2009 spring

Microstructural Characterization
of
Materials

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Contents for previous class

Microstructure: structure inside a material

that could be observed with the aid of a microscope

Observation of Microstructure: to make image

from the collection of defects in the materials

➡ **OM, SEM, TEM, EXAFS, AFM, SPM**

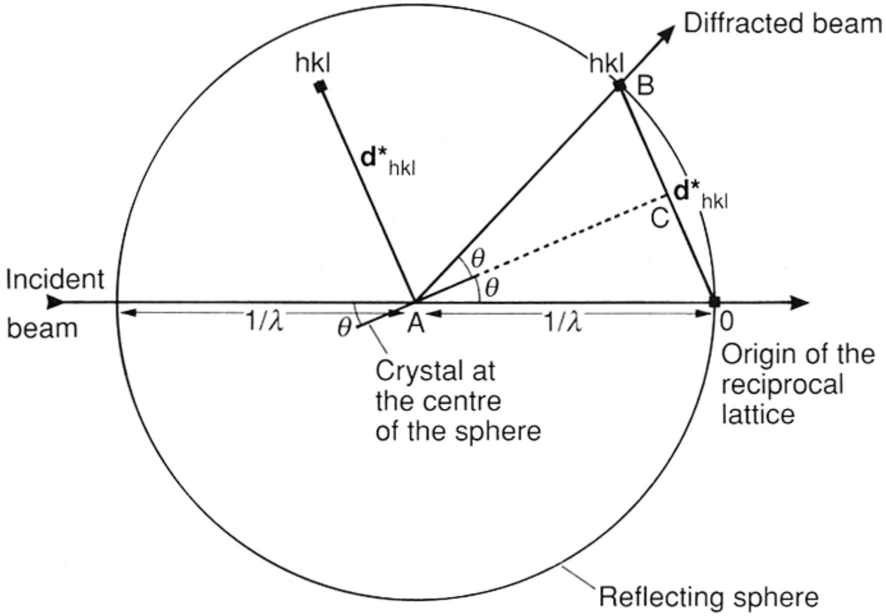
Length Scale of Microstructure

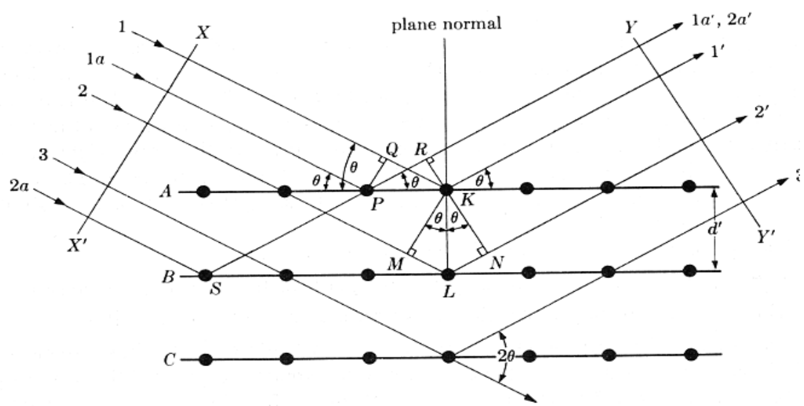
- **Many important intrinsic material properties are determined at the *atomistic length scale*.**

- **The Properties of materials are, how, often strongly affected by the *defect structure*. For example, polycrystals have different properties than single crystals just because of the variation of crystal orientation, combined with the anisotropy of the property. This immediately introduces the idea that the behavior of a material can vary from on location to another.**

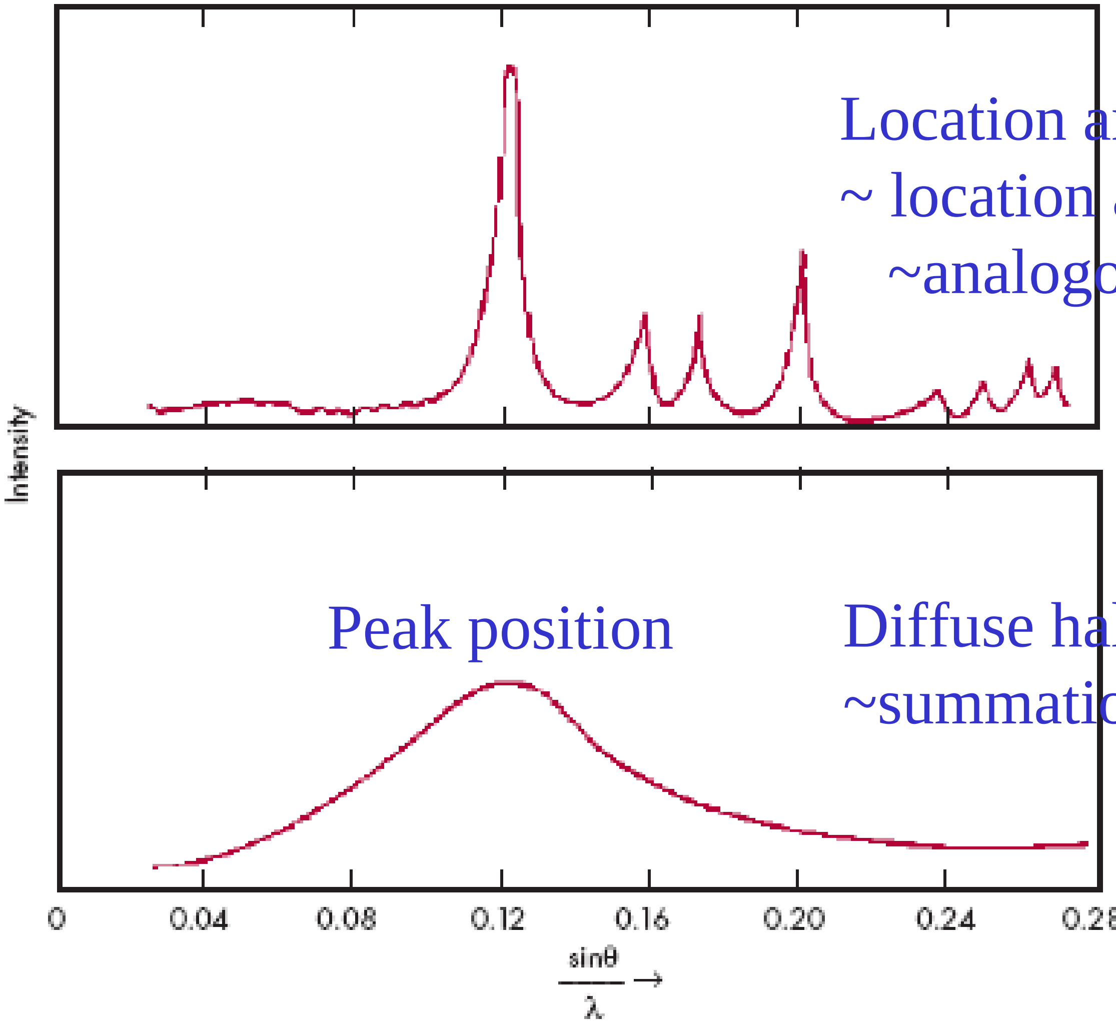
XRD (X-ray Diffraction)

X선을 결정에 부딪히게 하면 그 중 일부는 회절을 일으키고 그 회절각과 강도는 물질구조상 고유한 것으로서 이 회절 X-선을 이용하여 시료에 함유된 결정성 물질의 종류와 양에 관계되는 정보를 알 수 있다.





X-ray diffraction results



Location and intensity of peaks
~ location and arrangement of atoms
~analogous to a fingerprint

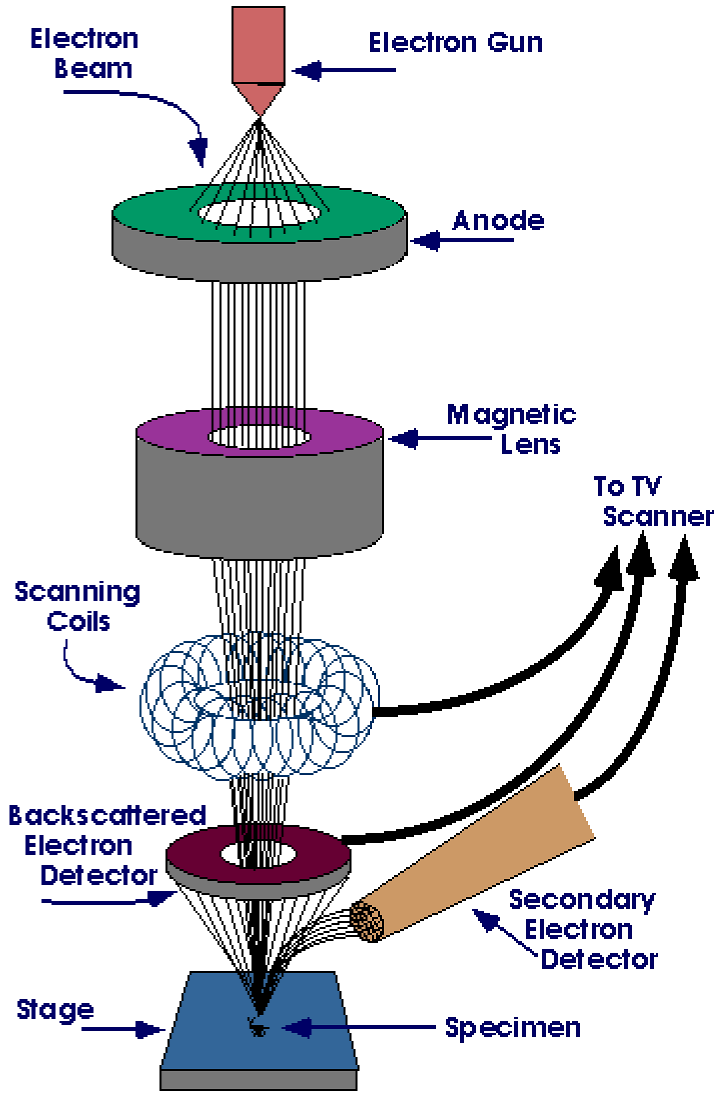
Peak position

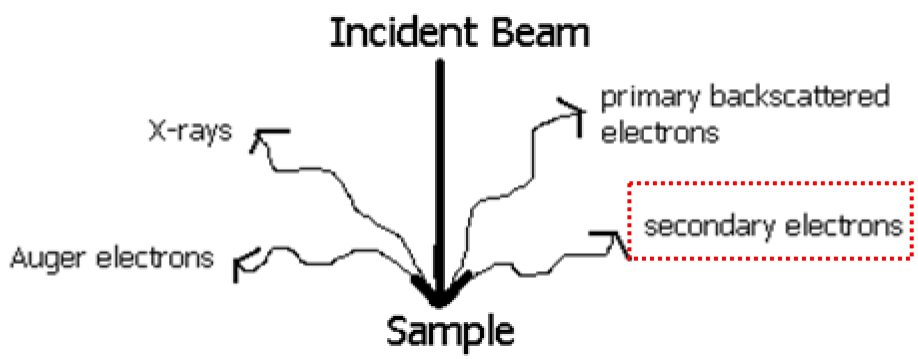
Diffuse halo pattern
~summation of interference

