Particles and Waves

Particles

- Discrete and occupy space
- Exist in only one location at a time
- Position and velocity can be determined with infinite accuracy
- Interact by collisions, scattering.

Waves

- Extended, do not occupy space
- Can exist in more than one location at a time
- Wavelength, speed can be determined with infinite accuracy
- Interact by interference, diffraction.

The classical mechanics of Newton
and the electromagnetism of Maxwell
seem to indicate that particles and waves
are very different entities

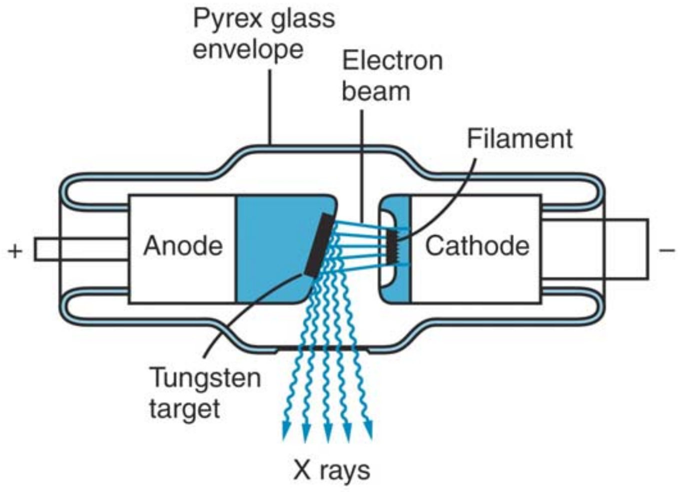
However, experimental observations
in the late 1800's and early 1900's
suggested that it might not be so.

Under certain circumstances
particles may behave as waves and
waves may behave as particles

