V

THE CONSTITUTION OF ATOMIC NUCLEI

THE modern chemical theory of atoms was proposed by John Dalton early in the nineteenth century. During that century atoms were thought of as very small indivisible hard particles. In 1897, Sir J. J. Thomson discovered electrons, which are small particles of negative electricity much lighter than atoms, and it was found that atoms contain electrons and so are not indivisible particles. In 1911, Lord Rutherford suggested that atoms consist of a minute, heavy particle or nucleus much smaller than the atom with electrons moving about outside the nucleus. According to this nuclear theory an atom is like the solar system. The sun and its planets are like the nucleus with the electrons moving round it.

Nearly all the weight of an atom is in the nucleus, the electrons only account for about one four-thousandth part of the weight.

The relative weights of the atoms of different elements are known accurately. They have been determined experimentally by several independent methods which give practically identical results. Table I gives the atomic weights of several elements, taking that of oxygen to be 16. These atomic weights are all nearly whole numbers, which suggests that the atoms are built up out of particles of atomic weight approximately unity. It is customary now to regard atoms as compounds of neutrons and ordinary hydrogen atoms, which both have atomic weights slightly

TABLE I

Atomic Weights

Neutron	1.0083	Beryllium	8.0071
Hydrogen	1.0079	Beryllium	9.0137
Hydrogen	2.0141	Beryllium	10.0149
Hydrogen	3.0162	Boron	10.0141
Helium	3.0170	Boron	11.0112
Helium	4.0033	Carbon	12.0037
Lithium	6.0162	Nitrogen	14.0075
Lithium	7.0170	Oxygen	16.0000

TABLE II

Element	Symbol	Neutrons	Protons	Electrons
Electron	$\bar{e}$	0	0	1
Neutron	${}_0n^1$	1	0	0
Hydrogen	${}_1H^1$	0	1	1
Hydrogen	${}_1H^2$	1	1	1
Hydrogen	${}_1H^3$	2	1	1
Helium	${}_2He^3$	1	2	2
Helium	${}_2He^4$	2	2	2
Lithium	${}_3Li^6$	3	3	3
Lithium	${}_3Li^7$	4	3	3
Beryllium	${}_4Be^8$	4	4	4
Beryllium	${}_4Be^9$	5	4	4
Beryllium	${}_4Be^{10}$	6	4	4
Boron	${}_5B^{10}$	5	5	5
Boron	${}_5B^{11}$	6	5	5
Carbon	${}_6C^{12}$	6	6	6
Carbon	${}_6C^{13}$	7	6	6
Nitrogen	${}_7N^{14}$	7	7	7
Nitrogen	${}_7N^{15}$	8	7	7
Oxygen	${}_8O^{16}$	8	8	8
Oxygen	${}_8O^{17}$	9	8	8

greater than 1. The neutron is a recently discovered particle which is electrically neutral.

The nucleus of an atom of ordinary hydrogen is called a proton, and it may be regarded as a particle of positive electricity. The positive charge of a proton is equal to the negative charge of an electron, and an atom of ordinary hydrogen consists of one proton with one electron moving round it. The proton and the electron attract each other just as the sun and a planet do. The nuclei of atoms are built up out of neutrons and protons, and the number of electrons outside the nucleus is equal to the number of protons inside it. There are no electrons inside the nucleus. Table II gives the numbers of neutrons, protons, and electrons in the atoms of the elements in Table I.

The chemical properties of an atom are determined by the number of electrons it contains so that, for example, the three different sorts of beryllium atoms with atomic weights approximately 8, 9, and 10, respectively, all contain four electrons and so all have the same chemical properties and are therefore regarded as atoms of the same element, beryllium, although they have different weights. The number of protons or electrons in the atom of an element is called the atomic number of the element. In the same way we have three sorts of hydrogen atoms with atomic weights approximately 1, 2, and 3, but all with the atomic number 1.

