Spectra, Energy levels and quantised states of an atom.

- **explain the production of atomic absorption and emission line spectra**
- **interpret spectra and calculate the energy of absorbed or emitted photons:**

  $\Delta E = hf$
- **analyse the absorption of photons by atoms, with reference to:**

  – the change in energy levels of the atom due to electrons changing state

  – the frequency and wavelength of emitted photons: E = hf = $\frac{hc}{\lambda}$

Electron standing waves

- **describe the quantised states of the atom with reference to electrons forming standing waves, and explain this as evidence for the dual nature of matter**

Paper	Multiple choice	Short Answer	Idea	Marks	%	Type
2022		15a	Energy level transitions	1	73%	Calculation
		15b	Emission line	1	72%	Concept
2022 NHT	17		Energy level transitions	1	NA	Calculation
		17	Absorption spectrum	3	NA	Explanation
		19a	$\Delta E = hf$	2	NA	Calculation
		19b	Quantised states of atom	3	NA	Explanation
2021	19		de Broglie wavelength, n	1	64%	Concept
		19a	$\Delta E = \frac{hc}{\lambda}$	2	50%	Calculation
		19b	Energy level transitions	2	31%	Concept
2021 NHT		17a	Emission line	1	NA	Concept
		17b	Energy level transitions	2	NA	Calculation
		17c	Absorption	2	NA	Explanation
2020	17		Energy level transitions	1	73%	Concept
	18		Quantised energy levels	1	68%	Concept
		17a	$\Delta E = \frac{hc}{\lambda}$	1	60%	Concept
		17b	$\Delta E = hf$	2	61%	Calculation
		17c	Energy level transitions	2	34%	Explanation
2019		18a	Energy level transitions	2	62%	Explanation
		18b	Energy level transitions	3	70%	Concept
2019 NHT	19		Absorption spectrum	1	NA	Concept
		15a	Energy level transitions	3	NA	Calculation
		15b	Wave model, energy levels	3	NA	Explanation
2018		19a	Emission spectrum	1	70%	Concept

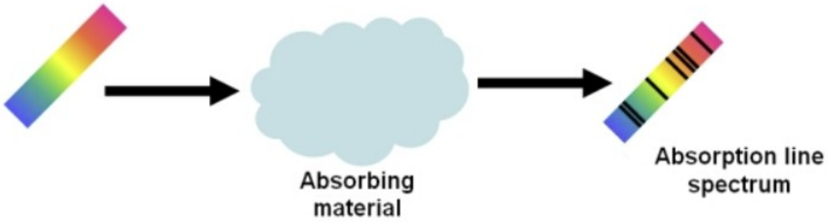
		19b	Emission spectrum	3	27%	Explanation
2018 NHT		12	Energy level transitions	3	NA	Concept
2017	17		Quantised states	1	59%	Concept
		18a	Energy level transitions	1	73%	Concept
		18b	Energy level transitions	2	49%	Calculation
		18c	Quantised states of atom	2	24%	Explanation

Spectra, Energy levels and quantised states of an atom questions can be grouped into the following ideas.

Spectra	
Concepts	Worked example 1
Absorption – Energy level diagram	
Concepts	Worked example 2
Emission - Energy level diagram	
Drawing transmissions	Worked example 4
ΔE calculations	Worked example 5
Quantised states, explanation	Worked example 6
E = $\frac{hc}{\lambda}$, E = hf	Worked example 3
Electron standing waves	
Quantised state of atoms, concept	Worked example 7
Standing wave pattern	Worked example 8

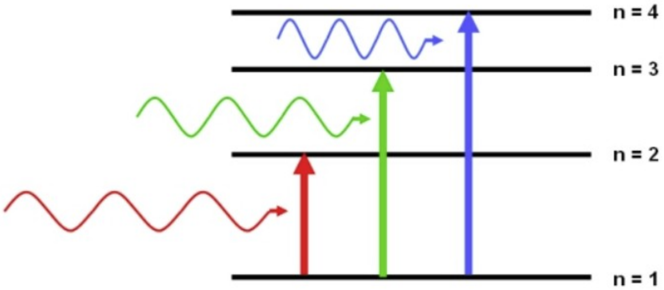
Absorption spectra

An absorption line will appear in a spectrum if an absorbing material is placed between a source and the observer. This material could be a cloud of interstellar gas or a cloud of dust.