Figure 3. Characteristic Diffraction Patterns from Crystalline Material (Top) and Amorphous Material (Bottom). [3]

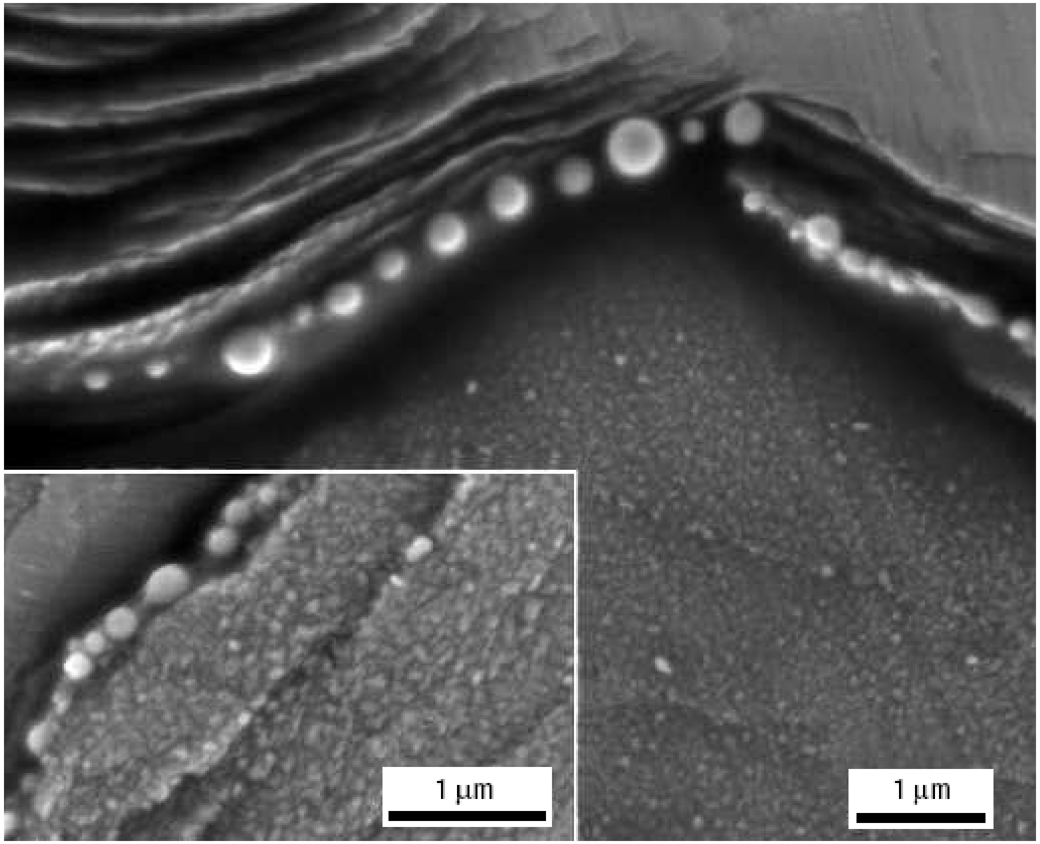
SEM (Scanning Electron Microscopy)

SEM은 Electron beam이 Sample의 표면에 주사하면서 Sample과의 상호작용에 의해 발생된 Secondary Electron를 이용해서 Sample의 표면을 관찰하는 장비이다.





Observation of SBs after three point beam bend test

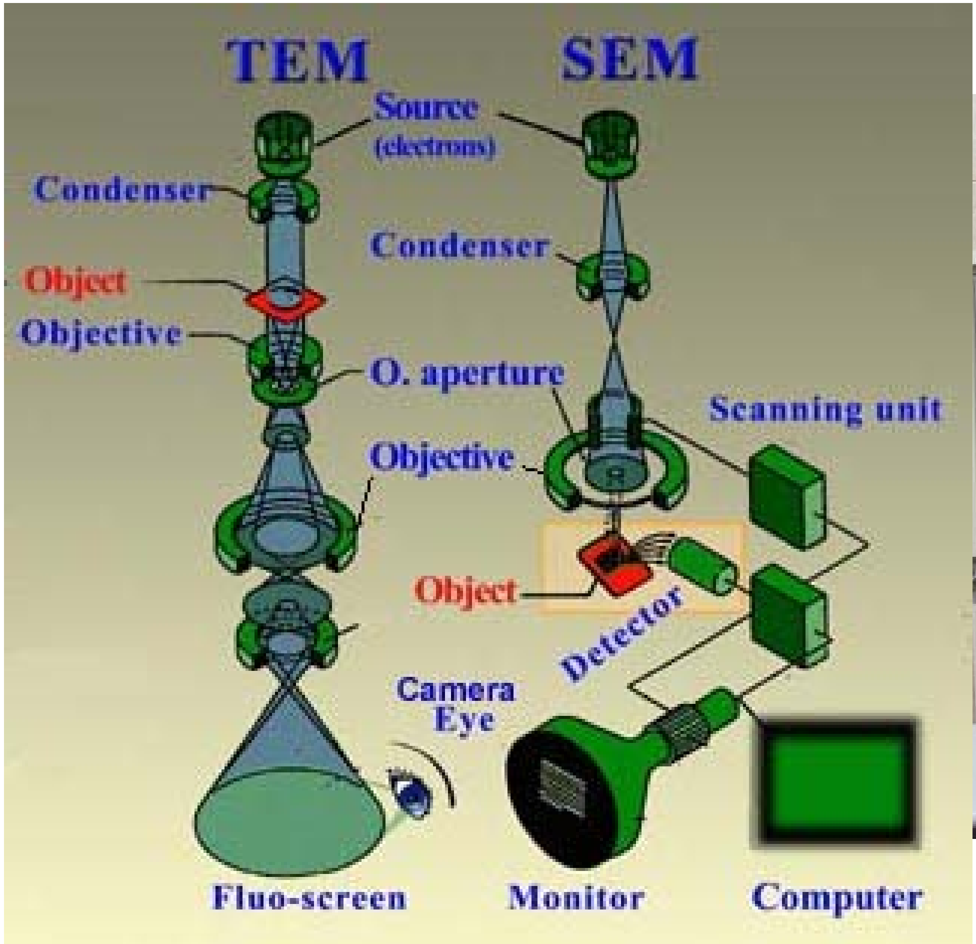


J. J. Lewandowski et al., Nature Mater. 5 (2006) 15

Melting of Sn coating on the surface of Vit. 1 on the compression side
→ evidence for temperature rise ($T_{m, Sn}$ = 232℃)

TEM (Transmission Electron Microscopy)

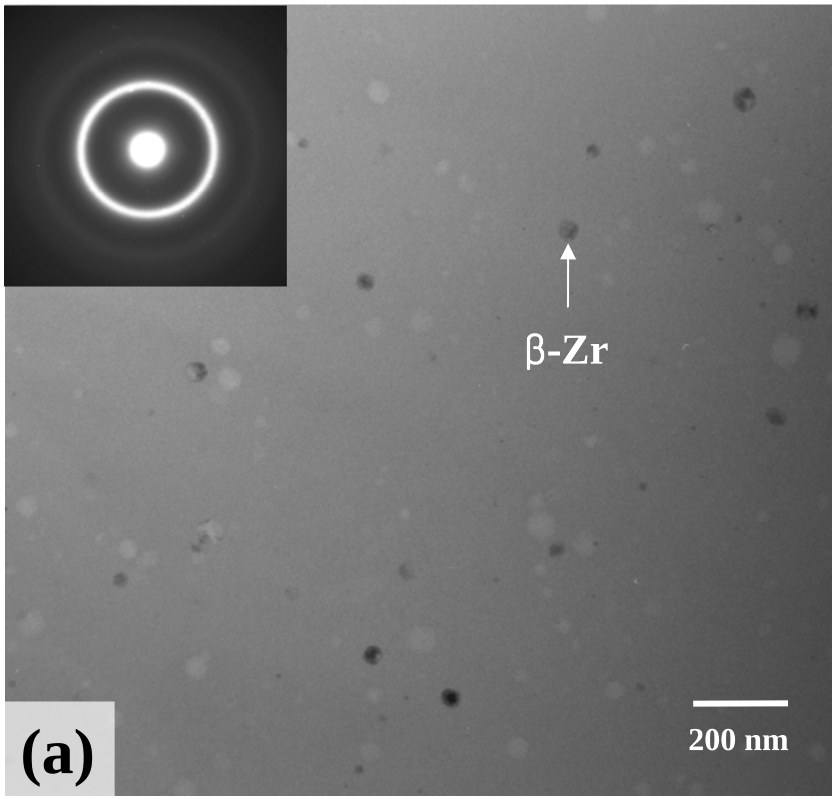
TEM은 electron beam이 통과할 수 있도록 ultrathin sections을 만들어 관찰할 수 있도록 하는 기능적 장치로 여러 가지 각각의 시스템으로 구성되어 있다.



