


**CH-110 Advanced
General Chemistry I**

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1

1



**Reminder: how to
study for this class**

- Solve exercises from the book! In addition to the ones we assign every week.
- Don't spend time reading or studying the slides. Start with exercises, go to slides to look for the appropriate material and formulas

Image source: ChatGPT
Studying in Light

2

2

PERIODIC TABLE OF THE ELEMENTS

Group	1	2											13	14	15	16	17	18
	I IA	II IIA											III IIIA	IV IVA	V VA	VI VIA	VII VIIA	VIII VIIIA
Period	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
	3 Li 6.94 2s ¹	4 Be 9.01 2s ²											5 B 10.81 2s ² 2p ¹	6 C 12.01 2s ² 2p ²	7 N 14.01 2s ² 2p ³	8 O 16.00 2s ² 2p ⁴	9 F 18.99 2s ² 2p ⁵	10 Ne 20.18 2s ² 2p ⁶
	11 Na 22.99 3s ¹	12 Mg 24.31 3s ²	3 IIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIII	9 VIII	10 VIII	11 IB	12 IIB	13 Al 26.98 3s ² 3p ¹	14 Si 28.09 3s ² 3p ²	15 P 30.97 3s ² 3p ³	16 S 32.06 3s ² 3p ⁴	17 Cl 35.45 3s ² 3p ⁵	18 Ar 39.95 3s ² 3p ⁶
	19 K 39.10 4s ¹	20 Ca 40.08 4s ²	21 Sc 44.96 3d ¹ 4s ²	22 Ti 47.87 3d ² 4s ²	23 V 50.94 3d ³ 4s ²	24 Cr 52.00 3d ⁵ 4s ¹	25 Mn 54.94 3d ⁵ 4s ²	26 Fe 55.84 3d ⁶ 4s ²	27 Co 58.93 3d ⁷ 4s ²	28 Ni 58.69 3d ⁸ 4s ²	29 Cu 63.55 3d ¹⁰ 4s ¹	30 Zn 65.41 3d ¹⁰ 4s ²	31 Ga 69.72 4s ² 4p ¹	32 Ge 72.64 4s ² 4p ²	33 As 74.92 4s ² 4p ³	34 Se 78.96 4s ² 4p ⁴	35 Br 79.90 4s ² 4p ⁵	36 Kr 83.80 4s ² 4p ⁶
	37 Rb 85.47 5s ¹	38 Sr 87.62 5s ²	39 Y 88.91 4d ¹ 5s ²	40 Zr 91.22 4d ² 5s ²	41 Nb 92.91 4d ⁴ 5s ¹	42 Mo 95.94 4d ⁵ 5s ¹	43 Tc (98) 4d ⁵ 5s ²	44 Ru 101.07 4d ⁷ 5s ¹	45 Rh 102.90 4d ⁸ 5s ¹	46 Pd 106.42 4d ¹⁰	47 Ag 107.87 4d ¹⁰ 5s ¹	48 Cd 112.41 4d ¹⁰ 5s ²	49 In 114.82 5s ² 5p ¹	50 Sn 118.71 5s ² 5p ²	51 Sb 121.76 5s ² 5p ³	52 Te 127.60 5s ² 5p ⁴	53 I 126.90 5s ² 5p ⁵	54 Xe 131.29 5s ² 5p ⁶
	85 Cs 132.91 6s ¹	86 Ba 137.33 6s ²	87 La 138.91 5d ¹ 6s ²	88 Ce 140.12 4f ¹ 5d ¹ 6s ²	89 Pr 140.91 4f ³ 6s ²	90 Nd 144.24 4f ⁴ 6s ²	91 Pm (145) 4f ⁵ 6s ²	92 Sm 150.36 4f ⁶ 6s ²	93 Eu 151.96 4f ⁷ 6s ²	94 Gd 157.25 4f ⁷ 5d ¹ 6s ²	95 Tb 158.93 4f ⁹ 6s ²	96 Dy 162.50 4f ¹⁰ 6s ²	97 Ho 164.93 4f ¹¹ 6s ²	98 Er 167.26 4f ¹² 6s ²	99 Tm 168.93 4f ¹³ 6s ²	100 Yb 173.04 4f ¹⁴ 6s ²	101 Lu 174.97 4f ¹⁴ 5d ¹ 6s ²	
	87 Fr (223) 7s ¹	88 Ra (226) 7s ²	89 Ac (227) 6d ¹ 7s ²	90 Th 232.04 6d ² 7s ²	91 Pa 231.04 5f ² 6d ¹ 7s ²	92 U 238.03 5f ³ 6d ¹ 7s ²	93 Np (237) 5f ⁴ 6d ¹ 7s ²	94 Pu (244) 5f ⁶ 7s ²	95 Am (243) 5f ⁷ 7s ²	96 Cm (247) 5f ⁷ 6d ¹ 7s ²	97 Bk (247) 5f ⁷ 7s ²	98 Cf (251) 5f ⁷ 7s ²	99 Es (252) 5f ⁷ 7s ²	100 Fm (257) 5f ⁷ 7s ²	101 Md (258) 5f ⁷ 7s ²	102 No (259) 5f ⁷ 7s ²	103 Lr (262) 5f ⁷ 7s ²	

