Atomic mass, isotopes, and mass number.

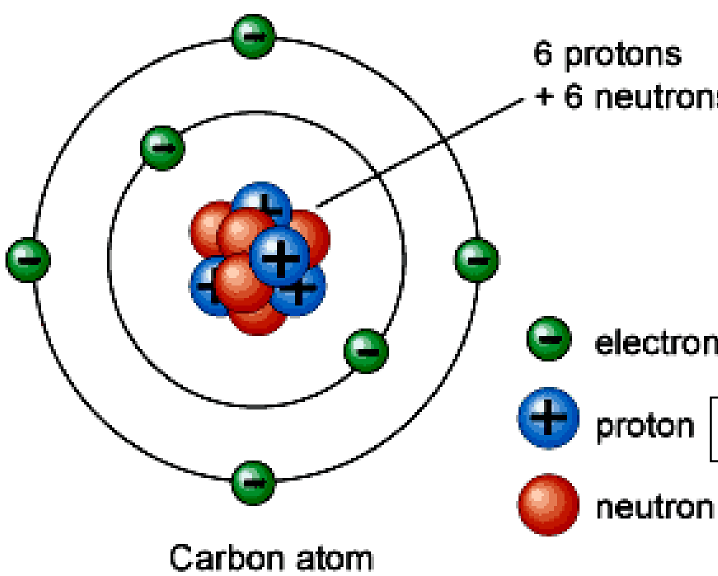
Witten by Katsuya Yamada (13 pages)

Every element in the periodic table of elements has isotopes. What is "isotope"?

Answers:

First of all, recall the atomic structure:

We consider a particular atom: Carbon atom (Carbon 12).



The nucleus.

The NET electric charge of the nucleus is POSITIVE since only positive charges are in the Nucleus {the neutrons (the red spheres) have no charges}.

electron: **<u>Negative</u> electric charge -1**

proton: **<u>Positive</u> electric charge +1**

neutron: **ZERO electric charge**

Simple minded picture of the structure of <u>Carbon atom</u>.
There are 6 *<u>protons</u>* and 6 *<u>neutrons</u>* within the nucleus.
There are 6 *<u>electrons</u>* orbiting the nucleus. Thus, the mass number is 6 + 6 = 12. (Carbon 12)

Since the total **negative** charge is exactly canceled out by the total **positive** charge, the TOTAL net electric charge of the WHOLE atom is zero. The atom as a whole is electrically neutral, neither positive nor negative.

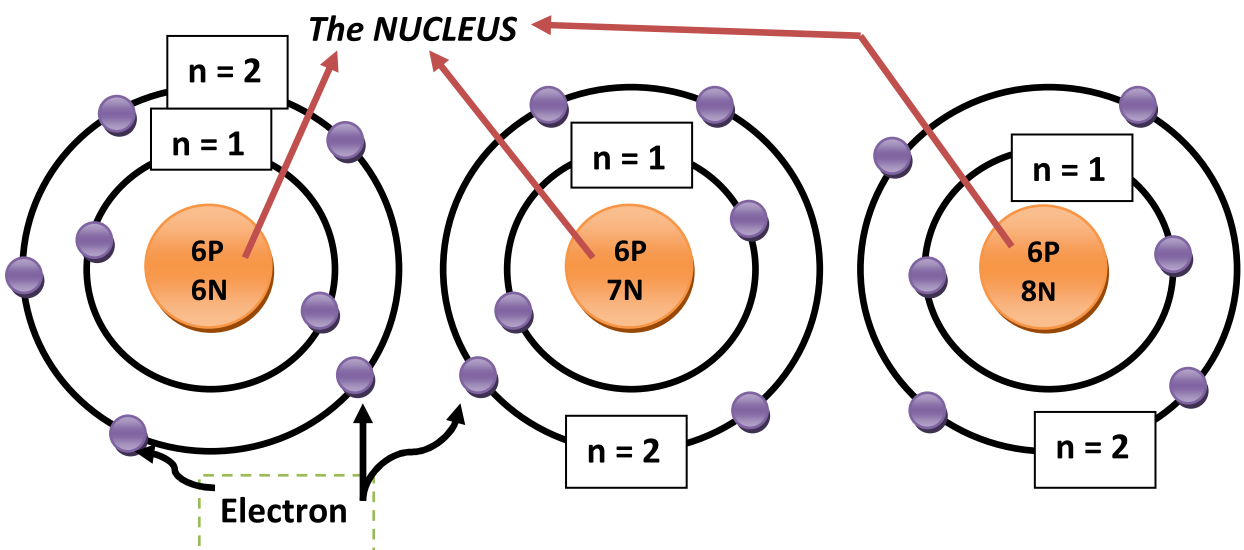
This picture is NOT drawn to scale and extremely enlarged!

