Phys 231 2021

Lecture 4

Mon: HW due 5pm

Weds: Read Waves OpenStax Univ Physics Ch 16.1
16.2
16.5

Quantized light-matter interactions

Quantum theory has had much success explaining interactions between light and matter at the microscopic level. The crucial facts are:

1) Any electromagnetic radiation is such that its energy is apportioned into indivisible quanta / photons. The energy of a single photon is

$$E = hf = \frac{hc}{\lambda}$$

where f = frequency of radiation and λ = wavelength.

2) When a photon is incident on matter either all of the energy is absorbed or else none is.

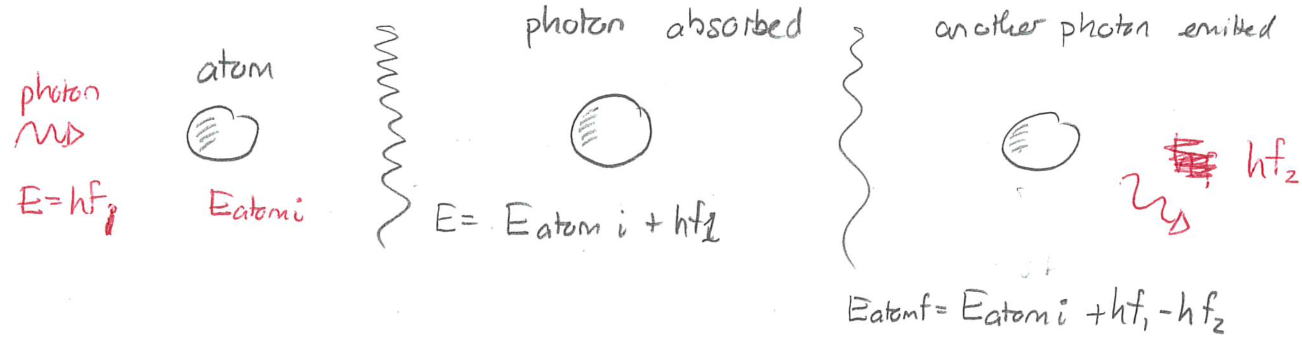
3) When matter emits photons it does so via a series of single photon emission events.

Demo: PSU-S Photoelectric Effect (absorption of a photon)

Demo: PSU-S Photon scattering (no energy absorbed.

Demo: PhET Model H atom - Bohr model
- show absorption / emission

Sometimes the matter an absorb a photon and subsequently emit another at a different frequency. In all cases energy is conserved.



Quiz!

These energy conservation rules that involve quantized energy for electromagnetic radiation arise throughout quantum theory.

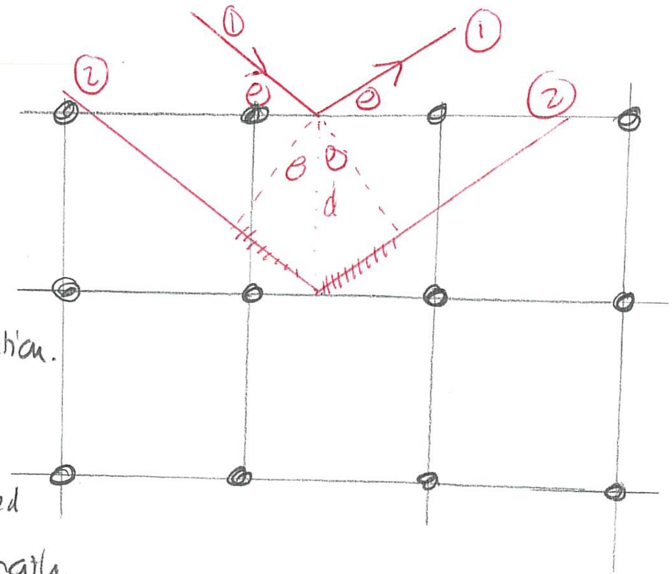
X-rays

X-rays are a form of electromagnetic radiation whose frequency is much larger than that of visible light. One way to produce X-rays is to have an energetic electron collide with a stationary metal target. The electron rapidly decelerates and this produces electromagnetic radiation.

Demo: Youtube Video.

How do we know that these are waves? One method would be to scatter X-rays off a crystalline material. A crystalline material is one whose nuclei arrange themselves in a regular lattice. Such experiments were originally observed by Max van Laue in 1912 and their results were analyzed by William Bragg (6).

The basic rules can be illustrated with a simplified model using a two dimensional rectangular lattice. The lattice contains a variety of planes and X-rays reflect off these.



Then consider the two illustrated beams. The law of reflection dictates their configuration.

It is clear that beam (2) traveled further than beam (1). The two shaded segments illustrate this. Each has length $d\sin\theta$. So beam (2) travels distance $2d\sin\theta$ further.

Constructive interference occurs when this is an even number of wavelengths.

Thus constructive interference and strong reflection occurs when:

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

for $m = 0, \pm 1, \pm 2, \ldots$

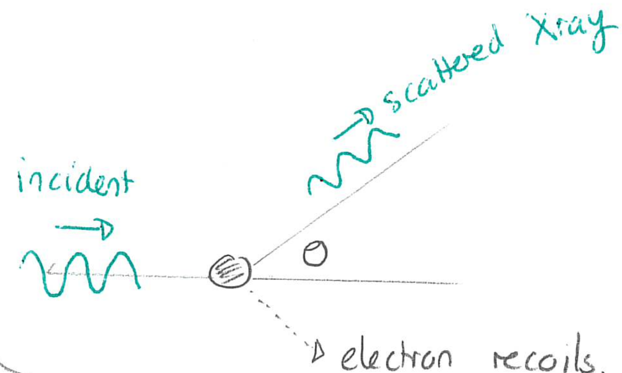
This is the <u>Bragg condition</u>

Demo: UPenn XRD Basics

This type of X-ray diffraction is used to determine crystal structures

Compton effect.

