CH-110 Advanced General Chemistry I

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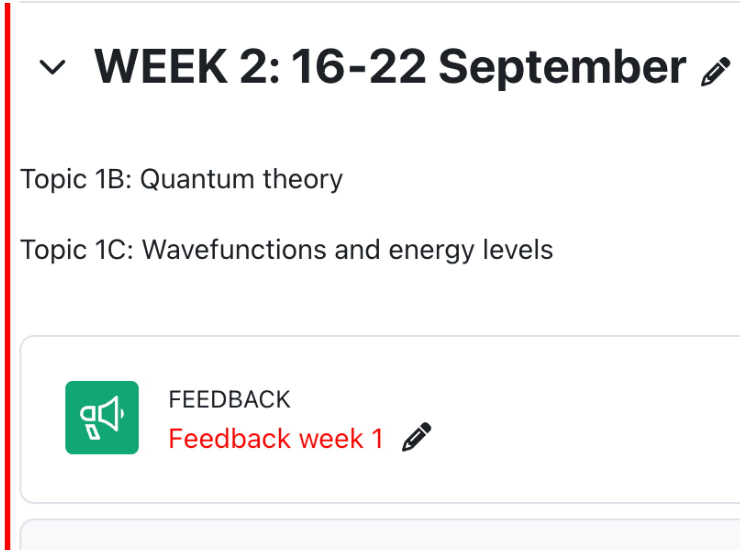
Housekeeping notes

- I've uploaded a periodic table in English on Moodle
- Slides: available at the earliest the day before (usually 30 minutes before class)
- I will post a final version of the slides after class.
- Exam questions will be posed in English and French
- Exercises will be uploaded every Tuesday. The solutions will be posted on Moodle the following Tuesday.
- **I've put a small feedback form online, it will be open until next Tuesday, September 24**.
- What will be asked on the exam?
- You would like to see more math? Come see me in the break or at the end of class.



PERIODIC TABLE OF THE ELEMENTS

Period	Group 1 I IA	2 II IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIIIB	9 VIIIB	10 VIIIB	11 IB	12 IIB	13 III IIIA	14 IV IVA	15 V VA	16 VI VIA	17 VII VIIA	18 VIII VIIA
1	1 H hydrogen 1.0079 $1s^1$																	2 He helium 4.00 $1s^2$
2	3 Li lithium 6.94 $2s^1$	4 Be beryllium 9.01 $2s^2$											5 B boron 10.81 $2s^22p^1$	6 C carbon 12.01 $2s^22p^2$	7 N nitrogen 14.01 $2s^22p^3$	8 O oxygen 16.00 $2s^22p^4$	9 F fluorine 19.00 $2s^22p^5$	10 Ne neon 20.18 $2s^22p^6$
3	11 Na sodium 22.99 $3s^1$	12 Mg magnesium 24.31 $3s^2$											13 Al aluminum 26.98 $3s^23p^1$	14 Si silicon 28.09 $3s^23p^2$	15 P phosphorus 30.97 $3s^23p^3$	16 S sulfur 32.06 $3s^23p^4$	17 Cl chlorine 35.45 $3s^23p^5$	18 Ar argon 39.95 $3s^23p^6$
4	19 K potassium 39.10 $4s^1$	20 Ca calcium 40.08 $4s^2$	21 Sc scandium 44.96 $3d^14s^2$	22 Ti titanium 47.87 $3d^24s^2$	23 V vanadium 50.94 $3d^34s^2$	24 Cr chromium 52.00 $3d^54s^1$	25 Mn manganese 54.94 $3d^54s^2$	26 Fe iron 55.84 $3d^64s^2$	27 Co cobalt 58.93 $3d^74s^2$	28 Ni nickel 58.69 $3d^84s^2$	29 Cu copper 63.55 $3d^{10}4s^1$	30 Zn zinc 65.41 $3d^{10}4s^2$	31 Ga gallium 69.72 $4s^24p^1$	32 Ge germanium 72.64 $4s^24p^2$	33 As arsenic 74.92 $4s^24p^3$	34 Se selenium 78.96 $4s^24p^4$	35 Br bromine 79.90 $4s^24p^5$	36 Kr krypton 83.80 $4s^24p^6$
5	37 Rb rubidium 85.47 $5s^1$	38 Sr strontium 87.62 $5s^2$	39 Y yttrium 88.91 $4d^15s^2$	40 Zr zirconium 91.22 $4d^25s^2$	41 Nb niobium 92.91 $4d^45s^1$	42 Mo molybdenum 95.94 $4d^55s^1$	43 Tc technetium (98) $4d^55s^2$	44 Ru ruthenium 101.07 $4d^75s^1$	45 Rh rhodium 102.90 $4d^85s^1$	46 Pd palladium 106.42 $4d^{10}$	47 Ag silver 107.87 $4d^{10}5s^1$	48 Cd cadmium 112.41 $4d^{10}5s^2$	49 In indium 114.82 $5s^25p^1$	50 Sn tin 118.71 $5s^25p^2$	51 Sb antimony 121.76 $5s^25p^3$	52 Te tellurium 127.60 $5s^25p^4$	53 I iodine 126.90 $5s^25p^5$	54 Xe xenon 131.29 $5s^25p^6$
6	55 Cs cesium 132.91 $6s^1$	56 Ba barium 137.33 $6s^2$	57 La lanthanum 138.91 $5d^16s^2$	72 Hf hafnium 178.49 $5d^26s^2$	73 Ta tantalum 180.95 $5d^36s^2$	74 W tungsten 183.84 $5d^46s^2$	75 Re rhenium 186.21 $5d^56s^2$	76 Os osmium 190.23 $5d^66s^2$	77 Ir iridium 192.22 $5d^76s^2$	78 Pt platinum 195.08 $5d^96s^1$	79 Au gold 196.97 $5d^{10}6s^1$	80 Hg mercury 200.59 $5d^{10}6s^2$	81 Tl thallium 204.38 $6s^26p^1$	82 Pb lead 207.2 $6s^26p^2$	83 Bi bismuth 208.98 $6s^26p^3$	84 Po polonium (209) $6s^26p^4$	85 At astatine (210) $6s^26p^5$	86 Rn radon (222) $6s^26p^6$
7	87 Fr francium (223) $7s^1$	88 Ra radium (226) $7s^2$	89 Ac actinium (227) $6d^17s^2$	104 Rf rutherfordium (261) $6d^27s^2$	105 Db dubnium (262) $6d^37s^2$	106 Sg seaborgium (266) $6d^47s^2$	107 Bh bohrium (264) $6d^57s^2$	108 Hs hassium (267) $6d^67s^2$	109 Mt meitnerium (268) $6d^77s^2$	110 Ds darmstadtium (271) $6d^87s^2$	111 Rg roentgenium (272) $6d^{10}7s^1$	112*	113	114	115	116	117	118

Lanthanoids (lanthanides) 6	58 Ce cerium 140.12 $4f^15d^16s^2$	59 Pr praseodymium 140.91 $4f^36s^2$	60 Nd neodymium 144.24 $4f^46s^2$	61 Pm promethium (145) $4f^56s^2$	62 Sm samarium 150.36 $4f^66s^2$	63 Eu europium 151.96 $4f^76s^2$	64 Gd gadolinium 157.25 $4f^75d^16s^2$	65 Tb terbium 158.93 $4f^96s^2$	66 Dy dysprosium 162.50 $4f^{10}6s^2$	67 Ho holmium 164.93 $4f^{11}6s^2$	68 Er erbium 167.26 $4f^{12}6s^2$	69 Tm thulium 168.93 $4f^{13}6s^2$	70 Yb ytterbium 173.04 $4f^{14}6s^2$	71 Lu lutetium 174.97 $5d^16s^2$
Actinoids (actinides) 7	90 Th thorium 232.04 $6d^27s^2$	91 Pa protactinium 231.04 $5f^26d^17s^2$	92 U uranium 238.03 $5f^36d^17s^2$	93 Np neptunium (237) $5f^46d^17s^2$	94 Pu plutonium (244) $5f^67s^2$	95 Am americium (243) $5f^77s^2$	96 Cm curium (247) $5f^76d^17s^2$	97 Bk berkelium (247) $5f^97s^2$	98 Cf californium (251) $5f^{10}7s^2$	99 Es einsteinium (252) $5f^{11}7s^2$	100 Fm fermium (257) $5f^{12}7s^2$	101 Md mendelevium (258) $5f^{13}7s^2$	102 No nobelium (259) $5f^{14}7s^2$	103 Lr lawrencium (262) $6d^17s^2$

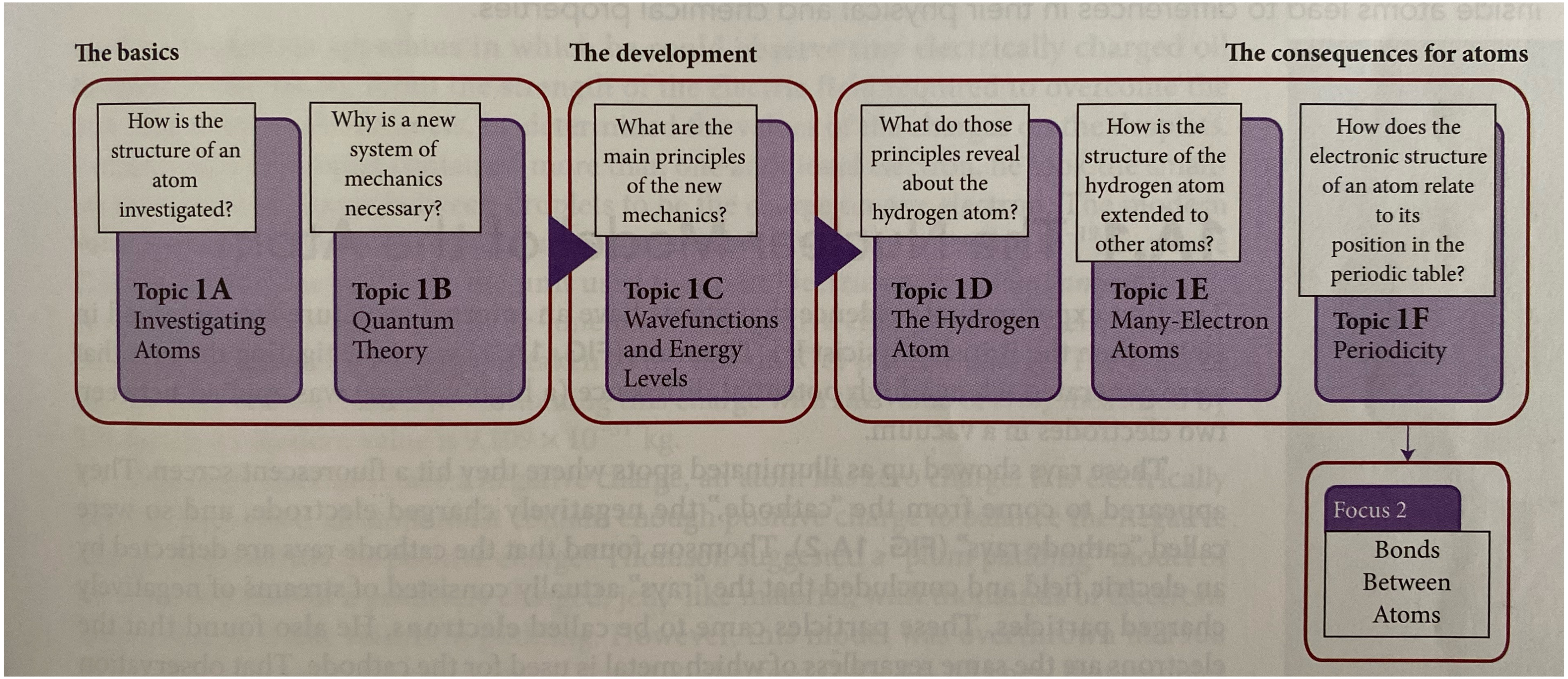
Molar masses (atomic weights) quoted to the number of significant figures given here can be regarded as typical of most naturally occurring samples.

