EXAMPLE GRAMMAR SCHOOL

ESAT Mock: Worked Solutions

Chemistry

Paper SMP-2026-09 · Version 1.5

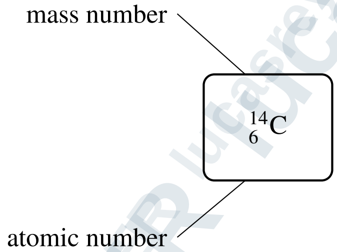
Staff copy

This document contains the answers. Keep it away from candidates until the paper has been sat. Marking guidance is in the separate mark scheme.

Question 1

C1.3 · Know and be able to use the terms atomic number and mass number, together with standard notation (e.g. C 12 6), and so be able to calculate the number of protons, neutrons and electrons in any atom o · ★★☆☆☆ · 45 s

An atom of a carbon isotope is represented by the standard notation shown. How many neutrons does it contain?



A. 9
B. 7
C. 20
D. 14
E. 8
F. 6

Answer E. Key idea

Standard notation $^{A}_{Z}X$: Z (lower) is the atomic/proton number, which defines the element and equals the electron count in a neutral atom, while A (upper) is the mass number, protons plus neutrons, so neutrons $= A - Z$. For carbon-14 ($^{14}_{6}$C): 6 protons, $14 - 6 = 8$ neutrons and 6 electrons.

Worked solution

Standard notation $^{A}_{Z}X$:

- Z (lower) = ATOMIC/proton number = number of protons (defines the element; = electrons if neutral).
- A (upper) = MASS number = protons + neutrons.
- Neutrons = A − Z.

For carbon-14 ($^{14}_{6}$C): 6 protons, 8 neutrons, 6 electrons (neutral).

Matches Option **E**.

Why the other options are wrong

- **A** (9): Off by one. *(Arithmetic Error)*
- **B** (7): Assumed a nucleus holds equal numbers of protons and neutrons and halved the mass number: 14 / 2 = 7. That works for carbon-12, not for this isotope; neutrons = A - Z = 14 - 6 = 8. *(Conceptual Error)*
- **C** (20): Added them; subtract instead. *(Arithmetic Error)*
- **D** (14): That's the mass number. *(Conceptual Error)*
- **F** (6): That's the proton number. *(Conceptual Error)*

Common mistake. Swapping A and Z in the notation.

Takeaway. **The Cheat Code:** 'A on top adds, Z at the bottom identifies': A = p + n, Z = identity. Neutrons = A − Z. Always.

Time-saving tip. A adds (p+n); Z identifies.

Question 2

C11.1 · Energetics · ★★☆☆☆ · 90 s

A student sets three changes going in identical open glass beakers on a bench in a laboratory held at 19 °C. In the first, magnesium ribbon is dropped into dilute hydrochloric acid and the thermometer climbs to 34 °C. In the second, citric acid solution is stirred into sodium hydrogencarbonate and the thermometer falls to 12 °C. In the third, two solids are ground together with a rod; no thermometer is used, but within a minute a film of ice forms on the outside of that beaker from moisture in the room air. Which statement about the three enthalpy changes is correct?

A. All three have a negative ΔH.
B. The first and second have a negative ΔH; the third is positive.
C. The first has a positive ΔH; the second and third are negative.
D. The first has a negative ΔH; the second and third are positive.
E. All three have a positive ΔH.
F. The first and third have a negative ΔH; the second is positive.

Answer D. Key idea

The sign of an enthalpy change records the direction energy travelled, not how large the change was. A reaction that pushes energy out into its surroundings leaves the chemicals lower in energy than they started, so ΔH is negative and the surroundings warm. A reaction that pulls energy in from its surroundings leaves the chemicals higher in energy, so ΔH is positive and the surroundings cool. A thermometer is only one way of seeing which way the energy went; anything showing the mixture has dropped below room temperature is the same evidence.

Worked solution

1. The first beaker

The thermometer climbs from the room's 19 °C to 34 °C. Energy has been pushed out of the reacting chemicals into the solution, the glass and the air, which is what exothermic means. The chemicals themselves end lower in energy than they began, so ΔH is negative.

2. The second beaker

Here the thermometer falls from 19 °C to 12 °C. Energy has been drawn out of the surroundings and into the reacting chemicals, so the change is endothermic and ΔH is positive.

3. The third beaker

There is no reading, but ice forms on the outside of the glass. Water vapour from the room can only freeze there if the outside of that beaker has been pulled below 0 °C, far below the room's 19 °C. Energy is therefore flowing from the room into the beaker, exactly as in the second one, so this change is endothermic too and ΔH is positive.

Sanity check: one beaker ended warmer than the room and two ended colder, so one ΔH is negative and two are positive, and every beaker has been classified from the direction energy crossed its wall rather than from what was put in it.

Matches Option **D**.

