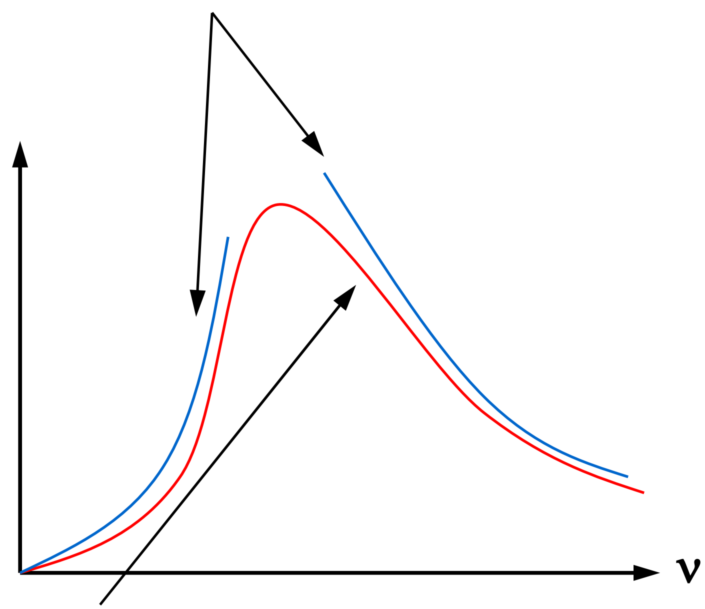
# Particle-Wave Duality

**Yet, the observation of black-body radiation and Planck's new theory, including his new constant, opened the door to viewing light as a particle!**




$$E = h\nu$$

$h \sim 6.6248 \times 10^{-34}$ joule-sec

**The intensity of light falling on a surface was given by the number of photons per second that hit the surface.**

**The photon WAS a particle!**

**This was a strange view, and not really accepted until Einstein used it to explain the photoelectric effect.**

[web]

**In classical physics, all things are either particles or waves.**

**Particles: atoms, electrons, cars, boats, houses, people…..**

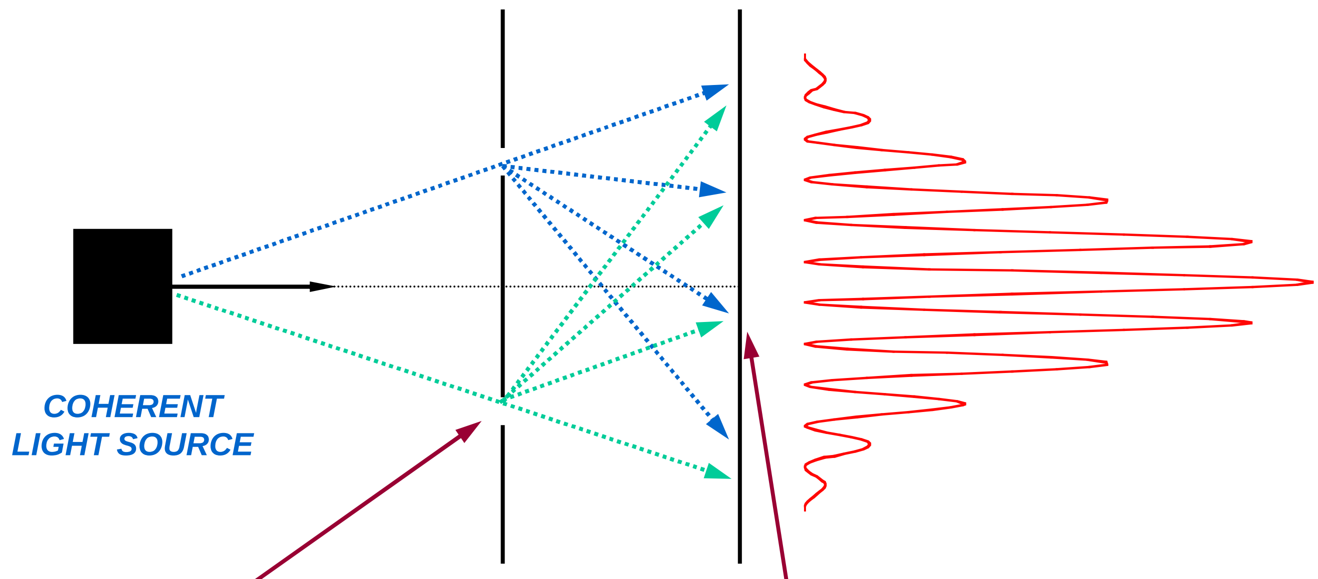
**Waves: light, heat, water motion, radio signals, ….**

