

PHYS12 CH:21 When Light Breaks the Rules

The Quantum Revolution

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December 2025

Outline

- 1 Introduction
- 2 Planck and Quantization
- 3 Photoelectric Effect
- 4 Dual Nature of Light
- 5 Summary

Alice's Rabbit Hole



Alice's Rabbit Hole



In Wonderland, nothing behaves as expected...
but there's still an underlying logic.

The Illusion of Understanding

What Your Brain Gets Wrong

You think: Light is a wave. Waves are continuous.

Reality: Light arrives in discrete chunks called photons.

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Reality: Light arrives in discrete chunks called photons.

This isn't intuition failing at extreme speeds or sizes.

This is everyday light fooling us constantly.

Learning Objectives

By the end of this section, you will be able to:

- **21.1:** Describe blackbody radiation and the ultraviolet catastrophe

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- **21.1:** Define quantum states and calculate photon energies
- **21.1:** Explain how photon energies vary across the EM spectrum

21.1 The T-Shirt Mystery

The Mental Model

Why is wearing a black T-shirt on a hot day unbearable, while a white shirt keeps you cool?

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Black shirts absorb and re-emit more radiation.

21.1 The T-Shirt Mystery

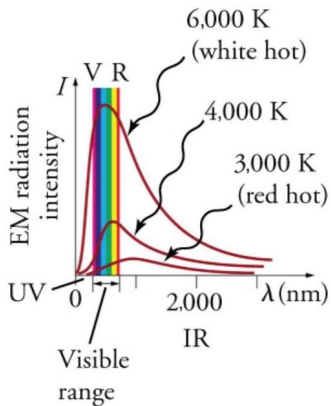
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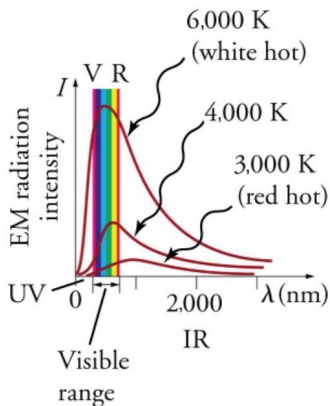
Black shirts absorb and re-emit more radiation.

A perfect black object that absorbs ALL radiation is called a **blackbody**.

21.1 The Blackbody Spectrum



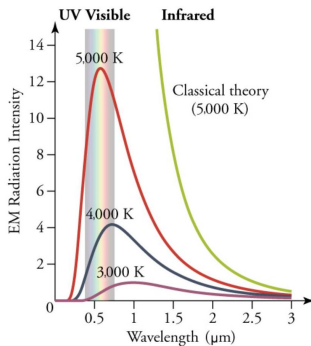
21.1 The Blackbody Spectrum



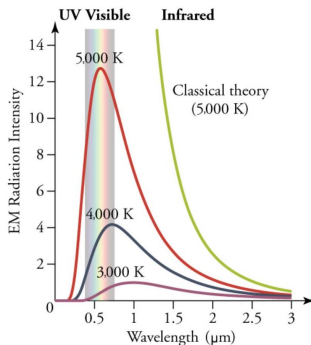
Key observations:

- Hotter objects radiate MORE total energy (area under curve)
- Peak wavelength SHIFTS leftward as temperature increases

21.1 The Ultraviolet Catastrophe



21.1 The Ultraviolet Catastrophe



The Classical Prediction

Theory predicted INFINITE energy at short wavelengths.

Reality: energy drops back down. **Physics was broken.**

21.1 Planck's Revolution

The Source Code: Quantized Energy

$$E = nhf$$

Energy is not continuous. Energy exists only in discrete chunks.

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- $n = \text{integer (0, 1, 2, 3...)}$
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- $f = \text{frequency}$

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Key insight: Energy comes in quantum packets, not continuous streams.

21.1 The Coin Analogy

Imagine This...

Pour coins through a funnel.

More pennies pass through than quarters.

Why? Quarters have higher value AND larger size.

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- High frequency = high energy = less probable at low temperatures
- Low frequency = low energy = more probable at low temperatures

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Same with photons:

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This *probability factor* explains why the blackbody curve drops at short wavelengths.

