The structure of atoms and the periodic table

1 Electric charge and Coulomb force

There are two kinds of electric charge: positive charge and negative charge. Positive charge and negative charge attract each other while similar charges (positive charge and positive charge or negative charge and negative charge) repel each other. This is called "Coulomb force," and the force is inversely proportional to the square of the distance between the two charges. For example, if the distance between two charges is doubled, the force is quartered. If the distance is tripled, the force becomes one ninth its previous value. We will talk more about this in our article "Electric charge and Coulomb force," but for our purposes in this article, this background is sufficient.

2 Structure of atoms

With this background, let us discuss the structure of atoms. An atom consists of a nucleus and electrons. The nucleus is at the center of an atom and the electrons orbit around the nucleus.[1] The nucleus consists of protons and neutrons. The constituents of the nucleus, i.e., protons and neutrons, are collectively called "nucleons." A proton has an electric charge of $+e$ while a neutron has no electric charge. An electron has an electric charge of $-e$. An atom has an equal number of protons and electrons so that the total charge of an atom is zero. The Coulomb attraction between the nucleus and the electrons enables the electrons to orbit around the nucleus, just like gravitational force enables the Earth to orbit around the Sun, and the Moon to orbit around the Earth. Also, inside the nucleus, protons and neutrons feel a force called "strong force" so that the nucleus doesn't fall apart despite the repulsion due to the Coulomb force between protons.

The size of nucleus is much smaller than the size of atom. The size of the nucleus of the smallest atom, the hydrogen atom, is about 1.75×10^{-15} meter, which is about 150,000 times smaller than the size of the whole hydrogen atom. The size of the nucleus of the largest atoms, such as uranium, is about 15×10^{-15} meter, which is about 20,000 times smaller than the size of the whole uranium atom. In other words, most of each atom consists of empty space.

[1] Strictly speaking, it should be "most of the electrons orbit around the nucleus. We will come back to this in our article entitled "Bohr model."

3 Rutherford model

Now, let us discuss how the nucleus was first discovered. In 1909, to understand the structure of atoms, Rutherford suggested his assistant Geiger and undergraduate assistant Marsden to direct a beam of what is called "alpha-particles" to a thin foil of either gold or aluminum. (The year before, Rutherford and Geiger had found that the charge of an alpha-particle is $2e$.) Surprisingly, Geiger and Marsden found out that about 1 in 8000 of the incident alpha-particles was scattered by more than 90 degrees. Regarding his surprise at this experimental result, Rutherford later remarked, "It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you." In late 1910, Rutherford figured out what was happening. As most of each atom is empty space, most alpha-particles go through the atoms in the thin foil un-deflected. However, as the nucleus is much smaller than the whole atom, a very small number of alpha-particles incidentally go near the nucleus, and are deflected significantly due to the Coulomb force between the nucleus and the alpha-particle. Thus, Rutherford came up with what is now called the "Rutherford model": He proposed an N-electron atom has a charge Ne or $-Ne$ at its center, and calculated the angle of deflection due to the Coulomb force between the charge $\pm Ne$ and the alpha-particle. (He noted that the answer doesn't depend on the sign of the charge of the nucleus.) He also didn't take account the Coulomb force due to orbiting electrons, but this is actually negligible and was accounted for later by other scientists. In other words, Rutherford made quantitative predictions of what proportion of the alpha-particles would be deflected and at what angles. Furthermore, he showed that the radius of the nucleus of a gold atom had to be less than 3.4×10^{-14} meter. (Compare this value with the size of the nucleus of the largest atom, mentioned earlier as 1.5×10^{-14} meter.) Geiger and Marsden performed these experiments again in 1912, and the results agreed with Rutherford's quantitative predictions of the angle deflection. Therefore, Rutherford can be regarded as the discoverer of the nucleus. Unfortunately, Rutherford never received the Nobel Prize for this discovery. However, he may not have been that unlucky, considering that he had already received a Nobel Prize for other work in 1908 (as mentioned in the previous article.) Rutherford may be the only scientist who achieved his most important and famous accomplishment after he had already received a Nobel Prize.