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


Lanthanoids (lanthanides)
6

Actinoids (actinides)
7

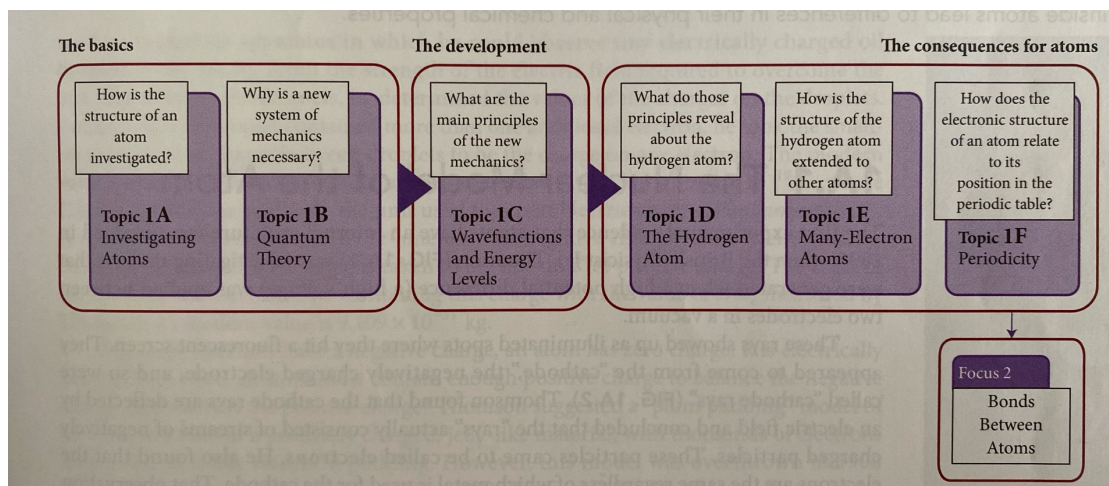
*The names of the elements 112 and higher have not yet been determined; both 112 and 114 have been confirmed.

Quantum Theory

Topic 1B



Overview Chapter 1 (Focus 1: Atoms)



Topic 1B

5

5

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)

Topic 1B

7

7

Radiation, Quanta, and Photons

Topic 1B.1



8

8

1B.1 Radiation, quanta, and photons

Recap last week

- Atomic spectrum of hydrogen:



- Empirical calculated by Ryberg: $\nu = R \left(\frac{1}{n_1^2} - \frac{1}{n_2^2} \right)$, $n_1 = 1, 2, \dots$, $n_2 = n_1 + 1, n_1 + 2, \dots$
- No rainbow, but discrete lines!
- If electrons could have any energy, then they should emit any color.

Topic 1B

9

9

1B.1 Radiation, quanta, and photons

The answer

Electrons in atoms can only occupy discrete energy levels.

Electron energies in atoms are **quantized**.



Image source: ChatGPT
Artsy rendition of electron energy quantization

Topic 1B

10

10

1B.1 Radiation, quanta, and photons

Planck-Einstein equation

Energy is exchanged in discrete packets (*quanta*).

