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Nuclear Chemistry

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NUCLEAR CHEMISTRY

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In 1919 Rutherford, in a paper modestly entitled "Collision of α-particles with Light Atoms," described the first experiment in nuclear chemistry, perhaps one should say the first controlled experiment in nuclear chemistry. Natural radioactivity which involves the transmutation of heavier elements was known at that time. In the disintegration of radioactive elements, radium, for example, we find the radium atom changing spontaneously into radium emanation, one of the noble gases, and helium, another noble gas. But such transformations proceed at a rate and in a manner entirely independent of any condition that the chemist or physicist has been able to impose on the elements.

In the experiment reported by Rutherford α-particles were shot into various gases, e. g., hydrogen, oxygen, and nitrogen. When the α particle strikes the nucleus of an atom, e. g., a hydrogen nucleus, it communicates to the atomic nucleus a certain fraction of its momentum and causes the struck nucleus to proceed through the gas. If the atomic nucleus which is struck has a mass less than that of the α particle, its velocity and range may be longer than that of the α particle. The range may be determined by the scintillations produced by the particles as they strike a sensitive screen or by the Wilson cloud track apparatus.

The Wilson cloud track apparatus contains a gas, usually air, saturated with water vapor. If the gas is suddenly expanded the water vapor will cool and condense. Water vapor condenses very readily on ions. If some ionizing agent is active in the air the water droplets will form about the ions. If an α particle is shot through the air its path is made visible as a white streak, a cloud in the form of a narrow pencil which gathers about the ions produced by the α particle. We see in these individual "tracks" a single atom as nearly as we probably ever shall see one. We can at least see the effects of individual atoms and can count them one by one.

The Wilson cloud track apparatus is very useful in studying nuclear processes, those in which a relatively small number of atoms is involved. By measuring the range of the ionizing particle in various gases and the radius of curvature in a magnetic field, the energy and ratio of charge to mass of the particle may be determined. The density of the cloud, and hence of the ions, along the path also gives some information concerning the ionizing particle.

The Rutherford-Bohr picture of the atom is used as a guide by the physicist in his study of the atom. In this picture the atom consists of a nucleus surrounded by a cloud of electrons which for some purposes are assumed to move in orbits and these orbits are placed in groups having different energies. The nucleus contains a positive charge equal to that of the total negative charge around it and the nucleus contains the greater portion of the mass of the atom. It is well to realize at once the size of the nuclei with which we are to deal. It is very small compared to the electron cloud or the diameter usually associated with the atom. If the nucleus is assumed to be the size of a pin-head, the atom would more than fill this room. The ratio of their diameters is of the order of 1 to 100,000.

Ordinary chemical properties of the elements depend on the outer shell of electrons. This shell may contain 1 to 8 electrons. The total number of orbital electrons equal to the net charge on the nucleus is called the atomic number. This number characterizes the atom more completely than any other single feature and we may have numbered the atoms instead of naming them; e. g., H 1, He 2, Li 3, Be 4, B 5, C 6, N 7, O 8, etc. to U 92. The atomic number determines the place of the element in the periodic table. Two atoms may have the same charge on the nucleus but have different masses. Such atoms are called isotopes. The total number of different species of atoms, considering atomic weights as determining species, is more than 280. The chemical properties, that is, the ordinary chemical properties of isotopes are identical. For example, there are two isotopes of chlorine, having atomic weights of 35 and 37, which cannot be separated by chemical processes. The nuclei of these isotopes, however, are different and isotopes may, and in general do have, different nuclear chemical properties.

To get atoms to react in the ordinary chemical ways, that is, to combine to form molecules, the atoms must be brought close together, we say in contact. To obtain nuclear changes we may expect that we shall need to bring nuclei into contact. Nuclei, however, have highly concentrated positive electric charges, we may say approximately point charges. To bring nuclei into contact or to have one nucleus penetrate another we must give them a large momentum (energy), otherwise the electric forces between the charges following the inverse square law will deflect the particles so that no collision results.