*The names of the elements 112 and higher have not yet been determined; both 112 and 114 have been confirmed.

Quantum Theory

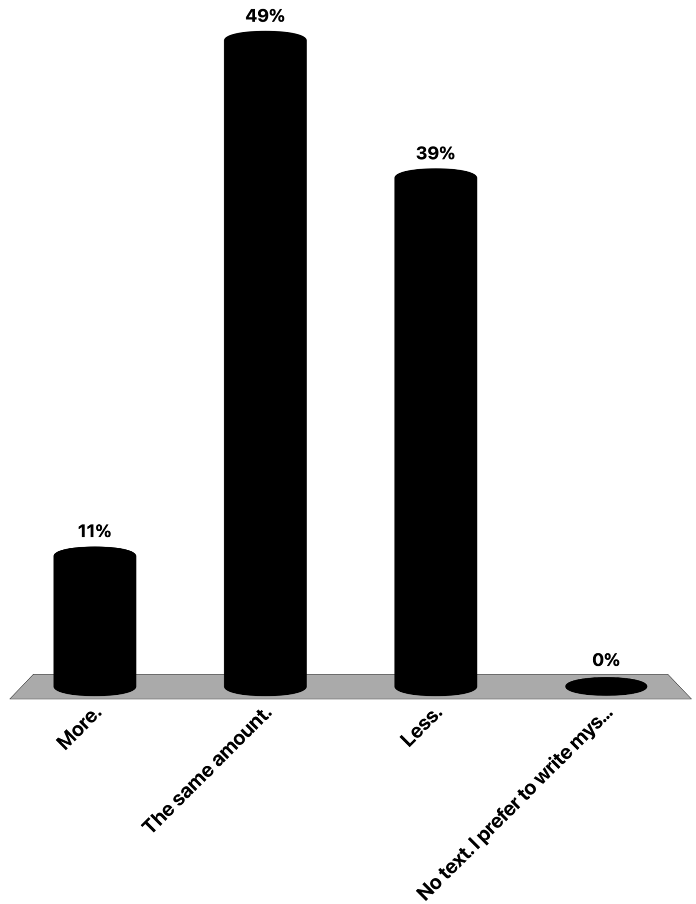
Topic 1B

Overview Chapter 1 (Focus 1: Atoms)



Poll test: how much text do you prefer on slides?

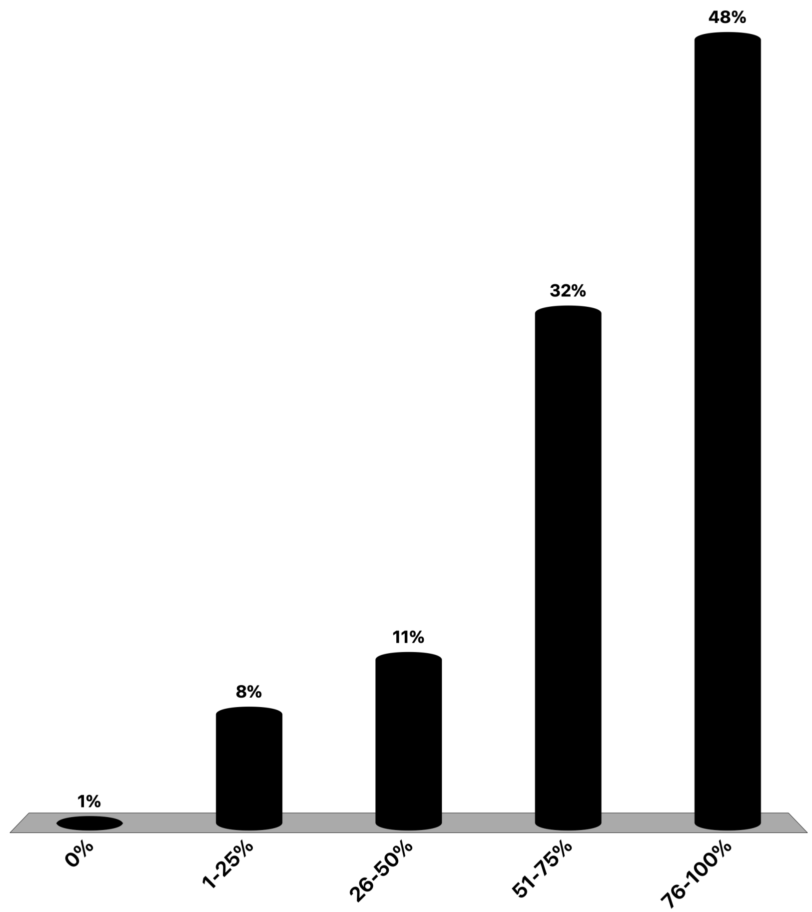
A. More.
B. The same amount.
C. Less.
D. No text. I prefer to write myself.



Session ID: 252032

Approximately what percentage of the material we've covered so far have you encountered in your previous studies?

A. 0%
B. 1-25%
C. 26-50%
D. 51-75%
E. 76-100%



Session ID: 252032

Topic 1B.1: Radiation, quanta, and photons
Topic 1B.2: Wave-particle duality
Topic 1B.3: The uncertainty principle

WHY DO YOU NEED TO KNOW THIS MATERIAL?

- The properties of electrons in atoms and molecules, which underlies the whole of **chemistry**, **can be understood only in terms of quantum mechanics.**

WHAT DO YOU NEED TO KNOW ALREADY?

- Concept of kinetic energy (Fundamentals A)
- Properties of electromagnetic radiation, specifically the **relationship between wavelength and frequency** (Topic 1A)

Radiation, Quanta, and Photons

Topic 1B.1

1B.1 Radiation, quanta, and photons

Setting the stage

- Towards end of 19^{th} century: scientists gathered more and more information about electromagnetic radiation.
- It becomes more clear: **many of the observations cannot be explained by classical mechanics**.
- Atomic spectrum of hydrogen: why are there spectral lines? This remained a big puzzle.

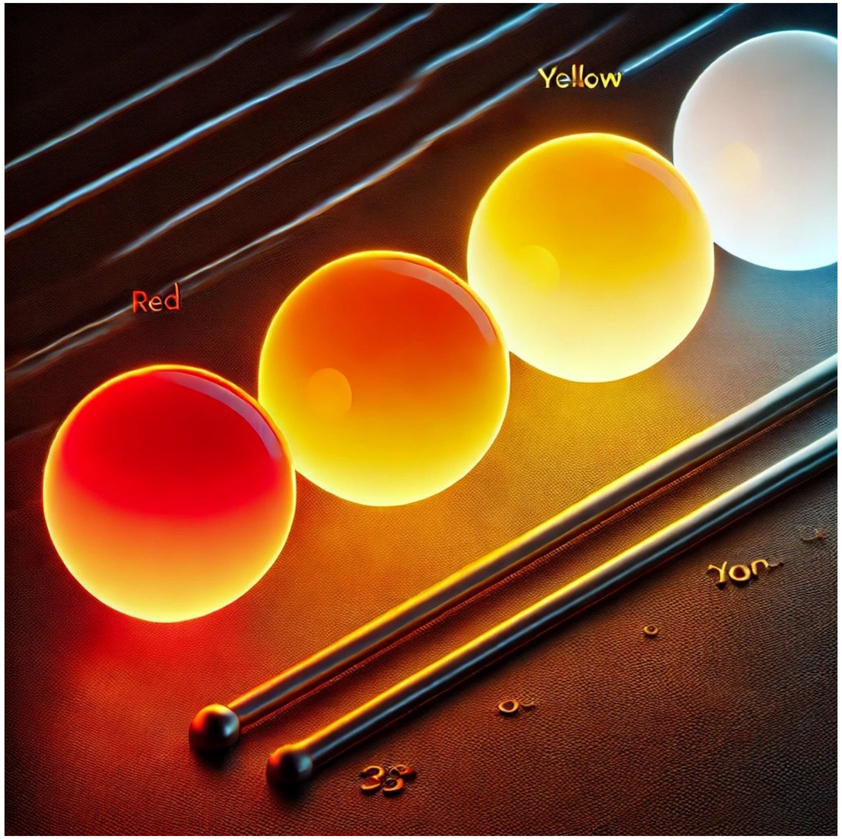
1B.1 Radiation, quanta, and photons

Black body experiment

- Nature of electromagnetic radiation was studied by heating objects:
- **Qualitative** observations:

  Incandescence: *if an object is heated to high enough temperatures, it begins to glow.*

  If temperature is raised higher: color of light turns from ***red*** *to* ***orange*** *to* ***yellow*** *to* ***white***.
- **Quantitative** assessments: measuring intensity of this radiation at each wavelength and repeat experiments at different temperatures.



1B.1 Radiation, quanta, and photons

What is black body radiation?

- A black body is an idealized object that **absorbs all radiation** (light, heat, etc.) that falls on it, and doesn't reflect or transmit any of that energy. It appears **completely black** when cold because it doesn't reflect any light.
- However, a black body doesn't just absorb energy—it also **emits radiation** when it gets hot. This emitted radiation depends only on the **temperature** of the black body, not on its material or shape. This is called **black body radiation**.
- The concept of black body radiation might feel strange because it doesn't behave exactly like other objects we encounter daily. **Most objects reflect or scatter some light** (which is why we see them), but a perfect black body doesn't.