Please go to the next page. Thank you!

Isotopes are atoms of the same element that differ in their number of neutrons in the nucleus. Since they are "the same element", all the isotopes represent the atoms that have the same number of protons in the nucleus of the atom and the same number of electrons orbiting the nucleus. Since the number of protons in the nucleus of an atom is defined as "the atomic number" of that atom, the isotopes of an element have the same atomic number.

For example, Carbon has at least three isotopes as shown below.

6P means 6 protons and 7N means 7 neutrons.



$^{12}_{6}C$ | $^{13}_{6}C$ | $^{14}_{6}C$

Carbon 12 | **Carbon 13** | **Carbon 14**

All three carbon atoms have 6 protons in the nucleus and 6 electrons around the nucleus. That is, all three carbon isotopes have the same atomic number. That's why the same name "Carbon". Yes, the atomic number (# of protons) in the nucleus of an atom determines the name of that atom. But the number of neutrons is

different in each isotope. In the nucleus of each Carbon isotope, Carbon 12 has 6 neutrons, Carbon 13 has 7 neutrons, and Carbon 14 has 8 neutrons, as clearly indicated in the figures on the preceding page. These numbers 12, 13, and 14 represent "MASS NUMBER". That is;

Mass Number = # of protons + # of neutrons.

In other words, in all the isotopes of the same element (atom), each isotope has a different mass number. Look at the figures on the preceding page. The mass number of Carbon 12 is 12, the mass number of Carbon 13 is 13, and the mass number of Carbon 14 is 14. But all of these isotopes have the same number of protons (the same atomic number) in the case of Carbon.

NOTE that the mass number is a WHOLE number (or an integer), NOT a fractional number simply because it represents a number of particles.

*Note that apart from the process of radioactive decay, the existence of neutrons does **not** play any important role in the chemical reaction (or chemical change). But the neutrons play the most important role in the NUCLEAR WEAPONS and NUCLEAR REACTORS (The nuclear powered plants)*

ATOMIC MASS.

The atomic mass is a <u>weighted average of the mass numbers</u> of the various isotopes of an element. The atomic mass is the decimal number listed on the periodic table and has units of amu (atomic mass units). An amu is equivalent to the mass of one proton.

In the isotopes of a given element, abundance of each isotope is different. What I mean is that % abundance of one isotope is more (or less) than that of other isotopes.

Again consider Carbon isotopes, Carbon 12, carbon 13, and Carbon 14.

<u>Carbon 14 is radioactive. What it means is that Carbon 14</u>

changes into a completely different element (Nitrogen). For this reason, Carbon 14 is not counted in computing the atomic mass (weighted average of mass number)*. This will be explained in more detail later in this note (See pages 8 though page 11.)* *Therefore, only non-radioactive isotopes are used when determining the atomic mass of an element. In the case of Carbon isotopes, we only consider Carbon 12 and Carbon 13, which are non-radioactive.*

As for the %abundance, Carbon 12 is 99% and Carbon 13 is only 1%. That is, Carbon 12 dominates in abundance. Now we are ready to compute the atomic mass (weighted average of mass number). To do so, we consider 100 Carbon atoms (naturally occurring Carbon atoms). 99 Carbon atoms are Carbon 12 and one Carbon atom is Carbon 13. Then the TOTAL mass number of Carbon 12 is

99 x 12 = 1188

The total mass number of Carbon 13 is

1 x 13 = 13.

Since the total number of Carbon atoms (both 12 and 13) is 100, the average mass number of these two isotopes is

$$\frac{1188+13}{100} = 12.01$$

This is the ATOMIC MASS of Carbon element. Because it represents the AVERAGE value (of mass number), atomic mass is a fractional number (But the mass number is a WHOLE number).