Effect of quenched-in quasicrystal nuclei

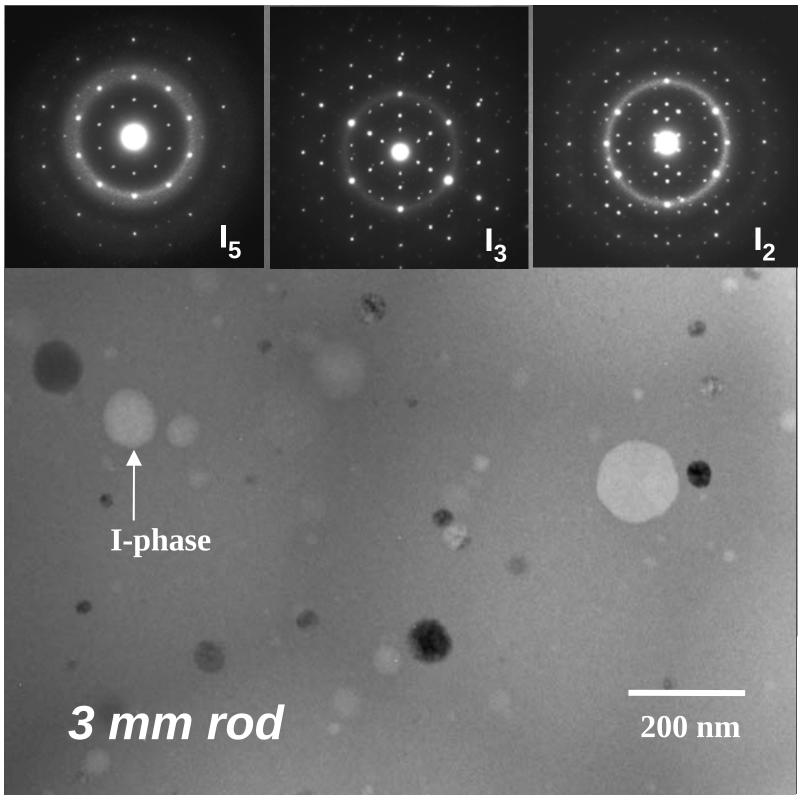
2 mm rod

(a) $Zr_{63}Ti_5Nb_2Cu_{15.8}Ni_{6.3}Al_{7.9}$



β-Zr particle(~70 nm) in amorphous matrix

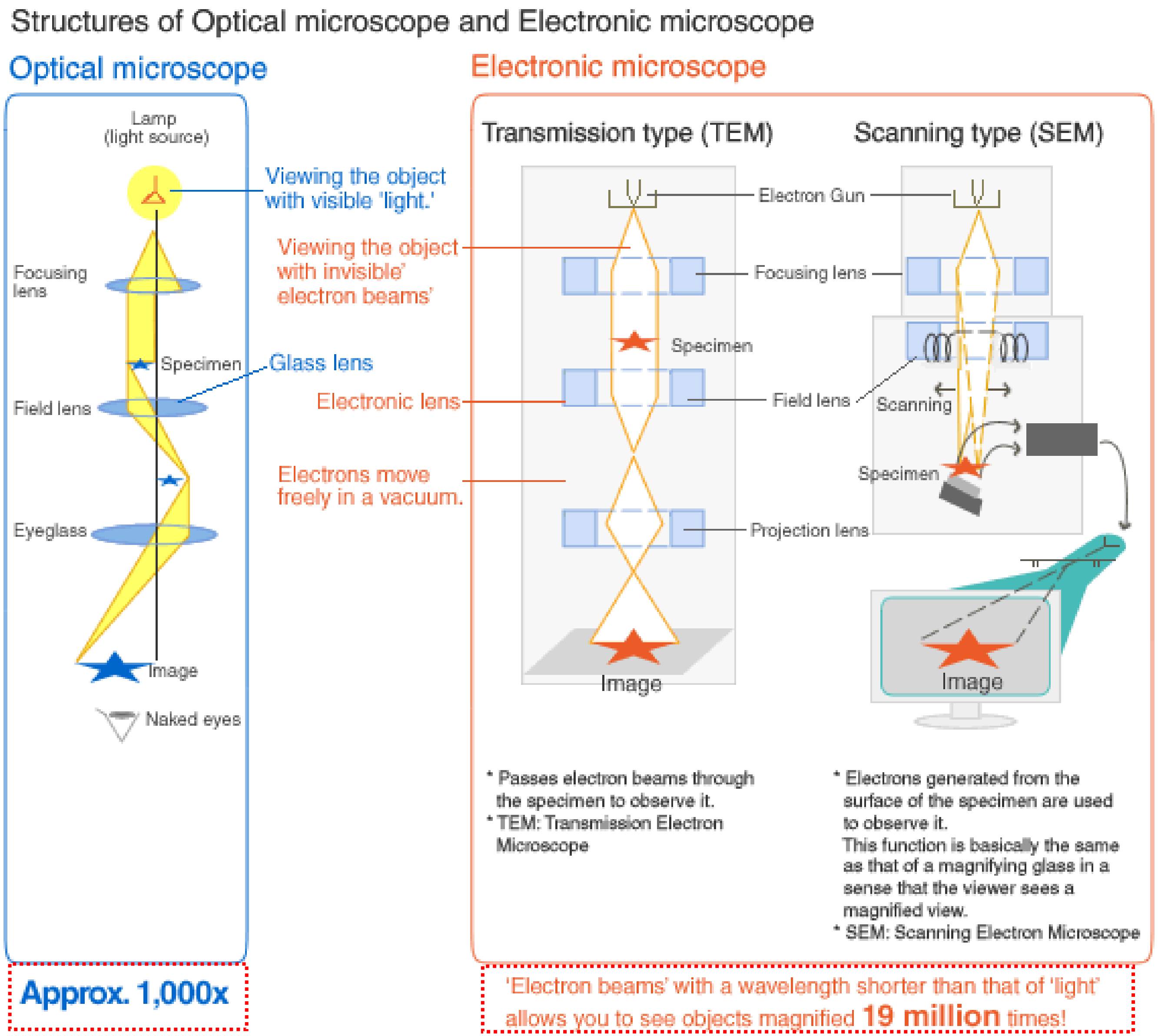
(b) $Zr_{57}Ti_8Nb_{2.5}Cu_{13.9}Ni_{11.1}Al_{7.5}$



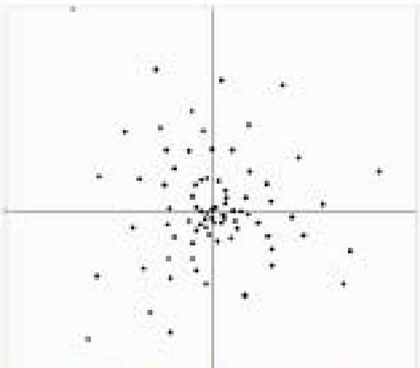
Fully amorphous structure

Optical Microscope

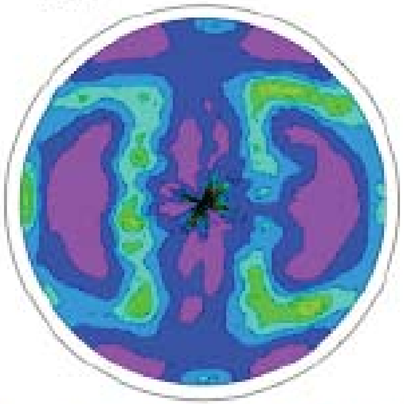
OM과 TEM은 기본적인 구성 즉 렌즈의 배열은 같으나 렌즈를 무엇을 사용하느냐 하는 차이 이다. OM은 유리(glass)를 EM은 magnetic lens를 사용한다. 광원은 OM이 시광을 EM이 전자(빔)를 사용하므로 전자현미경은 칼라 상을 볼 수 없는 것이다.

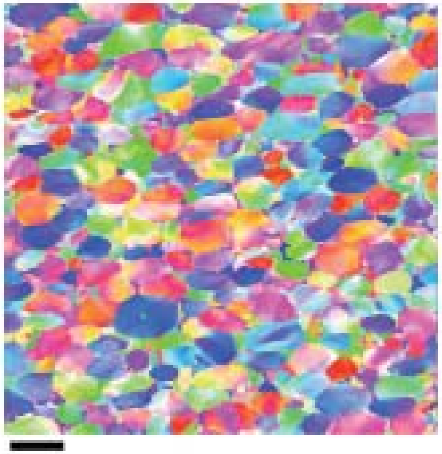


Crystal Orientation: texture



escher.epfl.ch/diffractOgram/





- The best method of quantifying texture is to measure the crystallographic orientation of a statistically representative set of grains in the material.
- Historically, this was a tedious exercise with Laue X-ray diffractograms that was only possible on single crystals or very coarse polycrystals.
- The standard characterization method for *texture* (crystallographic preferred orientation) in an average sense is to measure *x-ray pole figures*.
- A more modern technique is that of Orientation Imaging Microscopy (OIM), which is readily available in the SEM (and much used here at CMU). This technique produces a map of orientation measured on a regular grid of points (pixels).

Contents for today's class

- ➡ **Simple idea of analytical tools**

- ➡ **Quantum theory**
  - **Wave-particle duality**
  - **Photoelectronic effect** ➡ **Photons**
  - **Compton effect**

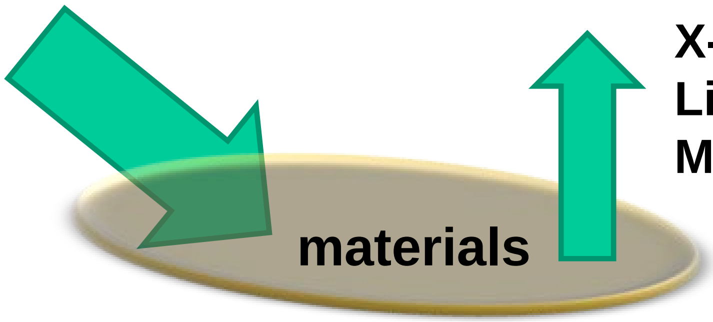
- ➡ **Quantum Nature of Photons**

- ➡ **Matter Waves ?**

- ➡ **Wave length *vs* size**

Simple idea of analytical tools

Electron
X-ray
Laser
Light
Shockwave
Mechanical



Electron
X-ray
Light
Mechanical

Analytical tool	Abbreviation	Source	Signal	Main Analysis
X-ray diffraction	XRD	X-ray	X-ray	Structure
Transmission Electron Microscopy Scanning Electron Microscopy	TEM SEM	Electron	Electron, Photon (X-ray, Light)	Structure/ Chemistry
X-ray Photoelectron Spectroscopy	XPS	X-ray	Electron	Surface chemistry/ bonding
Auger Electron Spectroscopy	AES	Electron	Electron	Surface chemistry
Energy Dispersive Spectroscopy Wavelength Dispersive Spectroscopy	EDS WDS	Electron	X-ray	Chemistry
Electron BackScattered Diffraction	EBSD	Electron	Electron	Structure/ chemistry

What is Quantum Theory?