Why the other options are wrong

- **A** (All three have a negative ΔH.): Assumes any change that runs on its own must be giving energy out, so all three are called negative. The second beaker's thermometer drops seven degrees, which cannot happen while the chemicals in it are warming their surroundings. *(All changes assumed exothermic)*
- **B** (The first and second have a negative ΔH; the third is positive.): Classifies the second beaker from what is in it rather than from the thermometer: an acid meeting a hydrogencarbonate is read as a neutralisation, and neutralisation is remembered as exothermic, so its ΔH is called negative. The reading is the evidence and it falls from 19 °C to 12 °C, which is energy drawn into the chemicals and a positive ΔH. The third beaker, with no reaction to recognise, is then read correctly from its frost, so the same candidate treats two beakers that both cool the room in opposite ways. *(Reaction type recalled in place of the reading)*
- **C** (The first has a positive ΔH; the second and third are negative.): Applies the convention the wrong way round throughout, calling the beaker that warmed positive and the two that cooled negative. The sign belongs to the chemicals, whose energy falls when they heat their surroundings. *(Sign convention inverted)*
- **E** (All three have a positive ΔH.): Treats every temperature change as a positive ΔH, reading the size of the change rather than its direction. The first beaker finished 15 °C above the room, which is energy leaving the chemicals, and that carries a negative sign. *(Direction of energy flow ignored)*
- **F** (The first and third have a negative ΔH; the second is positive.): Correct on the two beakers with thermometers, but credits the freezing of the condensed water to the mixture inside the third. The ice forms because that beaker is colder than the room, which is the signature of energy going in, not out. *(Frost misread as energy released)*

Common mistake. Reading the ice on the third beaker as evidence that energy was given out, on the grounds that freezing releases energy. Freezing does release energy, but the water that froze belongs to the room: it gave energy up because the mixture inside was taking energy from it.

Takeaway. The Cheat Code: Ask which way energy crossed the glass. Out of the chemicals means the surroundings warm and ΔH is negative; into the chemicals means the surroundings cool, frost included, and ΔH is positive.

Time-saving tip. Speed Heuristic: Sort the beakers by whether each ended warmer or colder than the 19 °C room, ignoring what is in them. One warmer and two colder means one negative and two positive, and only one option carries that split.

Question 3

C4.1 · Quantitative chemistry · ★★☆☆☆ · 85 s

A fertiliser is sold as pure ammonium sulfate, $(NH_4)_2SO_4$. Using A_r values $H = 1$, $N = 14$, $O = 16$, $S = 32$, calculate its relative formula mass.

- **A.** 132
- **B.** 118
- **C.** 96
- **D.** 130
- **E.** 128
- **F.** 228
- **G.** 84
- **H.** 114

Answer A. Key idea

A relative formula mass is the sum of the relative atomic masses of every atom in the formula, each counted as often as it appears. A subscript written outside a bracket multiplies the whole group inside it, every element and every subscript within, so the safe route is to evaluate each bracketed group once as a block, multiply that block by its subscript, and only then add the remaining atoms. Relative masses have no units, being ratios against carbon-12.

Worked solution

1. Price the ammonium block and apply the bracket

One ammonium group is one nitrogen and four hydrogens:

$$M_r(NH_4) = 14 + (4 \times 1) = 18$$

The subscript 2 outside the bracket multiplies everything inside it, the nitrogen and all four hydrogens alike, so the two ammonium groups contribute

$$2 \times 18 = 36$$

2. Price the sulfate block and add

$$M_r(SO_4) = 32 + (4 \times 16) = 32 + 64 = 96$$

$$M_r((NH_4)_2SO_4) = 36 + 96 = 132$$

Cross-check atom by atom rather than by block: 2 nitrogen = 28, 8 hydrogen = 8, 1 sulfur = 32, 4 oxygen = 64, and 28 + 8 + 32 + 64 = 132. The two routes agree, which confirms the bracket was expanded correctly.

Sanity check: the salt must weigh more than the sulfate part alone, 96, and the extra can only be the two light ammonium groups, worth 36 between them. A value below 100 would mean part of the formula had been lost, and a value near 200 would mean something had been double counted.

Matches Option **A**.

Why the other options are wrong

- **B** (118): Applied the outside subscript to the hydrogens and not to the nitrogen, doubling four hydrogens to eight but leaving one nitrogen, so $(NH_4)_2$ was priced as $14 + 8 = 22$ and then $22 + 96 = 118$. The subscript multiplies every atom inside the bracket, giving two nitrogens as well as eight hydrogens, so the block is worth 36. *(Bracket applied to hydrogen only)*
- **C** (96): Quoted the sulfate part alone, $32 + 64 = 96$, leaving out both ammonium groups. Those two groups add a further 36 to the formula mass. *(Cation omitted)*
- **D** (130): Priced the cation as ammonia rather than ammonium, $NH_3 = 14 + 3 = 17$, so the two groups came to $2 \times 17 = 34$ and the total to $34 + 96 = 130$. The group in this salt is NH_4, worth $14 + 4 = 18$, so the pair is worth 36. *(Ammonia used in place of ammonium)*
- **E** (128): Applied the subscript to the nitrogen only and left the hydrogens single, pricing $(NH_4)_2$ as $N_2H_4 = 28 + 4 = 32$, then $32 + 96 = 128$. The 2 outside the bracket multiplies the four hydrogens as well. *(Bracket partially expanded)*
- **F** (228): Read the subscript 2 as multiplying the entire formula instead of the bracketed group alone, so one unit was priced at $18 + 96 = 114$ and then doubled: $2 \times 114 = 228$. Only the ammonium group stands inside the bracket; the sulfate is outside it and is counted once. *(Bracket subscript applied to the whole formula)*
- **G** (84): Dropped the subscript on oxygen and priced the anion as SO: $36 + 32 + 16 = 84$. Sulfate carries four oxygens, worth 64, not one. *(Subscript on oxygen ignored)*
- **H** (114): Left the outside subscript unused and counted a single ammonium group: $18 + 96 = 114$. The bracket subscript doubles the whole group, so 36 is needed, not 18. *(Bracket subscript not applied)*

Common mistake. Multiplying only the first atom inside the bracket by the subscript, so $(NH_4)_2$ is treated as N_2H_4 and priced at 32 instead of 36. The subscript outside a bracket applies to every atom within it, giving two nitrogens and eight hydrogens.