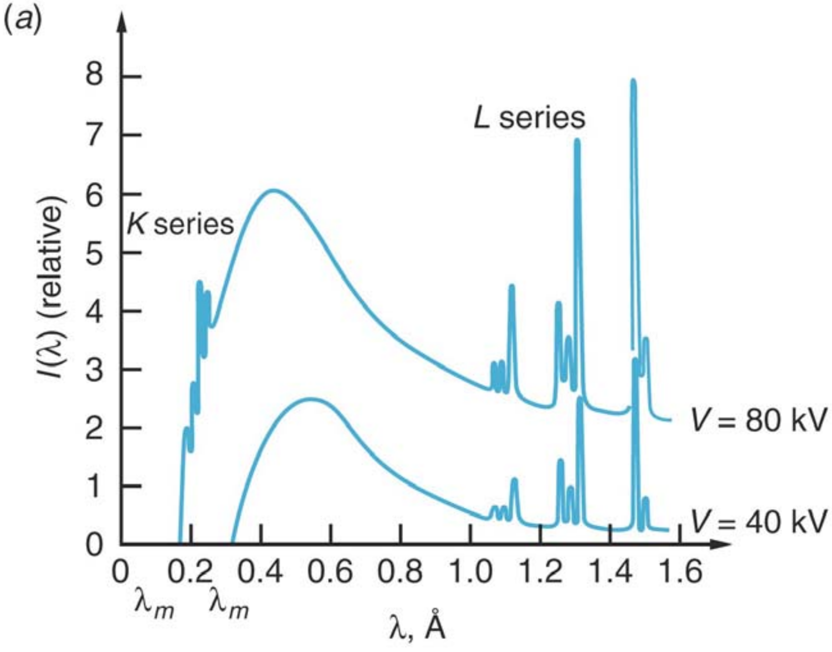
Waves as Waves
X-Rays

Wavelength: $\lambda \approx 0.1$ nm

Energy: $E(eV) = 1.24 / \lambda(\mu m) \approx 10$ KeV

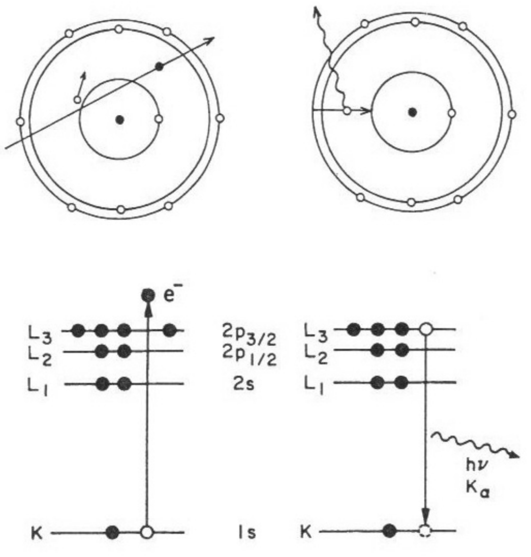


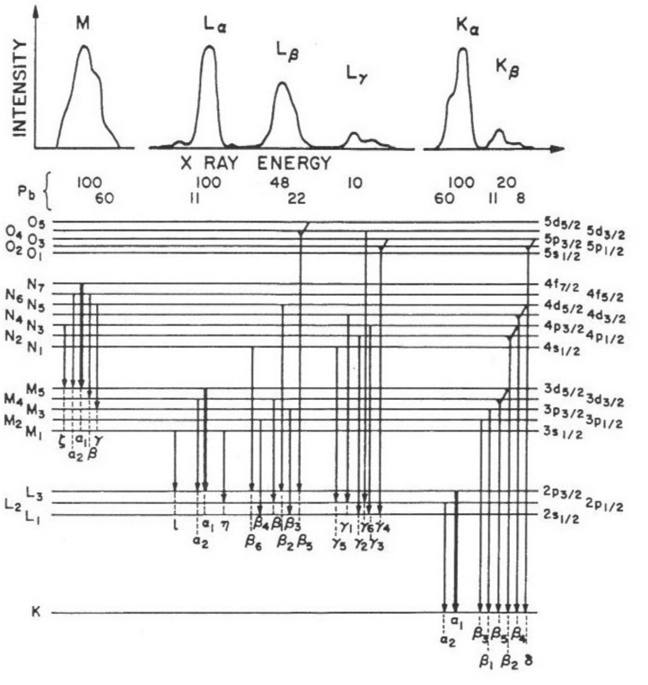
X-ray tube



X-ray spectra from tungsten

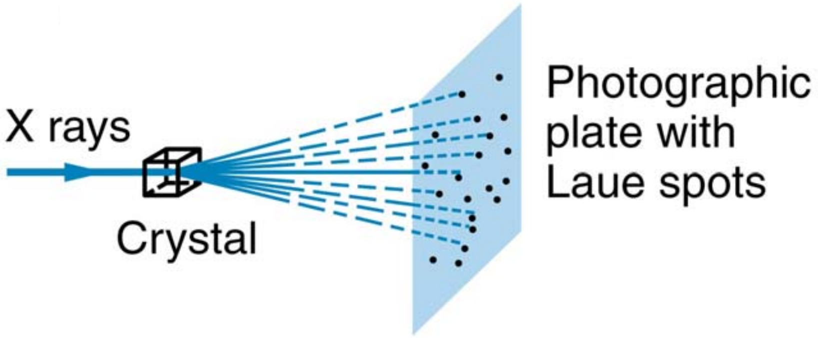
X-Ray Emission