1B.1 Radiation, quanta, and photons

Everyday objects to illustrate black body radiation

1B.1 Radiation, quanta, and photons

Black body experiment

- Hot object = "black body"
- **A black body emits and absorbs light without favoring certain wavelengths.**
- Its atoms and their electrons behave collectively, numerous transitions overlap in energy.
- Figure 1.B1 shows intensity of black-body radiation for a range of temperatures.

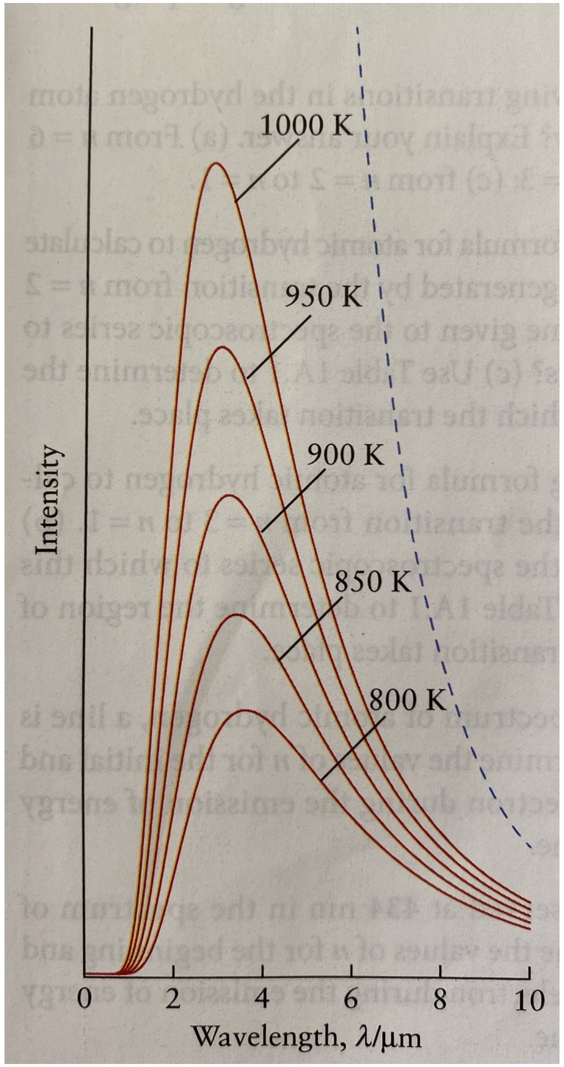


Figure 1.B1

1B.1 Radiation, quanta, and photons

Observations

- The higher T, the shorter the wavelength at the maximum.
- The higher T, the more intense the emission: The object glows brighter as it gets hotter.
- **No discrete lines** as in the atomic spectrum of hydrogen.

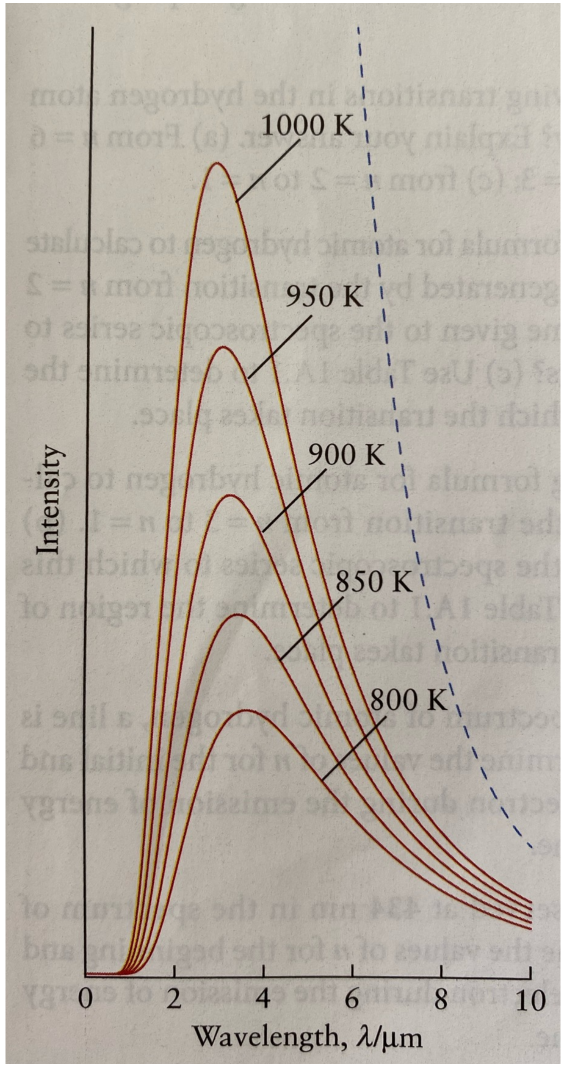


Figure 1.B1

1B.1 Radiation, quanta, and photons

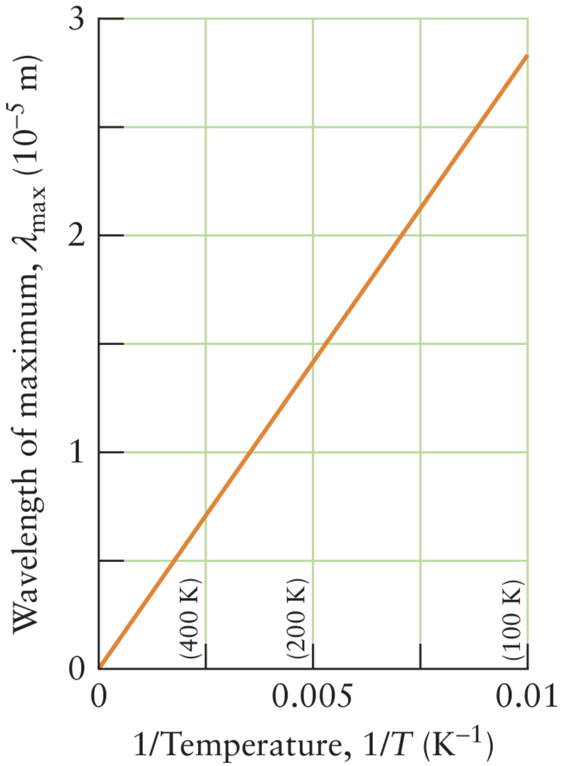
Wien's law

- In 1893, Wilhelm Wien discovered:
- The wavelength corresponding to the maximum intensity, λ_{max}, is inversely proportional to the absolute temperature, T
- As T increases, the wavelength of maximum intensity decreases

$$T\lambda_{max} = constant$$

- Empirical value of constant: 2.9 mm K

Figure 1.B2



1B.1 Radiation, quanta, and photons

Example 1B.1: **Determining temperatures from black-body radiation**

What is the temperature of the surface of the sun, assuming the sun can be treated as a black body? The maximum intensity of solar radiation occurs at 490 nm.

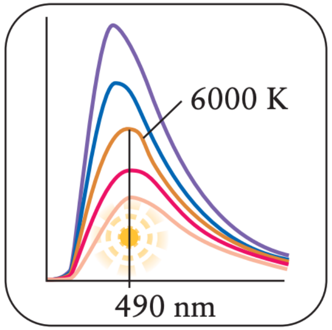
Anticipate We should be aware that objects glowing white hot are at temperatures of several thousand degrees.

PLAN Use Wien's law in the form $T = \text{constant}/\lambda_{max}$.

SOLVE

From $T = \text{constant}/\lambda_{max}$,

$$T = \frac{\overbrace{2.9 \times 10^{-3}\,\text{m}\cdot\text{K}}^{2.9\text{ mm}}}{\underbrace{4.90 \times 10^{-7}\,\text{m}}_{490\text{ nm}}} = \frac{2.9 \times 10^{-3}}{4.90 \times 10^{-7}}\,\text{K} = 5.9 \times 10^{3}\,\text{K}$$



Evaluate The surface temperature of the Sun is about 5900 K, in accord with our expectation.

1B.1 Radiation, quanta, and photons

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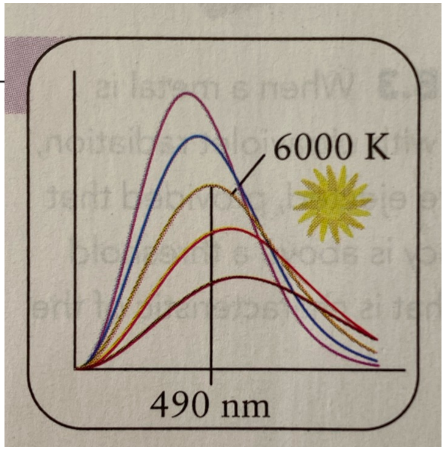

Note: the newest book has updated figures that are sometimes useful. If so, I will post them as pictures on the slides.

Evaluate The surface temperature of the Sun is about 5900 K, in accord with our expectation.

Find the temperature required for a black body to emit UV radiation with a wavelength of 260 nm. Units: K.

Rank	Responses
1	11153
2	11154
3	11000
4	11200
5	11153.84
6	1115

Values: 11000

Value Matches: 5

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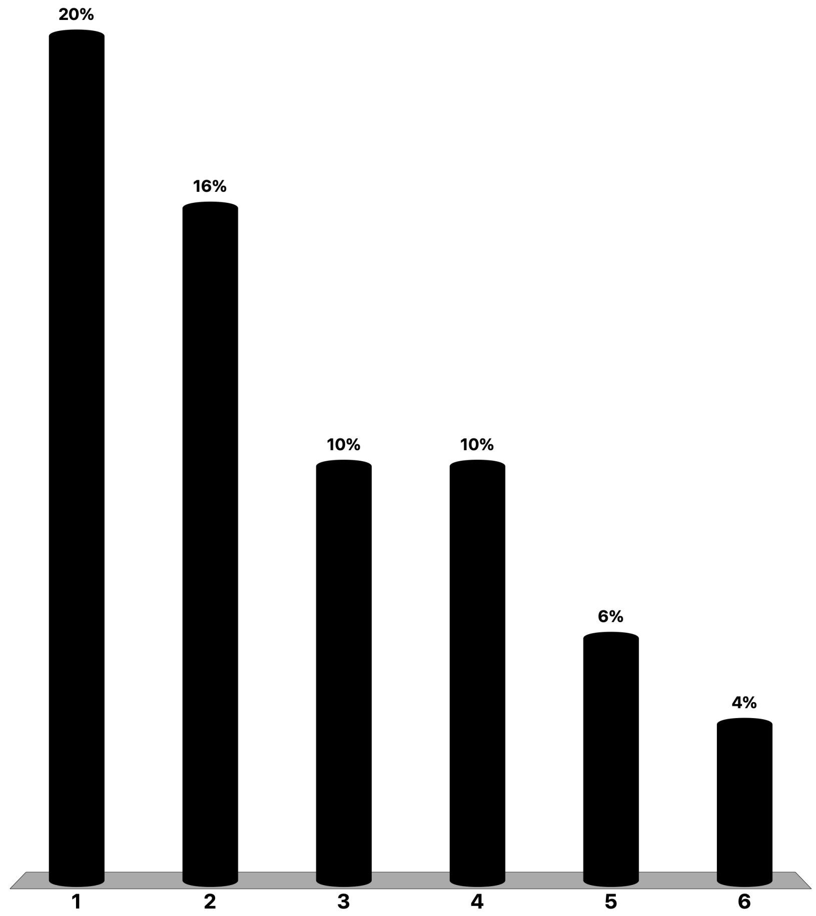

