: superposition of contributions from different volume elements

## Scattering from a cloud of free electrons

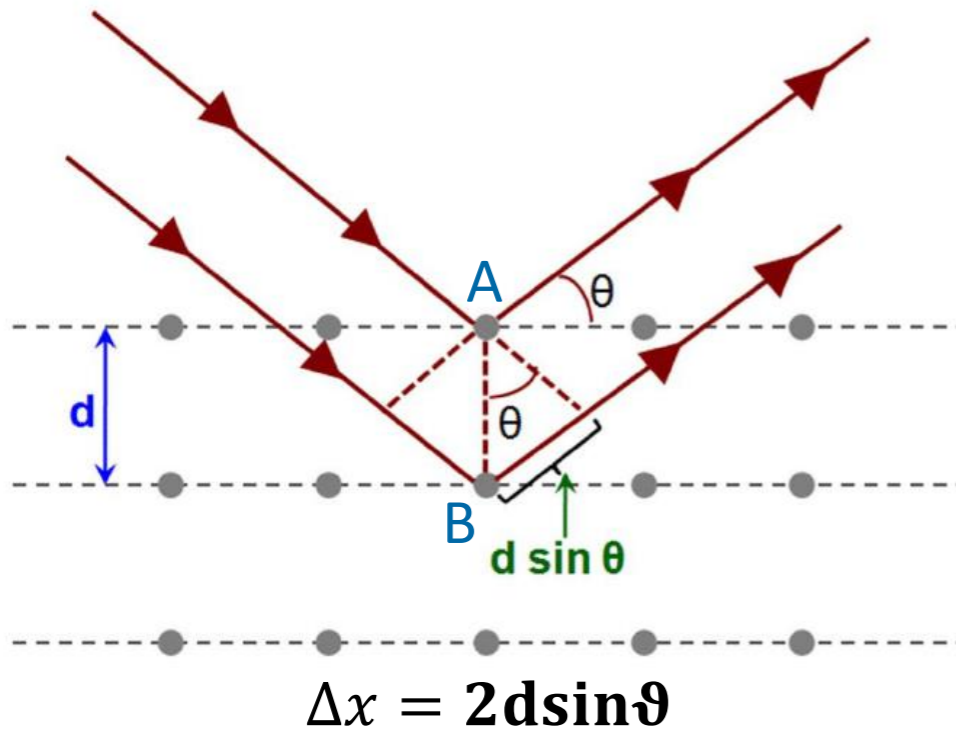
The scattering takes place **in all directions** with intensities depending on the electron density

At a **given angle** the scattered waves differ in amplitude and phases

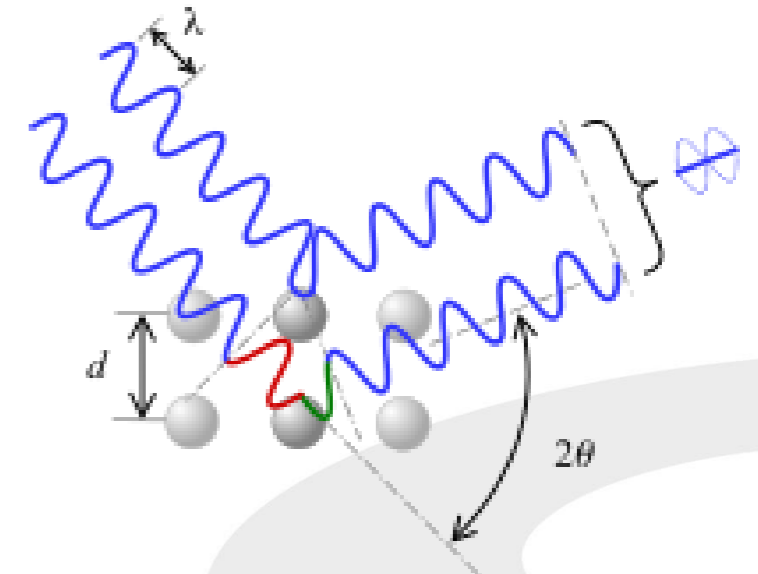
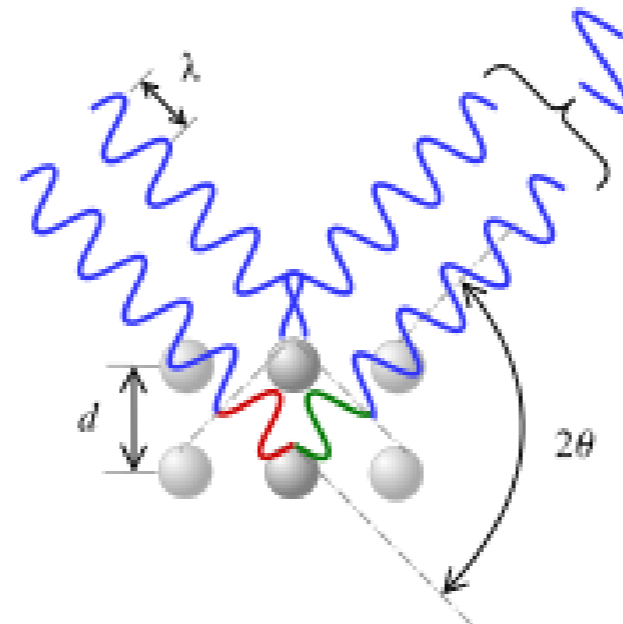
The **resulting wave** at a given angle is obtained by taking into account the amplitudes and the relative phases



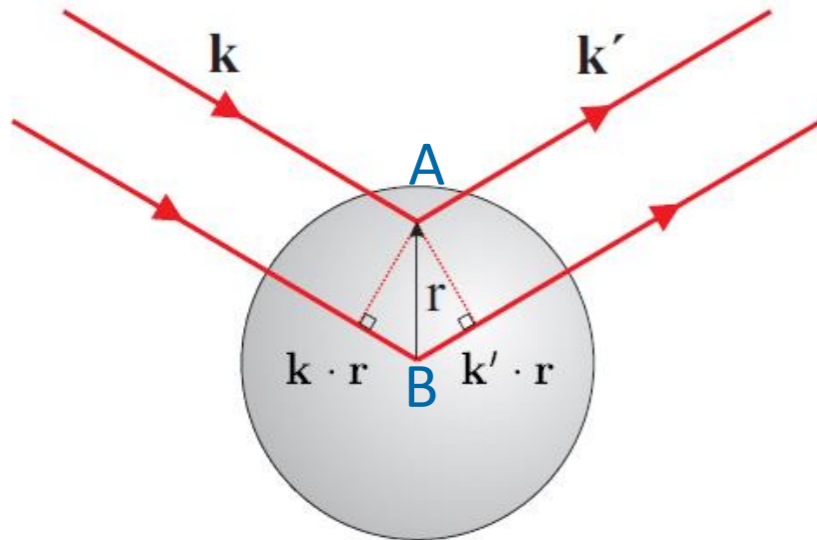
- Each scattered wave from an infinitesimal volume element has an **amplitude**  $\propto \rho(r)$
- Each scattered wave from an infinitesimal volume element has a **phase**  $\phi$  depending on the **distance** from a given origin



Interference depends on  $\lambda$ :



## Scattering from a cloud of free electrons - 3



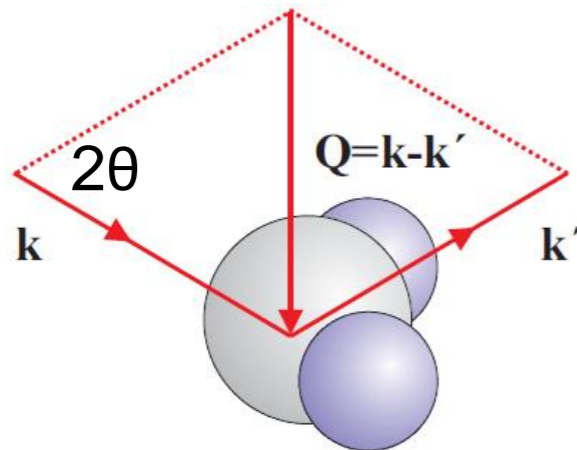
$\mathbf{k}$  = wave vector of the incident beam

$\mathbf{k}'$  = wave vector of the scattered beam

$\mathbf{k} \cdot \mathbf{r}$  phase difference of the **incident wave** in A and B

phase difference of the **scattered** wave in A and B

$$\Delta\phi(\mathbf{r}) = \mathbf{k} \cdot \mathbf{r} - \mathbf{k}' \cdot \mathbf{r} = (\mathbf{k} - \mathbf{k}') \cdot \mathbf{r} = \mathbf{Q} \cdot \mathbf{r}$$



$|\mathbf{k}| = |\mathbf{k}'| = 2\pi/\lambda$  (elastic scattering)

$\mathbf{Q} = \mathbf{k} - \mathbf{k}'$  **scattering vector** [ $\text{\AA}^{-1}$ ] describes scattering

$$|\mathbf{Q}| = \frac{4\pi}{\lambda} \sin \theta$$

$\hbar\mathbf{Q}$  **momentum transfer to the scattered photon**

It describes the total scattering amplitude as a function of  $\mathbf{Q}$

$$f^0(\mathbf{Q}) = \int \rho(\mathbf{r}) e^{i\mathbf{Q}\cdot\mathbf{r}} d\mathbf{r}$$

When  $Q \rightarrow 0$  all the different volume elements scatter in phase so that  $f^0(\mathbf{Q} = 0) = Z$