Quantum theory is a theory needed to describe physics on a **microscopic scale**, such as on the scale of atoms, molecules, electrons, protons, etc.

Classical theories:

Newton – Mechanical motion of objects (F = ma)
Maxwell – Light treated as a wave

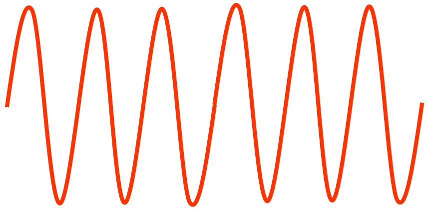
NEITHER OF THESE THEORIES QUITE WORK FOR ATOMS, MOLECULES, ETC.

Quantum (from Merriam-Webster)

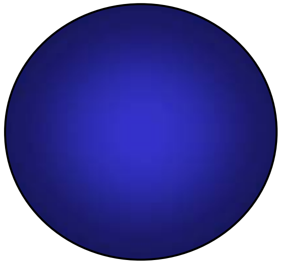
Any of the very small increments or parcels into which many forms of energy are subdivided.

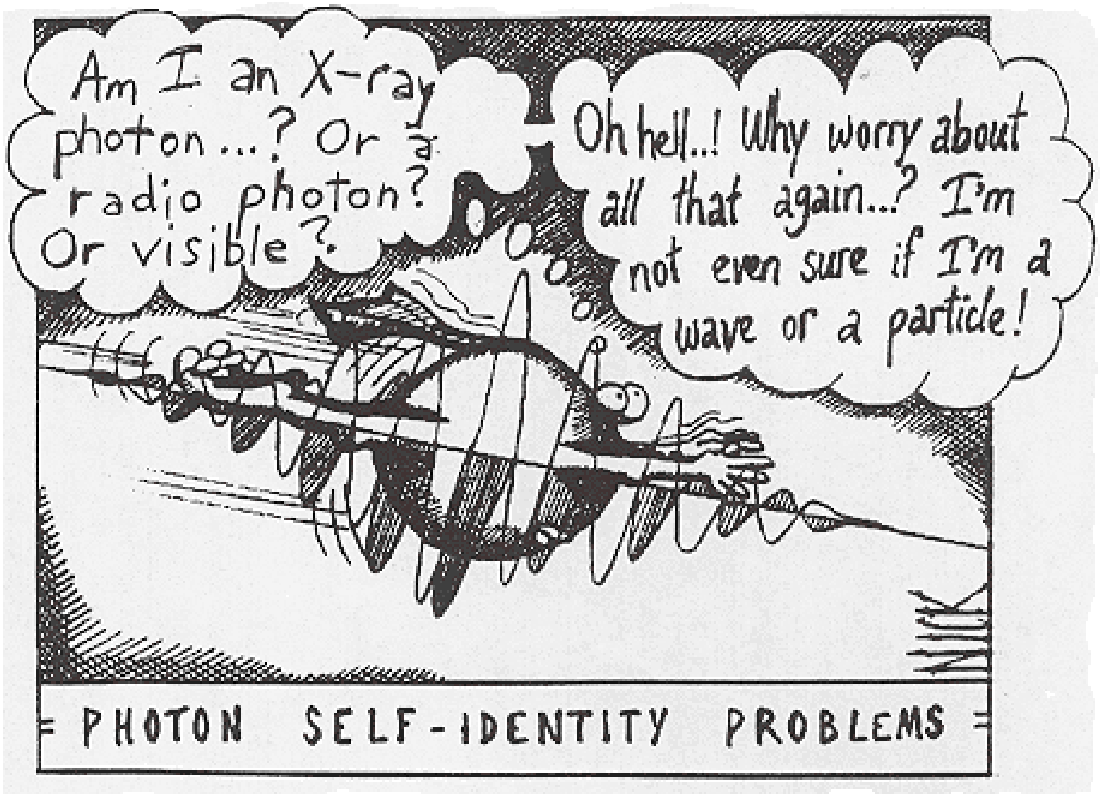
Light is a form of energy is a quantum of EM energy

The Wave – Particle Duality



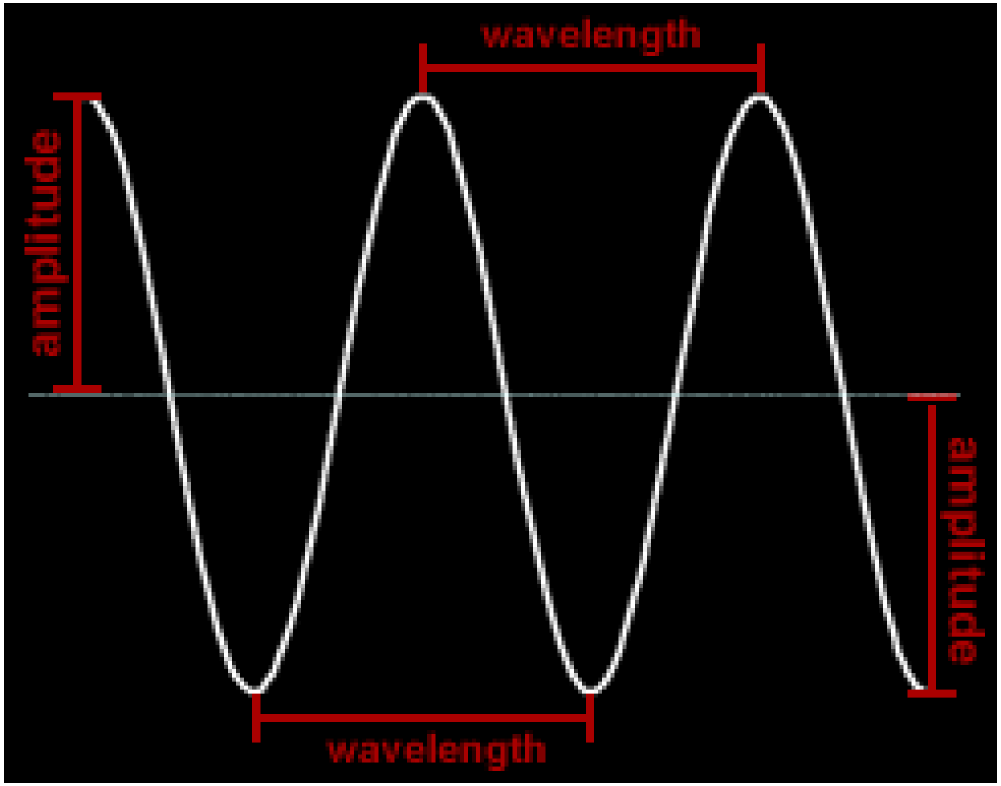
OR





Light Waves

Until about 1900, the classical wave theory of light described most observed phenomenon.



Light waves:

<u>Characterized by:</u>

- Amplitude (A)
- Frequency (ν)
- Wavelength (λ)

Energy of wave α A^2

And then there was a problem…

In the early 20th century, several effects were observed which could not be understood using the wave theory of light.

Two of the more influential observations were:

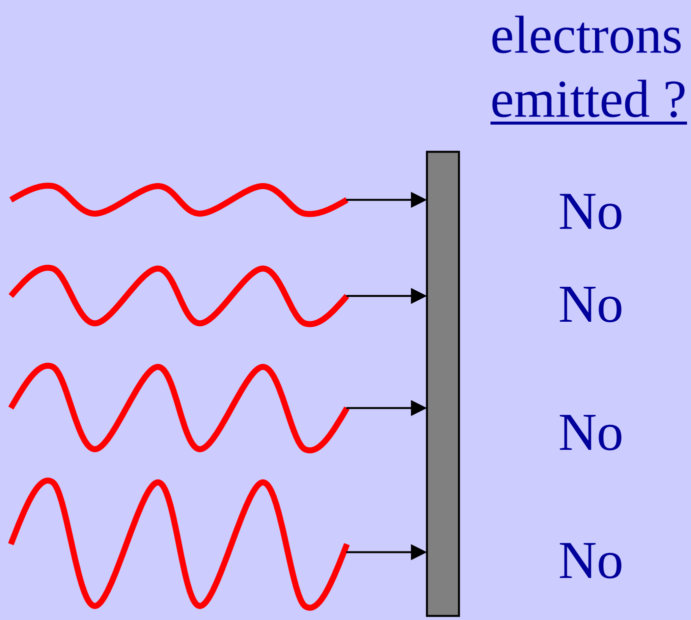
1) **The Photo-Electric Effect (광전효과)**

2) **The Compton Effect**

Photoelectric Effect (I)

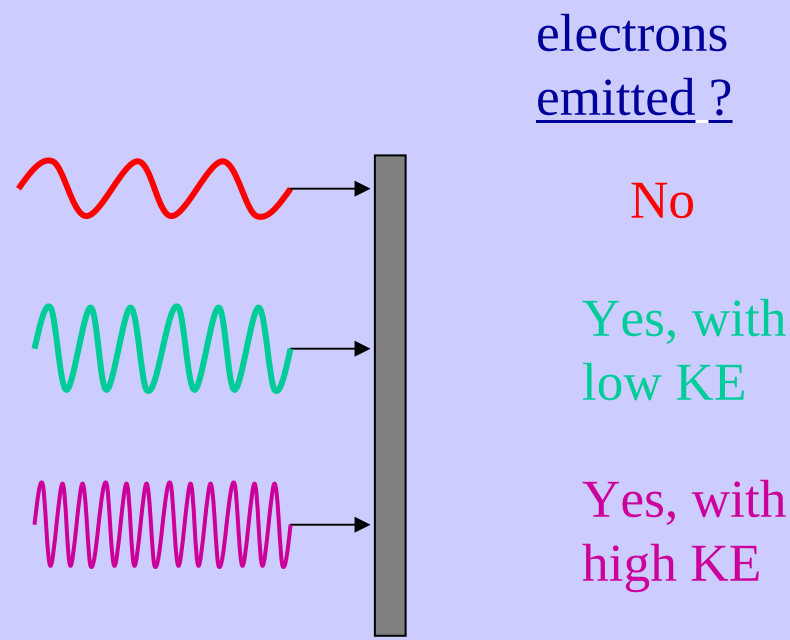
“Classical” Method

Increase energy by increasing amplitude



What if we try this ?