Answer part I

To find the temperature required for a black body to emit **UV radiation** with a wavelength of **260 nm**, we can use **Wien's law**, which relates the temperature of a black body to the wavelength of peak emission:

$$T\lambda_{max} = constant$$

Step 1: Convert the wavelength to meters:

$$\lambda_{max} = 260 \text{ nm} = 260 \times 10^{-9}\ m = 2.60 \times 10^{-7} m$$

Step 2: Rearrange Wien's law to solve for TTT:

$$T = constant/\ \lambda_{max}$$

Substitute the values:

$$T = \frac{2.9 \times 10^{-3}\ m\ K}{2.60 \times 10^{-7} m} = 1.1 \times 10^{4}\ K$$

Final Answer:

The temperature needed for a black body to emit UV radiation at **260 nm** is approximately **11'000 K**.

Answer part II: is that temperature observed on the sun?

Yes, **11’000 K** is a temperature that can be observed in certain regions of the Sun, though it is higher than the surface temperature of the Sun.

The **surface temperature** (or **photosphere**) of the Sun is around **5’500 K**, which emits mainly visible light and some ultraviolet (UV) and infrared radiation.

However, the **corona** (the outermost layer of the Sun’s atmosphere) has temperatures ranging from about **1 million K to 3 million K**. This layer emits **extreme UV radiation** and **X-rays** due to its high temperature, far exceeding the temperature required for UV radiation in the 260 nm range.

Thus, while the **surface** of the Sun is cooler than 11’000 K, the **corona** reaches temperatures well above this, and UV radiation is indeed a significant part of the Sun’s emission spectrum, especially in the **far UV** range.

1B.1 Radiation, quanta, and photons

The ultraviolet catastrophe

The observation in Figure 1.B1 is at odds with classical physics (Rayleigh-Jeans law), which predicts:

- Any hot body should emit intense ultraviolet radiation and even X-rays and γ (gamma) –rays.
- A hot object would devastate the countryside with high-frequency radiation.
- The human body at 37 °C would glow in the dark.

Clearly, a new theory was needed.

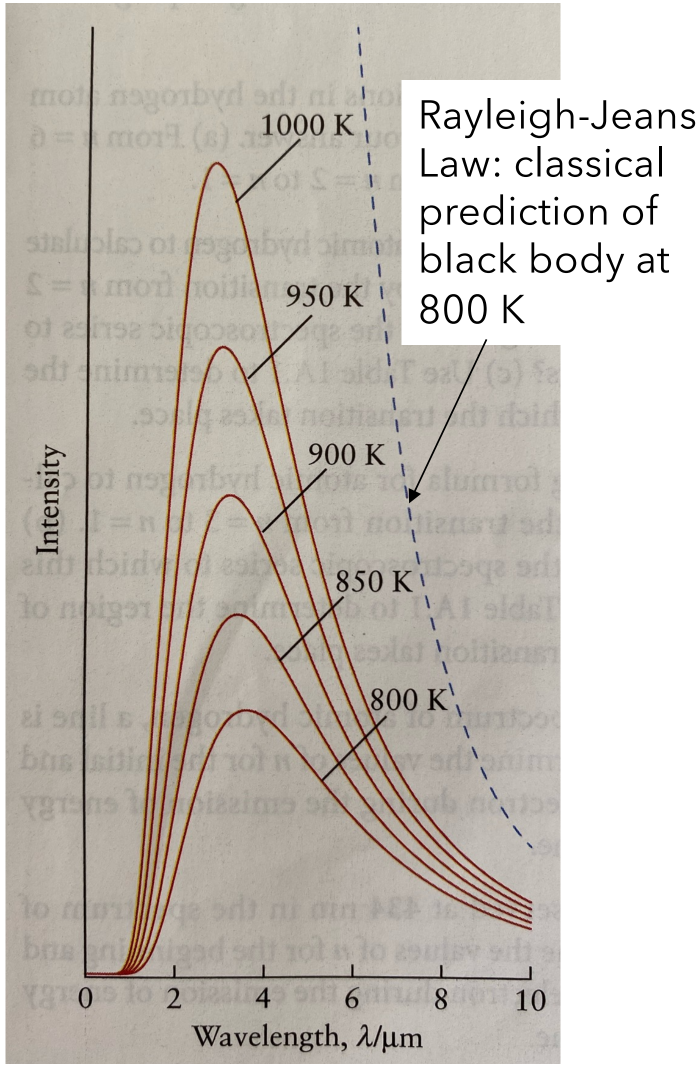

Figure 1.B1

The ultraviolet catastrophe

The answer

Energy is quantized!

1B.1 Radiation, quanta, and photons

Energy is transferred in quanta

- In 1900, Max Planck proposed that energy is exchanged between matter and radiation **in quanta, or packets, of energy**.
- A charged particle oscillating at a frequency ν can exchange energy, E, with its surroundings by generating or absorbing electromagnetic radiation only in discrete packets of energy of magnitude

$$E = h\nu$$

Planck's equation or Planck-Einstein relation

- The constant, h, is called Planck's constant (6.626×10^{-34} J s)
- **Interpretation**: If the oscillating atom releases a packet of energy of magnitude E into the surroundings, the radiation frequency $\nu = E/h$ will be detected.

1B.1 Radiation, quanta, and photons

Why the ultraviolet catastrophe is avoided

- At low temperatures, there is **not enough energy available to stimulate high-frequency oscillations**, so the object cannot generate UV radiation.
- As a result, the intensity curves in Fig. 1B.1 **die away at high frequencies** (short wavelengths).
- Planck's hypothesis also quantitatively matched experimental observations.
- Still, it was a revolutionary, new hypothesis: ***More evidence was needed.***

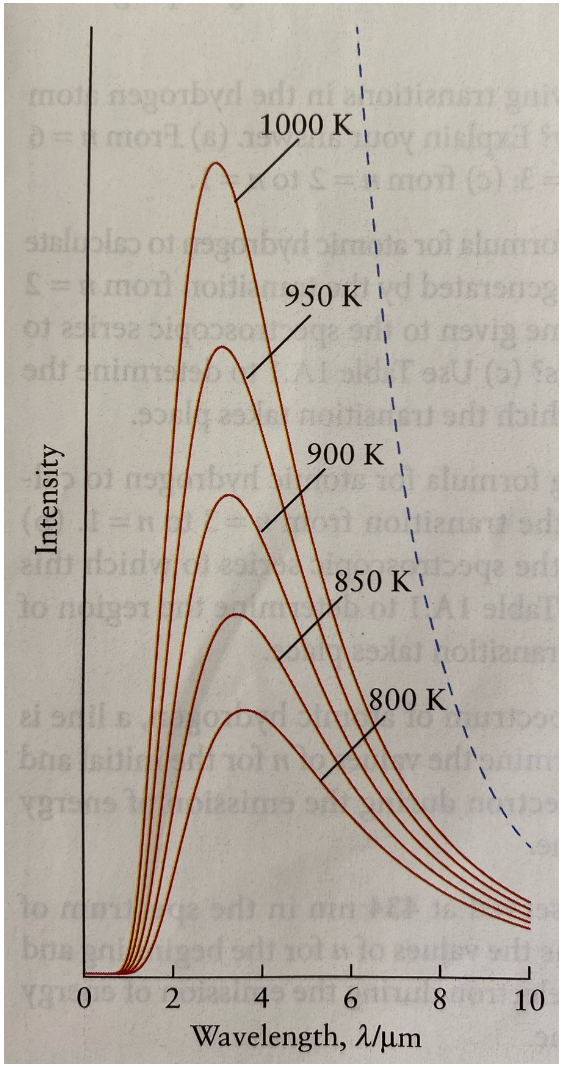

Figure 1.B1

1B.1 Radiation, quanta, and photons

Why is the distinct overlap of transitions useful in black body radiation?

Unlike the **discrete spectral lines** seen in the hydrogen atom (which correspond to specific electron transitions between energy levels), black body radiation has a **continuous spectrum**. This means that instead of emitting light at specific wavelengths, black bodies emit radiation across a wide range of wavelengths. Here's why this is useful:

1. **Emission Over a Continuous Range of Wavelengths:**
    1. *In black body radiation, the emitted light spans a **broad range of wavelengths** from infrared to visible light (and beyond), depending on the temperature. This makes black bodies useful for studying **thermal radiation** over a range of energies rather than just specific energy transitions.*
2. **No Spectral Lines = Simpler to Study Thermal Radiation:**
    1. *Because there are **no distinct spectral lines** (as in the hydrogen atom's emission spectrum), the study of black body radiation focuses on the **overall distribution of energy** across different wavelengths, which is much simpler to model for idealized systems.*
    2. *This continuous distribution is easier to compare to real-world objects like stars or heated metals, which don't exhibit discrete spectral lines as gases do.*

1B.1 Radiation, quanta, and photons

Summary: Why does black body radiation matter?

Understanding black body radiation was crucial in the early 1900s because it led to the development of **quantum theory**. Classical physics couldn't explain why black bodies behaved the way they did (this failure was called the **ultraviolet catastrophe**). It was only when physicist **Max Planck** proposed that energy is **quantized** (comes in discrete packets, or "quanta") that scientists could explain black body radiation correctly. This discovery opened the door to modern quantum mechanics!

What's the point of the black body experiment?

(Multiple correct answers possible!)

A. It showed that **the classical theory of radiation was insufficient** to explain the energy distribution of emitted radiation, particularly in the ultraviolet range.

B. It demonstrated that energy is emitted in **discrete packets (quanta)**, leading to the development of quantum theory.

