Chemistry Olympiad

ROYAL SOCIETY OF CHEMISTRY

UK Chemistry Olympiad support resources: introductory questions explainer

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1. The question about air

The trick to answering this question is making sure you break down the more complex calculations into a clear sequence of simple steps.

In this explanation we will model exactly how to do that.

(a)

(i) Use the periodic table to find the molar masses of each component of air.

Molar mass of N_2 = 2(14.01) = 28.02 g mol^{-1}

Molar mass of O_2 = 2(16.00) = 32.00 g mol^{-1}

Molar mass of Ar = 39.95 g mol^{-1}

(ii) To calculate the molar mass of air, calculate the masses of each of its components.

Mass of N_2 in 1 mole of air = 0.78 x 28.01 = 21.85 g

Mass of O_2 in 1 mole of air = 0.21 x 32.00 = 6.72 g

Mass of Ar in 1 mole of air = 0.01 x 39.95 = 0.40 g

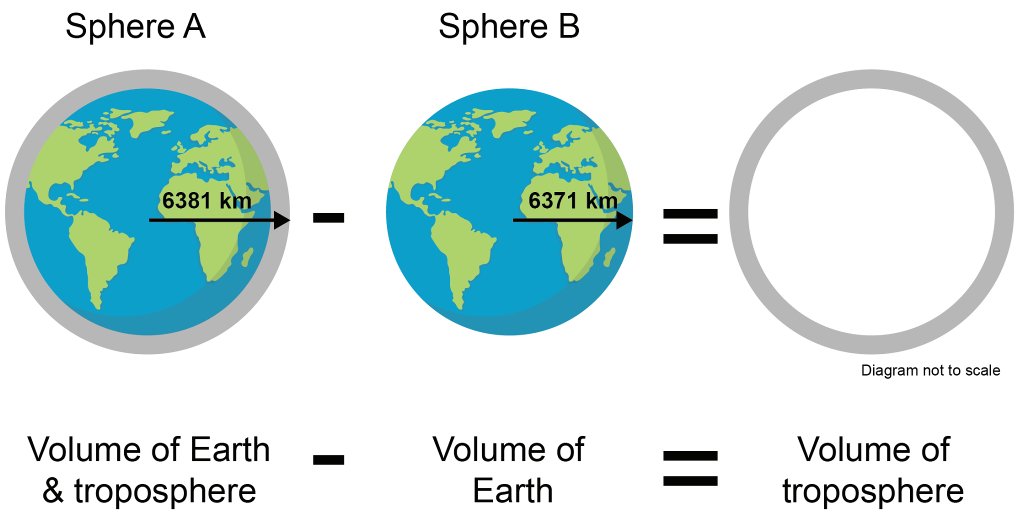
Then, add the masses together to find the molar mass of air.

Mass of 1 mole of air = 21.85 + 6.72 + 0.40 = 28.97 g

Mass of 1 mole of air = 29.0 g to three significant figures

(b)

(i) To calculate the volume of the troposphere, we need to calculate the difference in volume between two spheres.



