2009 spring

Microstructural Characterization of Materials

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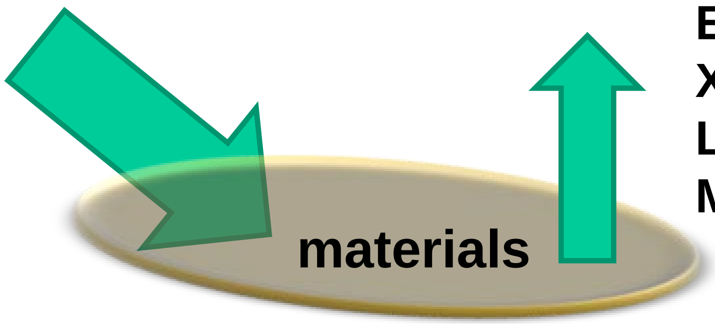
Contents for previous class

Simple idea of analytical tools

Source

Electron
X-ray
Laser
Light
Shockwave
Mechanical



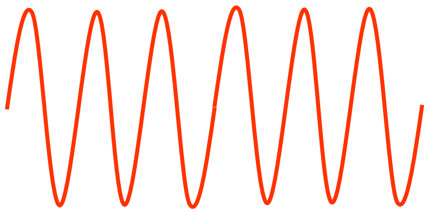
Signal

Electron
X-ray
Light
Mechanical

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

Light is a form of energy **is a quantum of electromagnetic energy**.

The Wave – Particle Duality



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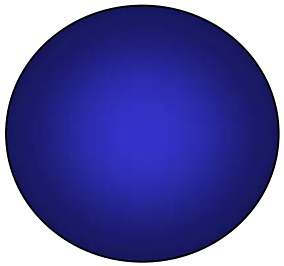
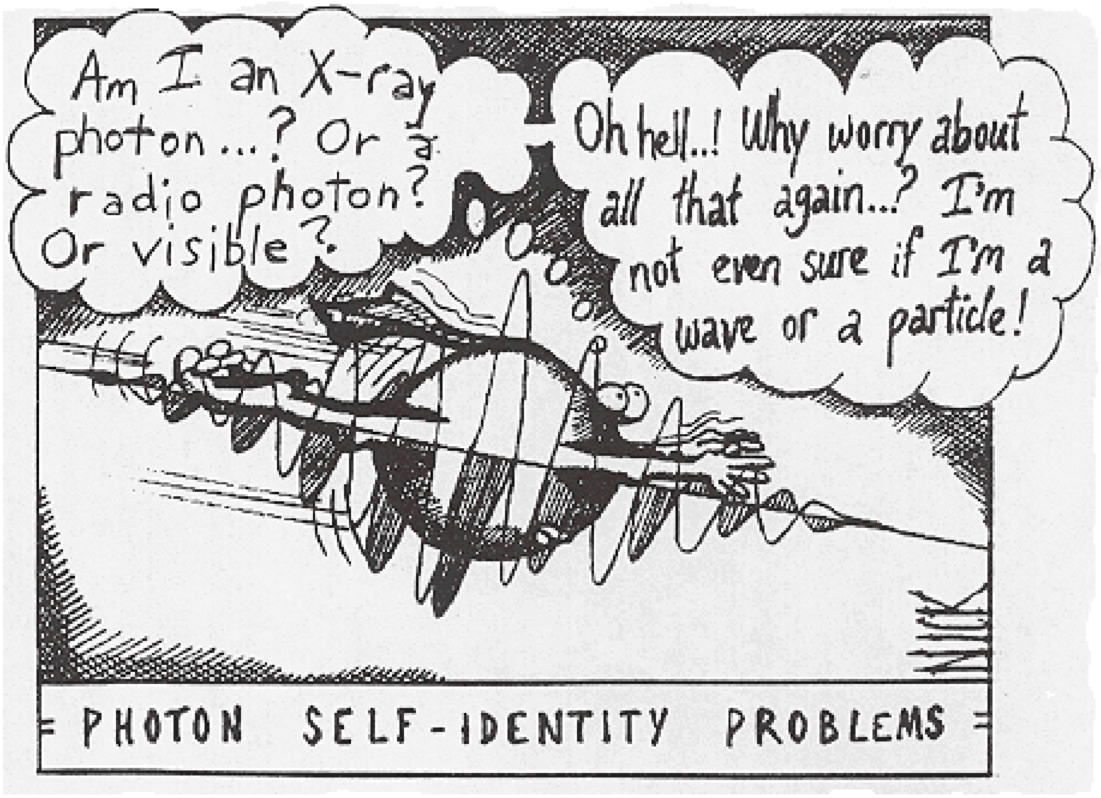




Summary of Photons

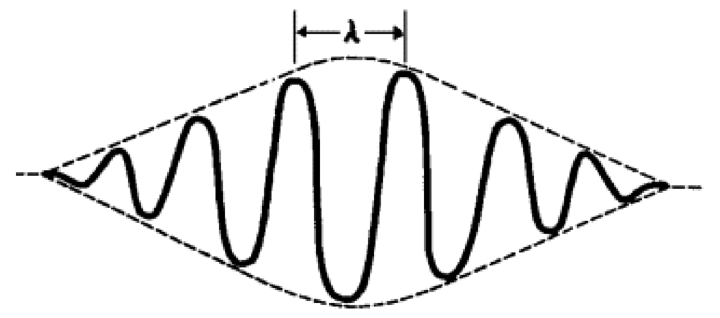


Figure 2

- Considering Quantum theory, **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