Incoming light (left) passes through a cloud of absorbing material, such as a cloud of interstellar gas. The light that leaves the cloud (right) shows absorption lines in the spectrum at discrete frequencies.

According to quantum mechanics, an atom, element or molecule can absorb photons with energies equal to the difference between two energy states.



Photons with specific energies will be absorbed by an atom, ion or molecule if this energy is equal to the difference between the energy levels. In this example, three different photon energies are required to promote an electron from the ground state (n = 1) to an excited state (n = 2, 3 and 4).

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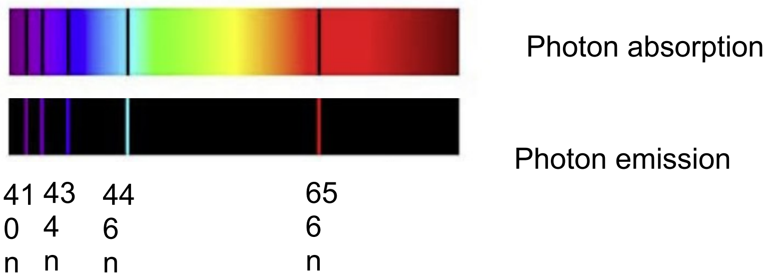
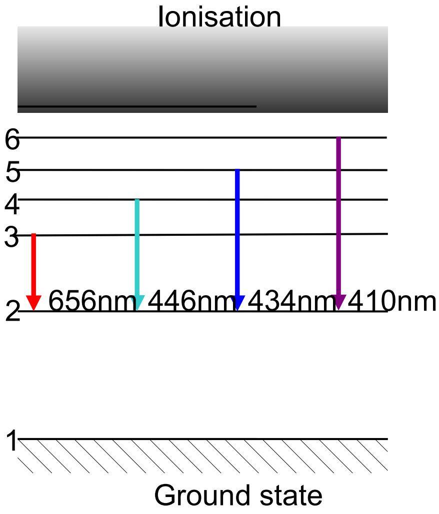
Energy levels in hydrogen

The ionisation energy for hydrogen is 13.6 eV. The ground state energy, level = 0 eV,

Photons can be emitted or absorbed.
Below are the absorption and emission lines for hydrogen (in the visible region).





Quantum physics

Max Planck proposed that energy travels in discrete packets called quanta. Prior to Planck's work, energy was thought to be continuous, but this theory left many phenomena

unexplained. In 1900 Max Planck began to study the range of electromagnetic radiation that emanates from a very hot body (black body radiation). When a body is heated, it first glows red; with further heating it turns to white and eventually blue (ie. the wavelength of light emitted becomes shorter and its frequency becomes higher with increasing temperature).

He found that $E = \frac{hc}{\lambda}$ (c = speed of light) **or** $E = hf$ (f is the frequency of the light).

Quantised energy levels in atoms - the Bohr model

The model for the atom that Rutherford proposed in 1911, that the atom consisted of a small dense, positively charged nucleus surrounded by a cloud of electrons, has a weakness because the accelerating electrons should radiate energy and spiral into the nucleus.

In 1913, Bohr, said that the electrons should not be considered to be orbiting like planets. He said that they simply existed outside the nucleus with certain amounts of energy. According to Bohr, the electrons in the atom existed in certain discrete ENERGY LEVELS.

- Each element has certain allowed energy levels that are unique to that element.
- Electrons can only exist in one of these allowable energy levels, not in between. Ie. energy levels are quantised.
- If an electron is given extra energy it can move up to a higher energy level by absorbing an amount of energy equal to the difference between the energy levels.
- When an electron in a higher energy level returns to its normal (ground state) energy level, it emits the energy in the form of a photon. The energy of the photon ($E = hf$) is equal to the difference in energy levels the electron moves between.