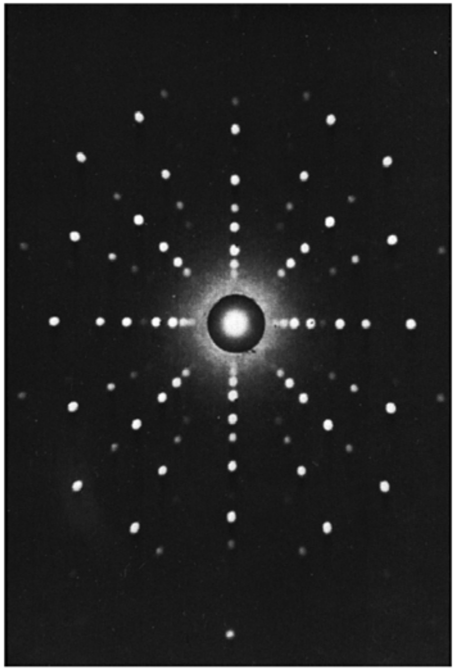




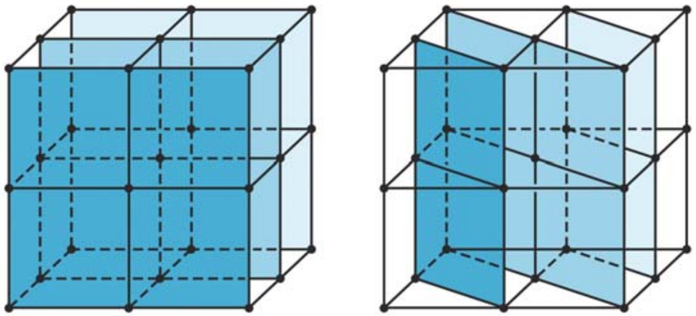
The energy of the emitted x-rays identifies the excited atom

X-Ray Diffraction

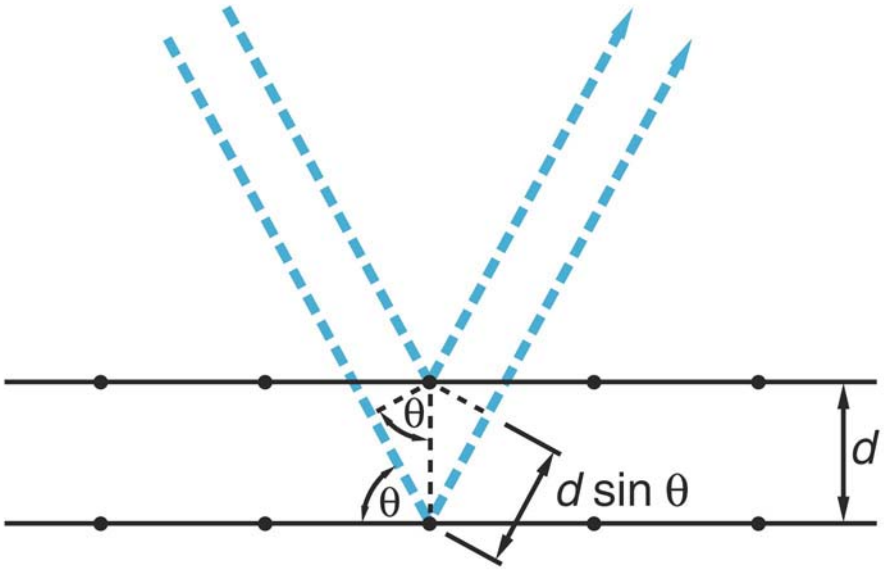




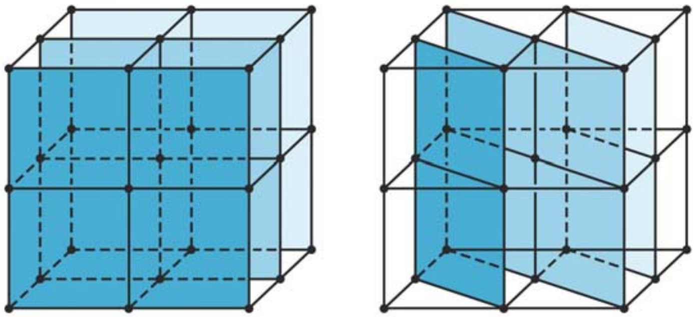
X-rays are diffracted by the periodically arranged atoms in a crystalline lattice



