Explainer: Moles

In this explainer, we will learn how to define the mole in terms of Avogadro's constant and convert the mass of a substance to an amount of moles.

In 1811, Amedeo Avogadro hypothesized that gases of equal volumes at equal temperatures and pressures contain the same number of gas particles. Nearly 100 years later, Jean Baptiste Perrin defined this number of particles as Avogadro's number in honor of Amedeo Avogadro's earlier hypothesis. Various experiments over the years have been used to determine the exact value of Avogadro's number. Previously, Avogadro's number was defined as the number of atoms of carbon-12 in 12 grams of carbon-12. Today, Avogadro's number is defined as exactly $6.02214076 \times 10^{23}$.

Definition: Avogadro's Number

Avogadro's number is equal to $6.02214076 \times 10^{23}$.

Avogadro's number is a very large value:

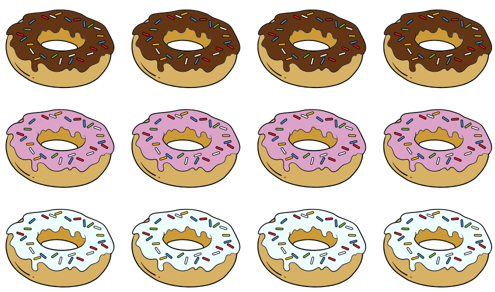
$$602\,214\,076\,000\,000\,000\,000\,000.$$

It is useful when counting very small entities like molecules, atoms, and protons; however, its large magnitude can make calculations difficult. To make working with Avogadro's number easier, scientists defined a new unit called the mole. The mole, frequently abbreviated as mol, is equal to Avogadro's number.

Definition: Mole (mol)

The mole is the SI unit of the amount of a substance (n). 1 mole $= 6.02214076 \times 10^{23}$ entities.

As a unit, the mole functions in a similar way to the unit dozen. We know that one dozen is equal to 12 items. If there are 12 donuts on a table, we could say that there is one dozen donuts. Similarly, if there are $6.02214076 \times 10^{23}$ donuts, we could say that there is one mole of donuts.



12 donuts = 1 dozen donuts

$6.02214076 \times 10^{23}$ donuts = 1 mole of donuts

In chemistry, the entities being referred to by the relationship

$$1 \text{ mole} = 6.02214076 \times 10^{23} \text{ entities}$$

include atoms, molecules, formula units, ions, and particles. Thus, one mole of protons is $6.02214076 \times 10^{23}$ protons, and $6.02214076 \times 10^{23}$ molecules of sucrose ($C_{12}H_{22}O_{11}$) is one mole of sucrose molecules.

When converting between moles and entities, it is useful to use Avogadro's constant (N_A). Avogadro's constant has the same numerical value as Avogadro's number, but it is given the unit mol^{-1}.

Constant: Avogadro's Constant (N_A)

It is a constant useful for converting between moles and entities that has the same numerical value as Avogadro's number and is given the symbol N_A:

$$6.02214076 \times 10^{23} \text{ mol}^{-1}.$$

Avogadro's constant is much more precise than is necessary for most calculations and is often rounded to $6.022 \times 10^{23} \text{ mol}^{-1}$. This is the value we will use from now on.

Avogadro's constant can be used to relate the number of moles (n) to the number of entities in the substance (N).

Equation: Calculating the Number of Entities from the Number of Moles Using Avogadro's Constant

The following equation can be used to convert between the number of entities and the number of moles:

$$N = N_A n,$$

where N represents the number of entities, N_A is Avogadro's constant, and n represents the number of moles.

When converting from moles into entities, we can substitute the number of moles and Avogadro's constant into the equation. If we wanted to determine how many sodium atoms there are in 12 moles of sodium atoms, we would solve as follows:

$$\begin{aligned}
N &= N_A n \\
N &= \left(6.022 \times 10^{23}\ \text{mol}^{-1}\right) \cdot 12\ \text{moles of atoms} \\
N &= 7.23 \times 10^{24}\ \text{atoms.}
\end{aligned}$$

Therefore, 12 moles of sodium atoms contain 7.23×10^{24} atoms of sodium.