Vary wavelength, fixed amplitude



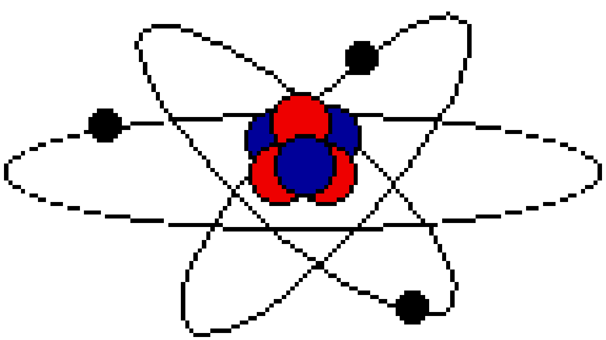
No electrons were emitted until the frequency of the light exceeded a critical frequency, at which point electrons were emitted from the surface! (Recall: small λ ➔ large ν)

Photoelectric Effect (II)

- ***Electrons*** are attracted to the (positively charged) nucleus by the electrical force.

- In metals, the outermost electrons are not tightly bound, and can be easily “liberated” from the shackles of its atom.

- It just takes sufficient energy…

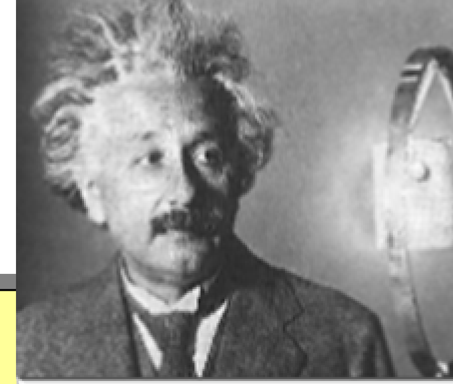


Classically, we increase the energy of an EM wave by increasing the intensity (e.g. brightness)

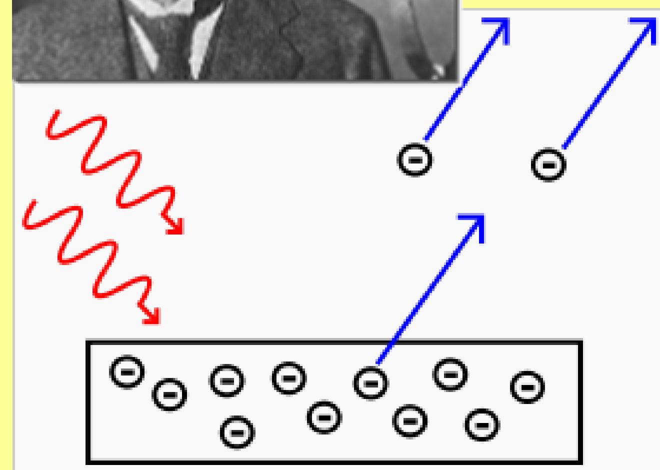
Energy α A^2

But this doesn’t work ??

PhotoElectric Effect (III)



Albert Einstein
1921 노벨물리학상



- ❑ An alternate view is that **light** is acting like a **particle**
- ❑ The light particle must have sufficient energy to "***free***" the electron from the atom.
- ❑ **Increasing the Amplitude is simply increasing the number of light particles, but its NOT increasing the energy of each one!**

  ➔ **Increasing the Amplitude does diddly-squat!**

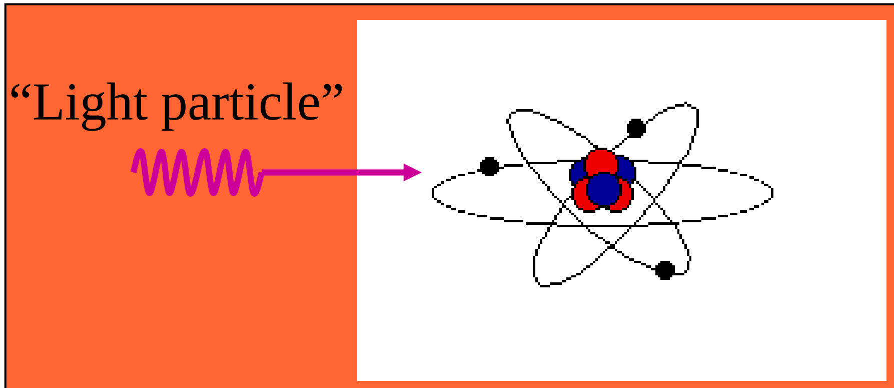
- ❑ However, if the energy of these "light particle" is related to their frequency, this would explain why higher frequency light can knock the electrons out of their atoms, but low frequency light cannot…

Photo-Electric Effect **(IV)**

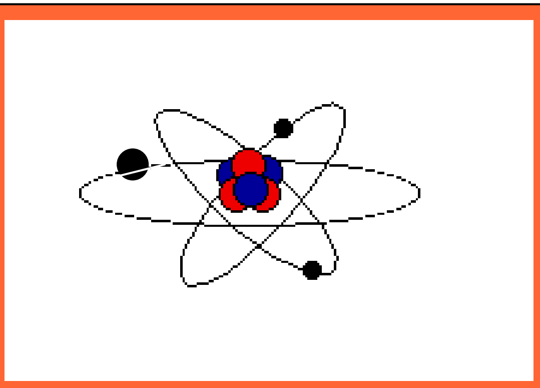
- In this “quantum-mechanical” picture, the energy of the light particle (photon) must overcome the *binding energy* of the electron to the nucleus.

- If the energy of the photon exceeds the binding energy, the electron is emitted with a $KE = E_{photon} - E_{binding}$.

- The energy of the photon is given by **$E=h\nu$,** where the constant $h = 6.6\text{x}10^{-34}$ [J s] is Planck’s constant.



Before Collision


After Collision

Photons

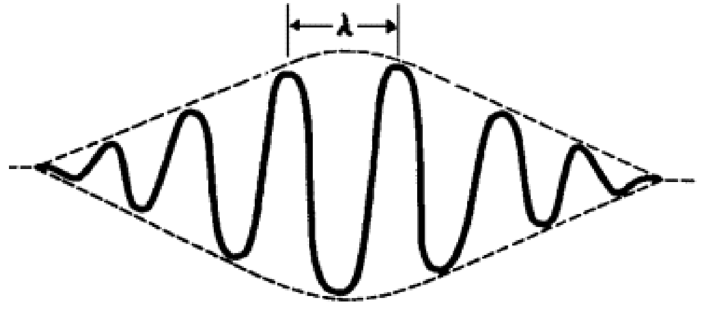


Figure 2

- ***Quantum theory*** describes light as a particle called a ***photon***

- According to **quantum theory**, a **photon** has an **energy** given by

$$E = h\nu = hc/\lambda$$

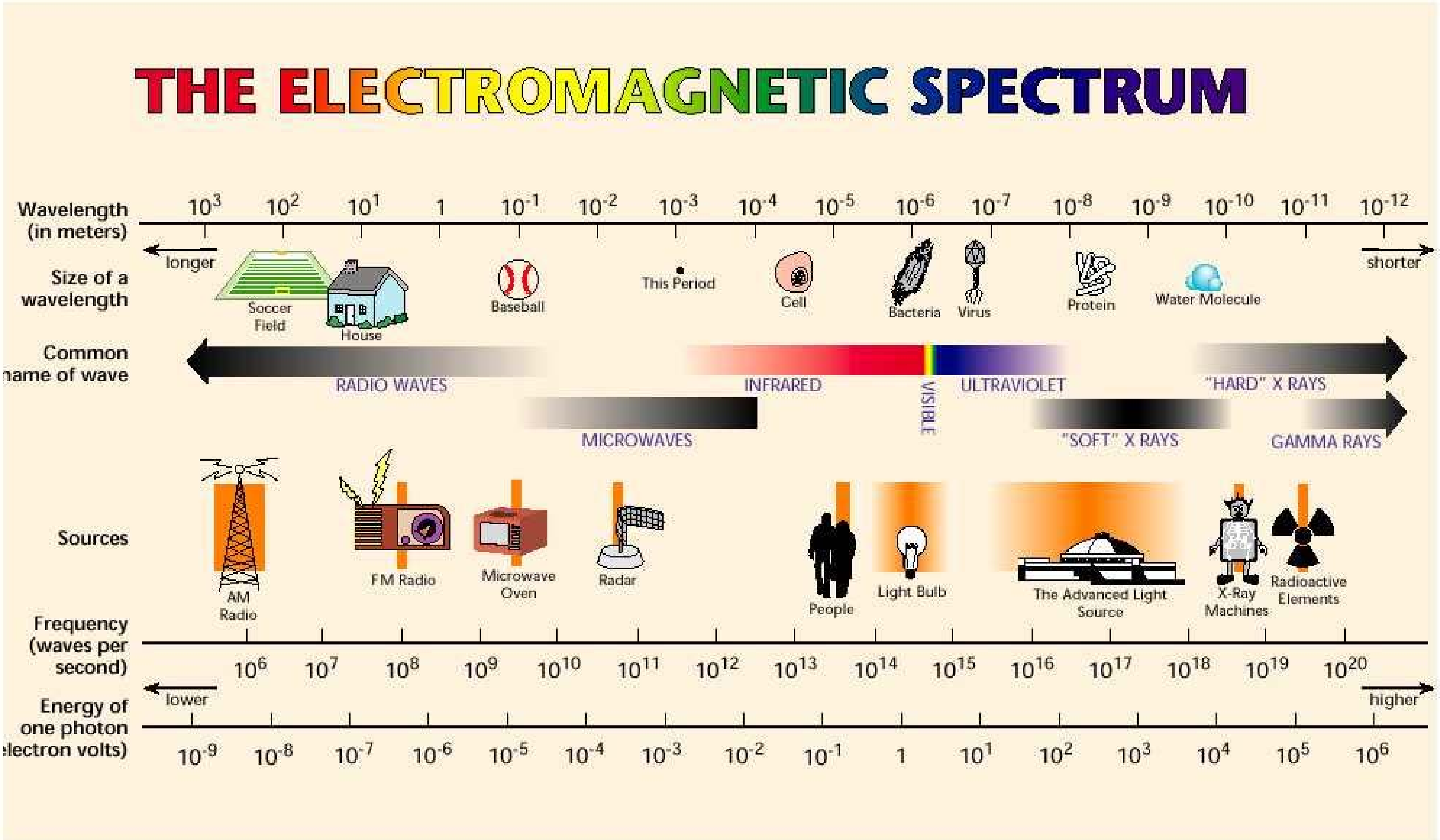
h = 6.6x10^{-34} [J s] Planck's constant, after the scientist Max Planck.
(c = speed of light)

