Physics 228

Photoelectric Effect
Energy and Momentum of Photons
Photon Absorption and Emission
Energy and Momentum of Photons

From the photoemission experiment we know that the energy of the photon is proportional to the frequency.

The proportionality constant is called “Planck’s constant”, denoted \( h \):

\[
E = hf = hc/\lambda.
\]

From the slope we obtain \( h = 6.626 \times 10^{-34} \text{ J}\cdot\text{s} \).

What is the rest mass of a photon? Apply \( E = \gamma mc^2 \) to photons \((v = c)\):

\[
m = \frac{E}{\gamma c^2} = \frac{E}{c^2} \sqrt{1 - \left(\frac{v}{c}\right)^2} = 0
\]

For a particle with zero rest mass the energy momentum relationship \( E^2 - p^2c^2 = (mc^2)^2 \) becomes \( E = pc \).

The momentum of the photon is then \( p = E/c = hf/c = h/\lambda \).
iClicker

Recall a previous clicker question: A torpedo moving at 0.8 c to the right explodes, sending out a flash of light in all directions. (The entire mass of the torpedo is converted to light.) Since the speed of light is independent of the speed of the source, the light shell expands around the point of explosion, in all directions in the same way:

Yet, from momentum conservation we expect the center of mass of the expanding light shell to be traveling at 0.8 c to the right. What gives?

a) The picture is incorrect: The light sphere actually moves forward as it expands.
b) The center of mass of the light is stationary, with zero total momentum.
c) Since photons have no mass, center of mass is not defined, and there is no momentum.
d) Due to the Doppler effect, the center of mass moves in the forward direction, while the geometric center is stationary.
e) Picture is incorrect: Due to length contraction, the light wave is actually an expanding ellipsoid (spheroid).
Work Function

If we apply a potential $V_0$ that just stops all the emitted electrons, we conclude that the maximum kinetic energy of the emitted electrons is:

$$K_{\text{max}} = -eV_0.$$ 

The experiment shows that the maximum kinetic energy is just the photon energy minus some offset $\phi$:

$$K_{\text{max}} = E - \phi = hf - \phi.$$ 

The downward shift of the curve $\phi$ is called the “work function” (not really a function but a constant) of the material from which the electrons are being emitted. It is typically a few electron-Volts (eV).
The work function depends on the material of the cathode:

- It represents the amount of work a photon has to do to remove a single electron from the cathode. The leftover photon energy is converted into kinetic energy of the electron.
Applications of Photoelectric Effect

- Photomultiplier tubes: ultra-sensitive light detectors, can detect single photons.
- Electron spectroscopy: Learn about the electron energy levels in different materials.
- Night vision cameras and night vision scopes.
The energy in electromagnetic waves is carried as indivisible lumps ("photons").

Each photon’s energy is proportional to the light frequency, with a proportionality constant $h$ ("Planck’s constant"): $E = hf$.

In the PE effect, a portion $\phi$ of the photon’s energy is used to remove an electron from the metal, while the rest is converted to kinetic energy of the electron.
Photon Absorption and Emission

These processes cause bright emission lines and dark absorption lines in the spectra of light sources.

\[ \nu = f = \text{frequency} \]
Spectra of Light Bulbs

(a) Continuous spectrum: light of all wavelengths is present.
(b) Line spectrum: only certain discrete wavelengths are present.

Black-body radiation

Atomic transitions
Example Pictures of Atomic Spectra

Demos!
iClicker

What is the rest mass of a photon?

a) Meaningless question, since a photon cannot be brought to rest.

b) Zero.

c) $E = mc^2$, and $E = hf$, so $m = hf/c^2$.

d) The same as its relativistic mass.

e) It must be nonzero, since “the Higgs particle gives mass to all particles”.
Wave-Particle Duality for Light

Wave nature of light:
• Maxwell’s equations
• Interference
• Diffraction
• Refraction
• Total internal reflection
• Brewster’s angle

Particle nature of light:
• Photoelectric effect
• Compton scattering (textbook)
• Pair production (textbook)
• Exposure of photographic film: silver grains turn dark (all or nothing)

We will see later that the same duality applies to matter (e.g., electrons and atoms).
Two-Slit Interference Revisited

- As we have seen, the interference pattern is defined by the wave nature of light.

- However, with a sensitive detector, we can see individual photons appear at distinct spots.

- Does an individual photon interfere only with other photons, or with itself?

- Can a single photon produce an interference pattern?
The wave and particle descriptions are complementary: Depending on what phenomena we are studying, we will use either the wave description or the particle description.

The square of the wave amplitude at a point in space just gives the probability that a photon will show up at that point.

The photons (particles) appear randomly according to the probability distribution predicted by the wave nature.

Summing over lots of photons, the wave pattern appears. (simulation)

The probability is determined by the wave nature of light, but we nonetheless detect individual photons/particles!
In a double-slit interference experiment, the light intensity is reduced such that only one photon strikes the detector (screen) each second. At any given time, the total number of photons “in transit” is thus either zero or one. Does an individual photon interfere with itself?

a) Yes, each photon produces a very faint interference pattern spread out over the entire screen.

b) No, since an individual photon can only pass through one slit or the other, thus, no interference.

c) No, since each photon produces a single pointlike flash, not an interference pattern.

d) Yes, since the location of each flash is subject to a probability distribution, which is an interference pattern.