The weight of an atom is always slightly less than the sum of the weights of the neutrons, protons, and electrons which it contains. Since the number of protons is always equal to the number of electrons, we may regard the atoms as made up of neutrons and of hydrogen atoms each containing one proton and one electron. The helium atom of atomic weight 4.0033 contains two neutrons and two hydrogen atoms, the total weight of which is 4.0324, thus:

$$
\begin{array}{r}
2\times 1.0083 = 2.0166 \\
2\times 1.0079 = \underline{2.0158} \\
\underline{4.0324}
\end{array}
$$

The loss of weight in this case is therefore the difference

$$
\begin{array}{r}
4.0324 \\
\underline{4.0033} \\
\underline{0.0291}
\end{array}
$$

In the same way for oxygen ${}_8O^{16}$ we have

$$
\begin{array}{r}
8\times 1.0083 = 8.0664 \\
8\times 1.0079 = \underline{8.0632} \\
\underline{16.1296}
\end{array}
$$

so that there is a loss of 0.1296, since the atomic weight of oxygen is exactly 16.

In ordinary chemical reactions the total weight of the products formed is always equal to that of the materials used up, so that there is no loss of weight, or at least the loss of weight is so small that it cannot be detected. It is therefore clear that the hypothetical formation of atoms by the combination of neutrons and hydrogen is a very different process from ordinary chemical combination.

According to Einstein, energy has weight, and it is believed that the loss of weight when atoms are formed out of neutrons and hydrogen is due to the emission of energy. An atom has less total energy than the neutrons and hydrogen atoms out of which it was formed, and so has less weight. The loss of weight is therefore a measure of the energy of formation.

The amounts of energy involved are very large. For example, if sixteen pounds of oxygen were formed by the combination of neutrons and hydrogen, the energy set free would weigh 0.1296 of a pound, or a little more than two ounces. This amount of energy is equivalent to more than two hundred thousand horse-power for one year. At one cent a kilowatt hour it would be worth about fifteen million dollars. It is possible that before our oil has been exhausted methods will be discovered for making available the energy of formation of atoms for commercial purposes. This will require the transmutation of elements with low energies of formation into elements with higher energies of formation, so setting free the difference. The science of the transmutation of the elements is a very recent growth and may be expected to develop rapidly. In the long run the study of the constitution of atomic nuclei may be expected to be profitable, just as so many other branches of pure science have proved to be.

The energies of formation of the elements in Table I are given in Table III. They were calculated by subtracting the atomic weight of the atom from the total atomic weights of the neutrons and hydrogen atoms out of which the atom is formed, so getting the loss of atomic weight. These losses are nearly multiples of a constant equal to 0.000415, and so may be conveniently expressed in terms of this quantity

TABLE III

ENERGIES OF FORMATION

(In terms of 0.000415 atomic weight units as unit)

Hydrogen	${}_1H^2$	5	Beryllium	${}_4Be^9$	143
Hydrogen	${}_1H^3$	20	Beryllium	${}_4Be^{10}$	160
Helium	${}_2He^3$	17	Boron	${}_5B^{10}$	161
Helium	${}_2He^4$	70	Boron	${}_5B^{11}$	188
Lithium	${}_3Li^6$	78	Carbon	${}_6C^{12}$	225
Lithium	${}_3Li^7$	96	Nitrogen	${}_7N^{14}$	255
Beryllium	${}_4Be^8$	139	Oxygen	${}_8O^{16}$	312

as unit. The energies of formation are proportional to the loss of atomic weight, and so may be expressed in terms of the same unit.