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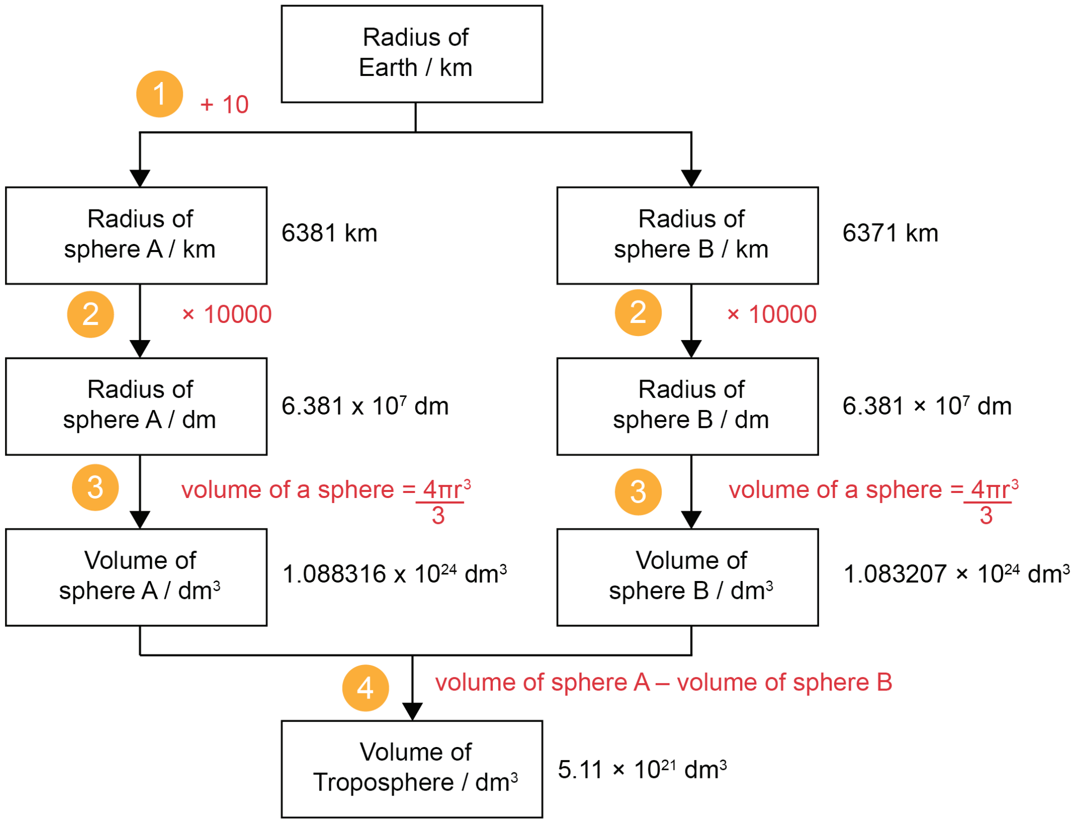
Path to answer:



Explanation of steps:

① Sphere A's radius is 10 km larger than Earth's because includes the troposphere, which ends around 10 km above the ground.

② The answer asks for the volume to be expressed in dm^3, so we need to convert from km to dm.

Since:

1 km = 1000 m
1 m = 10 dm

This means that:

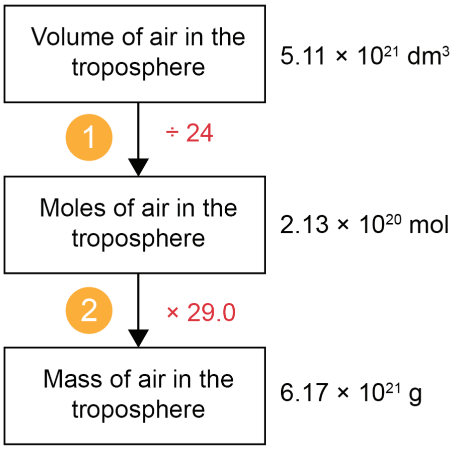
1 km = 10 000 dm

③ To find the volume of each sphere, we need to plug their radii into the following formula:

$$\text{volume of a sphere} = \frac{4\pi r^3}{3}$$

④ To find the volume of the troposphere, we must subtract the volume of sphere B from the volume of sphere A.

(ii) Path to answer:



Explanation of steps:

① The question states that ‘at standard room temperature and pressure, one mole of gas occupies a volume of 24 dm^{3v}’.

