History of chemistry up until the beginning of 20th century

1 Introduction

If you put a piece of iron into a strong acid solution, the iron melts down and seems to disappear inside the solution. If you burn a piece of paper, it becomes smoke. Steelmakers use complicated methods to make steel out of iron ore. If you mix two specific solutions, a certain solid forms at the bottom of the mixed solutions. Inside your body, complicated substances are secreted from your organs to help your digestion. Winemakers turn the juice of the grape into wine. These are some examples of chemical reactions. They happen everywhere. During chemical reactions, some substances may disappear and new substances may arise.

So then, what are the rules and the processes of chemical reactions? Why and how do they happen? This is what chemistry is about. In this article and the next, we will explain the basics of the basics of chemistry. In particular, this article will focus on the history of chemistry up until the beginning of 20th century.

Before the foundations of chemistry were established in the late 18th century, chemists were known as "alchemists" and chemistry as "alchemy." One of the most common goals of alchemists was to make expensive metals, such as gold and silver, from inexpensive metals such as lead, iron and copper. Even though they never succeeded, they immensely contributed to the development of chemistry. (We will soon explain why they were unable to succeed.)

2 Conservation of mass

If a piece of iron disappears in a strong acid solution, it means that the mass of the iron inside the solution is now zero. However, did the matter really disappear? The answer is no. If you measure the total mass of the reactants before chemical reaction (i.e., the piece of iron and the strong acid solution) and the total mass of the reactants after chemical reaction (i.e., whatever is inside the acid solution after the piece of iron disappeared), they are same.

This is called the "conservation of mass." This suggests that matter is neither destroyed nor created during chemical reactions, but only change its form; the iron we talked about is still there inside the solution. Conservation of mass was suggested by many chemists in the late 18th century based on numerous experiments. For example, the French chemist Antoine

Lavoisier burned a diamond in a closed jar by focusing sunlight using magnifying glass. The diamond disappeared, but the total weight of the closed jar didn't change. It meant that the material in the burned diamond was somewhere in the air in the jar, albeit in a different form. On other occasions, he burned sulfur and phosphorous and found out that their mass increased. However, he discovered that the mass increase exactly matched the mass decrease of the air used to burn them. He also heated mercury oxide, and found out that the mass decreased. However, the mass decrease exactly matched the mass increase of the gas released by the mercury oxide during the heating. Antoine Lavoisier was later executed during the French Revolution.

3 Law of definite proportions

In 1794, the French chemist Joseph Proust came up with the law of definite proportions. Let me explain what this is by providing an example. Tin and oxygen chemically interact together to form two kinds of new substances. Proust observed that each substance was made out of a certain ratio of tin and oxygen, and that this ratio differed for each of the two substances. The law that a certain substance is chemically made out of definite proportions of other substances is known as "law of definite proportions," and Proust confirmed the law for many different substances. However, even though Proust was eventually proved to be correct, at that time chemists such as Claude Berthollet claimed that a chemical substance could be made out of other substances within arbitrary proportions of a certain range.[1]

4 Dalton's atomic theory

The English scientist Dalton made a real breakthrough in 1808, when he proposed the following five postulates as part of the "atomic theory of matter" in his book "A New System of Chemical Philosophy." The parentheses are my own.

- 1. All matter is composed of very small particles called atoms.
- 2. All atoms of a given element are identical. (An element is a pure substance consisting of one kind of atoms.)
- 3. Atoms cannot be created, destroyed, or subdivided.
- 4. In chemical reactions, atoms combine with or separate from other atoms.
- 5. In chemical reactions, atoms combine with each other in simple, whole-number ratios to form combined atoms. (Simple, whole-number ratios mean ratio of two small integers, such as 1:2, 1:3, 2:3, 3:4. Combined atoms are now called "molecules.")

[1] Even though they are very rare, there are substances that don't obey the law of definite proportions. These are collectively called "berthollides." However, I did not know this fact until I did some research to write this article.