Takeaway. The Cheat Code: work in blocks. Find the M_r of each bracketed group first, multiply that whole block by its subscript, then add the rest. A bracket is never distributed to one atom and not the others.

Time-saving tip. Speed Heuristic: memorise the common ions as single numbers and reuse them. Ammonium is 18 and sulfate is 96, so this salt is $96 + 2 \times 18 = 132$ in one line, and those two block values reappear in every ammonium and every sulfate question on the paper.

Question 4

C2.4 · The Periodic Table · ★★☆☆☆ · 85 s

Element Q lies in the same Period as chlorine and two Groups to the left of it. A chlorine atom has the electron configuration 2, 8, 7. Which configuration belongs to an atom of Q?

A. 2, 8, 8
B. 2, 5
C. 2, 8, 2
D. 2, 8, 3
E. 2, 8, 4
F. 2, 8, 6
G. 2, 8, 5
H. 2, 8, 8, 1

Answer G. Key idea

Position in the Periodic Table and electron configuration carry the same information twice over. The number of electrons in the outermost shell is the Group number and the number of occupied shells is the Period, so a move across a Period changes only the last figure of the configuration.

Worked solution

1. Read chlorine's position out of its configuration

The last number is the outer shell. Chlorine has 7 electrons there, so it sits in Group 7. The count of numbers is the number of occupied shells: 2, then 8, then 7 is three shells, so chlorine sits in Period 3.

2. Move two Groups to the left and rebuild the configuration

Q is in the same Period, so it still has three occupied shells, and the two inner ones stay full at 2 and 8. Two Groups to the left of Group 7 is Group $7 - 2 = 5$, so Q has 5 electrons in its outer shell.

Putting the three shells together:

$$2, 8, 5$$

Check: $2 + 8 + 5 = 15$ electrons, so Q has atomic number 15. That is phosphorus, which does sit in Period 3 two columns to the left of chlorine, with sulfur between the two, and its five outer electrons read straight back as Group 5.

Matches Option **G**.

Why the other options are wrong

- **A** (2, 8, 8): Gave the configuration Q reaches once it has reacted rather than the configuration of the atom. A Group 5 atom gains three electrons to fill its outer shell, $5 + 3 = 8$, so Q^{3-} is 2, 8, 8, the same arrangement as argon. The stem asks for an atom of Q, which keeps its own 15 electrons and so is 2, 8, 5. *(Ion given instead of the atom)*
- **B** (2, 5): Counts chlorine's Period as 2 by counting only its full shells, the 2 and the 8, then puts Q's five outer electrons in a second shell. Three shells are occupied in 2, 8, 7, so Q keeps three: 2, 8, 5. *(Period read from the full shells only)*
- **C** (2, 8, 2): Takes the words 'two Groups' as the Group number itself, placing Q in Group 2 of Period 3, which is magnesium, 2, 8, 2. Two Groups to the left of Group 7 is Group 5. *(Group number taken from the wrong words)*
- **D** (2, 8, 3): Carried out the same instruction twice over, once to fix the Group and once again on the electron count: $7 - 2 = 5$, then $5 - 2 = 3$, which is aluminium, 2, 8, 3. The move across is made once, and Group 5 already means five electrons in the outer shell. *(Shift applied twice)*
- **E** (2, 8, 4): Read 'two Groups to the left' as leaving two Groups in between, so sulfur and phosphorus were both stepped over and Q was placed at silicon: $7 - 3 = 4$ outer electrons, 2, 8, 4. Two Groups to the left means two columns of movement, which lands on phosphorus with sulfur alone in between. *(Counted the Groups in between)*
- **F** (2, 8, 6): Moves one column instead of two, landing on Group 6, which is sulfur, 2, 8, 6. The move is $7 - 2 = 5$, so the outer shell holds five electrons, not six. *(Moved one column too few)*
- **H** (2, 8, 8, 1): Moves two places to the right instead of the left, passing argon, 2, 8, 8, and arriving at potassium, 2, 8, 8, 1. That atom has four occupied shells, so it is not even in chlorine's Period. *(Moved the wrong way)*

Common mistake. Reading 'two Groups to the left' as 'Group 2' and answering 2, 8, 2. The phrase counts two columns across from chlorine's own Group 7, which lands on Group 5, not on Group 2.

Takeaway. **The Cheat Code:** The last figure of a configuration is the Group and the count of figures is the Period. Stepping along a Period moves only that last figure, by one for each column crossed.

Time-saving tip. Speed Heuristic: Only the final figure changes. Chlorine ends in 7, so two columns to the left ends in 5, and the leading 2, 8 is untouched, which disposes of B at once; the answer must also keep exactly three shells, which disposes of H.

Question 5

C7.1 · Groups 1, 17 and 18 · ★★☆☆☆ · 90 s

A technician cuts a cube of sodium from a lump kept under oil and drops it into a trough of cold water. The cube floats, and within a second or two it melts into a ball that darts across the surface, leaving the water alkaline. Why does the cube melt?