**Particles and waves are distinct objects, and things just don't have the properties of both.**

**However, if we look a little closer, these facts and interpretations start to blur…**

# Light as a wave phenomenon:

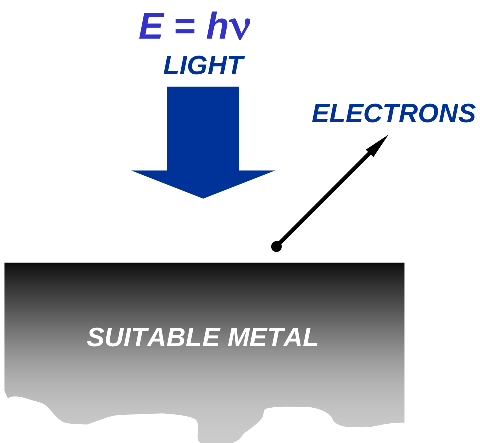
## *INTERFERENCE and DIFFRACTION*




*Light is diffracted by the aperatures*

*Just as for X-ray diffraction, the light has constructive and destructive interference where the diffracted beams come together*

# Light as a Particle




*IN THE PHOTOELECTRIC EFFECT A KEY OBSERVATION IS THAT ELECTRONS ARE ONLY EMITTED FROM THE METAL SURFACE IF THE FREQUENCY OF THE LIGHT EXCEEDS A CERTAIN VALUE*

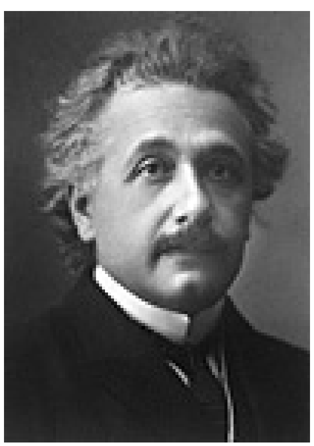
$E > E_0$ **(called the “work function”)**

**The number of emitted electrons was proportional to the number of arriving photons!**

**The kinetic energy of the photons emitted was given by**

$$(mv^2/2)_{electron} = E - E_0$$

**This effect remained unexplained until Einstein used the particle properties of light inferred from Planck’s theory!**

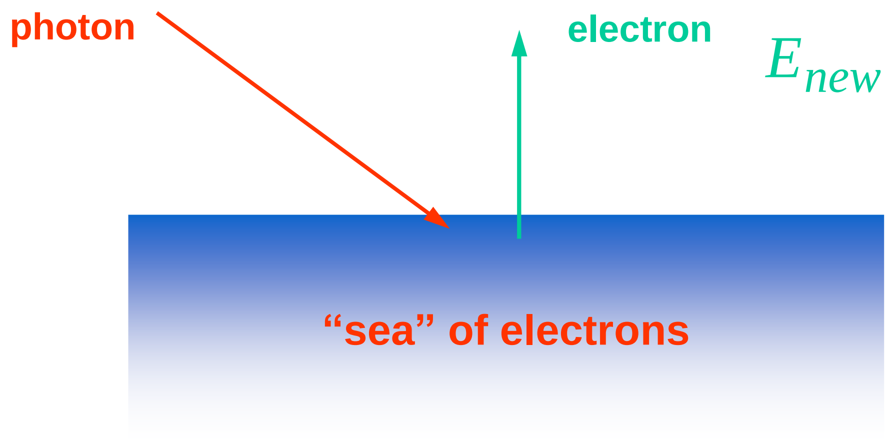


**Albert Einstein**
**Nobel Prize in physics, 1921**

# Light as a Particle

Einstein argued that this effect should be treated by considering the photon as a *classical* particle, with properties suggested by Planck's relationship.

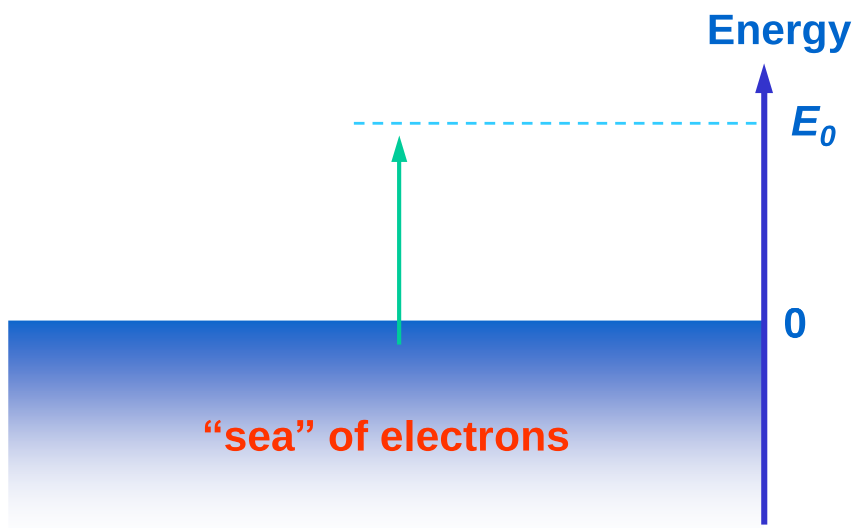
Then, one simply used classical scattering theory: the incoming particle would scatter off an electron in the solid, and transfer its energy to that particle (the electron).



