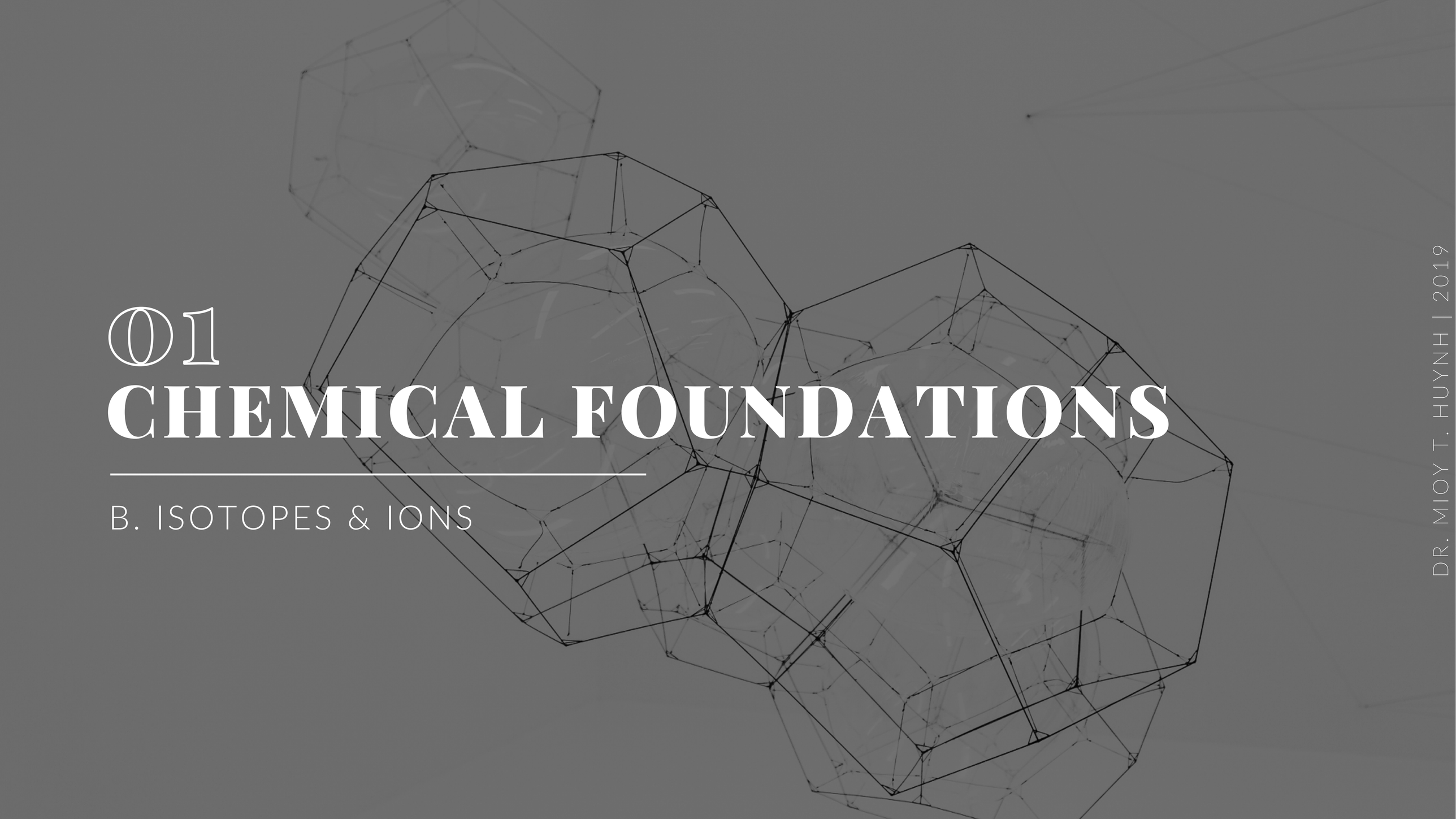


01 CHEMICAL FOUNDATIONS

B. ISOTOPES & IONS

DR. MIOY T. HUYNH | 2019

ISOTOPES

Objective: *Understand what isotopes are*
Be able to determine the number of protons and neutrons in an isotope given the mass number (A)