X-Ray Diffraction



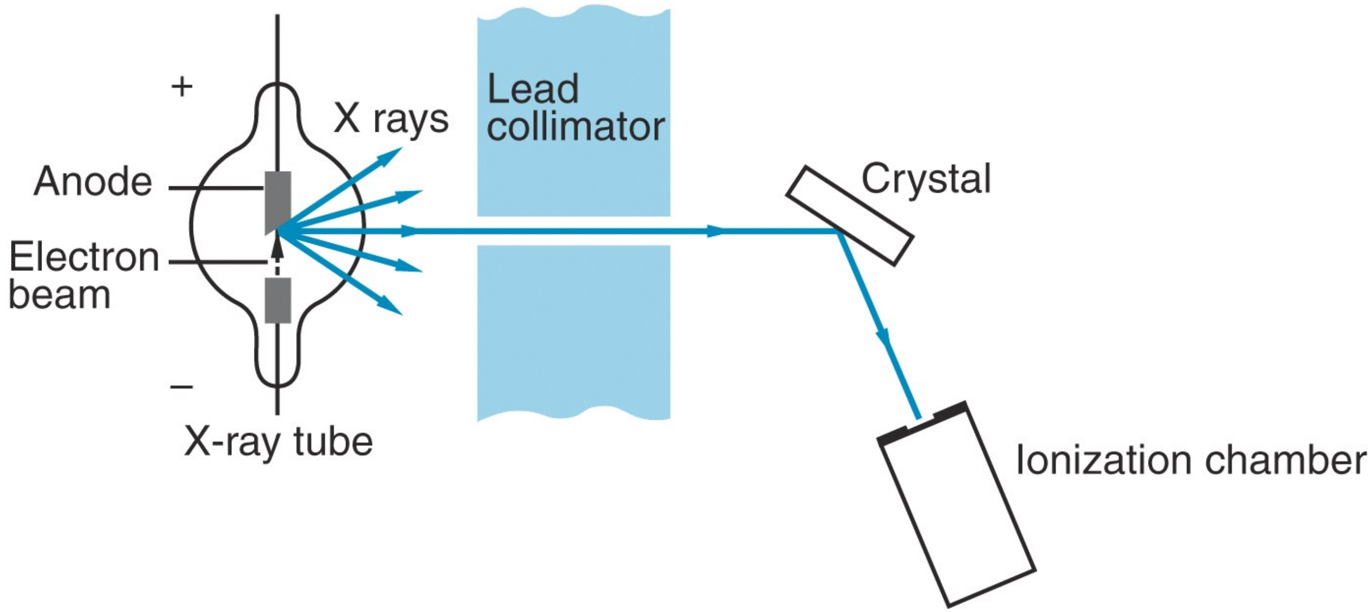
X-rays are diffracted by the periodically arranged atoms in a crystalline lattice