Let's see how these postulates explain the conservation of mass and the law of definite proportions. The conservation of mass is satisfied from the postulate 3 and 4. During chemical reactions, no new atoms are created or destroyed; atoms just rearrange themselves. As nothing is destroyed or created, the mass must be conserved. We can also explain the law of definite proportions from postulate 5. For example, we now know that two hydrogen atoms and one oxygen atom are combined together to form a single water molecule. Therefore, water is made out of definite proportions of hydrogen and oxygen atoms. If you are trying to make water from hydrogen atoms and oxygen atoms and if you have more than the double number of hydrogen atoms than the number of oxygen atoms, some hydrogen atoms will be left out after the chemical reaction, and they won't be part of the water molecules just formed. Similarly, if you have less than the double number of hydrogen atoms than the number of oxygen atoms, some oxygen atoms will be left out after the chemical reaction.

Furthermore, Dalton came up with the "law of multiple proportions," now sometimes called Dalton's law. Let me explain what this is. Tin and oxygen chemically react together to form "tin oxides." There are two kinds of tin oxides, and we know that according to the law of definite proportions, two definite, but different ratios of tin and oxygen combine to form these two substances. In this case, 100 grams of tin can combine either with 13.5 grams of oxygen or 27 grams of oxygen to form tin(II) oxide and tin dioxide, respectively. So, the ratio of 13.5 grams to 27 grams is simple, whole-number ratio of 1:2. Now let me state the law of multiple proportions: "If two elements form more than one compound (i.e. substances that are made out of more than one element) between them, then the ratios of the masses of the second element which combine with a fixed mass of the first element will be ratios of small whole numbers." In our example, the two elements are tin and oxygen, the compounds are the two different kinds of tin oxides, and the ratio is 1:2. So, what is the reason behind the law of multiple proportions? As 27 grams is double 13.5 grams, we can say that tin dioxide's molecules contain twice as many oxygens per tin atoms than tin(II) oxide molecules do. Therefore, say, if a tin(II) oxide molecule contains one tin atom and one oxygen atom, a tin dioxide molecule contains one tin atom and two oxygen atoms or two tin atoms and four oxygen atoms, or three tin atoms and six oxygen atoms and so on. (It actually contains one tin atom and two oxygen atoms.) Let me clarify once again. Let's assume that the law of multiple proportions were not satisfied and the ratio we calculated were given by 1:1.69. Then, say, if a tin(II) oxide molecule contains one tin atom and one oxygen atom, a tin dioxide molecule contains one tin atom and 1.69 oxygen atoms, or two tin atoms and 3.38 oxygen atoms, or three tin atoms and 5.07 oxygen atoms and so on. The number of tin atoms a tin(II) oxide molecule contains will never be a small integer. However, such a hypothetical case would violate postulates 3 and 5. There is no such thing as 1.69 atoms; we count atoms one by one and the number of atoms is always a positive integer.

The discovery of Dalton's law changed how chemists record their results. Earlier, they wrote, say, two kinds of tin oxides contain 12%(=13.5/(13.5+100)) and 21%(=27/(27+100)) of oxygen by weight. Now, they wrote one weight of tin combine either with 0.135 weights of tin or 0.27 weights of tin.

Now, as promised, let me explain why it is impossible to make expensive metals such as gold and silver from inexpensive metals such as lead, iron and copper. Gold is made out of a single element, namely gold atoms. So are other metals. For example, copper is made out of a single element, copper atoms. Given this, check out postulate 3 of Dalton's atomic theory. There is no way that copper atoms can be transformed into gold atoms. Therefore, it is impossible to make expensive metals from inexpensive metals. (Strictly speaking, atoms can be artificially transformed, which is what nuclear engineers do in nuclear reactors, but that is a different story. In any case, there is no cost efficient way to transform atoms of inexpensive metals into atoms of expensive metals.)

Problem 1. Let's say that a molecule C is made out of one atom of A and one atom of B, and a molecule D is made out of two atoms of A and three atoms of B. What are the ratios of the masses of B which combine with a fixed mass of A? Confirm that these are simple, whole number ratios. (Hint[2])

Problem 2. Carbon and oxygen chemically react together to form "carbon oxides." A first kind of carbon oxides contains 56% of oxygen by weight, and a second kind of carbon oxides contains 72% of oxygen by weight. Check that the law of multiple proportions holds. (You may not get the exact whole number ratios as the value 56% and 72% are rounded ones. But, you will get very close ones.)