As  $Q$  increases the different volume elements scatter out of phase and consequently  $f^0 \rightarrow 0$

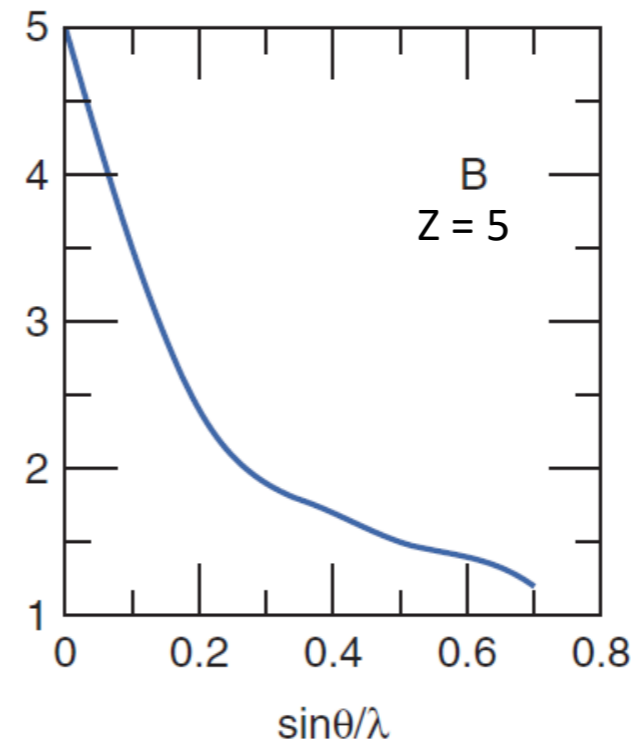
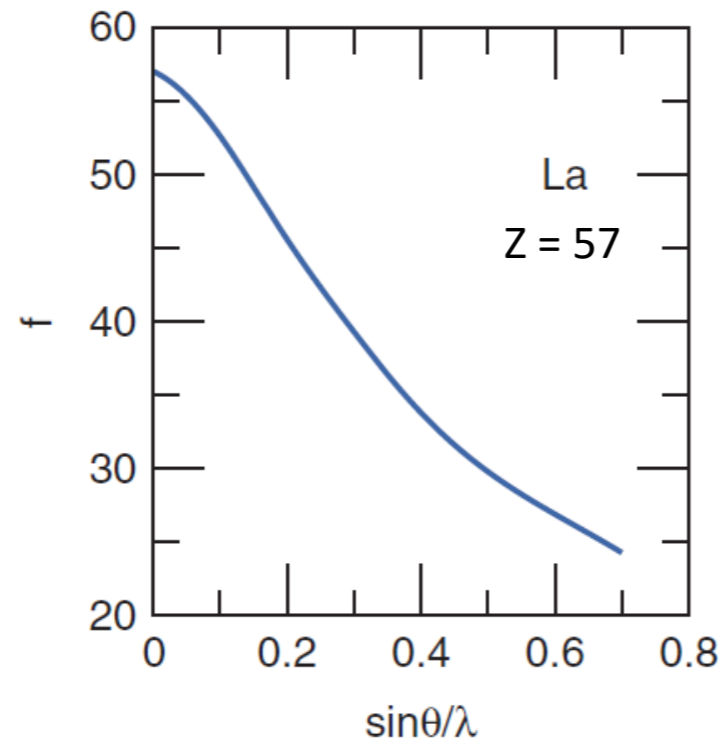
Typically, electron density is approximated to a sphere, and hence  $f^0$  depends only on  $|\mathbf{Q}|$

$$f^0(\sin \theta / \lambda) = \sum_{i=1}^4 a_i \exp(-b_i \sin^2 \theta / \lambda^2) + c$$



# Atomic scattering factor/Atomic form factor

$$f^0(\sin \theta / \lambda) = \sum_{i=1}^4 a_i \exp(-b_i \sin^2 \theta / \lambda^2) + c$$





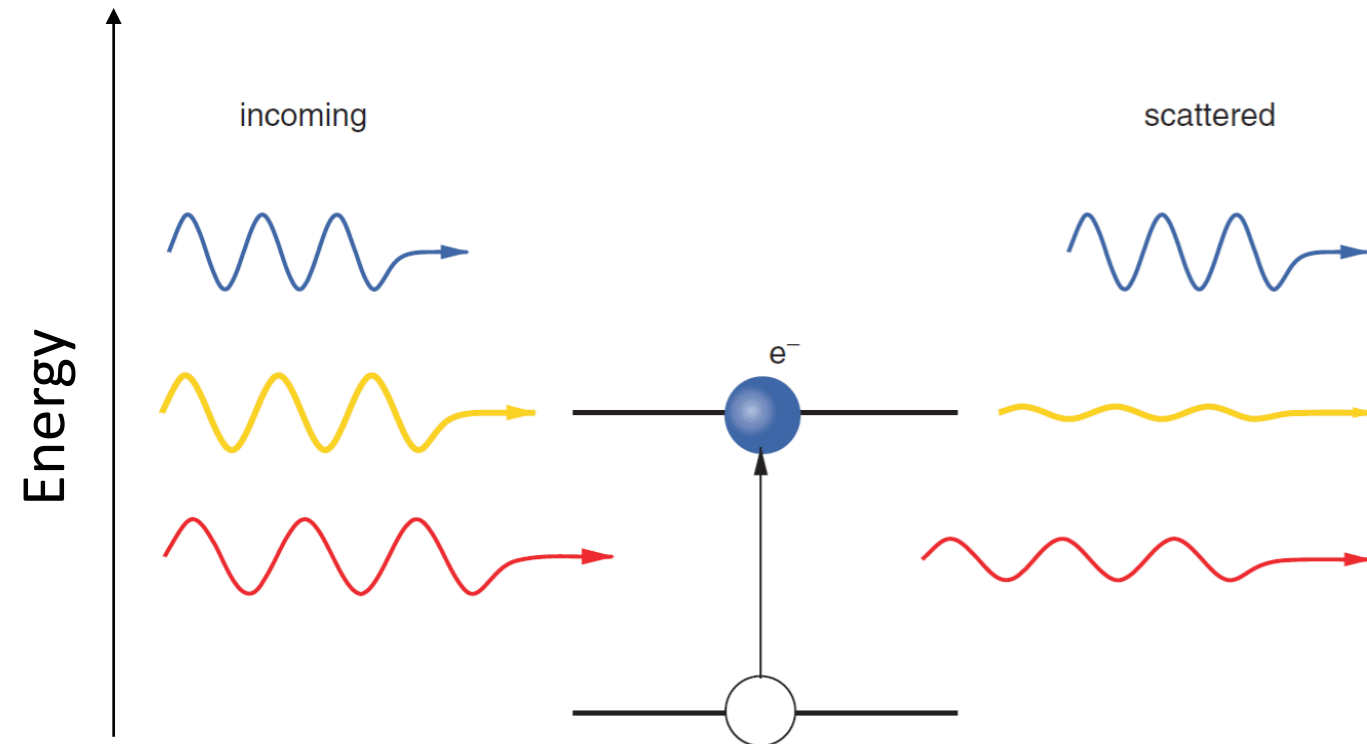
Time for a break!

...but the electrons are not free!

Quantum mechanics: atomic electrons are bound and have discrete energy levels

Correction terms (energy dependent!) must be added to scattering factor

As a general rule the atomic form factor is reduced of a factor  $f'$



When  $E_i \gg E_b$ :  
the electrons can be treated as free  
 $f' = 0$

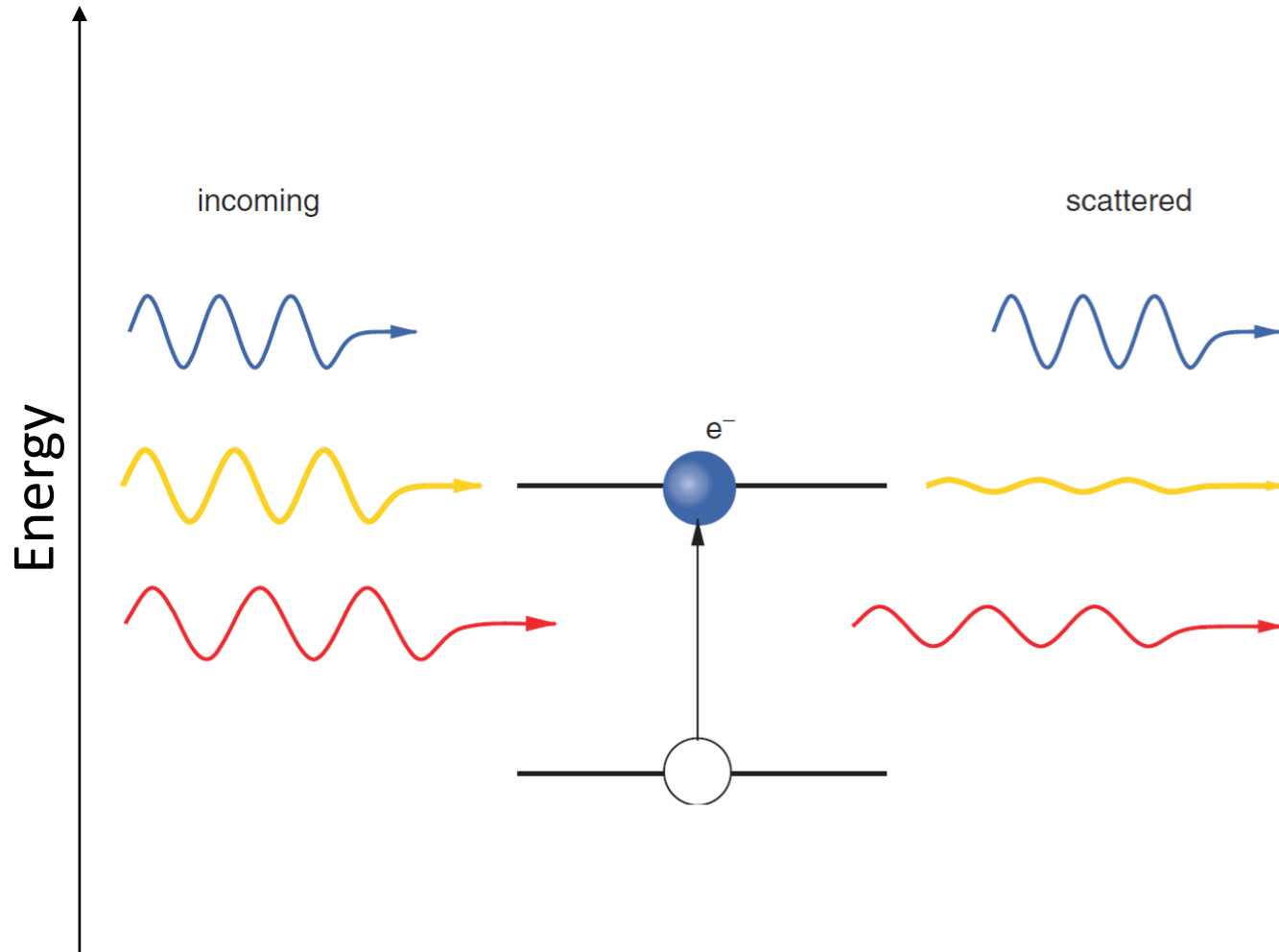
When  $E_i \ll E_b$ :  
The response (the oscillation amplitude) of  
these electrons will be damped