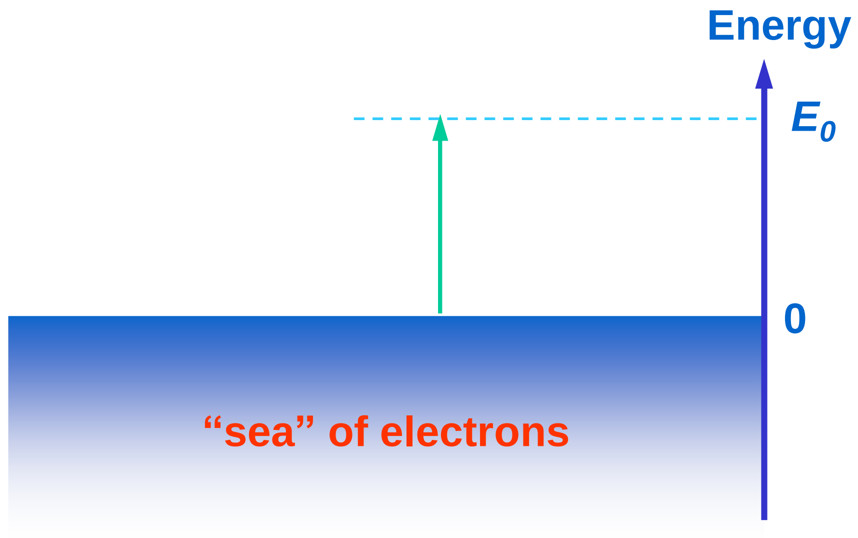

$$E_{new} = E_{old} + h\nu$$

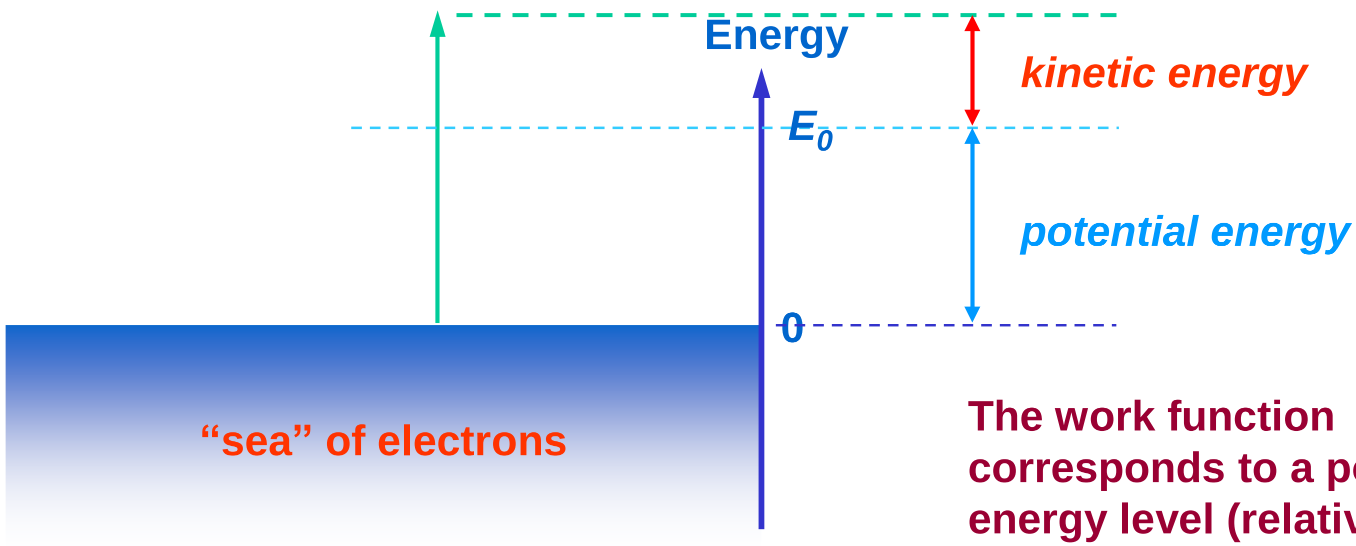
If the new energy exceeded the barrier height for “escape” from the solid, then the particle could be emitted.