Bragg Condition

$$2\ d \sin \theta = m\ \lambda$$

X-Ray Diffraction

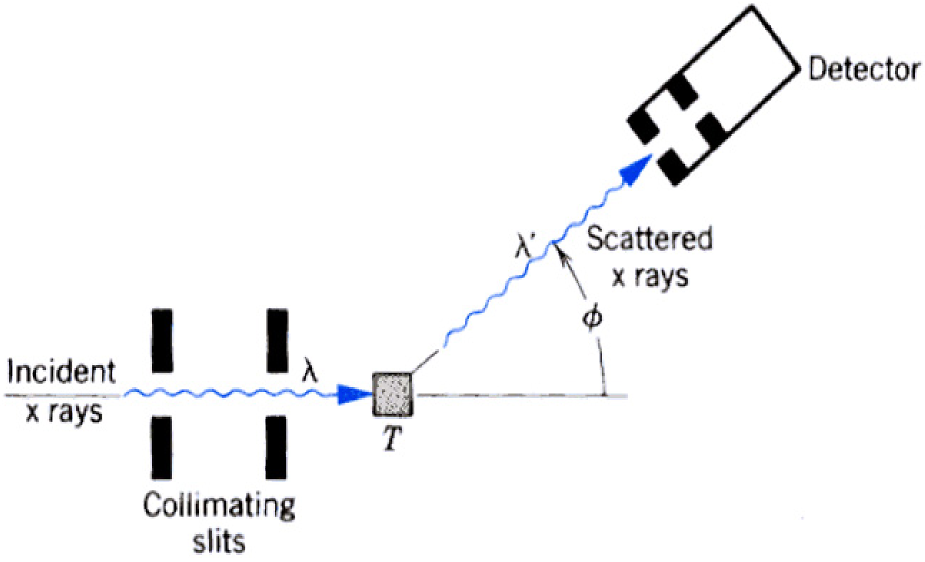


Bragg Condition

$$2\,d\sin\theta = m\,\lambda$$

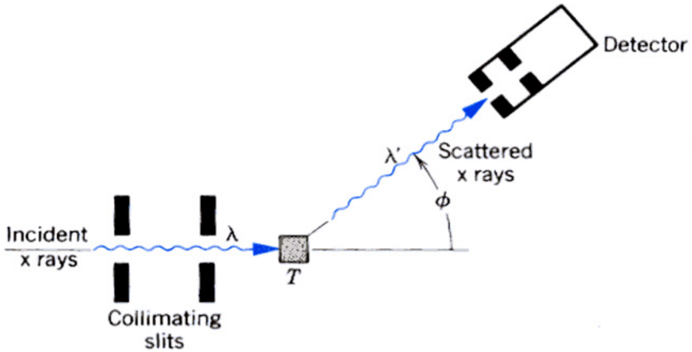
Waves as Particles
Compton Effect (1923)

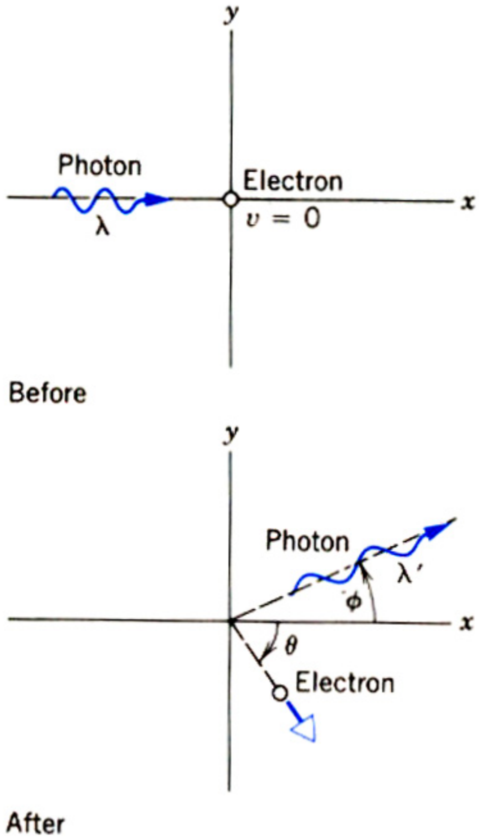
X-Ray Scattering



$$\lambda' - \lambda = (h / m_e c)(1 - \cos \phi)$$

Compton Effect





$$\lambda' - \lambda = (h / m_e c)(1 - \cos \phi)$$

The **Compton Effect** could be explained by assuming the collision between a stationary electron, and an incident 'particle', the **Photon**, of **mass zero, moment $P = h / \lambda$, and energy $E = h c / \lambda$**.

The Photon

The concept of the Photon as the quantum of energy (discrete, minimum value) for electromagnetic waves, was introduced by Max Plank, in 1900, in his attempt to explain the wavelength dependence of the energy emitted by a body at a given temperature T (called blackbody radiation).