$f' > 0$





## Correction terms for the atomic scattering factor - 2



When  $E_i = E_b$  (close to an absorption edge) x-rays are partially absorbed and  $f'$  has a **resonant** behavior.

After a delay, some **radiation is re-emitted**, which **interferes** with the **elastically scattered part**, thereby **altering the phase and the amplitude**

This is allowed by including a term  $if''$  that is imaginary and is related to absorption

## The term $f''$

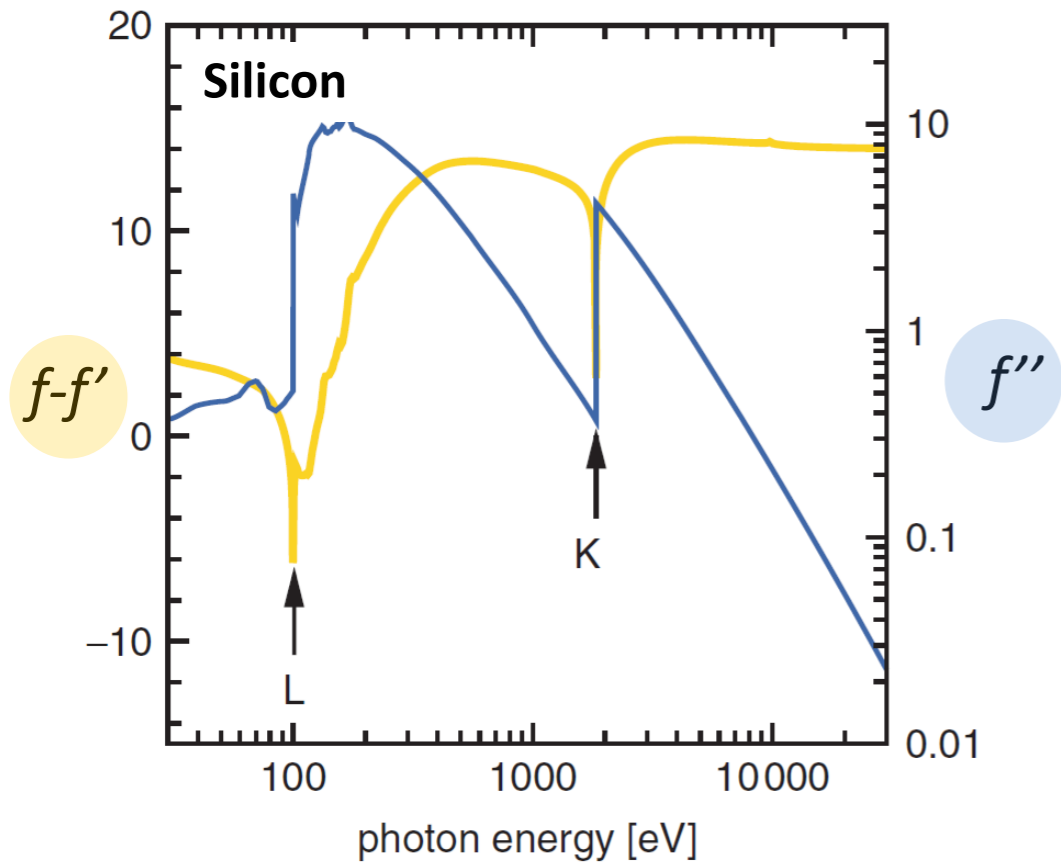
$f''$  is related to the photoabsorption cross section  $\sigma_a$  at that photon energy:  $f'' = \frac{\sigma_a}{2r_0\lambda}$

Dispersion  
corrections to  $f^0$

$$f(\mathbf{Q}, \hbar\omega) = \underbrace{f^0(\mathbf{Q}) - f'(\hbar\omega)}_{\text{Real part scattering}} + \underbrace{if''(\hbar\omega)}_{\text{Imaginary part absorption}}$$

$f'$  and  $f''$  are functions of energy: their behavior is correlated to the bound electrons

## Correction terms for the atomic scattering factor



- $f'$  and  $f''$  assume extremal values when  $h\nu =$  absorption edges
- The **real part  $f-f'$**  has a deep at the absorption edges and then converges to  $Z$
- **$f''$**  falls away as  $E^{-2}$  with discontinuity at the absorption edges

Dimensionless number describing how an EM wave propagates through a medium

$$n = \frac{c}{v}$$

*c* Speed of light in vacuum  
*v* Speed of light in the medium

*n* determines the refraction, the interface reflectivity, and the critical angle for total reflection

*n* is a factor by which the speed and  $\lambda$  are reduced with respect to vacuum

*n* varies with  $\lambda$ : due to this, white light splits into its constituent colors in prisms

Light propagation in absorbing materials can be described using a complex-valued refractive index:

$$n = n_R + in_I$$

The **real part** accounts for **refraction**, the **imaginary part** handles the **attenuation**

For x-rays,  $n$  is related to the **atomic scattering factors** of the individual atoms in a material:

Refraction index decrement

$$n = 1 - \delta + i\beta$$

$n_R$        $n_I$

→ Absorption index

$$n = 1 - \frac{r_0}{2\pi} \lambda^2 \sum_i N_i f_i(0)$$

Complex atomic scattering factor of the  $i^{\text{th}}$  atom

Number of atoms of type  $i$  per unit volume



## Real part of the refraction index

$$n = 1 - \frac{r_0}{2\pi} \lambda^2 \sum_i N_i f_i(0)$$

Complex atomic scattering factor in the forward direction of the  $i^{\text{th}}$  atom

$$n = 1 - \delta + i\beta$$

$\delta$  is the real part of  $f_i(0)$

Far from an absorption edge  $f''$  can be ignored:  $\sum_i N_i f_{1,i}(0) = \rho$

$$\Rightarrow \delta = \frac{2\pi\rho r_0}{k^2} \quad \text{Proportional to (photon energy)}^{-2}$$

Assuming  $\rho = 1 \text{ el}/\text{\AA}^3$ ,  $\delta \sim 5 \times 10^{-6}$ :  $\Rightarrow$

$$n_R = 1 - \delta \leq 1$$

## Snell's law - 1

If  $n_R < 1$ , then it exists a minimum incident angle  $\alpha_c$  angle such that:

incident angle

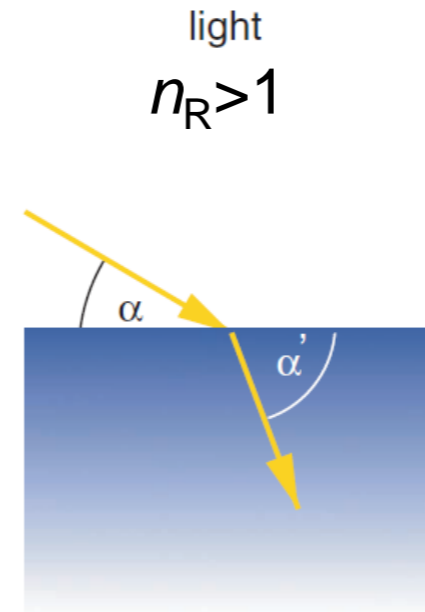
$$\frac{\cos \alpha}{\cos \alpha'} = n_R$$

refracted angle

$\alpha = \alpha_c$  critical angle:

