

Unit 15: Modern Physics

Unit 15 is where classical physics stops being enough. It covers the photon model of light and the photoelectric effect, the wave behavior of matter through the de Broglie wavelength, the quantized energy levels of the hydrogen atom, and the nuclear physics of decay, half-life, and mass-energy equivalence. These are the ideas behind solar cells, LEDs, atomic spectra, and nuclear power.

AP Physics 2

Modern Physics

About 14 minutes to read

How to use this guide

Read it in order the first time, because the ideas build on each other. Photons come first because the photoelectric effect uses the photon model, and both the atomic and nuclear sections use energy bookkeeping that starts with $E = hf$. Exam questions here are mostly conceptual with short calculations, so pay attention to which quantity controls which effect.

After the first read, use the trap boxes to review the distinctions the exam tests most often: frequency versus intensity, joules versus electron-volts, and emission versus absorption. Finish with the practice questions, then complete the recall check on the last page out loud and note any items you cannot explain yet.

What this unit is worth. Modern Physics is 12 to 15 percent of the AP Physics 2 exam. It is dense with exam-ready ideas for its size, because the same handful of concepts (photon energy, threshold frequency, decay bookkeeping, and mass-energy) appear in several question styles. Points lost here usually come from mixing up frequency and intensity, or from losing track of nucleons in a decay equation.

15.1 Photons: Light Comes in Packets

Max Planck proposed that light is emitted and absorbed in discrete packets called **photons**, and Einstein used that idea to explain the photoelectric effect. Each photon carries an energy $E = hf$, where h is

Planck's constant ($6.63 \times 10^{-34} \text{ J}\cdot\text{s}$) and f is the frequency of the light. Because $c = f\lambda$, this can also be written $E = hc/\lambda$, which is the form you use when a question gives you a wavelength instead of a frequency.

Higher frequency means more energy **per photon**. A single photon of violet light carries more energy than a single photon of red light, and a single X-ray photon carries far more than either. This is a per-photon statement. It says nothing about how many photons are in the beam.

Worked example. Find the energy of one photon of green light with $\lambda = 500 \text{ nm}$.

Step 1: Convert the wavelength to meters. $\lambda = 500 \text{ nm} = 5.00 \times 10^{-7} \text{ m}$.

Step 2: $E = hc/\lambda = (6.63 \times 10^{-34} \text{ J}\cdot\text{s})(3.00 \times 10^8 \text{ m/s}) / (5.00 \times 10^{-7} \text{ m}) = 3.98 \times 10^{-19} \text{ J}$.

Step 3: Convert to electron-volts. $1 \text{ eV} = 1.60 \times 10^{-19} \text{ J}$, so $E = 3.98 \times 10^{-19} / 1.60 \times 10^{-19} \approx 2.48 \text{ eV}$. One photon of 500 nm light carries about 2.48 eV.

Trap. Intensity controls how many photons arrive per second, not how much energy each photon carries. Doubling the brightness of a red beam does not give any photon more energy. It just sends more red photons. Questions that mix up per-photon energy with beam intensity are testing exactly this distinction.

15.2 The Photoelectric Effect

When light shines on a metal surface, electrons can be ejected. Einstein explained this with the photon model. One photon is absorbed by one electron, and if the photon has enough energy, the electron escapes the metal. The electron needs a minimum energy ϕ , the **work function**, to break free.

Whatever the photon has left over becomes the electron's kinetic energy: $K_{\max} = hf - \phi$. This is the photoelectric equation.

There is a **threshold**. If $hf < \phi$, no electrons are emitted, no matter how bright the light is and no matter how long you wait. The **threshold frequency** is $f_0 = \phi/h$, the frequency at which hf exactly equals the work function. Increasing the intensity of above-threshold light ejects more electrons per second, which raises the **photocurrent**, but it does not change $K_{\max}$. Only the frequency controls how fast each electron leaves.

Worked example. Light of wavelength 400 nm shines on a metal with $\phi = 2.00$ eV.

Step 1: Photon energy. $E = hc/\lambda = (6.63 \times 10^{-34})(3.00 \times 10^8) / (4.00 \times 10^{-7}) = 4.97 \times 10^{-19}$ J. Dividing by 1.60×10^{-19} J/eV gives 3.10 eV.

Step 2: $K_{\max} = hf - \phi = 3.10$ eV $- 2.00$ eV = 1.10 eV.

Step 3: Threshold. $f_0 = \phi/h = (2.00)(1.60 \times 10^{-19} \text{ J}) / (6.63 \times 10^{-34} \text{ J}\cdot\text{s}) = 4.83 \times 10^{14}$ Hz, which corresponds to $\lambda_0 = c/f_0 = 621$ nm. Any wavelength longer than 621 nm fails, no matter how bright.