The α particles from some radioactive substances have a velocity about 1/20 the velocity of light and therefore have sufficient momentum to collide intimately with and to enter the nucleus of the nitrogen atom as Rutherford's experiment showed. Later experiments showed that about a dozen light elements of low atomic number were disrupted by α particles. The process in nitrogen as shown by the Wilson cloud track apparatus involved the capture of the α particle and the explusion from the nucleus of a hydrogen particle. The α particle has a mass of 4 units and a charge of 2. The hydrogen particle has a unit mass and unit charge. The new atom formed had a mass 3 units larger than the old and a unit charge larger. Its atomic weight was therefore 14+3 or 17, and its atomic number 7+1 or 8. The new atom was an isotope of 0 ($_8O^{17}$).

Less than one α particle in 10,000 comes so close to the nitrogen nucleus that it enters and is captured by it. The number of α particles is limited by the amount of radioactive material available. If the physicist could produce high speed particles in the laboratory perhaps he could disrupt atoms in large numbers and be independent of radioactive substances. The desire to do this lead to the development of high voltage machines capable of producing electric fields within which an ion could be given sufficient energy to disrupt nuclei as α particles have done.

I shall not give a chronological history of these machines and methods of producing high voltage, but shall describe several of them. One of the obvious methods of producing high voltage is to use a transformer. Potential differences of a million volts are obtained in this way. The machines are large and have the disadvantage of producing an alternating field.

Another scheme is that of Van de Graaff. A static electric charge always resides on the *surface* of the conductor. In the Van de Graaff machine electric charges are *mechanically* brought *within* a spherical conductor by means of an insulating belt. The charges are then taken from the belt and allowed to charge the sphere. The charge and potential of such a system are limited practically by the leakage from the sphere. Leakage is determined by the size of the sphere and the distance it can be placed from surrounding objects. The radius of curvature of its parts must be large. One machine at Round Hill, Massachusetts has two spheres 15 feet in diameter and is housed in an airship hangar.

A method devised by Lawrence involves multiple acceleration of ions. Charged particles, i. e. ions, when moving at right angles to a magnetic field follow circular paths. The radius of curvature increases as the velocity of the ions increases. Hence the time required to traverse a portion of a circular arc is independent of the speed since the speed increases as the arc length increases. In the machine built by Lawrence the ions move in circular (spiral) paths at right angles to an intense magnetic field and pass through an accelerating electric field twice in each complete circuit. This electric field may give potential drops of the order of 20,000 volts. It is supplied by a constant frequency oscillator. Lawrence has obtained ½ microampere of ions at 3,000,000 volts. A dozen or more *cyclotrons,* as these machines are called, are being built in various laboratories. Machines producing 10,000,000 volt ions are planned. The one at the University of California has 65 tons of steel in its magnet and 9 tons of copper in its coils. The one at Princeton will require 8 tons of copper in its windings. You will note that the apparatus required for nuclear chemistry is of different order of magnitude from the test tube used in the ordinary chemical laboratory.

We shall now describe some of the results obtained with high speed ions. We shall give energy in terms of electron volts, i. e., a unit of energy equal to that acquired by an electron falling through a potential difference of one volt.

Several years ago physicists listed electrons (negatively charged) and protons (H nuclei positively charged) as the fundamental building blocks of nature. They toyed with the idea that perhaps there existed particles which had zero charge and which would therefore be very difficult to detect. Rutherford suggested that no container could hold matter composed of these particles, called neutrons. Since they lacked a charge they could pass readily through and between molecules. In 1930 Bothe and Becker noted that when α particles from Po bombarded a number of light elements a very penetrating radiation which they thought to be γ rays was produced. Madame Curie and Monsieur Joliot also noted this radiation. In 1932 Chadwick definitely showed that the radiation was not electromagnetic in character, i. e., composed of γ rays, but that it was a stream of very penetrating particles, which have been identified as neutrons. These particles actually passed through lead more readily than did hard X-rays or γ rays. A sheet of lead 2 cms thick placed between the source, Po on a Be plate, did not materially change the ionization in a detecting chamber. However, when paraffin was placed between the source and the detecting chamber the ionization was considerably *increased.* Chadwick showed that the radiation from the Po-Be source ejected protons ($_1H^1$) from the hydrogen in the paraffin. These protons having a range of 40 cm in air increased the ionization in the detector. In a variety of tests the radiation from the Po-Be source has been shown to be a stream of neutral particles and we may now add the neutron to our list of *fundamental particles.* One may be tempted to assume that the neutron is a close union of a proton and an electron. There is, however, little evidence to support that assumption and much against it. Neutrons have been yielded by other reactions than α particles on Be and their mass has been determined as very nearly that of a proton.