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

where

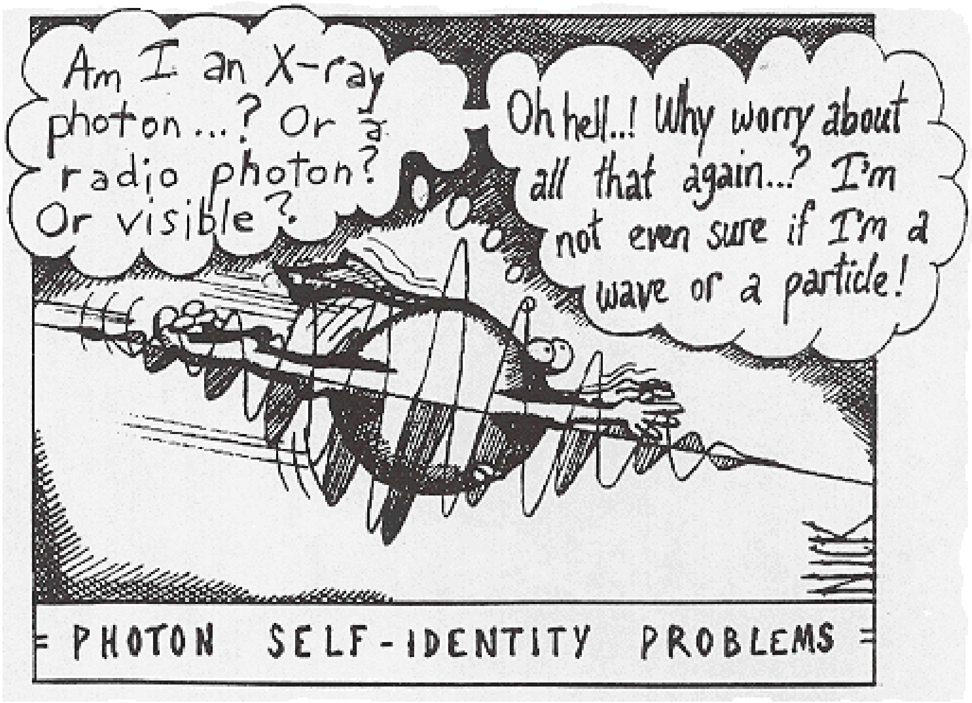
h = Planck's constant = 6.6×10^{-34} [J s] and,

c = speed of light = 3×10^{8} [m/s]

λ = wavelength of the light (in [m])

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

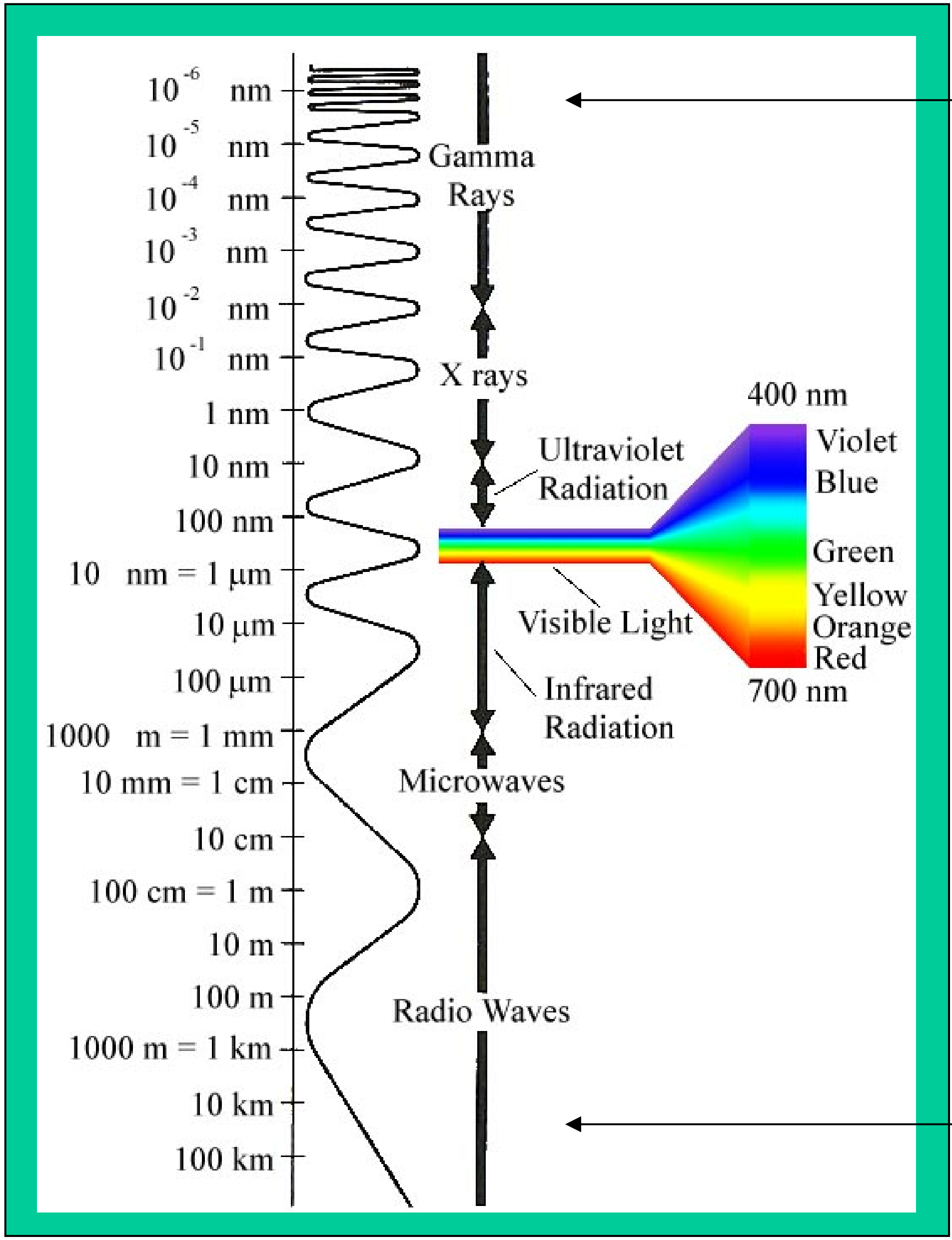
So is light a wave or a particle ?



On **macroscopic scales**, we can treat **a large number of photons as a wave**.

When dealing with **subatomic phenomenon**, we are often dealing with a **single photon**, or a few. In this case, you cannot use the wave description of light. It doesn't work !