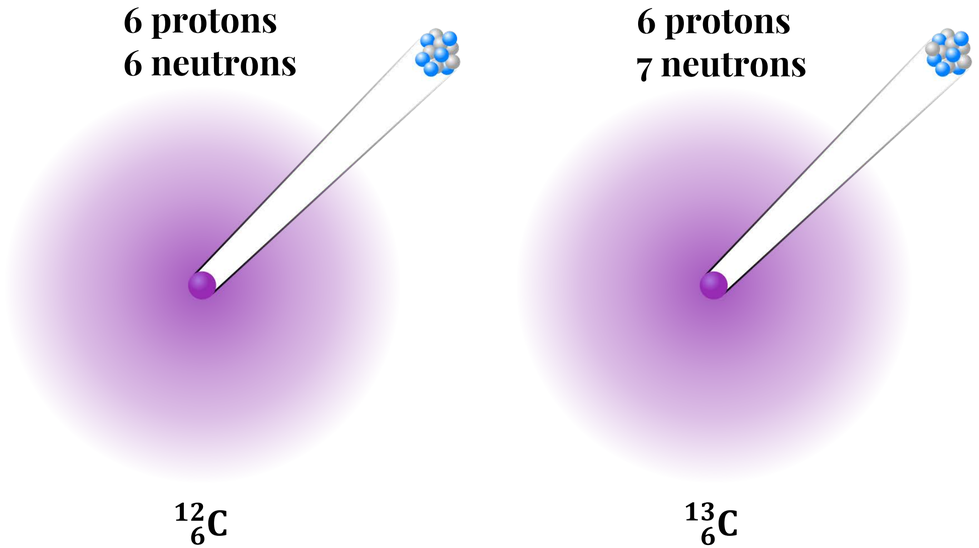
It is the atomic number (Z), or the number of protons, that defines an element. In other words, any atom of carbon (Z = 6) will always have 6 protons in its nucleus. But what about the number of neutrons?

It turns out that it is possible for different atoms of the same element to have *different* numbers of neutrons, and therefore different mass numbers (A), which is the sum of the numbers of protons and neutrons. Such atoms are called isotopes.

We often use either of the following notations to represent atoms and isotopes of an element (X):

$^{A}_{Z}X$ or ^{A}X

As an example, let us consider the two isotopes of carbon shown below: carbon-12 (^{12}C) and carbon-13 (^{13}C).



The difference between these two atoms is that ^{13}C has one more neutron (gray sphere in the inset) ^{12}C.

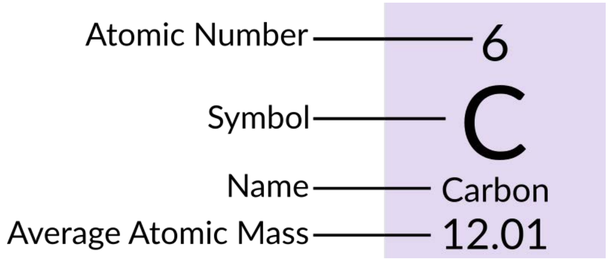
AVERAGE ATOMIC MASS

Objective: *How to calculate the average atomic mass of an element given the masses and abundances of its isotopes*

Any *natural* sample of carbon will contain a mixture of the two stable isotopes, ^{12}C and ^{13}C. Because the two isotopes have different mass numbers (A), due to different numbers of neutrons, they also have different masses (usually measured in units of amu).

As a result, the mass of *natural* carbon samples will always be comprised of these two isotopes. However, the two isotopes exist with different natural abundances in such samples, as shown in the table below.

Isotope	Z	A	Mass (amu)	Abundance
^{12}C	6	12	12.000000	98.89%
^{13}C	6	13	13.003355	1.11%



The mass presented on the periodic table for each element is actually the average atomic mass (m_X), which is the sum of the masses of each stable isotope (m_1, m_2, m_3, ...), weighted by the natural abundances (a_1, a_2, a_3, ...) of each isotope.

$$m_X = a_1 m_1 + a_2 m_2 + a_3 m_3 + \cdots$$

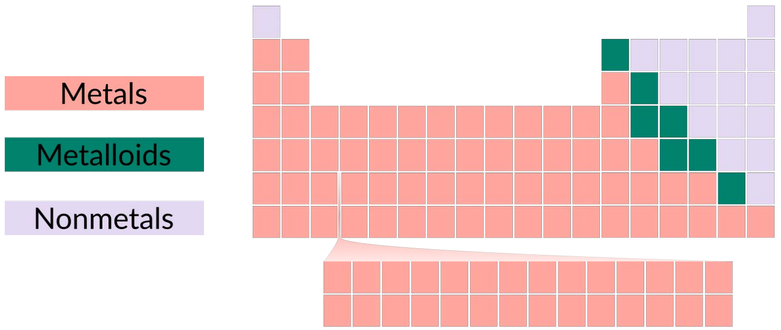
For carbon, the average atomic mass works out to be:

$$m_C = (0.9889)(12.000000\ \text{amu}) + (0.0111)(13.003355\ \text{amu})$$
$$= 12.01\ \text{amu}$$