The concept of photon was further developed by Albert Einstein in 1905 in his explanation of the Photoelectric Effect (emission of electrons upon illumination of a solid – typically in the UV or higher energy)

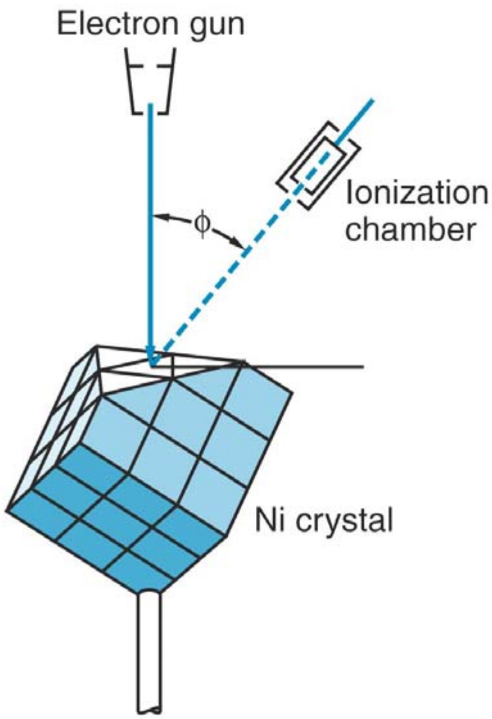
The Photon

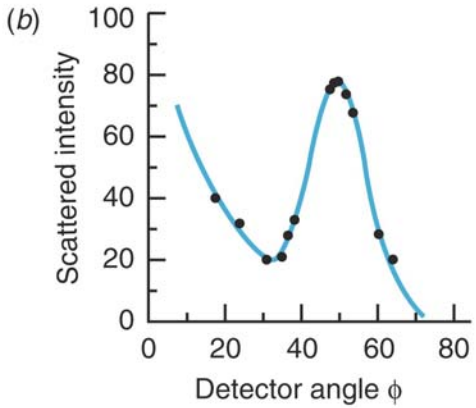
To explain certain experimental observations of the interaction of electromagnetic radiation with matter, it is necessary to describe the radiation as

a beam of photons: particles or quanta of energy with **mass zero, moment $P = h / \lambda$, and energy $E = h\,c / \lambda$**

instead of using the wave representation.