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- Standing waves on a string (harmonics)

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The Shock

But energy was thought to be *continuous*.
Planck proved otherwise.

21.1 Max Planck



21.1 Max Planck



"I was ready to sacrifice any of my previous convictions about physics."
- Max Planck, on quantization

21.1 The Photon Energy Equation

Nature's Rule for Light

$$E = hf = \frac{hc}{\lambda}$$

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Nature's Rule for Light

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Key insights:

- Higher frequency \rightarrow higher energy per photon
- Shorter wavelength \rightarrow higher energy per photon
- Planck's constant h links energy to frequency

Attempt: Photon Energy of a Light Bulb

The Challenge (3 min, silent)

A 100-W light bulb converts 10% of its power to visible light with average wavelength 580 nm. Calculate the number of visible photons emitted per second.

Given:

- Power in visible light: 10.0 J/s
- Wavelength: $\lambda = 580 \text{ nm}$
- $h = 6.626 \times 10^{-34} \text{ J}\cdot\text{s}$, $c = 3.00 \times 10^8 \text{ m/s}$

Find: Photons per second

Work silently. It's okay to get stuck.

Compare: Light Bulb Strategy

Turn and talk (2 min):

- 1 Which form of photon energy equation did you use?
- 2 How did you find energy per photon?
- 3 What's your strategy for finding number of photons?

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Name wheel: One pair share your approach (not your answer).

Reveal: Counting Photons

Self-correct in a different color:

Step 1 - Energy per photon:

$$E = \frac{hc}{\lambda} = \frac{(6.626 \times 10^{-34})(3.00 \times 10^8)}{580 \times 10^{-9}} = 3.43 \times 10^{-19} \text{ J}$$

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Step 2 - Photons per second:

$$\frac{\text{photons}}{\text{s}} = \frac{10.0 \text{ J/s}}{3.43 \times 10^{-19} \text{ J/photon}} = \boxed{2.92 \times 10^{19} \text{ photons/s}}$$

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Check: About 29 billion billion photons every second - no wonder light seems continuous!

21.1 Blue Fire vs Red Fire

Real-World: Danger by Color

A blue flame is more dangerous than a red flame.

Why?

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Why?

Blue light: shorter wavelength \rightarrow higher frequency \rightarrow **higher energy per photon**

Red light: longer wavelength \rightarrow lower frequency \rightarrow lower energy per photon

Each blue photon delivers more energy than each red photon.

21.1 Energy Across the Spectrum

Radiation	Wavelength	Energy/photon
Radio	1 m	2×10^{-25} J
Infrared	1000 nm	2×10^{-19} J
Visible	500 nm	4×10^{-19} J
UV	100 nm	2×10^{-18} J
X-ray	1 nm	2×10^{-16} J
Gamma	0.01 nm	2×10^{-14} J

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UV Hazard

UV photons carry enough energy to break DNA bonds (≈ 1 eV $= 1.6 \times 10^{-19}$ J).

That's why UV causes sunburn and cancer.

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- **21.2:** Explain why classical physics couldn't explain the effect
- **21.2:** Calculate photoelectron kinetic energy
- **21.2:** Describe applications in solar cells and technology

Light as a Battering Ram

Light can knock electrons out of metal.
How does a wave punch like a particle?

Light as a Battering Ram

Light can knock electrons out of metal.
How does a wave punch like a particle?

The Paradox

Classical physics: Light is a wave - spread out, continuous energy.

Reality: Light ejects electrons instantly, one photon at a time.