A photon of frequency ν has energy:

$$E = h\nu$$

Important formula.
Need to know how to apply.

Planck's constant: $h = 6.626 \times 10^{-34} \text{ J s}$

Interpretation: Each spectral line in the atomic spectrum of hydrogen corresponds to photons of a specific energy ($h\nu$)

Topic 1B

11

11

1B.1 Radiation, quanta, and photons

The photoelectric effect

- **More evidence for quantization** came from photoelectric effect
- What was observed:
 1. Electrons emitted only if light frequency > threshold (depends on metal).
 2. Emission is immediate (independent of intensity).
 3. Electron kinetic energy ↑ linearly with light frequency.

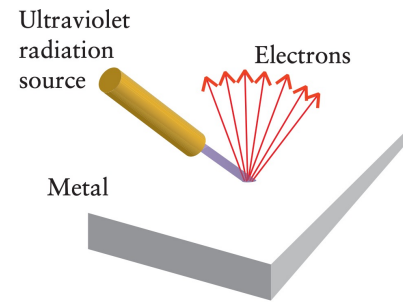


Figure 1.B3

Topic 1B

12

12

1B.1 Radiation, quanta, and photons

The photon (Einstein)

- Light consists of particles (*photons*), each with energy:
- $$E = h\nu$$
- Photon energy ↑ with frequency (UV > visible > IR).
 - Intensity = number of photons, not energy per photon.
 - **A photon is a packet of energy.**

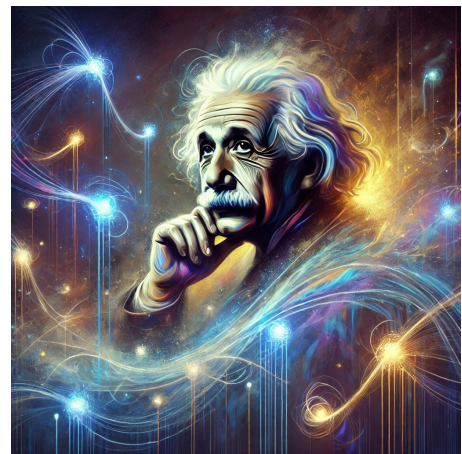


Image source: ChatGPT
Albert and the photon

Topic 1B

13

13

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/($\text{kJ} \cdot \text{mol}^{-1}$)	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.

Topic 1B

14

14

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 6.4×10^{14} Hz;
 (b) the energy per mole of photons, in joules per mole, of this frequency?

Topic 1B

15

15

1B.1 Radiation, quanta, and photons

The work function (Φ) of a metal

- Work function (Φ): minimum energy to eject an electron (in eV).
- Photon must have $h\nu \geq \Phi$.
- If $h\nu > \Phi$:

$$E_{\text{photon}} = h\nu = \Phi + \frac{1}{2}m_e v^2$$

- 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:
- $1 \text{ eV} = 1.602 \times 10^{-19} \text{ J}$

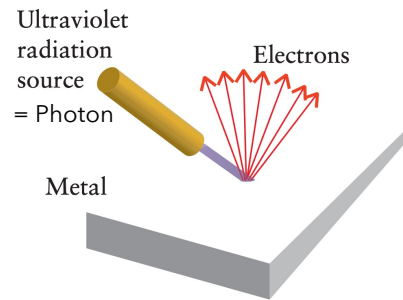


Figure 1.B3

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17

17

1B.1 Radiation, quanta, and photons

Einstein's photoelectric equation

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

Important formula.
Need to know how to apply.

