Photoelectric Effect

When a metal surface is exposed to a monochromatic electromagnetic wave of sufficiently short wavelength (or equivalently, above a threshold frequency), the incident radiation is absorbed and the exposed surface emits electrons. This phenomenon is known as the **photoelectric effect**. Electrons that are emitted in this process are called **photoelectrons**.

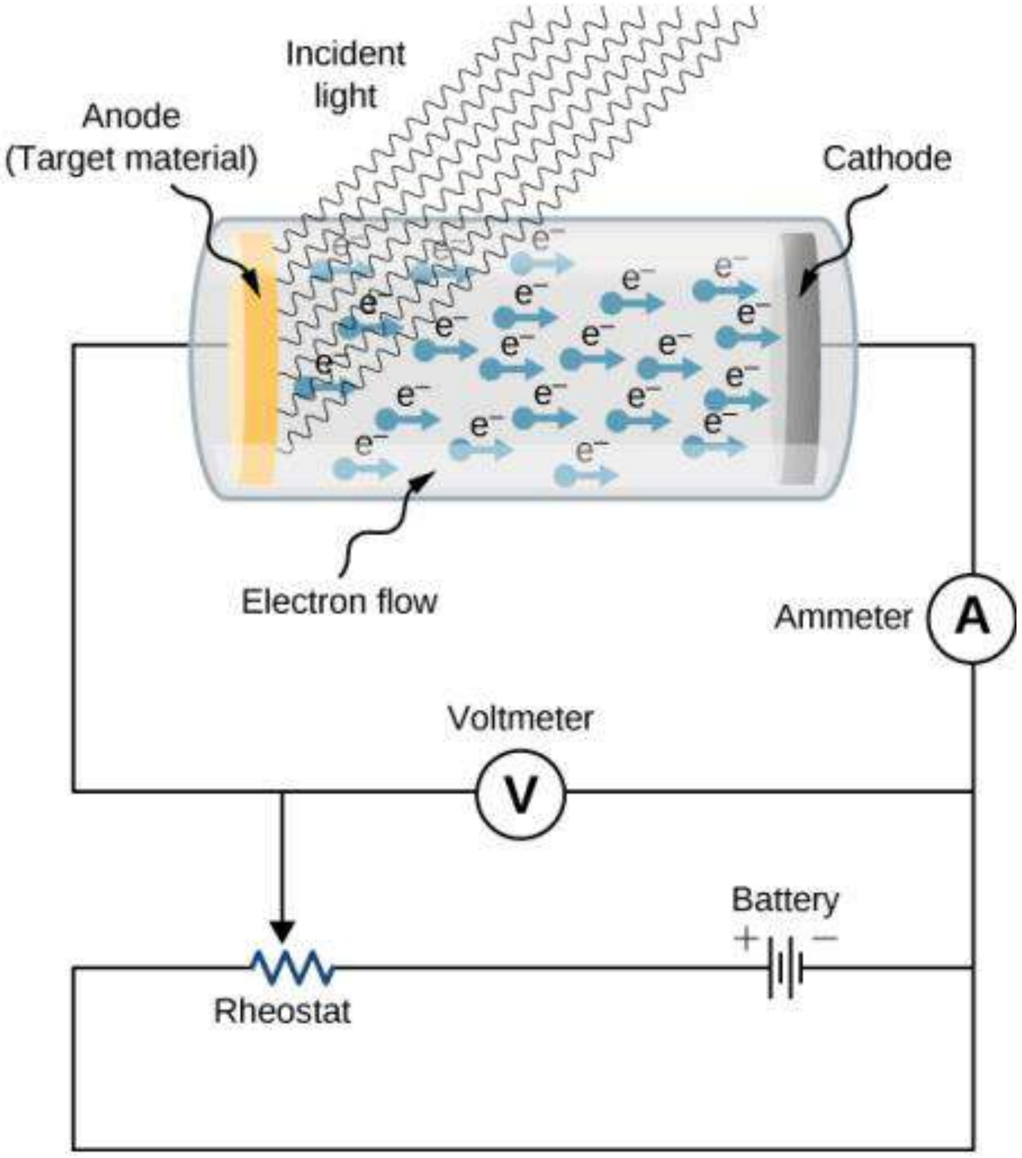
Characteristics of the Photoelectric Effect

The photoelectric effect has three important characteristics that cannot be explained by classical physics: (1) the absence of a lag time, (2) the independence of the kinetic energy of photoelectrons on the intensity of incident radiation, and (3) the presence of a cut-off frequency.