21.2 The Photoelectric Setup



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The experiment:

- Light strikes metal surface
- Electrons ejected (photoelectrons)
- Current measured - proves electrons are moving

21.2 Five Mysteries

Classical wave theory predictions:

- 1 Any frequency should eject electrons (just wait long enough)

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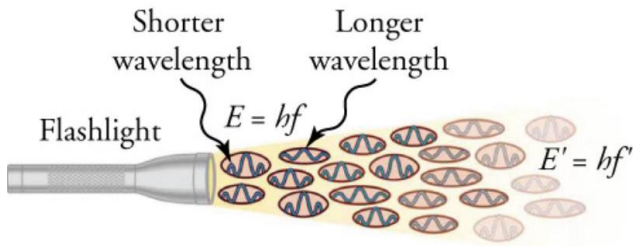
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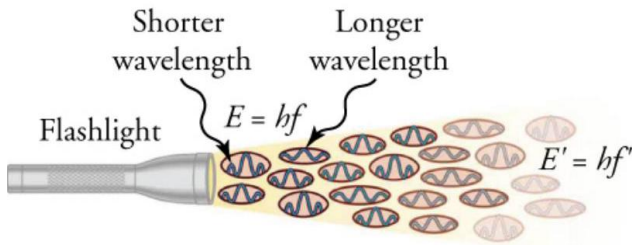
Experimental Reality

- 1 Threshold frequency exists - below it, NO electrons (ever!)
- 2 Brighter light ejects MORE electrons, not faster ones
- 3 Ejection is INSTANTANEOUS

21.2 Einstein's Photon Model

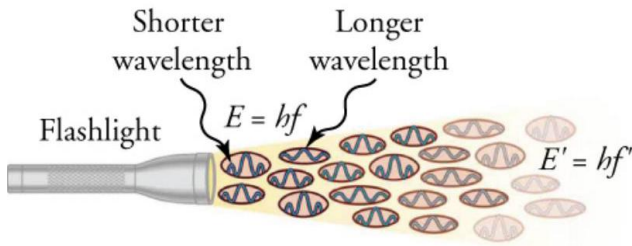


21.2 Einstein's Photon Model



Key insight: Light is not a continuous wave.
Light is a stream of **photons** - discrete packets of energy.

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Each photon energy: $E = hf$

21.2 One Photon, One Electron

The Mental Model

Each photon interacts with ONE electron.

If photon energy $<$ binding energy: electron stays bound.

If photon energy \geq binding energy: electron escapes!

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The Mental Model

Each photon interacts with ONE electron.

If photon energy $<$ binding energy: electron stays bound.

If photon energy \geq binding energy: electron escapes!

This explains ALL five observations:

- **Threshold:** $hf_0 = BE$ (minimum energy to escape)
- **Instant:** one photon, one collision
- **Brightness:** more photons = more electrons (not faster electrons)

21.2 The Photoelectric Equation

The Law of Energy Exchange

$$KE_e = hf - BE$$

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- KE_e = kinetic energy of ejected electron
- hf = photon energy
- BE = binding energy (work function)

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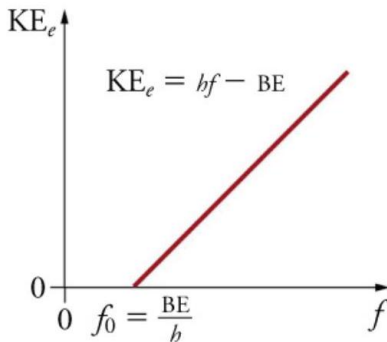
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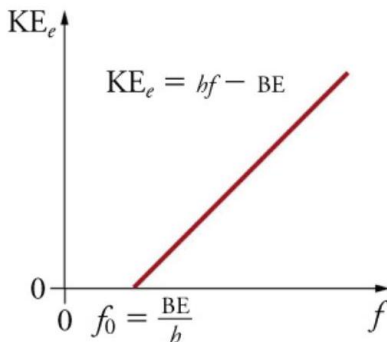
Photon energy budget:

- 1 Pay the escape cost (binding energy BE)
- 2 Leftover becomes kinetic energy

21.2 Kinetic Energy vs Frequency



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Key features:

- Below f_0 : NO electrons ejected ($KE = 0$)
- Above f_0 : KE increases linearly with f
- Slope = h (Planck's constant!)