C. It provided evidence that light behaves **only as a wave** and does not have particle-like properties.

D. It helped resolve the **"ultraviolet catastrophe"** by introducing the idea of quantized energy levels.

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Explanation

A) is **correct** because the black body radiation experiment revealed the **failure of classical physics** (specifically, the Rayleigh-Jeans law) to predict the energy distribution at shorter wavelengths, particularly in the ultraviolet range, leading to the **ultraviolet catastrophe**.

B) is **correct** because **Max Planck's explanation** of black body radiation showed that energy is emitted in **discrete packets (quanta)**, leading to the foundation of **quantum theory**.

C) is **incorrect** because the black body experiment helped demonstrate the **particle-like properties** of energy (quanta), not that light behaves only as a wave. In fact, the quantization of energy was a step toward understanding **wave-particle duality**.

D) is **correct** because Planck's introduction of **quantized energy** successfully explained why classical physics predicted an infinite amount of energy at high frequencies and resolved the **ultraviolet catastrophe**.

1B.1 Radiation, quanta, and photons

The photoelectric effect

- **More evidence** came from photoelectric effect
- Electrons are ejected from metal when exposed to UV radiation.
- What was observed:

1. No electrons are ejected unless the radiation has a **frequency above a certain threshold** value characteristic of the **metal**.
2. Electrons are **ejected immediately**, no matter how low the intensity of the radiation.
3. The **kinetic energy** of the ejected electrons increases linearly with the frequency of the incident radiation.

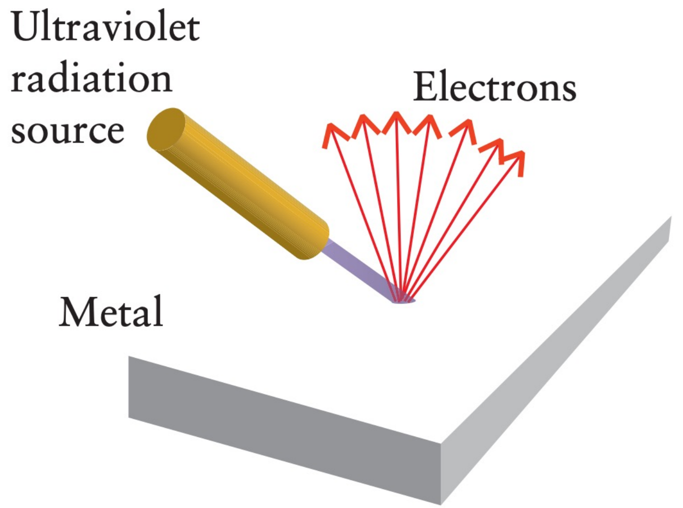


Figure 1.B3

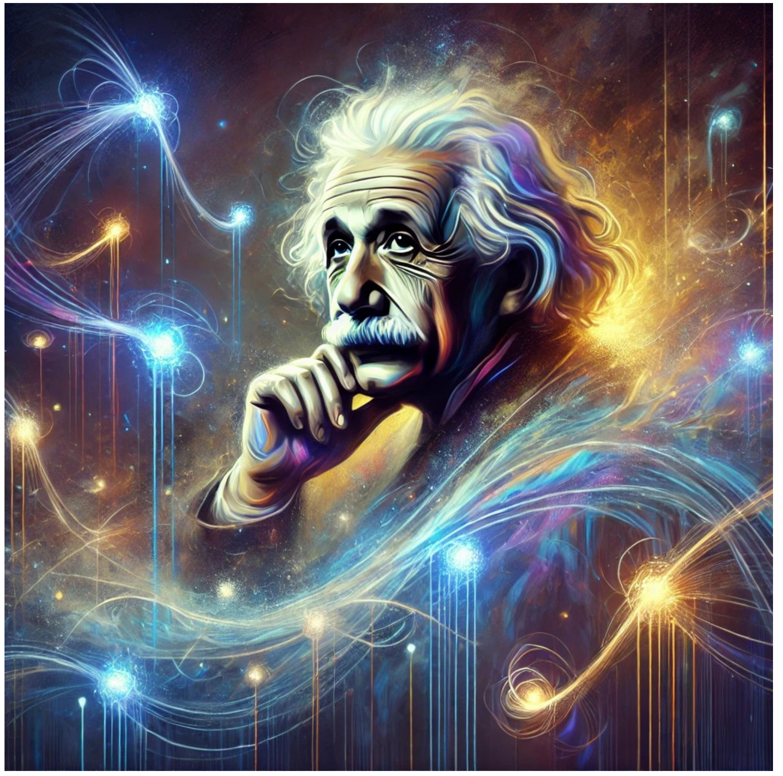
1B.1 Radiation, quanta, and photons

The photon

Albert Einstein explained these observations:

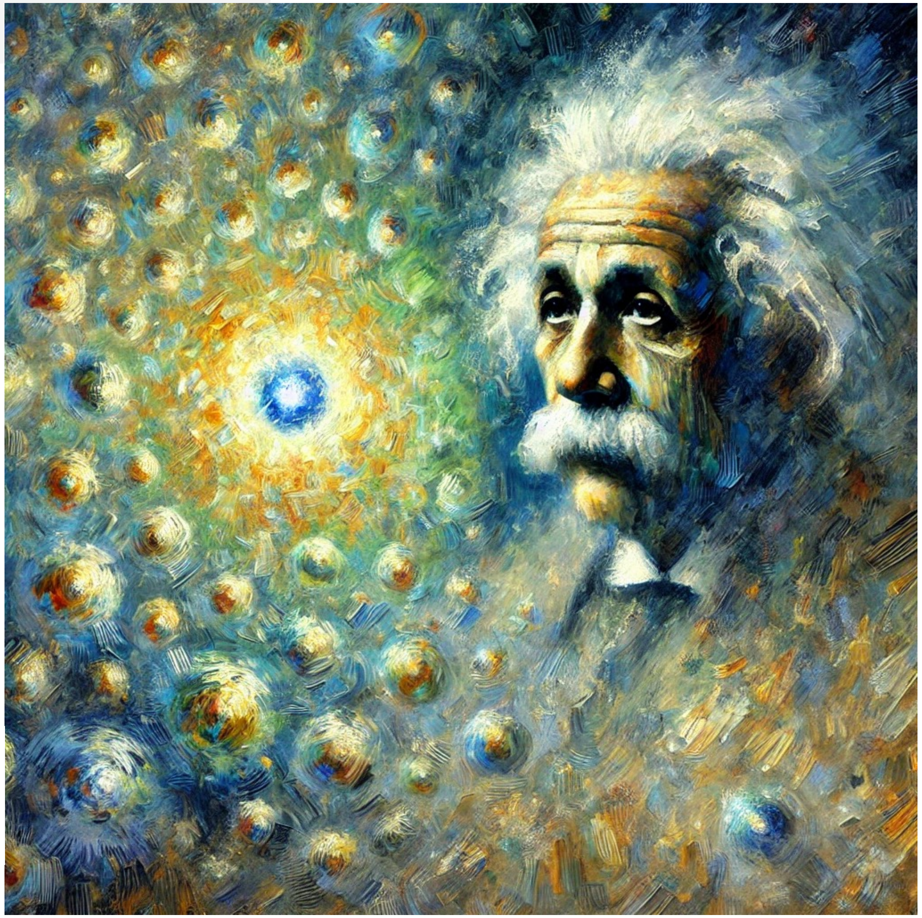
- Proposed that electromagnetic radiation consists of particles, later called **photons**.
- **A photon is a packet of energy**.
- The energy of a single photon is related to the frequency of the radiation by the equation $E = h\nu$.

  E.g. UV photons have more energy than photons of visible light.
- A beam of red light: a stream of photons, each having the same energy.
- A beam of yellow light: a stream of photons, each having the same and higher energy than red light.
- **Important distinction:** the intensity of radiation indicates how many photons are present. The equation $E = h\nu$ determines the energy of each individual photon.



1B.1 Radiation, quanta, and photons

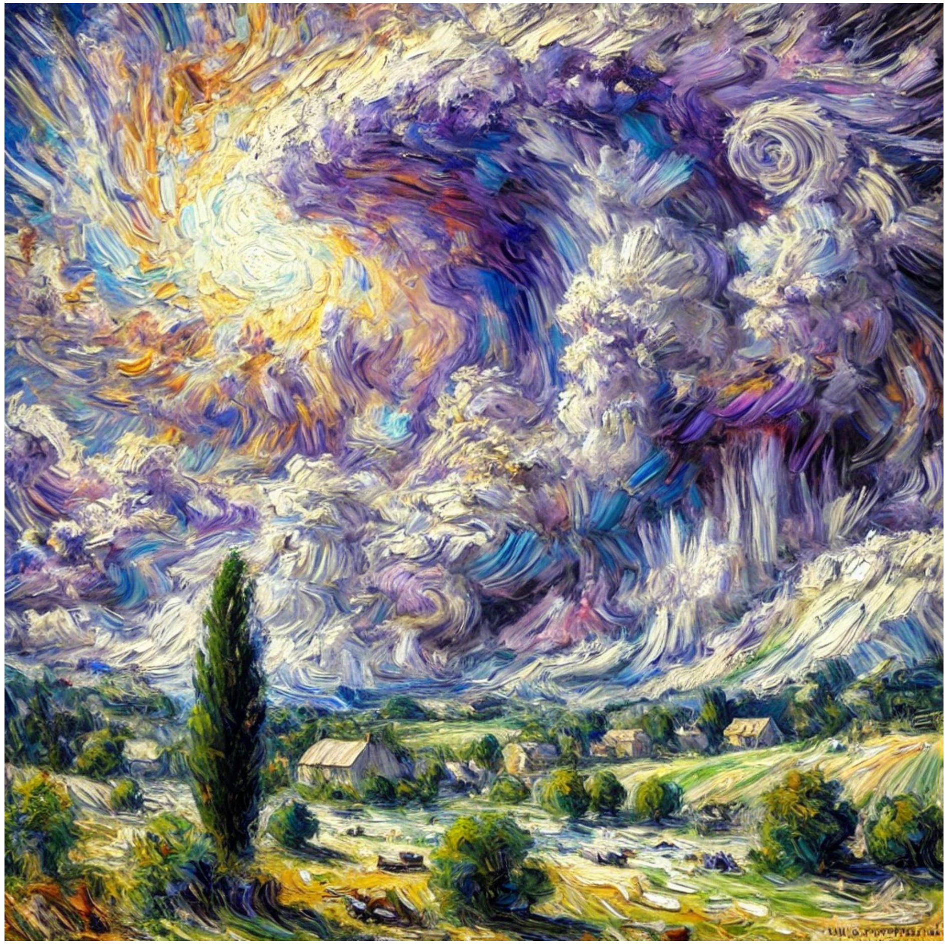
can you make albert einstein and the photon in the style of an artist at the time that he liked



Albert Einstein greatly admired artists like Paul Cézanne and was fond of impressionism and post-impressionism. For this version, I can blend Einstein's connection with photons into a Cézanne-inspired style, featuring bold, expressive brushstrokes and subtle transitions between colors.