Let's examine each of these characteristics.

The absence of lag time

When radiation strikes the target material in the electrode, electrons are emitted almost instantaneously, even at very low intensities of incident radiation. This absence of lag time contradicts our understanding based on classical physics.

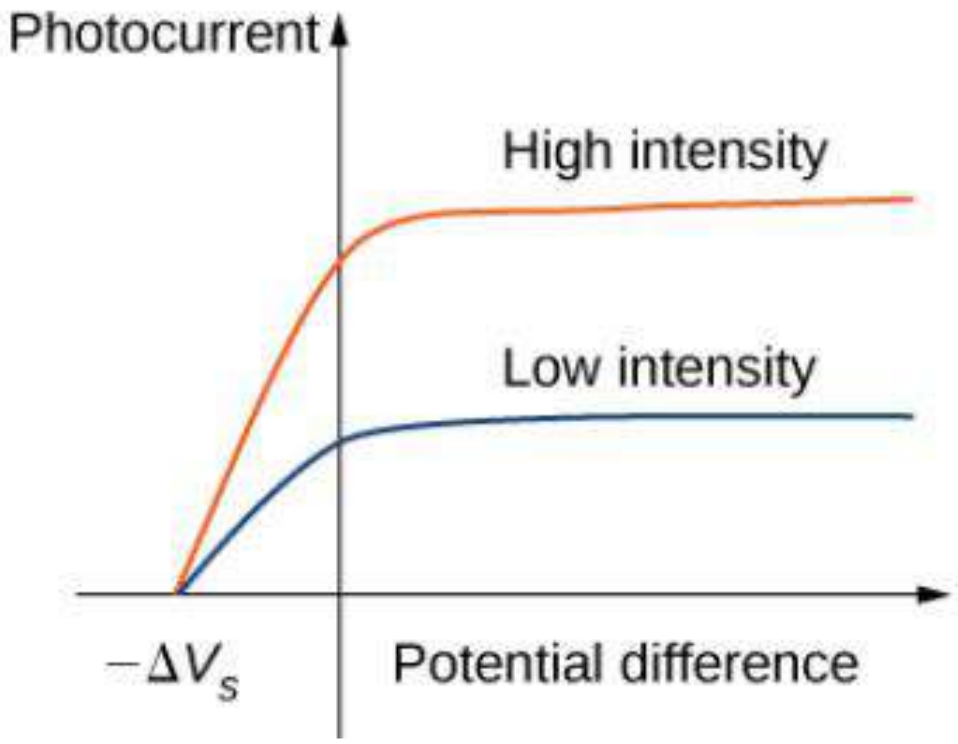


An experimental setup to study the photoelectric effect. The anode and cathode are enclosed in an evacuated glass tube. The voltmeter measures the electric potential difference between the electrodes, and the ammeter measures the photocurrent. The incident radiation is monochromatic.

