

Experiment: Determination of the molar mass of a gas

Introduction

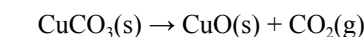
The ideal gas equation can be used to calculate the molar mass (M) of a gas when P , V , T , and the mass of the gas sample (m) are known:

$$PV = nRT$$

Given that $n = \frac{m}{M}$, this rearranges to

$$M = \frac{mRT}{PV}$$

In this experiment we will heat a known mass of copper carbonate in a test tube. The solid will undergo thermal decomposition, releasing Copper (II) Oxide + Carbon dioxide.



The carbon dioxide gas given off will be collected by displacement of water from an inverted glass tube.

After heating, the test tube and contents are reweighed.

We can determine the molar mass of the gas from the following data collected in this experiment:

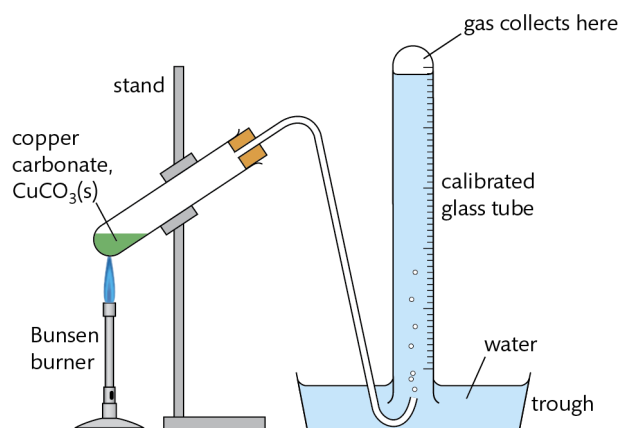
- mass (m) of gas: calculated from the loss in mass on heating the copper carbonate
- volume (V) of gas: measured from the volume of water displaced
- temperature (T) of gas: the measured room temperature
- pressure (P): the measured *room* pressure. This is the pressure exerted on the gas by the air in the room.

Equipment list

- **Chemicals / materials:** $\text{CuCO}_3(\text{s})$ (0.19-0.21 g per trial)
- **Apparatus:**
 - Balance (accurate to 2 decimal places)
 - Boiling tubes $\times 3$
 - Boiling tube plug with a hole in it
 - Retort stand
 - Test tube clamp $\times 2$ (one for the boiling tube, one for the eudiometer)
 - Eudiometer, filled with tap water
 - Bucket, filled with tap water
 - Delivery tube with attachment for boiling tube (fits into the hole in the plug)
 - Gas Pressure Sensor & Logger Pro Base Unit (1 for the whole class - your teacher has this!)

Method

1. Set up the apparatus as shown below. Try to ensure that the inverted eudiometer is full of water with no air trapped.



- Put approximately 0.2 g of copper carbonate, CuCO_3 , into the boiling tube and weigh the tube with contents carefully. Record the initial mass.
- Gently heat the sample until the graduated tube is about 3/4 full of gas.

Be very careful to avoid suck-back by taking the delivery tube out of the trough of water as soon as you stop heating. Allow time for the boiling tube to cool.

- Measure the volume of gas in the inverted tube.
- Reweigh the boiling tube and contents and record the final mass.
- Clean your apparatus and repeat 2 more trials

Results

Qualitative data:

Before experiment	During experiment	After experiment
The copper carbonate in the test tube was green and had a powdery texture. It didn't have any particular smell and it was cool to the touch. The water, the eudiometer and the test tube were also cool to the touch. There were no air bubbles entering the eudiometer.	The copper carbonate started to turn into black copper oxide. It kept its powdery texture. Carbon dioxide started entering in the eudiometer, and as the copper carbonate got hotter, the bubbles of CO_2 started coming out faster. There was no visible change in the water.	The green copper carbonate completely disappeared macroscopically, and turned into black copper oxide. Carbon dioxide bubbles stopped coming out a few seconds after the fire was turned off. The water and eudiometer remained cool to the touch, however, the test tube was significantly hotter. There was some burning smell.

Quantitative data

Table 1. Raw class data. Initial and final mass of reagents and products with test tube (g), initial and final volume of gas in the eudiometer (cm³), room pressure (kPa), and room temperature (K) for each trial; all with their respective uncertainties. Trials 1 and 2 are highlighted in yellow as they were determined to be outliers and thus, were excluded from calculations.