The hydrogen isotope of mass 2 has now been isolated and this nucleus, called the deuteron, is often used in nuclear disintegrations. We shall list it in our table of particles. (Table I).

The positron is now well established. It was discovered in the study of cosmic rays. Wilson cloud tracks were observed which had the same characteristics as electron tracks except that the sign of curvature seemed to be wrong. Anderson and others have definitely shown that the tracks are produced by positive electrons now called positrons and not by electrons travelling in a reverse direction from that expected.

We include in our Table I the neutrino. This particle of zero charge and mass equal to that of the electron, i. e., a light neutron, is postulated to describe the decay of some radioactive materials emitting β rays. Without some such particle it appears that energy

TABLE I.

PARTICLES COMMONLY INVOLVED IN NUCLEAR TRANSFORMATIONS. ATOMIC WEIGHTS ARE INDICATED BY SUPERSCRIPTS, ATOMIC NUMBERS BY SUBSCRIPTS

Particle	Name	Mass $O^{16}=16$	Charge
${}_0n^1$	Neutron	1.0085	0
${}_1H^1$	Proton	1.00807	+1
${}_{-1}e^0$	Electron	$\frac{1}{1847} \times 1.00807$	−1
${}_{+1}e^0$	Positron	$\frac{1}{1847} \times 1.00807$	+1
${}_0n^0$ (?)	Neutrino	$\frac{1}{1847} \times 1.00807$	0
${}_1H^2$	Deuteron	2.01423	+1
${}_2He^4$	Alpha (He)	4.00336	+2

and momentum are not conserved in a process in which the β ray (electron) is emitted.

Typical reactions which have been observed are given in Table II. The first reaction is that of deuterons on deuterons (heavy hydrogen). The products are neutrons (${}_0n^1$) and the helium isotope of mass three. Two reactions are possible when nitrogen is bombarded by α particles (${}_2He^4$). One may obtain an isotope of oxygen (${}_8O^{17}$) and the proton (${}_1H^1$) or one may obtain fluorine and a neutron. The ${}_9F^{17}$ is not stable but disintegrates into ${}_8O^{17}$ and ${}_{+1}e^0$ (positron). This "induced" radioactivity has a half-life of 1.1 min.

Neutrons having no charge enter nuclei relatively easily and Fermi and his co-workers have recorded a large number of reactions with *heavier* elements which have not been disinterrupted by *charged* particles. Often a proton is ejected when the neutron enters the nucleus and the resulting product is in many cases radioactive. A very recent paper by Cork and Lawrence reports that 5,000,000 volt *deuterons* (charged) may be driven into the platinum nucleus (heavy) and a proton ejected. The resulting heavy nucleus is radioactive. It thus appears that perhaps the nuclei of higher atomic