When converting from entities into moles, we can rearrange the equation to solve for moles:

$$n = \frac{N}{N_A}.$$

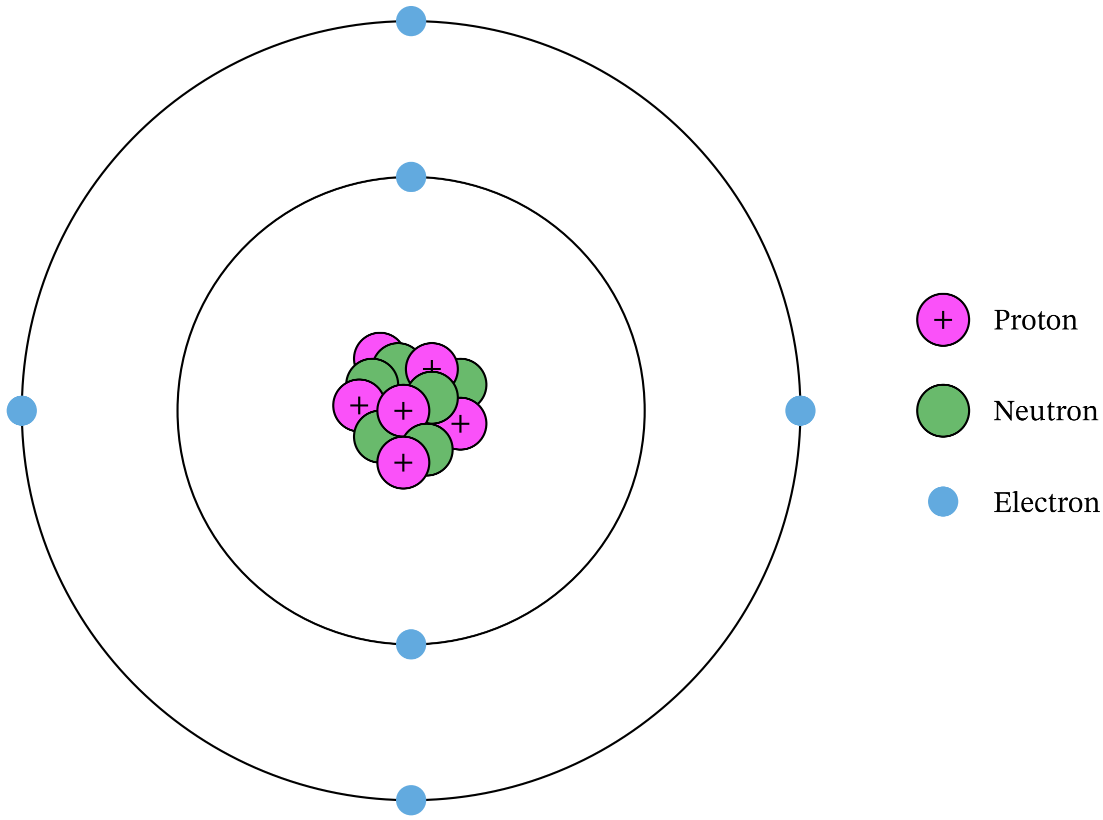
We can see that when solving for the number of moles, we should divide the number of entities by Avogadro's constant. If we wanted to determine how many moles of nitrogen atoms are in 8.50×10^{22} atoms of nitrogen, we would solve as follows:

$$\begin{aligned}
n &= \frac{N}{N_A} \\
n &= \frac{\left(8.50 \times 10^{22}\ \text{atoms}\right)}{\left(6.022 \times 10^{23}\ \text{mol}^{-1}\right)} \\
n &= 0.14\ \text{moles of atoms.}
\end{aligned}$$

Therefore, 8.50×10^{22} atoms of nitrogen is 0.14 moles of nitrogen atoms.