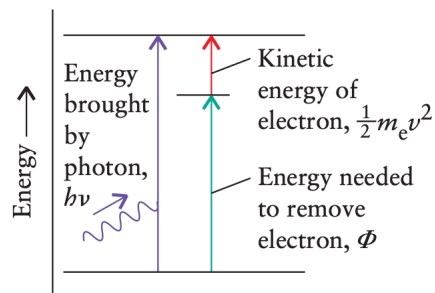


Figure 1.B4

Topic 1B

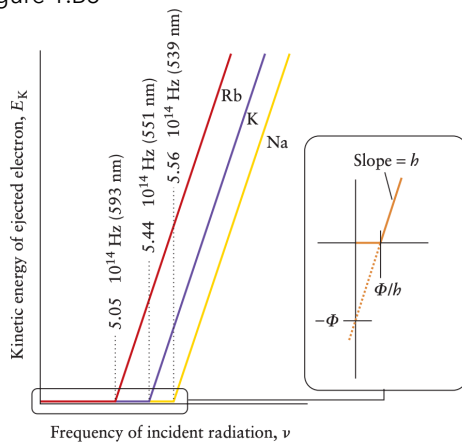
18

18

1B.1 Radiation, quanta, and photons

What does this equation tell you?

Figure 1.B5



- E_k increases linearly with frequency.
- Slope = h (same for all metals).
- x-intercept = threshold frequency $\nu_0 = \Phi/h$.
- y-intercept = $-\Phi$ (metal dependent).

Topic 1B

19

19

1B.1 Radiation, quanta, and photons

Einstein's theory provides the following interpretation

1. Photon must have $h\nu \geq \Phi$ to eject an electron.
2. Extra energy \rightarrow electron kinetic energy: $E_k = h\nu - \Phi$.
3. E_k increases linearly with frequency.

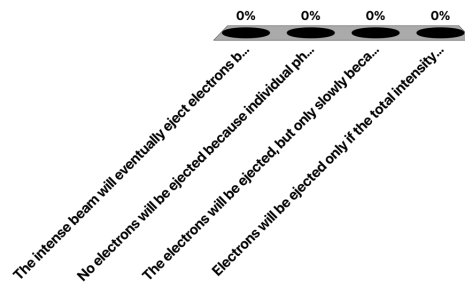
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20

20

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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21

1B.1 Radiation, quanta, and photons

Example 1B.3: Analyzing the photoelectric effect

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

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 $3.67 \times 10^{-19} \text{ J}$. 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?

Topic 1B

22

22

1B.1 Radiation, quanta, and photons

Example 1B.3: Analyzing the photoelectric effect

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

Topic 1B

23

23

1B.1 Radiation, quanta, and photons

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?

Topic 1B

25

25

1B.1 Radiation, quanta, and photons

Example 1B.3: Analyzing the photoelectric effect

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

Topic 1B

27

27

1B.1 Radiation, quanta, and photons

Summary

Planck's postulates the quantization of energy.

The photoelectric effect provides evidence for the particulate nature of electromagnetic radiation and the existence of photons.

Topic 1B

29

29

Wave-particle duality

Topic 1B.2



30

30

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 (Newton, Young, Maxwell)
- 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.**

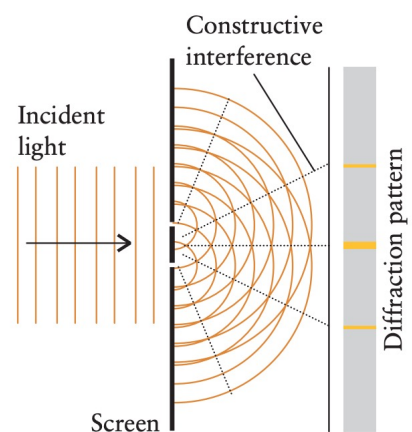


Figure 1.B6

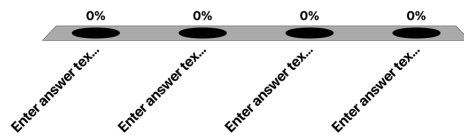
Topic 1B

31

31

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

- A. 0
- B. 2
- C. 3
- D. 5



32

1B.2 Wave-particle duality

The double-slit experiment

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



Dr. Quantum - Double slit experiment

Topic 1B

33

33

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.

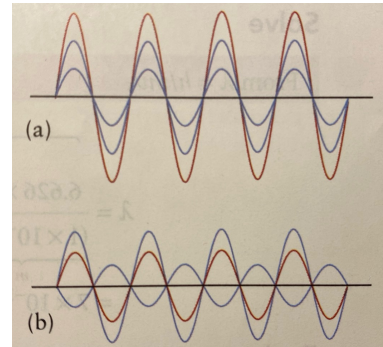


Figure 1.B7

Topic 1B

34

34

1B.2 Wave-particle duality

Wave or particle?