1B.1 Radiation, quanta, and photons

could you paint the ultraviolet catastrophe in the style of cezanne



1B.1 Radiation, quanta, and photons

The photon

TABLE 1B.1 Photon Energy*

Radiation type	Energy of photon/(10^{-19} J)	Energy per mole of photons/($kJ \cdot mol^{-1}$)	Energy of photon/eV
X-rays and γ-rays	$\geq 1.0 \times 10^3$	$\geq 6.0 \times 10^4$	$\geq 6.2 \times 10^2$
ultraviolet	5.7	340	3.6
visible light			
violet	4.7	280	2.9
blue	4.2	250	2.6
green	3.8	230	2.4
yellow	3.4	200	2.1
orange	3.2	190	2.0
red	2.8	170	1.8
infrared	2.0	120	1.3
microwaves and radio waves	$\leq 2.0 \times 10^{-3}$	≤ 0.12	$\leq 1.3 \times 10^{-3}$

* Values are to 2 sf.

1B.1 Radiation, quanta, and photons

Example 1B.2: **Calculating the energy of a photon**

What is (a) the energy of a single photon of blue light of frequency 6.4 x 10^{14} Hz; (b) the energy per mole of photons, in joules per mole, of this frequency?

SOLVE

(a) From $E(1\text{ photon}) = h\nu$,

$$E(1\text{ photon}) = (6.626 \times 10^{-34}\text{ J·s}) \times (6.4 \times 10^{14}\text{ Hz}) = 4.2 \times 10^{-19}\text{ J}$$

(b) From $E(\text{per mole of photons}) = N_A E$,

$$E(\text{per mole of photons}) = (6.022 \times 10^{23}\text{ mol}^{-1}) \times (4.2 \times 10^{-19}\text{ J})$$
$$= 2.5 \times 10^{5}\text{ J mol}^{-1}\text{, or }250\text{ kJ mol}^{-1}$$

To derive the energy in part (a), we have used 1 Hz = 1 s^{-1}, so J·s × Hz = J·s × s^{-1} = J.

1B.1 Radiation, quanta, and photons

The work function of a metal

- The energy required to remove an electron from a metal is called the **work function, *Φ*** (uppercase phi).
- Commonly expressed in eV (**electronvolt**), defined as the kinetic energy acquired by an electron when it is accelerated through a potential difference of 1 V.

$$1\ eV = 1.602\ x\ 10^{-19} J$$

- If the energy of a photon is less than the energy required to remove an electron from a metal, then the electron will not be ejected, regardless of the intensity of the radiation.
- If the energy of the photon, $h\nu$, is greater than Φ, then an electron is ejected with a kinetic energy E_k that is equal to the difference between the energy of the incoming photon and the work function:

$$E_k = h\nu - \Phi$$

$$E_k = \frac{1}{2} m_e v^2$$

$$\frac{1}{2} m_e v^2 = h\nu - \Phi$$

1B.1 Radiation, quanta, and photons

Einstein's photoelectric equation

$$\underbrace{\frac{1}{2}m_e v^2}_{\substack{\text{Kinetic}\\\text{energy of}\\\text{ejected}\\\text{electron}}} = \underbrace{h\nu}_{\substack{\text{Energy}\\\text{supplied}\\\text{by}\\\text{photon}}} - \underbrace{\Phi}_{\substack{\text{Energy}\\\text{required}\\\text{to eject}\\\text{photon}}}$$

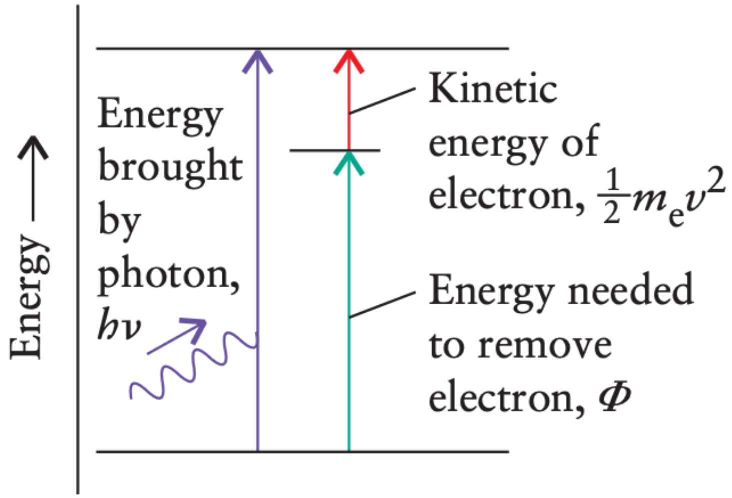
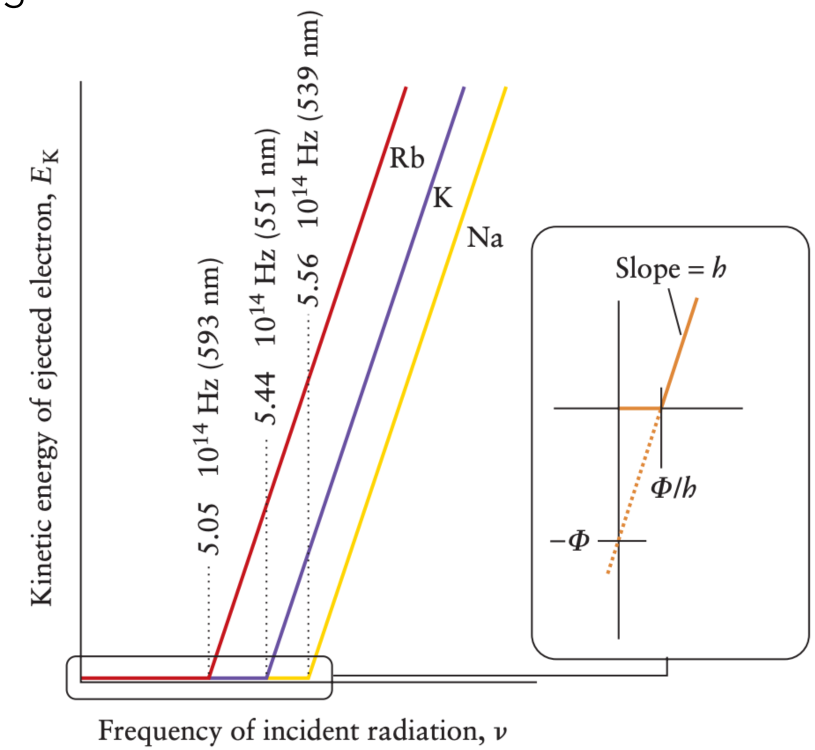


Figure 1.B4

1B.1 Radiation, quanta, and photons

What does this equation tell you?

Figure 1.B5



- Kinetic energy of an ejected electron varies linearly with frequency.
- Plot of kinetic energy vs. frequency:

  - Straight line of slope h, **same** for all metals

  - Extrapolated intercept with the vertical axis at $-\Phi$, **different** for each metal

  - The intercept with the horizontal axis corresponds to the zero kinetic energy of the ejected electron: Φ/h in each case.

1B.1 Radiation, quanta, and photons

Einstein's theory provides the following interpretation

1. An electron can be driven out of the metal only if it is hit by a photon with an **energy at least equal to the work function**, Φ. Therefore, the frequency of the radiation must have a certain minimum value, which necessarily depends on the work function of the metal.
2. If a photon has an energy that is greater than the work function, it can bring about the **immediate ejecton** of an electron.
3. The **kinetic energy** of the electron ejected from the metal increases linearly with the frequency of the incident radiation.

Imagine you are shining light on a metal surface to eject electrons. The metal has a work function of 5 eV. Your light source produces photons of 4 eV. What happens if you shine a very intense beam from Source A (with a large number of photons) on the metal surface?

A. The intense beam will eventually eject electrons because the **total energy of the many photons adds up** to more than 5 eV.

B. No electrons will be ejected because individual photons from Source A do not have enough energy to overcome the work function.

C. The electrons will be ejected, but only **slowly** because the individual photon energy is slightly less than the work function.

D. Electrons will be ejected only if the **total intensity of the light is increased** enough, regardless of the photon energy.

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Example 1B.3: **Analyzing the photoelectric effect**

You are developing a **radiation detector for a spacescraft**.

You use a thin layer of metallic potassium to detect certain ranges of electromagnetic radiation. You need to make some estimates of the physical properties involved. In one test, the speed of an electron emitted from the surface of a sample of potassium by a photon is 668 km s^{-1}.

(a) What is the kinetic energy of the ejected electron?

(b) The work function of potassium is 2.29 eV, corresponding to 3.67×10^{-19} J. What is the wavelength of the radiation that caused the photoejection of the electron?

(c) What is the longest wavelength of electromagnetic radiation that could eject electrons from potassium?

Example 1B.3: **Analyzing the photoelectric effect**

(a) What is the kinetic energy of the ejected electron?

Example 1B.3: **Analyzing the photoelectric effect**

(a) What is the kinetic energy of the ejected electron?

(a) From $E_k = \frac{1}{2}mv^2$,

$$E_k = \frac{1}{2} \times (9.109 \times 10^{-31}\ \text{kg}) \times (6.68 \times 10^5\ \text{m·s}^{-1})^2$$
$$= 2.03 \times 10^{-19}\ \text{J}$$

Example 1B.3: **Analyzing the photoelectric effect**

(b) The work function of potassium is 2.29 eV, corresponding to 3.67×10^{-19} J. What is the wavelength of the radiation that caused the photoejection of the electron?

(b) Convert the work function from electronvolts to joules.