When converting between moles and entities, it is important to pay attention to and recognize the relationship between different entities.

For example, consider the following atom of carbon-12.



An atom of carbon-12 contains six protons, six neutrons, and six electrons. Therefore, if there was one mole of carbon-12 atoms, then there would be 6.022×10^{23} carbon-12 atoms:

$$N = 1 \text{ mole of carbon-12 atoms} \cdot \frac{(6.022 \times 10^{23})}{1 \text{ mol}}$$
$$N = 6.022 \times 10^{23} \text{ carbon-12 atoms.}$$

However, if we wanted to know how many protons, neutrons, and electrons there are in one mole of carbon-12 atoms, then we would need to multiply the number of carbon-12 atoms by six for each subatomic particle as shown below:

$$6.022 \times 10^{23} \text{ carbon-12 atoms} \cdot \frac{6 \text{ protons}}{1 \text{ carbon-12 atom}} = 3.61 \times 10^{24} \text{ protons,}$$
$$6.022 \times 10^{23} \text{ carbon-12 atoms} \cdot \frac{6 \text{ neutrons}}{1 \text{ carbon-12 atom}} = 3.61 \times 10^{24} \text{ neutrons,}$$
$$6.022 \times 10^{23} \text{ carbon-12 atoms} \cdot \frac{6 \text{ electrons}}{1 \text{ carbon-12 atom}} = 3.61 \times 10^{24} \text{ electrons.}$$

Example 1: Determining the Number of Oxygen Atoms Present in a Given Number of Moles of Aluminum Nitrate

How many oxygen atoms are there in 4.0×10^{-3} moles of $Al(NO_3)_3$? Give your answer to 1 decimal place.

Answer

If this question had asked how many oxygen atoms are there in one formula unit of $Al(NO_3)_3$, we could easily have answered by looking at the chemical formula. We see that each nitrate ion has three oxygen atoms and that there are three nitrate ions in the formula:

$$3 \text{ oxygen atoms per nitrate ion} \times 3 \text{ nitrate ions} = 9 \text{ oxygen atoms.}$$

This gives us a total of nine oxygen atoms in one formula unit of $Al(NO_3)_3$.

However, this question does not want to know how many oxygen atoms there are in one formula unit, but how many oxygen atoms there are in 4.0×10^{-3} moles of $Al(NO_3)_3$. This means that we will need to convert the moles of $Al(NO_3)_3$ into formula units, as we know how many oxygen atoms there are per formula unit.

To convert between moles and a number of entities (in this case, formula units), we can use the equation

$$N = N_A n,$$

where N is the number of formula units, N_A is Avogadro's constant, and n is the number of moles. Avogadro's constant is $6.02214076 \times 10^{23}$ mol^{-1}. It is not necessary for us to use Avogadro's constant to this level of precision, so we can round it to 6.022×10^{23} mol^{-1}.

We can substitute Avogadro's constant and the number of moles into the equation:

$$N = \left(6.022 \times 10^{23} \text{ mol}^{-1}\right) \cdot \left(4.0 \times 10^{-3} \text{ moles of Al(NO}_3)_3\right).$$

Thus, we determine the number of formula units to be

$$N = 2.4088 \times 10^{21} \text{ formula units of Al(NO}_3)_3.$$

We have already established that one formula unit of $Al(NO_3)_3$ contains nine atoms of oxygen. To determine how many atoms of oxygen are in 2.4088×10^{21} formula units, we can multiply this value by nine oxygen atoms per formula unit:

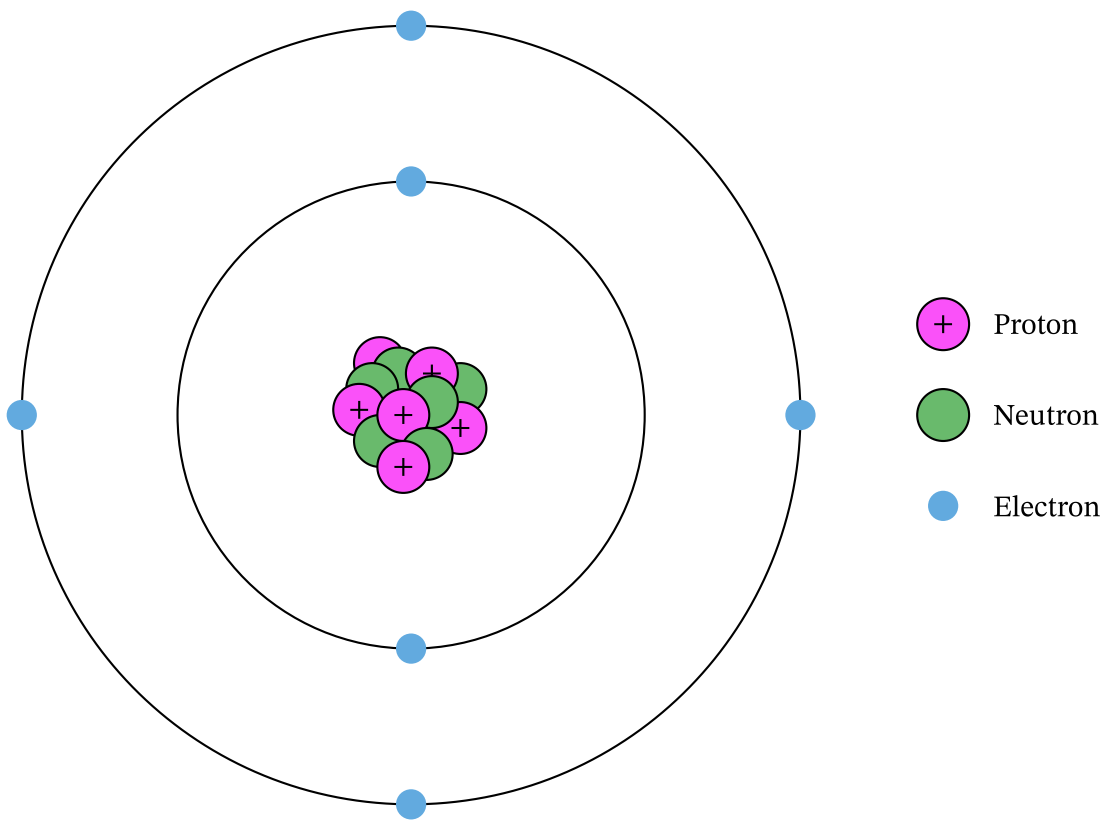
$$2.4088 \times 10^{21} \text{ formula units of Al(NO}_3)_3 \cdot \frac{9 \text{ oxygen atoms}}{1 \text{ formula unit of Al(NO}_3)_3} = 2.16792 \times 10^{22} \text{ oxygen atoms.}$$

Rounding the answer to one decimal place, we have determined that 4.0×10^{-3} moles of $Al(NO_3)_3$ contains 2.2×10^{22} atoms of oxygen.

Avogadro's number can also be used to relate the mass of a substance in grams to the number of entities in the substance, as the following relationship can be made:

$$6.022 \times 10^{23}\ \mathrm{u} = 1\ \text{gram}.$$

Let us consider a carbon-12 atom that contains six protons, six neutrons, and six electrons.