The barrier height is the “work function.”



The minimum photon energy is for the excited electron to sit right at the top of the electron "sea." Then, the emitted energy is 0.






**The work function corresponds to a potential energy level (relative to the electron "sea," which must be overcome for emission.**

$$E = E_0 + mv^2/2$$

**This is exactly the expected result.**

# Light as a Particle

- We can now understand why electrons are ONLY emitted in the photoelectric effect

    * If the frequency of the light EXCEEDS some critical energy

- Electrons are emitted from the metal surface by ABSORBING the energy of photons

    * A FINITE amount of energy must be absorbed to remove each electron

    * Thus a FINITE photon frequency is required for electrons to be emitted


[web]

# Light as a Particle Phenomenon

- **APPLICATION**

*** 1 eV is required to remove an electron from the surface of a metal. Can photons with frequencies of $10^{14}$ Hz and $10^{15}$ Hz be used to achieve this?**

$$\textit{Photon Energy } E = h\nu$$

$$10^{14}\ \mathrm{Hz}: E = h\nu = 6.6\times10^{-34}\times10^{14} = 6.6\times10^{-20}\ \mathrm{J} = 0.4\ \mathrm{eV}$$ ***INSUFFICIENT***

$$10^{15}\ \mathrm{Hz}: E = h\nu = 6.6\times10^{-34}\times10^{15} = 6.6\times10^{-19}\ \mathrm{J} = 4\ \mathrm{eV}$$ ***YES!***

*** What happens to the REMAINING 3 eV of photon energy when *f* = $10^{15}$ Hz?**

**⇒ It is supplied to the electron as KINETIC ENERGY**

**⇒ So it is able to ESCAPE from the surface of the metal**

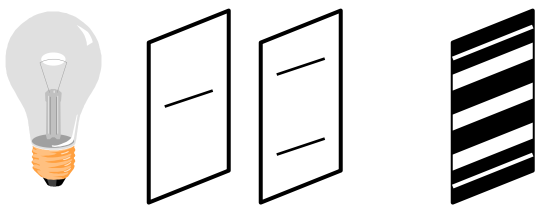
# What is Light?

- We are now faced with resolving an apparently **TRICKY** issue

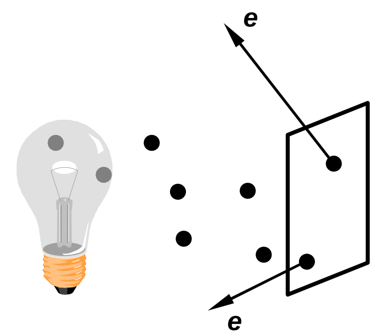
  ***** According to **CLASSICAL** physics light is a **WAVE** phenomenon

  ***** But we have just shown that it has a **PARTICLE** effect

  ⇒ **WHICH** interpretation should we believe?



***THE WAVE LIKE NATURE OF LIGHT IS SEEN IN THE DOUBLE SLIT EXPERIMENT IN WHICH AN INTERFERENCE PATTERN FORMS ON THE FAR SCREEN***




***THE PARTICLE LIKE NATURE OF LIGHT IS SEEN IN THE PHOTOELECTRIC EFFECT***

# What is Light?

• If we allow photons to pass through the apparatus **ONE AT A TIME** however

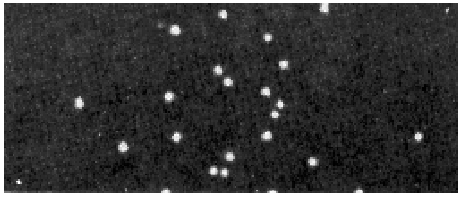
   * The interference pattern will **NO LONGER** be observed

   * Instead a series of **FLASHES** will be seen

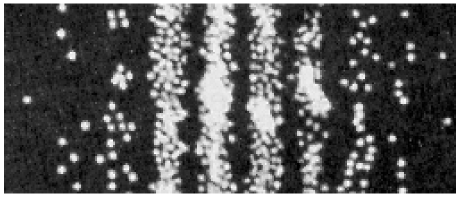
      ⇒ As **SUCCESSIVE** photons arrive on the screen

   * Eventually however the normal interference pattern will be built up!