The intensity of incident radiation and the kinetic energy of photoelectrons

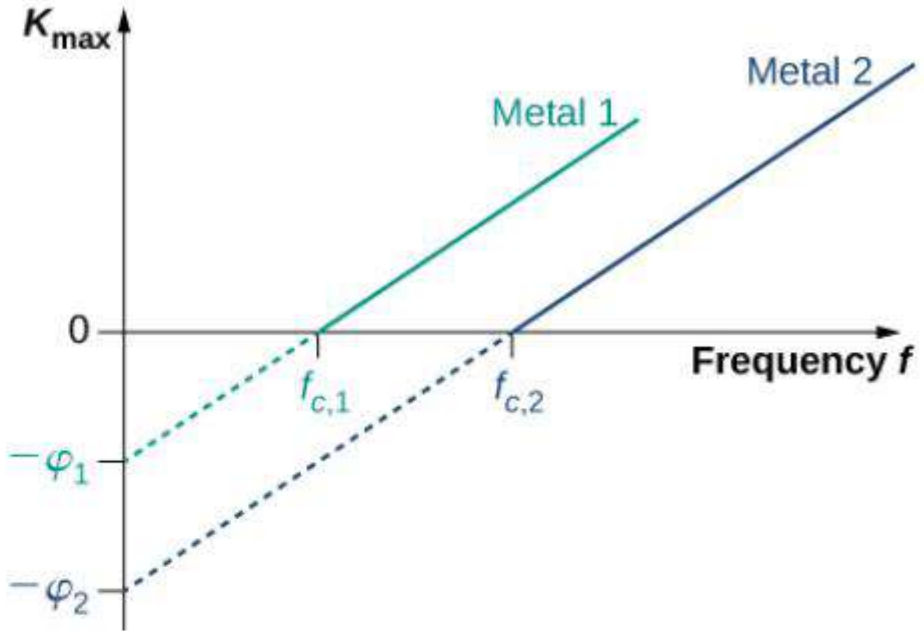
A photoelectron that leaves the surface has kinetic energy K. It gained this energy from the incident electromagnetic wave. When the stopping potential −ΔVs is applied, the photoelectron loses its initial kinetic energy Ki and comes to rest. Therefore, the largest kinetic energy of photoelectrons can be directly measured by measuring the stopping potential:

$$K_{\max} = e\Delta V_s.$$



The detected photocurrent plotted versus the applied potential difference shows that for any intensity of incident radiation, whether the intensity is high (upper curve) or low (lower curve), the value of the stopping potential is always the same.

The presence of a cut-off frequency



Kinetic energy of photoelectrons at the surface versus the frequency of incident radiation. The photoelectric effect can only occur above the cut-off frequency *fc*. Measurements for all metal surfaces give linear plots with one slope. Each metal surface has its own cut-off frequency

For any metal surface, there is a minimum frequency of incident radiation below which photocurrent does not occur. The value of this cut-off frequency for the photoelectric effect is a physical property of the metal: Different materials have different values of cut-off frequency. Experimental data show a typical linear trend (see Figure 6.10). The kinetic energy of photoelectrons at the surface grows linearly with the increasing frequency of incident radiation. Measurements for all metal surfaces give linear plots with one slope. None of these observed phenomena is in accord with the classical understanding of nature (as long as the light is shining, the photoelectric effect is expected to continue).

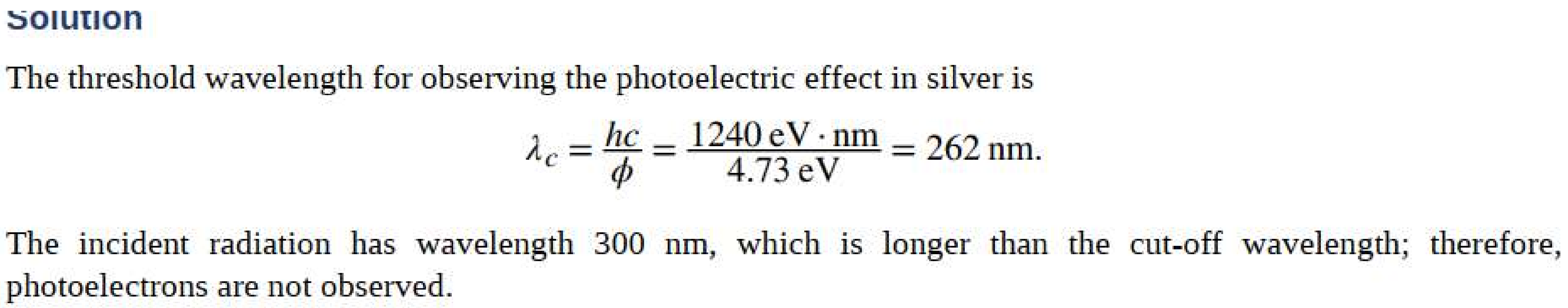
The Work Function

The essence of a **quantum phenomenon** is either a photon transfers its entire energy and ceases to exist or there is no transfer at all. This is in contrast with the classical picture, where fractional energy transfers are permitted. Having this quantum understanding, the energy balance for an electron on the surface that receives the energy $E\ f$ from a photon is

