Topic 3.11: Spectroscopy and the Electromagnetic Spectrum

Revision Notes · AP Chemistry

UNIT 3 · PROPERTIES OF SUBSTANCES AND MIXTURES

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Spectroscopy: How Radiation Meets Matter

Spectroscopy is the study of how electromagnetic radiation interacts with matter: how substances absorb, emit and transmit radiation across the whole spectrum.

Matter does not interact with every wavelength in the same way. Each substance absorbs and emits a characteristic set of wavelengths, set by its structure, so the pattern works like a fingerprint: measure which wavelengths a sample absorbs and you can identify what the substance is.

That one idea is why the topic exists. Everything else is learning what the regions of the spectrum are, how wavelength, frequency and photon energy are tied together, and which kind of change in matter each region can drive.

One Spectrum, Seven Regions

All electromagnetic radiation travels at the same speed in a vacuum, $c = 3.00 \times 10^8$ m/s. The regions differ only in wavelength and frequency, and they run in one fixed order.

From longest wavelength to shortest, the order is radio, microwave, infrared, visible, ultraviolet, X-ray, gamma. Radio waves have the longest wavelengths, from about a millimetre up to thousands of metres, and microwaves occupy the short wavelength end of that span, roughly 1 mm to 1 m. Infrared runs from about 1 mm down to 700 nm.

Visible light is one narrow window inside the whole range: about 400 nm at the violet end to 700 nm at the red end, with frequencies from 4.3×10^{14} to 7.5×10^{14} Hz. Just shorter than 400 nm

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comes ultraviolet, down to about 10 nm, then X-rays, then gamma rays below about 10 pm, the shortest wavelengths of all.

The boundaries between regions are approximate, and neighbouring regions overlap slightly at the edges, but the order never changes. Photon energy follows the same sequence: radio photons are the least energetic and gamma photons the most, with many orders of magnitude between the two ends.

The Two Equations That Run the Topic

Radiation travels in photons, discrete packets of energy. Two equations, built on two constants, connect everything: $c = \lambda\nu$ and $E = h\nu$. Here λ is wavelength in metres, ν is frequency in hertz (cycles per second), h is Planck's constant, 6.626×10^{-34} J·s, and E is the energy of one photon in joules.

Because both equations contain ν, they combine into a third: $E = hc/\lambda$. Photon energy can be worked out from frequency or from wavelength, whichever the question hands you.

Unit discipline decides most of the marks in this topic. Wavelength must be in metres before it enters either equation: 1 nm = 1×10^{-9} m, so 500 nm becomes 5.00×10^{-7} m. The energy from $E = h\nu$ or $E = hc/\lambda$ is per photon; multiply by Avogadro's number, 6.022×10^{23} mol^{-1}, when the question asks for energy per mole of photons.

How Wavelength, Frequency and Energy Move Together

Because c is constant, wavelength and frequency are inversely proportional: double the wavelength and the frequency halves. A wave diagram shows the same thing: more cycles packed into the same distance means a shorter wavelength, and so a higher frequency.

Frequency and photon energy are directly proportional: double the frequency and each photon carries twice the energy. Combining the two, photon energy is inversely proportional to wavelength: halve the wavelength and the photon energy doubles.

So the three quantities move in a locked pattern. Higher frequency always means shorter wavelength and greater energy per photon, and there is no arrangement in which frequency rises while photon energy falls.

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Energy per Photon Is Not Total Energy

Brightness, or intensity, is a count of photons: a brighter beam delivers more photons per second, each carrying exactly the same energy as before. Two beams of the same colour at different brightnesses deliver different total energies, because their photon counts differ.

What a photon can do to matter depends on its own energy, not on how many photons arrive. Ultraviolet photons carry enough energy to break bonds in skin molecules, which is why ultraviolet light causes sunburn. Visible photons do not, however many of them arrive, because each one falls short of the energy a bond breaking event needs.