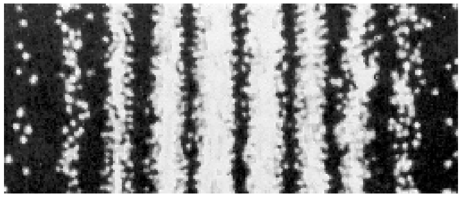
      ⇒ Showing that photons behave like particles **AND** waves



*AFTER 28 PHOTONS*



*AFTER 1000 PHOTONS*



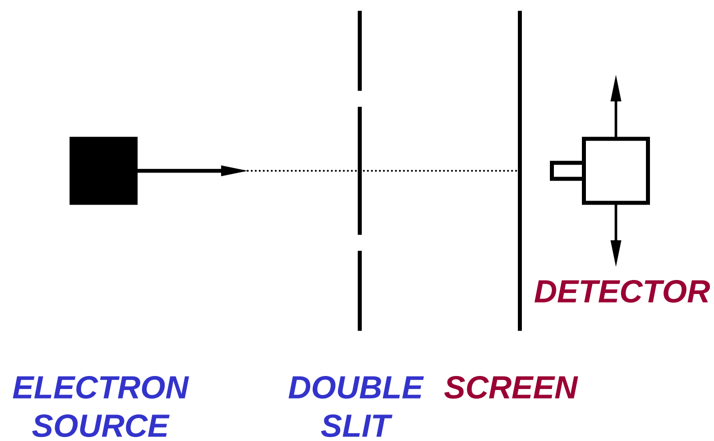
*AFTER 10,000 PHOTONS*

## Now, what about electrons?
## Electrons are definitely particles!

- **We normally think of electrons as POINT LIKE charges we can none the less**

*** In this experiment an electron beam is projected at a screen with two slits**

*** The electron distribution ARRIVING at another screen is then measured**



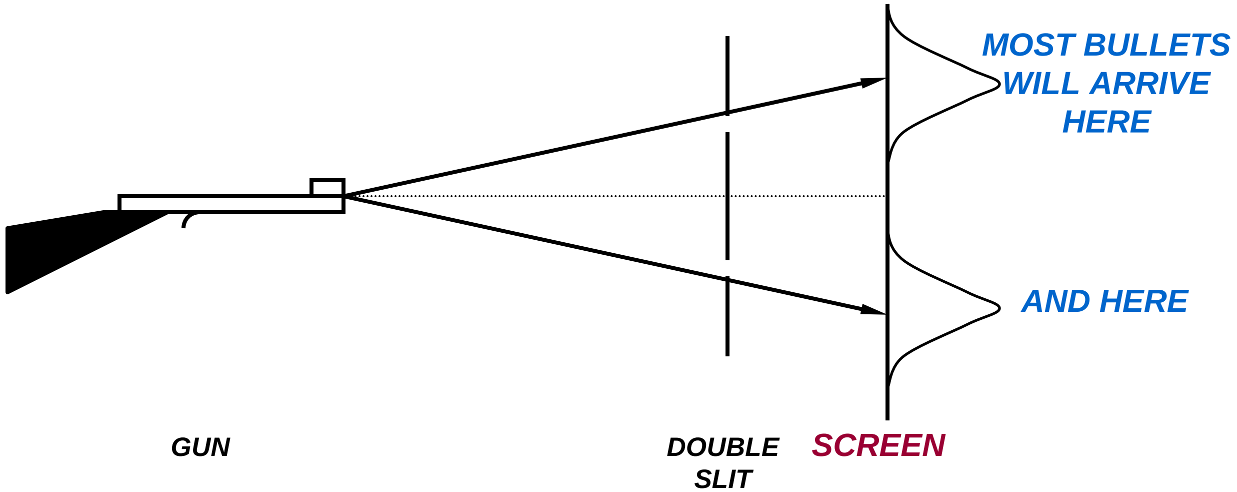

***IF WE MONITOR THE ARRIVAL OF ELECTRONS AT THE SCREEN THEN WHAT DO WE SEE AS WE MOVE THE DETECTOR?***

# Double Slit Experiment

• If electrons were purely PARTICLES what sort of behavior might we expect?