$$E_f = K_{\max} + \phi$$

where $K_{\max}$ is the kinetic energy, that an electron has at the very instant it gets detached from the surface. In this energy balance equation, ϕ is the energy needed to detach a photoelectron from the surface. This energy ϕ is called the **work function** of the metal.

- Example 6.5
  Photoelectric Effect for Silver
  Radiation with wavelength 300 nm is incident on a silver surface. Will photoelectrons be observed?



Solution

The threshold wavelength for observing the photoelectric effect in silver is

$$\lambda_c = \frac{hc}{\phi} = \frac{1240\ \text{eV}\cdot\text{nm}}{4.73\ \text{eV}} = 262\ \text{nm}.$$

The incident radiation has wavelength 300 nm, which is longer than the cut-off wavelength; therefore, photoelectrons are not observed.

Work Function and Cut-Off Frequency

When a 180-nm light is used in an experiment with an unknown metal, the measured photocurrent drops to zero at potential – 0.80 V. Determine the work function of the metal and its cut-off frequency for the photoelectric effect.

Solution

We use [redacted] to find the kinetic energy of the photoelectrons:

$$K_{\max} = e\Delta V_s = e(0.80\text{V}) = 0.80\,\text{eV}.$$

Now we solve [redacted] for ϕ :

$$\phi = hf - K_{\max} = \frac{hc}{\lambda} - K_{\max} = \frac{1240\,\text{eV}\cdot\text{nm}}{180\,\text{nm}} - 0.80\,\text{eV} = 6.09\,\text{eV}.$$

Finally, we use [redacted] to find the cut-off frequency:

$$f_c = \frac{\phi}{h} = \frac{6.09\,\text{eV}}{4.136\times 10^{-15}\,\text{eV}\cdot\text{s}} = 1.47\times 10^{-15}\,\text{Hz}.$$

The Compton Effect

The **Compton effect** is the term used for an unusual result observed when X-rays are scattered on some materials. By classical theory, when an electromagnetic wave is scattered off atoms, the wavelength of the scattered radiation is expected to be the same as the wavelength of the incident radiation. Contrary to this prediction of classical physics, observations show that when X-rays are scattered off some materials, such as graphite, the scattered X-rays have different wavelengths from the wavelength of the incident X-rays. This classically unexplainable phenomenon was studied experimentally by Arthur H. Compton and his collaborators, and Compton gave its explanation in 1923

$$\lambda' - \lambda = \frac{h}{m_0 c}(1 - \cos\theta).$$

A detector placed behind the target can measure the intensity of radiation scattered in any direction ϑ with respect to the direction of the incident X-ray beam. This **scattering angle**, ϑ, is the angle between the direction of the scattered beam and the direction of the incident beam. In this experiment, we know the intensity and the wavelength λ of the incoming (incident) beam; and for a given scattering angle ϑ, we measure the intensity and the wavelength λ' of the outgoing (scattered) beam.