4 Mass number, atomic number and neutron number

The mass of the proton and the mass of the neutron are almost the same, the former being about 1.6726×10^{-27} kg and the latter being 1.6749×10^{-27} kg. However, the mass of the electron is much smaller, about 1800 times smaller than that of the proton or neutron. Therefore, most of the mass of the atom comes from protons and neutrons, i.e. its nucleus. As the mass of the proton and the mass of the neutron are almost the same, we can approximately denote the mass of the atom by its total number of protons and neutrons. The proton number, called the atomic number, is commonly denoted by Z, and the neutron number is commonly denoted by N. The mass number, commonly denoted by A, is sum of them as follows:

$$A = Z + N \tag{1}$$

For example, the mass number of hydrogen is 1, because a hydrogen atom nucleus contains one proton and zero neutron. The mass number of carbon is 12, because a carbon atom nucleus contains 6 protons and 6 neutrons. You also easily see that the mass number of an atom must be quite close to the atomic weight introduced in the last article.

However, there can be a significant difference between the two for certain atoms. Let me explain why.

It also happens that some atoms can have the same proton number while having different neutron numbers. These are called "isotopes." Of course, isotopes have different mass numbers, as the mass number is the sum of the proton number and the neutron number. Scientists write the mass number at the top left corner of the symbols to distinguish isotopes. For example, chlorine has the atomic number 17. The isotope with the mass number 35 is denoted as ^{35}Cl, and the isotope with the mass number 37 is denoted as ^{37}Cl. One mole of ^{35}Cl weighs about 34.97 grams, a value indeed close to its mass number, 35. Similarly, one mole of ^{37}Cl weighs about 36.97 grams, a value indeed close to its mass number 37.

Now comes the point. On Earth, about three quarters of chlorine is ^{35}Cl, while about quarter of chlorine is ^{37}Cl. On average, chlorine's "average" mass number is about 35.5, as $35 \times 3/4 + 37 \times 1/4 = 35.5$. In other words, the atomic weight of chlorine is about 35.5.

Notice that this is not an integer. Before the atomic weight number of chlorine was measured in the 1820s and 1830s, all the known mass numbers were integers. This led the English chemist William Prout to suggest in the mid-1810s that every atom was made out of an integer number of hydrogen (which has a mass number of 1). Of course, this suggestion was disproved by the measurement of the non-integer mass number of chlorine.

Isotopes have the same chemical properties but different physical properties; they chemically react to other atoms in the same way, while having different densities, freezing points, and boiling points. For example, the usual hydrogen ^{1}H is made out of a proton and an electron, while the hydrogen isotope deuterium (^{2}H or D) is made out of a proton, a neutron and an electron. In other words, the nucleus of the usual hydrogen is a proton and the nucleus of the hydrogen isotope deuterium consists of a proton and a neutron. Heavy water, which consists of two deuterium and one oxygen ($^{2}H_2O$ or D_2O) has a freezing point of 3.8 Celsius and a boiling point of 101.4 Celsius. This differs from normal water, which has a freezing point of 0.0 Celsius and a boiling point of 100.0 Celsius. Heavy water is often used in nuclear reactors.

Another example of the practical application of isotopes is radiocarbon dating. About 99% of the carbon atoms on Earth are carbon-12 (i.e., (^{12}C), which is stable. In other words, they do not decay. However, one out of about every 10^{13} carbon atoms in the atmosphere is ^{14}C. Even though the ^{14}C atoms decay with half-life 5730 years, the proportion in the atmosphere (one out of every 10^{13} carbon atoms) remains constant, as they are continuously produced by nitrogen atoms bombarded by cosmic rays (particles that come from the universe and fall into the Earth). As every living thing, such as plants and animals, constantly eat substances such as carbon dioxide that contain atmospheric carbon, the proportion of ^{14}C in carbon atoms remain constant while the organism is alive. However, once the organism dies, it no longer consumes substances that contain carbon atoms, and the proportion of ^{14}C inside the living thing decreases with a half-life of 5730 years. Therefore, if you have an ancient piece of paper, and if you measure the proportion of ^{14}C in it, you can estimate when the tree that produced the paper died. This is how the Dead Sea scrolls and charcoal from ancient campfires were dated.

Radiocarbon dating is an example of radioactive dating. Another important example of radioactive dating is determining the age of rock. Potassium-40 (^{40}K) decays into Argon-40 (^{40}Ar) with a half-life of 1.25 billion years. Under usual conditions, if ^{40}K decays into Argon, it flies away as Argon is a gas. However, once a rock is formed and ^{40}K decays, the new Argon atoms formed as a result of the decay, are trapped inside the rock. Thus, by measuring the ratio of ^{40}K and ^{40}Ar present in the rock, scientists can determine the age of rock. As we know that rocks on the Earth are formed after the creation of the Earth, scientists can estimate the age of the Earth from the age of the oldest rocks. Actually, ^{40}K is not the only radioactive sample one can use to estimate the age of rock. There are many others, which allow us to cross-check. We now know that the Earth is about 4.5 billion years old. Although geologists were initially reluctant to accept the radioactive dating as they thought that physicists intruded their domain, a complete consensus was reached in the early 1930s.