- Photoelectric effect → particle behavior.
- Diffraction → wave behavior.
- Light shows **wave-particle duality**.
- Intensity = wave amplitude² = number of photons.

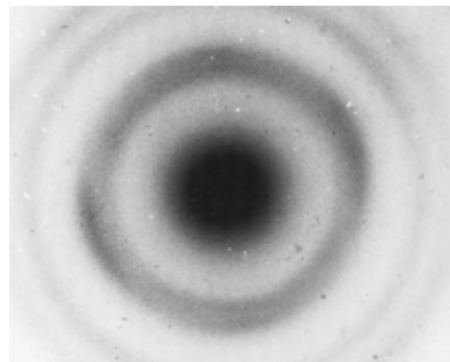


Figure 1.B8: Instead of behaving like little billiard balls, the electrons created a wave-like interference pattern, very similar to light diffraction. The bright and dark rings come from constructive and destructive interference of electron waves scattered by the crystal lattice.

Topic 1B

35

35

1B.2 Wave-particle duality

Matter has wave-like properties: The de Broglie relation

- **If light (wave) can act like particles, matter (particles) can act like waves.**

- Wavelength of a particle:

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

Important formula.
Need to know how to apply.

- The product of mass, m , and speed, v , is called the linear momentum, p , of a particle.
- Small mass / high speed \rightarrow shorter wavelength.

Topic 1B

36

36

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.

Topic 1B

37

37

1B.2 Wave-particle duality

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

Topic 1B

38

38

1B.2 Wave-particle duality

Summary

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

Topic 1B

40

40

The Uncertainty Principle

Topic 1B.3



41

41

1B.3 The uncertainty principle

Electrons do NOT have a definite trajectory

Limits of Classical Trajectories

- Classical particle: position + momentum known \rightarrow definite path.
- Electrons: wave-particle duality means position & momentum cannot both be known exactly.
- For heavy objects, uncertainty negligible; for subatomic particles, it's significant.

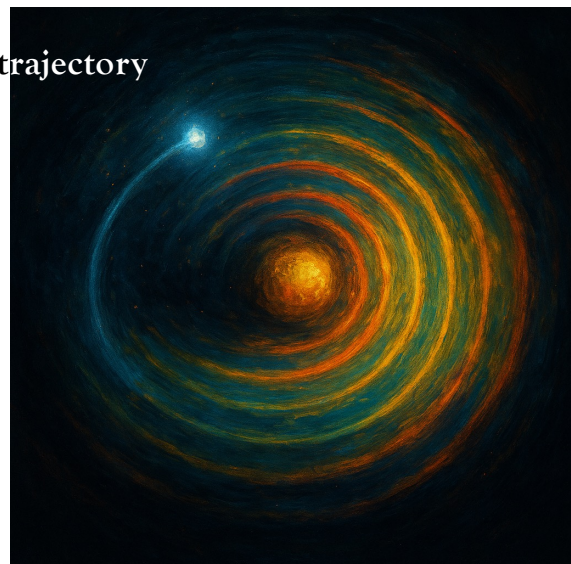


Image source: ChatGPT. Artsy rendition:
From Classical Paths to Quantum Uncertainty 42

Topic 1B

42

1B.3 The uncertainty principle

The Heisenberg uncertainty principle (1927)

- **Position and momentum cannot both be known exactly.**
- If position is known within Δx , momentum is uncertain by Δp :

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

Important formula.
Need to know how to apply.

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

Topic 1B

43

43

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.

Topic 1B

44

44

1B.3 The uncertainty principle

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

Topic 1B

45

45

1B.3 The uncertainty principle

Example 1B.5: Using the uncertainty principle

- (a)

Topic 1B

46

46

1B.3 The uncertainty principle

Example 1B.5: Using the uncertainty principle

(b)

Topic 1B

48

48

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.

Topic 1B

50

50

The skills you have mastered are the ability to

- 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.