Each region also matches a scale of change in matter. Microwave photons are absorbed in driving molecular rotations. Infrared photons match the energy gaps between vibrational states, so they set chemical bonds vibrating, which is why infrared spectroscopy reports on functional groups. Visible and ultraviolet photons match the energy gaps between electron energy levels, so they move electrons between levels.

Worked Examples

Example 1: Naming the region from a frequency. Radiation is detected at $\nu = 6.0 \times 10^{14}$ Hz. $\lambda = c/\nu = (3.00 \times 10^{8}) \div (6.0 \times 10^{14}) = 5.0 \times 10^{-7}$ m = 500 nm. That falls inside 400 to 700 nm, so the radiation is visible light, in the green part of the spectrum.

Example 2: The energy of one photon, compared. For green light of wavelength 5.00×10^{-7} m, $E = hc/\lambda = (6.626 \times 10^{-34} \times 3.00 \times 10^{8}) \div (5.00 \times 10^{-7}) = 3.98 \times 10^{-19}$ J, about 4.0×10^{-19} J. Red light at 700 nm gives $(1.99 \times 10^{-25}) \div (7.00 \times 10^{-7}) = 2.84 \times 10^{-19}$ J. The green photon carries 700 ÷ 500 = 1.40 times the energy of the red photon: the energy ratio is the wavelength ratio turned upside down.

Example 3: From one photon to a mole of photons. Multiply the green photon's energy by Avogadro's number: $3.98 \times 10^{-19} \times 6.022 \times 10^{23} = 2.40 \times 10^{5}$ J per mole of photons, which is 2.4×10^{2} kJ/mol. That is the same scale as chemical bond energies, which run to hundreds of kilojoules per mole, so a mole of visible photons carries energy comparable to the energy stored in a mole of chemical bonds.

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Traps That Cost Marks in Topic 3.11

Longer wavelength means more energy. Backwards. Photon energy is inversely proportional to wavelength, so the longest wavelengths of all, radio waves, carry the least energy per photon.

All light travels at c, so all light has the same frequency. The speed is shared; the frequency and wavelength are not. Colour is exactly the visible sign of photons differing in frequency while travelling at one fixed speed.

Doubling the wavelength doubles the photon energy. It halves it. With $E = hc/\lambda$ the energy ratio is the wavelength ratio flipped: wavelengths in the ratio 2:1 have photon energies in the ratio 1:2.

A brighter visible beam can do what ultraviolet light does. Brightness adds photons, not energy per photon. An event that needs one energetic photon, such as breaking a bond, cannot be triggered by any number of weaker photons.

Feeding nanometres straight into the equations. Using 500 instead of 5.00×10^{-7} m in $E = hc/\lambda$ shrinks the answer by a factor of 10^9. Convert the wavelength to metres first, every time.

The colour seen is the colour absorbed. The eye sees the wavelengths that are transmitted or reflected. A sample absorbing at 600 nm removes orange light from white light and appears blue-green, the complementary colour.

Per photon and per mole are the same number. They differ by Avogadro's number, a factor of about 10^{23}. Read the units the question asks for, then decide whether the multiplication is needed.

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Key Relationships to Remember

- $c = \lambda\nu$, with $c = 3.00 \times 10^{8}$ m/s for all electromagnetic radiation in a vacuum: wavelength and frequency are inversely proportional
- $E = h\nu = hc/\lambda$, with $h = 6.626 \times 10^{-34}$ J·s: photon energy rises with frequency and falls with wavelength
- Region order by rising photon energy: radio, microwave, infrared, visible, ultraviolet, X-ray, gamma; visible light spans about 400 nm (violet) to 700 nm (red), frequencies 4.3×10^{14} to 7.5×10^{14} Hz
- Energy per mole of photons = energy per photon × 6.022×10^{23} mol^{-1}
- Intensity is a photon count per second; the energy of each photon is set by its frequency alone
- Each substance absorbs and emits characteristic wavelengths, a fingerprint that identifies it; the colour seen is the complement of the colour absorbed
- Region matched to process: microwaves drive molecular rotation, infrared drives bond vibration, visible and ultraviolet drive transitions of electrons between energy levels

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