PHY140Y

18 The Particle Nature of the Photon

18.1 Overview

- Photons
- Photoelectric Effect
- Compton Scattering

18.2 Photons

Planck's hypothesis that matter has distinct energy states implied that photons also came in discrete energy states (at least those associated with black body radiation). This didn't address what the nature of light was. At this point, light was known to have "wave" properties: All of the early optics experiments showed that it reflected, refracted and diffracted. It also could interfere with itself. These were all properties of a wave.

A number of odd effects were observed that led to a different view of the photon. Perhaps the most striking are the photoelectric effect and Compton scattering. They both illustrated that the photon appeared to have some of the characteristics of a particle.

18.3 The Photoelectric Effect

The photoelectric effect was perhaps the first clear phenomenon that forced us to rethink the properties of light. Metals displayed the property that if light was incident on the metal, under certain circumstances the metal would give off electrons (what are called "photoelectrons"). These electrons could be detected by placing a voltage between the plate and a nearby metal screen so that the metal plate was held at negative potential relative to the screen. The photoelectrons would then accelerate from the plate and one could measure a current flow between the plate and the screen. Since the plate is kept at negative voltage, it is referred to often as a "photocathode."

This phenomenen has several unusual features:

- The magnitude of the current depends on the brightness of the light.
- The current flow only occurrs once the light is above a given frequency.
- The energy of the photoelectrons is given by

$$E_e = hf - \phi, \tag{1}$$

where f is the frequency of the light, h is Planck's constant, and ϕ is an energy that is characteristic of the metal and is called the "work function."

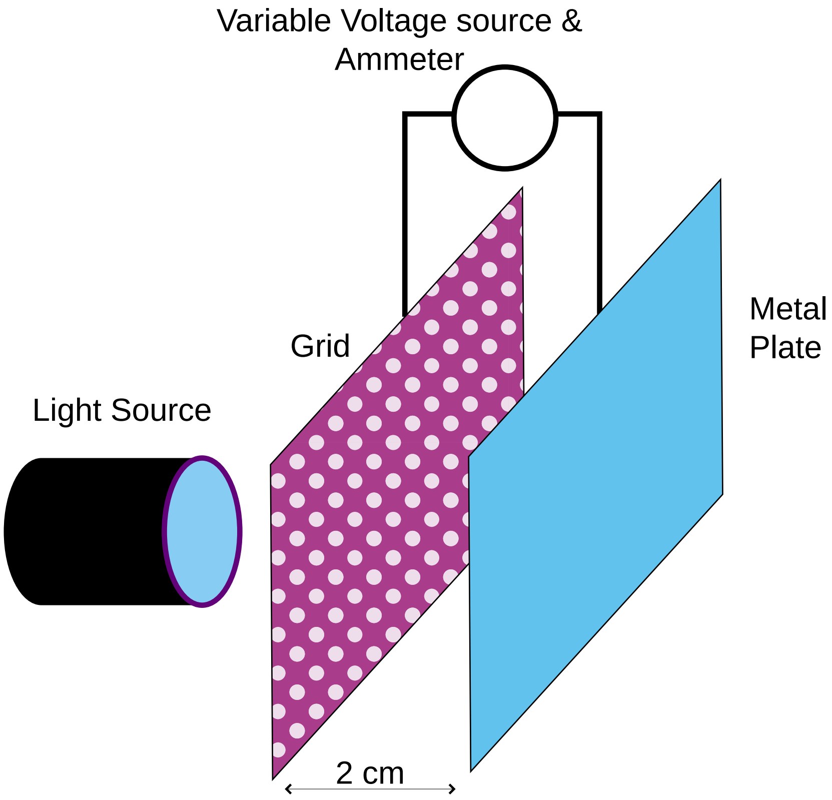

Figure 1: A device designed to measure the photoelectric effect.

Thus, the photoelectric effect only occurs if the frequency of the light is such that the the photoelectrons have non-zero energy E_e, as given by Eq. 1. A device for measuring the energy of the electrons is shown in Fig. 1, where we have a metal plate and screen connected to a variable voltage source. A light of a specific frequency shines on the screen, and provided that hf is greater than the work function ϕ of the metal, electrons will be emitted by the surface and some will find their way to the screen where they will generate a current flow. If a “retarding” voltage difference is applied that decelerates the electrons once they leave the surface, then only those electrons with kinetic energy greater than the electrostatic energy difference between the metal plate and screen will reach the screen and create a current flow. By determining the largest such retarding voltage that still allows a current flow, one in effect can measure the maximum kinetic energy of the photoelectrons for a given frequency of light, and using Eq. 1, one can then determine the work function of the metal.

The work function for various metals is shown in Table 1, along with the minimum light frequency that will generate photoelectrons.