$$\alpha' = 0 \quad \text{and} \quad \cos \alpha_c = n_R$$

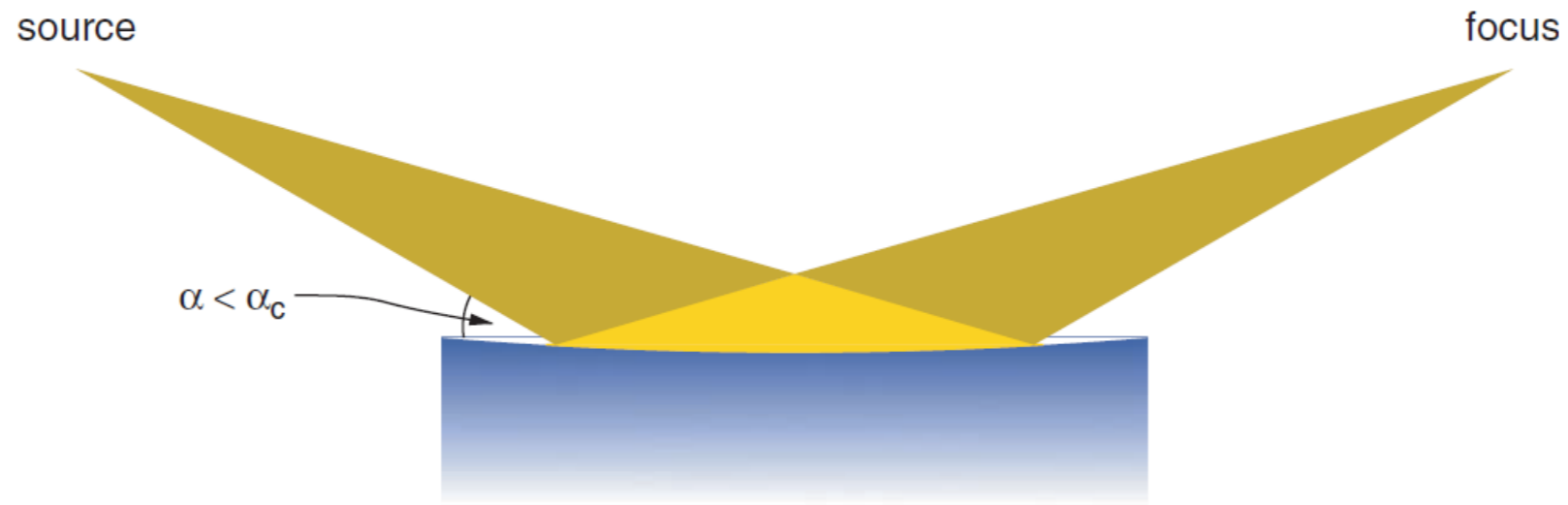
- for  $\alpha > \alpha_c$  refraction into the material
- for  $\alpha < \alpha_c$  *total external reflection*





## Practical use of $\alpha_c$

- Surfaces reflect x-rays but only at small angles  $\approx$  mrad
- Parabolic mirrors can focus x-rays at  $\alpha < \alpha_c$
- Low incident angles = large footprint and large mirrors





For  $\alpha < \alpha_c$  x-rays are «totally» reflected...

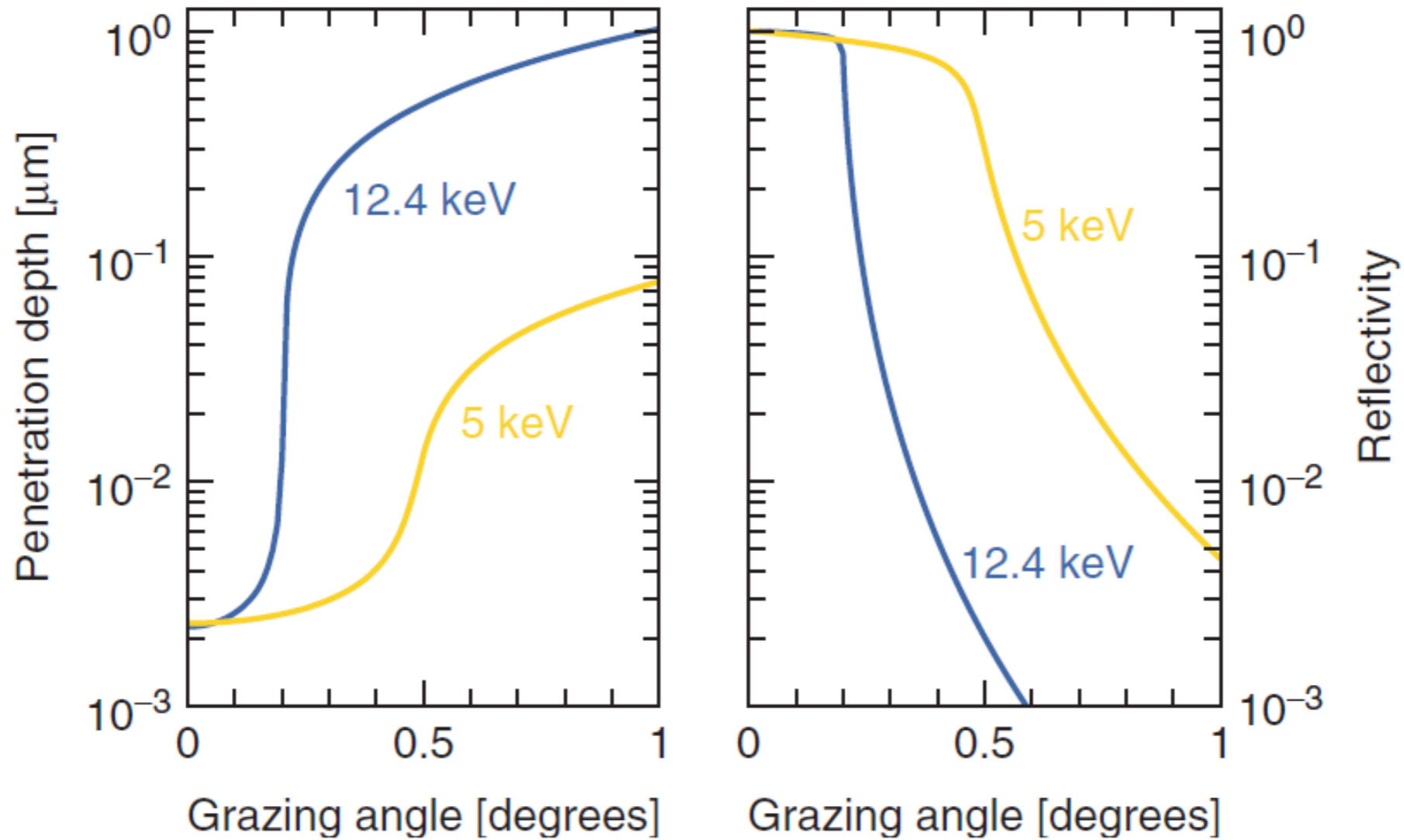
...but reflection itself requires a sort of interaction!

The penetration depth at  $\alpha < \alpha_c$  (few nm) is 3 orders of magnitude smaller than at  $\alpha > \alpha_c$

X-rays are a *surface-sensitive probe* down to the atomic level in grazing-incidence