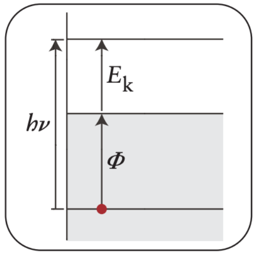
$$2.29\text{ eV} \times \frac{1.602 \times 10^{-19}\text{ J}}{1\text{ eV}} = 3.67 \times 10^{-19}\text{ J}$$

From $\frac{1}{2}m_e v^2 = h\nu - \Phi$, $h\nu = \Phi + \frac{1}{2}m_e v^2 = \Phi + E_k$,

$$h\nu = 3.67 \times 10^{-19}\text{ J} + 2.03 \times 10^{-19}\text{ J} = 5.70 \times 10^{-19}\text{ J}$$

so

$$\nu = \frac{5.70 \times 10^{-19}\text{ J}}{h}$$



Now use $\lambda = c/\nu$:

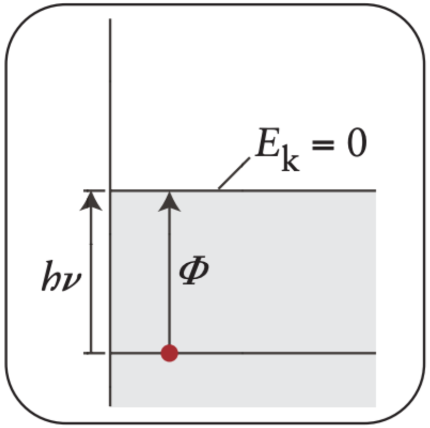
$$\lambda = \frac{(3.00 \times 10^{8}\text{ m}\cdot\text{s}^{-1}) \times (6.626 \times 10^{-34}\text{ J}\cdot\text{s})}{5.70 \times 10^{-19}\text{ J}}$$

$$= 3.49 \times 10^{-7}\text{ m} \quad \text{or} \quad 349\text{ nm}$$

Example 1B.3: **Analyzing the photoelectric effect**

(c) What is the longest wavelength of electromagnetic radiation that could eject electrons from potassium?

(c) To find the longest wavelength of radiation able to eject an electron, set $E_k = 0$ in Eq. 5, so $h\nu = \boldsymbol{\Phi}$, and therefore $\lambda = ch/\boldsymbol{\Phi}$.



$$\lambda = \frac{(3.00 \times 10^{8}\ \text{m·s}^{-1}) \times (6.626 \times 10^{-34}\ \text{J·s})}{3.67 \times 10^{-19}\ \text{J}}$$

$$= 5.42 \times 10^{-7}\ \text{m} \quad \text{or} \quad 542\ \text{nm}$$

1B.1 Radiation, quanta, and photons

Summary

Experimental observations on black-body radiation let to Planck's hypothesis of the quantization of energy. The photoelectric effect provides evidence for the particulate nature of electromagnetic radiation and the existence of photons.

Wave-particle duality

Topic 1B.2

1B.2 Wave-particle duality

The double-slit experiment

- Photoelectric effect → photons behave like particles
- Before: wave-like nature of electromagnetic radiation was well supported.
- Most compelling evidence for wave-like nature: **diffraction**, **the pattern of high and low intensities generated by an object in the path of a ray of light**.

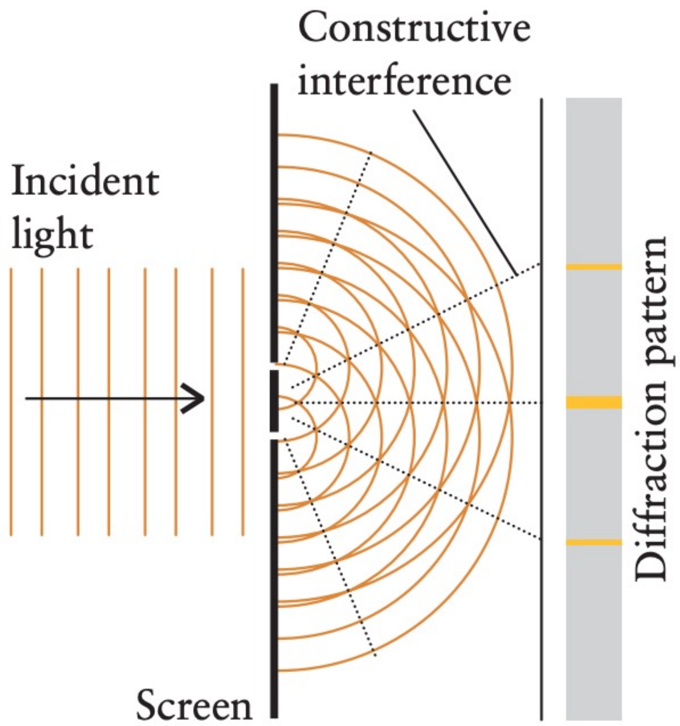


Figure 1.B6

How many bands would you expect to see on the screen if light behaved like particles in this experiment?

Rank	Responses
1	2
2	3
3	0
4	5
5	69
6	106

Values: 2

Value Matches: 26

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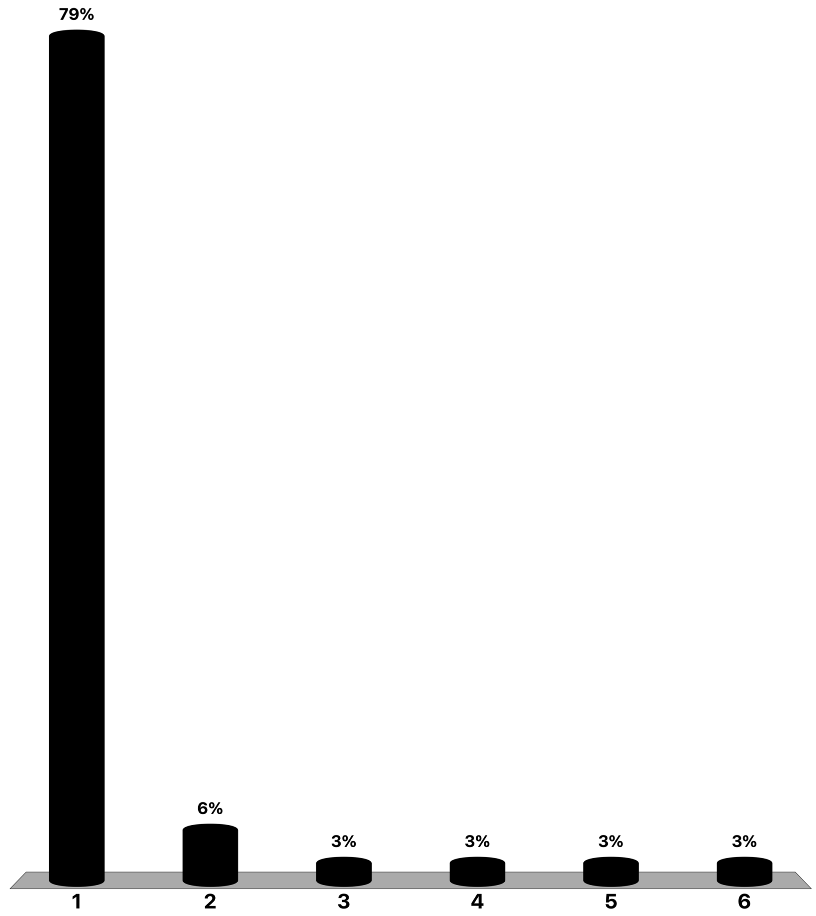

1B.2 Wave-particle duality

The double-slit experiment

- Homework: watch Dr. Quantum (link on Moodle)

Dr. Quantum - Double slit experiment

1B.2 Wave-particle duality

Constructive and destructive interference

(a) **Constructive interference**: if peaks coincide, the amplitude of the wave (its height) is enhanced.

(b) **Destructive interference**: if the peaks of one wave coincide with the valleys of another wave, the amplitude of the wave is diminished.

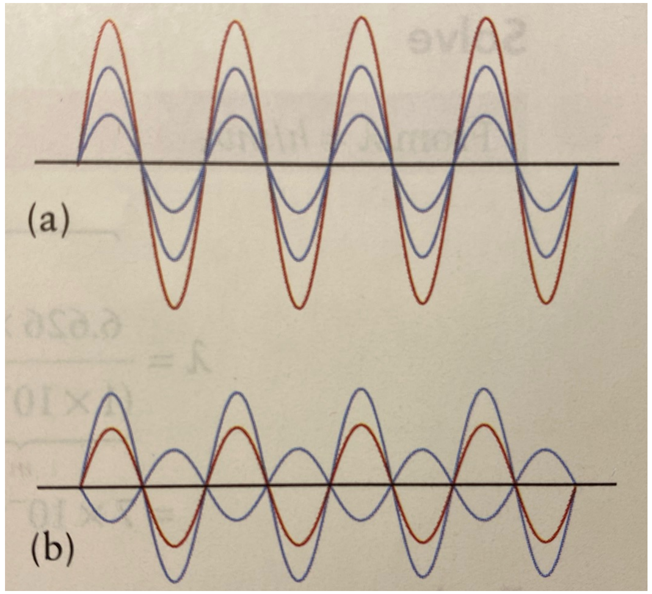

Figure 1.B7

1B.2 Wave-particle duality

Wave or particle?

Photoelectric effect → particle

Diffraction → wave

This conundrum is the heart of modern physics.

Experiments force us to accept the wave-particle duality of electromagnetic radiation, in which the concepts of waves and particles blend together:

- In the wave model, the intensity of the radiation is proportional to the square of the amplitude of the wave.
- In the particle model, intensity is proportional to the number of photons present at each instant

1B.2 Wave-particle duality

Matter has wave-like properties: The de Broglie relation

If electromagnetic radiation, long thought as a wave, has dual character, **could it be that matter,** which has been though as consisting of particles, **also has wave-like properties?**

In 1924, **Louis de Broglie** proposes that all particles should be regarded as having wave-like properties.

He suggested, the wavelength associated with a **«matter wave»** is inversely proportional to the particle's mass, m, and speed, v, and that

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

With $mv = p$, the linear momentum:

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

1B.2 Wave-particle duality

Example 1B.4: **Calculating the wavelength of a particle**

Now suppose you were de Broglie and you had just devised your formula. A friend points out that the world obviously isn't wave-like. Maybe you should check whether your formula has worrying consequences for everyday objects.

Calculate the wavelength of a particle of mass 1 g traveling at 1 m s^{-1}.

1B.2 Wave-particle duality

Example 1B.4: **Calculating the wavelength of a particle**

SOLVE

From $\lambda = h/mv$,

$$\lambda = \frac{6.626 \times 10^{-34}\ \text{J·s}}{(1 \times 10^{-3}\,\text{kg}) \times (1\ \text{m·s}^{-1})} = \frac{6.626 \times 10^{-34}}{1 \times 10^{-3}} \frac{\text{kg·m}^2\text{·s}^{-2}\text{·s}}{\text{kg·m·s}^{-1}}$$

$$= 7 \times 10^{-31}\,\text{m}$$

Evaluate As expected, this wavelength is very—in fact, undetectably—small; the same is true for any macroscopic (visible) object traveling at normal speeds.

1B.2 Wave-particle duality

Summary

Electrons (and matter in general) and radiation have both wave-like and particle-like properties.