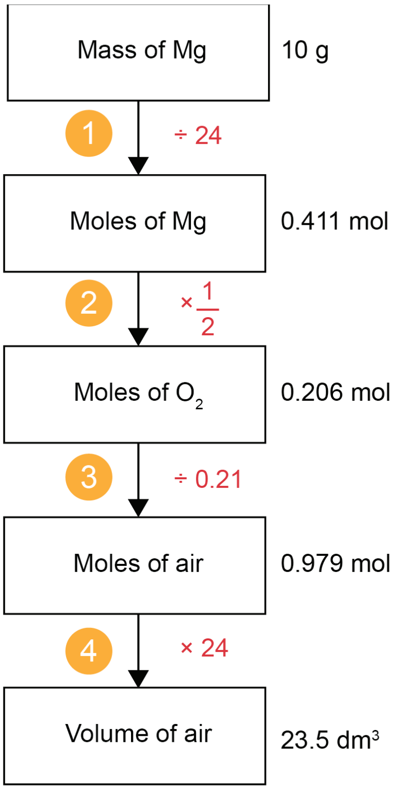
② In a) part ii) we calculated that 1 mole of air has a mass of 29.0g.

(c)

(i) Magnesium oxide has the empirical formula MgO, so the balanced equation is:

$$Mg + ½\,O_2 \rightarrow MgO$$

(ii) Path to answer:



Explanation of steps:

① The molar mass of Mg is 24.31 g

$$\text{mass} = \frac{\text{mass}}{\text{molar mass}}$$

② Magnesium and oxygen react in a 1: ½ mole ratio:

$$Mg + \tfrac{1}{2}\,O_2 \longrightarrow MgO$$

③ At the start of the question we are told that one mole of air contains 0.21 moles of O_2:

$$\text{moles of } O_2 \text{ in air} = \text{moles of air} \times 0.21$$

$$\text{moles of air} = \frac{\text{moles of } O_2 \text{ in air}}{0.21}$$

④ Earlier in the question we are told that 1 mole of gas occupies 24 dm^3

(d)

(i) Magnesium nitride has the empirical formula Mg_3N_2, so the balanced equation is:

$$3Mg + N_2 \rightarrow Mg_3N_2$$

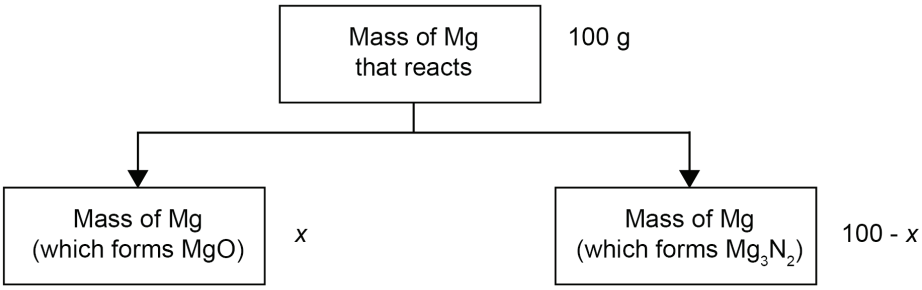
(ii) The question tells us that:

100 g of magnesium reacts fully

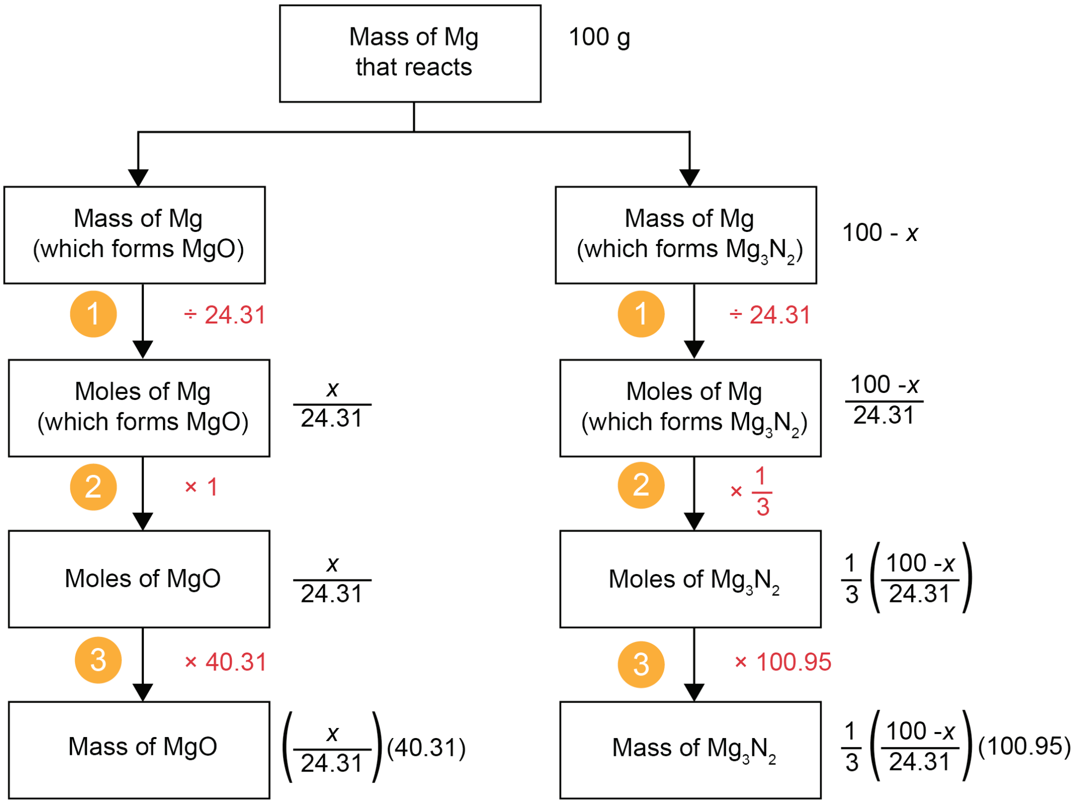
x g of magnesium reacts to form magnesium oxide

The remaining magnesium reacts to form magnesium nitride

This means the mass of magnesium which forms magnesium nitride is (100 - *x*) g.



(iii) Path to answer:



Explanation of steps:

① The molar mass of Mg is 24.31 g mol^{-1}

$$\text{moles} = \frac{\text{mass}}{\text{molar mass}}$$

② 1 mole of Mg reacts to form 1 mole of MgO

$$Mg + \frac{1}{2} O_2 \longrightarrow MgO$$

1 mole of Mg reacts to form ⅓ mole of Mg_3N_2

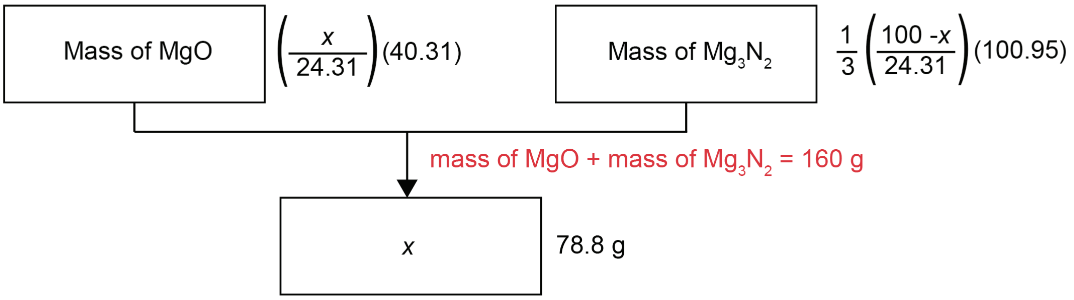
$$Mg + \tfrac{1}{3} N_2 \longrightarrow \tfrac{1}{3} Mg_3N_2$$

③ The molar mass of MgO is 40.31 g mol^{-1}

The molar mass of Mg_3N_2 is 100.95 g mol^{-1}

$$\text{mass} = \text{moles} \times \text{molar mass}$$

(iv) Path to answer:



Explanation:

Using our values from **(d)** part (ii) we have expressions for the mass of both MgO and Mg_3N_2 in terms of *x*.

We know from the question that the sum of the masses of MgO and Mg_3N_2 is 160 g.