Worked example 1: Spectra: Basic concepts.

A particular atomic system has energy levels as shown in the diagram.

ANSWER KEY

A. 20 eV photon and 1 eV photon emerge

B. 20 eV photon and 1 eV electron emerge

C. 1 eV electron only emerges

D. 1 eV photon only emerges

E. 15 eV photon only emerges

F. 15 eV electron only emerges

G. 21 eV photon only emerges

1972 Question 106, 1 mark

Use the answer key to specify what could emerge from the system when a 15 eV photon interacts with the system in its ground state.

Solution

A 15 eV photon needs to lose all its energy in one collision. This is not possible, so the photon will continue through without any interaction. Therefore the photon will emerge with 15 eV.

$\therefore$ **E (ANS), (76%)**

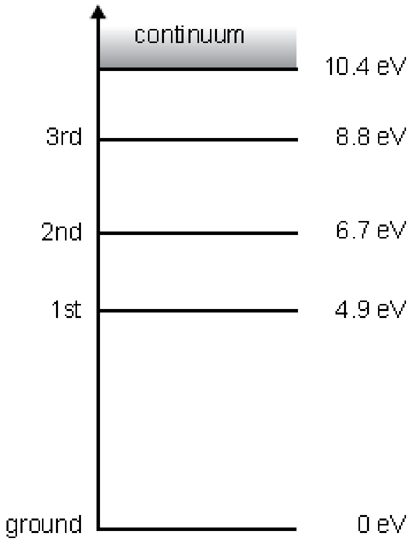
Current study design:

2021 NHT Question 17c

2019 Question 18a (62%)

Worked example 2: Absorption – Energy level diagram: Basic concepts.

The figure shows the energy levels of a mercury atom. The atom is initially in the **2nd** excited state.



2004 Question 6, 2 marks

Which one of the following photon energies could be absorbed by this atom and hence excite it into the **3rd excited** state?

A. 8.8 eV

B. 4.9 eV

C. 2.1 eV

D. 1.8 eV

Solution	**Current study design:**
Difference between 3^{rd} and 2^{nd}.	2022 NHT Question 17
∴ 8.8 – 6.7 = 2.1 eV	2019 NHT Question 19
∴ C (ANS), (65%)	

Worked example 3: Emission – Energy level diagram: . E = $\frac{hc}{\lambda}$, E = hf

The visible spectrum of the hydrogen atom is observed to emit photons of energy 2.6 eV.

2016 Question 21a, 2 marks

Calculate the wavelength of this emission spectral line.

Solution

For a photon, E = $\frac{hc}{\lambda}$

∴ λ = $\frac{4.14 \times 10^{-15} \times 3.0 \times 10^{8}}{2.6}$

∴ λ = 4.78 × 10^{-7}

∴ λ = 478 nm (ANS) (61%)

Current study design:

2022 Question 15a (66%)

2022 NHT Question 19a

2021 Question 19a (50%)

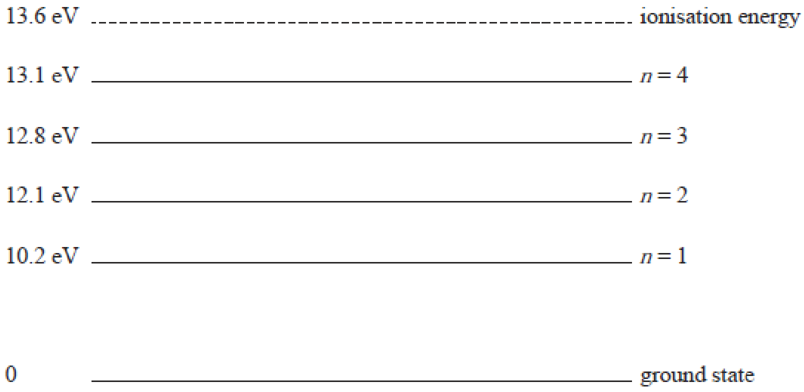
2020 Question 17a (60%)

2019 NHT Question 15a

2017 Question 18b (49%)

Worked example 4: Emission – Energy level diagram: Drawing transmissions.