* Think of the case where we fire BULLETS from a gun

* A very distinctive distribution of counts will be obtained

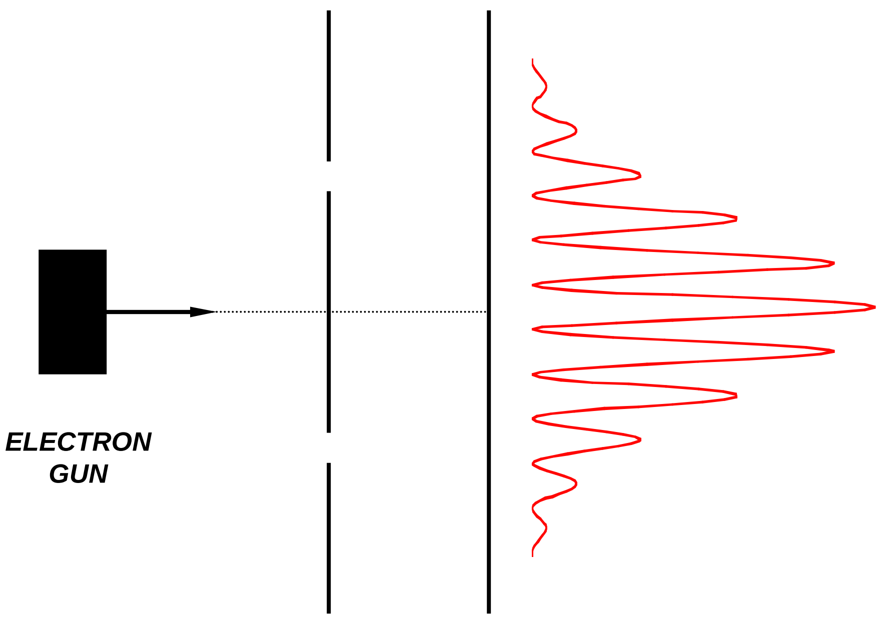


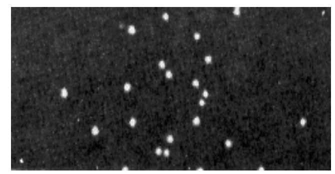

*MONITORING THE POSITION AND COUNTING THE NUMBER OF BULLETS THAT STRIKE THE SCREEN WE WOULD EXPECT THE PARTICLE-LIKE DISTRIBUTION SHOWN ABOVE*

# Double Slit Experiment

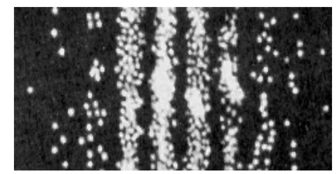
**When we perform the experiment with electrons, we find something DIFFERENT** [web]

**The electrons show an INTERFERENCE PATTERN that is Similar to that found when we perform the same experiment with LIGHT**