Problem 1. On Earth, about 4/5 of borons are ^{11}B and 1/5 of borons are ^{10}B. Estimate the atomic weight of boron.

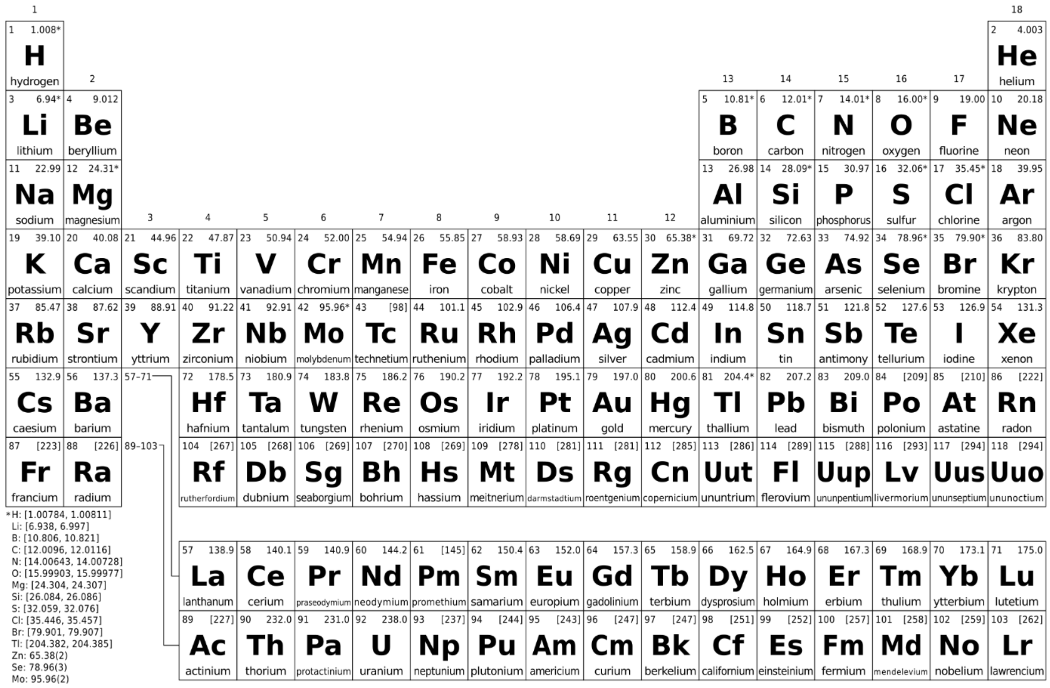
5 The atomic number and the periodic table

The atomic number was first precisely measured by the English physicist Henry Gwyn Jeffreys Mosely. Unfortunately, he never received the Nobel Prize as he volunteered for the British army during World War I and was killed in the Battle of Gallipoli in 1915 at the age of 27.

Before this measurement, the atomic number was regarded more or less as a semi-arbitrary sequential number based on the sequence of atomic mass, with some "modifications" to fit into the periodicities of atoms (i.e., the periodic table) as done by Mendeleev (as mentioned in the last article.)

Therefore, what Mosley found was that the sequence in the periodic table must not be a modified sequence of atomic mass, but just simply the sequence of the atomic number (i.e., the number of protons of the atom.) In other words, the reason why Mendeleev was not wrong much and mostly correct was that atoms with bigger atomic numbers tend to have bigger atomic masses, which makes the sequence of the atomic number roughly the same as the sequence of the atomic mass.

6 Periodic table revisited



Here, you see the periodic table. Hydrogen (H) has an atomic number of 1, helium (He) has an atomic number of 2, lithium (Li) has an atomic number of 3, and so on. In other words, the atoms are listed in the order of their atomic numbers, as mentioned. The elements that are in the same column share similar properties. For example, the elements in the second column from the right (i.e., F, Cl, Br, I, etc.) are called the "halogens," and they have very high chemical reactivity (i.e., combine easily with other elements to form new compounds.) On the other hand, the elements in the first column from the right are called "noble gases," and they have very low chemical reactivity (i.e., do not chemically react easily with other substances.)