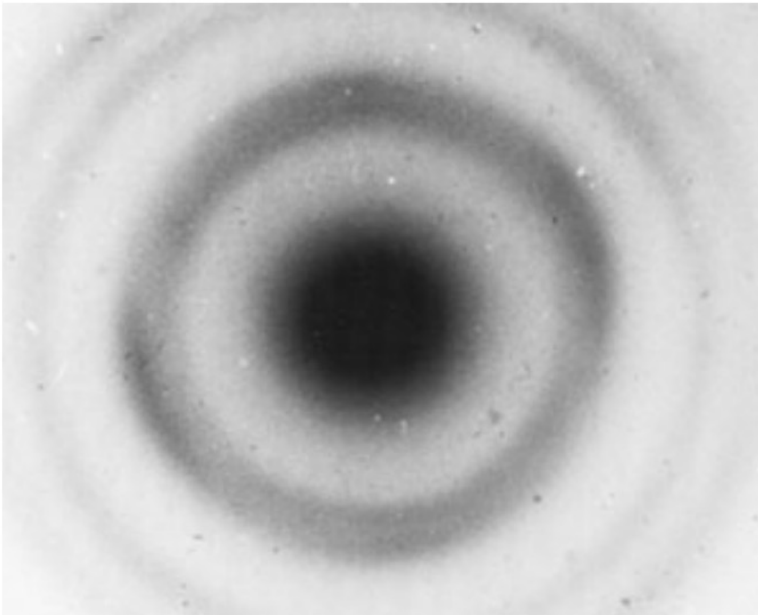

Figure 1.B8

Student quotes

“I LOVE THE THEORY AND THE PRACTICAL PART.”

Quantum mechanics bridges **theory** (such as wave-particle duality and the photoelectric effect) with **practical experiments** that verify the behavior of particles and waves.

“IT'S PRETTY SICK.”

Quantum phenomena like **wave-particle duality** and the **photoelectric effect** are often described as "mind-blowing" or "sick" because they defy classical intuition, introducing surprising, non-deterministic behaviors that fundamentally reshape how we understand light and matter.

The Uncertainty Principle

Topic 1B.3

1B.3 The uncertainty principle

Electrons do NOT have a definite trajectory

- **Classical mechanics**: a particle has a **definite trajectory** or path:
  - Location and linear momentum (speed, direction of movement) are known at each point.
- Electrons have wave-like and particle-like properties.
  - You cannot specify the precise location of a particle if it behaves like a wave.
- Wave-particle duality denies the possibility of specifying the location if the linear momentum is known, and so you cannot specify the trajectory of any particle exactly.
- **The uncertainty is negligible for heavy particles, but for subatomic particles, it can be huge**.

1B.3 The uncertainty principle

The Heisenberg uncertainty principle

- The impossibility of knowing the precise position if the linear momentum is known precisely is an aspect of the **complementarity** of location and momentum – if one property is known, then the other cannot be known simultaneously.
- The Heisenberg uncertainty principle, formulated in 1927 by Werner Heisenberg, expresses this complementarity quantitatively.
- It states that if the location of a particle is known to within an uncertainty Δx, then the linear momentum, p, parallel to the x-axis can be known simultaneously only to within an uncertainty $\Delta \mathrm{p}$, where

$$\Delta \mathrm{p} \times \Delta x \geq \frac{1}{2}\hbar$$

- The symbol $\hbar$, reads «h bar», stands for $\frac{h}{2\pi}$. Its value is 1.054 x 10^{-34} J s.

1B.3 The uncertainty principle

A note of interest

What do we mean by the ”uncertainty” ΔX in a property X?

Formally, it is the «standard deviation» of X, which is defined as $\Delta X = \sqrt{\langle X^2 \rangle - \langle X \rangle^2}$,

where the angle brackets denote mean values.

Example 1B.5: **Using the uncertainty principle**

To what extent does the Heisenberg uncertainty principle affect your ability to specify the properties of objects you can see? Can you be confident about their location? Estimate the minimum uncertainty.

(a) in the position of a marble of mass 1.0 g given that its speed is known to within ±1.0 mm/s and

(b) (b) the speed of an electron confined to an atom within the diameter 200.0 pm.

Example 1B.5: **Using the uncertainty principle**

SOLVE (a) First we convert mass and speed into SI base units. The mass, m, is 1.0×10^{-3} kg, and the uncertainty in the speed, Δv, is $2 \times (1.0 \times 10^{-3}\ \mathrm{m{\cdot}s^{-1}})$. The minimum uncertainty in position, Δx, is then:

From $\Delta p \Delta x = \frac{1}{2}\hbar$ and $\Delta p = m\Delta v$,

$$m\Delta v \Delta x = \frac{\hbar}{2} \quad \text{or} \quad \Delta x = \frac{\hbar}{2m\Delta v}$$

From $\Delta x = \hbar/2m\Delta v$,

$$\Delta x = \frac{1.054\,57 \times 10^{-34}\ \mathrm{J{\cdot}s}}{2 \times \underbrace{(1.0 \times 10^{-3}\ \mathrm{kg})}_{1.0\ \mathrm{g}} \times \underbrace{(2.0 \times 10^{-3}\ \mathrm{m{\cdot}s^{-1}})}_{2.0\ \mathrm{mm{\cdot}s^{-1}}}}$$

$$= \frac{1.054\,57 \times 10^{-34}}{2 \times 1.0 \times 10^{-3} \times 2.0 \times 10^{-3}} \frac{\mathrm{J{\cdot}s}}{\mathrm{kg{\cdot}m{\cdot}s^{-1}}}$$

$$= 2.6 \times 10^{-29} \frac{\mathrm{kg{\cdot}m^2{\cdot}s^{-2}{\cdot}s}}{\mathrm{kg{\cdot}m{\cdot}s^{-1}}} = 2.6 \times 10^{-29}\ \mathrm{m}$$

Evaluate As expected, this uncertainty is very small.

1B.3 The uncertainty principle

Example 1B.5: **Using the uncertainty principle**

(b) The mass of the electron is given inside the back cover; the diameter of the atom is $200. \times 10^{-12}$ m, or 2.00×10^{-10} m. The uncertainty in the speed, Δv, is equal to $\Delta p/m$:

From $\Delta p \Delta x = \frac{1}{2}\hbar$ and $\Delta p = m\Delta v$,

$$\Delta v = \frac{\Delta p}{m} \overset{\Delta p = \hbar/2\Delta x}{=} \frac{\hbar}{2m\Delta x}$$

From $\Delta x = \hbar/2m\Delta v$,

$$\Delta v = \frac{1.054\,57 \times 10^{-34}\ \text{J·s}}{2 \times \underbrace{(9.109\,39 \times 10^{-31}\ \text{kg})}_{m_e} \times \underbrace{(2.00 \times 10^{-10}\ \text{m})}_{200.\ \text{pm}}}$$

$$= \frac{1.054\,57 \times 10^{-34}}{2 \times 9.109\,39 \times 10^{-31} \times 2.0 \times 10^{-10}} \frac{\text{J·s}}{\text{kg·m}}$$

$$= 2.89 \times 10^5 \frac{\overbrace{\text{kg·m}^2\text{·s}^{-2}}^{\text{J}}\text{·s}}{\text{kg·m}} = 2.89 \times 10^5\ \text{m·s}^{-1}$$

Evaluate As predicted, the uncertainty in the speed of the electron is very large, nearly ± 150 km·s^{-1}.

1B.3 The uncertainty principle

Summary

The location and momentum of a particle are complementary; that is, the location and the momentum cannot both be known simultaneously with arbitrary precision. The quantitative relation between the uncertainty of each measurement is described by the Heisenberg uncertainty principle.

Student quotes

“BECAUSE I LOVE BREAKING BAD.”

“I LOVE BREAKING BAD.”

Walter White adopts the alias **"Heisenberg"** in the series. While this is a direct reference to **Werner Heisenberg**, one of the founders of quantum mechanics, it also reflects the **moral and personal uncertainty** in his life. Walter White’s transformation from a mild-mannered chemistry teacher into a ruthless drug kingpin embodies this **uncertainty**—as his actions become more extreme, his moral compass and the predictability of his behavior become less clear.

The skills you have mastered are the ability to

- Use Wien's law to estimate the temperature of a hot source.
- Use the relation $E = h\nu$ to calculate the energy, frequency, or number of photons emitted from a light source.
- Analyze the photoelectric effect in terms of a metal's work function.
- Estimate the wavelength of a particle of known linear momentum.
- Use the uncertainty principle to estimate the uncertainty in the location or speed of a particle.

Summary: You have seen that not all classical concepts are applicable to subatomic particles, and you now know that the concepts of waves and particles blend together. You have learned that one consequence of this blending is that it is impossible to specify the trajectory of a particle with arbitrary precision.

Student questions

What happens to the metal in the photoelectric effect experiment if you remove electrons from it?

Positive Charge: Yes, the metal gains a positive charge as electrons are ejected via the photoelectric effect.

Physical Change: There is generally no direct, significant physical change to the metal under typical experimental conditions.

Chemical Change: There are no direct chemical changes from the photoelectric effect itself, but the ejected electrons and positively charged surface could make the metal more susceptible to oxidation or other chemical reactions, depending on the surrounding environment.

For the Heisenberg uncertainty principle, why is there no uncertainty associated with mass ($\Delta \mathrm{p} = \mathrm{m}\Delta \mathrm{v}$)?

For typical applications of the **Heisenberg uncertainty rinciple**, mass is a **fixed, well-defined property** of the object or particle. For example, the mass of an electron or a marble doesn't fluctuate under normal conditions. Since **mass doesn’t change** in these scenarios, it has **no uncertainty**. Therefore, all the uncertainty in momentum Δp comes from the uncertainty in velocity Δv..

Definition	Example
Absorption occurs when a material takes in energy from incoming light or other electromagnetic radiation. The energy is often converted into other forms, such as heat or used to excite the material's electrons to a higher energy level.	When sunlight hits a black surface, the surface **absorbs** the light, converting it to heat, making the surface warm.
Emission is the process where a material releases energy, often in the form of light or electromagnetic radiation. This happens when electrons in atoms or molecules drop from a higher energy level to a lower one, releasing photons.	A heated metal filament in a light bulb **emits** visible light as electrons lose energy.
Transmission occurs when light or other radiation passes through a material without being absorbed or reflected. The material allows the radiation to move through it.	Light passing through a clear glass window is being **transmitted** through the glass.
Reflection is when light or other radiation bounces off the surface of a material rather than being absorbed or transmitted. The angle of incidence typically equals the angle of reflection.	A mirror **reflects** light, allowing you to see your reflection.

In short:

Absorption: Energy is taken in by a material.
Emission: Energy is released from a material.
Transmission: Light passes through a material.
Reflection: Light bounces off a material.