The Electromagnetic Spectrum



Shortest wavelengths
(Most energetic photons)

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

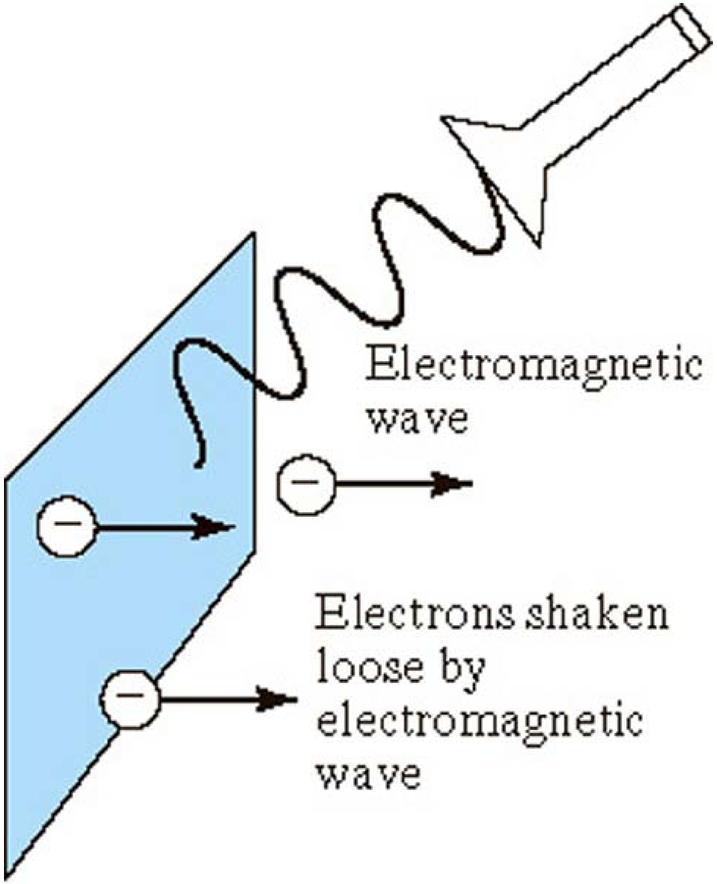
$h = 6.6 \times 10^{-34}$ [J*sec]
(Planck's constant)

Longest wavelengths
(Least energetic photons)

Contents for today's class

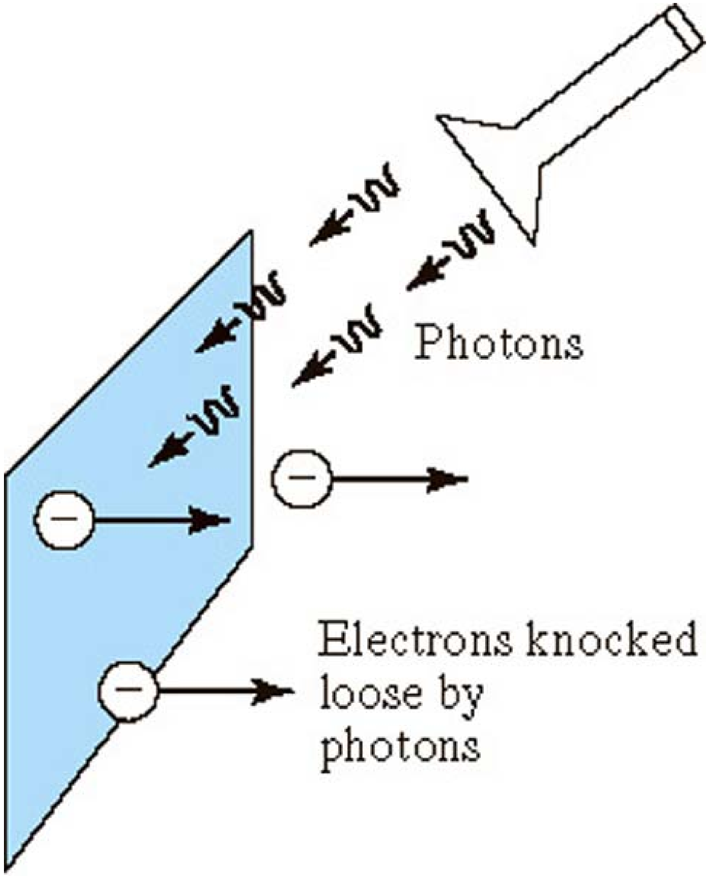
- ***Quantum Nature of Photons***
- ***How do we reconcile this with particle picture?***
- ***Matter Waves ?***
- ***Real photographs of an electron interference pattern***
- ***Wave length** vs **size***
- ***Remarks on Particle Probes***