Attempt: Violet Light and Calcium

The Challenge (3 min, silent)

Violet light with wavelength 420 nm strikes calcium metal.
Binding energy of calcium: $BE = 2.71 \text{ eV}$

Given:

- $\lambda = 420 \text{ nm} = 4.20 \times 10^{-7} \text{ m}$
- $BE = 2.71 \text{ eV}$
- $h = 6.626 \times 10^{-34} \text{ J}\cdot\text{s}$, $c = 3.00 \times 10^8 \text{ m/s}$
- Conversion: $1 \text{ eV} = 1.60 \times 10^{-19} \text{ J}$

Find: (a) Photon energy in eV

(b) Maximum kinetic energy of ejected electron in eV

Work silently. It's okay to get stuck.

Compare: Photoelectric Strategy

Turn and talk (2 min):

- 1 How did you find photon energy from wavelength?
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- 3 Which equation did you use for part (b)?

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Reveal: Photoelectric Calculation

Self-correct in a different color:

Part (a) - Photon energy:

$$E = \frac{hc}{\lambda} = \frac{(6.626 \times 10^{-34})(3.00 \times 10^8)}{4.20 \times 10^{-7}} = 4.74 \times 10^{-19} \text{ J}$$

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Part (b) - Electron kinetic energy:

$$KE_e = hf - BE = 2.96 \text{ eV} - 2.71 \text{ eV} = \boxed{0.25 \text{ eV}}$$

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Check: Small KE - photon energy barely exceeds threshold!

21.2 Solar Cells: Photons to Power



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How photovoltaic cells work:

- Photons strike semiconductor (usually silicon)
- Electrons freed via photoelectric effect
- Electrons flow as electric current
- Current powers devices or charges batteries

21.2 Photoelectric Devices Everywhere

Applications you use daily:

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All rely on one quantum principle: **photons create electric current**

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- **21.3:** Explain Compton scattering as photon-electron collisions

The Great Contradiction

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Light is a particle.

Both statements are true.

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Civilian View vs Reality

Civilian: "Something is either a wave or a particle. Pick one."

Physicist: "Light is both. It depends on how you look at it."

21.3 Two Faces of Light

Wave Evidence:

- Diffraction through slits
- Interference patterns
- Polarization
- Wavelength and frequency

Particle Evidence:

- Photoelectric effect
- Discrete energy $E = hf$
- Photon momentum
- Compton scattering

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- Photon momentum
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The Resolution

Light exhibits **wave-particle duality**. Which aspect you observe depends on your experiment.

21.3 Massless Momentum

The Source Code: Photon Momentum

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Photons carry momentum despite having zero mass.

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Key insights:

- Shorter wavelength = higher momentum
- Blue photons push harder than red photons
- Light exerts radiation pressure

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Real effects:

- Comet tails point away from Sun (photon pressure)
- Solar sails for spacecraft propulsion
- Optical tweezers manipulate cells using light

21.3 Photons as Billiard Balls

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Observations:

- Photon scatters at angle (like billiard ball)
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The Significance

Photons behave like classical particles in collisions.

Final proof of photon particle nature.

21.3 The Ultimate Twist

The Final Paradox

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Can matter (a particle) act like a wave?

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Answer: Yes. Louis de Broglie (1924) proposed:

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

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Consequence: Electrons, atoms, molecules - *everything* has a wavelength.

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Consequence: Electrons, atoms, molecules - *everything* has a wavelength.

Experimental proof:

- Electron diffraction creates interference patterns (1927)
- Electron microscopes use electron waves to image atoms
- Matter-wave duality is universal

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What You Now Know

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- 6 All matter exhibits wave-particle duality (de Broglie)

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- 6 All matter exhibits wave-particle duality (de Broglie)
- 7 Quantum mechanics governs the universe at atomic scales

Key Equations: Chapter 21

$$E = nhf \quad (\text{quantized energy - Planck}) \quad (1)$$

$$E = hf = \frac{hc}{\lambda} \quad (\text{photon energy}) \quad (2)$$

$$KE_e = hf - BE \quad (\text{photoelectric equation - Einstein}) \quad (3)$$

$$p = \frac{h}{\lambda} \quad (\text{photon momentum}) \quad (4)$$

Key constant:

$$h = 6.626 \times 10^{-34} \text{ J}\cdot\text{s} \quad (\text{Planck's constant})$$

Complete the assigned problems
posted on the LMS