Albert Einstein made the conceptual breakthrough in 1905 that allowed us to understand this phenomenon. He postulated that light is behaving like a particle when it interacts with the metal surface. We refer to a particle of light as a “photon” (and we normally denote it as γ, the greek letter *gamma*). The energy of a photon is $E_\gamma = hf$. A photon striking the metal plate collides with an electron in the metal, and occassionally transfers all of its energy to the electron. If the energy of the electron exceeds the work function for the metal, it escapes from the surface with the original energy of the electron less the work function, which we can think of as representing a

Metal	ϕ (eV)	f_{min} (s^{-1})	λ_{max} (Å)
Si	4.26	1.03×10^{15}	2,900
Al	4.28	1.03×10^{15}	2,900
Cs	2.14	0.52×10^{15}	5,770
Ni	5.15	1.24×10^{15}	2,410

Table 1: A sample of different metals with their work functions ϕ. The corresponding minimum frequency and maximum wavelength for the incident light to create photoelectrons is also shown.

potential energy barrier for an electron leaving the metal.

Einstein won the 1921 Nobel Prize in Physics for his theory of the photoelectric effect (he was also cited at that time for the Special Theory of Relativity as well).

18.4 Compton Scattering

A second phenomenon that supported this "particle" concept of light was discovered about twenty years later. Arthur Compton in 1923 was studying how the recently discovered x-rays scattered through thin material (he was using graphite as the scattering material). In particular, he was looking at how the wavelength of an x-ray changed as it scattered at different angles through the graphite foil.

He observed two things in his data:

1. There was a peak in the scattered x-ray wavelength distribution that was at the same wavelength as the incoming x-ray. This is what one would expect if the x-ray diffracts or reflects off an object passing through the graphite, and one would have expected this if the x-ray was behaving like a wave.
2. There was a second peak in the wavelength distribution shifted by $\Delta\lambda$ above the incident wavelength. The position of the peak was a function of the angle that the x-ray had scattered. In effect, the x-ray seemed to be losing energy in a well-defined way when it scattered through the graphite.

The second observation could not be described by any known wave phenomenon, but was a natural consequence if the x-ray was behaving like a photon and elastic-scattering off an electron in the graphite.

One can see this by thinking about how a massless photon would scatter off a stationary electron, requiring that energy and momentum conservation would hold. The picture in Fig. 2 illustrates the situation. Energy conservation requires that the total initial energy equals the total final energy, *i.e.*,

$$h\nu + m_e c^2 = h\nu' + \gamma_e m_e c^2, \tag{2}$$

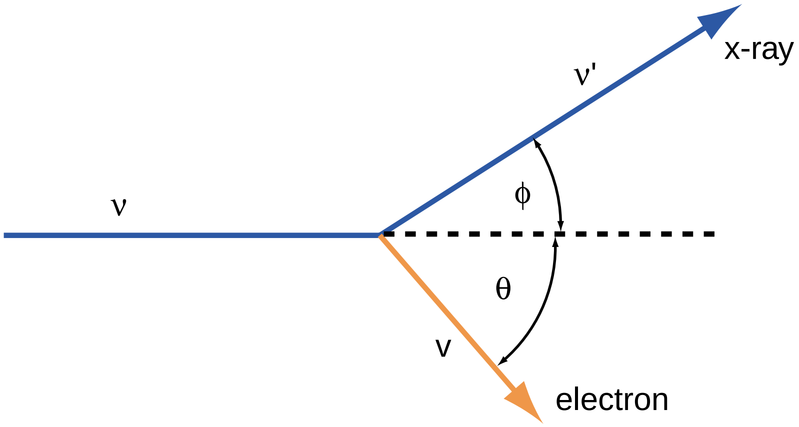

Figure 2: The kinematics of a photon elastic scattering off of a stationary electron.

where ν and ν' are the frequencies of the x-ray before and after the scatter, m_e is the mass of the electron and $\gamma_e = 1/\sqrt{1 - v^2/c^2}$ is the relativistic factor of the electron after the collision (v would be the velocity of the electron after the collision). Momentum conservation requires that

$$\begin{aligned} \frac{h\nu}{c} &= \cos\theta\left(\frac{h\nu'}{c}\right) + \cos\phi\,(m_e\gamma_e v) & (3) \\ 0 &= \sin\theta\left(\frac{h\nu'}{c}\right) - \sin\phi\,(m_e\gamma_e v)\,. & (4) \end{aligned}$$

This gives us three equations with four unknowns, so we can use two of the three equations to eliminate one of the angles and only keep the difference in frequencies (more traditionally, we express the result in terms of the difference in wavelengths). After suitable algebra (try it, it is good for the soul!), we arrive at the expression

$$\lambda' - \lambda = \frac{h}{m_e c}\,(1 - \cos\phi)\,. \tag{5}$$

The quantity $h/(m_e c)$ is often called the Compton wavelength of the electron and has a value $\lambda_C = 0.00243$ nm. It is exactly the shift in the wavelength that one should see if the x-ray scatters at 90°. This is in exactly in accord with Compton's original measurements.

What Compton scattering shows is that the photon does behave very much like a particle. Not only does it have the energy predicted by Planck and Einstein, but it also has a momentum given by $h\nu/c$. This led to the principle of "wave-particle" duality as one of the fundamental mysteries associated with what was shortly to become Quantum Mechanics.