An atom of carbon-12 has an atomic mass of 12 u. If there are 6.022×10^{23} atoms of carbon-12, or one mole of carbon-12 atoms, they would have a total mass of

$$\frac{12\ \mathrm{u}}{1\ \text{atom}} \cdot \left(6.022 \times 10^{23}\ \text{atoms}\right) = 7.2264 \times 10^{24}\ \mathrm{u}.$$

Since

$$6.022 \times 10^{23}\ \mathrm{u} = 1\ \text{gram},$$

we can convert the total mass in unified atomic mass units into grams:

$$\left(7.2264 \times 10^{24}\ \mathrm{u}\right) \cdot \frac{1\ \mathrm{g}}{\left(6.022 \times 10^{23}\ \mathrm{u}\right)} = 12\ \mathrm{g}.$$

We have determined that one mole of carbon-12 atoms has a mass of 12 grams. We can express this mass with the unit grams per mole (g/mol) to indicate that this is the mass for one mole of carbon-12 atoms. The mass of one mole of a substance is called the molar mass (M).

The molar mass of a substance can be quickly determined from the formula mass. The molar mass of a substance will have the same numerical value as the formula mass, but it will be given the unit grams per mole.

For example, water (H_2O) has a formula mass of 18 u. Thus, the molar mass of water is 18 g/mol. This means that one mole of water, 6.022×10^{23} molecules of water, will have a mass of 18 g.

The molar mass of a substance can be used to relate the known mass of a substance in grams (m) to the amount of that substance in moles (n).

Equation: Calculating the Number of Moles from the Mass Using the Molar Mass

The following equation can be used to calculate the number of moles a given mass of a substance contains:

$$n = \frac{m}{M},$$

where n is the number of moles, m is the mass in grams, and M is the molar mass in grams per mole.

Example 2: Calculating the Number of Moles of Selenium from a Given Mass

The recommended daily intake of selenium for an adult is approximately 0.068 mg. How many moles of selenium is this? Give your answer to 2 decimal places. [Se = 79 g/mol]

Answer

The mass of a substance can be related to the amount of the substance in moles by the following equation:

$$n = \frac{m}{M},$$

where n represents the number of moles, m is the mass in grams, and M is the molar mass in grams per mole. The molar mass of selenium is given in the question (79 g/mol) as is the mass of selenium (0.068 mg). However, in order to use the equation, the mass must be in grams.

There are 1 000 mg in 1 g. We can convert the mass from milligrams to grams by multiplying by 1 g per 1 000 mg:

$$0.068\ \text{mg} \cdot \frac{1\ \text{g}}{1\,000\ \text{mg}} = 6.8 \times 10^{-5}\ \text{g}.$$

Then, we can substitute the mass in grams and the molar mass into the equation:

$$n = \frac{\left(6.8 \times 10^{-5}\ \text{g}\right)}{79\ \text{g/mol}}.$$

Then, we can solve for the number of moles:

$$n = 8.60759\ldots \times 10^{-7}\ \text{moles}.$$

Rounding to two decimal places, we have determined that 0.068 mg of selenium is 8.61×10^{-7} moles of selenium.

Example 3: Calculating the Mass of Hydrazine from the Number of Moles of Hydrazine

What is the mass of 0.443 mol of hydrazine (N_2H_4)? Give your answer to 1 decimal place. [H = 1 g/mol, N = 14 g/mol]

Answer

The mass of a substance can be related to the amount of the substance in moles by the following equation:

$$n = \frac{m}{M},$$

where n represents the number of moles, m is the mass in grams, and M is the molar mass in grams per mole. The number of moles is given in the question (0.443 mol). We need to determine the mass (m). Rearranging the equation to solve for the mass, gives us the equation

$$m = nM.$$

Before we can substitute values into the equation, we will need to calculate the molar mass of hydrazine. The molar mass is the mass of one mole of substance. We are given the molar mass of hydrogen and the molar mass of nitrogen. One mole of hydrazine consists of two moles of nitrogen atoms and four moles of hydrogen atoms. To calculate the molar mass of hydrazine, we can multiply the molar mass of hydrogen by four and the molar mass of nitrogen by two:

$$\text{H:}\ 1\ \text{g/mol} \cdot 4 = 4\ \text{g/mol},$$
$$\text{N:}\ 14\ \text{g/mol} \cdot 2 = 28\ \text{g/mol}.$$