# Penetration depth and reflectivity



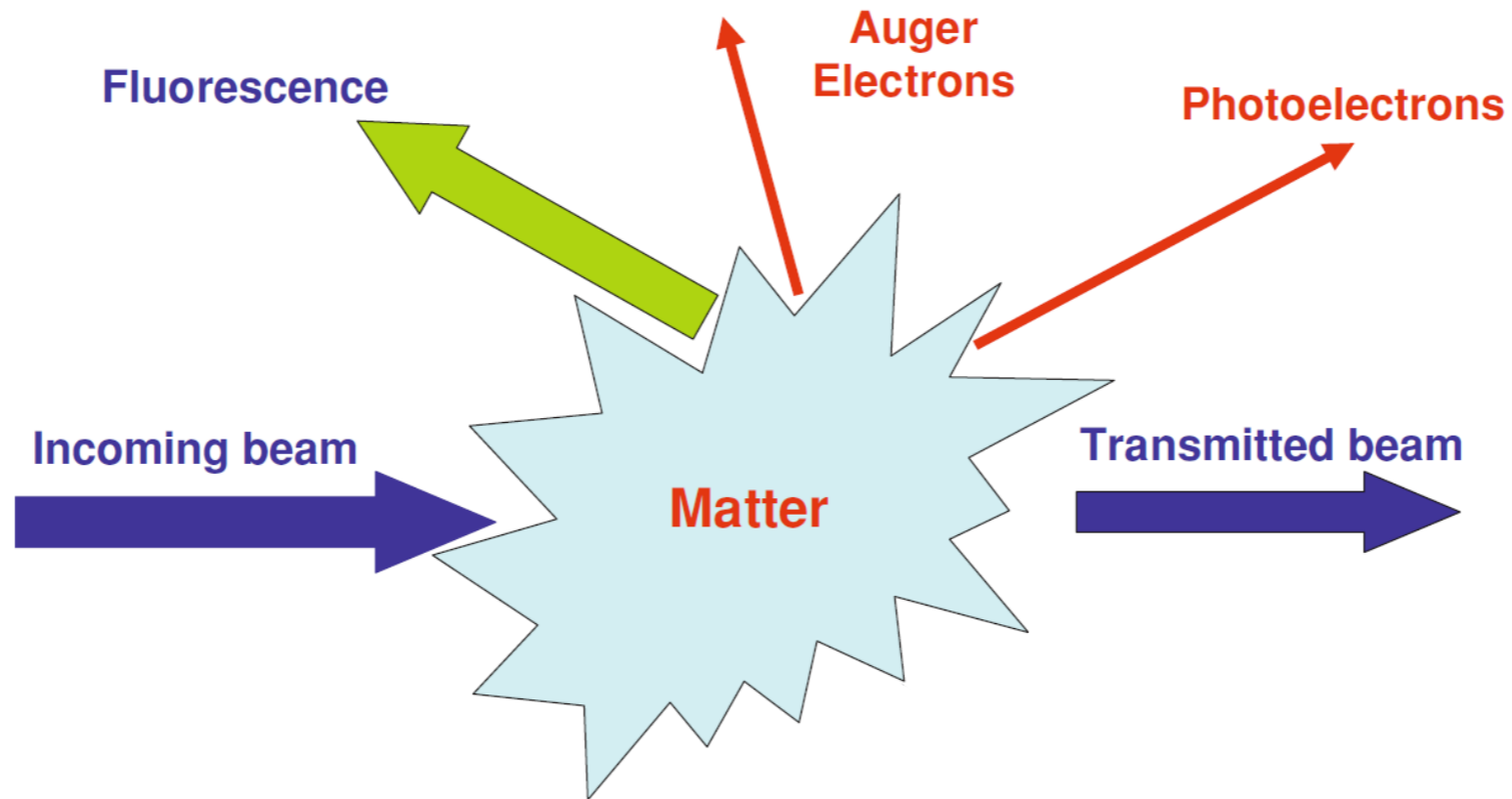


Elettra  
Sincrotrone  
Trieste

# Matter-radiation interaction: absorption



# Absorption



It is **element-specific** and a **function** of the x-ray **energy**

It increases with the atomic number of the element ( $\propto Z^4$ )

It decreases with increasing photon energy ( $\propto E^{-3}$ )

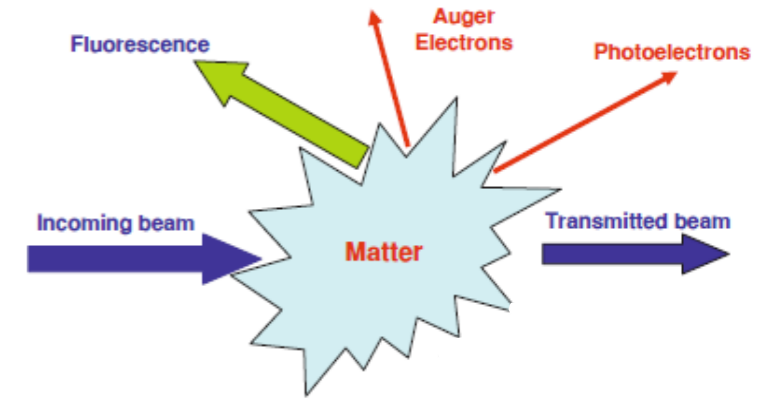


It is an indication of the **electron density** in the material and the electron **binding energy**

- Chemical substances having **different geometric ('allotropic') forms** (hence different densities) have **different absorption**
- Chemically-different compounds having the **similar electronic and mass densities** will have **similar absorption** properties (except close to absorption edges)



# Absorption



It measures the ability of a sample to **attenuate** the photon beam

The photon **excites** the absorber

When the excited state is above the vacuum level, one or more photoelectron can be emitted

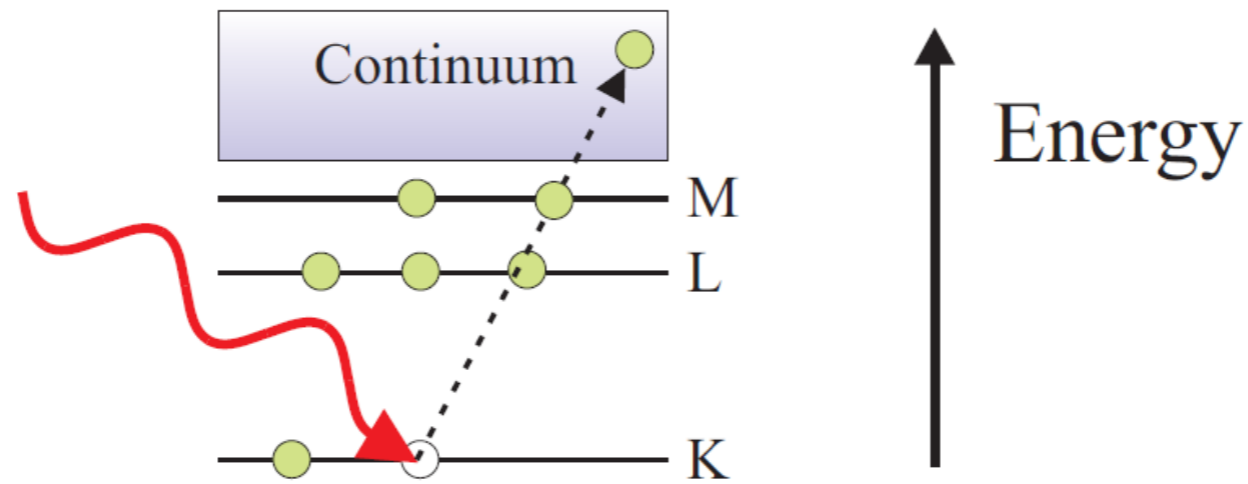
Secondary **photons** are re-emitted (fluorescence), or **electrons**

Quantitatively absorption is described by the **absorption coefficient** that can be measured

- **Directly** by measuring the attenuation of the beam as a function of the photon energy
- **Indirectly** by measuring:
  - *Photoelectrons*
  - *Fluorescence photons from the decay process*
  - *Auger electrons from the decay process*

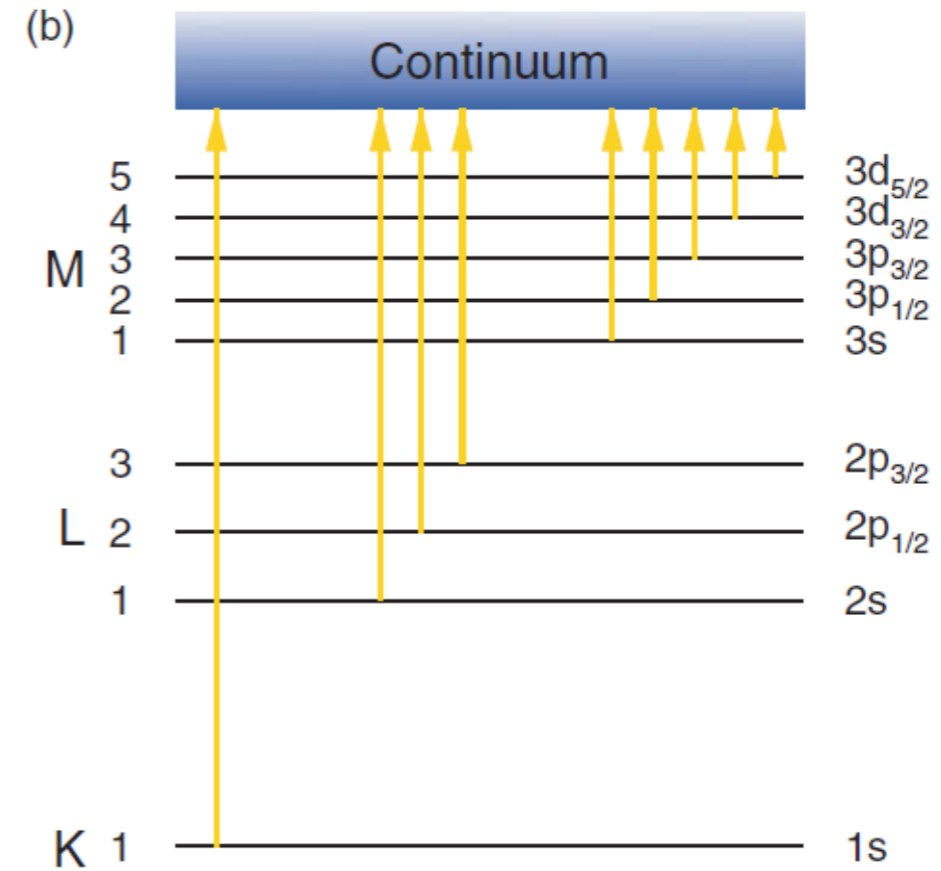
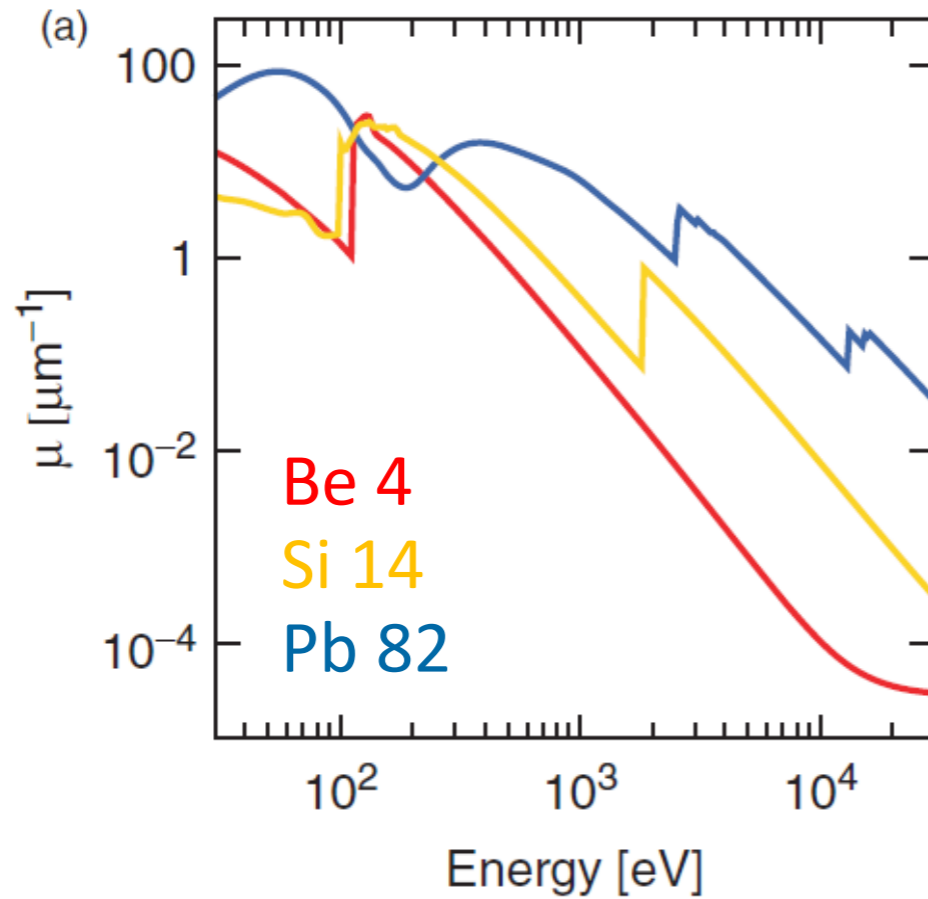
## Photoelectric absorption