Particles as Waves
Diffraction of Electrons
The Davisson-Germer Experiment

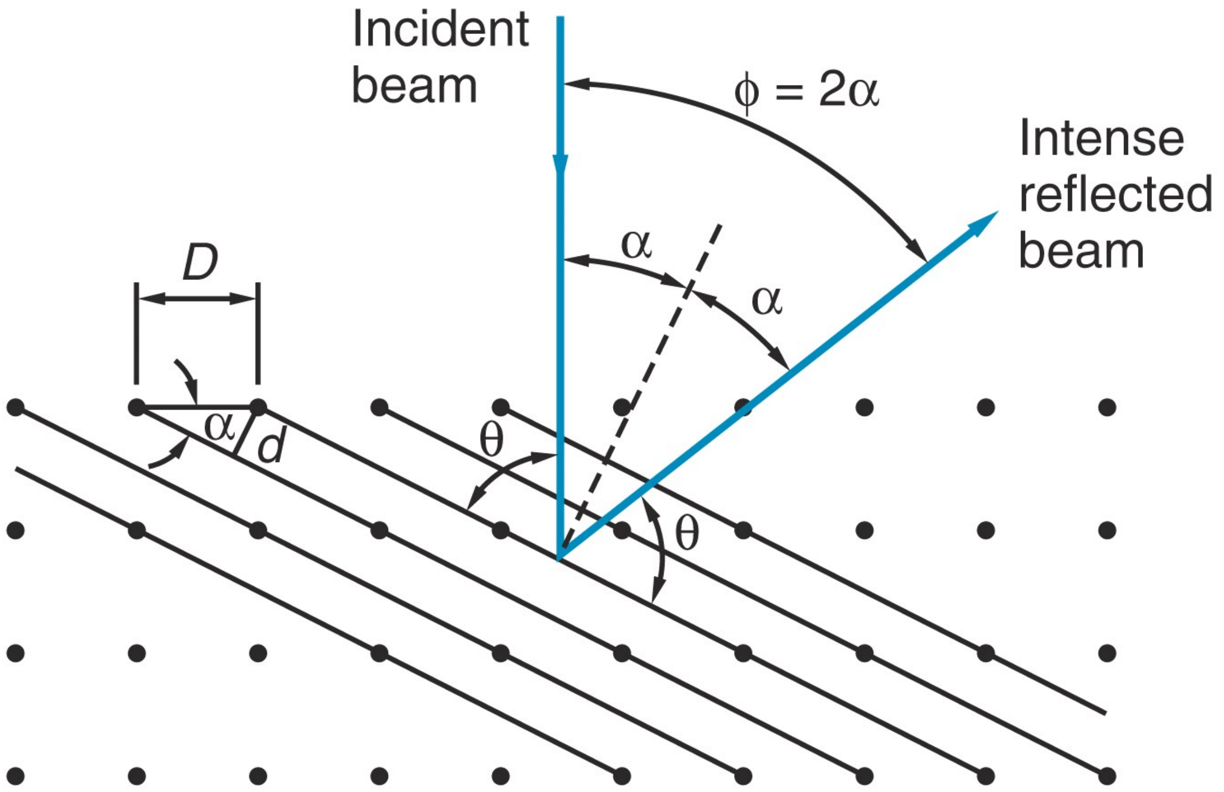




The strongly directional scattering could only be explained by assuming diffraction of an incident wave, with wavelength $\lambda = h / p$, where p was the momentum of the electrons