Another example;

Chlorine.

There are TWO non-radioactive chlorine isotopes; Chlorine 35 and Chlorine 37. But there are MANY radioactive chlorine isotopes. All the

radioactive isotopes change into completely different elements (atoms) taking some amount of time (Half life). We say that radioactive isotopes are UNSTABLE. On the other hand, non-radioactive isotopes are STABLE. For this reason, all the radioactive elements are NOT taken into account in determining the atomic mass (the weighted average of mass number). So we only consider non-radioactive (stable) chlorine isotopes; Chlorine 35 and Chlorine 37. Since the atomic number of Chlorine is 17, the number of neutrons in the nucleus of Chlorine 35 is 35 – 17 =18 and the number of neutrons in the nucleus of Chlorine 37 is 37 – 17 = 20. Only the number of neutrons is different (this is what it means "isotope".)
The % abundance of Chlorine 37 is 24.23 % and the abundance of Chlorine 35 is 75.77 %.
Then the weighted average mass number of the two Chlorine isotopes is

$$\frac{37 \times 24.23 + 35 \times 75.77}{100} = 35.48$$

Strictly speaking, we must know "mass in the atomic mass unit of each isotope" in calculating the atomic mass. I don't have time to explain it to you. You simply know that the weighted average mass (averaged over all isotopes) of Chlorine is 35.48 . That will be enough for Physical Science students.
Thus, the atomic mass (weighted average value of the mass number) of Chlorine is 35.48 (Your textbook says 35.45). Again, this is a fractional number.

From the arguments given above, it is obvious that the MASS-NUMBER of the most abundant isotope is obtained from the atomic

mass. How? Simply round off the atomic mass to obtain a whole number. This whole number is the mass number of the most abundant isotope.

In the case of Carbon, since the atomic mass is 12.01, the mass number of the most abundant Caron isotope is obtained by rounding off 12.01, which is 12 (A whole number). So the mass number of most abundant Carbon isotope is 12. Does this make sense? Oh yes it does. As is shown on the preceding page, the natural % abundance of Carbon 12 is 99% and that of Carbon 13 is only 1 %. Obviously the most abundant Carbon isotope is Carbon 12.

How about Chlorine? The atomic mass of Chlorine is, as computed above, 35.48. It becomes 35 after the figure 35.48 is rounded off. So, the most abundant isotope of Chlorine is Chlorine 35. Is this true? Oh yes. As shown above on the preceding page, the % abundance of Chlorine 35 is 75.77 %. Obviously Chlorine 35 is the most abundant. Remember that the atomic mass is a fractional number and the mass number is a whole number (an integer).

Thus

Mass number of the most abundant isotope

= Round off the atomic mass.

This is a whole number, NOT a fractional number!

One of the questions I ask in the test is the following. Look at the following data for one of the isotopes of Chlorine.

Atomic number 17

Number of neutrons 20 ← NOTE!

Atomic mass 35.48

Next page.

OK. What is the <u>mass number</u> of this Chlorine isotope based on the data above? Can you answer???????

Some students answer 35. Why? Because 35 is obtained by rounding off the atomic mass 35.48. But the mass number of the chlorine isotope based on the data given above is NOT 35! Why not? Remember the very definition of the mass number, which is

Mass # = # of protons + # of neutrons.

Since # of protons is the atomic number, which is 17 for the Chlorine and # of neutrons is 20 according to the data given above. Therefore, the mass number of Chlorine (# of protons + # of neutrons) is 17 + 20 = 37. Yes, the mass number of this Chlorine isotope whose data are given above is 37, NOT 35.

35 is the mass number of the MOST abundant Chlorine isotope (% abundance is 75.77 %), which we can obtain by rounding off the atomic mass 35.48. The chlorine isotope whose data are given on the preceding page is NOT the most abundant chlorine isotope. This is the reason why the answer is NOT 35.

Question:

According to the handed out periodic table of the elements, the atomic mass of Lithium (Li) is 7.00 and the atomic mass of Fluorine (F) is 19.00. Does this mean that each element has no isotopes (or equivalently only one isotope)?