Then, we sum these values:

$$4\ \text{g/mol} + 28\ \text{g/mol}.$$

Thus, we determine the molar mass of hydrazine to be 32 g/mol. We can now substitute the molar mass and number of moles into the equation:

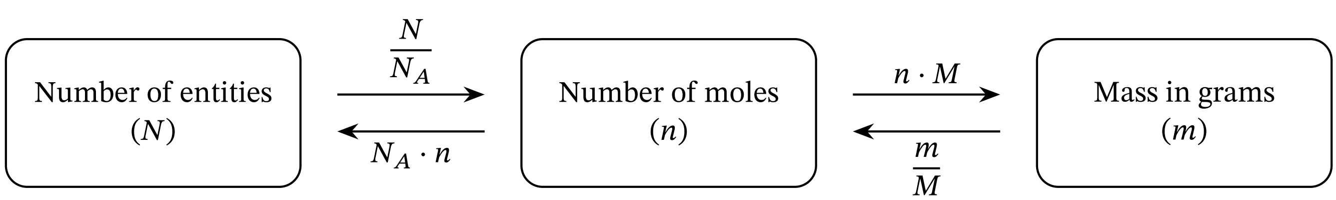
$$m = 0.443 \text{ mol} \cdot 32 \text{ g/mol}.$$

Thus, we determine the mass to be

$$m = 14.176 \text{ g}.$$

Rounding the answer to one decimal place, we have determined the mass of 0.443 moles of hydrazine to be 14.2 grams.

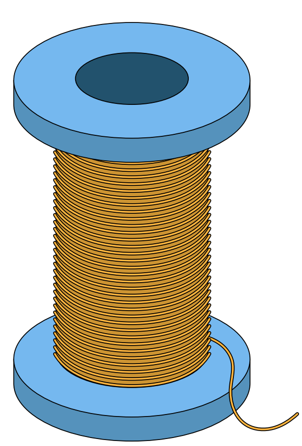
When we wish to relate the number of entities to the mass in grams or vice versa, we will need to convert our initial value into moles before proceeding. This process is outlined in the diagram below.



$N_A = 6.022 \times 10^{23} \text{ mol}^{-1}$ $\qquad$ M = Molar mass (g/mol)

Example 4: Calculating the Number of Copper Atoms given a Mass of Copper Wire

Copper is commonly used to fabricate electrical wire. How many copper atoms are in 5.00 g of copper wire? Give your answer to 2 decimal places. [Cu = 63.5 g/mol]



Answer

We are asked to determine the number of copper atoms given the mass of copper wire to be 5.00 grams. We cannot directly relate the number of atoms to mass; however, the number of atoms and mass can both be related to the number of moles.

The relationship between number of atoms, mass, and moles is represented in the diagram below.

$$\boxed{\begin{array}{c}\text{Mass in grams}\\(m)\end{array}} \xrightarrow{\frac{m}{M}} \boxed{\begin{array}{c}\text{Number of moles}\\(n)\end{array}} \xrightarrow{N_A \cdot n} \boxed{\begin{array}{c}\text{Number of entities}\\(N)\end{array}}$$

$$M = \text{Molar mass (g/mol)} \qquad N_A = 6.022 \times 10^{23}\ \text{mol}^{-1}$$

We can begin by converting the mass of copper into moles by substituting the mass and the molar mass of copper, given in the question to be 63.5 g/mol, into the following equation:

$$\begin{aligned} n &= \frac{m}{M} \\ n &= \frac{5.00\ \text{g}}{63.5\ \text{g/mol}} \\ n &= 0.07874\ldots\ \text{mol}. \end{aligned}$$

Next, we can convert the amount of copper in moles into atoms of copper by substituting the number of moles and Avogadro's constant ($6.022 \times 10^{23}\ \text{mol}^{-1}$) into the following equation:

$$\begin{aligned} N &= N_A n \\ N &= \left(6.022 \times 10^{23}\ \text{mol}^{-1}\right) \cdot 0.07874\ \text{mol} \\ N &= 4.7417\ldots \times 10^{22}. \end{aligned}$$

Rounding the answer to two decimal places, we have determined that 5.00 grams of copper wire has 4.74×10^{22} atoms of copper.