Diffraction of Electrons

$$n \lambda = D \sin \phi \quad \text{with } \lambda = h / p$$

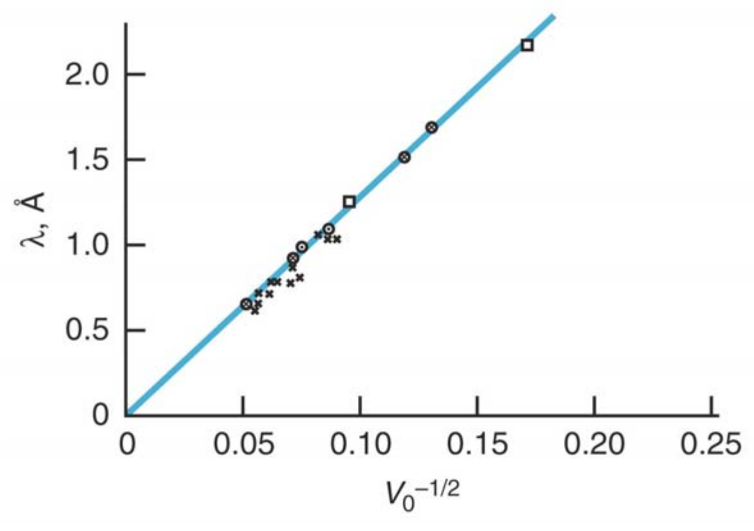


Diffraction of Electrons

$n\lambda = D\sin\phi$, $\lambda = h/p$, and $p = (2meV)^{1/2}$

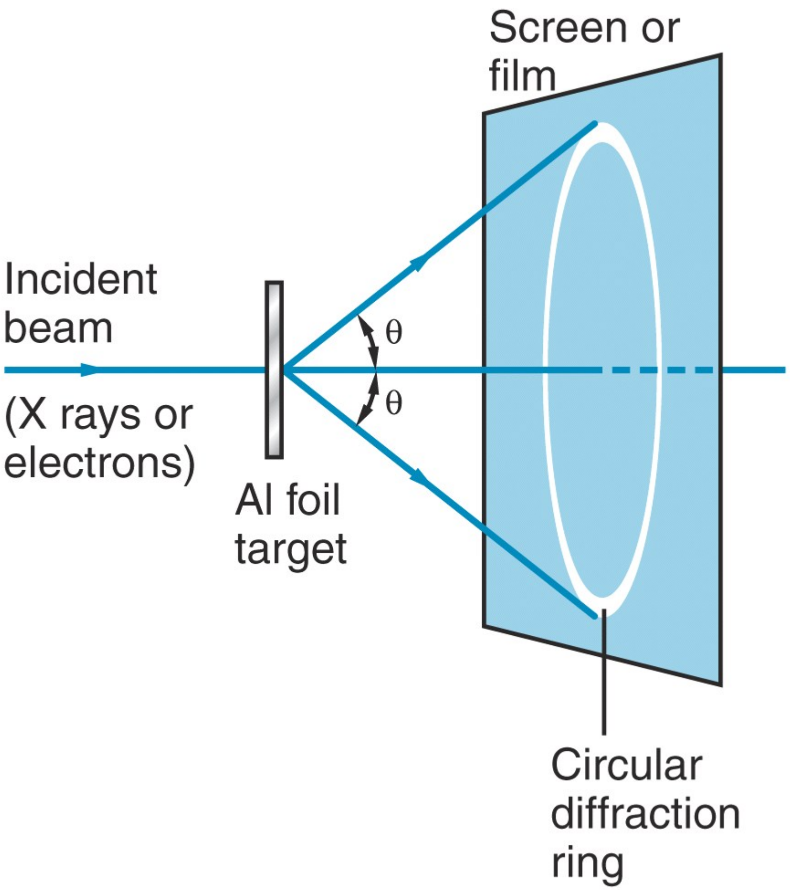
then $\lambda = h/(2meV)^{1/2}$

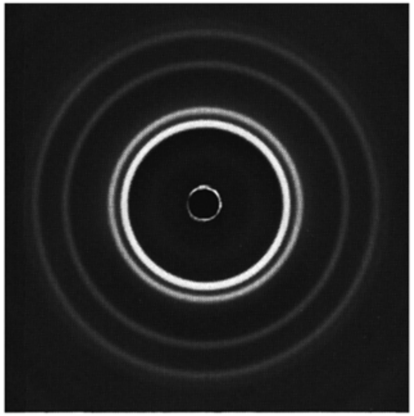
A plot of λ vs. $V^{-1/2}$ should give a straight line with slope $h/(2me)^{1/2}$



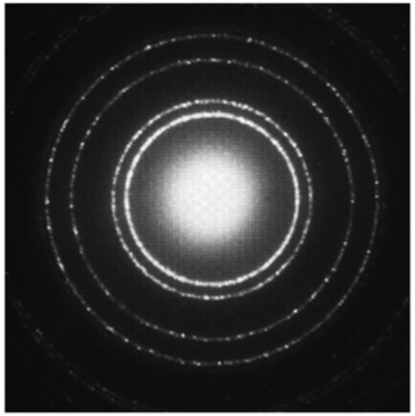
1. Set acceleration voltage to V
2. Perform expt, determine ϕ
3. Calculate λ from $n\lambda = D\sin\phi$
4. Plot λ vs. $V^{-1/2}$
5. Measure slope

Diffraction of Electrons and X-Rays in Aluminum





X-Rays



Electrons

The de Broglie Hypothesis

Louis de Broglie proposed in 1924 that the wave-particle duality that had been adopted for radiation, was also valid for particles.

Not only waves may behave as particles (under certain conditions) but also particles (in particular electrons) may behave as waves.

De Broglie proposed the following relations for the frequency and wavelength of the wave associated with an electron:

$$f = E / h \qquad \lambda = h / p$$

E is the total energy, and p is the momentum, of the particle or electron, and λ is called the de Broglie wavelength of the particle.

Wave-Particle Duality

1. Waves may exhibit particle-like properties (Compton effect) and

2. Particles may exhibit wave-like properties (electron diffraction)

The correlation between particles and waves was proposed by de Broglie:

$$f = E / h \qquad \lambda = h / p$$

For a non-relativistic particle $p = mv$ and $E = p^2 / 2m$

For a relativistic particle $E^2 = (mc^2)^2 + p^2 c^2$

For a photon $m = 0$ then $E = pc$ and $f = p c / h$

or $p = h / \lambda$ and $E = h c / \lambda$