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The answer;

No, it does not mean that. Remember that all radioactive isotopes are not taken into account in determining the atomic mass. Next page.

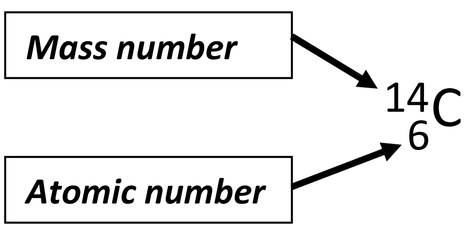
Both Lithium and Fluorine have radioactive isotopes.

Further, both elements have two or more than two stable (non-radioactive) isotopes. But Lithium 7 (Mass number) and Fluorine 19 (mass number) very much dominate over other non-radioactive isotopes. Because of this, the atomic mass of Lithium is extremely close to 7.00 and the atomic mass of Fluorine is extremely close to 19.00.

When radioactive isotopes are taken into account, just every element has isotopes.

We one more time consider radioactive Carbon 14 one more time.

Carbon 14



Excluding the isotopes with extremely short half lives, there are THREE isotopes of Carbon. They are:

$^{12}_{6}C$, $^{13}_{6}C$, $^{14}_{6}C$.

Question: *Why do all of these three elements have the same name "Carbon"?*

Answer: *The name of element is 100% determined by the atomic number of element (atom). The atom (the element) whose atomic number is 6 is named carbon. The atomic number of an atom is the same as the number of protons in its nucleus and also equal to the number of electrons surrounding the nucleus. All of the three elements in the above have the* *same atomic number 6. All of these three carbon isotopes have 6 protons and 6 electrons. That's why all three are same atom (or, the same element, the same name "carbon.) The only difference among these three isotopes is that each isotope has different number of neutrons. Therefore, each isotope has different mass number like 12, 13, and 14.* *Next page.*

Of these, only carbon-14 ($^{14}_{6}C$) *is radioactive. I will explain what "radioactive" means on the next page. But before explaining it, I will explain how Carbon 14 is formed. This explanation is just "for your information". Therefore, you may skip it. But you cannot skip the explanation that explains "What is radioactive" following it. OK?*

***For your information.** You may skip this.*

Carbon-14 is produced in the upper layers of the troposphere and the stratosphere by thermal neutrons absorbed by nitrogen atoms. When cosmic rays enter the atmosphere, they undergo various transformations, including the production of neutrons. The resulting neutrons (n) participate in the following reaction:

Neutron Nitrogen Carbon 14 Proton

$$n + {}^{14}N \rightarrow {}^{14}C + p$$

This is a nuclear reaction, not a chemical reaction.
A completely different element (or atom) is produced through the nuclear reaction. A neutron hits the nucleus of a nitrogen atom. Then a Carbon 14 results. One proton is emitted from this reaction. This is how Carbon 14 is produced in the high altitude of the atmosphere.
The highest rate of carbon-14 production takes place at altitudes of 9 to 15 km (30,000 to 50,000 ft) and at high geomagnetic latitudes, but the carbon-14 readily mixes and becomes evenly distributed throughout the atmosphere and reacts with oxygen to form radioactive carbon dioxide. Carbon dioxide also dissolves in water and thus permeates the oceans. Carbon-14 can also be produced in ice by fast neutrons causing spallation reactions in oxygen. *Go to the next page.*

OK. What is "radioactive" ?

Carbon-14 then goes through radioactive <u>beta decay</u>.

$$ {}^{14}_{6}C \rightarrow {}^{14}_{7}N + e^{-} + \bar{\nu}_e $$

Carbon   Nitrogen   Electron.   Anti-neutrino.

As seen in the equation above, by emitting an <u>electron</u> and an <u>electron-antineutrino</u>, carbon-14 (<u>half life</u> of 5730 years) <u>decays</u> into the stable (non-radioactive) isotope <u>NITROGEN-14</u>. I repeat; Carbon 14 changes into Nitrogen 14. When this occurs, particles named electron and anti-neutrino are "radiated". That's why carbon-14 is "radioactive isotope". Anyway, <u>any radioactive isotope changes into a completely different element</u>. This is what it means "radioactive".
The reaction shown right above is NOT a chemical reaction either, but "<u>NUCLEAR REACTION</u>" because a completely different element (Nitrogen) is formed. On the other hand, no new element (or no new atom) is produced from any chemical reaction (or chemical change).

