Chapter 2

Dream of Material Transmutation Realized by Nuclear Reaction

2.1 Alchemy

Alchemy in history

In a Greek legend, there is a King called Midas, who obtained a power to change anything that he touches with his hand into gold. As a result he lost the ability to take food. This story suggests that the human dream of turning ordinary metals into gold (alchemy) is more than 2500 years old.

This desire for transforming matter drove people in the ancient western world to experiment. Later, this tradition traveled to the Arabian countries and eventually back to Europe. In this process, alchemy developed various experimental techniques that were later adopted by chemistry, and it helped to prepare the ground for the birth of modern science in the 16th century by spreading the experimental attitude in the medieval Europe. Modern science build industrial society by finding rules from the vast knowledge and techniques accumulated during this long history of alchemy, and in that process, it seems to have abandoned the original dream of transforming matter.

Modern alchemy

However, from time to time, people are fascinated by magical power. Even Isaac Newton was said to have devoted more than a half of his effort into some supernatural phenomena. Just as we are attracted by supernatural phenomena, the 20th century scientists have been also curious about strange phenomena.

The dawn of the nuclear era has arrived after the discovery of radioactivity in uranium ore by E. Becquerel, which was done by accident as the discovery of X-ray by W.C. Röntgen, and the research work to discover radium by M. Curie. The spirit of alchemy was back again.

In 1926, a renowned German electrochemist F. Paneth made an attempt to convert hydrogen (protium) into helium. Electrolysis of water generates hydrogen and oxygen. He thought that if he used palladium for the cathode, it would absorb the hydrogen. Four hydrogen atoms would then combine to form helium. His experiment, however, did not show clear evidence for the generation of helium, finally.

Quantum physics was at its infant stage at that time and neutron had not been discovered yet. An atomic nucleus was considered to be made up with protons and electrons. Nuclear fission reaction had been discovered in the end of the 19th century and Rutherford had found an artificial radioactivity by 1919. Paneth must have speculated the possibility of nuclear fusion as the reverse reaction of nuclear fission. Palladium had been known to absorb large amount of hydrogen. Palladium can occlude (absorb and keep it inside) the same number of hydrogen atoms as its atoms ("occlude" is a term used to describe this unique property of certain metals to absorb and hold a large quantity of gas molecules). There is no way of knowing how Paneth had arrived at the idea of 4 hydrogen atoms turning into helium.

Nonetheless, it is not so difficult to understand his hunch that something must happen between those protons that were placed tightly from each other in solid. Paneth's attempt must have motivated the electrochemist Fleischmann to do his new experiment about 60 years later.

2.2 Nuclear Physics realized Material Transmutation

The discovery of the neutron in 1932 by J. Chadwick in England accelerated understanding of the nucleus. Nuclear fusion reaction was assumed as the energy production mechanism in stars including the sun. In a star such as the sun, a tremendous amount of hydrogen (protium) is pulled together by its gravitational force, which causes the gas to heat up and sustain the nuclear fusion reaction. The mass of the sun is 300,000 times as much as that of the earth and the volume is 1,300,000 times as much. Therefore the average density is only 0.26 times the earth. The mass of the sun per cubic centimeter is only 1.41 gram. At high temperature, gas becomes plasma, in which atoms break into nuclei and electrons. We can say the sun is made of plasma.

Nuclear fusion in heavenly bodies

In the solar plasma, hydrogen nuclei (protons) undergo thermal motion and collide with each other many times. They are trapped in the solar gravity field and there is a very small chance to escape the field. The nuclei failed to fuse the first time have many more chances to collide again. There are four main fusion reactions that are taking place in the sun (these reactions are almost never happen on the earth, where the temperature is much lower. The readers who are not familiar with these reactions can skip them):

Fusion Reactions occurring in the Sun

$p - p$ reaction (1)

$$p + p \rightarrow d + e^+ + \nu_e, \tag{2.1}$$
$$d + p \rightarrow {}^3\text{He} + \gamma, \tag{2.2}$$
$${}^3\text{He} + {}^3\text{He} \rightarrow {}^4\text{He} + 2p. \tag{2.3}$$

$p - p$ reaction (2)

$$p + p \rightarrow d + e^+ + \nu_e, \tag{2.4}$$
$$d + p \rightarrow {}^3\text{He} + \gamma, \tag{2.5}$$
$${}^3_2\text{He} + {}^4_2\text{He} \rightarrow {}^7_4\text{Be} + \gamma, \tag{2.6}$$
$${}^7_4\text{Be} + e^- \rightarrow {}^7_3\text{Li} + \nu_e + \gamma, \tag{2.7}$$
$${}^7_3\text{Li} + p \rightarrow 2{}^4_2\text{He}. \tag{2.8}$$

C − N − O cyclic reaction (1)

$${}^{12}_6\text{C} + p \rightarrow {}^{13}_7\text{N} + \gamma, \tag{2.9}$$
$${}^{13}_7\text{N} \rightarrow {}^{13}_6\text{C} + e^+ + \nu_e, \tag{2.10}$$
$${}^{13}_6\text{C} + p \rightarrow {}^{14}_7\text{N} + \gamma, \tag{2.11}$$
$${}^{14}_7\text{N} + p \rightarrow {}^{15}_8\text{O} + \gamma, \tag{2.12}$$
$${}^{15}_8\text{O} \rightarrow {}^{15}_7\text{N} + e^+ + \nu_e, \tag{2.13}$$
$${}^{15}_7\text{N} + p \rightarrow {}^{12}_6\text{C} + {}^4_2\text{He}. \tag{2.14}$$