5 Periodic table

In our nature, there exist many elements. In other words, there are many different kinds of atoms. Then, is there any way to classify them systematically? In 1817, German scientist Johann Wolfgang Döbereiner grouped some elements into four groups, with each group having three elements with similar chemical properties. For example, chlorine, bromine and iodine fell into the same group.

In 1864, British chemist John Newlands listed known elements in order of their atomic weights (i.e., weight of a single atom of an element)[3] and found a very interesting periodicity. For example, lithium, the 2nd element in atomic weight known to be at the time, sodium, the 9th element, potassium, the 16th element and so on seem to have similar chemical properties.[4] Here, the period is 7. If you add 7 to 2, it is 9, if you add 7 again it's 16. He called it "the law of octaves." He named it so, because a musical scale has seven notes (Do, Re, Mi, Fa, Sol, La, Ti) and it repeats again after an octave. Some chemists at the time ridiculed him, claiming that chemical elements could have been listed in alphabetical order as well.

In 1869, the Russian chemist Dmitri Mendeleev proposed a similar idea, but more com-

[2]Two atoms of A chemically react to two atoms of B to form molecule C.

[3]Actually, we now know that this is not an exact definition. An exact definition is the average weight of an atom of an element. You will see the difference of these two definitions in the next article.

[4]We now know that lithium is not the second element in atomic weight. Similarly, for the other elements.

plete with new predictions, which John Newlands couldn't come up with. Just like John Newlands, he listed elements in order of their atomic weights and found some periodicity of chemical properties of the elements. Stepping further, by closely examining the periodicity, Mendeleev successfully predicted some properties of the elements that were not discovered yet, which were later confirmed upon their discoveries. To put it differently, he correctly guessed that some elements didn't seem to follow the periodicity, not because there is no periodicity, but because there were elements that haven't been discovered yet. On other cases, he was wrong; he boldly claimed that the known atomic weights for a couple of atoms were wrong, to fit them into the periodicity. (However, their atomic weights were not wrong. We will talk why Mendeleev was wrong in the next article.) Now, this list of the elements, arranged in such a way that the periodicity of elements can be well represented, is called the "periodic table," and can be often seen on posters in science classrooms. We will talk more about Mendeleev's prediction and the periodic table in the next article.

Even though Mendeleev's discovery was a big breakthrough in chemistry, he never received the Nobel Prize, as Nobel laureate Svante Arrhenius argued that Mendeleev's discovery was too old to be awarded a Nobel prize. According to contemporaries, Arrhenius held a grudge against Mendeleev for his criticism on Arrhenius's "disassociation theory."

6 Symbol

It is customary to denote elements by what are called "symbols." For example, hydrogen is denoted as "H," carbon as "C," and oxygen as "O." Gold is denoted as "Au" after "*aurum*," the Latin name for gold. Tin is denoted as "Sn" after the Latin "*stannum*." These symbols are also used for molecules. For example, a water molecule which consists of two hydrogen atoms and one oxygen atom is denoted as "H_2O," and an oxygen molecule which consists of two oxygen atoms is denoted as "O_2."

7 Molar weight

Earlier I mentioned that Mendeleev listed elements in order of their atomic weights and found some periodicities in the list. At this point, you may wonder how he could know the atomic weights in 1869, long before the existence of atom was settled. How could one measure the weight of something of which the existence one was not sure of?

Actually, he didn't know the mass of individual atoms. But, what he knew was the *relative* atomic mass. For example, chemists in the 19th century knew that the atomic weight of carbon is about 12 times the one of the atomic weight of hydrogen, and the atomic weight of oxygen 16 times the one of hydrogen. Therefore, as a convention, chemists said the atomic weight of carbon is 12, the atomic weight of oxygen 16, the atomic weight of hydrogen 1, and so on. However, as we will see soon, this is not an exact statement, because the atomic weight of carbon is only *approximately* 12 times the one of hydrogen, and the one of oxygen only *approximately* 16 times the one of hydrogen.

Now, we can introduce the molar weight. It is the molecule version of the atomic weight. For example, carbon dioxide CO_2 (i.e., it contains one carbon atom and two oxygen atoms) has the molar weight of $44(= 12 + 16 \times 2)$, and carbon monoxide CO (i.e., it contains one carbon atom and one oxygen atom) has the molar weight of $28(= 12 + 16)$.