So, by relating both of these pieces of information, we can find *x*:

$$\left(\frac{x}{24.31}\right)(40.31) + \frac{1}{3}\left(\frac{100 - x}{24.31}\right)(100.95) = 160$$

expand brackets

$$\frac{40.31}{24.31}x + \frac{100(100.95)}{3(24.31)} - \frac{100.95}{3(24.31)}x = 160$$

× 24.31

$$40.31x + \frac{100(100.95)}{3} - \frac{100.95}{3}x = 160 \times 24.31$$

× 3

$$120.93x + 100(100.95) - 100.95x = 160 \times 24.31 \times 3$$

collect like terms & simplify

$$19.98x + 10095 = 11668.8$$

– 10095

$$19.98x = 1873.8$$

÷ 19.98

$$x = 78.8 \text{ g}$$

2. The question about bromine and its isotopes

(a)

(i), (ii) and (iii)

To answer these three questions, it's helpful to label both bromine atoms in the Br_2 molecule separately.

$$\mathrm{Br}_\alpha \text{ —— } \mathrm{Br}_\beta$$

It's also helpful to construct a table to consider all the possible isotopic configurations for the two bromine atoms.

We can use this table to calculate the probability that the bromine molecule has a mass of 158, 160 or 162:

$p(^{79}\mathrm{Br}) = 0.5$
$p(^{81}\mathrm{Br}) = 0.5$

$$\mathrm{Br}_\alpha \text{ —— } \mathrm{Br}_\beta$$

Br_α	Br_β	Probability	Mass
79	79	0.5 × 0.5 = 0.25	158
79	81	0.5 × 0.5 = 0.25	160
81	79	0.5 × 0.5 = 0.25	
81	81	0.5 × 0.5 = 0.25	162

Probablility that Br_2 has a mass of 158 = 0.25
Probablility that Br_2 has a mass of 160 = 2(0.25) = 0.5
Probablility that Br_2 has a mass of 162 = 0.25

(b)

On Alpha-Zar, the abundances of bromine isotopes are different than those on Earth, and, to work out these unfamiliar abundances, it helps to use algebra.

For example, if we assume the probability that a bromine atom is bromine-79 is *p*, then the probability a bromine atom is bromine-81 must be 1-*p* (since the two probabilities must sum to 1).

Then, using these algebraic values for probability, we can construct a similar table to the one we used before.

Except, for this table, we only need to consider the combinations of bromine atoms that result in a mass of 158.

$p(^{79}\mathrm{Br}) = p$
$p(^{81}\mathrm{Br}) = 1 - p$

$$\mathrm{Br}_\alpha \text{ —— } \mathrm{Br}_\beta$$

Br_α	Br_β	Probability	Mass
79	79	$p \times p = p^2$	158

This table tells us that, on Alpha-Zar, the probability that a molecule of Br_2 has a mass of 158 is p^2. We're also told in the question that 36.0% of Br_2 molecules have a mass of 158 on Alpha- Zar. In other words, we're told that the probability that a Br_2 molecule has a mass of 158 is 0.360, and we can use this information to work out the value of p:

$p(^{79}Br) = p$
$p(^{81}Br) = 1 - p$

$$Br_\alpha \text{ —— } Br_\beta$$

Br_α	Br_β	Probability	Mass
79	79	$p \times p = p^2$	158

Probablility that Br_2 has a mass of 158 = p^2
Probablility that Br_2 has a mass of 158 = 0.36

$p = 0.6$

Lastly, we can use this value of p to work out the abundances of bromine isotopes on Alpha- Zar:

On Alpha-Zar:

The probability a bromine atom is bromine-79 is 0.6 ⟶ The abundance of bromine-79 is 60%

The probability a bromine atom is bromine-81 is 0.4 ⟶ The abundance of bromine-81 is 40%

(c)

(i) To answer this question, you could compute each of the different masses from scratch.