Raw class data						
	Initial Mass of CuCO ₃ + test tube (± 0.01g)	Final Mass of CuO + test tube (± 0.01 g)	Initial volume of gas (± 0.05 cm ³)	Final volume of gas (± 0.05 cm ³)	Room Pressure (± 0.01 kPa)	Room Temperature (±0.1 K)
Trial 1	130.05	129.97	0.00	10.50	100.28	296.6
Trial 2	41.97	41.9	0.00	11.30	100.28	296.6
Trial 3	42.36	42.27	1.21	40.35	100.28	296.6
Trial 4	126.47	126.26	2.20	44.00	100.28	296.6
Trial 5	44.15	44.07	0.98	43.25	100.28	296.6
Trial 6	44.34	44.27	0.00	36.50	100.28	296.6
Trial 7	44.43	44.36	1.50	42.80	100.28	296.6
Trial 8	33.57	33.53	1.00	32.70	100.28	296.6
Trial 9	41.9	41.86	2.10	35.50	100.28	296.6
Trial 10	41.93	41.87	1.50	35.50	100.28	296.6
Trial 11	42	41.92	1.68	34.91	100.33	297.0
Trial 12	44.66	44.6	7.91	43.64	100.33	297.0
Trial 13	42.41	42.35	0.00	44.85	100.33	297.0
Trial 14	42.52	42.44	0.05	44.00	100.33	297.0
Trial 15	41.81	41.75	9.50	44.82	100.33	297.0
Trial 16	42.01	41.98	1.40	49.91	100.33	297.0
Trial 17	42.72	42.64	3.02	47.32	100.33	297.0
Trial 18	42.52	42.48	2.45	45.58	100.33	297.0
Trial 19	42.1	42.03	1.00	32.25	100.33	297.0
Trial 20	41.86	41.79	1.00	31.80	100.33	297.0

Analysis/Calculations

Table 2. Processed data. Mass of carbon dioxide (g), volume of carbon dioxide (dm³), temperature (K), and pressure (kPa) for each trial; all with their respective uncertainties. Molar Gas constant (R) (JK⁻¹mol⁻¹), which remains constant for all trials. Additionally, calculated molar mass through the ideal gas equation with its propagated uncertainty and their average. Molar mass (gmol⁻¹) is displayed in two significant figures, as the value with the least significant figures used to obtain it is the initial volume with two significant figures.

Processed data						
Mass (CO ₂) (±0.02g)	Volume (CO ₂) (±0.0001dm ³)	Temperature (±0.1K)	Pressure (± 0.01 kPa)	Molar Gas Constant (R) (dm ³ kPaK ⁻¹ mol ⁻¹)	Molar mass (gmol ⁻¹)	Molar mass uncertainty (±gmol ⁻¹)
0.09	0.03914	296.6	100.28	8.314	57	10
0.21	0.04180	296.6	100.28	8.314	120	10
0.08	0.04227	296.6	100.28	8.314	47	10
0.07	0.03650	296.6	100.28	8.314	47	10
0.07	0.04130	296.6	100.28	8.314	42	10
0.04	0.03170	296.6	100.28	8.314	31	20
0.04	0.03340	296.6	100.28	8.314	29	10
0.06	0.03400	296.6	100.28	8.314	43	10
0.08	0.03323	297.0	100.33	8.314	59	20
0.06	0.03573	297.0	100.33	8.314	41	10
0.06	0.04485	297.0	100.33	8.314	33	10
0.08	0.04395	297.0	100.33	8.314	45	10
0.06	0.03532	297.0	100.33	8.314	42	10
0.03	0.04851	297.0	100.33	8.314	15	10
0.08	0.04430	297.0	100.33	8.314	44	10
0.04	0.04313	297.0	100.33	8.314	23	10
0.07	0.03125	297.0	100.33	8.314	55	20
0.07	0.04800	297.0	100.33	8.314	36	10
Average					45	10

Sample calculations

Mass of carbon dioxide:

$$m(\text{CO}_2) (g) = m_0(\text{CuCO}_3 + \text{test tube}) (g) - m_f(\text{CuO} + \text{test tube}) (g)$$

Where $m(CO_2)$ is the mass of carbon dioxide (g), $m_0(CuCO_3 + test\ tube)$ is the initial mass of the test tube with copper (II) carbonate (g), and $m_f(CuO + test\ tube)$ is the final mass of the test tube with copper (II) oxide (g) for a given trial. For instance, the mass of carbon dioxide (g) on the third trial would be:
 $42.36g - 42.27g = 0.09g$.