Given this, let's go back to our earlier example. Tin is known to have the atomic weight of 118.7. As a tin(II) oxide molecule (SnO) has one tin atom and one oxygen atom, 118.7 grams of tin interact 16 grams of oxygen to form a tin(II) oxide. So, how much oxygen will interact with 100 grams of tin to form tin(II) oxide? Let's call this quantity x. Then we need to solve x for

$$118.7 : 16 = 100 : x \tag{1}$$

If you calculate this, you get roughly 13.5 gram as in our example in an earlier section. You can similarly check that 100 grams of tin interact with 27 grams of oxygen to form tin dioxide (SnO_2). You need to solve

$$118.7 : 16 \times 2 = 100 : y \tag{2}$$

You can also check that tin(II) oxide contains 12%(=16/(16+118.7)) of oxygen by weight, and tin dioxide 21%(=(16×2/)(16×2+118.7)) of oxygen.

Problem 3. Using the fact that the atomic weights of carbon and oxygen are 12 and 16 respectively, show that carbon monoxide (CO) contains 56% of oxygen by weight, and carbon dioxide (CO_2) contains 72% of oxygen by weight.

Problem 4. Using the fact that the atomic weights of hydrogen and oxygen are 1 and 16 respectively, calculate how much of oxygen would react with 1 gram of hydrogen to form water (H_2O).

So, how did chemists know the atomic weight in the 19th century? They solved problems such as Problem 3 and Problem 4 "backwards." For example, once they knew a water molecule contains two hydrogen atoms and one oxygen atom and measured how much of oxygen reacts with 1 gram of hydrogen, they can figure out exactly how heavy an oxygen atom has to be, compared to an hydrogen atom.

Finally, let me introduce the concept of "mole." We know that the weight of a carbon atom is about 12 times the weight of an hydrogen atom. Therefore, the number of carbon atoms in 12 grams of carbon atoms is roughly the same as the number of hydrogen atoms in 1 gram of hydrogen atoms. This number is called a "mole" and is roughly given by 6.02×10^{23}. This number is called "Avogadro constant." In other words, 1 mole (6.02×10^{23} atoms) of carbon atoms weighs about 12 grams, and 1 mole of hydrogen atoms weighs about 1 gram. The exact definition of mole (i.e., the value of Avogadro constant) has been updated quite several times, but the value of the constant will be fixed to exactly $6.02214076 \times 10^{23}$ in May 2019. Thus, the atomic weight of carbon is 12.011, because the weight of $6.02214076 \times 10^{23}$ carbon atoms is 12.011 grams, and the atomic weight of hydrogen is 1.008 because the weight of $6.02214076 \times 10^{23}$ hydrogen atoms is 1.008 grams.

8 The Law of Reciprocal Proportions

The German chemist Jeremias Richter discovered the law of reciprocal proportions in 1792, long before Dalton's atomic theory. Actually, according to an account, Dalton said that he had come up with his atomic theory while pondering upon Richter's work, even though many historians think what he said is unlikely.[5]

Anyhow, here I explain what the law of reciprocal proportions is, and how it can be explained by Dalton's theory. I never learned it when I was in Korean middle school where I learned the law of definite proportions and the law of multiple proportions, but I think that it is interesting enough to be included here.

The law of reciprocal says

> If two different elements B and C combine separately with the same weight of a third element A, the ratio of the masses in which B and C do so are either the same or a simple multiple of the mass ratio in which B and C combine.

Let me give you an example.[6] 1 gram of sodium (Na = A) combines with either 1.54 grams of chlorine (Cl = B) or 5.52 grams of iodine (I = C). The ratio of these two weights is $5.52/1.54 = 3.58$. On the other hand, 1 gram of chlorine (Cl=B) reacts with 1.19 g of iodine (I=C). This ratio of 1.19 obeys the law because it is a simple fraction (1/3) of 3.58.