Trap. The two classic mix-ups: (1) thinking brighter light ejects faster electrons. It ejects *more* electrons, at the same maximum speed. (2) Thinking a dim blue beam can never work while a bright red beam can. Frequency decides whether electrons come out at all, and intensity decides how many per second. Red light at 650 nm carries only 1.91 eV per photon, below the 2.00 eV threshold here, so it ejects nothing at any brightness.

15.3 Wave-Particle Duality and the de Broglie Wavelength

Light behaves as a particle in the photoelectric effect but as a wave in interference. Louis de Broglie proposed the reverse for matter: moving particles also have a wavelength, $\lambda = h/p = h/(mv)$, where p is the momentum. Electrons fired one at a time through a double slit build up an interference pattern, which is exactly what waves do. This was confirmed experimentally, and it is why electron microscopes can resolve details far smaller than visible light allows.

Worked example. Find the de Broglie wavelength of an electron moving at 1.00×10^6 m/s.

Step 1: Momentum. $p = mv = (9.11 \times 10^{-31} \text{ kg})(1.00 \times 10^6 \text{ m/s}) = 9.11 \times 10^{-25} \text{ kg}\cdot\text{m/s}$.

Step 2: $\lambda = h/p = (6.63 \times 10^{-34} \text{ J}\cdot\text{s}) / (9.11 \times 10^{-25} \text{ kg}\cdot\text{m/s}) = 7.28 \times 10^{-10} \text{ m}$, about 0.73 nm. That is comparable to the spacing between atoms, which is why electron waves interact strongly with crystals.

The effect is invisible for everyday objects. A 0.145 kg baseball thrown at 40 m/s has $\lambda = h/(mv) \approx 1.1 \times 10^{-34} \text{ m}$, far too small to detect. Wave behavior only shows up when the mass is tiny enough that h/p reaches atomic scales.

Trap. In $\lambda = h/p$, it is momentum in the denominator, not velocity alone. Two particles at the same speed do not share a wavelength unless their masses match. For an electron and a proton at the same speed, the electron has the longer wavelength, because its smaller mass gives it less momentum.

15.4 Atomic Models and Hydrogen Energy Levels

Rutherford fired alpha particles at gold foil and found that some bounced back, which showed that the atom's positive charge is concentrated in a tiny, dense **nucleus** with electrons orbiting around it. Bohr kept the orbiting electrons but quantized them: only certain orbits are allowed, and each orbit has a fixed energy. For hydrogen, the allowed **energy levels** are $E_n = -13.6 \text{ eV} / n^2$, where $n = 1, 2, 3, \dots$ is the energy level.

An electron **absorbs** a photon and jumps to a higher level, or **drops** to a lower level and **emits** a photon. The photon's energy equals the gap crossed: $\Delta E = E_{\text{high}} - E_{\text{low}} = hf$. The negative energies mean the electron is bound to the atom. It takes +13.6 eV to free an electron from the ground state, which is why the ground-state energy is written as -13.6 eV.

Worked example. An electron in hydrogen drops from $n = 3$ to $n = 2$.

Step 1: $E_3 = -13.6/9 = -1.51 \text{ eV}$. $E_2 = -13.6/4 = -3.40 \text{ eV}$.

Step 2: $\Delta E = E_3 - E_2 = -1.51 - (-3.40) = 1.89 \text{ eV}$. The photon carries away 1.89 eV.

Step 3: $\lambda = hc/\Delta E = (6.63 \times 10^{-34})(3.00 \times 10^8) / ((1.89)(1.60 \times 10^{-19})) = 6.57 \times 10^{-7} \text{ m} = 657 \text{ nm}$, the red H-alpha line. This is emission, so a photon leaves the atom.

Trap. Emission and absorption run in opposite directions. Emission: the electron drops down and a photon comes out. Absorption: a photon goes in and the electron jumps up. If a question asks for the wavelength of light emitted in a $3 \rightarrow 2$ transition, the answer is a photon with energy 1.89 eV, not the energy of either level by itself.

15.5 Nuclear Physics: Isotopes and Radioactive Decay

The nucleus is described by the **mass number** A , the total number of nucleons (protons plus neutrons), and the **atomic number** Z , the number of protons. **Isotopes** are atoms of the same element (same Z) with different numbers of neutrons, hence different A . Carbon-12 and carbon-14 are both carbon, $Z = 6$, but carbon-14 has two extra neutrons.