The energy levels for the hydrogen atom are shown below.

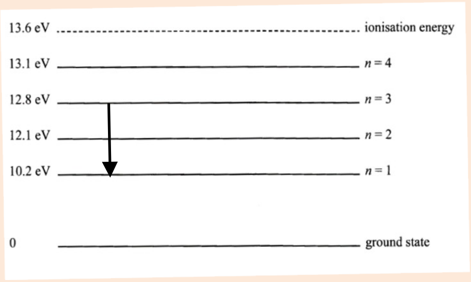


2016 Question 21b, 2 marks

Draw an arrow on the figure above to indicate the transition that could cause the spectral line calculated in **part a.**

Solution

The transition needs to be 2.6 eV. Therefore it goes from 12.8 down to 10.2.



(67%)

Current study design:

2022 Question 15b (72%)

2021 Question 19b (31%)

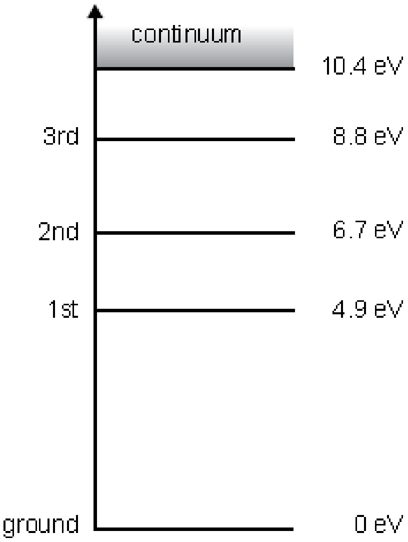
2021 NHT Question 17a

2020 Question 17 (73%)

2017 Question 18a (73%)

Worked example 5: Emission – Energy level diagram: Energy difference calculation.

The figure shows the energy levels of a mercury atom. The atom is initially in the **2nd** excited state.



2004 Question 5, 2 marks

Which **one or more** of the following photon energies can be emitted by a mercury atom which is initially in its **2nd excited** state?

A. 8.8 eV

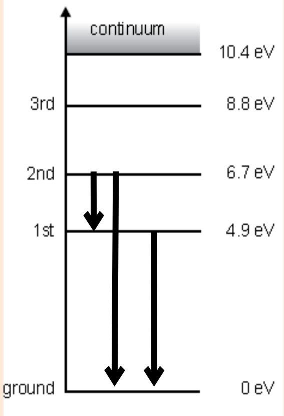
B. 4.9 eV

C. 2.1 eV

D. 1.8 eV

Solution

The transitions marked on the graph are possible.



This gives rise to photons with energies of:
1.8, 6.7 and 4.9 eV.
∴ **B, D (ANS), (65%)**

Current study design:

2022 NHT Question 17

2021 NHT Question 17b

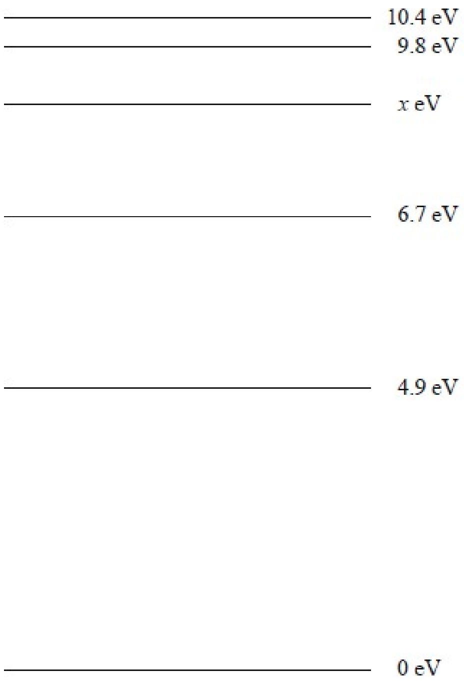
2020 Question 17b (61%)

2019 Question 18b (70%)

2018 NHT Question 12

Worked example 6: Emission – Energy level diagram: Quantised states, explanation.