IONS

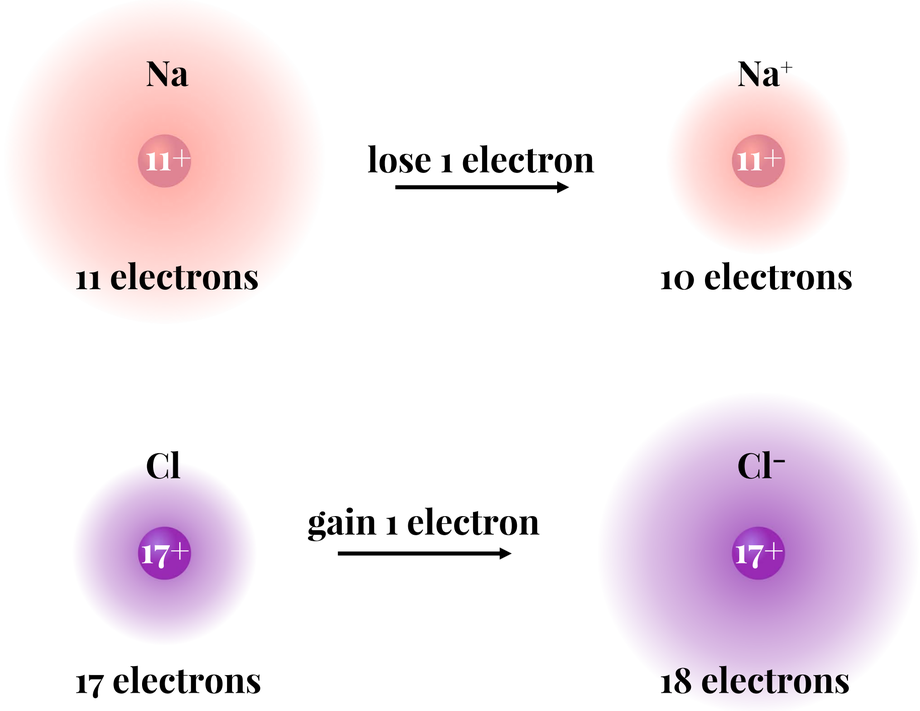
Objective: *Understand what ions (cations and anions) are*
Be able to determine the number of electrons in ions

In addition to having different numbers of neutrons, it is also possible for atoms of the same element to have different numbers of electrons. In these atoms, there is a net positive or net negative charge due to the unequal numbers of protons and electrons. These charged atoms are called ions.



Metals have a tendency to *lose* electrons to form *positively* charged ions called cations. Nonmetals have a tendency to *gain* electrons to form *negatively* charged ions called anions.

Some properties of ions, relative to neutral atoms, are also changed. For instance, the gain or loss of an electron will significantly increase or decrease the size of the ion, relative to the neutral atom, because of the uneven numbers of protons and electrons.



Additionally, solutions of ions are electrically conductive.

PRACTICE PROBLEMS

Fundamental Concepts

1. Complete the following chart.

Symbol:	$^{64}_{30}Zn$	$^{32}_{16}S$	$^{32}_{16}S^{2-}$
# protons			
# neutrons			
# electrons			
Mass Number (A)			

2. What is the symbol for the element with a −1 charge, 36 electrons, and 46 neutrons?

3. Boron exists in two stable isotopes: ^{10}B (10.0129 amu) and ^{11}B (11.00931 amu). If the atomic mass of boron is 10.811 amu, which is the best estimate for the natural abundances of each isotope?

   a) 40% ^{10}B and 60% ^{11}B
   b) 20% ^{10}B and 80% ^{11}B
   c) 60% ^{10}B and 40% ^{11}B

Problem-Solving Skills

4. There are three stable isotopes of magnesium, with masses of 23.9850, 24.9858, and 25.9826 amu. If the average atomic mass of magnesium is 24.3050 amu and the natural abundance of the lightest isotope is 78.99%, what are the natural abundances of the other two isotopes?