Question:

Why is radioactive carbon-14 excluded in computing the atomic mass of carbon?

Answer:

Since carbon-14 or $({}^{14}_{6}C)$ ***changes into a completely different element, which is Nitrogen, we are NOT allowed to include radioactive carbon-14 in computing <u>the average mass number</u>, which is called "the atomic mass". We need the average mass number of carbon isotopes only and it should not include Nitrogen! So, the radioactive carbon14, which changes into Nitrogen, should be excluded when computing the average mass number or "the atomic mass". The next page.***

Consider a pure carbon element that is some 100 pounds. This carbon element contains carbon-12, carbon-13, and carbon 14. Suppose there are 100 of carbon-14 isotopes in this element. There is no knowing which carbon-14 changes into Nitrogen and when it does so. "This" carbon14 may change into Nitrogen at 12 noon today and "that" carbon-14 may change into Nitrogen one week later, other carbon-14 may do so 500 years from now. It is fundamentally impossible for us to know when any carbon-14 changes into Nitrogen. All we can know is "the probability" that each carbon-14 changes into Nitrogen. Not all 100 carbon-14 atoms change in to Nitrogen at the same time. The time period during which half of existing carbon-14 's (in this example 50) change into Nitrogen is called "<u>the half life</u>". The half life of Carbon-14 is 5730 years! As I explained above, this will NEVER mean that all the carobon-14 atoms change into Nitrogen in 5730 years. Some of carbon-14 may change into Nitrogen right now at this very moment, some may do so midnight tonight, some do 1500 years from now, something like this.
There are two non-radioactive (stable) Carbon isotopes; Carbon 12 and Carbon 13.

<u>The most abundant non-radioactive carbon isotope</u> is carobon-12 or $\left({}^{12}_{6}\text{C}\right)$ simply because the rounded off atomic mass, which is 12.01, is 12. 99% of carbon element are made of $\left({}^{12}_{6}\text{C}\right)$.

"Question"

Consider element name Chlorine (Cl). According to the Periodic Table of the elements, its atomic number is 17. The atomic mass (average mass number) of Chlorine is 35.45. OK. One of the Chlorine isotopes (the nucleus) contains <u>20 neutrons</u>. Then calculate the <u>mass number</u> of this Chlorine isotope.

<u>Answer</u>:

Many students answer the following way: (On the next page.)

The mass number = the number obtained by rounding off the atomic mass (average mass number) which is usually a fractional number. Since the atomic mass of this "particular" Chlorine isotope is 35.45, we get 35 after rounding off. Therefore, the mass number of this "particular" Chlorine isotope is 35. This is WRONG! Why wrong?

In class, I said that the number obtained by rounding off the atomic mass is the mass number of the most abundant isotope.

We are not sure that the Chlorine that has 20 neutrons is the most abundant isotope of Chlorine. But since the atomic number is 17, it has 17 protons. Then, since there are 20 neutrons (given!) and the mass number is defined as

Mass number = number of protons + number of neutrons,

we have Mass number = 17 + 20 = 37.
Therefore, the mass number of Chlorine atom that has 20 neutrons is 37, not 35, which is obtained by rounding off the atomic mass 35.45.
Be careful!

Question:

Consider three Carbon isotopes $^{12}_{6}C$, $^{13}_{6}C$, and $^{14}_{6}C$. Which carbon isotope is the most abundant and why so?

The Answer:

Carbon 12 $\left(^{12}_{6}C\right)$. Why? Because . . . Look at the hand out Periodic Table of the Elements and find Carbon element. You will see that the ATOMIC MASS (The weighted average of mass number: averaged over the masses of all non-radioactive carbon isotopes). The atomic mass of Carbon element is 12.01. Because this is the average mass number, the rounded off atomic mass that is a whole number

(an integer) represents the most abundant isotope of Carbon. Since we get 12 when 12.01 is rounded off, the mass number of the most abundant carbon isotope is Carbon 12. That is, the most abundant carbon isotope is Carbon 12.