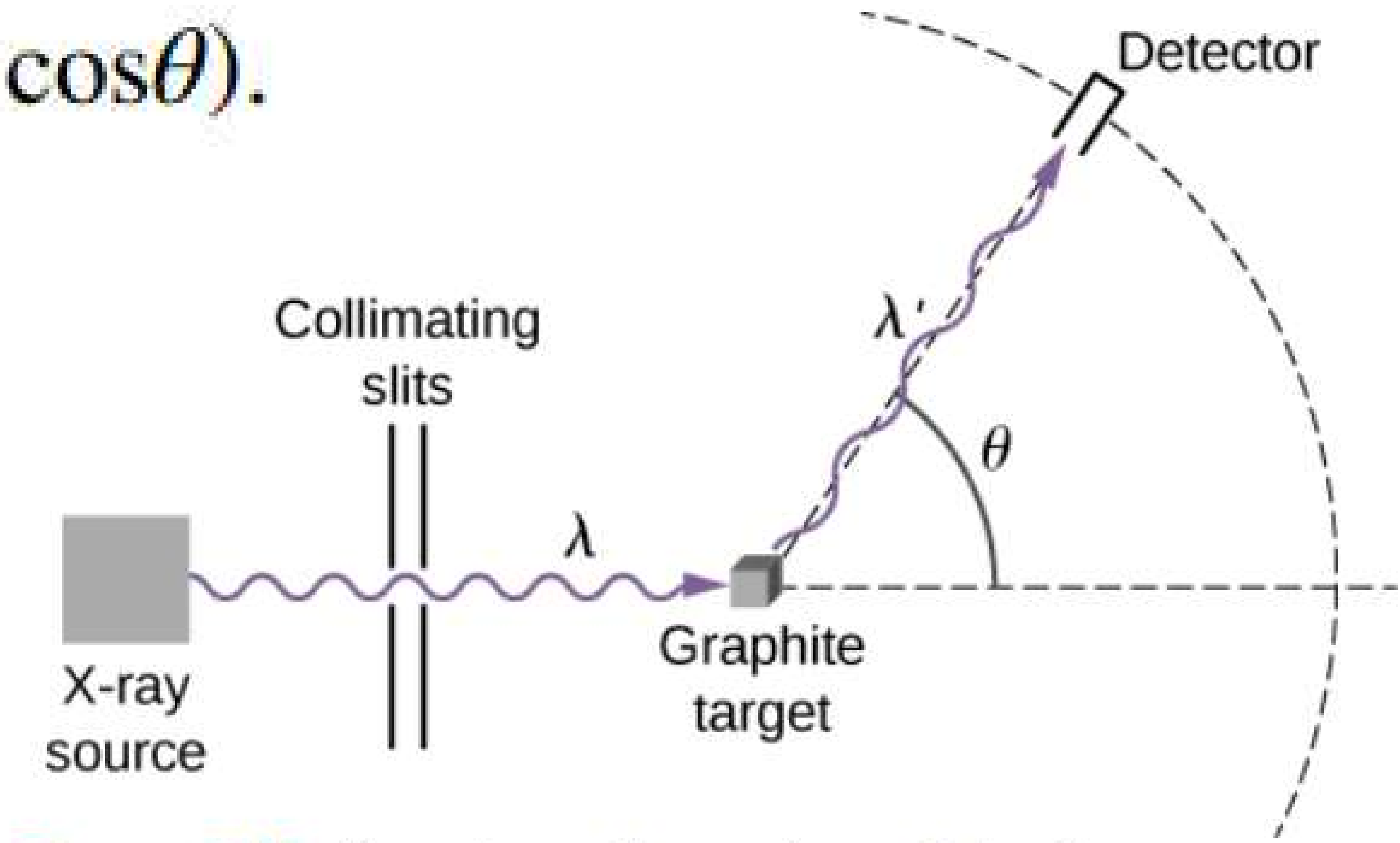


Figure 6.11 Experimental setup for studying Compton scattering.

he x-axis is the wavelength of the scattered X-rays and the y-axis is the intensity of the scattered X-rays, measured for different scattering angles (indicated on the graphs). For all scattering angles (except for ϑ = 0°), we measure two intensity peaks. One peak is located at the wavelength λ, which is the wavelength of the incident beam. The other peak is located at some other wavelength, λ'. The two peaks are separated by $\Delta\lambda$, which depends on the scattering angle ϑ of the outgoing beam (in the direction of observation). The separation $\Delta\lambda$ is called the **Compton shift**.