5. A compound XCl_2 contains an unknown ion (X^{n+}). If the ion X^{n+} contains 10 electrons, what is the identity of X?

6. A compound contains three times as many atoms of bromine as an unknown metal M. Metal M contains 23 electrons and 31 neutrons when it forms the compound. What is the mass number of M?

7. Consider the following two isotopes: $^{18}F^-$ and $^{15}N^{3-}$.

   a) Which isotopes have the same number of electrons as $^{17}O^{2-}$? There may be more than one answer.
   b) Which isotopes have the same number of neutrons as $^{17}O^{2-}$? There may be more than one answer.

PROBLEM 1

Complete the following chart. *See chart below.*

— answer —

Objective: *Be able to determine the number of protons and neutrons in an isotope given atomic symbol*

Be able to determine the number of electrons in an ion

Symbol:	$^{64}_{30}\mathrm{Zn}$	$^{32}_{16}\mathrm{S}$	$^{32}_{16}\mathrm{S}^{2-}$
# protons	30	16	16
# neutrons	34	16	16
# electrons	30	16	18
Mass Number (A)	64	32	32

Recognize that the atomic symbol ($^{A}_{Z}\mathrm{X}$) gives us the mass number (A) as well as the atomic number (Z).

For $^{64}_{30}\mathrm{Zn}$, the atomic number is Z = 30, which means that there are 30 protons in the nucleus. There are also 30 electrons in the neutral atom since the charges from the protons (+1 each) must cancel out with the charges from the electrons (–1 each). Because the mass number (A = 64) is the sum of the number of protons and neutrons, we can determine there are 34 neutrons in the nucleus ($64 = 30 + n$).

For $^{32}_{16}\mathrm{S}^{2-}$, the atomic number is Z = 16, which means that there are 16 protons in the nucleus. There would be 16 electrons in the neutral atom, but since we have S^{2-} there are two extra electrons, so 18 electrons in total. Because the mass number (A = 32) is the sum of the number of protons and neutrons, we can determine there are 16 neutrons in the nucleus ($32 = 16 + n$).

PROBLEM 2

What is the symbol for the element with a −1 charge, 36 electrons, and 46 neutrons?

— answer —

Objective: *Be able to determine the number of protons and neutrons in an isotope given atomic symbol*

Be able to determine the number of electrons in an ion

First, recognize that we have an ion because there is an overall (net) negative (−1) charge on the unknown atom.

Because we know the *anion* has 36 electrons, the *neutral* atom must have started with 35 electrons to begin with. Remember that electrons are negatively charged.

Second, if the neutral atom had 35 electrons, then it must also have 35 protons in order to balance out the charges. Remember that protons are positively charged. This means that the atomic number is Z = 35, which is Br.

Third, the mass number (A) is equal to the sum of the number of protons and neutrons: $A = 35 + 46 = 81$.

Finally, putting all this information together into a symbol: $^{81}_{35}\mathrm{Br}^{-}$

PROBLEM 3

Boron exists in two stable isotopes: ^{10}B (10.0129 amu) and ^{11}B (11.00931 amu). If the atomic mass of boron is 10.811 amu, which is the best estimate for the natural abundances of each isotope?

— answer —

Objective: *Be able to determine the average atomic mass of an element from isotope masses and natural abundances*

Recall that the average atomic mass of any element is a weighted average of the stable isotopes of that element. This means that for boron, the average atomic mass can be determined from the following expression.

$$m_{\mathrm{B}} = a_1 m_1 + a_2 m_2$$

where $m_1 = 10.0129$ amu, $m_2 = 11.00931$ amu, and a_1 and a_2 are the natural abundances of the two isotopes, respectively.

Because the average atomic mass is 10.811 amu, we can expect the heavier isotope (^{11}B) to have a greater abundance than the lighter isotope (^{10}B). In other words: $a_2 > a_1$. This leaves us with choices (a) and (b).

Moreover, notice that the average atomic mass is slightly closer in value to the mass of ^{11}B isotope's mass. Choice (a) is a bit more evenly split, which would result in an average atomic mass closer to 10.5 amu. Choice (b) is more abundant in ^{11}B, so that is the best estimate.

Note: You could also plug int the percentages to see which gives the closest answer.

PROBLEM 4

There are three stable isotopes of magnesium, with masses of 23.9850, 24.9858, and 25.9826 amu. If the average atomic mass of magnesium is 24.3050 amu and the natural abundance of the lightest isotope is 78.99%, what are the natural abundances of the other two isotopes?