Some nuclei are unstable and decay. In **alpha decay** the nucleus ejects a helium-4 nucleus, ${}^4\text{He}_2$. The mass number drops by 4 and the atomic number drops by 2. Check the bookkeeping on this example:



Nucleons: $238 = 234 + 4$. Charge: $92 = 90 + 2$. Both columns balance, as they must. The daughter is a different element because Z changed.

DECAY TYPE	WHAT IS EMITTED	WHAT CHANGES
Alpha (α)	${}^4\text{He}_2$ nucleus	A down by 4, Z down by 2
Beta-minus (β^-)	An electron, created in the nucleus	A unchanged, Z up by 1 (a neutron becomes a proton)
Gamma (γ)	A high-energy photon	A and Z unchanged; the nucleus drops to a lower energy state

Trap. Alpha decay changes both A and Z , but beta-minus decay leaves A alone. Students lose points by subtracting a nucleon in a beta decay the way they would in an alpha decay. In beta decay the nucleon count does not change. A neutron converts into a proton and an electron, and the electron is ejected.

15.6 Beta Decay, Gamma Decay, and Half-Life

In **beta-minus decay** a neutron in the nucleus converts into a proton and emits an electron. Written as a nuclear equation:



Check: nucleons $14 = 14 + 0$, charge $6 = 7 + (-1)$. The mass number stays at 14 while the atomic number rises by one, so carbon becomes nitrogen. The electron in beta decay comes from the nucleus itself, not from the atom's electron shells.

Gamma decay is different. An excited nucleus relaxes to a lower energy state by emitting a high-energy photon. Neither A nor Z changes, because no nucleons or protons leave. Gamma rays usually follow an alpha or beta decay that left the nucleus excited.

Half-life is the time for half of a sample's unstable nuclei to decay. After one half-life, half remains. After two, a quarter. After n half-lives, the fraction left is $(1/2)^n$. This is statistical. It describes the sample as a whole, and you cannot predict which individual nucleus will decay next.

Worked example. An 800 g sample has a half-life of 12 days. How much remains after 36 days?

36 days / 12 days = 3 half-lives. The fraction left is $(1/2)^3 = 1/8$. $800 \text{ g} / 8 = 100 \text{ g}$.

Trap. Half-life halves what is *left*, not what you started with. After 12 days, 400 g remains. After 24 days, 200 g, not 0 g. The decay is exponential, not linear, so do not subtract the same amount each period.

15.7 Mass-Energy Equivalence and Binding Energy

Einstein's **mass-energy equivalence**, $E = mc^2$, says that mass is a form of energy. In nuclear reactions the total mass of the products is slightly less than the total mass of the reactants, and the missing mass appears as released energy: $E_{\text{released}} = (\Delta m)c^2$. Because c^2 is enormous, a tiny mass change releases a huge amount of energy.

The same idea explains why nuclei hold together. A nucleus weighs less than the sum of its separate protons and neutrons. The missing amount is the **mass defect**, and it equals the **binding energy** that holds the nucleus together: $E_{\text{binding}} = (\Delta m)c^2$. **Binding energy per nucleon** peaks around iron-56, which is why both splitting heavy nuclei and merging light ones release energy. Either direction moves toward more tightly bound nuclei.

A useful conversion. One atomic mass unit equals $931.5 \text{ MeV}/c^2$, so a mass defect of 1 u corresponds to 931.5 MeV of binding energy. Nuclear energies are usually quoted in MeV for exactly this reason.

Trap. The mass defect is not a mistake or a loss of matter. It is the whole point: the "missing" mass is present in the nucleus as binding energy. And mass by itself is not conserved in nuclear reactions. What is conserved is the total mass-energy.

15.8 Fission and Fusion

In **fission** a heavy nucleus splits into lighter nuclei, usually after absorbing a neutron. The classic example is uranium-235 splitting into barium, krypton, and extra neutrons, which can trigger further fissions in a **chain reaction**. In **fusion**, light nuclei merge into a heavier one. The Sun fuses hydrogen into helium, and this process powers stars.

	FISSION	FUSION
Starting point	One heavy nucleus (e.g., uranium-235)	Light nuclei (e.g., hydrogen isotopes)
Process	Splits into lighter nuclei plus neutrons	Merge into a heavier nucleus
Energy source	Products weigh less than reactants; the mass difference leaves as kinetic energy and radiation	
Where it happens	Nuclear reactors, atomic weapons	Stars; fusion power plants do not exist yet

Both release energy for the same reason: the products have a greater binding energy per nucleon than the reactants, so mass becomes energy. Moving either direction on the binding-energy curve toward iron-56 releases energy.