However, a much quicker approach is to compute the lightest possible mass of BBr_3 and then swap lighter isotopes for heavier isotopes one-by-one, adding the difference in mass each time.

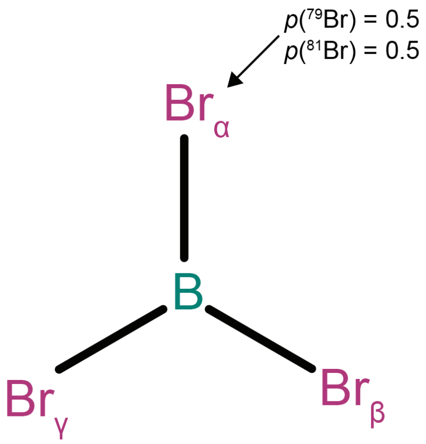
For instance, the lightest molecule of BBr_3, which contains one atom of boron-10 and three atoms of bromine-79, has a mass of 247.

However, if we swap one of the bromine-79 atoms for bromine-81, the molecule now has a mass of 249.

Or, if we swap the boron-10 atom for an atom of boron-11, the molecule now has a mass of 248.

(ii) and (iii)

First, like before, it’s useful to label the three bromine atoms on the molecule separately.



Then, like before, we can construct a table to help us consider the different possible isotopic configuration of the three bromine atoms.

Br_α	Br_γ	Br_β	Probability
. . .	. . .	. . .	. . .

In part (ii), we are only interested in the configurations where every bromine atom is bromine-79. There is only one configuration that satisfies these criteria:

Br_α	Br_γ	Br_β	Probability
79	79	79	0.5 × 0.5 × 0.5 = 0.125

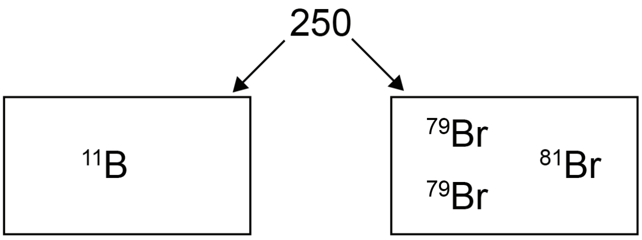
So the probability that every bromine atom in BBr_3 is bromine-79 is 0.125.

In part (iii) we are interested in all the configurations where exactly one bromine atom is bromine-81. There are three configurations which satisfy these criteria.

Br_α	Br_γ	Br_β	Probability
81	79	79	0.5 × 0.5 × 0.5 = 0.125
79	81	79	0.5 × 0.5 × 0.5 = 0.125
79	79	81	0.5 × 0.5 × 0.5 = 0.125

Each of these three configurations has a probability of 0.125, so the total probability that one bromine atom in BBr_3 is bromine-81 is 0.375.

(iv) For a BBr_3 molecule to have a mass of 250 it must consist of one boron-11 atom, two bromine-79 atoms and one bromine-81 atom.



The question tells us that the probability that a boron atom is boron-11 is 0.8, and in part (iii) we calculated the probability that exactly one bromine atom in BBr_3 is bromine-81 is 0.375.

So, by multiplying these two probabilities together, we can find the probability that a BBr_3 molecule has a mass of 250.