Classical Picture



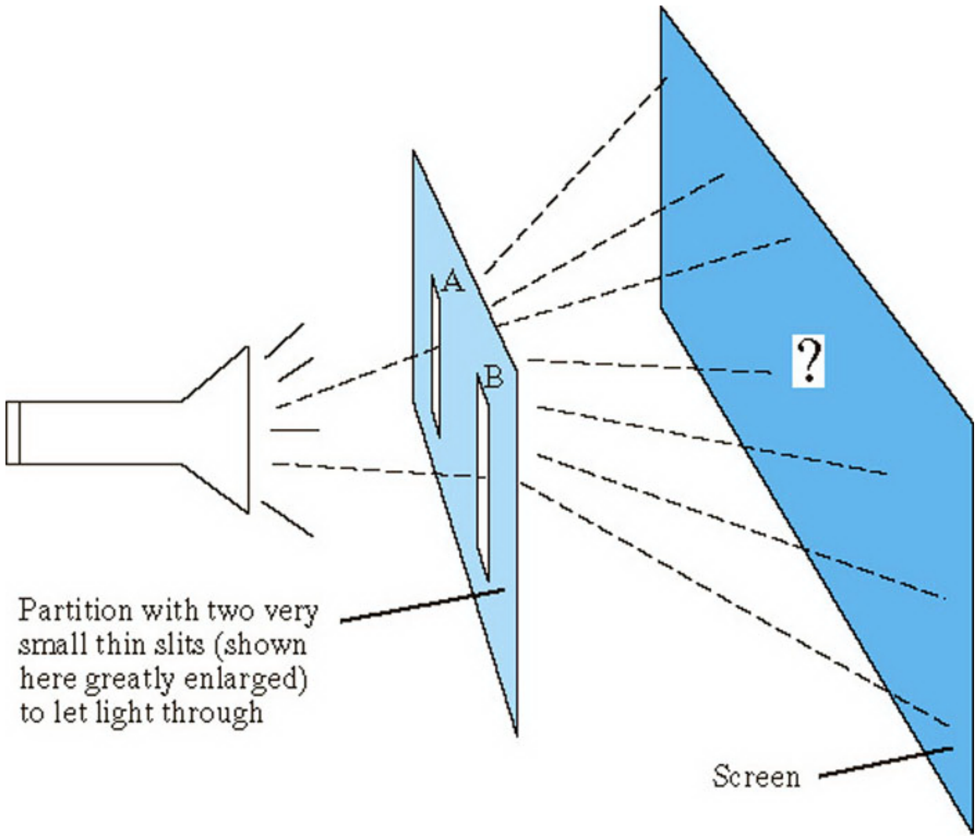
Energy of wave $\propto$ (Amplitude)^2

Quantum Picture

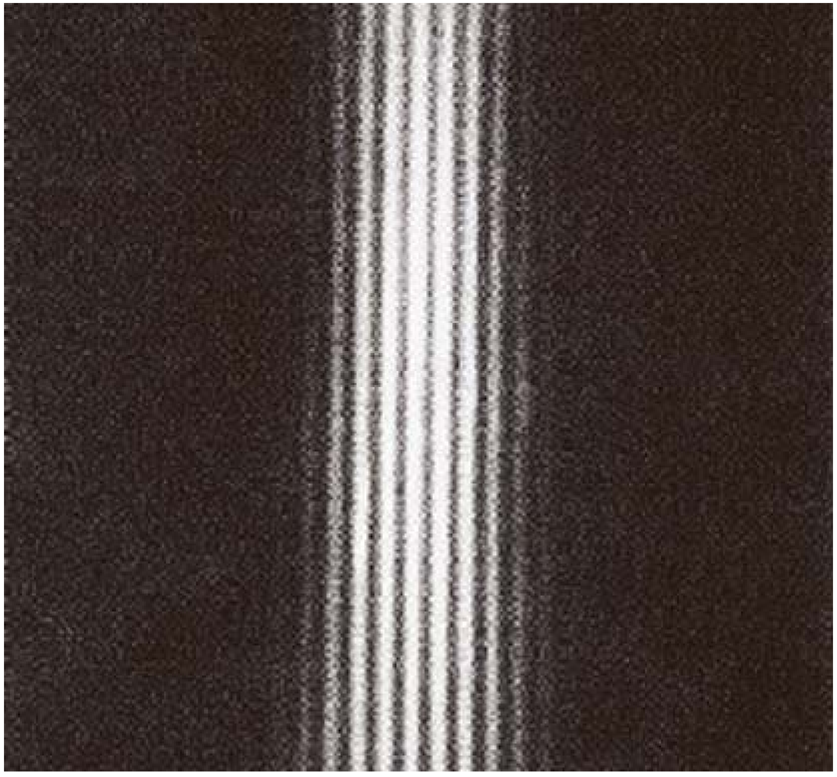


Energy/photon = hc / λ

Quantum Nature of Photons

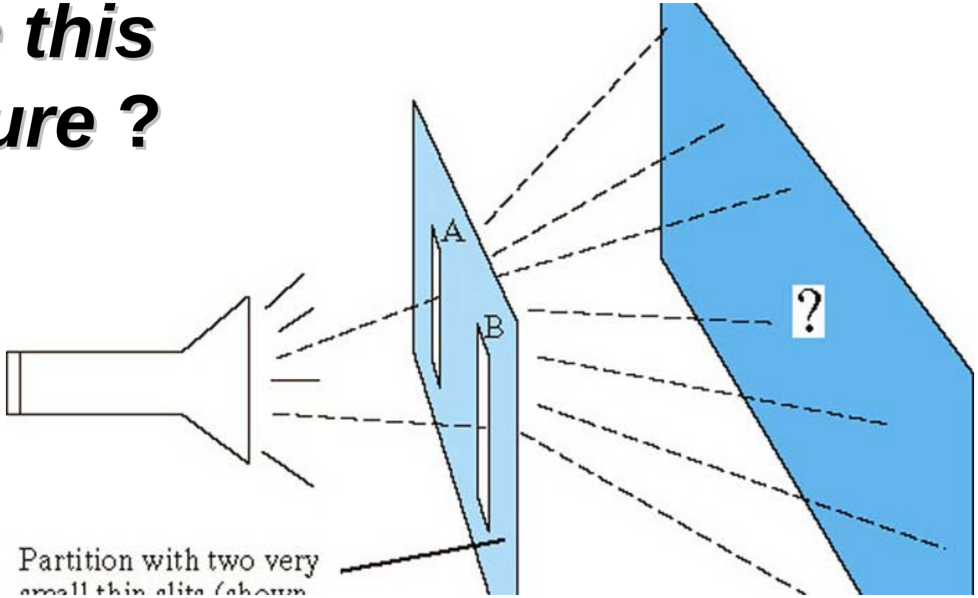


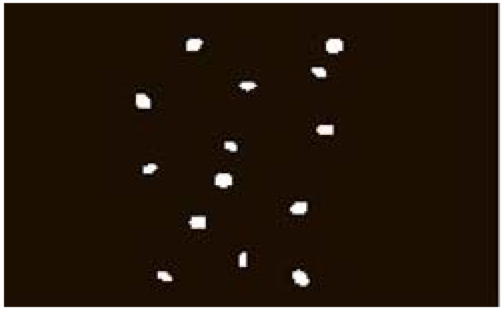
What do you expect to see ?



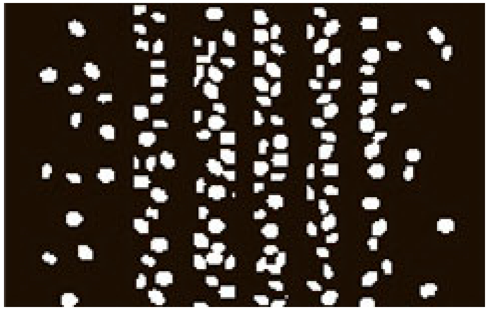
This was one of the defining characteristics of <u>waves</u>
➔ Interference

How do we reconcile this with the particle picture ?