The energies of formation represent the work done by the forces of attraction between the neutrons and protons when they combine together to form the atomic nucleus. It is supposed that these particles attract each other strongly when they are very near together or actually in contact. When two particles are connected together by the attraction between them, we may say that a bond or connection has been formed between them, and we may suppose that the formation of such a bond always involves the liberation of a definite amount of energy. On this view the energy of formation of a nucleus should be equal to the sum of the bond energies of the bonds formed in the nucleus. There are three different sorts of bonds which may be formed, namely, bonds between two protons, bonds between two neutrons, and bonds between a neutron and a proton. To account for the energies of formation we may try to find bond energies and arrangements of the neutrons and protons in the nucleus such as to give the correct energies of formation. I have found that taking the energy of a proton-proton bond equal to 21, that of a neutron-neutron bond equal to 9, and that of a proton-neutron bond equal to 10, makes it possible to find arrangements of the neutrons and protons giving the

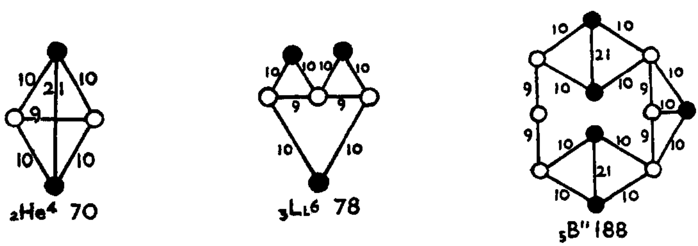


Figure 1

correct energies of formation. Figures 1 and 2 show such arrangements for several atoms. The black disks represent a proton and the circles a neutron. The lines connecting the neutrons and protons represent the bonds between them, and the numbers at each line are its energy of formation. The sum of the bond energies gives the energy of formation, and the sums agree with the values given in Table III. In this way we obtain possible arrangements and bond energies, but we do not know if the arrangements chosen are the actual

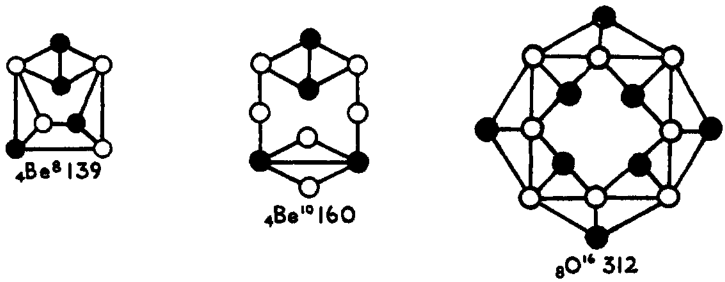


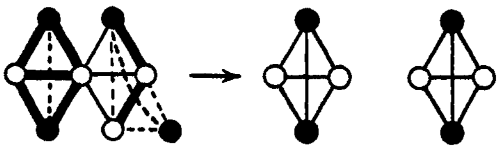
Figure 2

ones. Different arrangements with different bond energies might also give the correct energies of formation.

During the past fifteen years many cases of the artificial transmutation of one element into another have been discovered. The first such transmutation was discovered by Lord Rutherford in 1919. These transmutations, or nuclear reactions, as they are called, occur when a particle, such as a proton, moving with high velocity collides with an atom. The proton enters the nucleus of the atom, combining with it. The nucleus then disintegrates or explodes, emitting a particle which is not the same as the particle which previously combined with it. The atomic weight of the nucleus is thus altered, and it is changed into the nucleus of a different atom. For example, a lithium atom of atomic weight 7 can combine with a proton forming a new atom of atomic weight 8 which then disintegrates into two helium atoms each of atomic weight 4. This nuclear reaction may be represented by the equation

$$ {}_3Li^7 + {}_1H^1 \rightarrow {}_2He^4 + {}_2He^4 $$

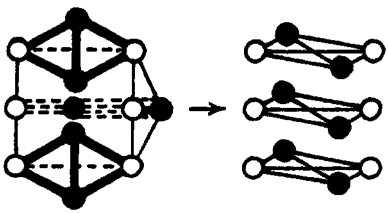
Figure 3 shows how the neutrons and protons may be supposed to be rearranged in this reaction. The bonds in the