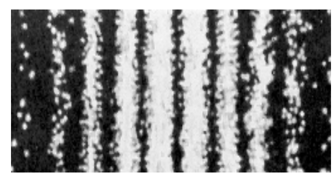


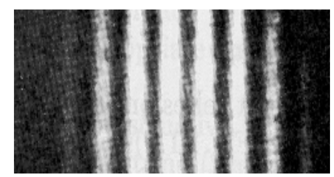
**AFTER 28 ELECTRONS**



**AFTER 1000 ELECTRONS**



**AFTER 10,000 ELECTRONS**



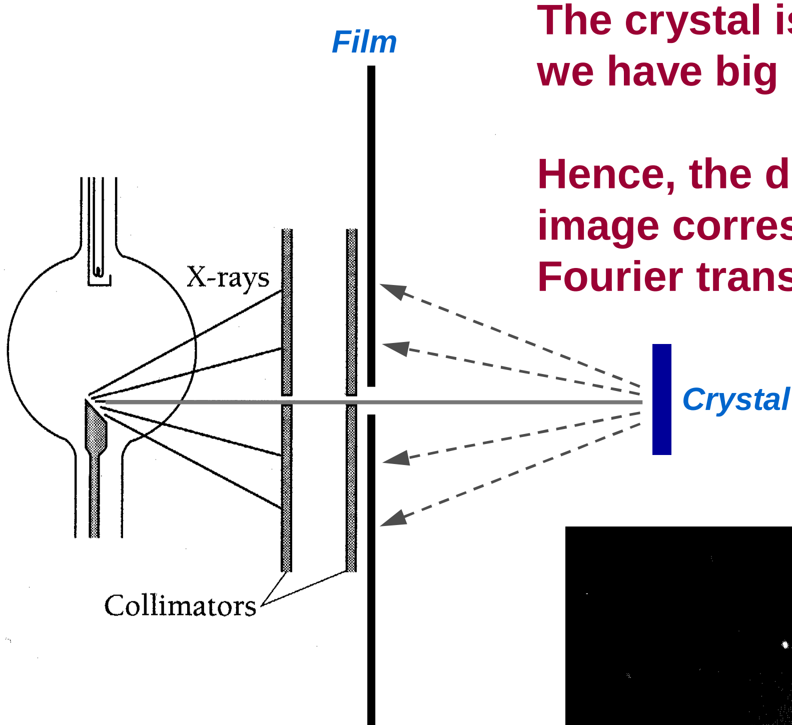
**TWO-SLIT PATTERN**

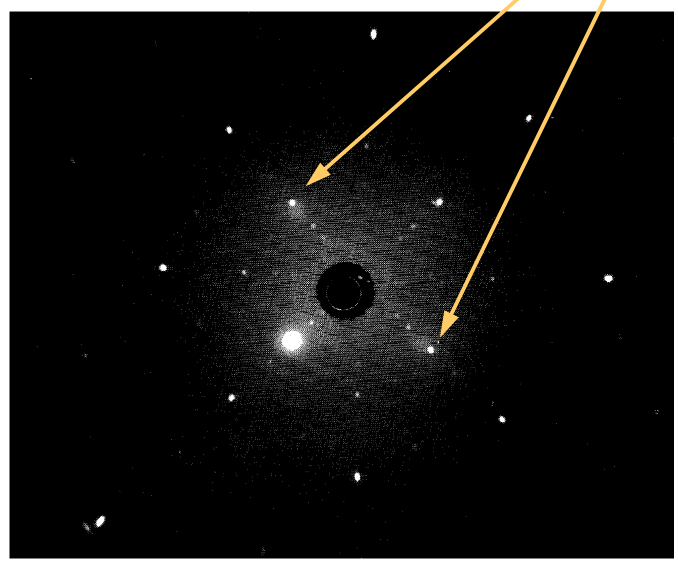
***Results are the same as for photons—electrons are a wave!***

# X-Ray Diffraction

The crystal is the reverse image of the slits in 3D (or we have big slits between the atoms).

Hence, the diffraction pattern is the reciprocal space image corresponding to the periodicity—it is the Fourier transform of the crystal structure.

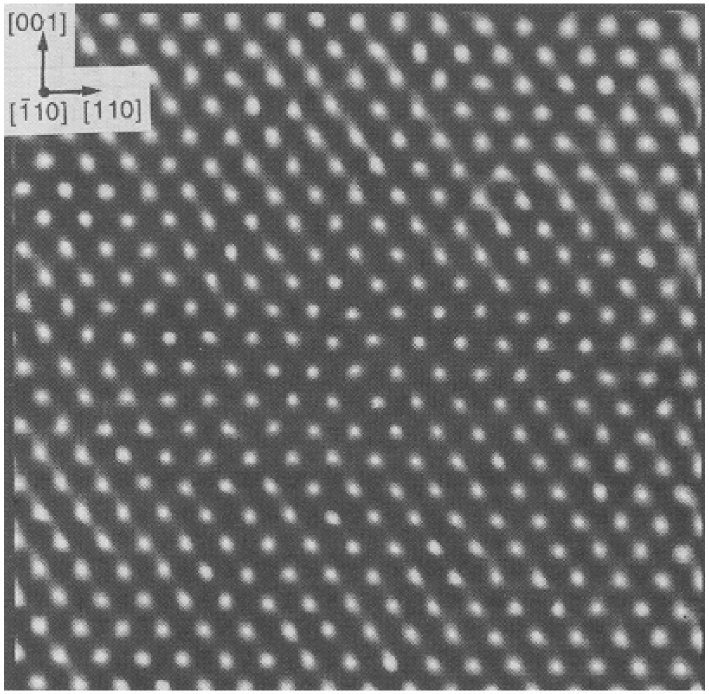


The points correspond to the NORMALs to the crystal planes (vectors in the reciprocal space).

This result is obtained whether we use X-rays or electrons (TEM).

Taking the inverse Fourier transform (achieved by passing through a lens) yields a replica of the lattice itself, which we call a *lattice-plane image* of the crystal structure.




So, in the TEM, we rely upon the *wave-nature* of the electrons to produce the high resolution images that show us the atomic structure.

# The “NEW” Mechanics:
# QUANTUM MECHANICS

We are led to conclude that ALL “things”, whether electrons or photons or automobiles or …… are both particle and wave!