A simplified diagram of the energy levels for a mercury atom is shown below.



2014 Question 22a, 2 marks

Explain why a mercury atom, while in the first excited state, is able to absorb a 1.8 eV photon, but cannot emit a photon of this energy.

Solution	**Current study design:**
If the atom is in the first excited state it has an energy value of 4.9 eV. It can absorb a 1.8 eV photon as this will raise it to the 6.7 eV energy level. If the atom was in its first excited state, at 4.9 eV, the only photon that it can emit will be one of 4.9 eV. There is no energy level 1.8 eV lower than the first excited state. **Therefore it can absorb a 1.8 eV photon, but not emit one. (40%)**	**2022 NHT Question 19b** **2020 Question 17c (34%)** **2018 Question 19b (27%)** **2017 Question 18c (24%)**

Worked example 7: Electron standing waves: Quantised state of atoms, concept.

2017 NHT Question 21, 4 marks

De Broglie suggested that the quantised energy states of atoms could be explained in terms of electrons forming standing waves.

Describe how the concept of standing waves can help explain the quantised energy states of an atom. You should include a diagram.

Solution

De Bröglie suggested that electrons have wave properties such as wavelength, and that the orbits (energy levels) that could exist were those where the wavelength of the electron set up a stable standing wave. This is consistent with the quantisation of energy levels, because standing waves have quantised wavelengths.

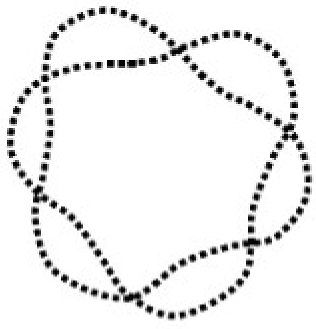
De Bröglie said that, in a similar way, the wavelength of the electrons orbiting the nucleus must 'fit' into the circumference of the orbit exactly. This will only happen with particular wavelengths and, therefore, energies and explains why energy levels are quantised.

Electrons with wavelengths that do not set up standing waves destructively interfere with themselves and cancel out.

The standing wave is formed when the circumference of the orbit is a whole number of wavelengths, from $2\pi r = n\lambda$

The energy of the electron is linked to the wavelength, $\lambda = \frac{h}{\sqrt{2mKE}}$, so if only certain wavelengths exist, then only certain energies values are permissible.

Representation of the n = 3 level.



Current study design:

2020 Question 18 (68%)

2019 NHT Question 15b

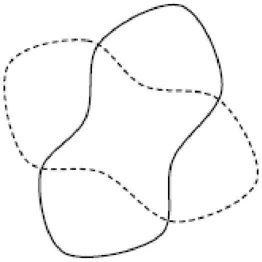
2017 Question 17 (59%)

Worked example 8: Electron standing waves: Quantised state of atoms, Wave pattern.

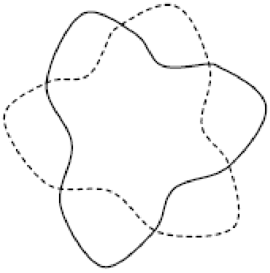
2004 Question 11, 2 marks

Which one of the following best represents the 'standing wave' state of an electron in a hydrogen atom where the circumference is equal to four wavelengths?

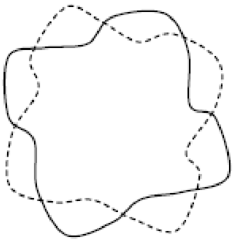
A.



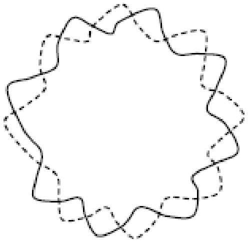
B.



C.



D.



Solution

The 'standing wave' will have four complete wavelengths. This corresponds to 8 nodes (intersections).

∴ C (ANS), (85%)

Current study design:

2021 Question 19 (64%)