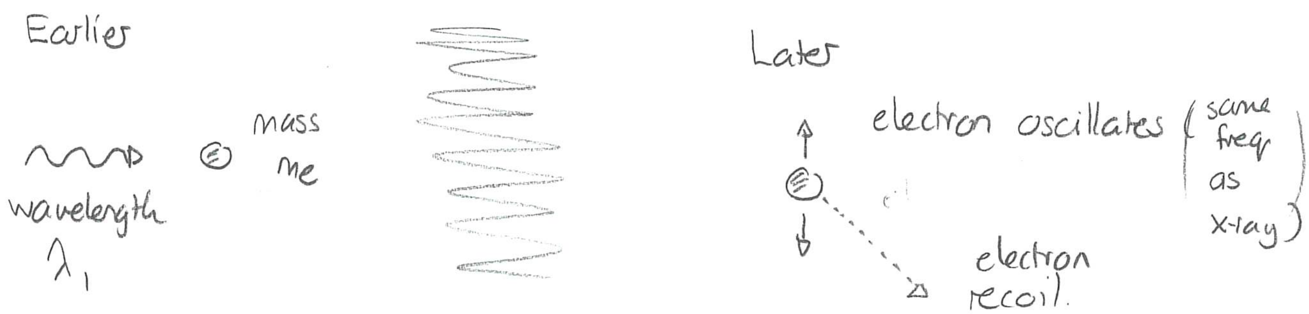
Consider electrons that are bombarded with X-rays. An observation is that X-rays are scattered from the electrons at various angles. As with light that is scattered by atoms we might expect that the wavelength of the scattered X-rays is the same as that of the incident X-rays. Experiments performed by A.H. Compton in 1923 indicated that this was not true. These showed.



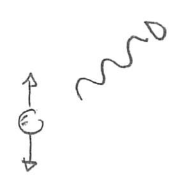
> The wavelength of the scattered X-ray was different to the wavelength of the incident X-ray. The difference depends on the scattering angle, θ.

A possible classical explanation uses various ideas from electromagnetism and waves:

1) the electromagnetic wave for the X-ray causes:



2) the oscillating electron emits electromagnetic radiation. If the electron were at rest the frequency of radiation = frequency of oscillation.



Then the scattered wavelength = incident wavelength

3) The electron recoils. There will be a Doppler shift in the frequency of the emitted radiation. Then the wavelength of the scattered X-ray will be shifted. Denote this by λ_2.

4) A classical calculation combines all of these and gives.

$$\lambda_2 - \lambda_1 = W \frac{\lambda_1}{m_e c^2} (1 - \cos\theta)$$

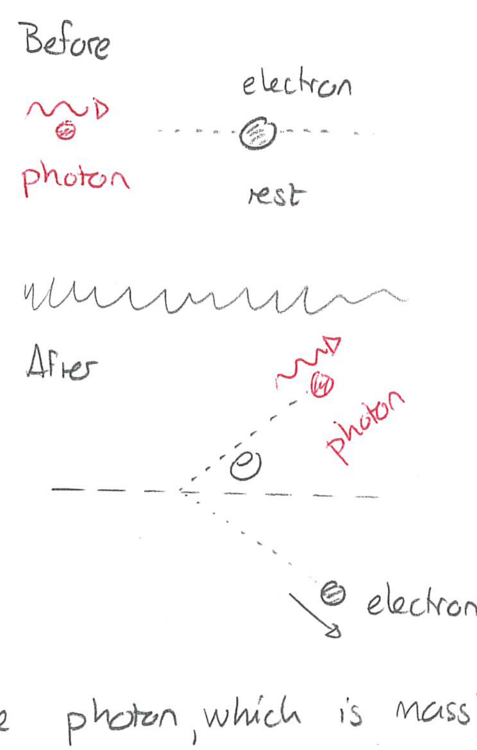
where W = total energy absorbed from the X-ray.

5) At any single angle the shift could be anything since the total amount of energy could be anything.

The actual experiment showed that the shift depended on the angle only and not the intensity.

<u>Compton's explanation</u>

Compton assumed that the X-rays were a stream of photons and that each photon could be treated as a particle. The situation could be analyzed as a collision between two particles. In this collision both energy and momentum must be conserved.



This does require a momentum for the photon, which is massless. The momentum will be non-zero. Both electromagnetic theory and special relativity predict this fact.

In relativity:

$$E^2 = p^2c^2 + m^2c^4$$

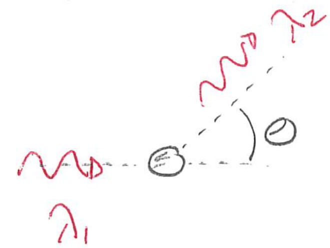
For a photon $m = 0$

$$E = |p| c \Rightarrow |p| = \frac{E}{c} = \frac{hc/\lambda}{c}$$

$$\Rightarrow \boxed{|p| = h/\lambda}$$

A detailed analysis of a relativistic collision yielded:

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



where m_e is the mass of the electron.

This predicts that the change in wavelength only depends on the scattering angle.

Demo: Compton paper data.

Quiz 2