Upon photon absorption, an electron is expelled from the atom, leaving it ionized





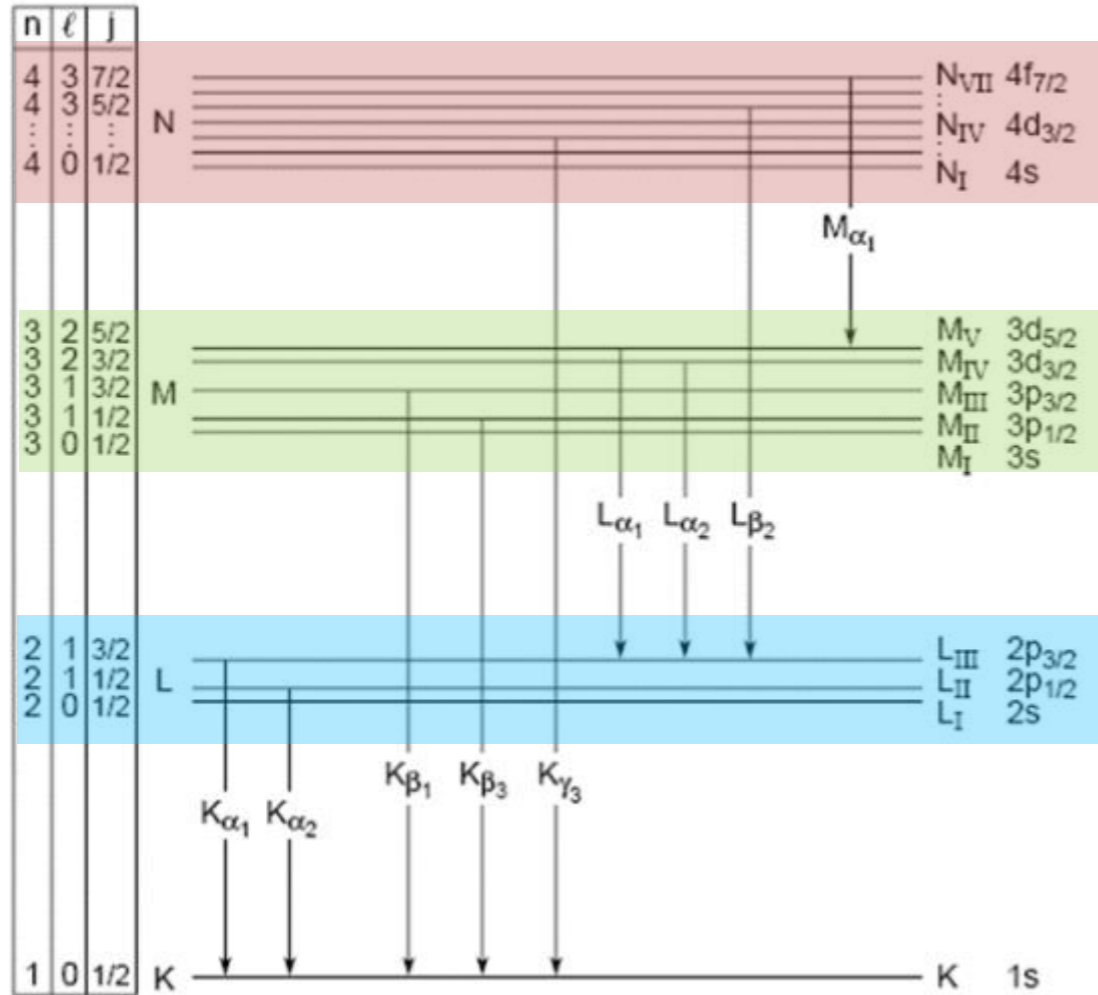
# The absorption coefficient







# Emission lines nomenclature



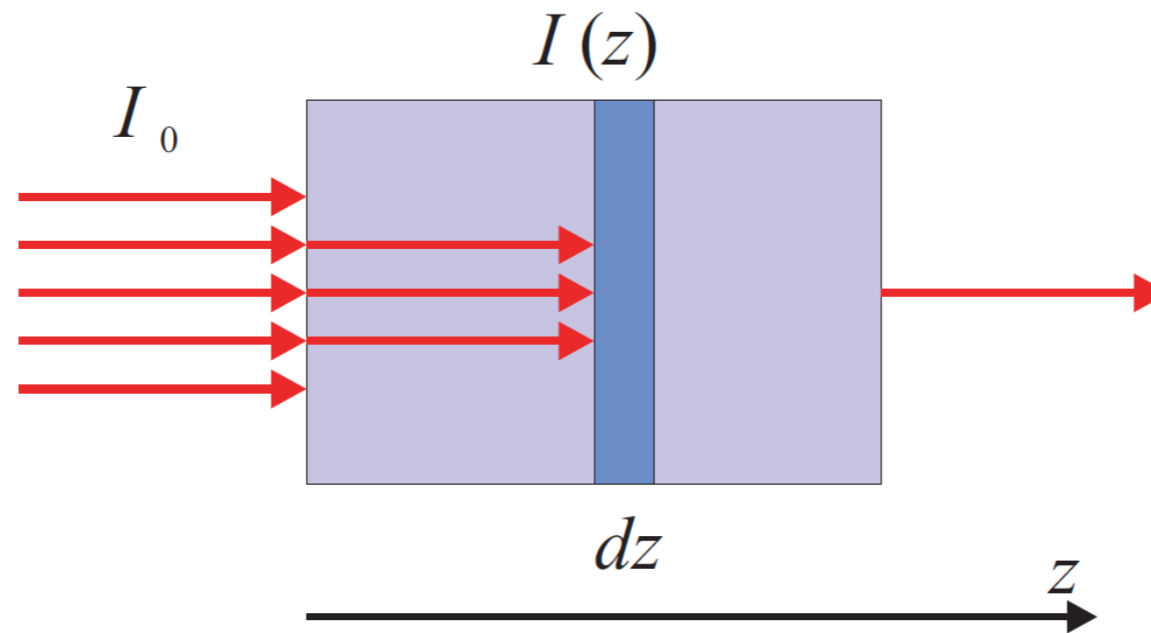
## Characteristic energy of the K<sub>α</sub> line (Moseley law)

X-ray frequency  $\nu = K(Z - 1)^2$  Atomic number

For K<sub>α</sub> lines,  $K = (2.47 \cdot 10^{15} \text{ Hz})$

## Measuring the absorption -1

Quantitatively, the absorption is given by the **linear absorption coefficient  $\mu$**   
 **$\mu dz$**  attenuation of the beam through an infinitesimal thickness  $dz$  at a depth  $z$



