Chapter 30   Quantum Physics

30.1 Blackbody Radiation and Planck’s Hypothesis of Quantum Energy

30.2 Photons and the Photoelectric Effect

30.3 The Mass and Momentum of a Photon

30.4 Photon Scattering and Compton Effect

30.5 The de Broglie Hypothesis and Wave-Particle Duality

30.6 The Heisenberg Uncertainty Principle
The "wave–particle duality" nature will be discussed in this chapter. We will learn that a wave can exhibit particle-like characteristics and a particle can exhibit wave-like characteristics. We will also see that light and other electromagnetic waves can exhibit some of the same characteristics that are normally associated with particles. In particular, we will find that electromagnetic waves can be regarded as being composed of discrete packets of energy, called photons, and that a photon has momentum, just as a particle does. This chapter concludes with an introduction to one of the most unusual scientific principle, the Heisenberg uncertainty principle, which places a limit on our knowledge of certain aspect of the physical world.
Light waves can behave like particles!
Particles like electrons can behave like waves!

The picture of a fly at the start of the chapter was taken using an electron microscope. In this case the electrons are behaving like waves.

Section 30.1: Objects that are hot appear different colors depending on how hot they are:
Dim Red - hot
Yellow - hotter
White hot - very hot
**Blackbody**

A perfect blackbody or, simply, blackbody is used when referring to an object that absorbs all the electromagnetic waves falling on it.

**Plank's constant**

At a constant temperature, a perfect blackbody absorbs and reemits all the electromagnetic radiation that falls on it. Max Plank calculated the emitted radiation intensity per unit wavelength as a function of wavelength. In his theory, Plank assumed that a blackbody consists of atomic oscillators that can have only quantized energies. Plank's quantized energies are given by $E = nhf$, where $n = 0, 1, 2, 3, \ldots$, $h$ is the Plank's constant (6.63 x $10^{-34}$ J.s), and $f$ is the vibration frequency.
A **Black Body** absorbs all the light that hits it. NO light is reflected, that is why it appears black. It does not need to be black. For example, a furnace. If all radiation is absorbed then it also is very effective at giving off or emitting radiation. That is-heat the black body to some temperature and measure the radiation that it emits.

For a black body, max intensity radiated blue shifts as temperature increases. Red hot is not as hot as blue hot.
E = nhf,  n=1,2,3 \ldots \\
= n(hc / \lambda) \\
E_i=2hf \\
E_f=hf

Electromagnetic wave of energy

\[ E=hf \]

To emit a single very high frequency photon requires a lot of energy.

How much energy in a photon of blue light at 400 nm? Express your result in eV.
In the photon model of light, a beam of light consists of many photons each with an energy $hf$. The more intense the beam, the more tightly packed the photons.
Emitted Energy is **quantized**

\[ E_n = n hf, \quad n=1,2,3 \ldots \]

h – Planck’s Constant = \(6.63 \times 10^{-34}\) Js

Light is emitted in discrete “chunks” called **PHOTONS**

Energy of a photon, \(E = hf\)

The suggestion is that light is a little **particle** of energy

BUT the amount of energy is related to the frequency.

**PARTICLES AND WAVES ARE RELATED!**
Photons

All electromagnetic radiation consists of photons, which are packets of energy. The energy of a photon is $E = hf$, where $h$ is Planck's constant and $f$ is the frequency of the light. A photon in a vacuum always travels at the speed of light $c$ and has no mass.

Photoelectric effect

The photon-electric effect is the phenomenon in which light shining on a metal surface causes electrons to be ejected from the surface.

Work function

The work function $W_0$ of a metal is the minimum work that must be done to eject an electron from the metal. In accordance with the conservation of energy, the electrons ejected from a metal have a maximum kinetic energy $KE_{\text{max}}$ that is related to the energy $hf$ of the incident photon by $hf = KE_{\text{max}} + W_0$. 
Since everyone thought light was a wave the theory was not initially accepted. Light has particle like properties and wave like properties! This is difficult to accept.

However, the theory was able to explain many other phenomena.