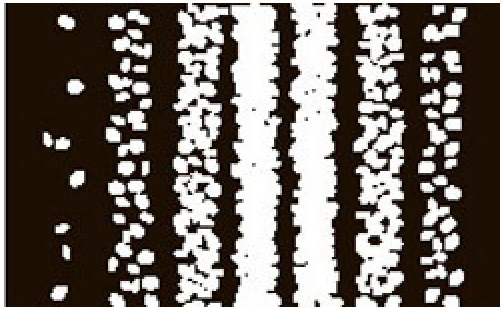




Very short exposure
14 photon impacts



Longer exposure
~150 photon impacts



Much longer exposure
a few thousand
photon impacts

Photons, Digital Camera & Images

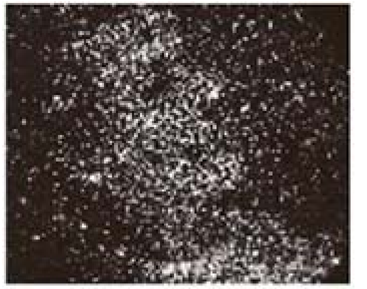
Using a digital camera with many pixels !

A given pixel is very, very small
➔ gives fine image resolution

The individual spots on this image and on the previous one are the actual results of individual photons striking the pixel array.

Wave picture cannot account for individual pixels in camera being hit.

~3000 photons



~10,000 photons

~100,000 photons

~1 M photons

~4 M photons

~30 M photons

Matter Waves ?

One might ask:

"If light can behave like a particle, might particles act like waves"?

The short answer is **YES**. The explanation lies in the realm of quantum mechanics, and is beyond the scope of this course.
However, you already have been introduced to the answer.

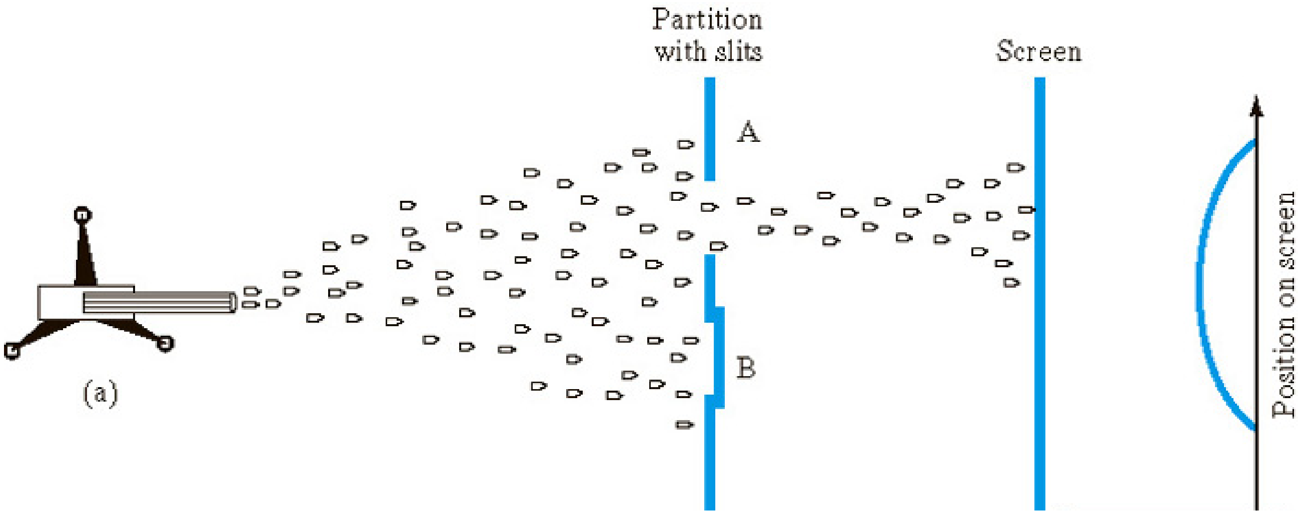
Particles, like photons, also have a wavelength given by:

$$\lambda = h/p = h / mv$$

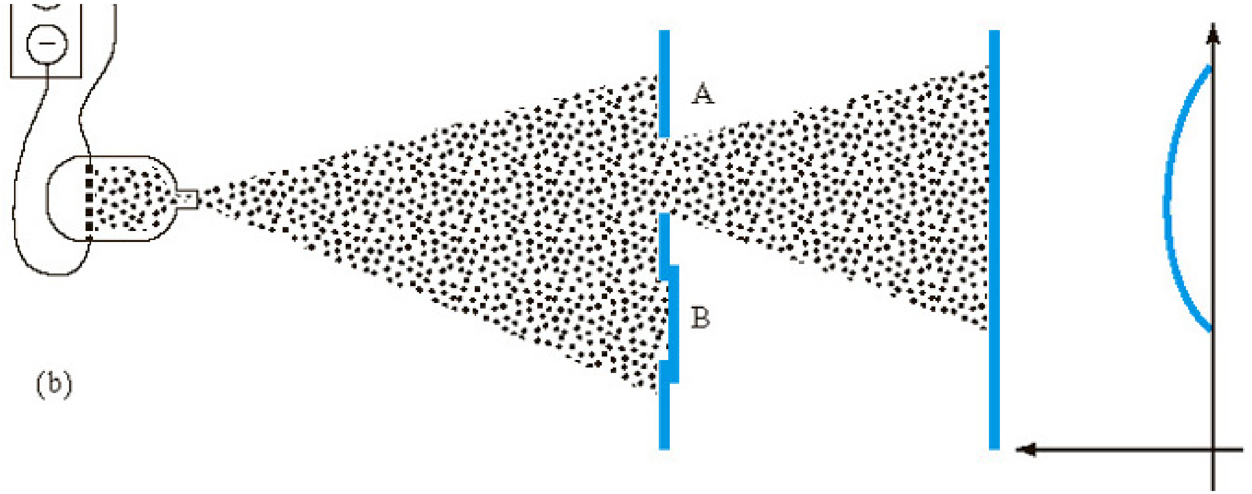
That is, the wavelength of a particle depends on its momentum, just like a photon!

The main difference is that **matter particles have mass**, and photons don't !

Do particles exhibit interference ?