The intensity  $I(z)$  through the sample fulfills the condition

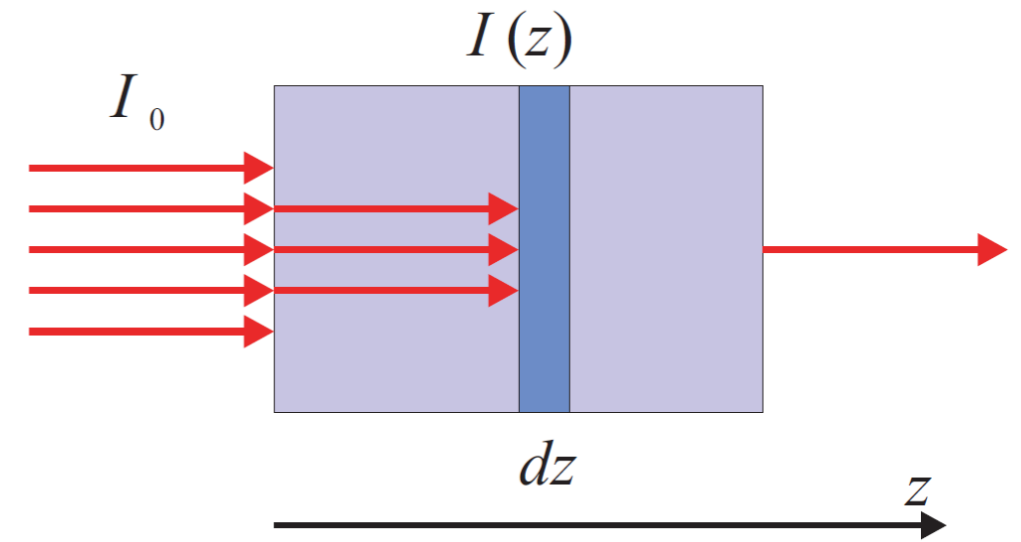
$$-dI = I(z)\mu dz$$

Which leads to the differential equation

$$\frac{dI}{I(z)} = -\mu dz$$

If  $I(z = 0) = I_0$ , ( $I_0$ : incident beam intensity) then

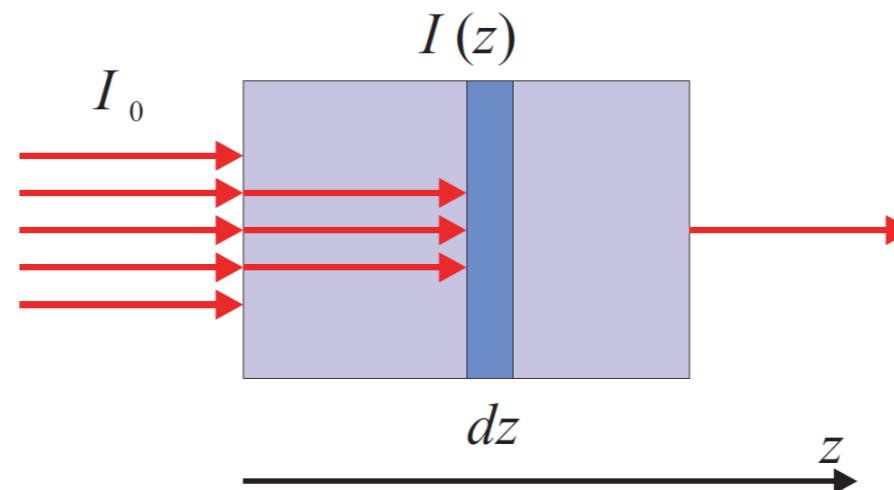
$$I(z) = I_0 e^{-\mu z}$$



## Measuring the absorption - 3

$$I(z) = I_0 e^{-\mu z} \Rightarrow \ln \frac{I_0}{I} = \mu z$$

Experimentally,  $\mu$  can be obtained from the ratio of the beam intensities before / after the sample





## Atomic absorption cross section $\sigma_a$

$$\mu = \underbrace{\rho_{at}}_{\text{Atomic number density}} \sigma_a = \left( \frac{\underbrace{\rho_m}_{\text{mass density}} \underbrace{N_A}_{\text{Avogadro's number}}}{\underbrace{A}_{\text{Atomic mass}}} \right) \sigma_a$$

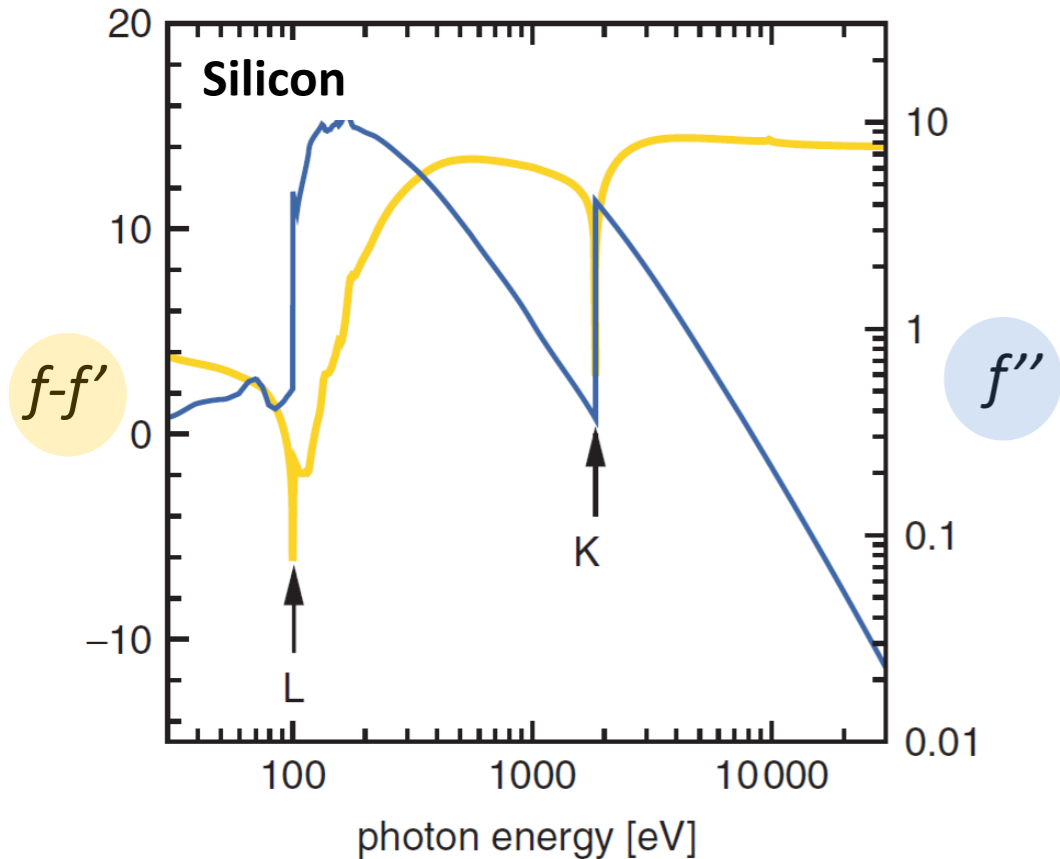
$$\sigma_a [\text{cm}^2] \dots \text{or} \dots \sigma_a [\textit{barn}]$$

$$1 \textit{ barn} = 10^{-28} \text{ m}^2$$

$$\sigma_a \left[ \frac{\text{cm}^2}{\text{g}} \right] = \frac{N_A}{A} \sigma_a [\text{cm}^2] = \frac{\mu}{\rho_m}$$

- Different atoms, each with a number density  $\rho_{at,j}$  and absorption cross section  $\sigma_{a,j}$
- Total probability for absorption in a layer  $dz$  is the sum over  $\rho_{at,j} \sigma_{a,j} dz$  the probability of absorption for an atom for type  $j$ :

$$\mu = \sum_j \rho_{at,j} \sigma_{a,j}$$



The **photoelectric absorption** arises from a physical process that is **different** from the scattering of a **photon**

However, **absorption and scattering are related**



# Absorption coefficient and n - 1

Refractive index  $n = 1 - \frac{r_0}{2\pi} \lambda^2 \sum_i N_i f_i(0)$

Complex atomic scattering factor in the forward direction of the  $i^{\text{th}}$  atom

$$f_i(0) = f_{i1} + if_{i2}, n = 1 - \delta + i\beta$$

$$n = 1 - \frac{r_0}{2\pi} \lambda^2 \sum_i N_i (f_{i1} + if_{i2})$$

$$n = 1 - \frac{r_0}{2\pi} \lambda^2 \sum_i N_i f_{i1} - \frac{r_0}{2\pi} \lambda^2 \sum_i N_i i f_{i2} \longrightarrow i\beta$$

$$\beta = \frac{r_0 \lambda^2 \rho}{2\pi} f_2 = \frac{2\pi r_0 \rho}{k^2} f_2$$

$$\text{since } f_2 \propto \frac{1}{E^2} \implies \beta \propto \frac{1}{E^4}$$





## Absorption coefficient and $n - 2$

For a wave travelling in vacuum

$$E(z, t) = E_0 \exp[i(k_0 z - \omega t)]$$

In a medium

$$E(z, t) = E_0 \exp[in k_0 z - \omega t]$$

Since  $n = 1 - \delta + i\beta$ :

$$E(z, t) = E_0 \exp(-\beta k_0 z) \exp[i((1 - \delta)k_0 z - \omega t)]$$

measures the damping  
in a medium



## Absorption coefficient and $n - 3$

In practice we measure the **intensity** which is  $\propto |E|^2$

$$|E(z, t)|^2 = E_0^2 \exp(-2\beta k_0 z) \exp[2i((1 - \delta)k_0 z - \omega t)]$$