- **A.** The oil clinging to the freshly cut surface catches fire on the water, and its flame melts the metal.
- **B.** Friction with the water, as the cube is driven across the surface, heats it up to its melting point.
- **C.** The hydrogen given off burns as it escapes, and that flame supplies the heat needed to melt the metal.
- **D.** Sodium's metallic bonding is weak, so the cold water breaks the lattice apart without any heating.
- **E.** Sodium's melting point is low, and its reaction with the water releases heat fast enough to reach that temperature.
- **F.** The sodium hydroxide formed dissolves into the metal and lowers its melting point below room temperature.

Answer E. Key idea

Two properties of the alkali metals meet in this demonstration. The chemical one is that a Group 1 metal reacts with water to give hydrogen and a dissolved hydroxide, releasing a great deal of energy in a very short time. The physical one is that these metals melt at temperatures far below those of ordinary metals. A reaction hot enough and a melting point low enough together explain a solid metal turning liquid in a trough of cold water.

Worked solution

1. Identify the reaction and where its energy goes

Sodium is an alkali metal, so with water it gives hydrogen and a hydroxide:

$$2Na + 2H_2O \rightarrow 2NaOH + H_2$$

The sodium hydroxide dissolving in the trough is why the water is left alkaline. The reaction is strongly exothermic, and it takes place at the surface of the cube, so the energy is delivered straight into a small piece of metal instead of being spread through the whole trough.

2. Bring in the physical property that makes melting possible

Alkali metals are soft and low melting, and sodium melts a little below 100 °C, which is extraordinarily low for a metal. A cube weighing a fraction of a gram needs very little energy to reach that temperature, so a reaction running fast at its surface carries it past the melting point in a second or two, and surface tension then pulls the liquid into a ball.

3. Rule out the other suggested sources of heat

Hydrogen escaping from sodium on cold water often does not ignite at all, and the ball forms whether it does or not, so no flame is needed. The oil is carried off by the knife and by the water. Friction is not the source either: a piece trapped on a floating scrap of filter paper stays where it is put and still melts. And the hydroxide formed is soluble, so it passes into the trough rather than into the metal, and cannot change the metal's melting point.

Sanity check: sodium warmed to 100 °C in a dry tube melts with no water and no flame anywhere near it, which shows the melting point is doing the work.

Matches Option **E**.

Why the other options are wrong

- **A** (The oil clinging to the freshly cut surface catches fire on the water, and its flame melts the metal.): Blames the storage oil. Most of it is wiped away by the cut and the rest floats off on the water, and a film thin enough to cling could not release the energy needed to melt the metal beneath it. *(Heat attributed to the storage oil)*
- **B** (Friction with the water, as the cube is driven across the surface, heats it up to its melting point.): Puts the heat into friction. A piece of sodium trapped on a floating scrap of filter paper stays where it is put and melts just the same, so the darting about cannot be the source; it is a consequence of the escaping gas. *(Heat attributed to friction)*
- **C** (The hydrogen given off burns as it escapes, and that flame supplies the heat needed to melt the metal.): Puts the heat in a flame rather than in the reaction. Hydrogen from sodium on cold water frequently does not ignite, and the ball still forms, so the melting cannot depend on the gas burning. *(Heat attributed to burning hydrogen)*
- **D** (Sodium's metallic bonding is weak, so the cold water breaks the lattice apart without any heating.): Explains the ball as a lattice coming apart in water instead of as metal that has been warmed past its melting point. Weak metallic bonding is the reason sodium's melting point is low, not a way of reaching it: the cube enters the water solid and rounds only after a second or two of reaction, and the same cube melts in a dry tube warmed to about 100 °C with no water present at all. *(Melting attributed to weak bonding rather than to heating)*
- **F** (The sodium hydroxide formed dissolves into the metal and lowers its melting point below room temperature.): Treats the product as acting on the metal. Sodium hydroxide is soluble and passes into the trough, which is why the water is left alkaline, and sodium's melting point is close to 100 °C, nowhere near room temperature. *(Product credited with lowering the melting point)*

Common mistake. Crediting the burning hydrogen with the melting. Sodium on cold water melts before any flame appears, and very often no flame appears at all. The heat comes from the reaction itself, released at the metal's surface faster than the cold water can carry it away.

Takeaway. **The Cheat Code:** when a Group 1 metal melts on water, two facts are working together: the reaction is strongly exothermic and the metal's melting point is unusually low. Neither fact on its own explains it, and no outside flame is needed.

Time-saving tip. Speed Heuristic: ask what each explanation needs before it can work. A flame, a burning oil film, friction and a hydroxide inside the metal are all extra assumptions, while a low melting point and an exothermic reaction are properties sodium has already.

Question 6

C4.8 · Quantitative chemistry · ★★☆☆☆ · 40 s

Calculate the volume of O_2 gas produced at room temperature and pressure (RTP) when 50.0 g of potassium chlorate decomposes according to the equation: $2KClO_3(s) \rightarrow 2KCl(s) + 3O_2(g)$ (Take molar gas volume at RTP = 24.0 dm^3 mol^{-1}, M_r of potassium chlorate = 122.5).