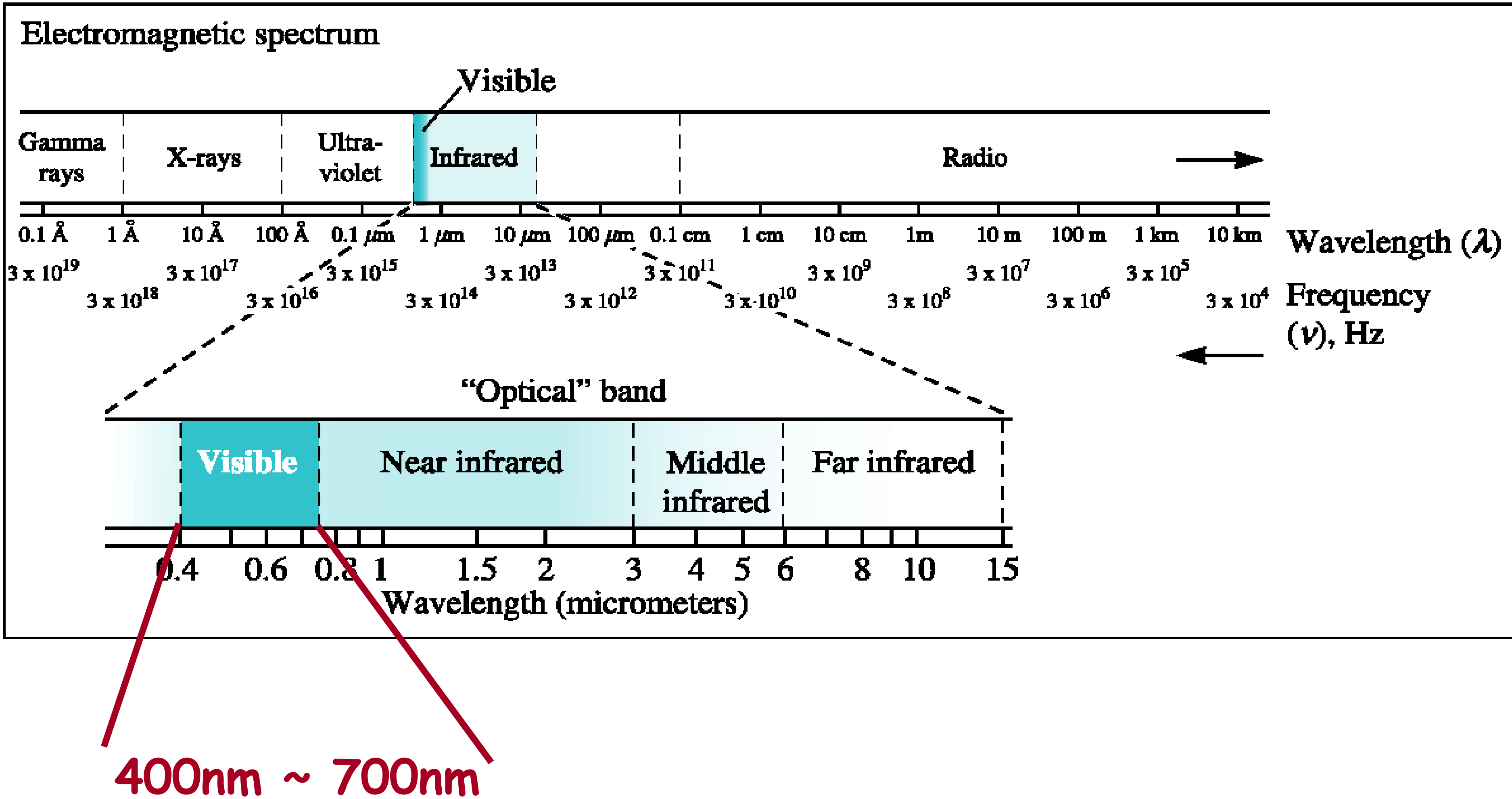
- The **energy of the light** is proportional to the frequency (inversely proportional to the **wavelength**) ! The higher the frequency (lower wavelength) the higher the energy of the photon.

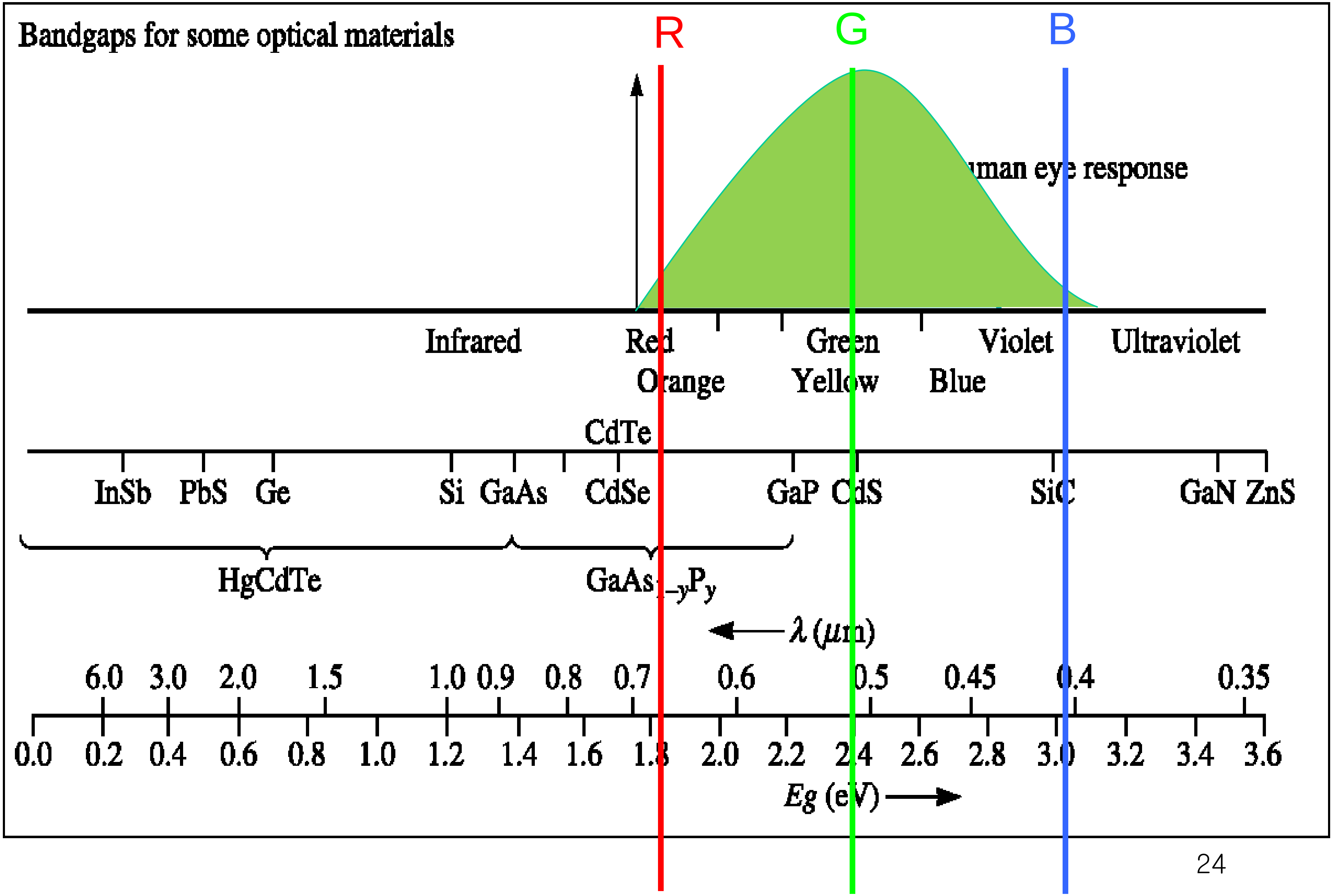
- 10 photons have an energy equal to ten times a single photon.

- **Quantum theory describes experiments to astonishing precision**, whereas the **classical wave description cannot**.