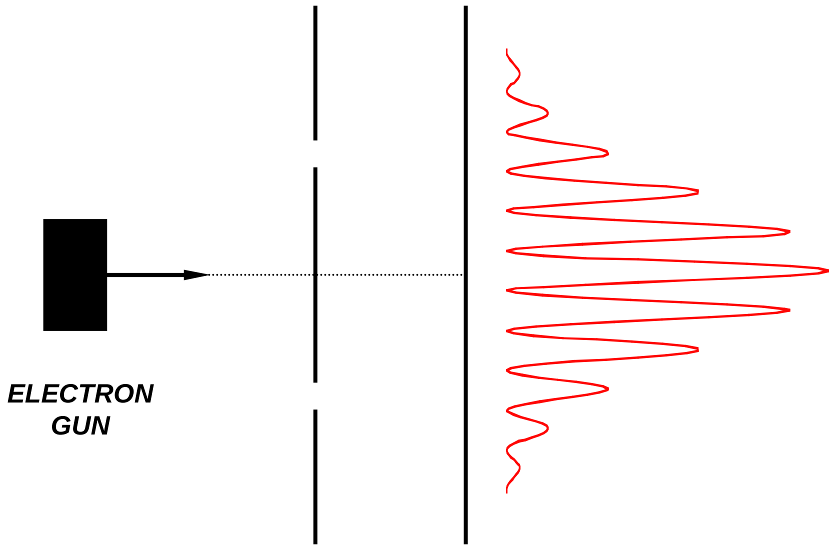
Which property we “measure” depends upon the type of measurement that is carried out.

* The two-slit experiment is a wave-like measurement

* The photo-electric effect is a particle-like measurement

This ***wave-particle duality*** is a part of the principle of **complementarity.** The complementarity principle is considered as Neils Bohr’s important contribution, yet he had trouble fully accepting a wave-based theory that was due to Schrödinger and the electron wave concept of de Broglie.

# The De Broglie Relation




We found that particles showed interference, and therefore behaved as waves.

But, the interference period is related to the wavelength of the wave—particles must have a wavelength!

The idea of a wavelength corresponding to quantum structures was put forward by Louis de Broglie, in his doctoral thesis at the University of Paris

$$E = mc^2 = mcc = pc$$

Prince Louis-Victor de Broglie
Nobel Prize in Physics, 1929

# The De Broglie Relation

**For particles, and particularly for photons, the energy can be given by Einstein's famous formula:**

$$E = mc^2 = mcc = pc$$

**The momentum of the photon is said to be *mc=p***

**But, the energy of the photon is also given by Planck's famous law:**

$$E = h\nu$$

**so that**

$$E = h\nu = h\frac{c}{\lambda} = pc \quad \Rightarrow \quad p = \frac{h}{\lambda}$$

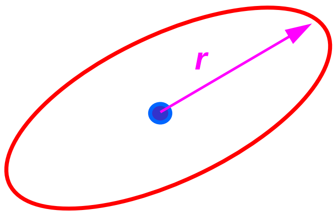
**de Broglie's relation**

# De Broglie Relation

**From the de Broglie relation, we now can find the wavelength for the particle:**

$$\lambda = \frac{h}{p}$$

***De Broglie postulated this relation in his thesis, and suggested that quantization in atoms followed by requiring an integer number of wave lengths in the electron orbit. While logical, this view was emphatically challanged by the Copenhagen group.***




$$2\pi r = n\lambda$$

**We must fit an integer number of wavelengths into the orbit.**

## There still remain differences between particles and waves:

| Particles | | Waves | |
|---|---|---|---|
| | $E = \frac{p^2}{2m}$ | $E = hf$ | |
| de Broglie wavelength | $\lambda = \frac{h}{p} = \frac{h}{\sqrt{2mE}}$ | $\lambda = \frac{c}{f} = \frac{hc}{E}$ | optical wavelength |
| | $k = \frac{2\pi}{\lambda} = \frac{\sqrt{2mE}}{\hbar}$ | $k = \frac{2\pi}{\lambda} = \frac{E}{\hbar c}$ | |

**While we use similar notation for particles and for true waves, various quantities are defined differently. Do not make the mistake of using *optical* definitions for *particles*.**

**Let us consider a photon and an electron, both of which have an energy of 1 eV (1.6 X $10^{-19}$ J)**

$$\lambda_{photon} = \frac{c}{f} = \frac{hc}{E} = \frac{(6.62618\times10^{-34}\,J\cdot s)(3\times10^{8}\,m/s)}{1.6\times10^{-19}\,J} = 1.24\times10^{-6}\,m$$

$$\lambda_{particle} = \frac{h}{p} = \frac{h}{\sqrt{2mE}} = \frac{6.62618\times10^{-34}\,J\cdot s}{\sqrt{2(9.1\times10^{-31}\,kg)(1.6\times10^{-19}\,J)}} = 1.23\times10^{-9}\,m$$

**There are 3 orders of magnitude difference in the size of the two wavelengths.**

**The fact that the wavelengths for particles are so small is why they are usually never observed. On the other hand, they become important when we deal with nano-technology, since we are on the same dimensional scale!**