$$\text{Probability that } BBr_3 \text{ has a mass of } 250 = 0.8 \times 0.375$$

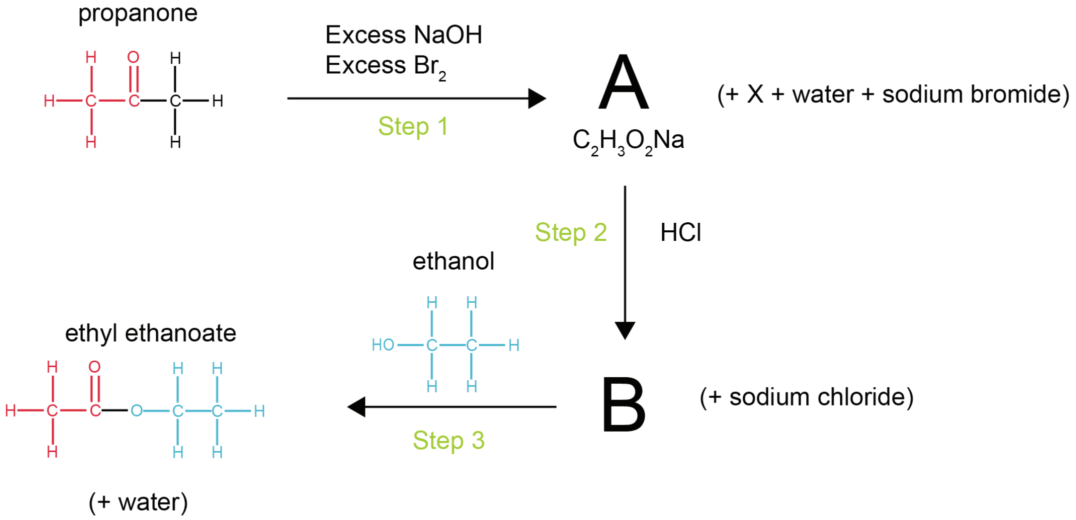
$$\text{Probability that } BBr_3 \text{ has a mass of } 250 = 0.3$$

(d)

(i) Based on the structure shown in the question, propanone contains three carbon atoms, six hydrogen atoms and one oxygen atom. This means its molecular formula is C_3H_6O.

(ii) Before you dive into answering questions like this, a useful trick is to look at the structure of the final product and try to figure out which parts of the reactants it came from.

For instance, it looks like the left hand side of the ethyl ethanoate molecule (highlighted red) was originally part of propanone and the right hand side (highlighted blue) was originally part of ethanol:



Finding the structure of **B**:

The key to answering this question is working backwards rather than forwards. The reaction taking place in step one is likely to be unfamiliar, but the reaction taking place in step three is taught at GCSE.

In step three, molecule **B** reacts with ethanol, an alcohol, to form ethyl ethanoate, an ester.

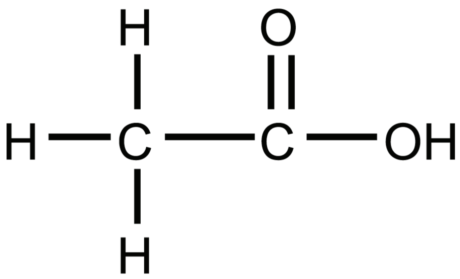
At GCSE, you are taught that esters are made by the following reaction:

alcohol + carboxylic acid → ester + water

Since ethanol is an alcohol, that means **B** must be a carboxylic acid.

Ethanol contains two carbon atoms and our ethyl ethanoate, our ester product, contains four.

This means that **B** must be a carboxylic acid that contains two carbon atoms, which means its structure must be:



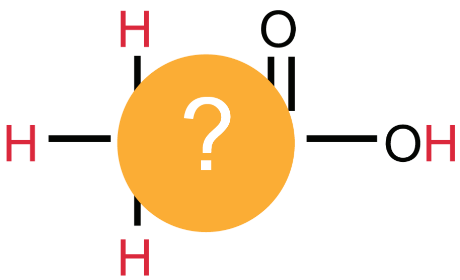
Finding the structure of **A**:

Now that we know the structure of **B**, we can work backwards to figure out the structure of **A**.

To do this, it's worth comparing the formulas of **A** and **B** and seeing how they differ.

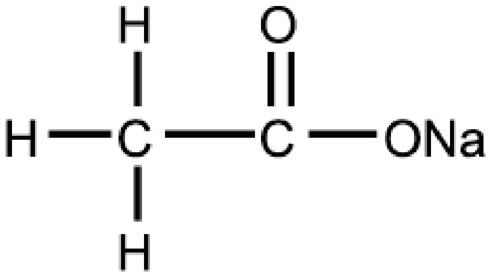
The formula of **A** is $C_2H_3O_2Na$ and the formula of **B** is $C_2H_4O_2$, which is a good indication that sodium is swapped for hydrogen during step two...