A. 29.39 dm^3
B. 14.69 dm^3
C. 7.35 dm^3
D. 13.71 dm^3
E. 1200.0 dm^3
F. 9.80 dm^3
G. 6.53 dm^3
H. 146.9 dm^3

Answer B. Key idea

Moles connect a mass to a gas volume. Divide the mass by M_r to get moles of $KClO_3$, scale by the equation's ratio of $\frac{3}{2}$ mol of O_2 per mol of $KClO_3$, then multiply by the molar gas volume, 24.0 dm^3 mol^{-1} at RTP.

Worked solution

1. Calculate moles of reactant

$$n = \frac{\text{mass}}{M_r} = \frac{50.0}{122.5} = 0.4082 \text{ mol}$$

2. Apply mole ratio from balanced equation

Moles of $O_2 = \frac{50.0}{122.5} \times 1.5 = 0.6122$ mol

3. Calculate gas volume at RTP

$V = n \times 24.0 \text{ dm}^3 \text{ mol}^{-1} = 0.6122 \times 24.0 = 14.69 \text{ dm}^3$

Matches Option **B**.

Why the other options are wrong

- **A** (29.39 dm^3): Multiplies by the 3 in front of O_2 but forgets the 2 in front of $KClO_3$: $\frac{50.0}{122.5} \times 3 = 1.2245$ mol, then $1.2245 \times 24.0 = 29.39$ dm^3. Using 3 rather than $\frac{3}{2}$ doubles the answer exactly. *(Divisor of the ratio dropped)*
- **C** (7.35 dm^3): Doubles the molar mass because of the 2 in front of $KClO_3$, dividing by $2 \times 122.5 = 245$, and then still applies the $\frac{3}{2}$ ratio: $\frac{50.0}{245} \times 1.5 = 0.3061$ mol, then $0.3061 \times 24.0 = 7.35$ dm^3. The ratio already accounts for the coefficients, so the mass is divided by 122.5 alone. *(Calculation / Conceptual Error)*
- **D** (13.71 dm^3): Finds the moles of oxygen correctly, 0.6122 mol, but multiplies by the molar volume at STP, 22.4 dm^3 mol^{-1}, instead of the 24.0 given for RTP: $0.6122 \times 22.4 = 13.71$ dm^3. *(Calculation / Conceptual Error)*
- **E** (1200.0 dm^3): Multiplies the mass straight by the molar volume without converting to moles: $50.0 \times 24.0 = 1200.0$ dm^3. The molar volume is the volume of one mole of gas, so the mass must first become moles of $KClO_3$ and then moles of O_2. *(Calculation / Conceptual Error)*
- **F** (9.80 dm^3): Converts the mass to moles correctly but reads the equation as one to one, taking one mole of O_2 per mole of chlorate: $50.0/122.5 = 0.4082$ mol, then $0.4082 \times 24.0 = 9.80$ dm^3. The equation gives three O_2 for every two $KClO_3$, so the moles of gas are 1.5 times the moles of solid. *(Mole ratio ignored)*
- **G** (6.53 dm^3): Applies the ratio upside down, $0.4082 \times \frac{2}{3} = 0.2721$ mol, then $0.2721 \times 24.0 = 6.53$ dm^3. The 2 belongs to $KClO_3$ and the 3 to O_2, so moving from chlorate to oxygen multiplies by $\frac{3}{2}$, not $\frac{2}{3}$. *(Mole ratio inverted)*
- **H** (146.9 dm^3): Works in cubic centimetres and converts back with the wrong factor: $0.6122 \times 24000 \approx 14690$ cm^3, then divides by 100 instead of 1000, giving 146.9 dm^3. There are 1000 cm^3 in 1 dm^3, so the volume is 14.69 dm^3. *(Calculation / Conceptual Error)*

Common mistake. Multiplying the mass directly by 24 without converting to moles first.

Takeaway. The Cheat Code: Go from mass to moles, through the coefficient ratio, then to volume, keeping the numbers as fractions: $\frac{50.0}{122.5} = \frac{20}{49}$, so $V = \frac{20}{49} \times \frac{3}{2} \times 24.0 = \frac{720}{49} \approx 14.69$ dm^3.

Time-saving tip. Speed Heuristic: Look at the relative magnitudes and units in the multiple-choice options to eliminate extreme or impossible values immediately.

Question 7

C3.4 · Chemical reactions and equations · ★★☆☆☆ · 85 s

In a blast furnace, iron(III) oxide (Fe_2O_3) is reduced by carbon monoxide to iron and carbon dioxide. Balanced with the smallest whole numbers, what is the sum of all the coefficients in this equation?

- **A.** 7
- **B.** 18
- **C.** 8
- **D.** 12
- **E.** 11
- **F.** 5
- **G.** 4
- **H.** 9

Answer H. Key idea

A balanced equation conserves every element, and once the coefficients are reduced to the smallest whole numbers there is only one set that does it. A formula written with no number in front of it still stands for one formula unit, so it counts when the coefficients are totalled.

Worked solution

1. Balance the equation

The skeleton is $Fe_2O_3 + CO \rightarrow Fe + CO_2$.

Iron first: two Fe atoms on the left need $2Fe$ on the right.

Carbon and oxygen travel together, so let the CO and the CO_2 coefficients both be x. Oxygen on the left is $3 + x$, three from the oxide and one from each CO, and on the right it is $2x$. Setting $3 + x = 2x$ gives $x = 3$.