So, why does this happen? The atomic weights of sodium (Na), chlorine (Cl) and iodine (I) are 23, 35.5, and 126.9 respectively. One mole of sodium atoms and one mole of chlorine atoms combine to form one mole of sodium chloride (NaCl) molecules. Therefore, 23 grams of sodium combine with 35.5 grams of chlorine. In our example, we had

$$\frac{35.5}{23} = 1.54 \tag{3}$$

Similarly, one mole of sodium (Na) atoms combine with one mole of iodine (I) atoms to form one mole of sodium iodide (NaI) molecule. Therefore, 23 grams of sodium combine with 126.9 grams of chlorine. In our example, we had

$$\frac{126.9}{23} = 5.52 \tag{4}$$

Given this, consider the fact that one mole of iodine atoms combine with three moles of chlorine atoms to form one mole of iodine trichloride (ICl_3). In other words, 126.9 grams of iodine combine with $106.5(= 35.5 \times 3)$ grams of chlorine to form iodine trichloride. In our example, we had

$$\frac{126.9}{35.5 \times 3} = 1.19 \tag{5}$$

[5] Nash, Leonard K. "The Origin of Dalton's Chemical Atomic Theory." *Isis*, vol. 47, no. 2, 1956, pp. 101−116. *JSTOR*, www.jstor.org/stable/227334.

[6] Holmyard, E.J. (1931). *Inorganic chemistry - a text book for colleges and schools* (1st ed.). pp. 16–17.

The point of the law of reciprocal relations was that the ratio of 5.52 obtained in (4) to 1.54 obtained in (3) is a simple multiple ratio of 1.19 obtained in (5). In other words,

$$5.52 \div 1.54 = 3.58 \tag{6}$$

and

$$3.58 \div 1.19 = 3 \tag{7}$$

which is indeed a simple ratio. So, why does such a coincidence happen?

Notice that (6) can be re-expressed using (4) and (3) as

$$\frac{126.9}{23} \div \frac{35.5}{23} = \frac{126.9}{35.5} \tag{8}$$

See that 23s in the denominators were canceled. Using (8) and (5), (7) can be re-expressed as

$$\frac{126.9}{35.5} \div \frac{126.9}{35.5 \times 3} = 3 \tag{9}$$

Notice that 126.9 and 35.5 were canceled. Therefore, all that is left is 3 in ICl_3.

In conclusion, the law of reciprocal proportions is satisfied because the atomic weight of each element has a fixed value, and a molecule contains a small positive integer number of atoms. The full version of the law of reciprocal proportions concerns a slightly more complicated chemical reactions, where two chemicals react to form two different chemicals, but the basic idea is same.

9 Do atoms really exist?

So far, we have seen many evidences for the existence of atoms, such as the law of definite proportions, the law of multiple proportions, and the law of reciprocal proportions. They are all pointing in one direction.

However, throughout the 19th century, many scientists were reluctant to accept the idea of atoms, even though they all knew these evidences, as they were only indirect ones and not direct ones. One of the most well-known opponents of atomic theory was the Austrian physicist and philosopher Ernst Mach. His philosophy was that only sensations were real. Therefore, he argued that atomic theory should be discarded, since we could not sense atoms directly and nobody should talk about what one cannot sense. He argued that atoms were mere hypothesis, and may be a convenient way to explain things but cannot be a reality.

Nevertheless, the problem of atomic theory was settled by experiments based on Einstein's paper on Brownian motion published in 1905, which I will now explain. If you put pollen grains or any other very small particles into water, or any other liquids, you will see that they randomly move. This is Brownian motion. Einstein suggested that it was due to the random motion of water molecules colliding randomly with the pollen grains. Notice that the random motions of pollen grains are possible because they are so small. If you put a bigger object into water, the random motion will be significantly smaller, as water molecules randomly colliding on one side of the big object will be more likely to be compensated by other molecules randomly colliding on the other side of the object. Think of it this way: if you randomly choose three SAT takers and calculate their average, the average is much more likely to be deviated from the average score of all SAT takers than the average score of hundred randomly chosen SAT takers. Einstein calculated what distance the very small particles move on average, given time of duration. This depends on the size of the small particle, the type of liquid in which the small particles are immersed, and the Avogadro number. In other words, by measuring the distance the very small particles move, one can deduce the Avogadro number. After learning this paper of Einstein, the French physicist Jean Perrin performed such experiments to verify Einstein's predictions. He tried different particles and different liquids, and they all agreed with the Avogadro number known at the time through the kinetic theory of gas, which we will talk about in later articles. Jean Perrin won the Nobel Prize in Physics in 1926 for these experiments.