Data used (Table 1):

	Initial Mass of $CuCO_3 + test\ tube$ ($\pm 0.01g$)	Final Mass of $CuO + test\ tube$ ($\pm 0.01\ g$)
Trial 3	42.36	42.27

Volume of carbon dioxide:

$$V(CO_2) (dm^3) = \frac{V_f(cm^3) - V_0(cm^3)}{1000}$$

Where $V(CO_2)$ is the volume of carbon dioxide (dm^3), V_0 is the initial volume of gas (cm^3) in the eudiometer, and V_f is the final volume of gas (cm^3) in the eudiometer for a given trial. For instance, the volume of carbon dioxide (dm^3) on the third trial would be: $\frac{40.35cm^3 - 1.21cm^3}{1000} = 0.03914dm^3$

Data used (Table 1):

	Initial volume of gas ($\pm 0.05\ cm^3$)	Final volume of gas ($\pm 0.05\ cm^3$)
Trial 3	1.21	40.35

Molar mass of carbon dioxide:

$$Mr (gmol^{-1}) = \frac{m(g) * R (dm^3 kPaK^{-1} mol^{-1}) * T(K)}{P(kPa) * V(dm^3)}$$

Where Mr is the molar mass of carbon dioxide ($gmol^{-1}$), m is the mass of carbon dioxide (g), R is the gas constant ($dm^3 kPaK^{-1} mol^{-1}$), T (K) is the temperature, P (kPa) is the pressure and V (dm^3) is the volume of carbon dioxide. For instance, the molar mass of carbon dioxide in the third trial would be:

$$\frac{0.09g * 8.314dm^3 kPaK^{-1} mol^{-1} * 296.6K}{100.28kPa * 0.03914dm^3} \approx 57gmol^{-1}$$

*Calculation rounded to two significant figures because the data used to calculate the mass (g) has at least two significant figures.

Data used (Table 2):

Mass (CO_2) ($\pm 0.02g$)	Volume (CO_2) ($\pm 0.0001dm^3$)	Temperature ($\pm 0.1K$)	Pressure ($\pm 0.01\ kPa$)	Molar Gas Constant (R) ($dm^3 kPaK^{-1} mol^{-1}$)
0.09	0.03914	296.6	100.28	8.314

Uncertainty of molar mass of carbon dioxide:

$$\pm Mr (\text{gmol}^{-1}) = \pm \left(\frac{\pm m(\text{g})}{m(\text{g})} + \frac{\pm T(\text{K})}{T(\text{K})} + \frac{\pm P(\text{kPa})}{P(\text{kPa})} + \frac{\pm V(\text{dm}^3)}{V(\text{dm}^3)} \right) * Mr (\text{gmol}^{-1})$$

Where $Mr (\text{gmol}^{-1})$ is the molar mass of carbon dioxide and $\pm Mr (\text{gmol}^{-1})$ is its uncertainty, $m (\text{g})$ is the mass of carbon dioxide and $\pm m (\text{g})$ is its uncertainty, $T (\text{K})$ is the temperature and $\pm T (\text{K})$ is its uncertainty, $P (\text{kPa})$ is the pressure and $\pm P (\text{kPa})$ is its uncertainty, and $V (\text{dm}^3)$ is the volume of carbon dioxide and $\pm V (\text{dm}^3)$ is its uncertainty. For instance, the uncertainty of molar mass of carbon dioxide for the third trial would be:

$$\pm \left(\frac{0.02\text{g}}{0.09\text{g}} + \frac{0.1\text{K}}{296.6\text{K}} + \frac{0.01\text{kPa}}{100.28\text{kPa}} + \frac{0.0001\text{dm}^3}{0.03941\text{dm}^3} \right) * 57\text{gmol}^{-1} \approx 10\text{gmol}^{-1}$$

Data used (Table 2):

Mass (CO ₂) (±0.02g)	Volume (CO ₂) (±0.0001dm ³)	Temperature (±0.1K)	Pressure (± 0.01 kPa)	Molar Gas Constant (R) (dm ³ kPaK ⁻¹ mol ⁻¹)	Molar mass (gmol ⁻¹)
0.09	0.03914	296.6	100.28	8.314	57