Balanced: $Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2$. Check the atoms: Fe $2 = 2$, C $3 = 3$, O $3 + 3 = 6$ against $3 \times 2 = 6$.

2. Add the coefficients, including the unwritten one

Fe_2O_3 carries no number in front of it, which means one formula unit, not none. The four coefficients are 1, 3, 2 and 3:

$$1 + 3 + 2 + 3 = 9$$

Sanity check: no smaller whole numbers balance this equation, and doubling every coefficient would give $2 + 6 + 4 + 6 = 18$, so 9 is the smallest sum available.

Matches Option **H**.

Why the other options are wrong

- **A** (7): Sets both carbon species to 2 so that they match the two iron atoms, $Fe_2O_3 + 2CO \rightarrow 2Fe + 2CO_2$, giving $1 + 2 + 2 + 2 = 7$. Oxygen is $3 + 2 = 5$ on the left and 4 on the right, so it is still unbalanced. *(Coefficients copied from the iron)*
- **B** (18): Doubles everything to keep the oxygen count even, $2Fe_2O_3 + 6CO \rightarrow 4Fe + 6CO_2$, and totals $2 + 6 + 4 + 6 = 18$. Every atom balances, Fe $4 = 4$, C $6 = 6$, O $6 + 6 = 12$ against 12, but the question asks for the smallest whole numbers and every coefficient here still divides by two. *(Coefficients not reduced)*
- **C** (8): Balances the equation correctly but adds only the coefficients that appear in print, $3 + 2 + 3 = 8$, missing the unwritten 1 in front of Fe_2O_3. *(Invisible coefficient dropped)*

- **D** (12): Reaches for the other blast furnace equation, reduction by carbon rather than by carbon monoxide: $2Fe_2O_3 + 3C \longrightarrow 4Fe + 3CO_2$ totals $2 + 3 + 4 + 3 = 12$. That equation is balanced, but the stem fixes carbon monoxide as the reducing agent, so CO stands on the left and CO_2 on the right. *(Coke equation recalled instead)*
- **E** (11): Totals the atoms rather than the numbers written in front of the formulae. On the left Fe_2O_3 contributes 5 atoms and $3CO$ contributes $3 \times 2 = 6$, giving 11, and since the equation balances the right hand side returns the same, $2 + 3 \times 3 = 11$. A coefficient is the multiplier in front of a formula, not the number of atoms that formula stands for. *(Atoms counted instead of coefficients)*
- **F** (5): Balances the iron and stops there, $Fe_2O_3 + CO \longrightarrow 2Fe + CO_2$, giving $1 + 1 + 2 + 1 = 5$. Oxygen is then $3 + 1 = 4$ on the left against 2 on the right. *(Stopped after the metal)*
- **G** (4): Treats the skeleton $Fe_2O_3 + CO \longrightarrow Fe + CO_2$ as already balanced and adds four invisible ones, $1 + 1 + 1 + 1 = 4$. It is not balanced: two Fe atoms on the left face one on the right. *(Skeleton equation counted)*

Common mistake. Adding only the numbers that are actually printed. Fe_2O_3 carries an invisible coefficient of 1, so totalling $3 + 2 + 3$ reports 8 for an equation that contains four species.

Takeaway. The Cheat Code: Balance the metal first, then the element that appears in only one compound on each side, and leave oxygen until last when it is split between two compounds. Then count every formula, including the ones whose coefficient is an unwritten 1.

Time-saving tip. Speed Heuristic: Carbon and oxygen move together here, so the CO and CO_2 coefficients must be equal, and the three spare oxygen atoms in Fe_2O_3 force both of them to be 3 with no trial and error at all.

Question 8

C8.2 · Separation techniques · ★★☆☆☆ · 90 s

A technician stirs dry sand, which does not dissolve, into a blue solution of copper(II) sulfate in water. Dry crystals of copper(II) sulfate must be recovered from the mixture, with no sand in them. Which pair of steps, carried out in this order, achieves that?

- **A.** Heat the whole mixture until every drop of water has boiled away, then collect the solid left in the dish.
- **B.** Boil the whole mixture and condense the vapour, then keep the clear liquid that collects in the receiver.
- **C.** Cool the whole mixture in ice until crystals appear, then pour it onto filter paper and dry what is caught.
- **D.** Pour the mixture onto filter paper, then heat the liquid that runs through until it is saturated and cool it slowly.
- **E.** Pour the mixture onto filter paper, then wash the solid caught in the paper with warm water and dry it.

Answer D. Key idea

A mixture is taken apart by physical processes chosen to match how each component is held in it. A solid that never dissolved is still a separate phase and can be strained out on filter paper, while a solid that has dissolved is spread through the solvent and is recovered as crystals by removing solvent until the solution is saturated and then cooling it so crystals grow. The order matters, because anything still undissolved when crystals form is trapped inside them.

Worked solution

1. Sort the mixture into its parts

Three things are present: water, which is the solvent; copper(II) sulfate, a solid that has dissolved in that water; and sand, a solid that has not dissolved at all. The wanted product is the dissolved solid, as dry crystals, so the water is a discard and the sand is an impurity to be removed.

2. Take out the insoluble solid first

Sand grains are far larger than the dissolved copper(II) sulfate, so filter paper holds the sand back and lets the blue solution pass. Every gram of the dissolved salt is carried through in that liquid, and the paper keeps the sand. Doing this first is what guarantees a clean product: solid left in the beaker while crystals grow is trapped inside them.

