Physics 112

Chapter 28 Notes—Part 1

Quantum Physics

28 Quantum Physics

The Physics of the very small often carries over many of the same grand themes—conservation of energy, momentum, and angular momentum—but offers many surprises as well.

We will look at a few aspects of quantum physics that have macroscopic implications. Of necessity we will skip many details, but we can still learn a lot by applying what we already know.

28.1 X-Rays and X-Ray Diffraction

- A very short wavelength form of electromagnetic radiation
- Often produced by accelerating electrons and then having the electrons collide with a target. The rapid stopping of an electron is accompanied by the emission of one or more X-ray photons.
- Short wavelength implies large photon energy

$$E_{\text{photon}} = hf = \frac{hc}{\lambda}$$

- X-rays penetrate matter well (hence medical X-rays)
- Small wavelength λ, hence useful for examining very small structures, including those on the atomic and molecular scale

X-Ray Diffraction

Since X-rays are waves, they obey our familiar rules of interference and diffraction. In particular, layers of atoms in a crystal lattice act like a diffraction grating. This allows us to probe new length scales and explore the atomic structure of matter.

For Phys 112, however, the basic interference calculations use the same ideas as we did in Ch. 16, so we will skip them here.

28.2 The Photoelectric Effect

We claimed that light comes in discrete bundles known as photons. This section describes one of the earliest experimental observations that clearly showed photons. Though interesting historically, the details can get a bit complicated. *We will skip all those details.*

Summary:

- Light energy comes in discrete bundles known as photons.

- Each photon has energy determined by its wavelength (or frequency):

  $$E_{\text{photon}} = hf = \frac{hc}{\lambda}$$

  where

  $$\begin{aligned} h &= 6.626 \times 10^{-34}\,\text{J s} \\ c &= 2.998 \times 10^{8}\,\text{m/s} \\ hc &= 1239.8\,\text{eV nm} \approx 1240\,\text{eV nm} \end{aligned}$$

- Each photon also carries momentum

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

- The photon-electron interaction can be viewed as a collision

28.3 Photons

Most everyday sources have huge numbers of photons, so we don't notice them. If there are N photons arriving each second, then the power is

$$P = NE_{\text{photon}}$$

Consider a simple red LED flashlight, with a power of 0.5 mW. How many photons per second does it emit?

$$\begin{aligned} P = NE_{\text{photon}} &\implies N = \frac{P}{E_{\text{photon}}} \\ E_{\text{photon}} &= \frac{hc}{\lambda} = \frac{1240\,\text{eV nm}}{655\,\text{nm}} = 1.89\,\text{eV} \\ E_{\text{photon}} &= 1.89\,\text{eV} \times 1.60 \times 10^{-19}\,\text{J/eV} = 3.03 \times 10^{-19}\,\text{J} \\ N &= \frac{0.000\,500\,\text{W}}{3.03 \times 10^{-19}\,\text{J}} = \boxed{1.65 \times 10^{15}\,\text{photons/second}} \end{aligned}$$

What if you had a green flashlight instead, with the same power 0.5 mW, but with a new wavelength 532 nm. How many photons per second would there be now?

$$\begin{aligned} P = NE_{\text{photon}} &\implies N = \frac{P}{E_{\text{photon}}} \\ E_{\text{photon}} &= \frac{hc}{\lambda} = \frac{1240\,\text{eV nm}}{532\,\text{nm}} = 2.33\,\text{eV} \\ E_{\text{photon}} &= 2.33\,\text{eV} \times 1.60 \times 10^{-19}\,\text{J/eV} = 3.73 \times 10^{-19}\,\text{J} \\ N &= \frac{0.000\,500\,\text{W}}{3.73 \times 10^{-19}\,\text{J}} = \boxed{1.34 \times 10^{15}\,\text{photons/second}} \end{aligned}$$

Interaction With Matter

The interaction of light with matter can often be thought of as collisions between individual photons and individual atoms (or electrons within an atom). Example 28.7 in the text uses this to explore how much current you can get from a solar cell.

Another important application is comparing the energy of an individual photon to the relevant binding energy for the atom or molecule under consideration. For biological systems, for example, ultraviolet light can be damaging even if visible light is not. Look at some typical wavelengths and energies:

Visible Light Yellow light has a wavelength on the order of 590.0 nm. The corresponding photon energy is

$$E_{\text{photon}} = \frac{hc}{\lambda} = \frac{1240\,\text{eV nm}}{590.0\,\text{nm}} = 2.10\,\text{eV}$$

UVA The Ultraviolet spectrum is broken up into ranges. The longest wavelength are in the range 315–400 nm. Suppose $\lambda = 350.0\,\text{nm}$. The corresponding photon energy is $E_{\text{photon}} = \frac{hc}{\lambda} = 3.54\,\text{eV}$. These photons are typically not quite energetic enough to cause direct damage to DNA, but they can still cause damage by more indirect routes.

UVB The next shorter range is called UVB, and is the range 280–315 nm. Suppose $\lambda = 300.0\,\text{nm}$. The corresponding photon energy is $E_{\text{photon}} = \frac{hc}{\lambda} = 4.13\,\text{eV}$. These photons are sufficiently energetic to cause serious skin damage. (They are also sufficiently energetic to help the body produce Vitamin D!)

Cell Phone signal Finally, there had been questions raised about whether the signals from cell phones might cause brain tumors. How much energy does a cell phone photon carry? Could it damage DNA?

A typical frequency of a cell phone signal is 1.90 GHz. The corresponding wavelength (in nanometers) is $\lambda = \frac{c}{f} = 1.58 \times 10^{8}\,\text{nm}$, and the photon energy is $E_{\text{photon}} = \frac{hc}{\lambda} = 7.86 \times 10^{-6}\,\text{eV}$. This is far too small to damage DNA.