— answer —

Objective: *Be able to determine the natural abundances of isotopes given their masses and the average atomic mass*

Recall that the average atomic mass of any element is a weighted average of the stable isotopes of that element. For magnesium, this is:

$$m_{\mathrm{Mg}} = a_1 m_1 + a_2 m_2 + a_3 m_3$$

where $m_1 = 23.9850$ amu, $m_2 = 24.9858$ amu, $m_3 = 25.9826$ amu, and $a_1 = 0.7899$. We want to determine a_2 and a_3.

Let's reassign $a_2 = x$. Because the abundances must sum to 100%, we can formulate the following expressions for a_2 and a_3:

$$a_1 + a_2 + a_3 = 1.0 \quad \rightarrow \quad a_1 = 0.7899 \quad a_2 = x \quad a_3 = 1.0 - 0.7899 - x = 0.2101 - x$$

We can use these expressions for a_2 and a_3 to plug into the average atomic mass formula above to solve for x (which is a_2):

$$m_{\mathrm{Mg}} = a_1 m_1 + x m_2 + (0.2101 - x) m_3$$

$$24.3050\ \text{amu} = (0.7899)(23.9850\ \text{amu}) + (x)(24.9858\ \text{amu}) + (0.2101 - x)(25.9826\ \text{amu})$$

$$x = 0.1000 = a_2$$

Therefore, the abundances are:

$$a_1 = 0.7899 \quad a_2 = 0.1000 \quad a_3 = 0.1101 \quad \rightarrow \quad a_1 = 78.99\% \quad a_2 = 10.00\% \quad a_3 = 11.01\%$$

PROBLEM 5

A compound XCl_2 contains an unknown ion (X^{n+}). If the ion X^{n+} contains 10 electrons, what is the identity of X?

— answer —

Objective: *Be able to determine the charge of an ion*

Be able to determine the identity of an atom from its atomic number (Z)

First, recognize that the compound contains chloride anions: Cl^-.

Because there are two chloride anions in the compound, the charge of the X cation must be +2 or X^{2+} to make the compound neutral overall.

Second, if X^{2+} cation contains a charge of +2, then the cation had to lose two electrons because each electron carries a –1 charge. Therefore, the neutral atom of X would have contained 12 electrons originally.

Third, the neutral atom would need to have 12 protons, or an atomic number of Z = 12, which corresponds to Mg.

The identity of X is Mg (or Mg^{2+}).

PROBLEM 6

A compound contains three times as many atoms of bromine as an unknown metal M. Metal M contains 23 electrons and 31 neutrons when it forms the compound. What is the mass number of M?

— answer —

Objective: *Be able to determine the charge of an ion*

Be able to determine the identity of an atom from its atomic number (Z)

First, recognize that the compound has this general formula: MBr_3.

Because there are three bromide anions (Br^-) in the compound, the charge of the M cation must be +3 or M^{3+} to make the compound neutral overall.

Second, if M^{3+} cation contains a charge of +3, then the cation had to lose three electrons because each electron carries a −1 charge. Therefore, the neutral atom of M would have contained 26 electrons originally.

Third, the neutral atom would need to have 26 protons, or an atomic number of Z = 26, which corresponds to Fe.

The mass number for Fe would be A = 26 + 31 = 57.

PROBLEM 7

Consider the following two isotopes: $^{18}F^{-}$ and $^{15}N^{3-}$.

a) Which isotopes have the same number of electrons as $^{17}O^{2-}$? There may be more than one answer.

b) Which isotopes have the same number of neutrons as $^{17}O^{2-}$? There may be more than one answer.

— answer —

Objective: *Be able to determine the number of protons and neutrons in an isotope*

Be able to determine the number of electrons in an ion

For each ion, let's determine the number of protons, neutrons, and electrons.

Symbol:	$^{18}_{9}F^{-}$	$^{15}_{7}N^{3-}$	$^{17}_{8}O^{2-}$
# protons	9	7	8
# neutrons	9	8	9
# electrons	10	10	10
Mass Number (A)	18	15	17

Therefore, both $^{18}_{9}F^{-}$ and $^{15}_{7}N^{3-}$ contains the same number of electrons (10) as $^{17}_{8}O^{2-}$.

And, $^{18}_{9}F^{-}$ contain the same number of neutrons (9) as $^{17}_{8}O^{2-}$.