Higher penetration ← → *Lower penetration*

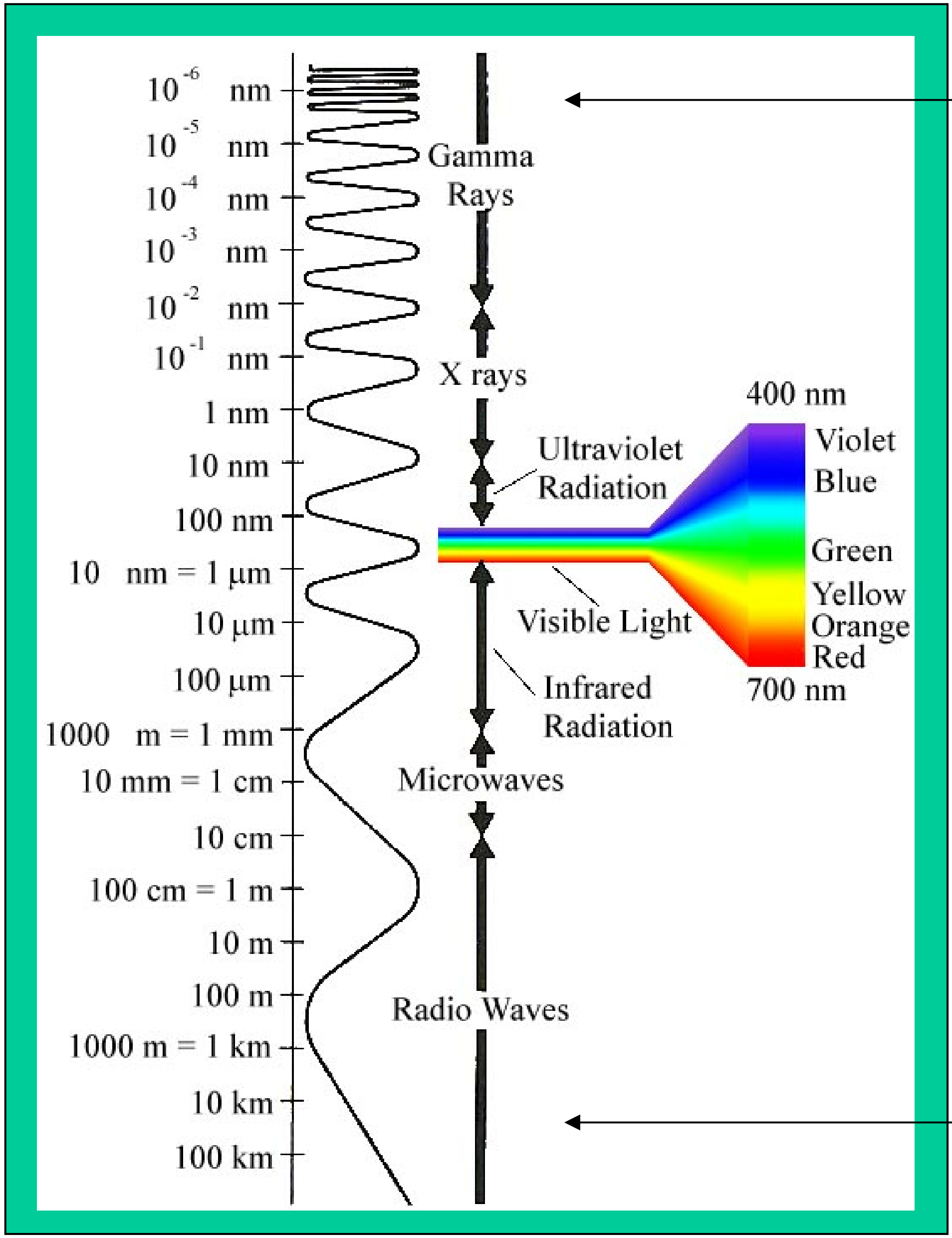



Electromagnetic spectrum
Visible
Gamma rays
X-rays
Ultra-violet
Infrared
Radio
0.1 Å
1 Å
10 Å
100 Å
0.1 μm
1 μm
10 μm
100 μm
0.1 cm
1 cm
10 cm
1m
10 m
100 m
1 km
10 km
Wavelength (λ)
3 x 10^19
3 x 10^18
3 x 10^17
3 x 10^16
3 x 10^15
3 x 10^14
3 x 10^13
3 x 10^12
3 x 10^11
3 x 10^10
3 x 10^9
3 x 10^8
3 x 10^7
3 x 10^6
3 x 10^5
3 x 10^4
Frequency (ν), Hz
"Optical" band
Visible
Near infrared
Middle infrared
Far infrared
0.4
0.6
0.8
1
1.5
2
3
4
5
6
8
10
15
Wavelength (micrometers)
400nm ~ 700nm



Bandgaps for some optical materials
R
G
B
Human eye response
Infrared
Red
Orange
Green
Yellow
Blue
Violet
Ultraviolet
CdTe
InSb
PbS
Ge
Si
GaAs
CdSe
GaP
CdS
SiC
GaN
ZnS
HgCdTe
$GaAs_{1-y}P_y$
λ (μm)
6.0
3.0
2.0
1.5
1.0
0.9
0.8
0.7
0.6
0.5
0.45
0.4
0.35
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
3.2
3.4
3.6
E_g (eV)

The Electromagnetic Spectrum



Shortest wavelengths
(Most energetic photons)

$$E = h\nu = hc/\lambda$$

$h = 6.6 \times 10^{-34}$ [J*sec]
(Planck's constant)

Longest wavelengths
(Least energetic photons)

Momentum

In physics, there's another quantity which we hold just as sacred as energy, and this is ***momentum***.

For an object with mass, momentum is given by:

$$\vec{p} = m\vec{v}$$

The units are: [kg] [m/s] == [kg m/s]

Unlike energy, which is a scalar, ***momentum*** is a ***vector***. That is it has both magnitude & direction. The direction is along the direction of the velocity vector.

The reason it is important in physics, is, because like Energy:

TOTAL MOMENTUM IS ALWAYS CONSERVED

Do photons carry momentum ?

DeBroglie's proposed that the a photon not only carries energy, but also carries momentum.

But, $\vec{p} = m\vec{v}$, and photon's have m=0, so how can it be that the momentum is not zero??

DeBroglie postulated that photons carry momentum, and their momentum is:

$$p = E / c$$

If we substitute: $E = hc/\lambda$ into this equation, we get:

$$p = h / \lambda$$

Momentum carried by a photon with wavelength λ

DeBroglie's Relation

DeBroglie's relation

$p = h / \lambda$

Photons carry momentum !!!

$\lambda = h / p$

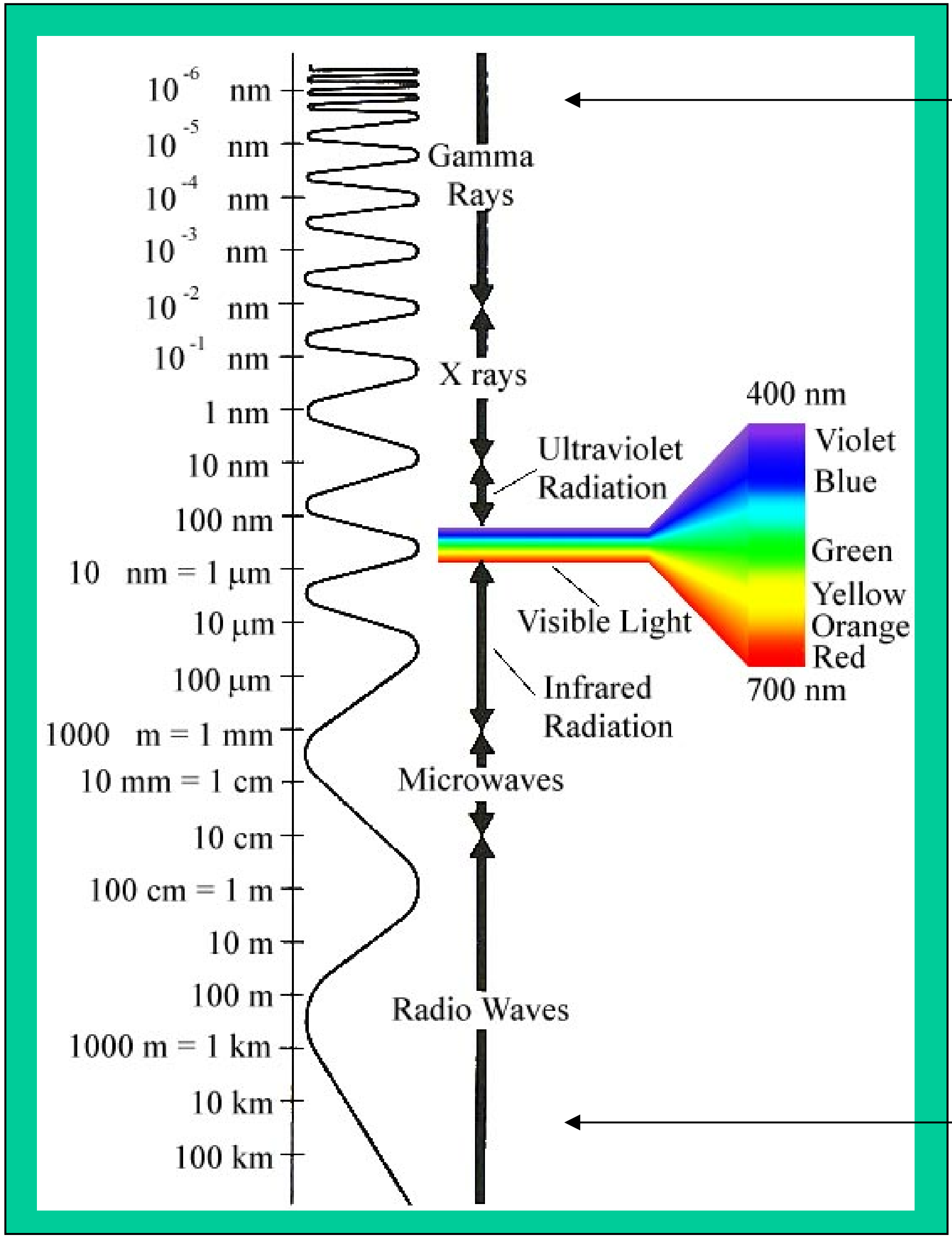
$E = hc / \lambda$

Photons also carry energy !!!

Both energy & momentum are <u>inversely proportional</u> to the wavelength !!!