Outliers:

$$\text{Lower range limit} = Q_1 - (1.5 * IQR)$$

$$\text{Upper range limit} = Q_3 - (1.5 * IQR)$$

$$IQR = Q_3 - Q_1$$

Where Q_n is the n-quartile and IQR is the interquartile range. The interquartile range would be:

$0.04334\text{dm}^3 - 0.03336\text{dm}^3 = 0.00998\text{dm}^3$, the lower range limit for the volume of carbon dioxide would be: $0.03336\text{dm}^3 - (1.5 * 0.00998\text{dm}^3) = 0.01839\text{dm}^3$, and the upper range limit would be: $0.04334\text{dm}^3 + (1.5 * 0.00998\text{dm}^3) = 0.05830\text{dm}^3$. Since the volume of carbon dioxide of trails 1 and 2 is lower than the lower range limit, they are considered outliers and therefore they were excluded from the calculations.

Data used (Table 2):

All values for volume of carbon dioxide (dm³) (table 2).

Percentage error:

$$\%Error = \left| \frac{Mr_a - Mr_t}{Mr_t} \right| * 100\%$$

Where Mr_a is the experimental value obtained for the molar mass of carbon dioxide (gmol⁻¹) and Mr_t is the literature value for the molar mass of carbon dioxide. The percentage error for the molar mass (gmol⁻¹) of carbon dioxide is: $\left| \frac{45-44.01}{44.01} \right| * 100\% = 2.2\%$ (International Baccalaureate Organization, 2017).

Data used (Table 2):

Average	Molar mass (gmol ⁻¹)
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	45
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Periodic table (CO₂ molar mass) (International Baccalaureate Organization, 2017).

Percentage uncertainty of molar mass of carbon dioxide:

$$\% \pm Mr = \pm \frac{\pm Mr (g mol^{-1})}{Mr (g mol^{-1})} * 100\%$$

Where % $\pm Mr$ is the percentage uncertainty of the molar mass of carbon dioxide, $\pm Mr (g mol^{-1})$ is the absolute uncertainty of the molar mass of carbon dioxide, and $Mr (g mol^{-1})$ is the molar mass of carbon dioxide. The percentage uncertainty for the experimental value of carbon dioxide obtained is: $\pm \frac{10...g mol^{-1}}{45...g mol^{-1}} \approx \pm 30\%$

Data used (Table 2):

	Molar mass (g mol ⁻¹)	Molar mass uncertainty (\pm g mol ⁻¹)
Average	45	10

Conclusion

In table 2, the mass of carbon dioxide (g), the volume of carbon dioxide (dm³), temperature (K), and pressure (kPa) were calculated for each trial. This data was then used to calculate the molar mass of carbon dioxide through the use of an adapted equation of ideal gases, $Mr (g mol^{-1}) = \frac{m(g) * R (dm^3 kPa K^{-1} mol^{-1}) * T(K)}{P(kPa) * V(dm^3)}$, where

$$n(mol) = \frac{m(g)}{Mr (g mol^{-1})} \text{ was substituted in}$$

$P(kPa) * V(dm^3) = n(mol) * R (dm^3 kPa K^{-1} mol^{-1}) * T(K)$ (International Baccalaureate Organization, 2017). This alternative formula allowed the calculation of the molar mass of carbon dioxide, which, after averaging all the different molar masses obtained, is found to be $45 \pm 10 g mol^{-1}$. This value is a good approximation to the actual molar mass of carbon dioxide, as its literature value, obtained from the *Chemistry Data Booklet*, is $44.01 g mol^{-1}$, which is within the range of the experimental value and has indicates that it is relatively accurate (2017). Additionally, this result's lack of precision and accuracy is justifiable, as the formula used to obtain these values works better when the gas is under low pressure and has a high temperature (Tenny & Cooper, 2021). Another trend found in the data results (table 2) is that, on average, the mass of carbon dioxide produced was around 0.07g. This is a reasonable value considering that when using stoichiometry to find the theoretical mass yield of carbon dioxide when copper (II) carbonate is decomposed in carbon dioxide and copper (II) oxide should be $\frac{0.20g}{123.56 g mol^{-1}} * 44.01 g mol^{-1} = 0.07g$ (International Baccalaureate Organization, 2017). In conclusion, the molar mass of carbon dioxide is found to be $45 \pm 10 g mol^{-1}$ (table 2).