The intensity drops by an amount  $1/e$  over a depth  $1/2\beta k_0$

In terms of the absorption coefficient:  $\frac{I}{I_0} = \exp(-\mu z)$ , then:

$$\mu = 2\beta k_0$$

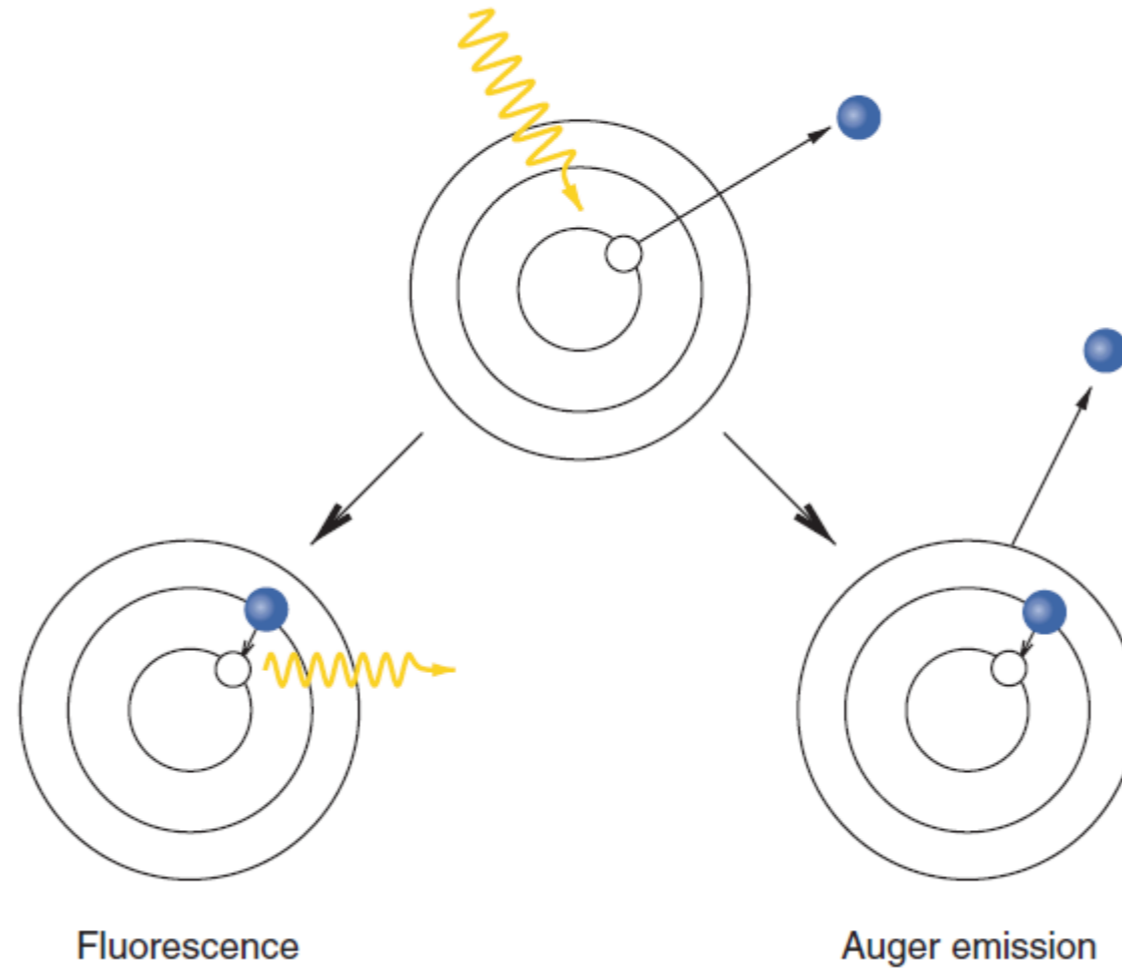
Therefore:

$$f_2 = \frac{k^2}{2\pi r_0 \rho} \beta = \frac{k^2}{2\pi r_0 \rho} \frac{\mu}{2k} = \sigma_a \frac{k}{4\pi r_0} = \sigma_a \frac{2\pi}{\lambda} \frac{1}{4\pi r_0} = \frac{\sigma_a}{2r_0 \lambda}$$

$f''$  related to the photoabsorption cross section  $\sigma_a$  at that photon energy



## Secondary effects



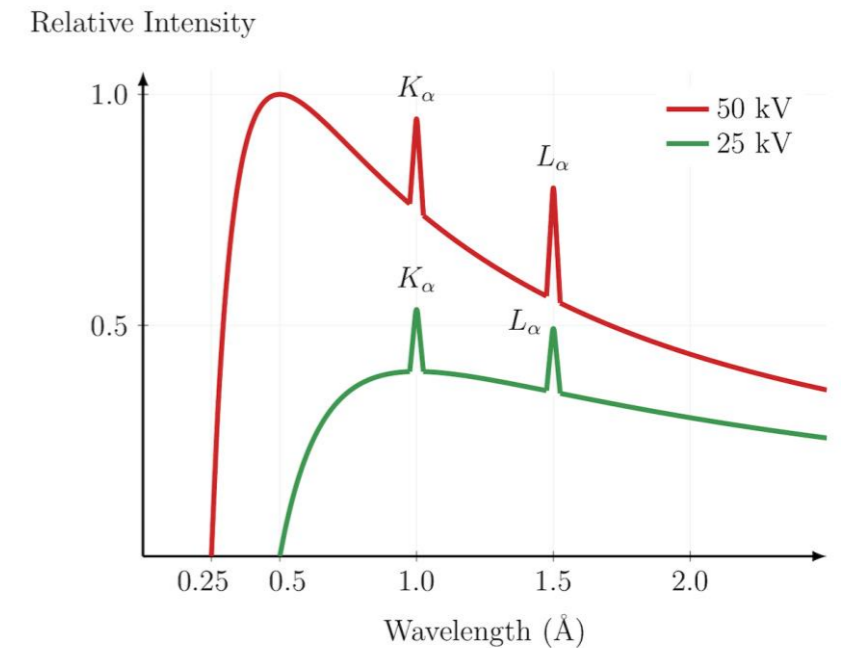


## X-ray fluorescence - 1

Any material emit fluorescence if bombarded it with x-rays or high-energy electrons.

If electrons are used, the energy spectrum of the emitted light has two parts:

- A broad background is produced as electrons collide with the atoms due to the strong deceleration (**Bremsstrahlung**). It has a maximum cut-off energy corresponding to the highest kinetic energy of the electrons impinging on the target
  - The sharp fluorescence lines, which are characteristic for each element
- 
- In the case of excitation by x-rays, the Bremsstrahlung is missing...



These characteristic x-ray lines result from the transition of an outer-shell electron relaxing to the hole left behind by the ejection of the photoelectron from the atom

This occurs on a timescale of the order of 10 to 100 fs

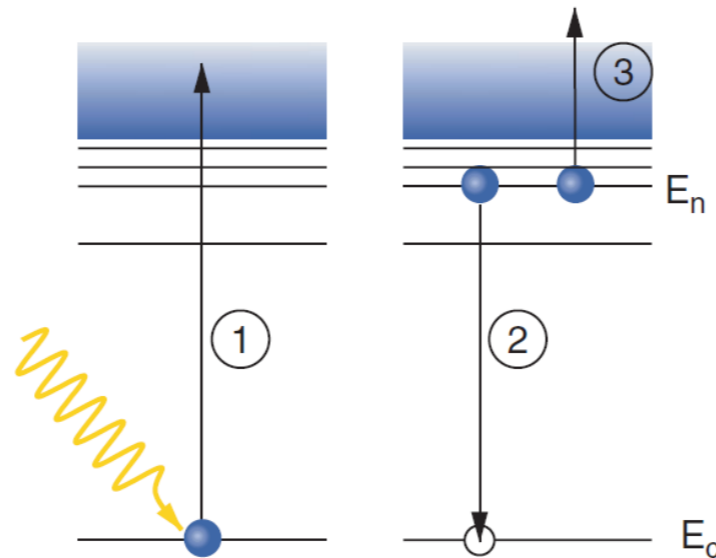
The energy difference between the two involved levels is well defined → lines are very sharp

From Heisenberg's uncertainty principle  $\Delta E \Delta t \sim \hbar$ , the natural linewidth is  $\sim 0.01$  eV, (but depends on the element and on the transition)

It is a three-electron process:

1. a core electron ( $E_c$ ) is emitted upon absorption
2. an outer electron ( $E_n < E_c$ ) fills the hole of the photoelectron
3. the excess energy ( $\Delta E = E_c - E_n$ ) is transferred to the Auger electron

Auger emission may occur for those electrons whose binding energy is  $< \Delta E$

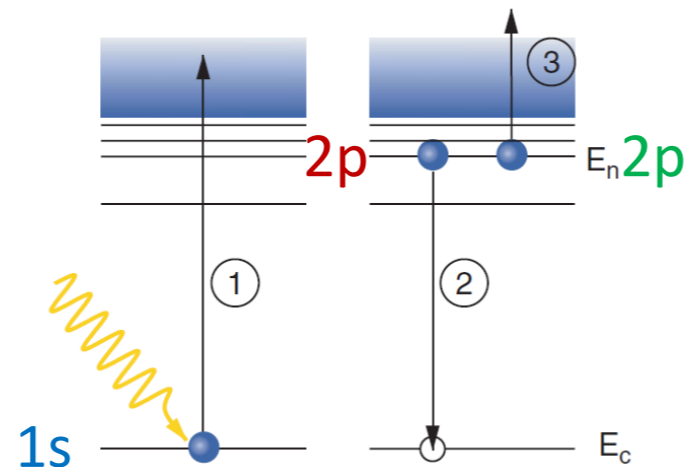


$$KE = E_c - E_n - E_A$$

3 letters: 3 electronic levels involved in Auger emission  
(using Barkla notation of  $K, L, M, \dots$ )

For a **KLL** Auger electron:

- **K** is the core-level from which the photoelectron originates (with energy  $E_C$ )
- **L** is the level from which the electron that fills the core-hole originates (energy  $E_N$ )
- **L** is the original level of the Auger electron (energy  $E_A$ )



## Fluorescence or Auger?

- The probability of Auger emission increases with decreasing energy difference between the excited atom and the atom after Auger emission
- LMM events are more likely than KLL events
- Lower Z atoms have higher Auger yields
- Higher Z elements have larger positive charges at the nucleus: electrons are more tightly bound and the probability of Auger emission is lower