Einstein's explanation of Brownian motion is not just about our nature; it finds application in finance. The ups and downs of prices, such as stock prices, show the characteristics of randomness usually seen in Brownian motion. If you are interested in learning more, you can read *The Physics of Wall Street: A Brief History of Predicting the Unpredictable* written for laymen by my Harvard classmate Prof. James Owen Weatherall.

10 Radioactivity

In late 1895, the German physicist Wilhelm Röntgen discovered a new type of rays, which penetrates soft objects such as cardboards or human tissues, but not hard objects such as metals or human bones. Röntgen named it "X-rays" because "X" is often used in mathematics to denote something that is unknown. We now know that X-rays are a type of light (i.e. electromagnetic waves), but the name just stuck. Notice how X-rays are different from visible light that human eyes can see. Visible light cannot penetrate not only hard objects such as metals or human bones but also soft objects such as cardboards or human tissues. If it could, you would be able to see what is inside a cardboard box without opening it. By 1896, X-rays were widely used for medical purposes, such as to diagnose bone fractures or gunshot wounds.

In early 1896, the news of the discovery of X-ray reached France. The French physicist, Henry Becquerel, then, wondered if phosphorescence materials, which re-emit light for up to several hours after absorbing light, also emit X-rays. To test this idea, he wrapped a photo plate with black papers and placed metal coins and a certain uranium compound, a type of phosphorescence material on it, and placed all of them to sunlight. Of course, he wrapped it with black papers to protect the photo plate from direct sunlight while allowing it to be exposed to X-rays. When he developed the photo plate, it was found that the rays from the uranium compound penetrated the black papers, but not the metal coins. Thus, Becquerel concluded that his idea was correct, and reported this finding to the French Academy of Sciences on February 27th 1896.

He tried to repeat this experiment on Wednesday 26th and Thursday 27th, but the sun was out only intermittently, so he placed his wrapped photo plates and the uranium compound in his drawer waiting for the sun to come out again. However, the sun was not out for the following days. On Sunday, March 1st, he developed the photo plates anyway, expecting to see some feeble, remnant X-rays having come out of the uranium compound long after it absorbed sunlight. However, to his surprise, the image in the photo plates was not weak but as clear as in the previous experiment; the uranium compound casted off rays even when it hadn't absorbed sunlight beforehand. Thus, Becquerel discovered that the uranium compound casts off rays similar to X-rays.

These rays were first called "uranic rays," but in 1898 the German physicist Gerhard Carl Schmidt and the Polish-born French chemist and physicist Marie Curie independently found that thorium also casts off these rays. Therefore, Marie Curie named these rays "rayons de Becquerel" or Becquerel rays in her 1898 paper. In the same paper, she also used the term "radioactive substance" which is now in common use. For example, uranium and thorium are radioactive substances. Marie Curie also found "All uranium compounds are active, the more so, in general, the more uranium they contain." She also showed that radioactivity is an atomic property. For example, if the molecules of a certain matter contain uranium atoms and thorium atoms, it shows radioactivity; the radioactivity of a certain matter doesn't disappear or appear through chemical reactions which merely re-arrange the radioactive atoms. She also found that two minerals which contained uranium compounds in them showed more radioactivity than the amount of uranium in them predicted. She concluded that the minerals contain an element much more radioactive than uranium. Thus, she introduced the concept that radioactive properties are a diagnostic for the discovery of new substances. Soon, Marie Curie's husband the French physicist Pierre Curie joined her in the research, and they found other new radioactive elements, radium and polonium.

In 1902, the New Zealander physicist Ernest Rutherford and his English student Frederick Soddy proposed the following transformation theory: "radioactive bodies contain unstable atoms of which a fixed fraction decay per unit time. The rest of the decayed atom is a new radio-element which decays again, and so forth, till finally a stable element is reached."[7] Rutherford explained to Soddy that they were going to name this the transformation theory, because if they named it the transmutation theory, "they'll have our heads off as alchemists." Notice also that transformation theory implies that the radioactivity of a substance is proportional to its amount. It is a step forward compared to the earlier quote of Marie Curie that a greater amount of radioactive substance has more radioactivity. Furthermore, it implies that there are "half-lives," the amount of time it takes an initial amount of substances to decay to half its size. For example, let's say that it took a minute for a hundred atoms to halve to fifty atoms. In other words, fifty atoms decayed and fifty were left. Now, if we have a sample of a thousand of these same atoms, we have ten times more atoms than the original sample. As it has a fixed fraction decay per unit time, ten times more atoms (five hundred)

[7] p113 *Inward Bound* by Abraham Pais

will decay during a minute. Therefore, it will take exactly a minute again for the atoms to be halved. Five hundred will be remaining. Afterwards, it will take exactly another minute again for the remaining atoms to be halved. Two hundred fifty will be remaining, and so on. This is the concept of half-life. Of course, we could introduce third-life or quarter-life as well, but they are redundant and the half-life is simplest, as you can see in the following problem.