Evaluation

Throughout the execution of this lab, as mentioned above, the molar mass is found to be $45 \pm 10 g mol^{-1}$, however, its literature value is $44.01 g mol^{-1}$. This reveals that there is a 2.2% error, indicating that the calculated value is relatively accurate. Nonetheless, the percentage uncertainty for the molar mass of carbon dioxide is found to be $\pm 30\%$, indicating that the data is not precise, relatively speaking. This is due to the sources of error and uncertainties that affected the accuracy and precision, found in the methodology of this experiment.

First, the tools used to measure the volume (dm^3), mass (g), temperature (K), and pressure (kPa) of carbon dioxide all have random uncertainties, however, only the mass (g) uncertainty is relatively significant. The percentage uncertainty for these measurements is of $\pm 0.3\%$ for volume (dm^3), $\pm 0.03\%$ for temperature (K), and $\pm 0.01\%$ for pressure; meaning that these sources of error are relatively insignificant. On the other hand, the percentage uncertainty of the average mass (g) of carbon dioxide was $\pm 30\%$, making it a very significant source of error. In order to reduce the uncertainties of these measurements, a new experiment can be made were more precise, and ideally digital to avoid human estimation error, tools are used to measure these variables. Additionally, this new experiment should be done in a controlled environment in order to minimize temperature and pressure variations. In particular, the tool used to measure mass (g) would need to be covered to avoid any air currents or other externalities affecting the readings.

Additionally, the limitations of the ideal gas equation when used on real gases should be considered. It is known that this equation works better with monatomic gases at high temperatures and low pressure, so a systematic error can be expected in this experiment due to the consistent, relatively low temperature and not as low pressure (Tenny & Cooper, 2021). The significance of this error cannot be determined with the collected data. Even though there's nothing that can be done about carbon dioxide not being diatomic without changing the aim of this experiment, this source of error can be minimized by performing the experiment in a vacuum environment and by subjecting the carbon dioxide to higher temperatures. This can be achieved in more technologically advanced labs but would be very difficult to accomplish in a high school environment.

Finally, the point of reference for the pressure and temperature measurements is also a source of error. The temperature (K) and pressure (kPa) values used for the calculation of molar mass weren't taken directly from the gas, but from the air in the room. The significance of this source of error cannot be determined with the data collected, as it is dependent on the temperature (K) and pressure (kPa) difference between the room and the carbon dioxide. However, it can be minimized by implementing temperature and pressure sensors on the instruments where carbon dioxide will pass through and be measured.

In addition to these sources of error and uncertainty, the high percentage uncertainty of the molar mass of carbon dioxide, $\pm 30\%$, is also due to the propagated uncertainty of all the other variables. All the percentage uncertainties of the other variables were added together to get this uncertainty, with the most significant one being the uncertainty of the mass (g) of carbon dioxide.

Nonetheless, the method employed has some strengths. For instance, it is more accessible as it can be performed with instruments commonly found in a school lab, whereas the suggestions that have been made so far would require specialized instruments and tools that are hard to obtain. Additionally, the sources of error caused by random uncertainties can be reduced by doing multiple trials or using larger quantities of reactants.

There are some extensions to the experiment that would allow it to be more accurate and precise. For instance, instead of decomposing copper (II) carbonate into carbon dioxide and copper oxide, barium azide (BaN_6) could be heated to decompose it into elemental barium (Ba) and nitrogen gas (N_2), which has a lower molar mass than carbon dioxide, and therefore would have a behaviour closer to the one of an ideal gas. Additionally, instead of letting the gas occupy more volume to leave pressure the same, another method could be tried where volume is fixed—by maintaining the reaction in a closed system—, and a pressure sensor measures the pressure (kPa) to calculate the molar mass. Using different methods could help to reduce any systematic errors that were present in each method, allowing data to be more accurate.

In conclusion, the experimentally obtained value for the molar mass of carbon dioxide (gmol^{-1}), is relatively accurate with a 2.2% percentage error compared to the literature value, and it is relatively imprecise, with a $\pm 30\%$ percentage uncertainty.

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