**The photoelectric effect:** Some metals give of electrons when you shine light on them

If light is a wave you expect that very intense light will result in the liberation of lots of electrons and that this will be independent of the frequency of the light.
The photoelectric effect can be studied with a device like that shown. Light shines on a metal plate, ejecting electrons, which are then attracted to a positively charged "collector" plate. The result is an electric current that can be measured with an ammeter.
The maximum kinetic energy of photoelectrons as a function of the frequency of light. Note that sodium and gold have different cutoff frequencies, as one might expect for different materials. On the other hand, the slope of the two lines is the same, $h$, as predicted by Einstein's photon model of light.
If the frequency of the light hitting the photoelectric material is varied. Below a certain frequency, $f_0$, NO electrons are emitted by the material. NO MATTER WHAT THE LIGHT INTENSITY IS.

For $f=f_0$ the emitted electrons have no KE. Increasing the intensity does not increase the KE of the electrons. It does increase the number of electrons emitted, however. Increasing $f$ will increase the electron KE.
The photoelectric effect: characteristics

1 Photocurrent $\propto$ intensity
2 KE of photoelectrons $\propto$ frequency but not intensity.
3 Below $f_0$ there is no photoelectron emission.
   Even for extremely intense light.
4 Photoemission is immediate even for extremely low intensity light.

The latter three observations CANNOT be predicted by considering light to be a wave.

Think about a weak and a strong person trying to move a rock. Millions of weak people one at a time will never move the rock, however a single strong person will easily move the rock.
Einstein explained the photoelectric effect by using the particle nature of light. Photons of discrete energy can be used provide energy to electrons to overcome the attractive metallic forces. Any excess energy of the photon is transferred to KE of the electron. Note: All of the energy of the photon is used up.

Light, $E=hf$

$$KE_{e_\infty} = \frac{1}{2} m_e v^2$$

$KE_{\text{max}} = hf - W_0$

$$hf = \frac{hc}{\lambda} = W_0 + \frac{1}{2}mv^2$$

$$f_o = \frac{W_0}{h}$$

Different for different metals
Questions
1. The photons emitted by a source of light do NOT all have the same energy. Is the source monochromatic?

2. Which of the colored lights (red, orange---blue) on a Christmas tree emits photons with the most and least energy?

3. Does the photon emitted by a higher wattage red light have more energy than a photon emitted by a lower wattage red bulb?

4. Radiation of a given wavelength causes electron emission from one metal but not from another. Explain.
Radiation of wavelength of 281 nm shines on a metal surface and ejects electrons with a maximum speed of $4.38 \times 10^5$ m/s. Which of the following metals is it?

Potassium, Work function, $\Phi_0 = 2.24$ eV  
Calcium, Work function, $\Phi_0 = 2.71$ eV  
Uranium, Work function, $\Phi_0 = 3.63$ eV  
Aluminum, Work function, $\Phi_0 = 4.08$ eV  
Gold, Work function, $\Phi_0 = 4.82$ eV
Remember, 1 eV = 1.6x10^{-19} J

The metal is aluminum, Work function, \( \Phi_0 = 4.08 \text{ eV} \)
The maximum wavelength that can give photoelectrons from a platinum surface is 196 nm. When light of wavelength 141 nm shines on the surface what is the maximum speed of the ejected electrons.

The first part of the problem is telling you what the work function is:

\[
\frac{hc}{\lambda} = \Phi_0 = \frac{(6.63 \times 10^{-34} \text{ Js})(3 \times 10^8 \text{ m/s})}{191 \times 10^{-9} \text{ m}} = 1.08 \times 10^{-18} \text{ J} = 6.5 \text{ eV}
\]

\[
\frac{hc}{\lambda} = \Phi_0 + \frac{1}{2} mv^2
\]

So

\[
\frac{1}{2} mv^2 = \frac{hc}{\lambda} - \Phi_0
\]

\[
\frac{1}{2} mv^2 = \frac{(6.63 \times 10^{-34} \text{ Js})(3 \times 10^8 \text{ m/s})}{141 \times 10^{-9} \text{ m}} - 1.08 \times 10^{-18} \text{ J} = 1.41 \times 10^{-18} \text{ J} - 1.08 \times 10^{-18} \text{ J} = 0.33 \times 10^{-18} \text{ J}
\]

\[
v = \sqrt{\frac{2(0.33 \times 10^{-18} \text{ J})}{9.1 \times 10^{-31} \text{ J}}} = \sqrt{7.25 \times 10^{11}} = 8.5 \times 10^5 \text{ m/s}
\]
\[ \frac{hc}{\lambda} = \Phi_0 + \frac{1}{2} m v^2 \]