As mentioned in the last article, Mendeleev successfully predicted several elements. Let's look at two of his most successfully predictions, and see how he did it. Please reference the periodic table. Mendeleev predicted some properties of gallium (Ga) and germanium (Ge) in the fourth line of the periodic table between zinc (Zn) and arsenic (As). Check also that they are one place below aluminum (Al) and silicon (Si). As "eka" is one in Sanskrit, he had called them eka-aluminum and eka-silicon, before gallium and germanium were discovered. He predicted that eka-aluminum's atomic weight was about 68 and eka-silicon's atomic weight was about 72, as these values have to be between the atomic weight of zinc (Zn), 65, and the atomic weight of arsenic (As), 75. The actual values are 69.7 and 72.6. As eka-silicon is between silicon (Si), of which the volume of one mole of atoms is about 11cm^3, and tin (Sn), of which the volume of one mole of atoms is about 16cm^3, he reasoned that the volume of one mole of eka-silicon atoms is about 13cm^3. As the mass of one mole of eka-silicon atoms was guessed to be 72 grams as just mentioned, it implies that the density of eka-silicon was about

$72/13{=}5.5$g/cm^3. The actual value is 5.35g/cm^3. The volume of one mole of eka-aluminum was assumed to be 11.5cm^3, a value between the actual volume of one mole of zinc (Zn) at about 9, and the predicted volume of one mole of eka-silicon at 13. This implies that the density of eka-aluminum is about $68/11.5{=}5.9$g/cm^3. The real value is also about 5.9g/cm^3. He also successfully predicted the properties of several compounds of these elements.

You may wonder why the elements show periodicity. We will see later in our article entitled "Hydrogen atom" that this is a consequence of quantum mechanics. On the Internet, I saw someone asking the reason behind the periodicity, and what conditions were imposed to lead to such a periodicity. I answered that everything naturally followed from the Schrödinger equation, and there were no extra conditions imposed at all. The questioner didn't seem to be satisfied by my answer. Nevertheless, I firmly believe that you will be satisfied once you learn how to solve the Schrödinger equation for the hydrogen atom. Even though the hydrogen atom is the simplest and easiest atom to solve the Schrödinger equation, its solution can qualitatively explain the periodicity of atoms. As I mentioned in our earlier article on the history of physics, chemists now solve the Schrödinger equation by using supercomputers to predict the properties of various molecules. This of course includes the periodic table. Actually, chemistry majors learn how to solve the Schrödinger equation in their quantum chemistry class. Physics majors also learn the Schrödinger equation in their quantum mechanics class, but their focus is entirely different. For example, I never learned how to solve the Schrödinger equation except for the simplest cases. What I mostly learned in quantum mechanics class is about the mathematical structure of Schrödinger equation than methods to solve the Schrödinger equation in various situations. Actually, solving Schrödinger equation doesn't just require supercomputers. If one knows how to make supercomputers solve the Schrödinger equation easier and faster, it is a great achievement. Novel Prizes in Chemistry were awarded for such achievements in 1998 and in 2013.