3. Recover the dissolved solid from the clear liquid

Heat the blue filtrate to drive off part of the water until the solution is saturated, which is when a drop on a cold rod crystallises. Then let it cool slowly. Solubility falls as the temperature falls, so the excess salt comes out of solution as crystals, which are filtered off and dried.

Sanity check: the sand never dissolved, so it can only leave on filter paper, and the salt was dissolved, so it returns as crystals by concentrating and cooling. Boiling everything to dryness would leave a powder still mixed with sand.

Matches Option **D**.

Why the other options are wrong

- **A** (Heat the whole mixture until every drop of water has boiled away, then collect the solid left in the dish.): Boiling every drop away does bring the salt out, but sand cannot evaporate: the dish is left holding copper(II) sulfate powder mixed with the sand, which the question forbids. It also gives a powder rather than the crystals asked for. *(Conceptual Error)*
- **B** (Boil the whole mixture and condense the vapour, then keep the clear liquid that collects in the receiver.): Condensing the vapour keeps the water and throws away the target. The copper(II) sulfate is not volatile, so it stays in the flask with the sand, and the liquid collected in the receiver is pure water. *(Wrong component kept)*
- **C** (Cool the whole mixture in ice until crystals appear, then pour it onto filter paper and dry what is caught.): Cooling does grow crystals, but the sand is still suspended in the liquid, so the paper catches sand and crystals together. With no water removed first the solution is not saturated either, so the crop is tiny. *(Correct steps, wrong order)*
- **E** (Pour the mixture onto filter paper, then wash the solid caught in the paper with warm water and dry it.): This keeps the wrong fraction. The paper traps the sand, while the copper(II) sulfate is in the liquid that runs through, and washing the paper with warm water only dissolves any salt still clinging to the sand. *(Residue and filtrate confused)*

Common mistake. Reaching for the heat first. Boiling the whole mixture to dryness does drive off the water, but the sand is still sitting in the dish, so the solid recovered is a mixture rather than pure copper(II) sulfate, and evaporating to dryness gives a fine powder rather than crystals.

Takeaway. **The Cheat Code:** Take the insoluble solid out before you take the water out. Filter first, then concentrate and cool. Filtering after the crystals have grown just collects the impurity along with them.

Time-saving tip. Speed Heuristic: Ask which half you are keeping. Here it is the dissolved solid, so the water must leave and the liquid running through the paper is the valuable half. That single question kills every route that keeps the condensed vapour or the residue on the paper.

Question 9

C4.1 · Quantitative chemistry · ★★☆☆☆ · 45 s

Calculate the relative molar mass, M_r, of magnesium hydroxide, $Mg(OH)_2$. (A_r(Mg) = 24, A_r(O) = 16, A_r(H) = 1.)

- **A.** 58
- **B.** 42
- **C.** 57
- **D.** 82
- **E.** 41
- **F.** 26
- **G.** 56
- **H.** 29

Answer A. Key idea

M_r is the sum of the A_r values, each multiplied by its subscript: $24 + (2 \times 16) + (2 \times 1) = 58$.

Worked solution

1. Read the subscripts off the formula

$Mg(OH)_2$ contains $1 \times$ Mg, $2 \times$ O, $2 \times$ H.

2. Multiply each A_r by how many of that atom there are

$M_r = 24 + (2 \times 16) + (2 \times 1)$

3. Add the contributions

$M_r = 58$

M_r is a *relative* mass, so it carries no units.

Matches Option **A**.

Why the other options are wrong

- **B** (42): Reads the 2 as belonging to the H it stands next to, giving $24 + 16 + (2 \times 1) = 42$. The bracket closes after the H, so the 2 also applies to the O, which contributes $2 \times 16 = 32$. *(Bracket applied to the hydrogen only)*
- **C** (57): Doubles the O but leaves the H single: $24 + (2 \times 16) + 1 = 57$. The subscript sits outside the bracket, so it multiplies everything inside it and the hydrogen contributes $2 \times 1 = 2$. *(Bracket applied to the oxygen only)*
- **D** (82): Mg was counted twice. Each element in the formula contributes exactly once, multiplied by its subscript. *(Double counting)*
- **E** (41): Every subscript was read as 1, so the repeated atoms were counted only once. Each subscript multiplies the A_r of the atom it follows. *(Ignored subscripts)*
- **F** (26): The contribution of O was left out altogether. Work through the formula atom by atom so nothing is missed. *(Omitted a term)*
- **G** (56): Drops the hydrogen because A_r(H) = 1 looks too small to matter: $24 + (2 \times 16) = 56$. Every atom in the formula contributes, and the two hydrogen atoms add 2. *(Hydrogen discarded as negligible)*
- **H** (29): Exactly half the true value, $58 \div 2 = 29$, the result of halving the total somewhere. M_r is a plain sum, with no division anywhere. *(Spurious division)*

Common mistake. Ignoring a subscript that sits outside a bracket, such as the 2 in $Mg(OH)_2$, which applies to *both* the O and the H.

Takeaway. The Cheat Code: work left to right through the formula and write the running total as you go. A subscript outside a bracket multiplies everything inside it, so expand the bracket before you add anything.

Time-saving tip. Read what the question actually asks for before you calculate: a large share of lost marks here come from producing a correct intermediate value and stopping one step early.