So

\[ \frac{1}{2} m v^2 = \frac{hc}{\lambda} - \Phi_0 \quad \text{Since } \Phi_0 = \frac{hc}{\lambda_0} \]

\[ = \frac{hc}{\lambda} - \frac{hc}{\lambda_0} \]

\[ v = \sqrt{\frac{2hc}{m} \left( \frac{1}{\lambda_1} - \frac{1}{\lambda_0} \right)} \]

\[ = \sqrt{\frac{2(6.63 \times 10^{-34} \text{ Js})(3 \times 10^8 \text{ m/s})}{9.1 \times 10^{-31} \text{ kg}} \left( \frac{1}{191 \times 10^{-9} \text{ m}} - \frac{1}{141 \times 10^{-9} \text{ m}} \right)} \]
Photoelectric effect: application
A photon is a particle! It is a weird particle in that it travels at the speed of light and has no mass.

However, it has energy and momentum!

\[
\begin{align*}
\frac{p_\gamma}{E_\gamma} &= \frac{1}{c} \
p_\gamma &= \frac{E_\gamma}{c} = \frac{hf}{c} = \frac{hc}{\lambda} = \frac{h}{\lambda}
\end{align*}
\]

\[
p_\gamma = \frac{h}{\lambda}
\]

A photon has energy and momentum-Radiation pressure.
An X-ray photon scattering from an electron at rest can be thought of as a collision between two particles. The result is a change of wavelength for the scattered photon. This is referred to as the Compton effect.
**Compton effect**

The Compton effect is the scattering of a photon by an electron in a material, the scattered photon having a smaller frequency than the incident photon. The magnitude $p$ of the photon's momentum is $p = h/\lambda$, and in the Compton effect, part of it is transferred to the recoiling electron. The difference between the wavelength $\lambda'$ of the scattered photon and the wavelength $\lambda$ of the incident photon is related to the scattering angle $\theta$ by

$$\lambda' - \lambda = (h/mc)(1 - \cos\theta),$$

where $m$ is the mass of the electron and the quantity $h/mc$ is known as the Compton wavelength of the electron.
The Compton Effect: Not all of the radiation (x-rays) is transferred to the metal.
Energy Conservation: \[ hf = hf' + K \quad f \geq f' \]

Momentum Conservation:
\[
\frac{h}{\lambda} = \frac{h}{\lambda'} \cos \theta + p_e \cos \phi
\]
\[
0 = \frac{h}{\lambda'} \sin \theta - p_e \sin \phi
\]
\[
\lambda = \frac{c}{f} \quad \text{and} \quad \lambda' = \frac{c}{f'}
\]
\[
\Delta \lambda = \lambda' - \lambda = \frac{h}{m_e c} (1 - \cos \theta) = (2.43 \times 10^{-12} m)(1 - \cos \theta)
\]
\[
= (2.43 \times 10^{-12} m)(1 - \cos \theta)
\]

Compton wavelength for an electron

Maximum change for \( \theta = 180 \)
**** de Broglie wavelength

The de Broglie wavelength of a particle is \( \lambda = \frac{h}{p} \), where \( p \) is the magnitude of the relativistic momentum of the particle. Because of its de Broglie wavelength, a particle can exhibit wave-like characteristics. The wave associated with a particle is the wave of probability.

Wave–particle duality

The wave–particle duality refers to the fact that a wave can exhibit particle–like characteristics and a particle can exhibit wave–like characteristics.
Scattering of X-rays or particles from a crystal. Note that waves reflecting from the lower plane of atoms have a path length that is longer than the path of the upper waves by the amount $2d \sin \eta$. 
Figure 30-16 Uncertainty in position and momentum

- Reciprocal relationship between the uncertainty in position ($\Delta y$) and the uncertainty in momentum ($\Delta p_y$). As in Figure 30-15, the curves at the right indicate the number of electrons detected at any given location.
Heisenberg uncertainty principle

The Heisenberg uncertainty principle places limits on our knowledge about the behavior of a particle. The uncertainty principle indicates that \((\Delta p_y)(\Delta y) \geq \frac{\hbar}{2\pi}\), where \(\Delta y\) and \(\Delta p_y\) are, respectively, the uncertainties in the position and momentum of the particle. The uncertainty principle also states that \((\Delta E)(\Delta t) \geq \frac{\hbar}{2\pi}\), where \(\Delta E\) is the uncertainty in energy of a particle when the particle is in a certain state and \(\Delta t\) is the time interval during which the particle is in the state.