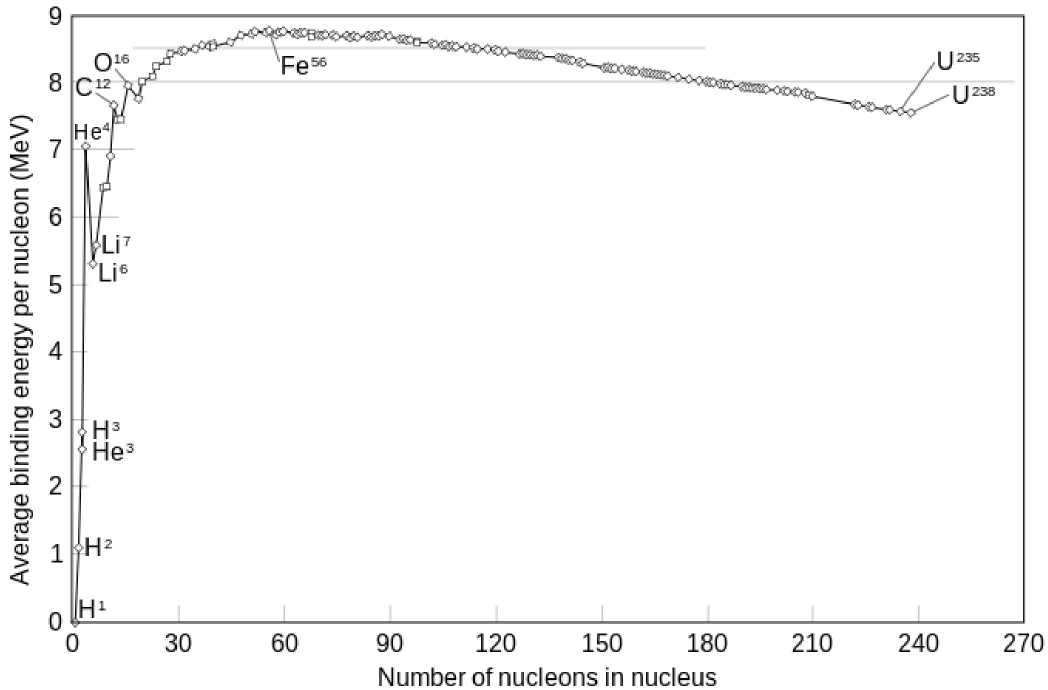
7 Radioactivity revisited

In the last article, we talked about Rutherford and Soddy's "conservation of radioactivity" and that radioactivity is "a process which lies wholly outside the sphere of known controllable forces." So why is this so? It is because radioactivity is a nuclear phenomenon. Let me explain. We can control chemical processes. For example, if you burn a paper, the carbon atoms in the paper combine with the oxygen atoms in the air to become carbon dioxide molecules. Notice that this is a chemical process; the carbon atoms and the oxygen atoms are there and not changing: only their arrangements have changed. Of course, it goes without saying that the nuclei of carbon atoms and the nuclei of oxygen atom are there, untouched, as well. In other words, chemical reactions, which we can control, do not touch the nuclei. Moreover, it is not simple to control the nuclei. That is the reason why radioactivity was a process that was beyond known controllable forces. However, nowadays we actually can control radioactivity. Nuclear fission (i.e. nuclei splitting) in a nuclear reactor is a good example. If you shoot neutrons at uranium atoms and a neutron is absorbed by a uranium nucleus, the uranium nucleus becomes more unstable and gets split into two smaller nuclei. This releases a huge amount of energy and is how nuclear power plants and nuclear bombs work.

Of course, in the days when Rutherford and Soddy came up with "conservation of radioactivity," the nucleus had not been discovered yet, so they couldn't have known that radioactivity was a nuclear phenomenon. Moreover, even after the nucleus was discovered, physicists couldn't find any means to explain the mechanism of radioactivity before quantum mechanics was discovered in 1925. In 1928, Gamow explained alpha decay, one of the two types of radioactive decay, using tunneling. We will explain tunneling in our article "Tunneling" in the section "Historical Introduction to Quantum Mechanics." The electroweak interaction, the mechanism behind beta decay -the other type of radioactive decay- was only fully explained in 1960s, after many breakthroughs. The Nobel Prize in 1979 was given to three physicists who developed the electroweak theory.

At this point, it may be appropriate to introduce alpha-decay and beta-decay. In his first paper on "Becquerel rays" in 1899, Rutherford found that the Becquerel rays are inhomogeneous. He found out that there were actually two types of radiation in the Becquerel rays with different penetrating abilities. He named them alpha-radiation and beta-radiation. The beta-radiation is more penetrating.

It was later found out that the alpha-rays, produced during the alpha-radiation, are actually the nuclei of Helium atoms, which consists of two protons and two neutrons each. During alpha-radiation, a nucleus emits an alpha particle, (i.e., the nucleus of a Helium atom) and leaves a left-over nucleus. For example, the nucleus of uranium 238 (i.e., ^{238}U,) which consists of 92 protons and 146 neutrons, becomes the nucleus of thorium 234 (i.e., ^{234}Th,) which consists of 90 protons and 144 neutrons, after emitting an alpha particle. Also, it was later found out that the beta-rays are electrons.