...but which hydrogen is added?



Well, since the three hydrogen atoms on the left are also present in both the starting reactants (propanone) and the products (ethyl ethanoate), it's unlikely that they're introduced during step two.

This means the hydrogen attached to oxygen must be the one added during step two, which means the structure of **A** is:



(e)

To find the identity of molecule **X**, we first need to answer two related questions: how many carbons atoms are in molecule **X** And how many bromine atoms are in molecule **X**?

How many carbon atoms are in molecule **X**?:

To answer this question, we need to use the following information given to us in the question: for every 1 mole of propanone that reacts, 1 mole of **A** and 1 mole of molecule **X** form.

This tells us three coefficients of the balanced equation, which is shown below (substances with known coefficients shown in red):

$$C_3H_6O + ?NaOH + ?Br_2 \longrightarrow C_2H_3O_2Na + X + ?H_2O + ?NaBr$$

Since the coefficient of C_3H_6O is one, this means that there must be three carbon atoms on the left hand side of the equation.

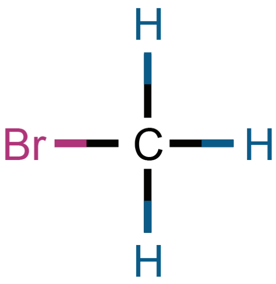
If there are three carbon atoms on the left hand side of the equation, then there must also be three carbon atoms on the right hand side of the equation.

So, since there are two carbon atoms in the formula of **A** ($C_2H_3O_2Na$), this means **X** must contain one carbon atom.

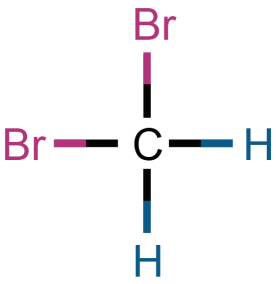
How many bromine atoms are in molecule **X**?:

We now know that **X** contains only one carbon atom, and the question also tells us that **X** contains at least one hydrogen atom.

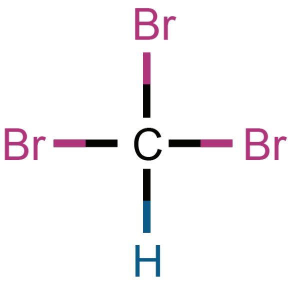
There are only three molecules which fit the above criteria, and all that's left to do is select the correct one.



CH_3Br



CH_2Br_2



$CHBr_3$

To pick the correct structure of molecule **X**, we next need to use the following information given to us in the question: Assuming hydrogen and carbon have only one isotope, molecule **X** has four possible masses.

Since we're assuming that hydrogen and carbon only have one isotope, bromine isotopes must be responsible for the molecule **X**'s four possible masses.

So, if we consider the possible masses of one, two and three bromine atoms we can see that molecule **X** must contain three bromine atoms.

Possible masses of:

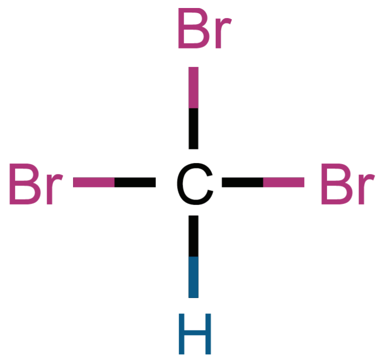
One bromine atom	79	81		
Two bromine atoms	158	168	162	
Three bromine atoms	237	239	241	243

Identifying **X**:

We now know that **X** must contain:

- One carbon atom
- At least one hydrogen atom
- Three bromine atoms

Of the three possible structures for **X** suggested above $CHBr_3$ is the only molecule which satisfies these criteria. This means that **X** must be $CHBr_3$.



$CHBr_3$