C − N − O cyclic reaction (2)

$${}^{14}_7\text{N} + p \rightarrow {}^{15}_8\text{O} + \gamma, \tag{2.15}$$
$${}^{15}_8\text{O} \rightarrow {}^{15}_7\text{N} + e^+ + \nu_e, \tag{2.16}$$

$$
\begin{aligned}
{}^{15}_{7}\mathrm{N} + p &\rightarrow {}^{16}_{8}\mathrm{O} + \gamma, &(2.17)\\
{}^{16}_{8}\mathrm{O} + p &\rightarrow {}^{17}_{9}\mathrm{F} + \gamma, &(2.18)\\
{}^{17}_{9}\mathrm{F} &\rightarrow {}^{17}_{8}\mathrm{O} + e^{+} + \nu_e, &(2.19)\\
{}^{17}_{8}\mathrm{O} + p &\rightarrow {}^{14}_{7}\mathrm{N} + {}^{4}_{2}\mathrm{He}. &(2.20)
\end{aligned}
$$

Where p stands for proton, d for deuteron, e^+ is positron, γ is photon, and ν_e represents neutrino. The nuclear symbols such as ${}^{3}_{2}\mathrm{He}$ for helium-3 are explained in the Appendix 17.2.

The C-N-O cycles (1) and (2) were discovered by H.A. Bethe and C.F. von Weizsäcker. These reactions assume the pre-existence of carbon and nitrogen isotopes ${}^{12}_{6}\mathrm{C}$ and ${}^{14}_{7}\mathrm{N}$. In fact these elements are found in stars. They are recreated at the end of reaction and the number remains unchanged. In this regard, these nuclei can be considered as catalysts. We will treat the catalyst in more detail in the next chapter.

Nuclear fusion on Earth

The first nuclear fusion on the earth was realized rather unfortunately as a form of the hydrogen bomb. This negative heritage, however, created a dream of obtaining an unlimited source of energy by controlling nuclear fusion reaction. In 1950, the possibility of obtaining a controlled thermal nuclear fusion was theoretically predicted. The idea was to create a plasma to cause fusion reaction in a controlled manner and to use it as an energy resource. Since it is impossible to duplicate the reactions happening in the sun, the following reactions were proposed as the most likely scenario:

Nuclear Reactions available in the Controlled Thermonuclear Fusion

Nuclear Reaction with Pre-existence of Neutron n

$$
n + {}^{6}_{3}\mathrm{Li} \rightarrow {}^{4}_{2}\mathrm{He} + t + 4.8\ \mathrm{MeV}. \qquad (2.21)
$$

Nuclear Reaction with Pre-existence of High-Energy Proton p (ε)

$$
\begin{aligned}
p(\varepsilon) + {}^{6}_{3}\mathrm{Li} &\rightarrow {}^{4}_{2}\mathrm{He} + {}^{3}_{2}\mathrm{He} + 4.0\ \mathrm{MeV} + \varepsilon, &(2.22)\\
p(\varepsilon) + {}^{11}_{5}\mathrm{B} &\rightarrow 3\,{}^{4}_{2}\mathrm{He} + 8.7\ \mathrm{MeV} + \varepsilon. &(2.23)
\end{aligned}
$$

Nuclear Reaction with Pre-existence of High-Energy Deuteron $d\ (\varepsilon)$

$$d(\varepsilon) + d \rightarrow t + p + 4.0 \text{ MeV} + \varepsilon, \quad (2.24)$$
$$d(\varepsilon) + d \rightarrow {}^3_2\text{He} + n + 3.3 \text{ MeV} + \varepsilon, \quad (2.25)$$
$$d(\varepsilon) + t \rightarrow {}^4_2\text{He} + n + 17.6 \text{ MeV} + \varepsilon, \quad (2.26)$$
$$d(\varepsilon) + {}^3_2\text{He} \rightarrow {}^4_2\text{He} + p + 18.4 \text{ MeV} + \varepsilon. \quad (2.27)$$

Where n and t represent neutron and triton, respectively. The numbers on the right hand sides represent the released energy in MeV (See Appendices 17.2 and 17.4 for details).

It has become evident, however, that even the easiest of all the fusion reactions requires a condition that is not easy to achieve. In order to generate energy out of the $d - t$ reaction, for example, it requires a plasma with a temperature 100 million K (10^8 K) at a density of 10^{15} cm^{-3}, which has to be confined more than 1 second. The higher the temperature of the plasma, the harder it is to be confined. It is as if trying to catch an eel with bare hands. The livelier the eel, the more difficult to grab them. Despite the worldwide effort by so many scientists and engineers with so much money and so much time over the last 40 years, the only thing that is certain now is that we do not even know if there will be controlled nuclear fusion by the year 2050.