$ {}_3Li^7 + {}_1H^1 \longrightarrow {}_2He^4 + {}_2He^4 $

Figure 3

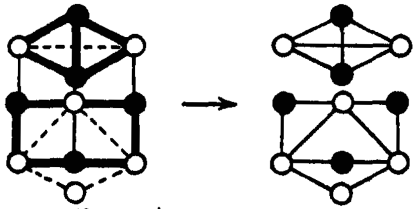
lithium atom which remain unchanged are represented by thick lines, the new bonds to be formed by dotted lines, and the bonds which disappear by thin lines. A very similar transmutation occurs when a boron atom combines with a proton and then disintegrates into three helium atoms. This



$ {}_5B^{11} + {}_1H^1 \longrightarrow 3\,{}_2He^4 $

Figure 4

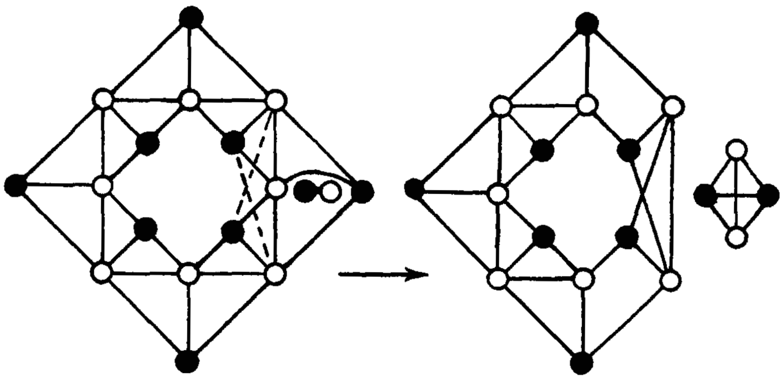
is shown in Figure 4. When boron ${}_5B^{10}$ combines with a neutron, we get the transmutation into lithium and helium shown in Figure 5. The boron ${}_5B^{10}$ after combining with the



$_{5}B^{10} + _{0}N^{1} \rightarrow _{2}He^{4} + _{3}Li^{7}$

Figure 5

neutron may also disintegrate into two helium atoms and one hydrogen atom of atomic weight 3. Another nuclear reaction is shown in Figure 6. Oxygen combines with hydrogen of atomic weight 2 and then disintegrates into nitrogen and helium. These examples are perhaps sufficient to show that the assumed nuclear constitutions are compatible with the observed nuclear reactions or transmutations. All known



$_{8}O^{16} + _{1}H^{2} \longrightarrow _{7}N^{14} + _{2}He^{4}$

Figure 6

nuclear reactions involving the elements considered can be represented in a similar way.

The atoms formed in nuclear reactions sometimes have more than the normal amount of energy, which means that some of the bonds of the normal atom are absent or have less than the normal energies of formation. For example, the atom of hydrogen $_1H^2$ has energy of formation 5 instead of the normal value 10 for a bond between a neutron and a proton. The atom of helium $_2He^4$ is sometimes formed with energies of formation 40 or 30 instead of the normal value 70. Atoms with less than the normal energy of formation are called excited atoms, and such atoms usually emit radiation with energy equal to the difference between the normal energy of formation and their lower energy of formation and so change to normal atoms. The helium atom with energy of formation 30 changes to one with 40 emitting radiation with energy 10, and then changes to a normal atom emitting radiation with energy 30.

The suggested nuclear constitutions, therefore, appear to be supported by the evidence at present available, but, of course, they may require modification as new facts are discovered. In such a recently developed branch of physics, final conclusions are not to be expected for a long time.

The further study of nuclear reactions may be expected to result in the determination of the constitutions of the nuclei of the elements of higher atomic weights. Such knowledge should be of great value, and nuclear reactions are being studied experimentally in several laboratories in this country and in Europe. Unfortunately, the equipment required for such work is very elaborate and costly, so that laboratories where ample funds are available have a great advantage over those with limited resources.

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