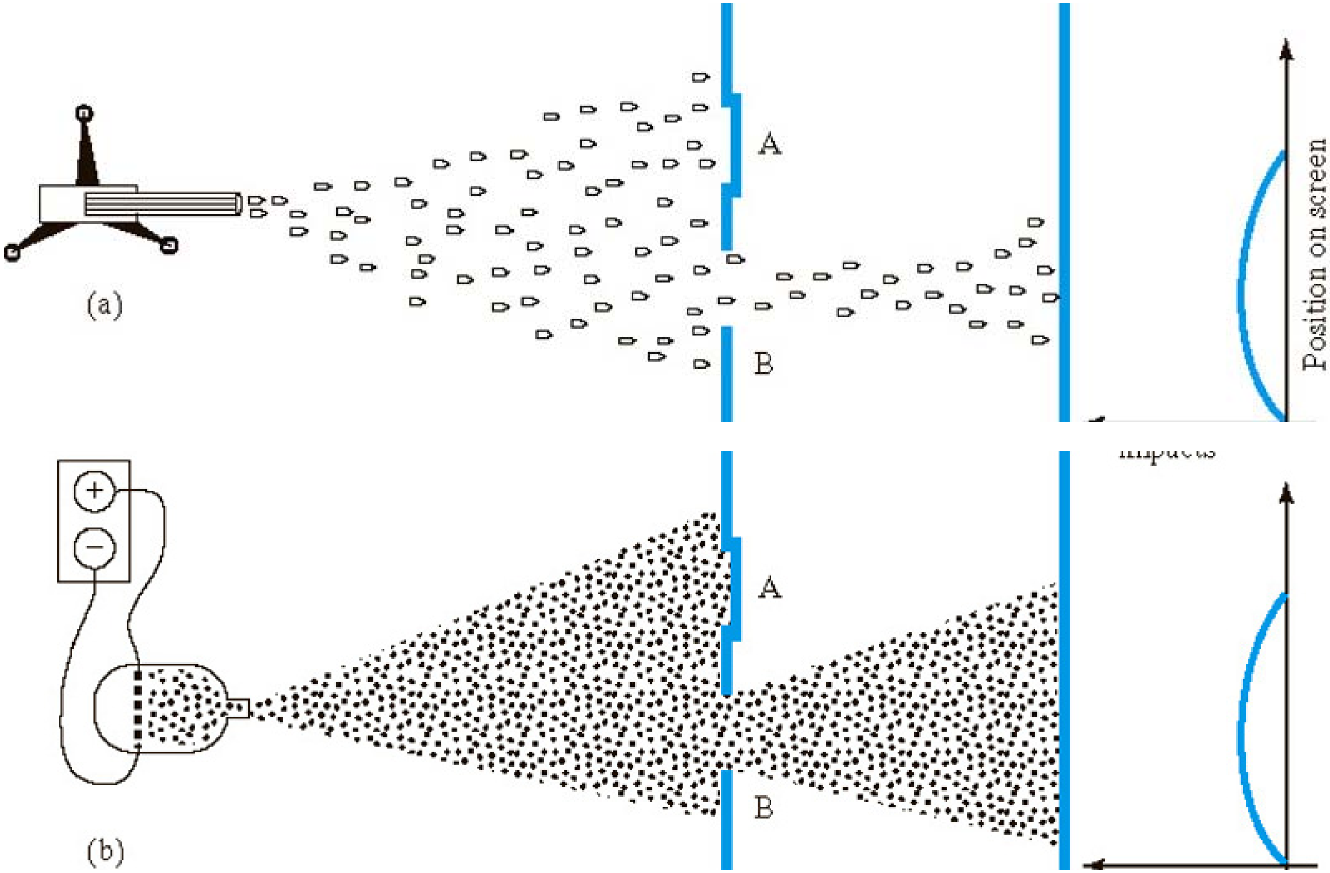


Firing bullets
at a
“double -slit”
with one slit
closed



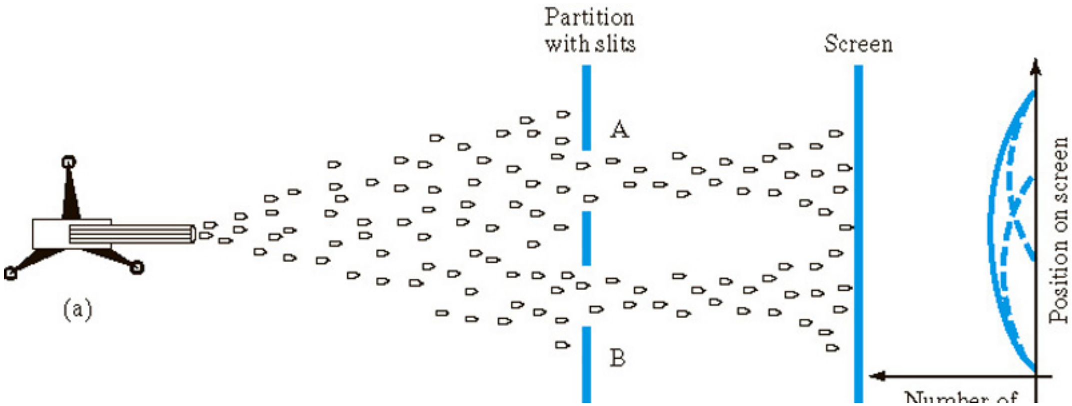
Firing electrons
at a
“double -slit”
with one slit
closed

What about the other slit ?

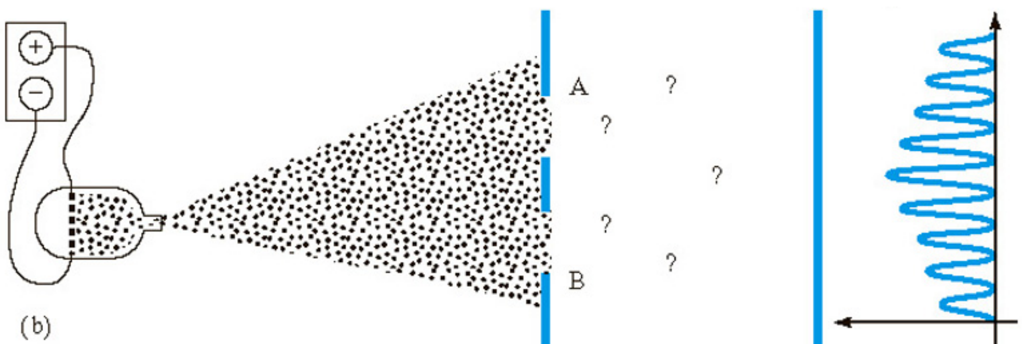


Again, you just get a rather expected result…

What if both slits are open ?