TABLE II

TYPICAL NUCLEAR REACTIONS

${}_1H^2 + {}_1H^2 = {}_2He^3 + {}_0n^1$	${}_8O^{16} + {}_0n^1 = {}_6C^{13} + {}_2He^4$
${}_3Li^7 + {}_1H^1 = 2\,{}_2He^4$	
${}_3Li^7 + {}_1H^2 = 2\,{}_2He^4 + {}_0n^1$	${}_{20}Ca^{40} + {}_2He^4 = {}_{21}Sc^{43} + {}_1H^1$
${}_7N^{14} + {}_2He^4 = {}_8O^{17} + {}_1H^1$	${}_{21}Sc^{43} \rightarrow {}_{20}Ca^{43} + {}_{+1}e^0$ (4 hr)
${}_7N^{14} + {}_2He^4 = {}_9F^{17} + {}_0n^1$	
${}_9F^{17} \rightarrow {}_8O^{17} + {}_{+1}e^0$ (1.1 min)	${}_{21}Fe^{56} + {}_0n^1 = {}_{25}Mn^{56} + {}_1H^1$
${}_6C^{12} + {}_1H^1 = {}_7N^{13}$	${}_{25}Mn^{56} \rightarrow {}_{26}Fe^{56} + {}_{-1}e^0$ (2–5 hr)
${}_7N^{13} \rightarrow {}_6C^{13} + {}_{+1}e^0$ (10.5 min)	

number may be disintegrated by *charged* particles if sufficient energy is given those particles.

Altogether some 120 reactions have been fairly definitely established. We note that the equations in Table II balance in a manner different from the ordinary chemical equation. Here the total atomic number, the total charge on the nucleus is conserved and so is the total mass but the number of atoms and the atomic symbols may be different on one side from those on the other. The equations show that the same colliding particles do not always produce the same results. These differences are sometimes traced to differences in energy of the colliding particle but in many cases the reasons for the differences are not known. The efficiencies of the processes also vary from reaction to reaction for different energy of the particles. One transmutation may take place for every hundred thousand colliding particles and another may occur once for every 10,000,000 particles. It does not appear likely that these methods will be used to produce large quantities of the elements.

The equations as given in Table II are not strictly balanced. We should include the kinetic energy of the colliding particles and write the masses very much more accurately than they are indicated by the mass numbers written as superscripts. The theory of relativity leads us to consider mass and energy as equivalent through the relation energy $=$ mass $\times C^2$, where C is the velocity of light. Nuclear transmutations have verified experimentally this relation. Table III shows several reactions balanced by the inclusion of the energy. Introduction of numerical values into the relation, energy $=$ mass $\times C^2$, lead to, 1 MEV (million electron volt) $= .00107$ mass unit ($O^{16} = 16$).

The products of the reactions often involve protons (${}_1H^1$) and neutrons (${}_0n^1$). In the texts of a year or two ago you will find statements that protons and electrons are in the nucleus because in radioactive disintegrations electrons, (${}_{-1}e^0$) i.e., β rays are ejected. And if such particles come from the nucleus, were they not in it? This argument was attacked some years ago by Bragg, I believe, who drew this analogy. Suppose the nearest you could approach a shotgun was a mile. You could not examine it closer but must describe shotguns by what you observe at the distance of a mile. Our description would probably say that shotguns contained puffs of smoke since puffs of smoke came from them. But maybe puffs of smoke are manufactured as they are ejected and if we could examine the shotguns at closer range we would not find puffs of smoke within them. It now seems that our argument that because electrons come from the nucleus there are electrons in the nucleus is invalid. Electrons are formed from protons and neutrons, i.e., a neutron may become a proton and in the process send out an electron. There are a number of lines of evidence, which cannot be given here, that indicate the nucleus is composed of protons and neutrons.

A striking result of recent experiments is that in reaction with the nucleus; a γ ray or very hard X-ray may produce an electron and a positron.

Since the amounts of material involved in nuclear reactions are *very* small one may well ask how the products are identified. One method involves the Wilson cloud tracks. The length of forks and angles between them give information concerning the mass and velocity of the ionizing particles. Conservation of mass and momentum are assumed at collision.