Confusions That Cost Points

PAIR	HOW TO KEEP THEM STRAIGHT
Photon energy vs beam intensity	Energy per photon is set by frequency ($E = hf$). Intensity sets how many photons arrive per second. Bright red light is many low-energy photons.
Frequency vs intensity in the photoelectric effect	Frequency decides whether electrons come out at all, and how fast. Intensity decides how many come out per second.
Emission vs absorption	Emission: the electron drops, a photon leaves. Absorption: a photon enters, the electron jumps up.
Joules vs electron-volts	$1 \text{ eV} = 1.60 \times 10^{-19} \text{ J}$. A 2.48 eV photon is $3.98 \times 10^{-19} \text{ J}$. Convert before you subtract a work function given in eV from a photon energy computed in joules.
Alpha vs beta decay bookkeeping	Alpha: $A - 4$, $Z - 2$. Beta-minus: A unchanged, $Z + 1$. Check both columns every time.
Fission vs fusion	Fission splits heavy nuclei. Fusion merges light ones. Both release energy because the products bind more tightly per nucleon.

Practice Questions

Original questions written for this guide in the style of the AP exam. Answers and explanations are on the next page, so complete the questions before checking them.

1. Which of the following photons carries the most energy?

1. A photon with wavelength 650 nm (red)
2. A photon with wavelength 500 nm (green)
3. A photon with wavelength 420 nm (violet)
4. All three carry the same energy because they are all light

2. A beam of red light ($\lambda = 650$ nm) shines on a metal with work function $\phi = 2.00$ eV, and no electrons are emitted. Which change is certain to cause electrons to be emitted?

1. Make the red light brighter
2. Shine the red light on the metal for a longer time
3. Replace the red light with blue light of the same intensity
4. Replace the metal with one that has a larger work function

3. Light with a frequency above the threshold frequency shines on a metal, and electrons are emitted. The intensity of the light is doubled while the frequency stays the same. What happens?

1. $K_{\max}$ doubles
2. Twice as many electrons are emitted per second, and $K_{\max}$ is unchanged
3. The work function of the metal doubles
4. Electrons stop being emitted because the extra light interferes

4. An electron and a proton move at the same speed. How do their de Broglie wavelengths compare?

1. The electron's wavelength is greater
2. The proton's wavelength is greater
3. The two wavelengths are equal
4. It cannot be determined without knowing the speed

5. In the hydrogen atom, which of the following transitions emits a photon with the greatest energy?

1. $n = 3$ to $n = 2$
2. $n = 4$ to $n = 2$
3. $n = 2$ to $n = 1$
4. $n = 4$ to $n = 1$

6. A $^{238}\text{U}_{92}$ nucleus undergoes alpha decay. What are the mass number A and atomic number Z of the daughter nucleus?

1. $A = 234$, $Z = 90$
2. $A = 237$, $Z = 91$
3. $A = 234$, $Z = 91$
4. $A = 238$, $Z = 90$

7. A 120 g sample of a radioactive isotope has a half-life of 5 days. How much of the sample remains after 15 days?

1. 0 g
2. 15 g
3. 24 g
4. 40 g

8. Which of the following statements is true about both fission and fusion?

1. Both are chemical reactions that rearrange electrons
2. Both release energy by forming nuclei with less binding energy per nucleon
3. Both begin with heavy nuclei like uranium
4. Both produce products whose total mass is less than the total mass of the reactants

