Lecture 2 — The Photoelectric Effect & Compton Scattering

Reading: Engel 4th ed., Chapter 1 (Sections 1.3–1.4)

Learning Objectives

- Describe the photoelectric effect and its key experimental features
- Apply Einstein's photoelectric equation to calculate kinetic energies and threshold frequencies
- Explain why the classical wave theory of light fails to account for the photoelectric effect
- Describe Compton scattering and derive the Compton wavelength shift
- Recognize that electromagnetic radiation carries momentum in discrete quanta (photons)

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1. The Photoelectric Effect

Experimental Setup

When light strikes a clean metal surface, electrons can be ejected. The emitted electrons are called **photoelectrons**. A collector electrode at a variable potential measures the resulting current.

Key Experimental Observations

1. **Threshold frequency:** No electrons are emitted below a certain frequency ν_0, regardless of light intensity
2. **Instantaneous emission:** Electrons are emitted immediately (< 10^{-9} s), with no time delay
3. **Kinetic energy depends on frequency:** The maximum kinetic energy of emitted electrons increases linearly with frequency, independent of intensity

4. **Current depends on intensity:** The number of emitted electrons (photocurrent) is proportional to light intensity

Classical Predictions vs. Experiment

Feature	Classical Prediction	Experimental Result
Threshold frequency	No threshold; sufficient intensity should eject electrons at any frequency	Sharp threshold exists
Time delay	Energy accumulates slowly; delay expected at low intensity	Emission is instantaneous
KE dependence	KE should depend on intensity	KE depends on frequency only

Classical wave theory fails on all counts.

Einstein's Explanation (1905)

Einstein proposed that light consists of discrete energy packets — **photons** — each carrying energy:

$$E_{\text{photon}} = h\nu$$

When a photon strikes the metal, it transfers all its energy to a single electron. The electron must overcome the **work function** ϕ (the minimum energy needed to escape the surface). Any remaining energy becomes kinetic energy:

$$\boxed{KE_{\max} = h\nu - \phi}$$

or equivalently:

$$\frac{1}{2}m_e v_{\max}^2 = h\nu - \phi$$

The **threshold frequency** is:

$$\nu_0 = \frac{\phi}{h}$$

Below this frequency, a single photon lacks sufficient energy to liberate an electron.

The Stopping Potential

The maximum kinetic energy can be measured using a **stopping potential** V_s:

$$eV_s = KE_{\text{max}} = h\nu - \phi$$

A plot of V_s vs. ν is linear with slope h/e and intercept $-\phi/e$.

> **Historical note:** Robert Millikan experimentally confirmed Einstein's equation in 1916, despite initially trying to disprove it. Einstein received the 1921 Nobel Prize primarily for this work.

> [!NOTE] **Concept Check 2.1** If you double the intensity of light striking a metal surface while keeping the frequency constant (and above ν_0), how do the maximum kinetic energy and the number of emitted electrons change?

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2. Work Functions of Common Metals

Metal	ϕ (eV)	ν_0 (10^{14} Hz)	λ_0 (nm)
Cs	2.1	5.1	590
Na	2.3	5.6	540
Cu	4.7	11.3	264
Pt	5.6	13.5	222

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3. Compton Scattering (1923)

The Experiment

Arthur Compton directed X-rays at a graphite target and measured the scattered radiation. He observed that the scattered X-rays had a **longer wavelength** than the incident beam, and the wavelength shift depended on the scattering angle.

Classical Failure

Classical electromagnetic theory predicts that scattered radiation has the **same** frequency as the incident radiation (Thomson scattering). The observed wavelength shift cannot be explained classically.

Quantum Explanation

Compton treated the X-ray beam as a stream of photons, each with:

- Energy: $E = h\nu$
- Momentum: $p = h\nu/c = h/\lambda$

The scattering is a **collision** between a photon and an electron, governed by conservation of energy and momentum.

The Compton Wavelength Shift

Applying conservation laws to the photon-electron collision:

$$\boxed{\Delta\lambda = \lambda' - \lambda = \frac{h}{m_e c}(1 - \cos\theta)}$$

where:

- λ = incident wavelength
- λ' = scattered wavelength
- θ = scattering angle
- $\frac{h}{m_e c} = 2.426 \times 10^{-12}$ m is the **Compton wavelength** of the electron

Key features:

- $\theta = 0^\circ$: no shift (forward scattering)
- $\theta = 90^\circ$: $\Delta\lambda = h/(m_e c)$
- $\theta = 180^\circ$: $\Delta\lambda = 2h/(m_e c)$ (maximum shift, backscattering)

Significance

Compton scattering provides direct evidence that photons carry **momentum** as well as energy, behaving as particles in collisions. This was powerful confirmation of the photon concept.

> [!NOTE] **Concept Check 2.2** In a Compton scattering experiment, why do we observe a range of wavelengths in the scattered radiation rather than a single shifted wavelength? (Hint: Think about what the scattering angle θ represents).

4. The Photon — Summary of Properties

$$E = h\nu = \frac{hc}{\lambda}$$

$$p = \frac{h}{\lambda} = \frac{h\nu}{c} = \frac{E}{c}$$

$$m_{\text{rest}} = 0 \quad \text{(photons are massless)}$$

The photon is a quantum of electromagnetic radiation that exhibits both wave properties (interference, diffraction) and particle properties (photoelectric effect, Compton scattering).

Key Equations Summary

Equation	Expression
Photon energy	$E = h\nu = hc/\lambda$
Photoelectric equation	$KE_{\text{max}} = h\nu - \phi$
Threshold frequency	$\nu_0 = \phi/h$
Stopping potential	$eV_s = h\nu - \phi$
Photon momentum	$p = h/\lambda$
Compton shift	$\Delta\lambda = \frac{h}{m_e c}(1 - \cos\theta)$

Recent Literature Spotlight

"Field-Driven Attosecond Charge Dynamics in Germanium" *M. Lucchini, S. A. Sato, G. D. Lucarelli, B. Moio, G. Inzani, et al.*, Nature Photonics, **2023**, 17, 1059–1065. DOI

Using attosecond transient reflectivity spectroscopy, the authors tracked the ultrafast injection of charge carriers into the conduction band of germanium with sub-femtosecond time resolution. This work provides a direct window into the photoelectric effect at its most fundamental timescale — showing that the "instantaneous" ejection of electrons actually unfolds over attosecond delays governed by the crystal band structure.

Practice Problems

1. **Photoelectric effect.** Light of wavelength 250 nm strikes a sodium surface ($\phi = 2.3$ eV). (a) Calculate the energy of each photon in eV. (b) Calculate the maximum kinetic energy of the emitted electrons. (c) What is the stopping potential?

2. **Threshold wavelength.** What is the longest wavelength of light that can eject electrons from a platinum surface ($\phi = 5.6$ eV)?

3. **Compton scattering.** X-rays of wavelength 0.0711 nm are scattered from a carbon target. Calculate the wavelength of the X-rays scattered at (a) 45°, (b) 90°, and (c) 180°.

Next lecture: Wave-Particle Duality & the de Broglie Relation