Finally, to conclude this article, let us discuss nuclear binding energy. I already mentioned that a nucleus is made out of nucleons, i.e., protons and neutrons. A nucleus has less energy than the total energy of individual nucleons. This is actually the reason why a nucleus is formed rather than individual nucleons remaining separate; every object in the whole universe prefers to have less energy (strictly speaking, potential energy, which we will introduce in our later articles). For example, the reason a stone falls down is because it has less energy when it is lower. The amount of energy a nucleus has less than the total energy of individual nucleons is called the nuclear binding energy. Below, you see the graph of nuclear binding energy per nucleon in the nucleus. For example, you can see that ^{4}He has 7 MeV of nuclear binding energy per nucleon. This means that the energy of the Helium nucleus is 28 MeV less than the energy of two protons and two neutrons. In other words, these four nucleons are better off as Helium than remaining separate. This also suggests that these four individual nucleons could become Helium atoms if the conditions are right. This is actually what is happening inside the Sun; nucleons, such as protons (i.e., hydrogen nuclei), combine together to become Helium nuclei. Such a process is an example of "nuclear fusion:" Two or more nuclei fuse together to become a bigger nucleus. It is the direct opposite of nuclear fission. Notice also that every time a Helium nucleus is formed, it releases 28 MeV of energy because of the conservation of energy, which says that the total energy is conserved. (We will talk about the conservation of energy in our article "The conservation of energy.") This is the source of energy from which the Sun is radiating light so that every creature on Earth can live.

Now, recall what alpha-decay and nuclear fission are. Both are processes in which one nucleus splits into two or more nuclei. This is possible because they are better off as split nuclei rather than one single nucleus. (Of course, this doesn't guarantee that this always happens; it happens only when the conditions are right.) In other words, the total energy of split nuclei is less than the energy of the original single nucleus. This is possible only when the total nuclear binding energy of split nuclei is bigger than the nuclear binding energy of the original single nucleus. (Remember that the nuclear binding energy is defined by the energy less than the individual/separate nucleons.) As the number of nucleons is conserved, the nuclear binding energy of split nuclei per nucleon must be bigger than the nuclear binding energy of the original single nucleus for alpha-decay or nuclear fission to happen. Now reference the figure again. Nuclear binding energy per nucleon is highest for iron 56 (^{56}Fe), and the nuclear binding energy per nucleon of larger nuclei such as uranium 238 is smaller. Therefore, nuclear fission is a possibility for nuclei larger than that of iron, but not for smaller ones.

Similarly, for nuclear fusion to happen, the nuclear binding energy of the single, combined, nucleus must be bigger than the total nuclear binding energy of the original, individual, separate nuclei. Now, reference the figure again. Nuclear binding energy per nucleon is highest for iron 56 and the nuclear binding energy of smaller nuclei is smaller. Therefore, nuclear fusion is a possibility for nuclei smaller than that of iron, but not for larger ones.

This observation has an important consequence in nuclear astrophysics. Nuclear fusion occurs inside the core of stars such as the sun, so elements heavier than iron cannot be synthesized inside these cores. These heavier elements are formed during supernova explosions (i.e., the death of a star) which are much more extreme and abnormal conditions than the regular conditions inside the core of stars. I am not an expert on this and if you are interested, you should look up "supernova nucleosynthesis" on Wikipedia.

Summary

- Positive charge and negative charge attract each other while similar charges repel each other. This is called "Coulomb force."
- An atom consists of a nucleus at the center and electrons orbiting around it.
- The constituents of the nucleus, i.e., protons and neutrons are called "nucleons."
- A proton has an electric charge of $+e$ while an electron has an electric charge of $-e$.
- An atom has an equal number of protons and neutrons, so that the total charge of an atom is zero.
- The nucleus of an atom is much smaller than the whole atom; most of an atom consists of empty space.
- The atomic number is the number of protons in an atom.
- The mass of the electron is much smaller than that of proton or atom.

- The mass number A, the atomic number Z, and the neutron number N satisfy

$$A = Z + N$$

- Atoms that have the same proton number while having different numbers is called "isotopes."
- Isotopes have the same chemical properties but different physical properties. They chemically react to other atoms in the same way, while having different densities, freezing points and boiling points.
- From radioactive dating, geologists can find out the age of the Earth, and historians can find out the age of old papers which they are interested in.
- The periodic table is in the order the atomic number, i.e., the number of protons in an atom.
- From the periodic table, Mendeleev successfully predicted the properties of several elements before they were discovered.
- A nucleus has less energy than the total energy of individual nucleons. The difference is given by the nuclear binding energy. The bigger the binding energy, the more stable a nucleus is.
- Nuclear fusion and nuclear fission happen to make atoms more stable.