➔ The highest energy photons are those which have **small wavelength** (that's why gamma rays are so dangerous)

The Electromagnetic Spectrum



Shortest wavelengths
(Most energetic photons)

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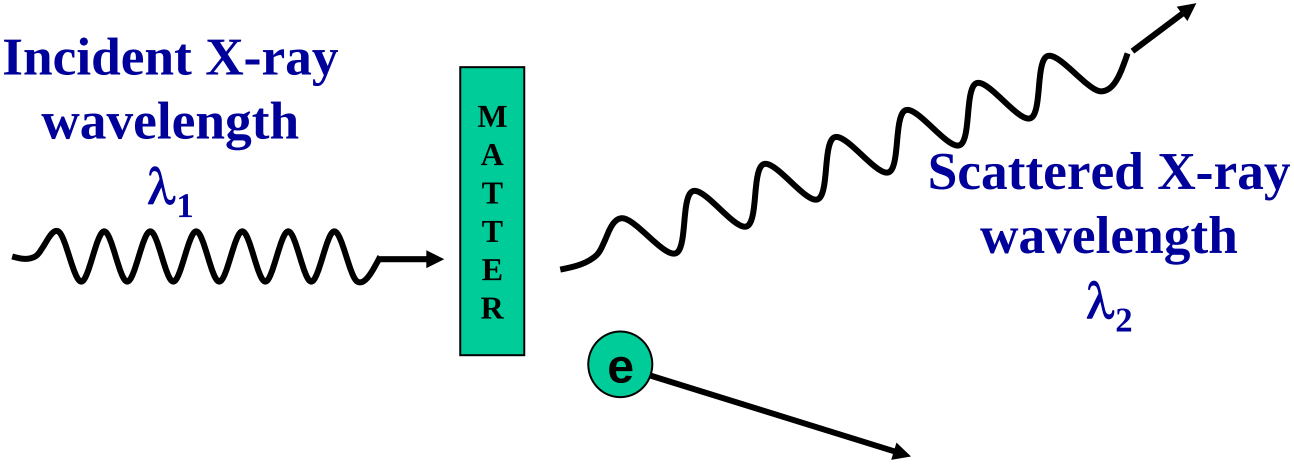
(Planck's constant)

Longest wavelengths
(Least energetic photons)

The Compton Effect

In 1924, A. H. Compton performed an experiment where X-rays impinged on matter, and he measured the scattered radiation.

Louis de Broglie



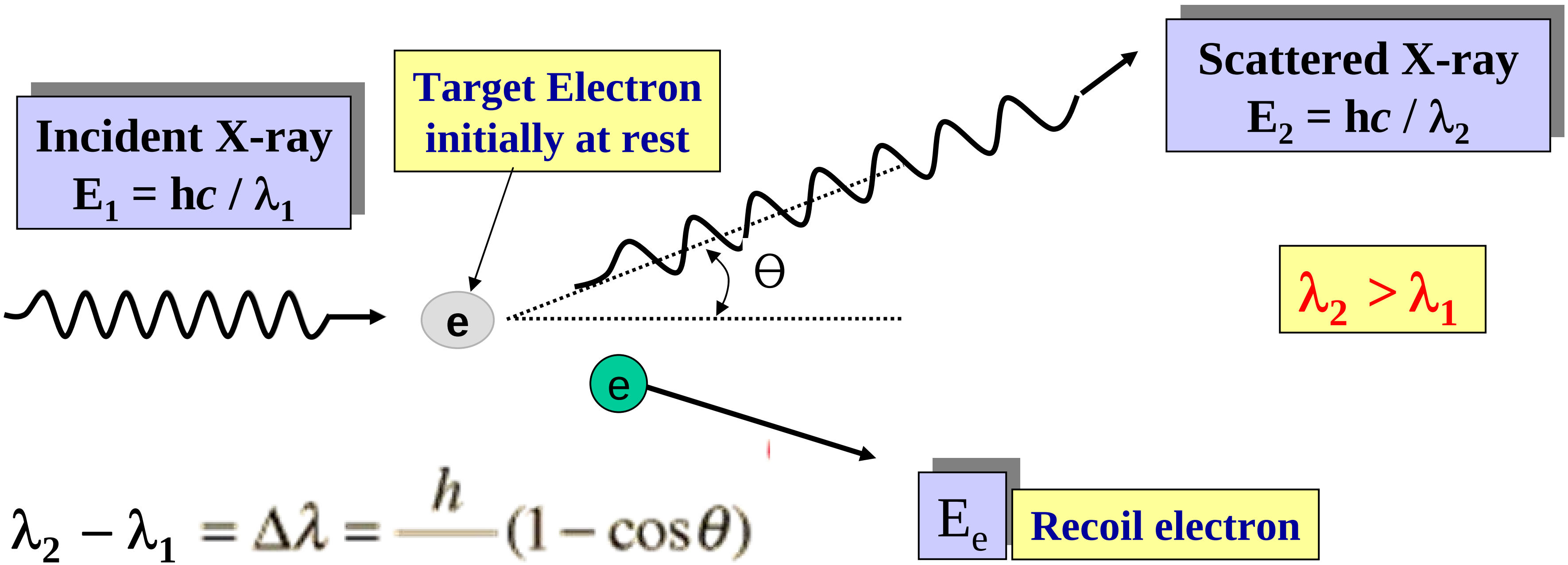
$\lambda_2 > \lambda_1$

Electron comes flying out

Problem: According to the wave picture of light, the incident X-ray should give up some of its energy to the electron, and emerge with a lower energy (*i.e.*, the amplitude is lower), but should have $\lambda_2=\lambda_1$.

It was found that the scattered X-ray did not have the same wavelength ?

Quantum Picture to the Rescue



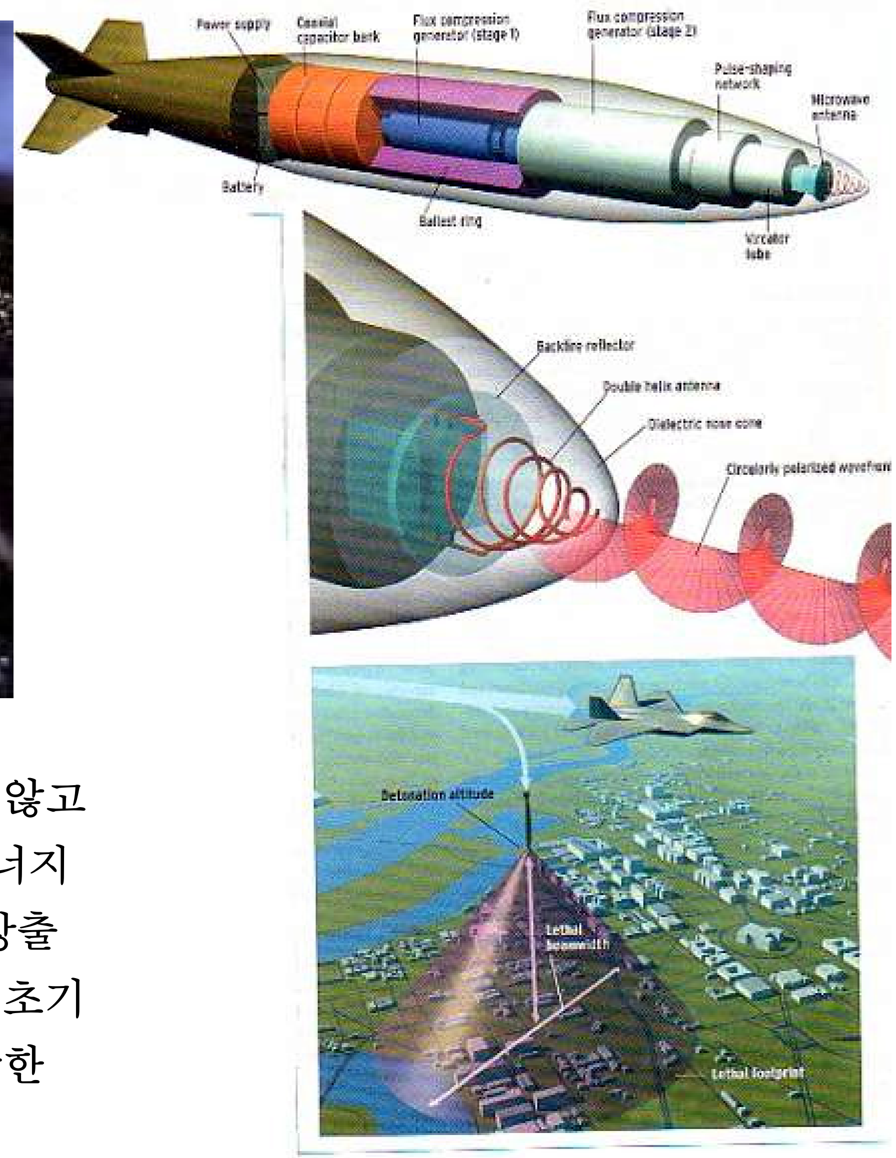
$$\lambda_2 - \lambda_1 = \Delta\lambda = \frac{h}{m_0 c}(1-\cos\theta)$$

Compton found that if you treat the photons as if they were particles of zero mass, with energy **E=hc/λ** and momentum **p=h/λ**

➔ The collision behaves just as if it were 2 billiard balls colliding !

Photon behaves like a particle with energy & momentum as given above!

Electromagnetic Bomb (E-bomb)



전자폭탄은 전자기 펄스로 사람에게는 피해를 주지 않고 상대방의 전자장비를 무력화하는 신종무기다. 고에너지 상태의 빛을 원자번호가 낮은 원자에 쏘면 전자를 방출한다는 콤프턴 효과를 이용하여 전자폭탄 내부에서 초기 전자기 펄스가 만들어지고 이를 수천만 암페어의 강한 전자기 펄스로 압축하여 작동한다.

Summary of Photons

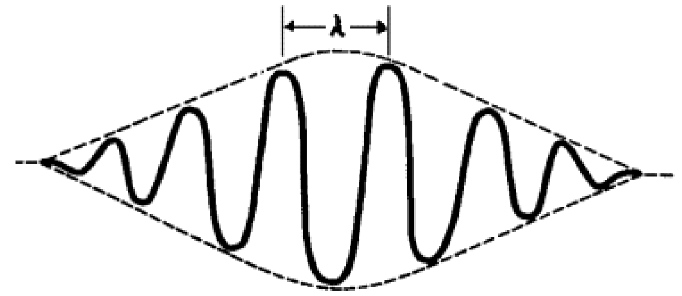


Figure 2

- **Photons** can be treated as "***packets of light***" which behave as a particle.

- To describe interactions of light with matter, one generally has to appeal to the particle (quantum) description of light.

- A single photon has an **energy** given by

$$\mathbf{E = h}\boldsymbol{c}\mathbf{/\lambda,}$$

where

h = Planck's constant = $6.6\text{x}10^{-34}$ [J s] and,

c = speed of light = $3\text{x}10^{8}$ [m/s]

λ = wavelength of the light (in [m])

- Photons also carry **momentum**. The momentum is related to the energy by: $\mathbf{p = E / \boldsymbol{c} = h/\lambda}$