TABLE III

1 MEV = .00107 Mass Units

$0^{16} = 16$

Lithium bombarded with 200,000 volt deuterons yields 11,400,000 volt alpha particles

$$_3Li^6 + {_1H^2} + E_i = 2\ {_2He^4} + E_f$$

$$6.01614 + 2.01423 + .00021 = 2 \times 4.00336 + .0244$$

$$8.0306 \rightarrow 8.0302$$

Oxygen bombarded with 500,000 volt deuterons yields 3,000,000 volt alpha particles

$$_8O^{16} + {_1H^2} + E_i = {_7N^{14}} + {_2He^4} + E_f$$

$$16.000 + 2.01423 + .0005 = 14.0076 + 4.00336 + .0032$$

$$18.0147 \rightarrow 18.0142$$

A second method is to use radioactive indicators. As we have noted, many reactions produce an atom which is unstable and spontaneously breaks down just as do natural radioactive materials. If, for example, one is testing for $_7N^{13}$ which is radioactive he may expect to find it in the gaseous phase and that it will be removed at a temperature lower than that of liquid nitrogen. The presence of very minute amounts of radioactive material can be detected by their ionizing ability or the Wilson cloud tracks they produce. We can in fact count individual atoms by this process and in this way the elements formed in some reactions are determined.

If one is testing for the formation of radioactive $_{11}Na^{24}$ formed when magnesium is bombarded by deuterons

$$({_{12}Mg^{24}} + {_1H^2} = {_{11}Na^{24}} + {_2He^4} \text{ and } {_{11}Na^{24}} = {_{11}Mg^{24}} + {_{-1}e^0})$$

some Na would be added to the Mg after it had been bombarded by the deuterons. If the radioactive constituents follow the Na when it is separated from the magnesium by the usual chemical means one can conclude that the radioactive atom is an isotope of Na.

The discovery that many of the products of disintegration were radioactive was made by Curie and Joliot, daughter and son-in-law of the Curies of the past generation who contributed so much to our knowledge of naturally radioactive elements. They noted that when B was bombarded by α particles a radioactive gas was formed which emitted positrons. By radioactive we mean that the emission of positrons continues for some time after the bombardment of the B has been stopped. The equations are

$$({}_5B^{10} + {}_2He^4 = {}_7N^{13} + {}_0n^1 \text{ and } {}_7N^{13} = {}_6C^{13} + {}_{+1}e^0)$$

The N^{13} isotope formed is unstable breaking down into ${}_6C^{13}$ with the emission of the positron. The stability of an atom formed by nuclear reactions depends upon its mass relative to the sum of the masses of the free particles into which it may be decomposed. If the mass of the atom formed is greater than that of the sum of the masses of free particles, it may break up into such parts and the excess mass appear as kinetic energy of these parts.

Numerous "artificial" radioactive products, as they are called, have been produced. Fermi and his co-workers have bombarded by neutrons a large number of the heavier elements and determined the half life of the radioactive elements formed. By half-life we mean the time required for one half the atoms to disintegrate.

Elements in the first part of the periodic table, the lighter elements, may be made radioactive by bombardment with various products. Consider, for example, ${}_{11}Na^{24}$. It may be formed in at least five different ways. The half life of this atom is 15 hours and the efficiency of production is such that considerable quantities may be produced. Lawrence hopes to produce in one day radioactive Na equal in β ray activity to one gm of radium.

The practical uses of nuclear chemistry are not obvious. Since ${}_{11}Na^{24}$ emits γ rays it may be used therapeutically. Perhaps in the future if we have an ulcer of the stomach we may be given a dose of common table salt made radioactive. The radioactive Na will irradiate the stomach, within a few hours be converted into harmless magnesium which element may, however, do us some good.

CAST IRON PAVING BLOCKS

Abstract

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Minnesota has enormous quantities of iron ore, a part of which is high grade and is being utilized at the present time. The remainder is low grade but of such a nature that high grade ore can be manufactured from it. There is no possibility of exhausting the total supply of iron ore within this State for many generations, and, therefore, new uses for iron have been investigated in order to increase the market for ore.

Cast iron paving blocks have been in use for several years in France, Germany, Italy, and England, and have been declared to be superior to brick, granite block, wood block, or asphalt as a surfacing material over concrete for heavily trafficked streets and high-