With bullets, you get what appears to be a simple “sum” of the two intensity distributions.

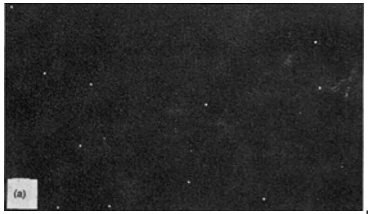


With electrons, you find an “interference” pattern, just like with light waves ?

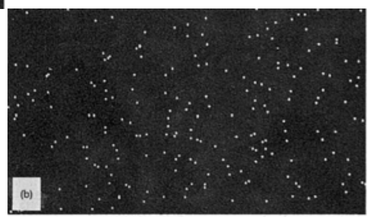
Huh ? Come again ?

So, forms of matter do exhibit wave behavior (electrons) and others (bullets) don’t ? What’s going on here ?

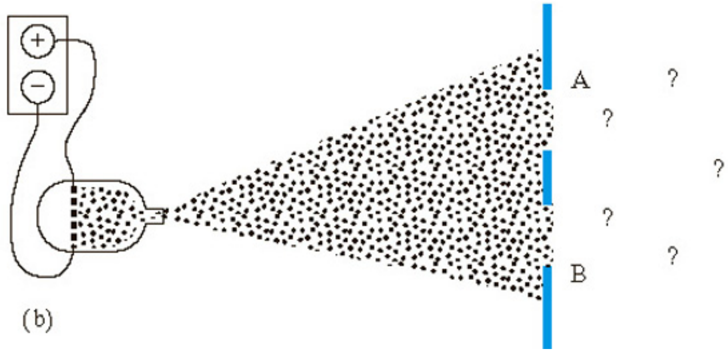
Real photographs of an electron interference pattern…

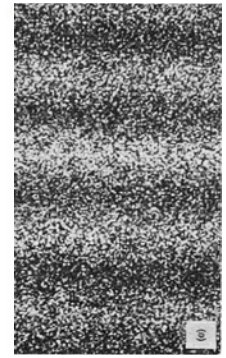


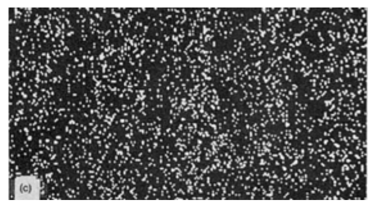
.01 [s]
10 electrons



.1 [s]
100 electrons

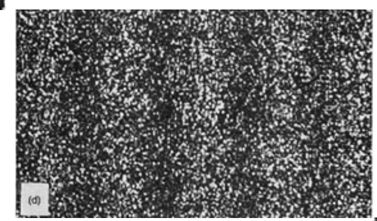






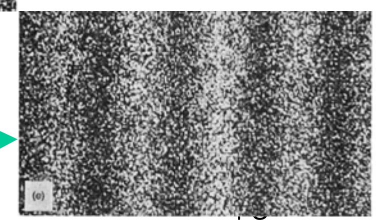
3 [s]
3000 electrons

20 [s]
20,000 electrons



70 [s]
70,000 electrons

Notice the clear interference fringes. Clear indication of wave phenomenon.



Matter Waves (cont)

Compute the wavelength of a 1 [kg] block moving at 1000 [m/s].

$\lambda = h/mv = 6.6\text{x}10^{-34}$ [J s] / (1 [kg])(1000 [m/s])

= **$6.6\text{x}10^{-37}$ [m].**

This is **immeasureably small.**

➔ For ordinary "everyday objects", we don't experience that *matter can behave as a wave*.

But, what about small particles ?

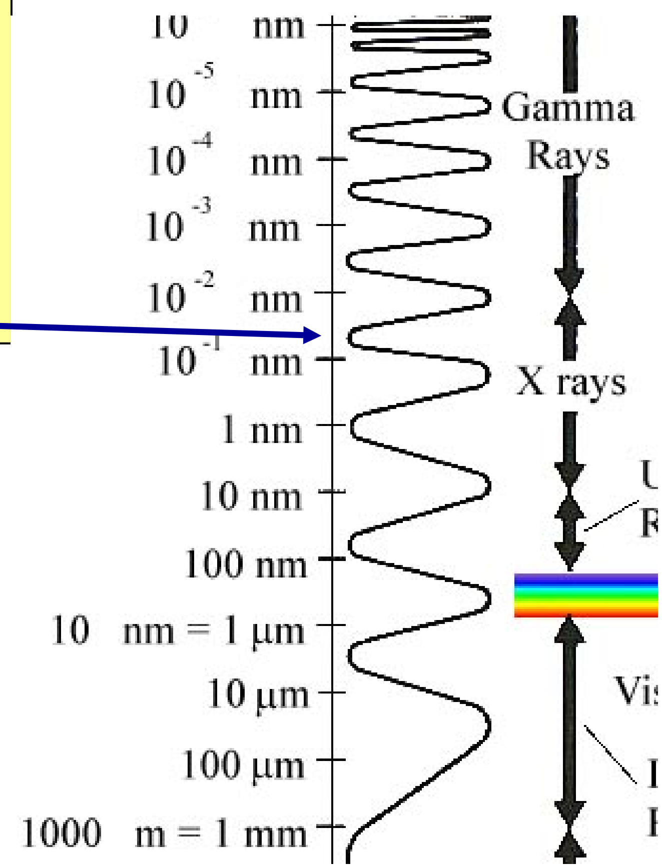
Compute the wavelength of an electron ($m = 9.1 \times 10^{-31}$ [kg]) moving at 1×10^{7} [m/s].

$\lambda = h/mv$

$= 6.6 \times 10^{-34}$ [J s]/(9.1×10^{-31} [kg])(1×10^{7} [m/s])

$= 7.3 \times 10^{-11}$ [m].