Problem 5. Suppose we introduced "quarter-life." Explain, then, why the "quarter-life" is exactly double the half-life.(Hint[8]) This shows that "quarter-life" is redundant; we can figure out the quarter-life once we know the half-life. (Figuring out the "third-life" seems harder, but after learning "logarithm" from our later article "Logarithm" you will be able to do so using a scientific calculator. It's about 1.585 half-life.)

We will approach half-life mathematically in our later article "Differential equations." This allows us to determine a half-life, without actually waiting for the atoms to decay to half; we can determine a half-life within a much shorter period of time. Anyhow, half-lives of radioactive substance were first measured by Rutherford.

In 1903, Rutherford and Soddy went further than Marie Curie's assertion that radioactivity was an atomic property. They proposed a new principle called the "conservation of radioactivity": "Radioactivity, according to our present knowledge, must be regarded as a process which lies wholly outside the sphere of known controllable forces, and cannot be created, altered or destroyed."[9] They came to such a conclusion because many experiments verified it. For example, Marie Curie measured the radium heat production due to its radioactivity at liquid hydrogen temperature. Rutherford measured the radioactivity of radium bromide at 2500 degree Celsius. In both cases, no deviation from the case of room temperature was observed. Similarly, no deviation was observed under different pressures, under different concentrations, or in the presence of strong magnetic field.[10]

In 1901, Röntgen received the first awarded Nobel Prize in Physics for his discovery of X-rays. In 1903, Becquerel and the Curie couple received the Nobel Prize in Physics for their work on radioactivity. In 1908, the physicist Rutherford was awarded the Nobel Prize in Chemistry for "his investigations into the disintegration of the elements, and the chemistry of radioactive substances." He jokingly remarked that among all the half-lives he had measured, his transformation from physicist to chemist was the shortest. In 1911, after the death of Pierre Curie, Marie Curie alone received the Nobel Prize in Chemistry for her discovery of the elements radium and polonium. We will talk more about radioactivity in the next article.

Summary

[8]Remember that, in our example, among the initial thousand atoms, only two hundred fifty were remaining after two minutes.

[9]E. Rutherford and F. Soddy, *Phil. Mag.* **5**, 576, 1903 requoted in p 115 *Inward Bound* by Abraham Pais.

[10]However, in 1947, Segré and Daudel independently found out that the chemical environment can affect the radioactivity in certain cases. By now, many such cases have been reported, but they are rare and the effect is less than a few percent. In any case, I personally did not know of any such cases until I read the history book *Inward Bound*.

- The conservation of mass suggests that matter is neither destroyed nor created during chemical reactions, but only change its form.
- The law of definite proportion says that a certain substance is chemically made out of definite proportions of other substances.
- The law of multiple proportions says, "If two elements form more than one compound (i.e. substances that are made out of more than one element) between them, then the ratios of the masses of the second element which combine with a fixed mass of the first element will be ratios of small whole numbers."
- Dalton's atomic theory naturally explains the conservation of mass, the law of definite proportion, and the law of definite proportion. The law of definite proportion can be explained from Dalton's postulate that, in chemical reactions, atoms combine with each other in simple, whole-number ratios to form combined atoms.
- The periodic table lists elements in such a way that the periodicity of elements can be well represented. It is mostly in order of their atomic weights, with some exceptions.
- The atomic theory was proven correct by Einstein who inferred the rough size of molecules from Brownian motion.
- 1 mole of carbon atoms weighs about 12 grams, and 1 mole of hydrogen atoms weighs about 1 gram.
- X-rays penetrate soft objects such as cardboards or human tissues, but not hard objects such as metals or human bones.
- Radioactivity is an activity of casting rays (called "radiation") due to decay of unstable atoms.