Question 10

C2.2 · The Periodic Table · ★★★☆☆ · 85 s

Tellurium has a higher relative atomic mass than iodine, 127.6 against 126.9, yet every modern Periodic Table places tellurium first, with iodine falling in the halogen column beneath bromine. Which rule does the modern table order its elements by?

- **A.** Elements are ordered by increasing number of neutrons, and tellurium's atoms hold fewer neutrons than iodine's atoms.
- **B.** Elements are ordered by increasing relative atomic mass, with awkward pairs swapped to keep chemical families together.
- **C.** Elements are ordered by decreasing atomic radius, and tellurium's atoms are larger than iodine's atoms.
- **D.** Elements are ordered by increasing proton number, and tellurium has 52 protons against iodine's 53.
- **E.** Elements are ordered by increasing number of outer-shell electrons, six for tellurium and seven for iodine.
- **F.** Elements are ordered by increasing number of occupied electron shells, which is greater for iodine than for tellurium.

Answer D. Key idea

The modern Periodic Table is ordered by proton number, and every rival ordering is either a consequence of that rule or an approximation to it. Proton number is fixed for an element, since all of its isotopes share it, so it hands each element exactly one position and increases by exactly one from each element to the next. Relative atomic mass is an average taken over an isotope mixture, so it can run backwards between neighbours, which is why the tellurium and iodine pair is the standard test of which rule the table actually obeys.

Worked solution

1. Test the relative atomic mass rule against what the table does

If relative atomic mass set the order, the lighter element would come first. Iodine at 126.9 is the lighter of the pair, so a mass ordered table would read iodine and then tellurium. Every modern table reads tellurium and then iodine, so the observed order contradicts the mass rule outright. The chemistry contradicts it as well: mass ordering would drop iodine into the column headed by oxygen and sulfur, where it would be expected to form compounds of the type H_2X and to have no halogen behaviour, whereas iodine in fact forms HI, NaI and I_2 exactly as chlorine and bromine do.

2. Apply the proton number rule and check both facts at once

Tellurium has 52 protons and iodine has 53. Counting up in proton number puts tellurium at position 52 and iodine at position 53, which is the order the table uses, with no exception made and nothing moved by hand. The same rule lands iodine in Group 7 beneath bromine, which is where its chemistry says it belongs.

Sanity check: every isotope of one element shares its proton number but differs in mass, so only proton number gives each element a single unambiguous place in the sequence. Relative atomic mass cannot, and the tellurium and iodine pair is precisely where that failure shows.

Matches Option **D**.

Why the other options are wrong

- **A** (Elements are ordered by increasing number of neutrons, and tellurium's atoms hold fewer neutrons than iodine's atoms.): Substitutes the neutron count for the proton count, and states the fact backwards as well. Iodine's only stable isotope holds $127 - 53 = 74$ neutrons, while tellurium's common isotopes hold $128 - 52 = 76$ and $130 - 52 = 78$, so tellurium carries more neutrons rather than fewer, and those extra neutrons are exactly why it is the heavier element despite having one proton less. Neutron count also differs from one isotope of an element to the next, so it cannot fix a single place for each element. *(Neutron count used in place of proton count)*
- **B** (Elements are ordered by increasing relative atomic mass, with awkward pairs swapped to keep chemical families together.): This is Mendeleev's rule with a patch stitched on. Mass ordering gives iodine at 126.9 before tellurium at 127.6, so the pair has to be swapped deliberately to keep iodine with the halogens. The modern table needs no such patch, because proton number already gives the observed order. *(Superseded rule kept with an exception)*
- **C** (Elements are ordered by decreasing atomic radius, and tellurium's atoms are larger than iodine's atoms.): Uses a trend in place of a rule. Atomic radius does fall from tellurium to iodine across Period 5, but it jumps back up at the start of the next Period, so it cannot generate one continuously increasing sequence for the whole table. *(Periodic trend mistaken for the ordering)*
- **E** (Elements are ordered by increasing number of outer-shell electrons, six for tellurium and seven for iodine.): Works inside a single Period and fails everywhere else. Tellurium has six outer electrons and iodine seven, which happens to give the right order for this pair, but the count drops back to one at the start of the next Period, so the sequence breaks at every row boundary. *(Local pattern generalised)*
- **F** (Elements are ordered by increasing number of occupied electron shells, which is greater for iodine than for tellurium.): Occupied shells label the Periods, not the sequence within one. Tellurium and iodine both lie in Period 5 and so have the same number of occupied shells, which cannot separate them at all, let alone place tellurium first. *(Period label used as the ordering rule)*

Common mistake. Accepting relative atomic mass as the ordering rule and treating tellurium and iodine as an exception that was moved by hand to tidy the columns. Nothing was moved: proton number produces that order automatically, and it is mass ordering, not the table, that fails.

Takeaway. **The Cheat Code:** when a table position and a relative atomic mass disagree, back the proton number. Mass is an average over isotopes and can invert between neighbours, while proton number counts up by one every single time.

Time-saving tip. Speed Heuristic: an ordering rule has to give a whole number that rises by exactly one from each element to the next, right across the table. Radius rises and falls, outer electrons reset at the start of every Period, shell count is constant along a Period, and mass inverts here. Only proton number survives that filter.

END OF SOLUTIONS

Questions 11 to 27 are in the full paper

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