Example 5: Calculating the Number of Oxygen Atoms in a Given Mass of Oxygen Gas

How many oxygen atoms are there in 224 g of O_2? Give your answer to 2 decimal places. [O = 16 g/mol]

Answer

Mass cannot be directly related to atoms, a number of entities. However, both the mass and the number of entities can be related to the number of moles.

The relationship between number of molecules, mass, and number of moles is shown in the diagram below.

$$\begin{array}{c}\text{Mass in grams}\\(m)\end{array} \xrightarrow{\frac{m}{M}} \begin{array}{c}\text{Number of moles}\\(n)\end{array} \xrightarrow{N_A \cdot n} \begin{array}{c}\text{Number of entities}\\(N)\end{array}$$

M = Molar mass (g/mol) $\qquad$ $N_A = 6.022 \times 10^{23}\ \text{mol}^{-1}$

We can begin by calculating the number of moles of oxygen gas using the following equation:

$$n = \frac{m}{M}.$$

We were given the mass of oxygen gas in grams, but we were not given the molar mass. As the chemical formula of oxygen gas is O_2, the molar mass of oxygen gas will be equal to two times the molar mass of an oxygen atom:

$$M = 2 \times 16\ \text{g/mol} = 32\ \text{g/mol}.$$

We can substitute the mass and molar mass into the equation:

$$n = \frac{224\ \text{g}}{32\ \text{g/mol}}.$$

Then, we can solve for the number of moles:

$$n = 7\ \text{mol}.$$

Next, we can substitute the number of moles and Avogadro's constant ($6.022 \times 10^{23}\ \text{mol}^{-1}$) into the following equation:

$$N = N_A n$$

$$N = \left(6.022 \times 10^{23}\ \text{mol}^{-1}\right) \cdot 7\ \text{mol}.$$

Then, we can solve for the number of molecules of oxygen gas:

$$N = 4.2154 \times 10^{24}\ \text{molecules of oxygen gas}.$$

The question asks for the number of oxygen atoms, not the number of oxygen molecules. Oxygen gas is a diatomic molecule that consists of two oxygen atoms. We multiply the number of oxygen gas molecules by the number of atoms of oxygen per molecule:

$$4.2154 \times 10^{24}\ \text{molecule of}\ \mathrm{O_2} \times \frac{2\ \text{atoms of oxygen}}{1\ \text{molecule of}\ \mathrm{O_2}}.$$

We can then calculate the number of oxygen atoms:

$$4.2154 \times 10^{24}\ \text{molecule of}\ \mathrm{O_2} \times \frac{2\ \text{atoms of oxygen}}{1\ \text{molecule of}\ \mathrm{O_2}} = 8.4308 \times 10^{24}\ \text{atoms of oxygen}.$$

Rounding the answer to two decimal places, 224 g of oxygen gas contains 8.43×10^{24} atoms of oxygen.

Key Points

- The amount of a substance is measured in moles.
- One mole of a substance contains $6.02214076 \times 10^{23}$ entities.
- The number of entities (N) and the number of moles (n) can be related using Avogadro's constant, $6.022 \times 10^{23}\ \text{mol}^{-1}$, via the equation $N = N_A n$.
- The molar mass (M) is the mass of one mole of substance and is given in grams per mole (g/mol).
- The mass of a substance (m) and the number of moles (n) can be related using the molar mass (M) via the equation $n = \frac{m}{M}$.