= 0.073 [nm]

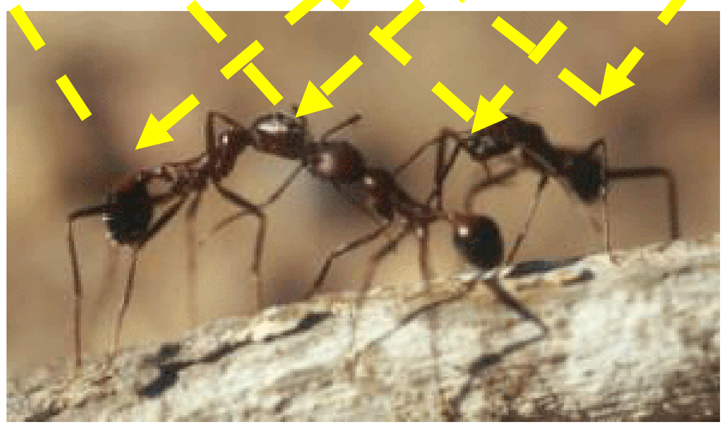


These electrons have a wavelength in the region of X-rays

How do we see ?

Light reflects (scatters) from
a surface and reaches our eye.

Our eye forms an image
of the object.

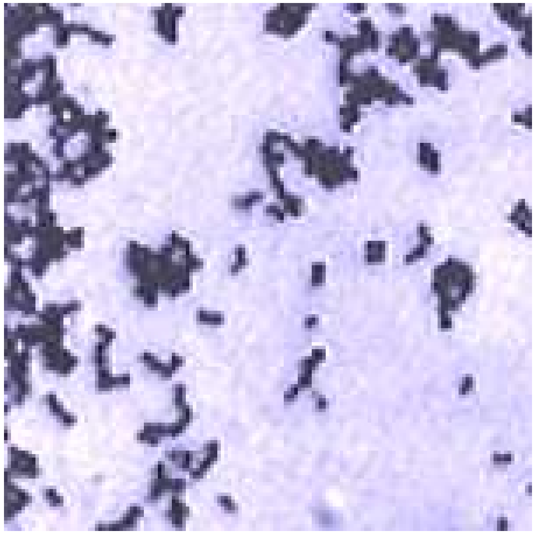


Wavelength versus Size

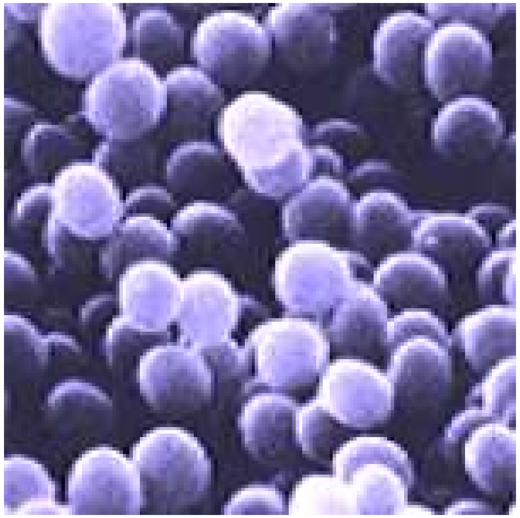
Even with a visible light microscope, we are limited to being able to resolve objects which are at least about

10^{-6} [m] = 1 [μm] = 1000 [nm] in size.

This is because visible light, with a wavelength of ~500 [nm] cannot resolve objects whose size is smaller than it's wavelength.



Bacteria, as viewed using visible light



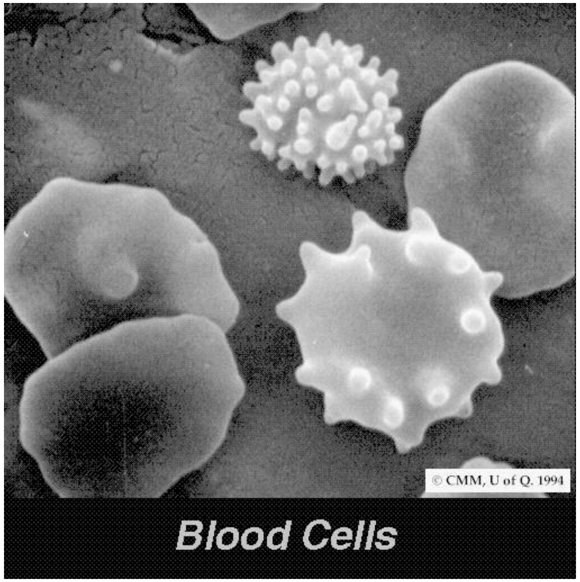
Bacteria, as viewed using electrons !

Electron Microscope

➔ The **electron microscope** is a device which uses the **wave behavior of electrons** to make images which are otherwise too small for visible light!

This image was taken with a Scanning Electron Microscope (SEM).

These devices can resolve features down to about 1 [nm]. This is about 100 times better than can be done with visible light microscopes!



IMPORTANT POINT HERE:

High energy particles can be used to reveal the structure of matter !

Remarks on Particle Probes

- We have now asserted that **high energy particles** (electrons in the case of a SEM) can provide a way to **reveal the structure of matter** beyond what can be seen using an optical microscope.

- The **higher the momentum of the particle**, the smaller the deBroglie wavelength (λ **= h/m*v***).

- As the **wavelength decreases**, **finer and finer details about the structure of matter are revealed** !

- We will return to this very important point.
  - ➔ To explore matter at its smallest size, we need **very high momentum particles** !
  - ➔ Today, this is accomplished at facilities often referred to as "**atom-smashers**". We prefer to call them "**accelerators**"
  - ➔ More on this later !

Summary

- ***Light*** is made up of ***photons***, but in macroscopic situations, it is often fine to **treat it as a wave**.

- When looking at the microscopic world, there is only 1 thing that works… Light is made up of photons (particles of light).

- Photons carry both energy & momentum.

  $E = hc / \lambda$ $\qquad\qquad$ $p = E/c = h / \lambda$

- Matter also exhibits wave properties. For an object of mass m, and velocity, v, the object has a wavelength, $\lambda = h / m\text{v}$

- One can probe 'see' the fine ***details of matter*** by using **high energy particles** (they have a small wavelength !) ➔ Can reveal the tiniest things !