Answer Key

- 1. C.** Photon energy is $E = hc/\lambda$, so shorter wavelength means more energy per photon. Violet at 420 nm beats green at 500 nm and red at 650 nm. A and B pick longer wavelengths, which carry less energy. D confuses intensity with per-photon energy: a bright beam of red light contains more photons, not more energetic ones.
- 2. C.** The red photons each carry 1.91 eV, below the 2.00 eV work function, so no brightness or exposure time can make them eject electrons. Blue light at 450 nm carries 2.76 eV per photon, above the threshold, so it ejects electrons with $K_{\max} = 0.76$ eV. A fails because intensity changes the number of photons, not the energy of each one. B fails because waiting does not let one electron save up energy from many photons. D makes it worse: a larger work function raises the threshold, not lowers it.
- 3. B.** Doubling the intensity sends twice as many photons per second, so twice as many electrons are ejected per second. But $K_{\max} = hf - \phi$ depends only on frequency and the work function, neither of which changed. A confuses the electron count with the electron energy. C treats the work function as a property of the light; it is a property of the metal and does not change. D invents a nonexistent interference effect.
- 4. A.** De Broglie wavelength is $\lambda = h/p = h/(mv)$. At the same speed, the electron's much smaller mass gives it less momentum, and momentum is in the denominator, so the electron's wavelength is longer. B reverses this, treating the heavier particle as the one with the longer wave. C ignores mass entirely and compares speeds alone. D is unnecessary: the mass ratio already decides the comparison, whatever the speed is.
- 5. D.** The emitted photon energy is the size of the gap crossed: $3 \rightarrow 2$ is 1.89 eV, $4 \rightarrow 2$ is 2.55 eV, $2 \rightarrow 1$ is 10.2 eV, and $4 \rightarrow 1$ is 12.75 eV. The $4 \rightarrow 1$ drop crosses the most energy levels, so it emits the most energetic photon. A is the tempting familiar H-alpha line, but it is the smallest gap listed. B crosses more levels than A yet ends higher up, so its gap is smaller than C's. C is a large drop but still smaller than the full $4 \rightarrow 1$ fall.
- 6. A.** Alpha decay ejects ${}^4\text{He}_2$, so A drops by 4 ($238 \rightarrow 234$) and Z drops by 2 ($92 \rightarrow 90$). B subtracts only one nucleon and one proton, which matches no decay type. C gets the nucleons right but forgets that the alpha particle carries away two protons. D describes a gamma emission, where neither A nor Z changes.
- 7. B.** 15 days is three half-lives ($15/5 = 3$), so the fraction left is $(1/2)^3 = 1/8$, and $120 \text{ g} / 8 = 15 \text{ g}$. C may come from guessing a fraction without counting half-lives. D treats the decay as linear, dividing by 3 instead of halving three times. A assumes all of it is gone after a few half-lives, but exponential decay only approaches zero; it never reaches it.
- 8. D.** Both processes release energy for the same reason: the products weigh slightly less than the reactants, and the missing mass appears as energy via $E = mc^2$. C is true only of fission; fusion starts with light nuclei. A confuses nuclear reactions with chemical ones; electrons are not the story here. B reverses the binding-energy logic: energy is released because the products have *greater* binding energy per nucleon, binding the system more tightly.

When you check your answers, note which distinction each miss came from. Make a flashcard for that distinction and drill it spaced out over the next few days instead of rereading the whole section. If you

missed one of these questions, the same distinction is worth practicing again in Rycal, where the Modern Physics deck has flashcards for it and more practice questions use the same kinds of traps.

One-Page Recall Check

Say each answer out loud before you look back, and mark the ones you cannot finish. Anything you cannot say out loud yet belongs in your flashcard deck. In Rycal, add those items to the Modern Physics deck and let spaced review bring them back over the next few days.

- Write $E = hf = hc/\lambda$ and explain what each symbol means.
- Compute the energy, in joules and in eV, of one photon with $\lambda = 600 \text{ nm}$.
- State the photoelectric equation and define the work function.
- Explain why light below the threshold frequency ejects no electrons, no matter how bright.
- Describe what doubling the intensity of above-threshold light changes, and what it does not change.
- Write the de Broglie relation and explain why a baseball shows no measurable wave behavior.
- State whether an electron or a proton at the same speed has the longer de Broglie wavelength, and why.
- Write the hydrogen energy level formula and compute ΔE for the $n = 3$ to $n = 2$ transition.
- Explain the difference between emission and absorption of a photon.
- Define isotope, and give the A and Z changes in alpha decay and in beta-minus decay.
- Write and balance the alpha decay of $^{238}\text{U}_{92}$.
- Explain half-life, and find the fraction of a sample that remains after 4 half-lives.
- State $E = mc^2$ and explain what the mass defect becomes.
- Compare fission and fusion: what splits, what merges, and why both release energy.

Where to go next. Turn every missed item above into flashcards and drill them spaced out over several days rather than in one sitting. In Rycal, open the Modern Physics deck under AP Physics 2. The deck covers the terms in this guide, and its practice questions target the same traps named here. If you have a test date, add it in the Test Planner. You can also start your next review with a Brain Dump, then check what you missed against this guide.

Key terms for this unit

Photon, Planck's constant, Photoelectric effect, Work function, Threshold frequency, Photocurrent, Wave-particle duality, de Broglie wavelength, Rutherford model, Bohr model, Energy level, Emission, Absorption, H-alpha line, Isotope, Mass number, Atomic number, Alpha decay, Beta-minus decay, Gamma decay, Daughter nucleus, Half-life, Mass-energy equivalence, Mass defect, Binding energy, Binding energy per nucleon, Fission, Fusion, Chain reaction, Electron-volt.

About this guide. Written for Rycal and aligned to the College Board AP Physics 2 course framework, Unit 15. All questions and explanations are original Rycal writing. Rycal is independent and is not affiliated with or endorsed by the College Board.